Magnetic and Electrical Separation, Vol. 5, pp. 231-263
Reprints available directly from the publisher
Photocopying permitted by license only

APPLICATION OF *MAGSTREAM* IN MINERAL SANDS SEPARATION

T. KOJOVIC

Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Isles Road, Indooroopilly, Qld 4068, Australia

(*Received April 18, 1994, revised June 16, 1994*)

Abstract The *Magstream* separation process, developed by Intermagnetics General corporation, offers an alternative method for both laboratory and plant mineral separations. It is based on the concept of using a fluid whose effective density is magnetically derived. The separator can be applied to both purely gravimetric separation of non–magnetic materials and magnetic–gravimetric separation of paramagnetic material.

The separation density can be easily adjusted by changing the speed of rotation or process fluid concentration. A separation band can be drawn on a plot of particle density and magnetic susceptibility to illustrate the separation of particles that would be achieved. The process fluid is a non–toxic, water–based bio–degradable magnetic fluid, and relatively inexpensive compared to heavy liquids and sodium polytungstates.

The Model 100 separator available at the Julius Kruttschnitt Mineral Research Centre is portable and suitable for analysing small batch samples. The separator selectivity is at best ± 0.1 SG units, which may cause a lower grade of products in separations of materials with a small SG differential.

The separator has been evaluated for mineral sands applications. Several good applications of *Magstream* have been identified. Particularly effective separations were quartz/heavy mineral concentrate, kyanite/zircon, monazite/zircon and rutile/zircon (multiple passes required).

This paper describes the *Magstream* process, operation, the mathematical model of separation, and presents the results of the separation case studies in detail.

INTRODUCTION

The *Magstream* separator offers a new method in magnetic fluid sink–float separation technology. In this recent development [1], centrifugal forces on essentially non–magnetic particles in rotating magnetic fluids are opposed by radially inward buoyant forces. This results from an outward magnetic attraction on the radially confined fluid. This approach was shown to achieve net separation forces many times those possible with sink–float, using relatively dilute, low–viscosity static fluids of flowing slurries. The development of both a relatively inexpensive, raw ferromagnetic fluid concentrate from a by–product of paper manufacturing, and also high–gradient and lower–cost NdFeB permanent magnets led to the development of the *Magstream* separator described in this paper.

The potential applications of *Magstream* include characterisation of samples in mineral exploration or areas where the environmental issues and or cost of separations required would rule out the use of conventional heavy liquid separations. *Magstream* could also be used to reduce the sample size required for grain counting, quality control and application testing.

The objective of the evaluation project conducted by the Julius Kruttschnitt Mineral Research Centre (JKMRC) was to therefore identify appropriate areas of application of the *Magstream* in the mineral sands industry. The technical capability of a *Magstream* M–100 has been demonstrated through the separations completed for sponsors of this project. Some of the more critical issues examined include TBE and bromoform equivalent separations.

This paper describes the *Magstream* process, outlines the operating parameters, and presents the results of one of the major separations investigated, namely quartz/heavy mineral concentrate.

THE *MAGSTREAM* PROCESS

The *Magstream* process was developed by Intermagnetics General Corporation (IGC), New York, who have expertise in the development and manufacture of new superconducting materials and magnets. IGC is a leading producer of high–field

magnets for research and medical imaging applications. Recent developments in permanent magnet technology led to the development and patenting of a new process now recognised by the trademark *Magstream*™. Traditional magnetic sink–float (magnetohydrostatic) separation methods are well described by Andres et al. [2], and Andres [3] reviews their evolution to more practical separation processes.

The process offers a new method for both gravimetric and magnetic separation. A combined magnetic/gravimetric separation is, however, limited to weakly paramagnetic particulate materials. Separations can be accomplished over an extended range of density split points from 1.3 g/cm^3 to over 20 g/cm^3. The operation of the *Magstream* is based on the following particle physical properties:

– specific gravity SG_p

– volume magnetic susceptibility K_p

and uses a process fluid (Magfluid™) having

– magnetization M_f, and

– specific gravity SG_f.

A comprehensive analytical model of the *Magstream* process, illustrated in Figure 1, has been developed and confirmed in extensive tests by IGC [1, 4].The materials to be separated are slurried in a process fluid and fed down through a long, annular rotating duct surrounded by a multipole magnet. Radial fins on the flow guide extend to the duct wall and divide the separation annulus into equal sectors to ensure uniform rotation of slurry over the length of the separation zone. As the particulate materials pass through the separator they are acted on by lateral (radially directed) separation forces.

An inwardly directed buoyant force, caused by an outward attraction of the magnetic fluid by the surrounding magnetic field, "buoys" particles against an outward rotational centrifugal force (the drag force is negligible compared to this buoyant force). By balancing the buoyant and centrifugal forces at an effective density cut–point midway between those of the particles to be separated, the less 'dense' particles (lights) will be driven radially inwards and more 'dense' particles (sinks) will be driven radially outwards.

In the case where some particles are magnetic, they will also be attracted by the magnetic field, causing the final sinks product to contain some particles with lower specific gravity than might otherwise be expected. The final separation therefore achieved is based on a combination of particle density and magnetic properties.

The operation of the *Magstream* is therefore similar to that of a heavy medium centrifuge, except that the effective density of the fluid is magnetically derived. allowing it to be adjusted by changing the speed of rotation or concentration (magnetic strength) of the process fluid.

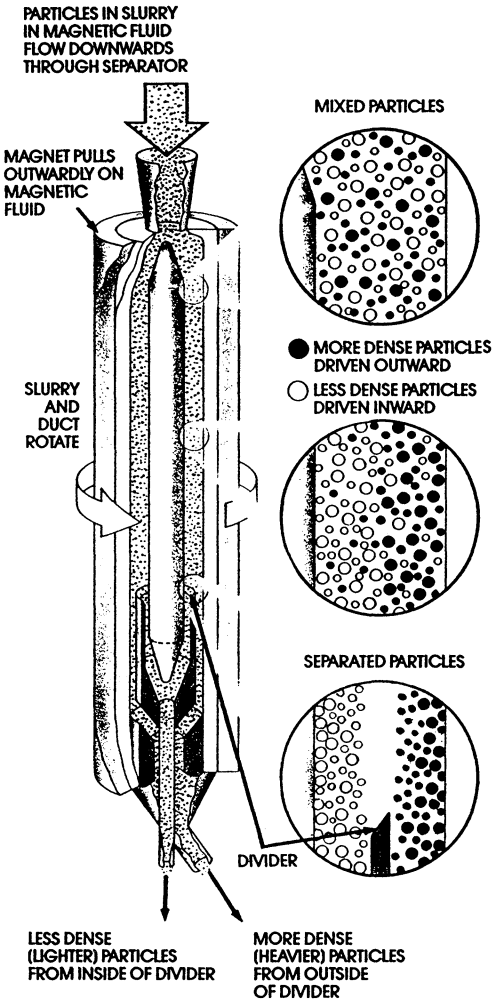

Fig.1 Schematic model of *Magstream* Process (Model 200 shown, IGC (1988)

This is the case with the model 50, 100 and 200 separators, where the magnetic field is constant, being due to a NdFeB permanent magnet. However, the Model 1000 has a variable magnetic field, thus allowing further control of the separation process.

The operation of the Model 50 and Model 100 *Magstream* separators differs from the schematic of Fig.1 only in the manner in which the separated products are collected. The Model 50 and 100 separators are intended for batch mode operation and as such, the products are accumulated in separate nested collection cups for later removal from the separator. The upper rim of the inner cup thus acts as a splitter.

In the Model 200 the products are collected in separate filter bags through which the fluid is drained for recirculation to the feed mixing funnel.

Equipment Description

The Model 100 separator, shown in Fig. 2, was designed to provide precise separation of materials in the size range –590 +63 μm at rates of 20 to 40 grams per minute. Lower rates of feed are necessary for finer materials as was noted early in the evaluation programme. Depending on the mineralogy of the sample to be separated, the Model 100 can separate approximately 100 grams of material per batch run.

The standard hardware of the separator consists of a structural frame, a stationary permanent magnet, and a drive system for spinning a separation cup assembly within the bore of the magnet at precisely controlled speeds of rotation. Controls for the separator, located on the face panel, include a power on/off switch, a 10 turn potentiometer dial for setting drive speed, and a digital meter to indicate separation cup speed in revolutions per minute.

The separator is mounted in a transportable case from which it may be operated in the laboratory or field. Alternatively, the separator may be removed from the case and installed on a bench top or laboratory cart deck, as is necessary with the Model 50.

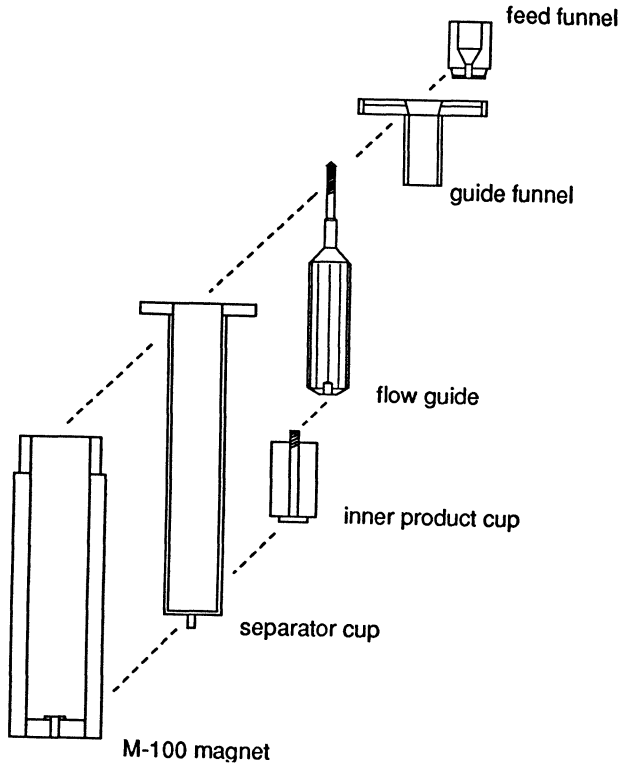

Fig.2 Schematic of the *Magstream* Model 100 and its separation components

The Model 200 separator is a bench mounted separator system for fixed laboratory installations. Adaptable for both batch (viz. Model 100) and semicontinuous processing of larger samples (up to 3 kg), the Model 200 unit uses peristaltic pumps to draw material continuously through the separator while recirculating the Magfluid.

Magstream Magnetic Field Strength

The field strength of the *Magstream* permanent magnet was measured using a Bell model 4048 Gauss/Tesla meter. The instrument was supplied with a flat Hall

effect probe which was used to measure the field strength within the bore of the magnet. An axial probe would have been more appropriate to use because of the edge effects. The measurements were made at set heights in the bore. At each height, the field was measured at four equally spaced points around the circumference.

The readings varied significantly with any movement of the probe, suggesting that a jig would be required if accurate and consistent measurements are required. However, the measurements clearly indicate that the field in not uniform around the circumference. Also, the magnetic field gradually increases from the bottom of the bore, and peaks at two–thirds of the way up the bore.

One particularly interesting fact is that the field strength is close to zero at the centre of the bore. The maximum field strength at the wall of the magnet bore is around 5000 Gauss, or 0.5 Tesla. Inside the separation cup assembly the maximum is reduced to approximately 4400 Gauss. The magnetic field strength of the JKMRC Model 100 varies approximately as $1320.r$ Oersted/cm across the radius r within the annular separation region, where the inner and outer walls are at 1.94 cm and 2.42 cm, respectively.

In comparison, the JKMRC Permroll magnetic separator (Ore Sorters, 1988), fitted with a permanent magnetic roll consisting of 4 mm wide NdFeB magnet disks, has a maximum field strength of approximately 8000 Gauss on the surface of the roll/magnet. A schematic diagram of a permanent magnetic roll separator is provided in Fig. 3, which shows in simple terms the principle of operation.

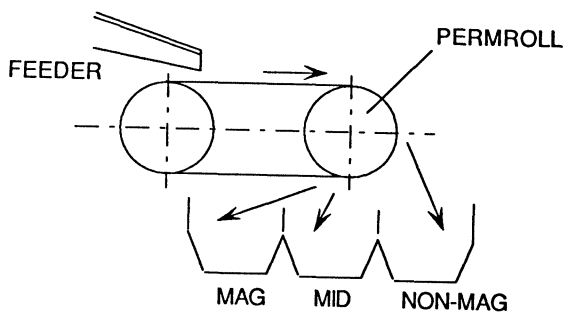

Fig. 3 Schematic of permanent magnetic roll separator

In explanation, feed mineral is introduced to a belt circulating between a permanent magnetic roll and a non–magnetic idler roll via the feeder. The feedstock travels with the belt towards the magnetic roll, at which point it is exposed to the separation forces. Magnetic particles will be pinned to the roll via a radial magnetic force emanating from the roll. Non–magnetic particles will be thrown from the roll due to the effects of centrifugal force, and to a lesser extent, the force of gravity. These particles join the non–mags or the middlings streams. The pinned magnetic particles travel 180° around the roll where they are removed from the influence of the magnetic roll by the belt. At this point they leave the belt and fall under the influence of gravity into the mags stream.

Process Fluid

The *Magstream* separator used a non–toxic*, relatively low–viscosity, water–based bio–degradable magnetic fluid into which feed samples are slurried and from which the separated products are filtered. The process fluid concentrate is a colloidal suspension of magnetite precipitated from a ferrous salt, with lignin sulphonate as a surfactant. The mean particle size is approximately 0.1 μm.

Being based on a by–product from the paper manufacturing industry, the fluid is relatively inexpensive compared to conventional heavy liquids and sodium polytungstates. The process fluid known by the trademark Magfluid™ has the following characteristics:

Table 1 Typical characteristics of Magfluid concentrate

pH	10 -12
SG_f	1.15 - 1.2
magnetization M_f (emu/cm^3)	3.5 - 5
colour	dark brown to black
chemical name	Iron Lignosulphonate
cost (<15 to >100 litres)	AUS$20-$10/litre

* by the standard definition of the USA Federal Health and Safety Administration. It is not listed as a carcinogen.

The Magfluid concentrate supplied by IGC needs to be diluted with distilled water prior to use in the separator. The property of the Magfluid that is critical in *Magstream* separations is its magnetization. An approximate linear relationship exists between process fluid magnetization M_f and specific gravity SG_f. This relationship holds true through a wide range of dilution, but may vary from batch to batch of fluid. A calibrated fluid magnetization vs. specific gravity chart is provided with each shipment of Magfluid.

The specific gravity of any working fluid, regardless of dilution, can then be measured to determine its magnetization. The temperature of the fluid should also be measured to permit correction for temperature–dependent changes in specific gravity. An example of the sensitivity of the *Magstream* process to specific gravity of operating fluid is given in Table 2.

Table 2 Effect of Magfluid specific gravity on separation density SG_{sp}

SG_f	M_f	N (rpm)	SG_{sp}
1.100	2.565	307	4.38
1.105	2.695	307	4.55

A precision hydrometer and mercury thermometer are supplied for fluid characterisation. Each litre of working fluid may be prepared from as little as 0.1 to as much as 0.8 litres of concentrate, depending on the magnetization required to effect the separation in question. The volume of working fluid needed for operation is approximately 350 mℓ for the batch (Model 50/100) and 6 litres for semi–continuous mode of operation (Model 200).

Some fluid is lost during machine cleaning and product washing operations. Actual fluid make–up requirements are subject to operating practices, but with careful operation and vacuum filtering of separated products, losses of fluid can be kept to under 1 litre of working fluid per 10 kilograms of sample feed. In the absence of vacuum filtration, fluid losses have been as high as 1 litre per 4 kilograms of sample feed. The fluid may be recovered by evaporation in industrial–scale operations.

Magstream Separation Forces

This section outlines briefly the mathematical model of the *Magstream* separation process. The separation of essentially non–magnetic particles* based mainly on differences in their densities will be used to illustrate the *Magstream* process [5]. A list of symbols and associated units is provided below. All equations presented here are valid for consistent use of the electromagnetic cgs, or 'emu' units. Svoboda [7] provides background description of magnetic forces and units.

Centrifugal force on particle per unit volume (outward):

$$f_{dc}/V = SG_p w^2 r \tag{1}$$

Inward buoyancy force per unit volume resulting from centrifugal force on fluid

$$f_{bc}/V = -SG_f w^2 r \tag{2}$$

Magnetic field design – gradient varies linearly with radius (IGC):

$$\text{Grad } H = F_m.r \tag{3}$$

Magnetic buoyant force per unit volume caused by outward magnetic attraction on fluid (inward):

$$f_{bm}/V = -M_f \text{Grad } H = -M_f.F_m r \tag{4}$$

Magnetization of particle (paramagnetic or diamagnetic)

$$M_p = K_p.H \tag{5}$$

Magnetic attraction force per unit volume on a magnetic particle (outward):

$$f_{dm}/V = M_p \text{Grad } H = K_p H.F_m r \tag{6}$$

---

*volume magnetic susceptibility $K_p < 30\times10^{-6}$ (cgs units)

w	angular speed of rotation (radians/s)
r	position from axis of rotation (cm)
f/V	force per unit volume ($g.cm.s^{-2}cm^{-3}$ or 1.02×10^{-3} gram force/cm^{-3})
SG_p	specific gravity of particle (g/cm^3)
SG_f	specific gravity of fluid (g/cm^3)
M_f	magnetization of Magfluid (typically 0.5–3.5 emu/cm^3)
K_p	particle volume magnetic susceptibility ($<750\times10^{-6}$ in cgs^3units)
H	magnetic field strength (2830 Oe inner wall, 4370 Oe outer wall of duct)
F_m	instrument magnet factor (JKMRC Model 100: approximately 1320 Oe/cm^2)

In this example where $M_f \gg M_p$, the force f_{dm} is negligible and the particle experiences a net force approximately equal to the sum of the first three forces:

$$F/V \approx f_{dc} + f_{bc} + f_{bm} = [w^2(SG_p - SG_f) - M_f F_m].r$$

Defining a split point, SG_{sp}, as that specific gravity SG_p for which the force balance F = 0 gives:

$$F/V = f_{dc} + f_{bc} + f_{bm} = 0 \qquad \text{or} \qquad [w^2(SG_{sp} - SG_f) - M_f F_m].r = 0$$

hence

$$SG_p = SG_f + \frac{M_f F_m}{w^2}, \qquad \text{independent of radial position } r\text{, of particle}$$

Substituting w = 2π N/60 (N in rpm) and F_m gives

$$N = C_m \sqrt{\frac{M_f}{SG_{sp} - SG_f}} \tag{7}$$

where C_m = 347 (instrument magnet calibration factor).

The net force increases linearly with radius, and is directed radially inward, (–), or radially outwards (+), depending on the:

– relative s.g. of the particle ($SG_p - SG_f$)
– speed of duct rotation (N)

– magnetization (concentration) of the magnetic fluid (M_f), and
– instrument magnet factor (F_m).

Under the same conditions of rotation, fluid magnetization and magnetic field, the net force on particle #1 can be positive and the net force on particle #2 can be negative, as shown in Fig. 4. Note that the two particles of different densities (SG_{p1} and SG_{p2}) shown are driven in opposite directions regardless of their size, shape or position in the separation duct.

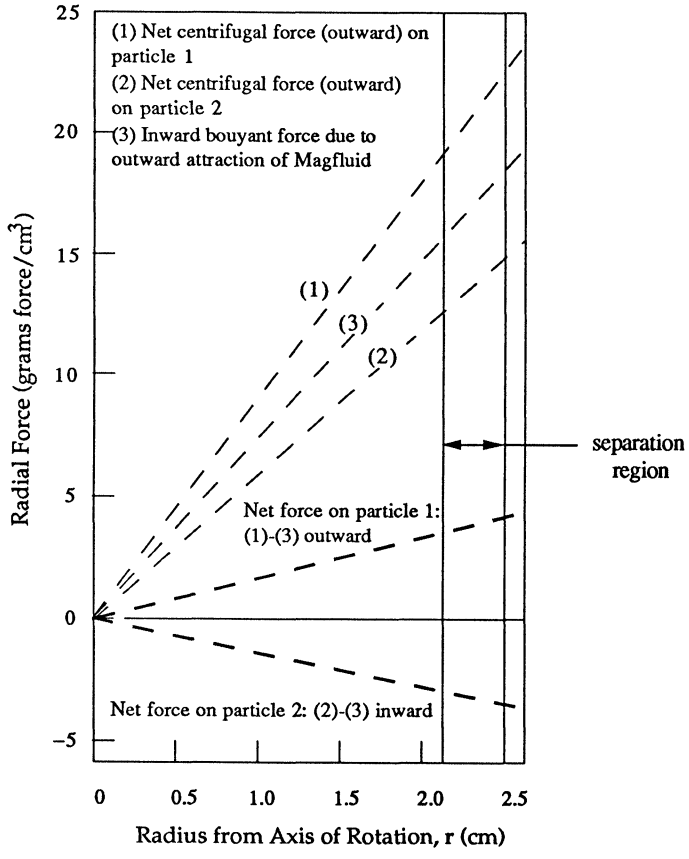

Fig. 4 Illustration of centrifugal and magnetic buoyant forces (producing large net opposite separation forces on on–magnetic particles of different specific gravities, $SG_{p1} > SG_{p2}$)

By increasing the centrifugal forces on the particles and also the opposing buoyancy forces in proportion, the net outward force on one particle and net inward force on the other particle are increased, amplifying the opposite net driving forces for separation. Thus the net *Magstream* separating forces are greater than the net sink/float forces that would be achieved using solely a heavy liquid.

As illustrated above, the magnet calibration factor C_m is a key variable in the process, being an integral part of two of the four separation forces. This factor was introduced by IGC to account for small variations in field strength between otherwise identical rare earth magnets in the *Magstream* units, and allow truer calibration relative to absolute specific gravity. The Model 1000E separator which has a variable magnetic field has therefore a variable C_m.

Operating Parameters

This section provides a simplified description of the selection of parameters for basic operation. A more comprehensive working description of the separator operation is detailed in the Model 200 manual [5].

The key element in using the *Magstream* is the planning of separations. *Magstream* separations may be mathematically and graphically described, and thereby planned. The operator may choose to use any of a range of fluid concentrations (magnetizations) to achieve a particular separation.

Once a suitable concentration of process fluid has been selected and its properties established (M_f and SG_f), the speed of rotation N required to achieve separation at the desired specific gravity split point SG_{sp} is calculated using eq. (7). Note that for any given process fluid, increasing the speed of rotation will effectively lower the specific gravity split point of separation.

Since the value of the magnetic field gradient in the separator varies across the radius within the annular separation region, there is a band of separation. This band graphically describes a separation based on the combination of particle density and magnetic properties. The effect is illustrated in Fig. 5 by plotting the specific gravity and particle volume magnetic susceptibility of each member of a

mineral suite on a graph of particle SG_p versus volume magnetic susceptibility K_p and superimposing a Magstream effective separation band (shown in dark) for any combination of M_f, N, SG_{sp} and SG_f using intercept points.

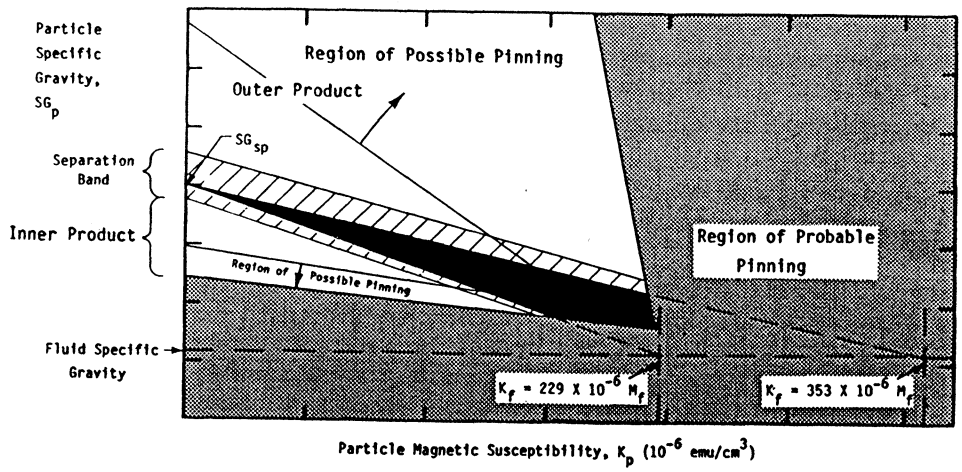

Fig. 5 *Magstream* separation band for a typical separation based mainly on differences in particle specific gravities [5].

Note that the intercepts of the boundary lines of the band with a line representing the actual fluid specific gravity (shown dashed horizontal in Fig. 5) is given by the effective susceptibilities of the fluid, $K_f = M_f/H$ where H is the magnetic field, at the fields of the inner and outer walls of the duct,respectively. The two boundary lines define a band of uncertainty as to which separation product a particle will move into, depending on its initial radial position as it enters the separator.

Particles with SG_p and K_p properties located above the band in the cross–hatched region will report to the outer product with 90% probability while the particles whose properties are located below the band in the cross–hatched region will report to the inner product with 90% probability. These probabilities are inherent to the *Magstream* process and their existence is related to the efficiency of the separator (see discussion below). Particles having properties located within the band have an equal probability of reporting to both products. Beyond these gross–hatched regions, which together define a dynamic separation band as shown,

particles should report to the appropriate product with greater than 90% probability. The separation performance of the *Magstream* separator can be conveniently described by a partition curve, as shown in Fig. 6.

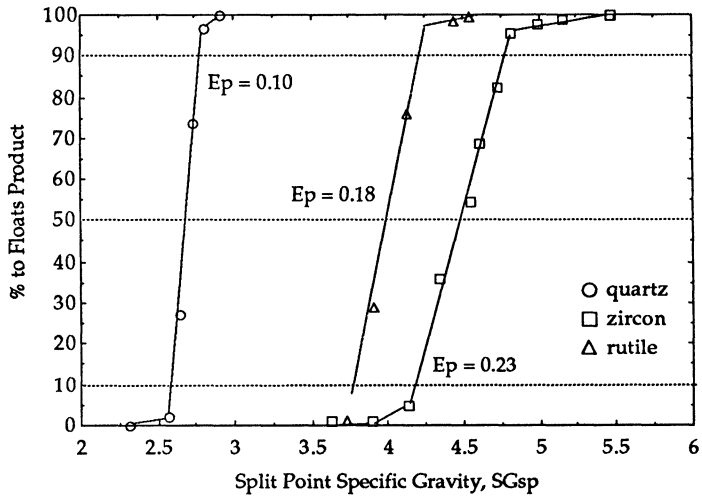

Fig. 6 Partition curves for monomineral feeds [1].

The efficiency of the partition curve (or selectivity of the separator) can be expressed in several ways but IGC have chosen to use $Ep_{90\text{-}10}$ value, that is

(8)

Data from single mineral experiments under various feed and flow conditions, conducted by IGC, suggest that the *Ep* of the *Magstream* process can be approximated by the following simple expression:

(9)

It is clear from eq. (9) that greater precision of separation (narrower dynamic band and lower *Ep*) is achieved, at a given split point, by using a higher magnetization fluid. Separations are also more precise if the specific gravity split point is reduced. The effect of particle shape and size on *Ep* has not yet been determined.

A more concentrated fluid tends to reduce the influence of magnetic characteristics of the particles, while a more dilute process fluid increases the sensitivity of the separator to the particle magnetic properties. However, more concentrated fluids tend to produce stronger forces on particles having specific gravity values very far from the specific gravity split point.

Very strong forces can "pin" these particles against the inner or outer walls of the annular separation duct, either clogging the separator or possibly interfering with the separation. A key element in the planning of *Magstream* separations is therefore to sequence separations and adjust the separation parameters so that particles that might be pinned, such as quartz in a rutile/zircon separation, are removed prior to separation that use a high magnetization fluid.

Successive passes at the same split point can also be used to achieve higher product purity; for example taking a second pass to remove 90% of the 10% of an impurity that remains in a concentrate after the first pass (e.g. rutile/zircon separation). A fluid with M_f in the range of 1.0 to 1.5 is therefore recommended for initial separations or for first removing the extreme light non–magnetics and then the extreme heavies and magnetics, before using a more concentrated fluid to separate particles more closely located on the SG_p vs. K_p diagram.

If the *Magstream* separator is used with very slow duct rotation (to ensure distribution of the feed), separation is accomplished based only on the magnetic properties of the particles, independent of their densities. However, lowering the fluid magnetization much below 0.5 emu/cm^3 tends to reduce the separation driving forces to an unacceptable level.

Treatment Rates of Samples

Treatment rate of samples using the *Magstream* is dependent on the following variables:

1. Sample composition
2. Planning of separating conditions
3. Preparation of Magfluid concentration

4. Recovery of Magfluid from products (filtering, decanting etc.)
5. Number of passes (thus drying time between passes).

In the test work carried out at the JKMRC, it has been found that the time to treat one sample of typical sand–sized material is approximately 20 minutes, for samples of 20 to 100 g. It is important to note that the work at the JKMRC is carried out with vacuum filtering, one set of product cups and standard feeding nozzles. A set of duplicate batch–mode product collection assemblies would enable the sample throughput to be effectively doubled for one separator. Depending on the mineralogy and size of sample, 80 to 100 *Magstream* separations per day may be possible with two *Magstream* Model 100 separators.

Particle size has been identified in the JKMRC test work as the major factor which can affect sample treatment rates. This is because the rate of particle settling under gravity through the Magfluid or the terminal settling velocity is determined by the normal hydrodynamic laws. Particle size therefore has a strong influence on terminal velocity. The time required to complete a separation is determined by the settling time of the smallest particle through the Magfluid, and thus on the terminal velocity.

Operating Costs (Excluding Labour and Equipment Costs)

Before a decision could be made to depart from the use of heavy liquids (H.L.) in routine laboratory analysis, a comparison of operating costs is necessary. Currently there is limited information on the labour/equipment costs, but a comparison of fluid costs is available (see Table 3).

Table 3 Comparison of fluid costs (AUS$, April 1991)

Fluid	SG	Cost/litre
Bromoform (BF)	2.89	52
Tetrabromoethane (TBE)	2.96	45
Methylene Iodide (MI)	3.3	475
Clerici Solution	5.0	1940
Sodium Polytungstate	2.90	197
Magfluid	1.5-20.0	15

A simple example comparing *Magstream* and heavy liquid loss costs is presented below for a quartz/heavy mineral concentrate (HMC) separation.

Magstream

For 100 separations/day @ 100 g/sample: Quartz/HMC separation, 90% +125 μm

Magstream conditions: $SG_f = 1.07$, $M_f = 1.75$, feed rate 25 g/min

Fluid loss: 150 ml/kg of dry solids, no evaporation recovery

Fluid cost per day: 1.5 ℓ Magfluid \$15/ℓ = \$22.50

Thus, cost per sample: \$0.23

Conventional heavy liquids

Typical losses with H.L.: 10 – 20 mℓ/100 g (bromoform) or 5 mℓ/100 g (Clerici)

Thus, cost per sample is \$0.52 to \$1.04 (bromoform) or \$9.70 (Clerici).

The above calculations show clearly that *Magstream* fluid losses are less expensive than heavy liquid losses. However, further information will be required to assess the true operating cost of *Magstream* versus heavy liquids analysis.

MAGSTREAM APPLICATIONS IN MINERAL SANDS

The previous section has described some of the main features of the *Magstream* separation process. It is clear that this new process offers several advantages over traditional use of heavy liquids. These include:

Simplicity of operation and ease of training

Minimum laboratory construction costs (i.e. no fume hoods and accessory safety equipment are required)

No exposure of operating personnel to hazardous chemicals

Elimination of the need to dispose of hazardous materials

Operation at high or low separating densities.

However, the main reason for choosing to depart from the use of heavy liquids still remains the accuracy the results. This question was extensively addressed in the evaluation project, the main results of which are presented in the next section.

Quartz/Heavy Mineral Separation

A planned series of tests was undertaken to evaluate the *Magstream* as an alternative to the traditional use of heavy liquids in heavy mineral separations. Two Western Australian companies were approached to supply samples and associated heavy liquids analysis results for the study. A minimum of five replicate samples of their wet concentrator feed, concentrates and tailings were considered necessary for the evaluation.

Before each batch of samples was treated, a screen analysis and settling rate tests were performed on each type of sample. As previously noted, the latter is necessary to determine the recommended maximum volumetric sample feed rate and minimum wait time after sample feed before stopping rotation and removing product separates. This settling test, although it assumes the particles to be treated are effectively non–magnetic, does provide a clear indication as to how the particle size and density of the material to be treated will affect the separation.

The *Magstream* separation conditions chosen for the evaluation were intended to provide a good balance between Ep precision level, likelihood of pinning, treatment rate and ease of product filtering.

Case Study #1 – West Coast Company A

The material supplied consisted of day shift samples of a wet concentrator head feed, tailings and concentrate. The feed is predominantly ilmenite, with the remainder being made up of leucoxene, rutile, zircon, staurolite, kyanite and quartz. Although there were some replicate samples, most were of a particular day. This was somewhat different to that requested, but enabled the evaluation of *Magstream*/TBE on the basis of daily variation in sample heavy mineral grade.

The screen analysis of the three sample types, given in Table 4, shows that approximately 85 to 90% of the minerals are in the size range – 0.5 + 0.125 mm, the heavy minerals being significantly finer than the quartz. The samples supplied were coarser than the sand deposits examined to date, for example Company C (see Table 6).

Table 4 Company A sample screen analysis

Sieve Size (mm)	Head Feed wt% ret.	Tails wt% ret.	Conc wt% ret.
+1.0	-	-	-
-1.0 +0.5	12.73	14.19	0.09
-0.5 +0.25	70.27	73.08	9.48
-0.25 +0.125	15.26	11.81	81.05
-0.125 +0.063	1.78	0.91	9.35
-0.063	0.01	0.01	0.03
	100.0	100.0	100.0

As expected from the screen analysis results, the relatively coarse material settled very quickly in water, resulting in the following recommended maximum feed rates:

sample	Q_{max} *(cm³/min)*	M_{max} *(g/min)*
conc	13	32 (@ 2.45 g/cm³)
head feed	22	38 (@ 1.71 g/cm³)
tails A	22	34 (@ 1.54 g/cm³)

The sample feed rates used in the tests were lower than recommended, ranging from 10 to 20 g/min. As the Company A minerals appeared to quite free of iron oxide coatings, a *Magstream* equivalent TBE type separation, having the following parameters, was chosen for the evaluation:

$SG_f = 1.068$ $M_f = 1.739$
$SG_{sp} = 2.96$ $Ep_{90\text{-}10} = \pm 0.14$ SG (estimate)

It was necessary to sub–divide the supplied concentrate samples (approximately 250 g) because they were too large to process in the *Magstream* Model 100. All other samples, being 60 to 100 g, were treated as supplied.

As the concentrate samples had in excess of 70% ilmenite, the magnetic loading on the *Magstream* would be detrimental to the separation efficiency. To avoid this problem, the Permroll magnetic separator was used to quickly scalp most of the ilmenite from each concentrate sample before proceeding to the *Magstream.* The Permroll was set up with the thickest belt (0.71 mm), the feeder gate at its smallest opening, and the roll speed kept constant at 200 rpm. This configuration

is known to recover only the heavy minerals which are magnetically susceptible. The results of the *Magstream* separations are compared with corresponding heavy liquid analysis results in Table 5.

Table 5 *Magstream* vs. TBE separation comparison – Company A

Head Feed			Tails			Conc		
sample date	M/S2.96 % HM	TBE % HM	sample date	M/S2.96 % HM	TBE % HM	sample date	M/S2.96 % HM	TBE % HM
1-10-90	5.0	4.1	1-10-90	1.00	0.66	3-10-90	98.9	97.3
1-10-90	4.7	4.1	1-10-90	0.88	0.66	5-10-90	99.2	98.3
3-10-90	5.7	5.2	3-10-90	0.94	0.73	5-10-90	99.4	98.3
3-10-90	5.4	5.2	3-10-90	0.86	0.73	6-10-90	98.7	99.0
6-10-90	5.6	5.2	4-10-90	1.19	0.94	6-10-90	98.6	99.0
mean	5.3	4.8	mean	0.97	0.74	mean	99.0	98.4
s.d.	0.4	0.6	s.d.	0.13	0.12	s.d.	0.3	0.7

A statistical comparison of the three sets of results was carried out to tests whether there is a significant difference between the two methods of analysis. Applying the t–test to the paired comparisons [8], and assuming the results are independent observations normally distributed, the 5% level of significance suggests that the two methods are different in result for the feed and tailings samples. At the same level of significance, the results for the concentrate samples are not statistically different.

From the replicate samples in each set, it appears that the precision of the *Magstream* may be slightly better than that using the TBE analysis method; although the difference may be of no practical significance; more data are required to confirm this conclusion.

The results in Table 5 show a consistent offset between the results of the two analysis methods. In all but two cases the *Magstream* % heavy mineral is higher than reported by TBE. The reason for this offset has been previously noted and illustrates the effect of the *Magstream* Ep_{90-10} on the accuracy of separation. In other words, the expected ± 0.14 Ep level results in some quartz being misplaced into the sinks fraction. As there is probably very little or no material between 2.96 and 3.10 to be misplaced into the floats fraction, the net result is a higher %heavy minerals indication. To overcome the effect of Ep in heavy mineral determinations

it is therefore necessary to operate the *Magstream* at a higher notional split point than the heavy liquid density, particularly if the light heavies (< 3.5 SG) that may be present are of no interest. This strategy was successfully adopted in the case study below.

Case Study #2 – West Coast Company B

The material supplied consisted of six replicate samples of feed, tailings and concentrate. The feed is predominantly ilmenite, with the remainder being made up of leucoxene, rutile, zircon, monazite, staurolite, kyanite and quartz. This batch of samples enabled the evaluation of *Magstream* vs. bromoform, on the basis of actual experimental variation in determining the heavy mineral grade.

The screen analysis of the three wet concentrator streams, given in Table 6, shows that all minerals are – 0.5 mm, the heavy minerals being finer than the quartz. In addition, company B material is finer than that of company A, as indicated by the relative amounts in the + 0.5 mm fraction. As expected from the screen analysis results, the company B material settled quickly in water, resulting in the following recommended maximum feed rates:

sample	Q_{max} *(cm³/min)*	M_{max} *(g/min)*
conc	13	32 (@ 2.45 g/cm³)
feed	15	23 (@ 1.71 g/cm³)
tails	15	23 (@ 1.54 g/cm³)

Table 6 Company B sample screen analysis

Sieve Size (mm)	Feed wt% ret.	Tails wt% ret.	Conc wt% ret.
+0.5	-	-	-
-0.5 +0.25	53.93	67.93	3.85
-0.25 +0.125	39.73	24.49	84.59
-0.125 +0.063	5.94	4.11	11.25
-0.063	0.39	0.46	0.31
	100.0	100.0	100.0

The sample feed rates used in the tests were lower than recommended, ranging from 10 to 20 g/min. The minerals showed abundant iron oxide coatings and a *Magstream* equivalent bromoform–type separation would not be expected to provide accurate results. That is, the iron oxide coatings would render some of the quartz to be weakly magnetic, causing it to report to the *Magstream* sinks fraction. In addition, any iron in the lattice or inclusions would elevate the specific gravity of quartz beyond 2.7 SG. For this reason, a higher density *Magstream* equivalent separation, having the following parameters, was chosen for the evaluation:

Magstream separation conditions:

$SG_f = 1.073$, $M_f = 1.868$

$SG_{sp} = 3.3$, $Ep_{90\text{-}10} = \pm\ 0.17$ SG (estimate)

It was necessary to sub–divide the supplied samples (approximately 200 g) because they were too large to process in the *Magstream* Model 100. The concentrate samples had in excess of 75% ilmenite and, as in the company A test work, the Permroll was used to quickly scalp most of this ilmenite before proceeding to the *Magstream.* The Permroll was set up with the thickest belt (0.71 mm), the feeder gate at its smallest opening, and the roll speed kept constant at 200 rpm. The results of the *Magstream* separations are compared with corresponding heavy liquid analysis results in Table 7.

Table 7 *Magstream* vs. bromoform separation comparison – Company B samples

Feed			Tails			Conc		
sample no.	M/S3.30 % HM	BF % HM	sample no.	M/S3.30 % HM	BF % HM	sample no.	M/S3.30 % HM	BF % HM
1	24.0	24.2	1	1.3	1.2	1	94.6	94.7
2	24.5	24.4	2	1.4	1.2	2	94.7	94.7
3	25.4	24.7	3	1.1	1.1	3	95.1	94.8
4	25.3	25.1	4	1.2	1.2	4	94.7	94.7
5	25.3	26.0	5	1.3	1.2	5	94.9	94.7
mean	24.9	24.9	mean	1.3	1.2	mean	94.8	94.7
s.d.	0.6	0.7	s.d.	0.11	0.05	s.d.	0.2	0.05

A statistical comparison of the three sets of results above was required to test whether there is a significant difference between the two methods of analysis. If it is assumed that the results are independent observations, normally distributed, and that both sample variances are estimates of the same population variance, then the t–test can be applied to compare two sample means.

However, the replicate sample results in each set indicate that the precision of the bromoform analysis method is better (lower variance) than that using *Magstream* for the tailings and concentrate samples. Using an F–test, the difference was found to be significant for the concentrate, thereby violating the t–test assumption of same variance.

As the means are very similar for all three sets of results, the unequal–variance t–test [8] was considered suitable to test if the methods are different. This approach ignores the possibility of the distributions being different in shape, in which case the difference of the means may be of no interest. Using this technique all three sets of comparisons were tested, showing no evidence at the 5% level of significance that the mean assay results are different.

The slight offset between the results of the two methods for the tailings assays is attributed to the higher concentration of quartz in the tailings sample with heavy iron oxide coatings and inclusions, clearly seen under the microscope.

It is clear from the results presented in Tables 5 and 7 that *Magstream* can be used to perform accurate heavy liquids–type separations. provided the particle size is predominantly over 100 μm, the minerals are not excessively coated with iron oxides or inclusions, and the separations are carried out at densities higher than conventional heavy liquids. Although separations at, say, 3.3 SG may exclude the light heavy minerals (e.g. alumino–silicates), the *Magstream*–derived % heavy minerals should indicate the 'true' or very very heavy mineral content, which is the key information.

Rutile/Zircon Separation

In the JKMRC study of a wet concentration plant several samples were submitted for analysis of separation performance. In this study the samples required assaying

for ilmenite, rutile, zircon and'others' mainly consisting of leucoxene. Samples from the main streams in the plant were analysed using the *Magstream* and Permroll magnetic separator. Three *Magstream* separations were carried out for each sample:

(1) $SG_{sp} = 5.7$ to remove ilmenite/monazite
(2) $SG_{sp} = 4.0$ to remove leucoxene
(3) $SG_{sp} = 4.4$ to separate zircon from rutile.

The rutile and zircon fractions were passed over the Permroll to remove any residual weakly magnetic minerals (i.e. magnetic leucoxene). The rutile and zircon assays were then obtained by grain counting the *Magstream* products. The results of these separations are shown in Table 8.

Table 8 *Magstream* separation results on rutile/zircon samples

Sample Number		Wt. (%)	zircon (%)	zircon (dist'n %)	rutile (%)	rutile (dist'n %)
1	Calc. head	100.0	44.4	-	53.7	-
	sinks	41.5	96.2	89.9	2.9	2.3
	floats	58.5	7.6	10.1	89.7	97.7
2	Calc. head	100.0	44.0	-	53.8	-
	sinks	41.4	90.1	84.8	9.9	7.6
	floats	58.6	11.4	15.2	84.8	92.4
3	Calc. head	100.0	44.9	-	53.2	-
	sinks	40.5	96.6	87.1	2.4	1.9
	floats	59.5	9.7	12.9	87.7	98.1
4	Calc. head	100.0	32.0	-	65.9	-
	sinks	29.6	94.8	87.7	2.4	1.1
	floats	70.4	5.6	12.3	92.6	98.9

Magstream separation conditions:

$SG_f = 1.10$ $M_f = 2.54$

$SG_{sp} = 4.4$ $Ep_{90\text{-}10} = \pm\ 0.25$ (estimate)

The results show that rutile/zircon separations are not straightforward using the *Magstream*, the grade of the zircon and rutile products being typically between

85% and 95% for one–pass separations. The equivalent grades for Clerici (thallium malonate–formate) separations are 98% to 99% for zircon and 95% to 96% for rutile.

The contamination of the two products is unavoidable because the Ep_{90-10} partition curve width, that is the 90% cleanliness regions (Fig. 7) associated with the separation band tends to overlap the relatively small difference in their specific gravity (s.g. of rutile is typically 4.2 – 4.3, while the s.g. of zircon can vary from 4.2 to 4.8, most being 4.6 – 4.7).

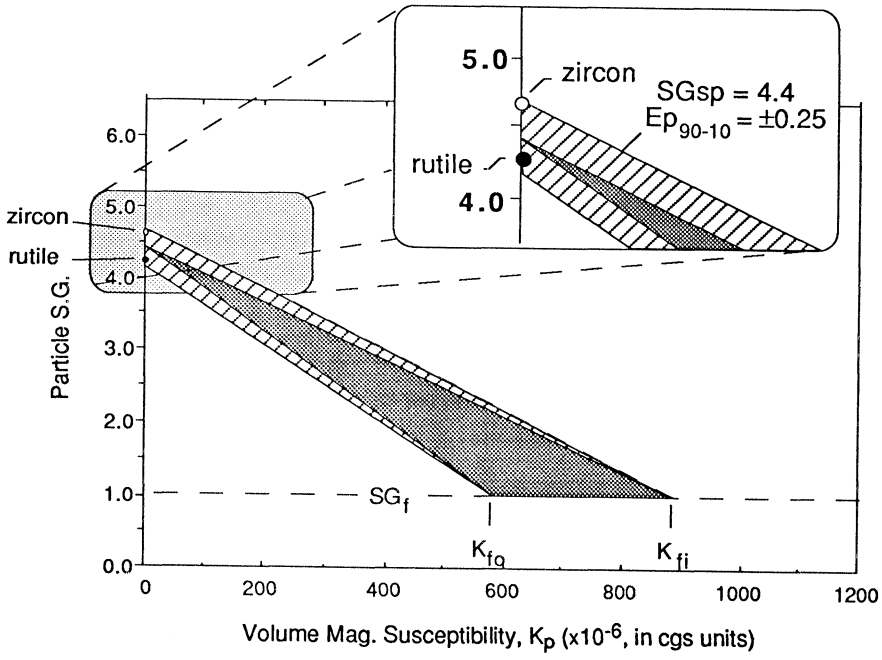

Fig. 7 *Magstream* SG_{sp} versus K_p chart for rutile/zircon separation (inset showing Ep_{90-10} regions overlapping mineral properties)

The results from IGC monomineral studies, shown previously in Fig. 6, suggest that it is not possible to expect better than 90% grades for single pass separations. Due to the nature of the *Magstream* process, the zircon/rutile products would be also expected to contain any weakly magnetic minerals, for example leucoxene.

The results therefore indicate that the *Magstream* cannot provide, in a single pass, results comparable to Clerici separations. However, as noted earlier, the results may be improved if successive passes are used.

To test this theory, a series of tests on rutile/zircon mixtures was therefore undertaken to assess the effect of multiple passes. Near concentrate Magfluid was used in the tests to improve the Ep of separation (SG_f = 1.102, M_f = 2.604, Ep = ± 0.25). The results obtained indicate that three passes would be required to achieve 93% to 95% grade rutile and over 98% grade zircon, results very comparable to Clerici.

Monazite/Zircon Separation

Four samples were obtained from the west coast of Australia for investigation of monazite/zircon separations. The samples included both product zircon and product monazite which were used to establish the optimum separation conditions. The sample descriptions are summarised in Table 9.

Table 9 West Coast mineral sand sample description

Sample Type	Sample Description
1	Residue monazite, zircon, rutile, leucoxene
2	70-80% monazite + residual zircon
3	HMC (most of ilmenite removed)
4	HMC (most of ilmenite removed)
'A' grade product zircon	65.5% min. ZrO_2
'A' grade product monazite	61%min. REO + ThO_2, 10%max. Insol

This separation appears possible when graphically described on an SG_{sp} versus K_p chart (see Fig. 8). The initial objective was to determine the optimum *Magstream* operating conditions which would yield a clean zircon product in the floats and clean monazite product in the sinks fraction (see Table 10). Once this condition was identified using the product grade samples, four samples were processed at the same condition. The weight splits of the major separations are given in Table 11. Mineral assays for zircon and monazite have been estimated from XRF assays.

Table 10 Chemical analysis of *Magstream* separation products

Sample Name	Magstream Product	Mass Split (%)	TiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	ThO_2 (%)	P_2O_5 (%)	ZrO_2 (%)	SiO_2 (%)
zircon	floats	99.9	0.10	0.07	0.60	0.011	0.08	64.9	33.0
	sinks	0.1	0.60	0.10	0.68	0.006	0.08	65.7	33.1
monazite	floats	13.7†	7.56	3.91	3.20	4.54	19.4	9.88	6.80
	sinks	86.3	0.20	0.28	0.20	6.84	27.0	1.48#	1.66

†represents Total Acid Insolubles, # magnetic zircon

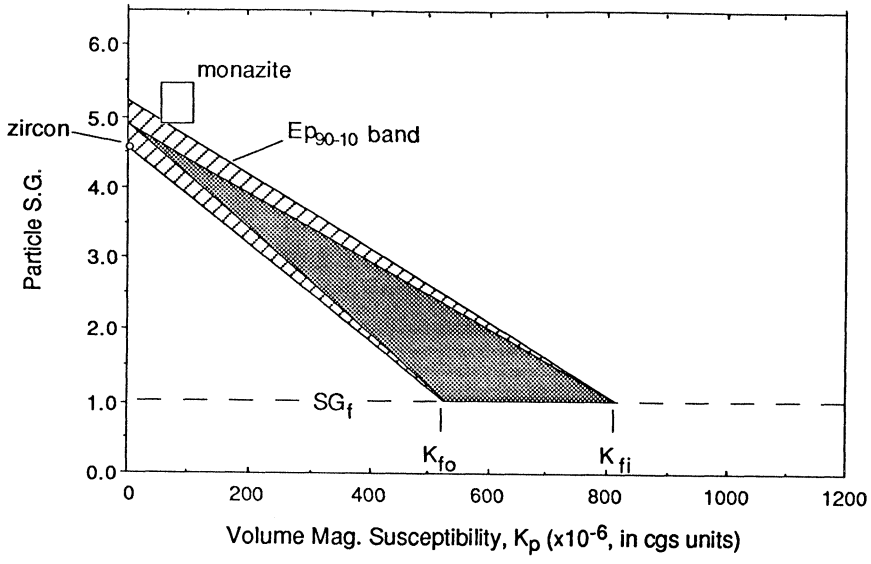

Fig. 8 *Magstream* SG_{sp} versus K_p chart for monazite/zircon separation

The above results show two interesting features. Firstly, it appears possible using the selected *Magstream* split point $SG_{sp} = 4.9$ to upgrade the monazite product by eliminating most of the acid insolubles (staurolites, TiO_2, ZrO_2 etc.), approximately 10% of the material. At this same separation density, 99.9% of the zircon was recovered to the floats fraction.

With the exception of sample 2 (monazite filter bed feed), the *Magstream* recovered approximately 98% of the zircon to the floats fraction, and 82% to 87%

of the monazite to the sinks fraction. The XRF indicates most of the rare earth oxides would be recovered. In addition, the results show a consistent recovery of monazite of about 85%, even for the samples with low grades present (samples 1, 3 and 4).

Table 11 *Magstream* separation results on monazite/zircon samples

Sample Number		Wt. (%)	zircon (%)	zircon (dist'n %)	monazite (%)	monazite (dist'n %)
1	Calc. head	100.0	6.2	-	0.9	-
	sinks	31.5	0.5	2.5	2.4	84.7
	floats	68.5	8.8	97.5	0.2	15.3
2	Calc. head	100.0	17.1	-	77.1	-
	sinks	73.5	3.9	16.8	92.2	87.9
	floats	26.5	53.6	83.2	35.1	12.1
3	Calc. head	100.0	26.1	-	0.6	-
	sinks	11.7	3.4	1.5	4.8	86.4
	floats	88.3	29.1	98.5	0.1	13.6
4	Calc. head	100.0	22.1	-	0.9	-
	sinks	16.0	2.4	1.7	4.8	82.1
	floats	84.0	25.8	98.3	0.2	17.9

Magstream separation conditions:

$SG_f = 1.09$ $M_f = 2.29$

$SG_{sp} = 4.9$ $Ep_{90\text{-}10} = \pm\ 0.35$ SG (estimate)

The monazite will, however, still be associated with any ilmenite present in the sample. The expected $Ep_{90\text{-}10}$ value of ± 0.35 for the *Magstream* separation conditions chosen would account for some of the reduction in monazite recoveries observed in the actual plant samples (see Fig. 8). Some of monazite elements, for example $(Th)PO_4$, also have densities lower than 4.9 SG and would be expected to report to the floats fraction. The reason why sample 2 shows a lower recovery of zircon (83%) is not clear from the XRF analysis, but it may be due to a greater proportion of iron–stained zircon.

Kyanite/Zircon

One potential industrial application identified for the *Magstream* was scavenging of zircon from kyanite tailings. Four samples were supplied to the JKMRC for a preliminary investigation. The minerals contained in the samples were zircon, kyanite, quartz, staurolite, leucoxene and monazite.

The primary objective of the separations was kyanite rejection, such that subsequent high–tension and magnetic cleaning of the zircon would produce a marketable product. This separation appears relatively easy as graphically described on an SG_{sp} versus K_p chart (see Fig. 9).

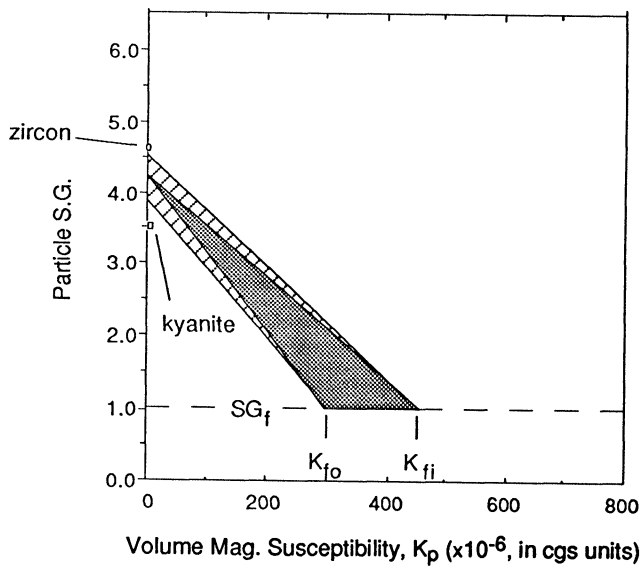

Fig. 9 *Magstream* SG_{sp} versus K_p chart for kyanite/zircon separation

The products from the *Magstream* separations were chemically assayed, the results of which are shown in Table 12. The results were very good, even on the most "difficult" material in the reserves (sample 1). As a result, the viability of industrial–scale *Magstream* in this application is being investigated.

Table 12 *Magstream* separation results on kyanite/zircon samples

Sample Number		Wt. (%)	ZrO_2 (%)	ZrO_2 (dist'n %)	Al_2O_3 (%)	Al_2O_3 (dist'n %)
1	Calc. head	100.0	46.0	-	4.3	-
	sinks	74.8	60.1	97.7	0.4	6.1
	floats	25.2	4.2	2.3	15.9	93.9
2	Calc. head	100.0	28.0	-	12.6	-
	sinks	45.5	60.6	98.4	1.2	4.4
	floats	54.5	0.8	1.6	22.1	95.6
3	Calc. head	100.0	17.3	-	42.2	-
	sinks	25.7	64.9	96.1	0.2	0.1
	floats	74.3	0.9	3.9	56.7	99.9
4	Calc. head	100.0	30.8	-	20.5	-
	sinks	45.4	64.9	95.8	0.1	0.2
	floats	54.6	2.4	4.2	37.5	99.8

Magstream separation conditions:

$SG_f = 1.06$ $M_f = 1.3$

$SG_{sp} = 4.25$ $Ep_{90\text{-}10} = \pm\ 0.43$ SG (estimate)

CONCLUSIONS

The *Magstream* Model 100 separator operates in a batch mode and can treat approximately 100 g of mineral sand material in the particle size range − 600 + 60 μm, per batch run. Although the accuracy of the separator is dependent on several variables, its operation is simple. The user selects an equivalent specific gravity split point, records the fluid conditions, then, after a simple calculation, sets the rotational speed to allow the separation to proceed. Depending on the sample particle size, mineralogy and quantity, the separations are completed in 15 to 20 minutes, and subsequent separations at another split point require only a quick resetting of the speed.

Magstream is most useful for separations based primarily on the specific gravity differences between particles, and its performance can be enhanced by prior removal of even weakly magnetic particles, where possible, by conventional means.

The tests showed that the *Magstream* is not a direct equivalent of heavy liquid separations in (for example) bromoform or TBE solutions, but that if the correct combination of operating conditions is selected, excellent and reproducible separations are possible. Particularly effective separations were found to be quartz/HMC, kyanite/zircon, monazite/zircon and rutile/zircon (multiple passes required).

The *Magstream* offers safe, rapid and effective testing of mineralogical samples on a laboratory scale. In some cases it is a realistic alternative to separations using toxic heavy liquids, and operates over a far greater density range. The *Magstream* has the potential to replace bromoform, TBE, methylene iodide and Clerici separations, with one separator. Fluid losses are less expensive than heavy liquid analysis. Industrial–scale operation may also be viable; this possibility is currently being examined.

ACKNOWLEDGEMENTS

The author would like to thank the companies and the individual members of their staff for their cooperation and assistance throughout the evaluation programme. The work described in this paper has been completed within JKMRC/AMIRA project P255, the industrial sponsors of which were:

- AMC (now RGC Mineral Sands)
- Cable Sands
- Mineral Deposits
- RZ Mines
- Tiwest Joint Venture
- Westralian Sands
- Wimmera Industrial Minerals

The author would also like to express his appreciation to IGC for their technical support

REFERENCES

[1] M.S. Walker et al.: *Miner. Metall. Process.* **7** (1990), 209

[2] U.T. Andres, G.M. Bunin and B.B. Gill: *J. Appl. Mech. Tech. Phys.* **7** (1966), 109

[3] U.T. Andres: *Magnetohydrodynamic and Magnetohydrostatic Methods of Mineral Separation.* John Wiley and Sons, New York, Israel University Press, Jerusalem , 1976

[4] M.S. Walker and A.L. Devernoe: *Intl.J. Min. Proc.* **31** (*1991*), *195*

[5] *Operating Manual for the Laboratory Permroll Magnetic Separator*, Ore Sorters, 1988

[6] *Operating Instructions for the Magstream Model 200 Laboratory Separator.* IGC, 1988

[7] J. Svoboda: *Magnetic Methods for the Treatment of Minerals.* Elsevier, New York, N.Y., 1987

[8] W.H. Press et al.: *Numerical Recipes.* Cambridge University Press, Cambridge, 1986.

Toni Kojovic graduated in 1984 with the First Class Honours in Mechanical Engineering from the Queensland Institute of Technology, and was awarded a PhD degree in 1989 for research at the JKMRC concerned with the development of a computer–based automated model building procedure. The integrated software is now in routine use at the JKMRC. In 1989 he joined the Mineral and Coal Processing Group at the JKMRC as Research Fellow with responsibility for research in magnetic, electrostatic and magnetohydrostatic separation. In 1993 he was appointed Project Leader for the AMIRA Mineral Sands Project. He is also technical consultant to a number of particle breakage–related projects. In line with his interests in mineral sand separation, he is currently developing a mathematical model for the Permroll magnetic separator and electrostatic screen plate separator, and plans to evaluate the potential of an industrial production Magstream installation.

Keywords: Magstream, magnetohydrostatic separation, mineral sands separation, heavy liquids.