Flowsheet development of two distinct rare earth-bearing heavy mineral sand ores

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The industrial, economic, and political importance of rare earth elements (REE) continues to increase globally, since they are vital for many important electronic products and critical in supporting the transition to green energy technologies. Common sources of REE include the minerals monazite and xenotime, which are frequently found in detrital heavy mineral sand resources.

This paper presents the results of the mineralogical and metallurgical test work of two distinct REE-bearing heavy mineral sand ores. The diverse range of characteristics affects their amenability to beneficiation techniques.The impact of the unique properties of each ore type on the resultant beneficiation flowsheets developed by considering these differences are examined. In particular, the efficacy of froth flotation is compared in parallel to conventional dry mineral separation techniques for the secondary upgrade circuits.

Keywords: Rare earth minerals, metallurgical characterisation, processing techniques synergies

INTRODUCTION

Rare earth elements (REE) comprise the 15 lanthanides elements in the periodic table with atomic numbers ranging from 57 to 71. Because of their similar physical and chemical characteristics, scandium (atomic number 21) and yttrium (atomic number 39) are often included with the lanthanides.

Although often occurring together, rare earth elements are further divided into two groups. The 'light' rare earth includes elements with atomic numbers 57 through 63 (lanthanum to europium) and the 'heavy' rare earth are elements with atomic number from 64 to 71 (gadolinium to lutetium). Yttrium has similar properties to the heavy group (see Table I).

Rare earth metals have a wide range of uses and play a crucial role in supporting evolving technologies required to support the transition to clean energy applications such as wind turbines, photovoltaic solar panels, or electric vehicles.

A common source of REE includes the minerals monazite and xenotime, frequently found in detrital heavy mineral sand resources.

After mining, mineral sands and therefore by extension, monazite and xenotime, beneficiation is often completed by a combination of size classification, gravity concentration and upgrade by wet or dry magnetic separation, as well as electrostatics. In addition to the complexity of process circuits required to achieve acceptable grade and recoveries, conventional mineral separation plants must deal with industrial hygiene problems caused by the elevated natural radioactivity of monazite.

This paper discusses outcomes from metallurgical test work on rare earth-bearing mineral sands ores originating from Africa (ore-1) and Australia (ore-2). Specifically, this paper discusses the influence of both the minerals' characteristics on the resultant process routes. In addition, the circuit development strategy considered risks associated with dry processing of radioactive monazite and therefore targeted a pathway to produce mixed rare earth mineral concentrates using wet processing techniques only.

Table I. Classification of rare earth elements

Light REE			**Heavy REE**		
Element name	Symbol	Atomic number	Element name	Symbol	Atomic number
Scandium	Sc	21	Yttrium	Y	39
Lanthanum	La	57	Gadolinium	Gd	64
Cerium	Ce	58	Terbium	Tb	65
Praesidium	Pr	59	Dysprosium	Dy	66
Neodymium	Nd	60	Holmium	Ho	67
Promethium	Pm	61	Erbium	Er	68
Samarium	Sm	62	Thulium	Tm	69
Europium	Eu	63	Ytterbium	Yb	70
			Lutetium	Lu	71

MINERAL, CHEMICAL, AND METALLURGICAL CHARACTERISATION

Overview

Characterisation is an essential activity for the understanding of the fundamental features of the ore. It highlights the physical, chemical and interrelation of the mineral components of an ore and represents a vital tool in assessing potential beneficiation techniques that may be used to efficiently separate valuable from non-valuable components.

Ore characterisation is also comparatively a low cost and short duration component of a typical total project development but can quickly outline suitable beneficiation techniques worth evaluating, thereby providing opportunities to improve project outcomes by focusing studies on methods that might have a better chance of being successful. It can also identify technical difficulties and assist in the establishment of realistic targets at an early stage of the project.

In this paper, the methods used to determine the chemical composition of an ore include x-ray florescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS). Techniques for determining the mineralogical composition are optical microscopy and quantitative electron microscopy (QEMSCAN).

Particle size distribution analyses and density profile analyses by float-sink methods were also used to characterise the ore and provide further insight into the requirement for feed classification and the amenability to separation by gravity separation.

Elemental composition

The elemental composition of each ore sample was analysed using standard fusion and XRF techniques. The results of the analysis are shown in Table II. The data generally indicate a comparable composition with dominant SiO_2 at 81.5% for ore-1 and 82.2% for ore-2. Tracer analysis of valuable mineral monazite indicate similar CeO_2 grade of 0.031% and 0.026%. Differences in the ratio of titania- and zirconia-bearing minerals are evident, though overall grades are low in comparison to SiO_2.

Table II. Ore sample chemical composition

Description	TiO_2	Fe_2O_3	SiO_2	Al_2O_3	ZrO_2	P_2O_5	U	Th	CeO_2
Unit	%	%	%	%	%	%	ppm	ppm	%
Detection limit	0.01	0.01	0.01	0.01	0.01	0.001	10	10	0.002
Ore-1	3.04	5.32	81.5	5.31	0.28	0.059	10	115	0.031
Ore-2	1.81	5.11	82.2	6.25	0.50	0.085	23	61	0.026

Particle size distribution

The particle size distribution of each sample is shown in Figure 1. Both samples show comparable proportion of fines at 16.8% and 15.2% by mass less than 45 µm . Likewise, both samples have comparable proportions of coarse particles with sizes greater than 500 µm . Ore-2 sample is, however, significantly finer with an average particle size in the order of 85 µm, compared to an average particle size of 220 µm for ore-1. Salient information gleaned from the particle size distribution therefore suggests that both ore material require de-sliming to remove ultrafine particles and prepare feed suitable for beneficiation. Equipment type, operating conditions and circuit configuration would then need to be tailored to account for the difference in the average particle size for each ore.

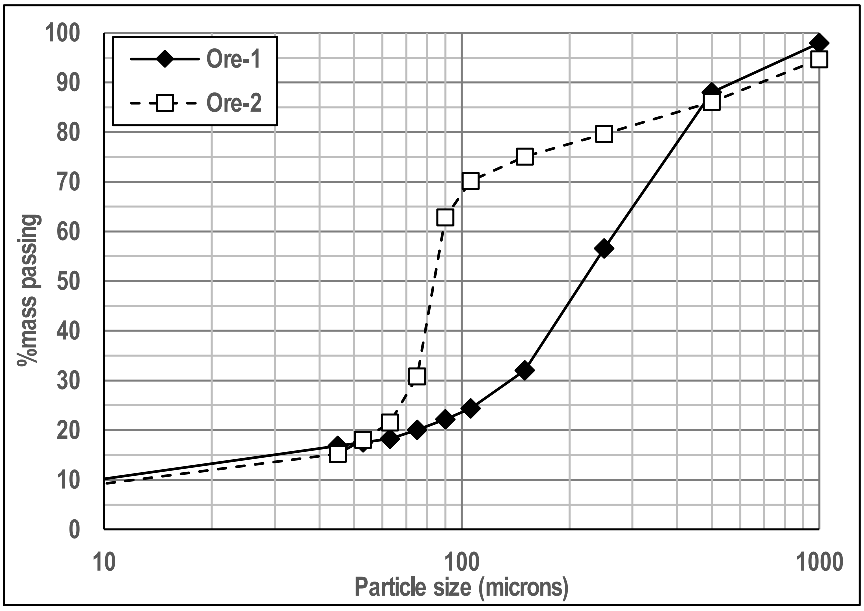

Figure 1. Samples particle size distribution.

Density profile

The specific gravity of minerals is known to vary according to their chemical composition (Mursky, 1953). For instance, monazite has a range of specific gravities between 4.6 and 5.4; xenotime has a range of specific gravities between 4.4 and 5.1.

A sub-sample from each ore type was washed through a 20 µm sieve to remove fines that would otherwise interfere with the heavy liquid viscosity. The retained sand fractions were sequentially separated at 2.85, 3.60 and 4.05 SG. Density separations were conducted using a heavy liquid float-sink (washability) method. Different heavy liquids were used depending on the desired separation density; bromoform liquid for SG 2.85 and thallium malonate formate (TMF) solution for 3.60 SG and 4.05 SG.

The result of the density profile analysis for each ore type is presented in Figure 2. It is noted that separations for ore-2 was completed using a centrifuge due to its very fine sizing. The term total heavy mineral (THM) refers to the minerals which have a density greater than 2.85 and the characterisation results indicate the samples contain comparable THM at 7.45% (ore-1) and 6.25% (ore-2). However, the proportion of very heavy minerals with SG greater than 4.05 is vastly different. Close to 90% of the THM in ore-1 has an SG greater than 4.05, whilst just about 51% of the THM in ore-2 has an SG greater than 4.05.

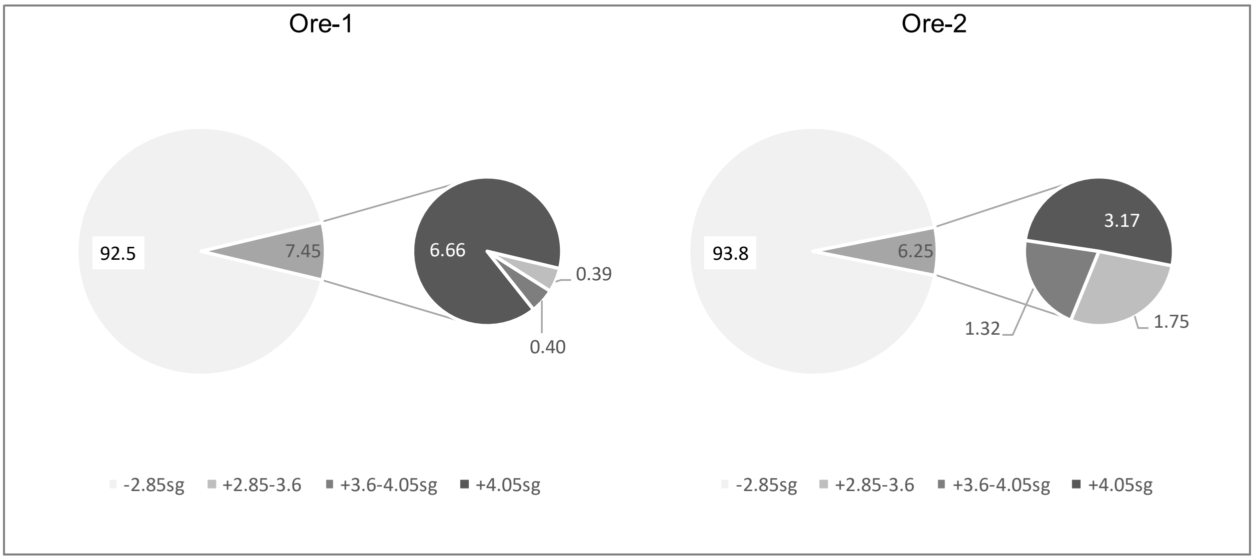

Figure 2. Samples density profile.

Mineral composition

The mineral composition of the THM fraction for ore-1 was determined using QEMSCAN. The mineral composition of ore-2 was estimated by XRD and validated by XRF assays. The results of the analysis are shown in Table III and indicate the THM fraction derived from each sample contains major titania minerals, minor REE minerals and moderate zircon, aluminosilicates, and other minerals.

Table III. Mineral composition of the THM fraction derived from each sample

Description	**REE-minerals**	**Zircon**	**Ti-minerals**			**Al-Silicates**	**Others**
			High Fe	**High Ti**	**High Si**		
Unit	%	%	%	%	%	%	%
Detection limit	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ore-1	1.79	7.20	74.1	6.10	n/a	4.40	6.41
Ore-2	2.35	18.0	31.6	12.3	15.4	10.1	10.2

BENEFICIATION PROCESS CIRCUIT DEVELOPMENT

General discussion

Beneficiation plants for mineral sand ores generally include the following three principal processing circuits:

Feed Preparation Plant

Run of mine ore is scrubbed and de-slimed to liberate mineral particles from clay and prepare feed with sizing suitable for beneficiation. Trash, rocks and barren oversize are also removed as part of the feed preparation.

Primary Concentrator Plant

The objective of the primary concentrator plant (PCP) is to remove unwanted minerals (gangue) from the prepared ore and to produce a raw or intermediate concentrate. The process often requires a combination of (wet) classification, gravity and magnetic separation to concentrate the valuable minerals contained in the ore. Elevated throughput capacity of primary stages of separation are typically required for processing low grade ores.

The PCP typically focusses on maximising recovery of valuable minerals to concentrate. In other words, the process aims at maximising the rejection of gangue minerals to tailings.

Mineral Separation Plant

The PCP concentrate is processed to separate valuable component minerals and upgrade them to the level of purity required to produce commercial products. The circuits often utilise a combination of wet and dry separation processes. Wet processes include wet high intensity magnetic separators, gravity spirals separators or wet shaking tables as well as froth flotation. Dry processes include dry magnetic separators (rare earth drum, rare earth roll, induced roll magnetic separators) and electrostatic separators.

Methodology and test work procedure description

The results of the characterisation tests were used to conceptualise a series of more detailed physical separation evaluation tests for the purpose of delineating a process flowsheet for each ore type.

Each of the samples discussed are quite distinct in terms of their particle size distribution and specific density profiles. There are however key similarities that are intrinsic to the nature of the type of resource. The specific gravity of the valuable REE minerals is known to occur in the range >4.0 g/cm^3 and it is known to display low to moderate magnetic susceptibility and low electrical conductivity (Baker, 1962). The identified major gangue minerals, quartz, display significant lower specific gravity.

These physical properties were exploited using commercially proven feed preparation and gravimetric separation techniques to produce intermediate mixed heavy mineral concentrates from each of these distinctly different ore types.

The heavy mineral concentrate was then used to separate valuable component minerals and upgrade them to the level of purity required to produce commercial products. Conventional dry mill techniques and hybrid techniques using froth flotation were compared.

Feed preparation plant circuit

Feed classification was performed using both rotating and circular vibrating screens and hydro-cyclones, in line with typical industry practices.

Primary concentrator plant circuit

Gravimetric separation was performed using spiral separators. The spiral separator test work was conducted in a closed-circuit test rig consisting of a full-sized spiral separator (single start), a sump, pump and full-stream deflection samplers, as shown in Figure 3. The pump discharge reported to a distributor with a portion of the feed stream directed to the spiral feed box and the remainder returning to the feed sump. The test rig was started up with water and solids added to the sump until the required test parameters were established. The spiral feed stream flows down the spiral trough with the high-density material migrating toward the centre column and the low-density material being transported to the outer edge of the trough. Concentrate splitters recover the high-density material to a concentrate channel, while intermediate density and low-density streams are directed by further splitters into individual product collection channels within the product collection box. Each stream then returns to the sump via timed, full-stream deflection samplers. Sub-samples of each stream were then representatively extracted, using a riffle splitter, for assay purposes.

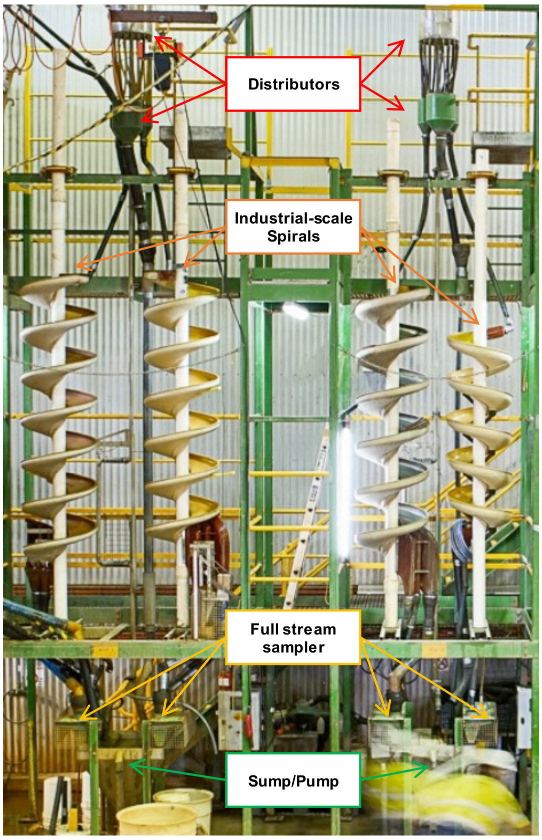

Figure 3. Spiral test rig set-up.

For each stage, separation performance curves (recovery vs. mass yield, grade vs. mass yield) are then defined at the nominal conditions, using the specified gravity spiral model. Assuming acceptable performance is achieved, the sample is then processed through an open circuit bulk sample processing step to generate feedstock for subsequent evaluation. A wide range of operating conditions and/or different equipment types or models may be tested to assess the impact on performance and assist in delineating a flowsheet meeting the process objectives.

As illustrated in Figure 4, the procedure is repeated successively through steps of closed-circuit performance tests followed by open circuit bulk sample processing until the final heavy mineral concentrate grade is produced.

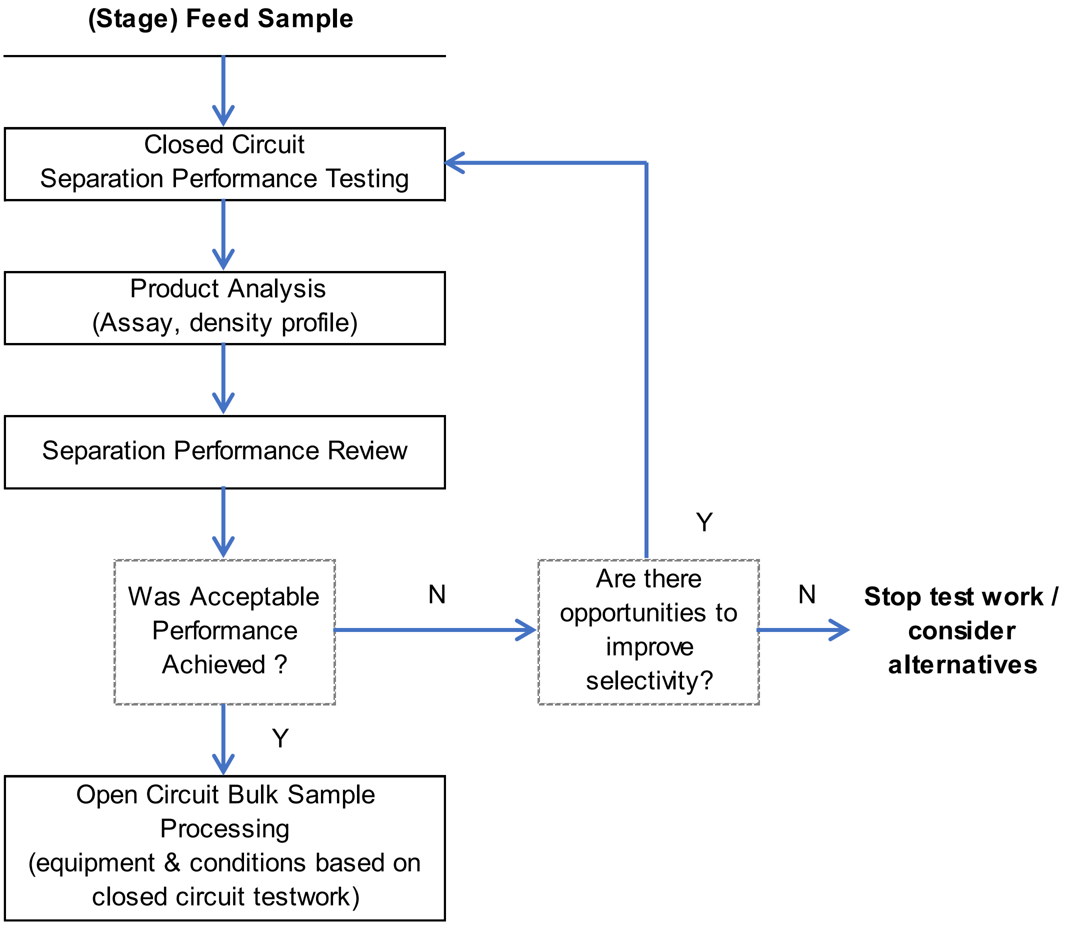

Figure 4. General flowsheet development methodology.

MSP circuit
Dry magnetic test work was conducted on a single-stage Reading laboratory-scale high intensity permanent rare earth drum (RED) or rare earth roll (RER) magnetic separator. A non-magnetics retreat configuration was typically selected. For subsequent stages the feed rate was reduced according to the weight split and the selected fraction re-treated to simulate a three-stage production unit.

Electrostatic separation tests were performed using a single-stage, laboratory-scale Carrara high tension roll (HTR) separator. Feed material was pre-heated to 100°C and passed over the separator operating at the required feed rate, roll speed and electrode voltage to generate conductor, middling and non-conductor fractions. A middling retreat configuration was typically selected. For subsequent stages the feed rate was reduced according to the weight split and the selected fraction re-treated to simulate a three-stage production unit.

The wet shaking table employed was a laboratory-scale Wilfley No13 model. Dry feed was introduced at a constant rate into the feed box and dilution water was added. The products were collected into buckets with the aid of manually positioned splitters. Products were then dewatered and dried. The dried products were weighed, and a sub-sample extracted from each using a riffle splitter for assay purposes.

For froth flotation evaluation, a series of small batch performance tests were performed on freshly attrition sub-samples to establish a suitable regime, define recovery, and upgrade performance as well as provide preliminary flotation kinetics information. The testing matrix aimed to determine effectiveness of sodium silicate and starchy polysaccharide as depressants/regulators to reduce titania and zirconia minerals reporting to flotation concentrate, and determine the effectiveness and dosage of carboxylic acid as a collector for flotation of phosphorous rare earth minerals. Upon establishment of suitable conditions either a batch bulk test or series of locked-cycle tests were performed.

CASE STUDIES

The development of process flowsheets for each ore type is discussed in the relevant case studies. The information provided is a brief overview of the detailed work that has been carried out over recent years. Detailed stage by stage separation, unit specification and performance are not reported. However, the key aspects of each design in relation to the characterisation data, the product grade and operational constraints are presented.

Ore-1 Sample

FPP

As identified during the characterisation phase the ore contained a high proportion of ultra fines particles and therefore a stage of de-sliming was included as part of the feed preparation plant circuit development. In addition, barren oversize with size >2 mm was removed. The natural good liberation of the valuable minerals in the -2.0+0.045 mm size range facilitated the high recovery (>97%) of rare earth minerals to the PCP feed relative to the run-of-mine ore.

PCP

Initial spiral concentration showed very high separation efficiency whilst utilising conventional gravity spiral models and loadings of 2.5 t/h per spiral start during the initial stages and loadings of 1.5 t/h per spiral start during the final upgrade stages.

A five-stage circuit consisting of roughing, scavenging, cleaning, recleaning and finishing was evaluated and shown diagrammatically in Figure 5. This flowsheet arrangement achieved a final concentrate assaying >90% THM, with assay grade of 0.4% CeO_2, 39% TiO_2 and 4.5% ZrO_2. Based on CeO_2 distribution, the overall recovery of monazite (and other REE-minerals) was determined to be 94.7%, which was comparable to the recovery of zircon (95.2%) and TiO_2 bearing minerals (93.4%).

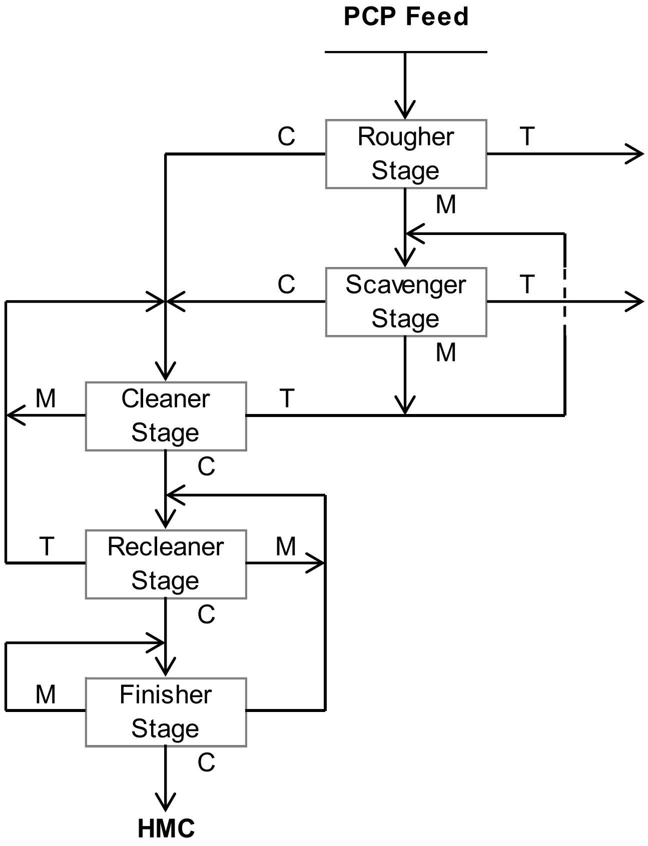

Figure 5. Ore-1 PCP circuit.

Initial conventional MSP

Initial concept for the mineral separation plant (MSP) flowsheet utilised conventional dry mill techniques based on the relative coarse size of the heavy minerals as well as the elevated proportion of ilmenite in the feed. A stage of mechanical attrition was included to remove staining from the mineral surface with the aim of improving selectivity through the dry circuit.

An overview of the circuit configuration is shown in Figure 6; two stages of dry RED separation, one stage of dry HTR and one stage of dry RER separation were required to isolate the monazite and xenotime into a medium grade raw concentrate with grade 11.5% CeO_2 and 1.47% Y_2O_3. Recovery of REE minerals, based on CeO_2 performance, was 92.9% relative to the MSP feed. Final upgrading required additional stages of HTR, wet gravity separation by wet shaking table and dry magnetic separation. Final grades of 23.0% CeO_2 and 2.50% Y_2O_3 were achieved and overall recovery relative to the MSP was calculated to be 77%.

The complexity of the circuit is consistent with overlapping physical properties of the mineral components in the gravity concentrate. Minerals compete against each other when processed through the series of electrostatic, magnetic and gravity separation steps. For example, ilmenite and monazite are both para-magnetic minerals, with modest variance in magnetic susceptibility. Aluminum-silicates, zircon and monazite are non-conductive minerals, with modest difference in electrostatic response. Zircon and monazite are also both relatively high specific gravity (SG) minerals, thereby limiting the efficacy of gravity separation techniques.

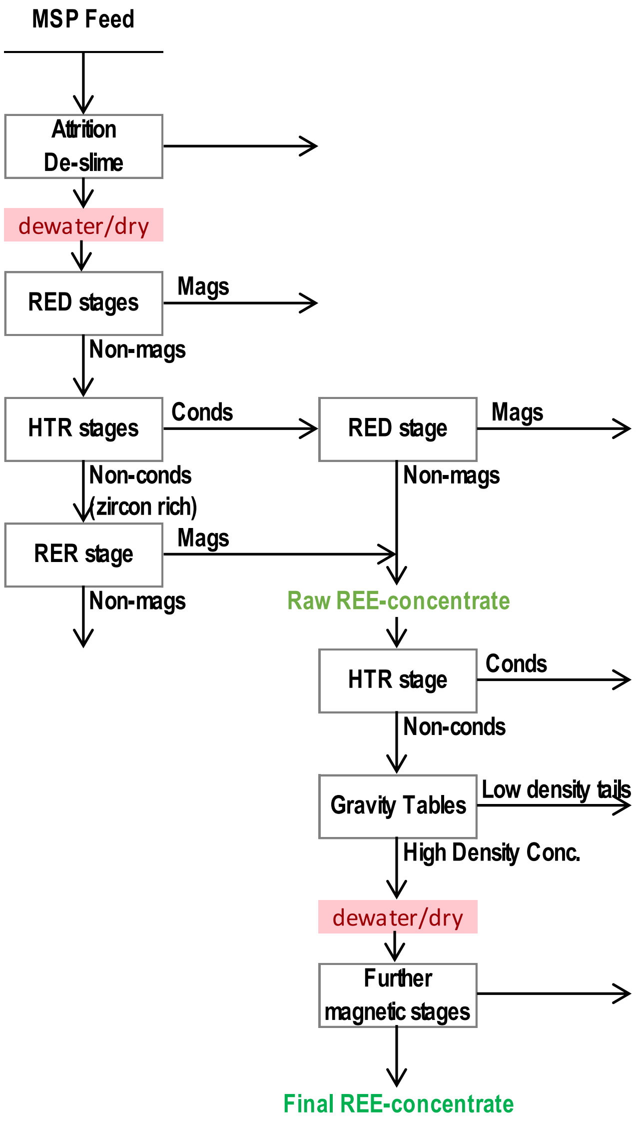

Figure 6. Ore-1 conventional MSP circuit.

Discussion

Due to their high SGs, monazite and xenotime co-report to concentrate with other heavy minerals in the initial PCP. During the subsequent MSP separation steps, the passage through numerous units of operation results in incomplete recovery, and the minerals disperse unevenly through other mineral concentrates, with a propensity to report to zircon-rich fractions.

Further to the poor selectivity, minerals separation plants with attritioning of mineral surfaces followed by drying create the potential for dust particles containing uranium and thorium to become airborne during separation. The dust represents a major occupational health hazard and control requires the installation of hooding on equipment to extract and contain the radioactive dust.

Alternative MSP

Consideration of the problem led to the renewed option of using froth flotation. Whilst flotation has been used to upgrade titania, zirconia and rare-earth minerals, there has been limited use within the mineral sands industry since advances in the performance of dry electrostatic and magnetic separators. There are very few references of utilising flotation to beneficiate low grade feedstocks (Andrews, 1990) and the technique has been considered as competitive rather than complementary to gravity, magnetic and electrostatic separation.

The criteria for the initial concept for an alternative, hybrid process was to extract the naturally occurring radioactive REE-minerals by wet separation techniques ahead of conventional dry mill techniques for the separation of zircon and titania minerals. The key elements for a successful separation were high recovery of REE-minerals to the flotation concentrate and high recovery of the titania and zirconia minerals to the tails.

Acceptable recovery and upgrade were achieved through conventional wet gravity separation techniques, hence only the beneficiation the gravity concentrate was considered.

A carboxylic acid collector was used based on well documented favourable selectivity (Andrews, 1990). Sodium silicate and a starchy polysaccharide were used as depressants to reduce titanium bearing minerals and zircon reporting to flotation concentrate. Operating pH was regulated with the addition of caustic soda and set in the range 9.2-9.5. From key observation to successful separation was the requirement for several stages of mechanical attritioning and de-sliming prior to flotation.

Overall, a single stage of flotation was shown to outperform the multistage conventional dry mill process. The flowsheet schematics is shown in Figure 7.

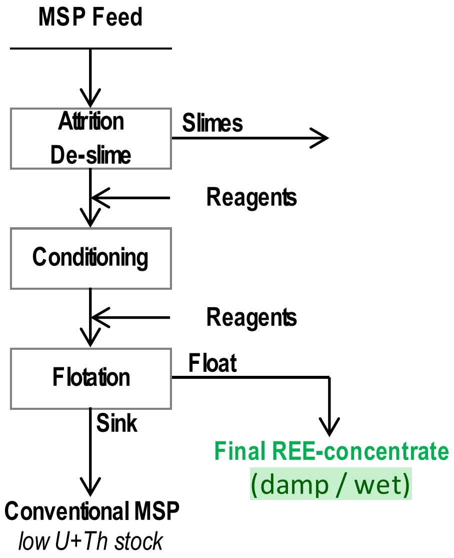

Figure 7. Ore-1 upfront flotation MSP circuit.

The comparative CeO_2 grade-recovery performance is summarised in Figure 8.

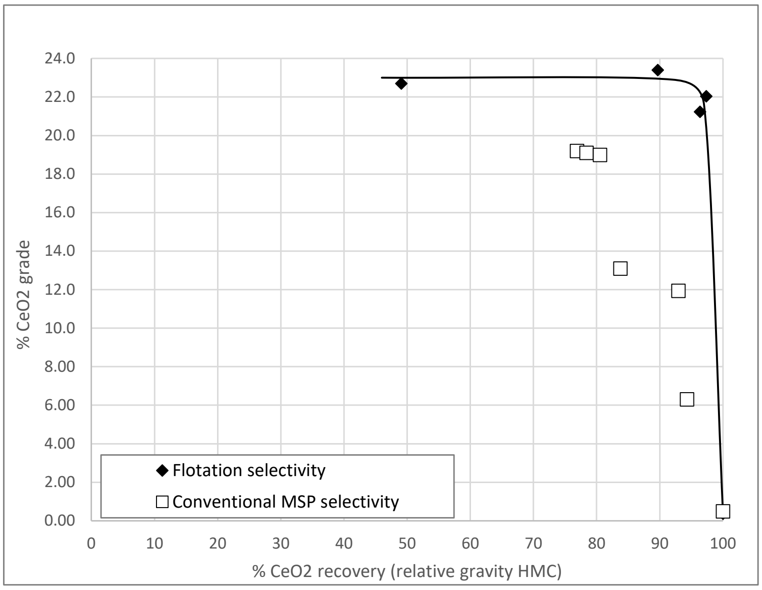

Figure 8. Ore-1 comparative MSP circuit performance.

Final grades of 21.3% CeO_2 and 3.50% Y_2O_3, were achieved and overall recovery relative to the MSP was calculated to be 97.4%. Less than 1% of the Ti-minerals and Zr-minerals were shown to report to the flotation concentrate thereby meeting the criteria for successful concept flowsheet configuration.

A comparison of the REE-concentrates chemical composition is shown in Table 4.

Table IV. Ore-1 REE-concentrate chemical composition

Description	TiO_2	Fe_2O_3	SiO_2	Al_2O_3	ZrO_2	P_2O_5	U	Th	CeO_2	Y_2O_3
Unit	%	%	%	%	%	%	%	%,	%	%
Detection Limit	0.01	0.01	0.01	0.01	0.01	0.01	0.001	0.001	0.01	0.01
Conventional MSP	3.31	2.77	1.45	0.34	1.72	26.9	0.36	4.24	23.0	2.50
Hybrid MSP	0.96	0.57	1.88	0.72	0.92	28.5	0.30	3.54	21.3	3.50

Ore-2 Sample

FPP

As identified during the characterisation phase, the ore contained high level of ultra fine particles and therefore de-sliming was included as part of the feed preparation plant circuit development. In addition, barren oversize with size >2 mm was removed.

Due to the very fine sizing of the valuable minerals, processing was completed using a two-stage de-sliming circuit to maximise the recovery of ultra fine valuable minerals, notably those in the range -45+20 µm. FPP recovery of in-size rare earth mineral to the PCP feed was >97% relative to the run-of-mine ore and consistent with performance achieved by ore-1.

Initial PCP results

Initial spiral concentration showed relatively poor separation efficiency while utilising conventional gravity spiral models operating at typical loadings. The separation performance was consistent with the fineness of the minerals as well as the elevated proportion of near-density minerals.

Discussion

While alternative beneficiation techniques are available and were considered (flotation, enhanced gravity separation), the use of gravity spirals was pursued because they are recognised as a low-cost and environmentally friendly process (Burt, 1999). In recent years several new process technologies have emerged, allowing ever-finer materials to be successfully beneficiated. Fine mineral spiral separators are just one of these technologies that have the potential to efficiently separate mineral species down to 30 µm. Spirals are simple, low energy beneficiation equipment that have proven to be metallurgically efficient and cost-effective since their widespread commercial introduction.

Conventional spiral separator

A broad range of spiral separator designs is available for various applications including different density minerals, varying particle sizes and range of feed grades. Depending on the application, each spiral separator model has a unique profile and features to ensure it performs efficiently.

Very fine heavy particles below approximately 53 µm are typically carried in the highly turbulent outer regions of the trough and are lost to tailings due to their failure to migrate inwards to the concentrate collection area. In addition, coarse particles are also swept along in the middle and outer region of the spiral due to rolling outwards owing to low friction (Holland-Batt, 1995).

For spirals to perform efficient separations outside the traditional operating window, unique conditions need to prevail in the flowing medium. Such conditions can only be provided by the trough geometry, trough features and/or feed characteristics e.g., flow rate or slurry density.

Fine mineral spiral separator

Considerable effort has been expended on the development of new gravity separators to achieve separation at finer sizes and more discrete processing capabilities to accommodate difficulties such as smaller particle density differences. The FM1 spiral was specifically developed to operate down to 30 µm while achieving acceptable recoveries. More recently, the MG12 model was demonstrated to achieve better selectivity than the FM1, when operating under particular conditions.

The key factor in the design of a fine mineral spiral separator is the overall control of turbulence (Reynolds numbers) across the entire trough to ensure conditions throughout the flowing medium are conducive to controlled settling (Holland-Batt, 1991). Also, due to the low settling velocities encountered by very fine mineral particles, the separation processes take longer to fully develop. Accordingly, a fine mineral spiral separator is typically longer than traditional units to allow these very delicate processes to produce an adequate separation. In addition, due to the laminar flows and the relatively small bed depths on a spiral trough of such design, longer residence time is required for useful separation to occur.

Holland-Batt (1995) indicated that on conventional spiral separators, the greatest recovery and grade are obtained from the first two to four turns of the spiral separator, with further, but reduced performance gained from additional turns. For the FM1 and MG12 spiral separators, a contrary effect has been observed, with improved selectivity being obtained progressively down the spiral separator. It is for this reason that the FM1 and MG12 spiral separators have multiple off-takes that need to be operated such that small increments of high-grade high density mineral concentrate cuts are taken progressively down the spiral trough.

Another feature of spiral troughs for beneficiating fine minerals requires that greater attention is needed during feed preparation to ensure feed sizing is maintained within reasonable limits, especially regarding top size.

Alternative PCP flowsheet design considerations

A five-stage circuit consisting of roughing, scavenging, cleaning, recleaning feed preparation and recleaning was evaluated and is shown diagrammatically in Figure 9. This flowsheet arrangement achieved a final concentrate assaying >90% THM and 0.85% CeO_2 with an overall recovery of in-SG (+2.85 sg) CeO_2 of 93.8% which is consistent with the performance of ore-1.

Key to the successful use of gravity spirals was the tight control of the operating load / laminar flow to the spiral trough and the inclusion of an intermediate feed preparation stage removing unwanted, interfering gangue ahead of the final recleaner stage.

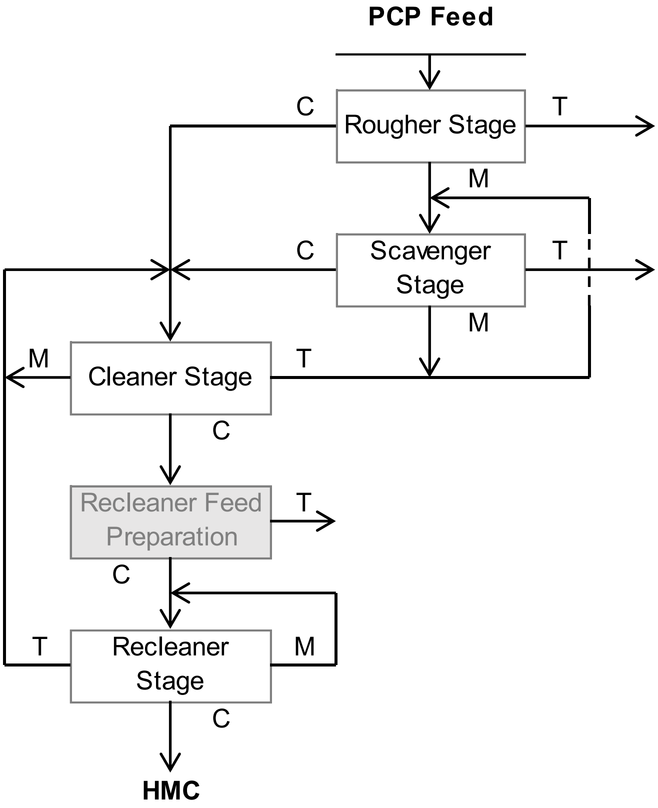

Figure 9. Ore-2 PCP circuit.

MSP

Like ore-1 HMC, the gravity concentrate produced from the processing of ore-2 was subjected to further beneficiation using both conventional MSP techniques and flotation. As observed in the earlier section, the up-front froth flotation achieved far superior results.

The conventional MSP process required the combination of six stages of dry HTR separations and three stages of dry RER separation to isolate the monazite and xenotime into a medium grade raw concentrate with 6.2% CeO_2. Recovery was 92.3% relative to the MSP feed. Final upgrade required additional stages of gravity separation by wet shaking table and dry magnetic separation. Final grades of 19.5% CeO_2 with 5.21% Y_2O_3 was achieved at recovery of 81.1% relative to the MSP feed.

The upfront flotation MSP process required attrition and a single stage of mildly alkaline flotation. Final grades of 21.3% CeO_2 and 6.89% Y_2O_3 were achieved. REE recovery relative to the MSP was calculated to be 97.0%.

A comparison of the REE-concentrate chemical composition is shown in Table V.

Table V. Ore-2 REE concentrate chemical composition

Description	TiO_2	Fe_2O_3	SiO_2	Al_2O_3	ZrO_2	P_2O_5	U	Th	CeO_2	Y_2O_3
Unit	%	%	%	%	%	%	%	%,	%	%
Detection Limit	0.01	0.01	0.01	0.01	0.01	0.01	0.001	0.001	0.01	0.01
Conventional MSP	3.47	3.20	3.46	0.26	5.75	24.6	0.26	3.29	19.5	5.21
Hybrid MSP	0.90	0.98	3.53	2.34	1.12	26.7	0.31	3.84	21.3	6.89

CONCLUSIONS

Two distinct mineral sand samples containing rare-earth minerals monazite and xenotime were evaluated for the purpose of developing beneficiation flowsheets. It was found that the concentration of rare-earth minerals in the run-of-mine ore was comparable with CeO_2 assay of 0.03% only.

Detailed understanding of the samples' particle size distributions, specific gravity profiles, chemistry and mineralogy through simple metallurgical characterisation allowed the definition of tailored laboratory test work programs. These led to the development of flowsheets specific to the unique characteristics of the samples.

In both samples, rare-earth-bearing minerals were able to be recovered and upgraded by conventional feed preparation and gravity separation techniques using spiral separators. Careful selection and control of the spiral separators coupled with intermediate re-cleaner feed preparation permitted the use of simple gravity spirals for the beneficiation of the ore-2 despite its significantly finer average particle size range of 85 µm compared to 220 µm for ore-1.

The study also showed that froth flotation of the rare-earth minerals contained in the gravity heavy mineral concentrate is highly selective and effective. This upfront flotation circuit offers advantages over the dry and wet conventional processing methods because the rare-earth minerals which are naturally radioactive are extracted from the circuit upfront, using a wet-only process. The circuit configuration therefore alleviates potential onerous occupational health issues which are linked to the generation of radioactive dust in conventional mineral sand operations. In addition, flotation achieved both superior recovery and upgrade of the rare-earth minerals compared to the conventional circuits, thereby improving projects economics.

The paper demonstrated the value of considering the varying beneficiation techniques as complementary processes rather than competing technologies.

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REFERENCES

Andrews, W. H., Collins, D. N., Hollick C. T. (1990). The Flotation of Rare Earths - A Contribution to Industrial Hygiene, *The AusIMM Annual Conference*. The Australian Institute of Mining and Metallurgy, Rotorua, New Zealand. pp. 243-252.

Baker, G. (1962). *Detrital Heavy Minerals in Natural Accumulates: with special reference to Australian occurrences*, Australasian Institute of Mining and Metallurgy. Pp. 18,19, 82 & 83.

Burt, R. (1999). The Role of Gravity Concentration in Modern Processing Plants. *Minerals Engineering*, 12 (11), pp. 1291-1300.

Holland-Batt, A. B., Holtham, P.N. (1991). Particle and fluid motion on spiral separators. *Minerals Engineering*, 4 (3-4), pp. 457-482.

Holland-Batt, A. B. (1995). Some design considerations for spiral separator. *Minerals Engineering*, 8 (11), pp. 1381-1395.

Mursky, G.A. and Thompson R. M. (1958). A specific gravity index for mineral, *Canadian Mineralogist*, 6, pp. 273-287.

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