Use of Multi-Gravity Separators to recover Rare Earth Minerals

Johnny Mogalanyane[1], Cobus Robertson[2] and Albert Venter[1]

1. CoreMet Mineral Processing, Pretoria, South Africa; johnny.mogalanyane@coremet.co.za; albert.venter@coremet.co.za
2. Obsideo Consulting, Pretoria, South Africa; cobus@obsideo-consulting.com

Abstract: Rare Earth Elements (REE) are classified as a group of 17 elements which include the fifteen lanthanides, yttrium, and scandium. Rare earths play a critical role in different industries, including, agriculture and military application, as such their commercial demand and strategic importance are rising. The continuous depletion of REE resources has placed significant interest in developing high-efficiency beneficiation and eco-friendly metallurgical processes. Currently, new REE deposits are being explored to meet the supply demand, however a vast majority of these deposits have rare earth minerals for which processing knowledge is limited. Commercially, the only REE bearing minerals that have been extracted on a large scale include xenotime, bastnäsite and monazite, these can be beneficiated using gravity, magnetic, electrostatic, and flotation separation techniques.

This paper reviews the performance of the Multi Gravity Separator (MGS) in beneficiating rare earth minerals found in monazite. Tests were done at three grind sizes. Some of the key benefits of the MGS include high-grade and high-recovery processing of fine materials, sustainable and chemical-free operation, and self-regulation to manage varying material grades without losses.

The study results indicated that it is possible to beneficiate rare earth elements using the MGS across the three grind sizes tested. The upgrade ratios ranged from 2.13-3.07, 2.3-24.8, and 2.0-14.0, with recoveries ranging from 84.7-94.1%, 62.9-93.0%, and 63.4-94.7% respectively. The MGS allows for the design of a simplified processing circuit capable of handling high feed variability, producing on-specification concentrate with high REO recoveries and low operating costs.

Key words: *Multi gravity separator, Rare Earth, Monazite, Upgrade ratio*

1. Introduction

1.1 Background

Rare earth minerals are divided into two main categories, which are light rare earth elements and heavy rare earth elements (Cheng et al., 2024). The light rare earth elements include those from lanthanum (La) to europium (Eu), while the heavy rare earth elements include gadolinium (Gd) to lutetium (Lu) as well as yttrium (Y) (Cheng et al., 2024). As of 2021, global rare earth reserves were estimated at approximately 125 million tonnes, with China holding 35% of these reserves and supplying over 97% of the global demand (Cheng et al., 2024 and Jordens et al., 2013). Heavy rare earth elements are considered the most economically critical due to their lower natural abundance. The demand for rare earths has increased in recent years due to the wide range of applications where REEs are utilisied.

Rare earth elements (REEs) are widely used in various high-technology applications, including high-strength permanent magnets, phosphors for electronic displays, renewable energy technologies, and as alloying agents in metals (Cheng et al., 2024). Rare earths significantly improve iron, copper and nickel alloy performance.

In 2011, the Chinese government restricted the annual exports of rare earth oxides to approximately 35,000 tonnes to address domestic development needs against the increasing global demand (Jordens et al., 2013). The restriction on Chinese exports, combined with rising global demand, has led to the development of numerous new rare earth mining projects (Jordens et al., 2013). However, each of the new projects are characterised by unique mining and processing difficulties (Cheng et al., 2024). Jordens et al., 2013, states that the issues facing potential REE producers are as follows:

- Limited technical expertise outside of China.
- Radioactive waste issues from REE extraction.
- High capital costs for new REE plants, often near a billion dollars.
- Unpredictable and non-transparent market prices, as REEs are sold on contract.
- Short start-up periods needed to meet demand.
- Inconsistent demand for individual REEs, potentially leading to oversupply and price fluctuations for cerium and lanthanum unless additional uses are found for these two elements.

A rare earth deposit only has economic value, if the minerals can be extracted in a cost-effective, efficient and environmentally responsible manner. Although many deposits have been explored worldwide, only a few are mined for rare earths (Bisaka et al., 2017).

1.2 Exploited REE

Jordens et al., 2013, indicates that the three most commonly extracted rare earth bearing minerals are monazite, bastnäsite and xenotime.

Monazite is a phosphate mineral and contains approximately 70% rare earth oxide (REO). Monazite primarily contains cerium (Ce), lanthanum (La), praseodymium (Pr), and neodymium (Nd), with the composition varying by deposit (Jordens et al., 2013). Monazite typically contains 20%-30% Ce_2O_3, 10%-40% La_2O_3, and 4%-12% ThO_2. Unlike bastnäsite, monazite generally includes more radioactive elements such as thorium and a variable amount of uranium (Cheng et al., 2024). Beach sand is the primary raw material for producing monazite concentrate, which is easy to mine and has high economic value. Monazite is a by-product of extracting ilmenite, rutile, cassiterite, and zircon from beach sands (Cheng et al., 2024).

Monazite-rich beaches are primarily exploited in Australia, India, and Brazil, as well as in South Africa, the USA, China, and Malaysia. The 20th century witnessed widespread monazite mining from these beaches. However, due to the environmental pollution caused by the inefficient utilisation of thorium in monazite, many countries have banned its exploitation. This has resulted in a gradual decrease in monazite production (Cheng et al., 2024). The beach sands monazite deposits are typically beneficiated via high-capacity gravity separation, to take advantage of the high specific gravity followed by additional gravity, magnetic, electrostatic and occasionally flotation separation steps (Cheng et al., 2024).

Bastnäsite is the most common RE mineral and the primary source of light rare earth elements with a rare earth content of approximately 70% rare earth oxide, that is mainly Ce,La, Pr and Nd (Gupta & Krishnamurthy, 2005). Over the past 50 years, bastnäsite has substituted monazite as the primary mineral source of rare earth elements. This shift is mainly due to the discovery and development of the world's largest REE mines, the Bayan Obo mine in China and the Mountain Pass mine in the United States (Jordens et al., 2013). Bastnäsite is chemically susceptible to weathering, which causes rare earth oxides (REO) to dissolve and combine with available phosphates (Gupta & Krishnamurthy, 2005). Xenotime is classified as an yttrium phosphate mineral which comprises of a rare earth oxide content of approximately 67%. In comparison to both the monazite and the bastnäsite, the xenotime, contains lower concentrations of Ce, La, Pr and Nd (Jordens et al., 2013).

1.3 Beneficiation

According to Gupta & Krishnamurthy, 2005, the challenge in exploiting rare earth minerals is that they are not often found in economically viable concentrations and the fact that they are rarely found as pure metals. Instead, they occur in various forms such as silicates, oxides, carbonates, phosphates, and halides.

Metallurgical processes designed for the beneficiation of rare earths, exploit either, the difference in specific gravities, magnetic properties, conductivity, and surface chemistry between the REE and their associated minerals (Gupta & Krishnamurthy, 2005). The most common beneficiation methods used involves either, gravity separation, magnetic separation, electrostatic separation and froth flotation. According to Jordens et al., 2013, with the exception of monazite and bastnäsite, there is very limited research on the flotation of rare earth minerals such as xenotime.

The most common beneficiation method used for REE beneficiation especially for carbonatites is flotation due to the complex and fine mineralisation which require grinding to below 100µm (Marion et al., 2020 & Suli et al., 2017). A review of the available literature on rare earth flotation by Marion et al., 2020, concludes that surface chemical studies are required to improve the understanding of bastnäsite and monazite flotation. The study further states that while hydroxamates have been found to be effective collectors for the flotation of carbonates and phosphates, they unfortunately do not offer the same effectiveness in the selectivity of rare earth bearing silicate minerals. Marion et al., 2020, indicates that in most cases optimal flotation occurs at a pH of 9 and requires optimised suite of collectors, activators and depressant that is depending on the ore mineralogy and associated gangue minerals. This means that costly chemicals are required for flotation as well as effluent neutralisation. Furthermore, a variable ore body can be challenging if the feed to the plant is poorly controlled (variable ratios of ore types).

The use of electrostatic separators is typically limited to dry applications, this implies that ores would need to be dried before electrostatic separation, this requires a substantial amount of energy and as a consequence, the use of electrostatic separation is limited in industrial application (Jordens et al., 2013). Furthermore, electrostatic separation is challenging at sizes below 40µm (Suli et al., 2017)

Rare earth minerals have a specific gravity ranging from 2.9 to 7.2, while silicate minerals, the most common gangue minerals, have a lower specific gravity. This difference in density makes gravity separation an effective method for beneficiation of rare earth minerals. The most commonly used gravity separation techniques are shaking tables, spiral concentrators, and conical separators (Cheng et al., 2024). Suli et al., 2017, also emphasises that these type of gravity separators are highly effect in recovering RE minerals larger than 100µm but does not perform as well on RE minerals smaller than 100µm. For this reason, flotation is the main beneficiation route. Even in cases where standard gravity equipment is used the concentrates are grinded finer before further cleaning in a flotation circuit in order to obtain the required grades. This complicates the process flowsheet where different size fractions and grind sizes need to be controlled.

The Multi Gravity Separator (MGS) operates similarly to a shaking table to separate and upgrade fine material. It uses centrifugal force to impart enhanced gravity, which forces heavier materials against the drum wall where the heavy particles are transported towards to top end of the drum by a scraper blade, while the lower density tailings are agitated by the shaking motion and flows with gravity towards the lower end of the drum. As shown in Figure 1, the drum is rotating and translating (shaking motion). The feed is introduced into the centre of the drum onto a diffuser ring that accelerates the feed onto the drum surface. Additional wash water is introduced higher up in the drum to further clean the concentrate that is being scraped towards the top end of the drum.

Some of the benefits of using an MGS in a gravity circuit include:

- High grade and recovery from material smaller than 100µm down to 10µm
- Ability to separate efficiently at densities above 4g/cm^3.
- Can operate on process water and does not require potable or specially treated water.
- Sustainable and chemical-free processing.
- Suitable for concentrating various valuable metal-bearing ores.
- Self-regulating and able to handle significant changes in material grade without losses.
- Ability to adjust to changes in feed pulp density by modifying wash water levels.
- Can produce saleable grade concentrate from low-grade tailings in one step and can also function as a rougher or cleaner to optimise capacity and recovery.

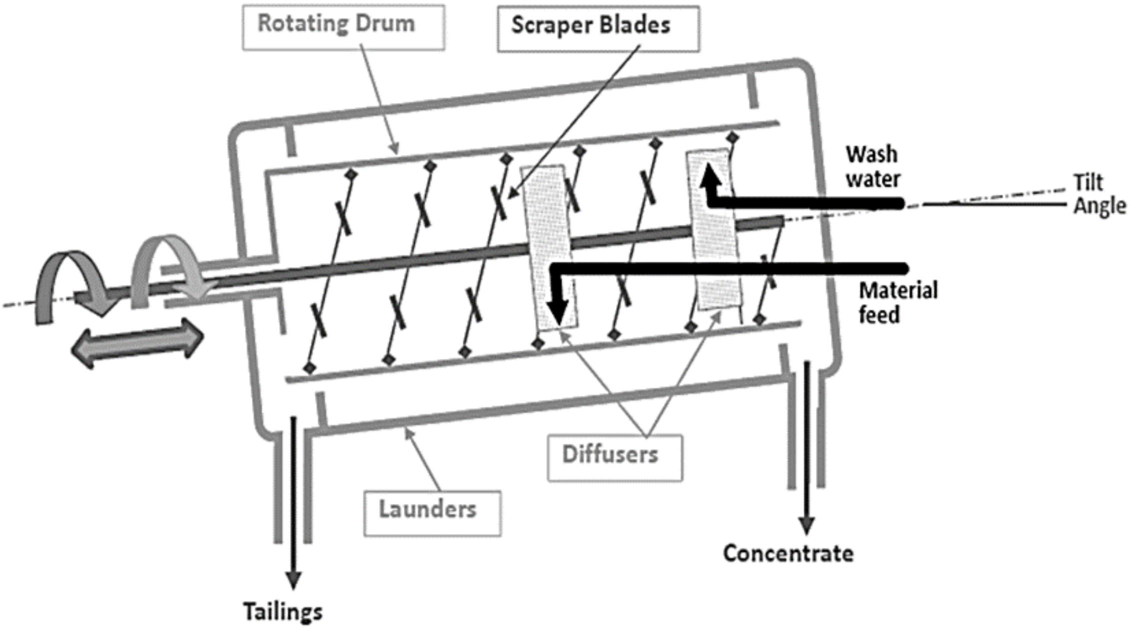

Figure 1: Diagram of the MGS operating principles

2. Methodology

2.1 Sample description

The current work is focused on two different sample sources. Due to confidentiality agreements both clients' names and the sample source names are kept anonymous.

2.1.1 Heavy Mineral Sand Samples

The set of samples are labelled HM (heavy minerals). The HM set of samples originated from a mineral sand beach placer deposit with the main RE host mineral being monazite. Three different size fractions were tested, namely:

i. -180+106µm with a head grade of 2.86% monazite
ii. -106+45µm with a head grade of 17.36% monazite
iii. -180+45µm with a head grade of 5.77% monazite

The different sample sizes were investigated to see whether narrower size ranges would increase recovery in the MGS. As can been seen from the head grades from the different fractions the monazite was more concentrated in the -106+45µm fraction. The -106+45µm fraction contributed only 20.1% on a mass basis while it contained 60.4% of the monazite in the combined -180+45µm fraction.

2.1.2 Carbonatite Samples

The second set of samples originated from a carbonatite hard rock deposit. The two samples are labelled CHR-A (Carbonatite Hard Rock) and CHR-B. In the carbonatite hard rock samples, the main RE containing mineral is monazite. The resource also contains minor RE minerals such as bastnäsite, synchysite and florencite.

The CHR samples underwent similar sample preparation. The samples were grinded in a ball mill, screened at 75µm and then the screen undersize was deslimed using a 40mm hydrocyclone. This then produced a -75+10µm fraction for MGS testwork.

Sample CHR-A originated from a high-grade mineralisation in dolomite carbonatite and had a head grade of 7.35% total rare earth oxide (TREO). Sample CHR-B originated from a brecciated carbonatite and had a head grade of 2.95% TREO. Due to the difference in the ore mineralisation CHR-A and CHR-B has different gangue minerals. The CHR-A sample's main gangue minerals are ankerite-dolomite, strontianite, apatite, calcite and quartz compared to the CHR-B sample's main gangue minerals that are ankerite-dolomite, K-feldspar, biotite, apatite and quartz.

2.2 Method

The MGS C900 test unit was used for the test work (Figure 2). The efficiency of separation in the MGS is influenced by several parameters, including drum speed, tilt angle, shake amplitude, wash water flow rate, and slurry density (Deniz, 2021). The current test work focused on determining the grade, recoveries and yields by varying the drum speeds and wash water flow rates. The drum angle (7.5º), the shake amplitude (10mm) and the shake frequency (5.8Hz) were kept constant for all testwork.

Slurry was prepared in the mixing tank at the required density of 45% solids by mass. It was then fed into the MGS using a peristaltic pump. The MGS tests were conducted with varying drum speeds and wash water flow rates. At each combination of drum speed and wash water flow rate, timed concentrate and tailing samples were collected. The timed concentrate and tailing samples were weighed, dried, and prepared for chemical analysis. The results from the chemical analysis enabled the determination of the grade and recovery at different drum speeds and wash water flow rates.

Figure 2: MGS C900 test unit, mixing tank and peristaltic pump that was used for the testwork

2.2.1 Heavy Mineral Sand Sample Testwork

In the case of the HM samples the request was to upgrade the monazite from approximately 10% to 35%, thus an upgrade ratio of 3.5. The rotational speed was varied from 137.5rpm (revolutions per minute) up to 162.5rpm. This correlates to a G-force of 4.8 up to 6.8. Two wash water settings were tested, namely 4lpm (litre per minute) and 6lpm.

2.2.2 Carbonatite Testwork

The carbonatite samples were tested to verify a proposed flowsheet. It was required to produce a final concentrate with a minimum of 45% TREO. The flowsheet consisted out of a rougher and cleaner step. The rougher testwork was used to select specific settings to produce bulk concentrates that were then used for the cleaner testwork.

For the cleaned step the rotational speed was varied between 150rpm and 180rpm. This correlates to a G-force of 5.8 up to 8.3. Two wash water settings were tested, namely 4lpm and 6lpm. For the cleaner stage the drum speed was changed from 140rpm up to 170rpm, which correlates to a G-force range of 5.0 up to 7.4.

3. Results and Discussion

3.1 Heavy Mineral Sample Testwork

As previously indicated the majority of the monazite in the Heavy Mineral sample was located in the -106+45µm fraction with the head grade (17.36%) in this fraction being 6 times higher than the monazite concentration in the -180+106µm fraction (2.86%). The requirement for the client was to produce a monazite concentration in excess of 35% with an expected upgrade ratio of 3.5. The results for the MGS testwork on the HM samples are shown in Figure 3. It is clear from the results that the MGS could achieve the required final concentrate value of greater than 35% monazite in a single pass for both the -180+45µm and -106+45µm fractions. In the case of the -180+45µm fraction the required grade was achieved at a monazite recovery of 85% to concentrate. The MGS achieved monazite recoveries in excess of 90% to concentrate in -106+45µm fraction, while maintaining grades in excess of 40%. However, for the -180+106µm fraction the maximum concentration was 25.2% monazite at a recovery of 63.4%.

In terms of the upgrade ratio (see Figure 4) the MGS was able to achieve upgrade ratio more than 3.5 for all three size fractions. On the -180+106µm fraction the MGS could achieve an upgrade ratio of nearly 9 at a monazite recovery of approximately 63%. This shows the MGS can selectively separate high-density minerals. For the other two fractions it was possible to achieve the require 3.5 upgrade at recoveries of 85% and higher.

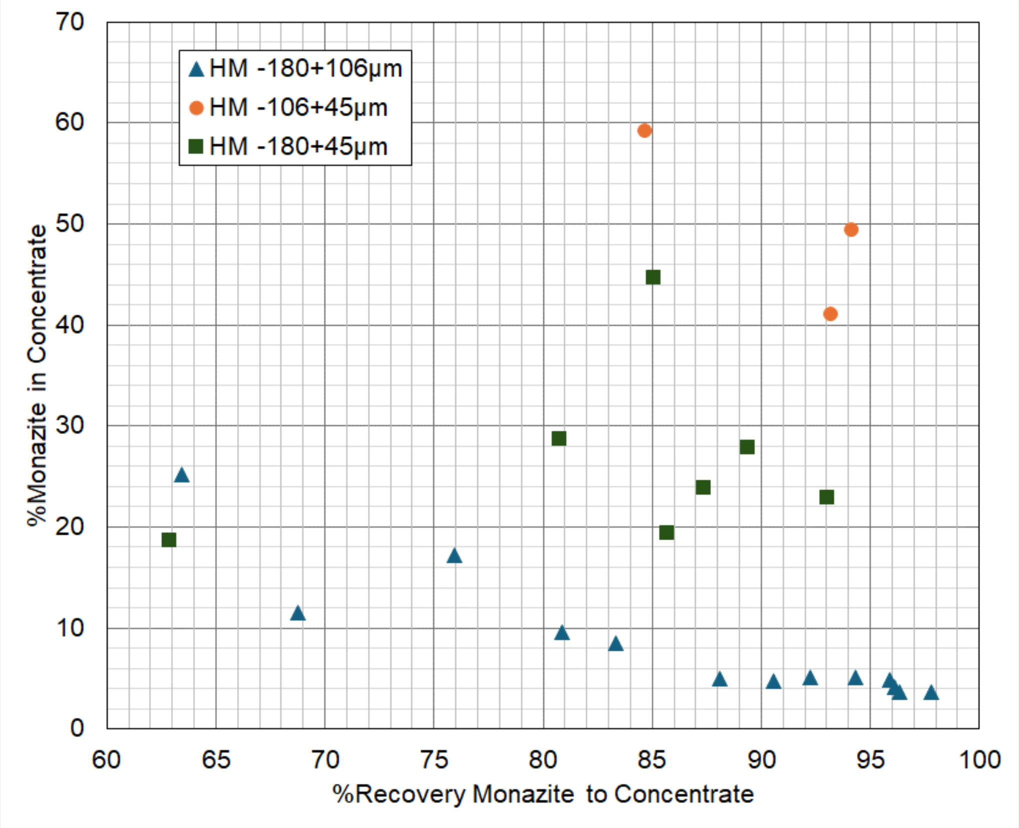

Figure 3: Monazite grade versus recovery for the MGS tests on the three HM samples

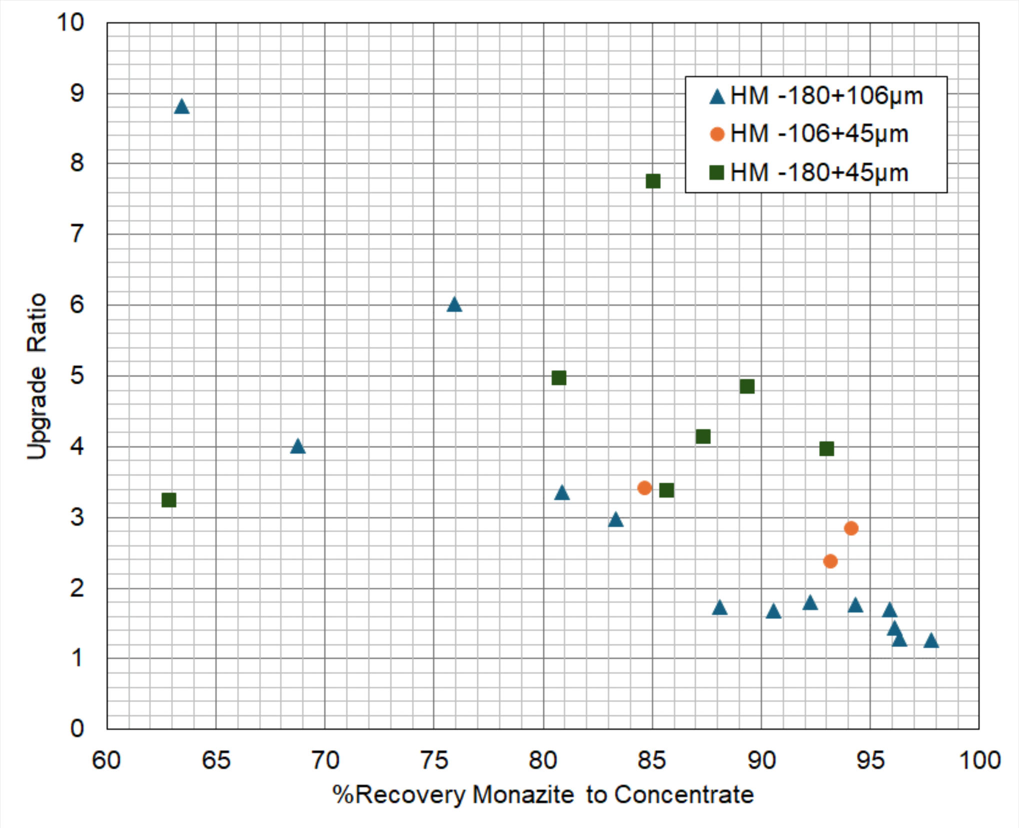

Figure 4: Monazite upgrade versus recovery for the MGS tests on the three HM samples

3.2 Carbonatite Testwork

The carbonatite testwork target was a minimum grade of 45% TREO. Initially a rougher stage test was performed on the two sample as shown in Figure 5. It was possible to upgrade the CHR-A sample to 35% TREO with a recovery over 80% while the CHR-B sample could be upgraded to approximately 42.5% TREO at a 46%. However, the grade-yield relationship shown in Figure 6 clearly indicates that to achieve the high grades it requires mass yields below 5%. This is not ideal from an operational point of view since this will require high process stability to maintain the required upgrade. For this reason, it is better to perform a rougher followed by a cleaner in order to optimise grade and recovery.

The following bulk concentrates were produced:

- CHR-A Rougher concentrate of 21.44% TREO at a recovery of 79.1%.
- CHR-B rougher concentrate of 15.16% TREO at a recovery of 71.3%.

The cleaner test results (shown in Figure 7 and Figure 8) indicates that it was possible to achieve the desired target of 45% TREO for both samples with recoveries in over 75%. The yields in both cases are over 10% which would simply the operational control. These results were achieved on samples that were 100% passing 106µm which traditionally would need to be processed through a flotation circuit.

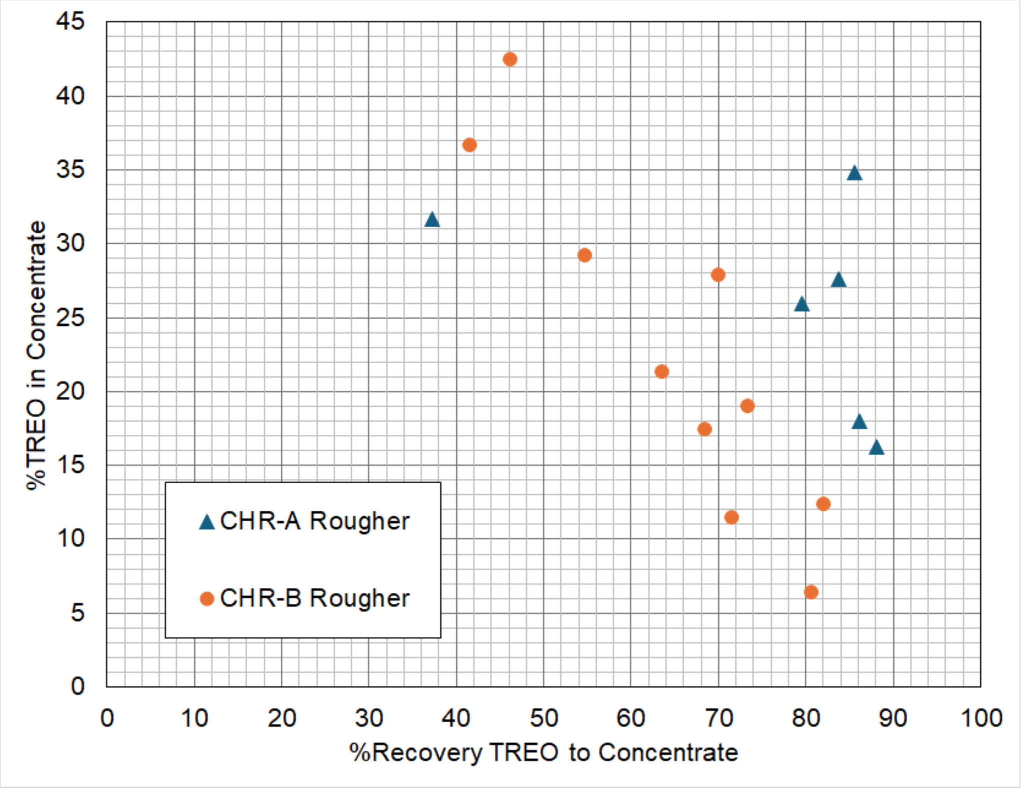

Figure 5: TREO grade versus recovery for the rougher MGS tests on the two carbonatite samples

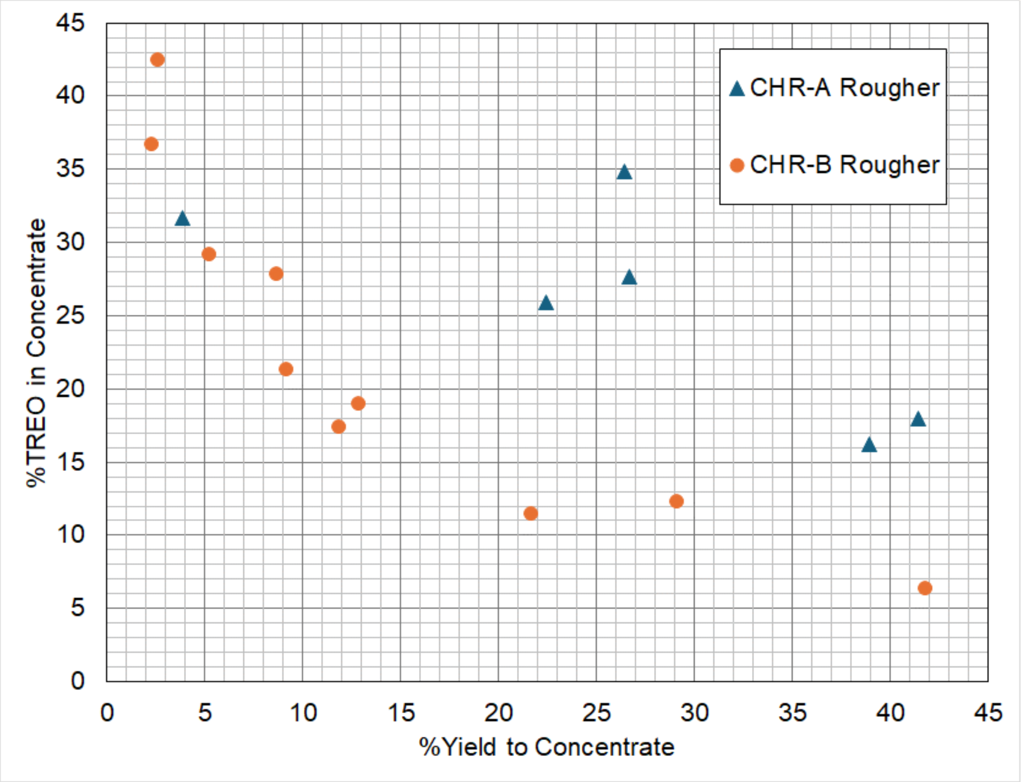

Figure 6: TREO grade versus yield for the rougher MGS tests on the two carbonatite samples

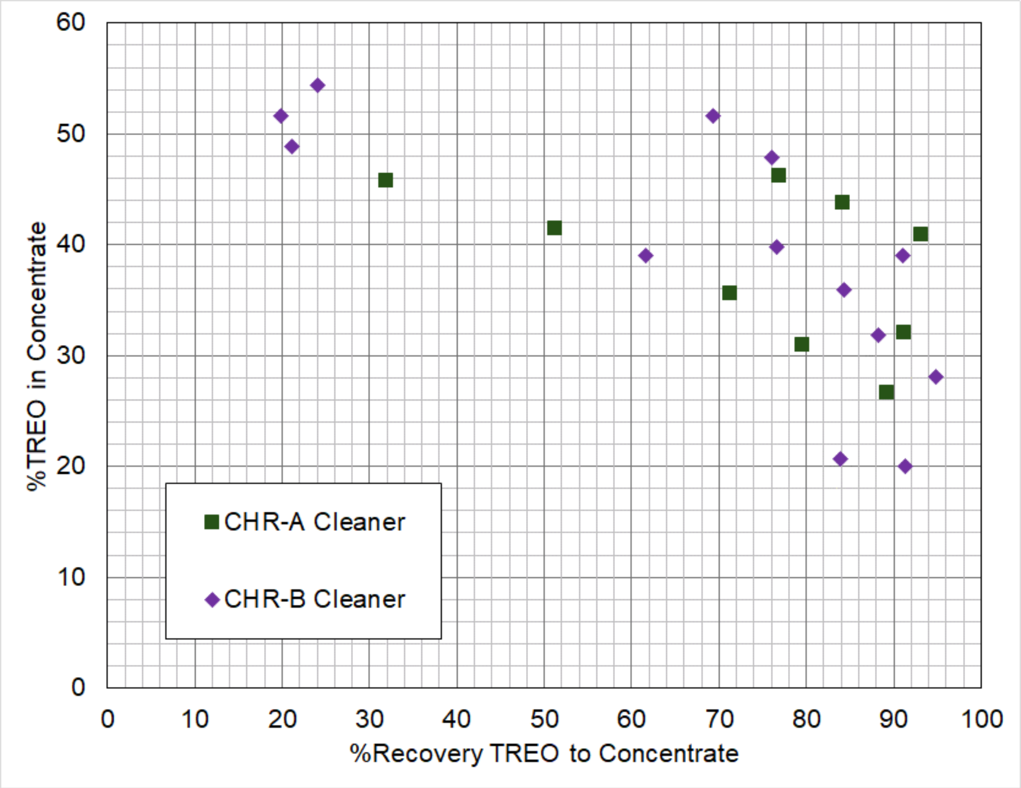

Figure 7: TREO grade versus recovery for the cleaner MGS tests on the two carbonatite samples

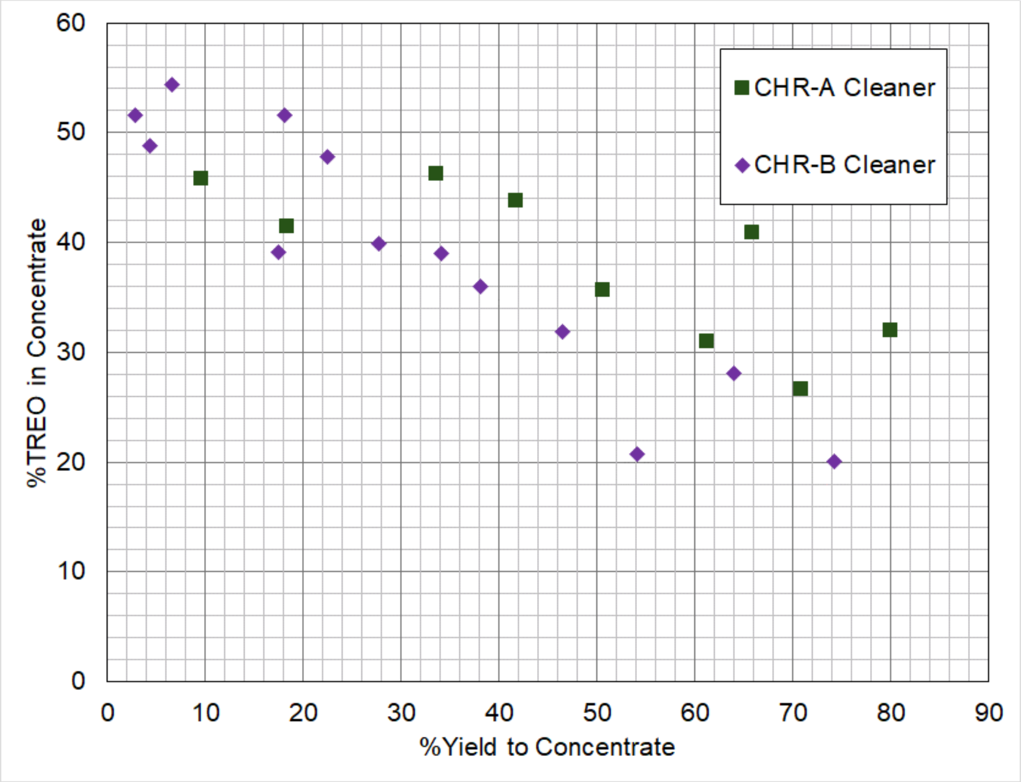

Figure 8: TREO grade versus yield for the cleaner MGS tests on the two carbonatite samples

The testwork showed that the MGS is able to successfully recover and upgrade TREO from both CHR-A and CHR-B even though there are significant differences in the sample mineralogy. The testwork further confirmed that the MGS is able to recover TREO in the size fraction below 75µm down to 10µm, thus providing an alternative to flotation where the differences in changes in mineralogy can require frequent adjustments in the flotation collector suite.

The result of the testwork was that a simplified flowsheet could be developed where all the material is grinded down to below 100µm and then undergoes gravity separation (rougher and cleaner) to obtain combined recoveries of over 75% with concentrate grades above 45% TREO before final magnetic cleaning. This removed the need for flotation with it added cost on chemicals, water treatment and effluent treatment as well as additional environmental management such lining of slimes dams.

The further advantage of the MGS' ability to recover RE minerals down to 10µm is that it also reduces the risk of losses due to overgrinding, which enables the opportunity to optimise the grind size.

4. Conclusion

The current testwork on the two different sources, a heavy mineral placer deposit and a carbonatite hard rock, showed that the MGS is highly effective in recovering RE minerals with recoveries in above 80% and up to 95% being achieved. Furthermore, the MGS can maintain upgrade ratios of over 3 thus providing both high recover and high grade. The testwork showed the MGS can effectively recover RE minerals down to 10μm, which is in the same range as flotation. The testwork on the CHR-A and CHR-B samples showed that it is possible to successfully recover and upgrade RE minerals with different mineral compositions as long as the RE minerals are liberated without any significant operational changes.

The MGS allows for simplification of rare earth beneficiation plants by allowing all the material to be grinded to the same top size before separation and also removing or limiting the need for the use of chemicals and additional water treatment.

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