# RARE EARTH PRODUCTION FROM AN AUSTRALIAN CLAY HOSTED DEPOSIT

By

[1]Chantelle Bardadyn and [1]Jess Page

[1]Wallbridge Gilbert Aztec, Australia

Presenter and Corresponding Author

**Chantelle Bardadyn**
cbardadyn@wga.com.au

## ABSTRACT

Australian Rare Earths (AR3) is progressing inputs to feasibility studies and approvals for their Koppamurra Project in South Australia, rich in clay hosted rare earth elements (REE) that are critical to producing renewable energy technologies and de-carbonising the world's energy landscape. The Project is led by a highly credentialled team, supported by world class consultants and advisors with proven expertise in the rare earths and mining industries.

AR3, in collaboration with Wallbridge Gilbert Aztec (WGA) metallurgists and process engineers, and experts from ANSTO, SGS Lakefield and University of Toronto, have substantially progressed a comprehensive metallurgical test work program to evaluate and select a process for economic recovery of the REEs from the deposit. The flowsheet evaluation is supported by robust data collection and storage by the WGA Data Analytics team, who have securely consolidated drilling and test work data, and identified geometallurgical relationships through machine learning applications.

Understanding the ore's metallurgical response is critical for developing an economic process flowsheet. Through mineralogical studies, bench-scale beneficiation and extraction tests and a recent large-scale test work program, a preliminary process flowsheet has been developed and continually updated based on insights derived from test work. The following insights have recently been derived:

- Leach optimisation test work conducted at ANSTO and University of Toronto demonstrated an average recovery of 65%, up to 77% of the four key magnet REEs, being Nd, Pr, Dy and Tb, in the pH range 1.5 to 2.0 at ambient conditions. This recovery was maintained whilst significantly reducing acid consumption from the dissolution of the gangue minerals, iron and aluminium, by 50%. Further leach tests on samples from spatially diverse locations within the deposit, provided consistent metallurgical response to varied pH, leach time and solids density, despite the geographic spread.

- Solid-liquid separation experts, Metso Outotec and GBL / IFS have progressed test work to develop process technology selection and determine optimal separation conditions.

- Bench-scale size separation test work at SGS showed early potential for >30% mass rejection and >50% gangue mineral rejection in a coarse waste stream, whilst maintaining REE grade in the product stream. This may provide both an opportunity to reduce material throughput and acid consumption, leading to commercially attractive equipment sizing and reagent requirements.

- An 850 kg composite sample extracted from the Koppamurra Trial Pit was processed by ANSTO in December 2022 for generation of a mixed rare earth carbonate and product specification analysis. This significant step change in the scale of test work, covering the entirety of the process flowsheet, will inform design and operational criteria for testing of a 500-tonne bulk sample at an even larger pilot scale.

These insights provide both an environmentally sound and commercially attractive process pathway to economic production of a high-quality specification REE product. Pipeline test work in further optimising particle size separation, solid-liquid separation, impurity removal and carbonate precipitation will contribute to finalising the process flowsheet and provide key inputs to both the mining lease application and a scoping study.

*Keywords: Rare Earth Elements, Clay Hosted, Renewable Energy Technologies, Mining Lease Application*

# INTRODUCTION

Rare earth elements (REE) play a vital and increasing role in numerous everyday devices and are critical to renewable energy technologies for decarbonising the world's energy landscape. The REE industry is driven by the demand for rare earth containing high strength permanent magnets (REPM), as components in renewable energy technologies.

The projected five-fold increase in demand for REE by 2030 underscores their importance. Nevertheless, supply is volatile due to China's dominance in the industry and dwindling reserves, with the country currently accounting for approximately 70% of global annual mined production[(1)]. Furthermore, China is the exclusive producer of the the two heavy rare earth elements (HREE), dysprosium and terbium, which enable REPMs to function at high temperature[(2)]. Currently only two mines outside of China are operational, namely Mountain Pass in the US and Mount Weld in Australia. Hence, diversifying the rare earth supply chain is now a pressing concern for the industry.

This pre-eminent position of China can be attributed, in part, to their tenure of ionic clay hosted deposits, as opposed to the hard rock variety. The former deposits tend to exhibit shallower depths and do not necessitate energy-intensive techniques such as blasting, milling, or crushing. Additionally, they typically do not generate radioactive tailings, thereby making the mining and processing of these deposits more simple and economically favourable in comparison to the hard rock deposits.

Australian Rare Earths (AR3) flagship Koppamurra deposit represents one of only three advanced ionic clay hosted REE deposits outside China[(3)]. AR3, in collaboration with Wallbridge Gilbert Aztec (WGA) metallurgists and process engineers, together with experts from ANSTO, SGS Lakefield and the University of Toronto, have substantially progressed a comprehensive metallurgical test work program for Koppamurra. The program, having now encompassed 142 (unique) samples and 24 composites with a range of spatial and mineralogical diversity, has undergone 11 phases of test work, including mineralogy, rare earth element extraction extents and minerals processing methods. Through these efforts, a comprehensive understanding of the ore’s metallurgical behaviour has been attained, which is essential in the development of an environmentally sustainable and commercially attractive process flowsheet.

As a first in Australia for an ionic clay hosted rare earth resource, AR3 recently produced a mixed rare earth carbonate (MREC) at pilot scale, under ambient temperatures and pressures. This significant step change in the scale of test work, covering the entirety of the process flowsheet, will inform design and operational criteria for larger scale testing of a 500-tonne bulk sample.

## DEPOSIT DESCRIPTION

### Resource

AR3 currently hold multiple exploration licenses across southeast South Australia and western Victoria, as presented in Figure 1. A substantial JORC Resource (ASX March 2023) of 101 Mt at 818 ppm Total Rare Earth Oxide (TREO), incorporates the results from two completed drilling programs, with another program currently underway. The Resource defined to date is <5% of the total 4,000 km$^2$ of granted exploration tenure.

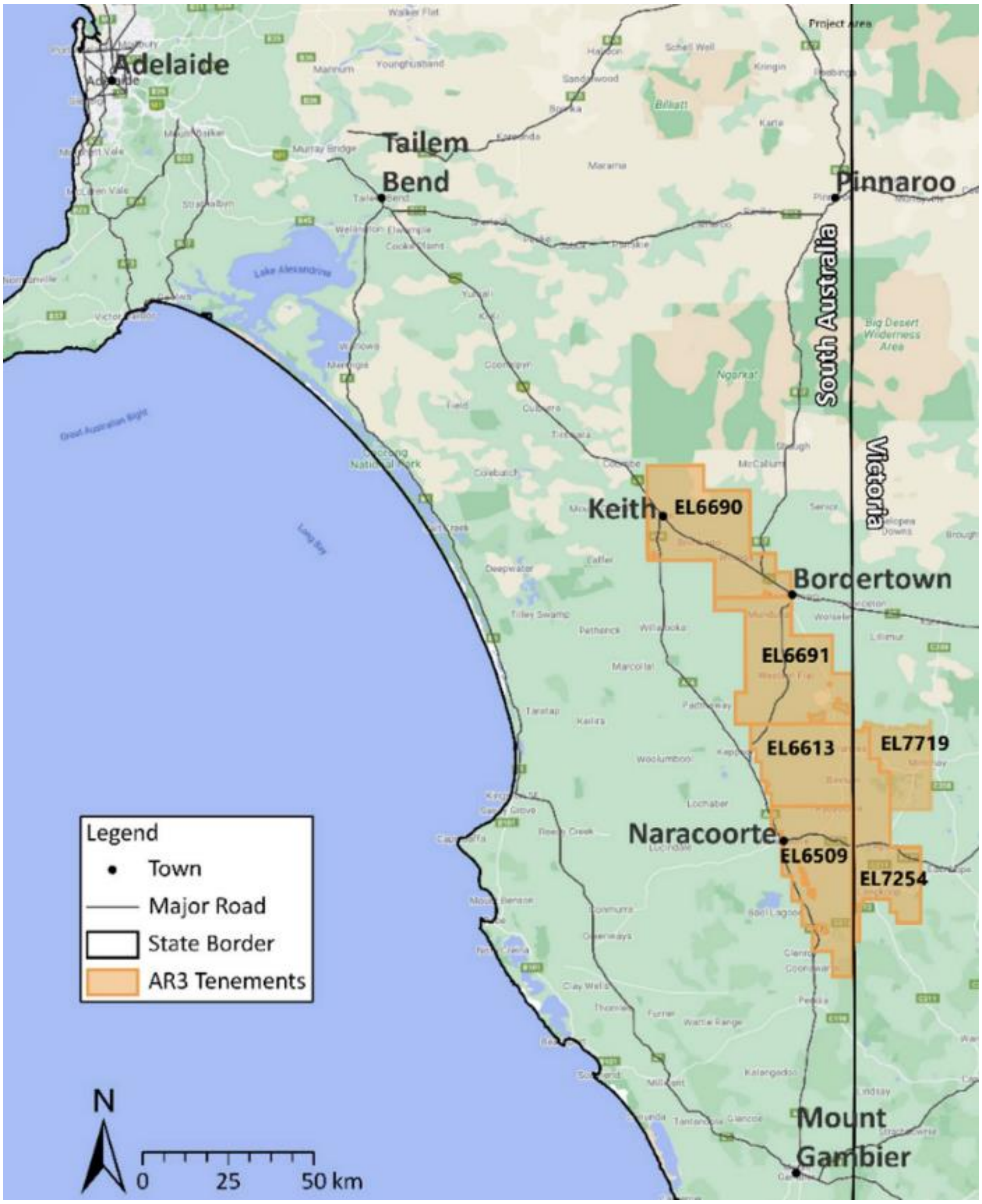


**Figure 1: AR3 tenement areas across southeast South Australia and western Victoria.**

Koppamurra is characterised by a shallow, REE mineralised clay sediment, <10 m from surface, deposited above the Gambier limestone base, as presented in Figure 2.

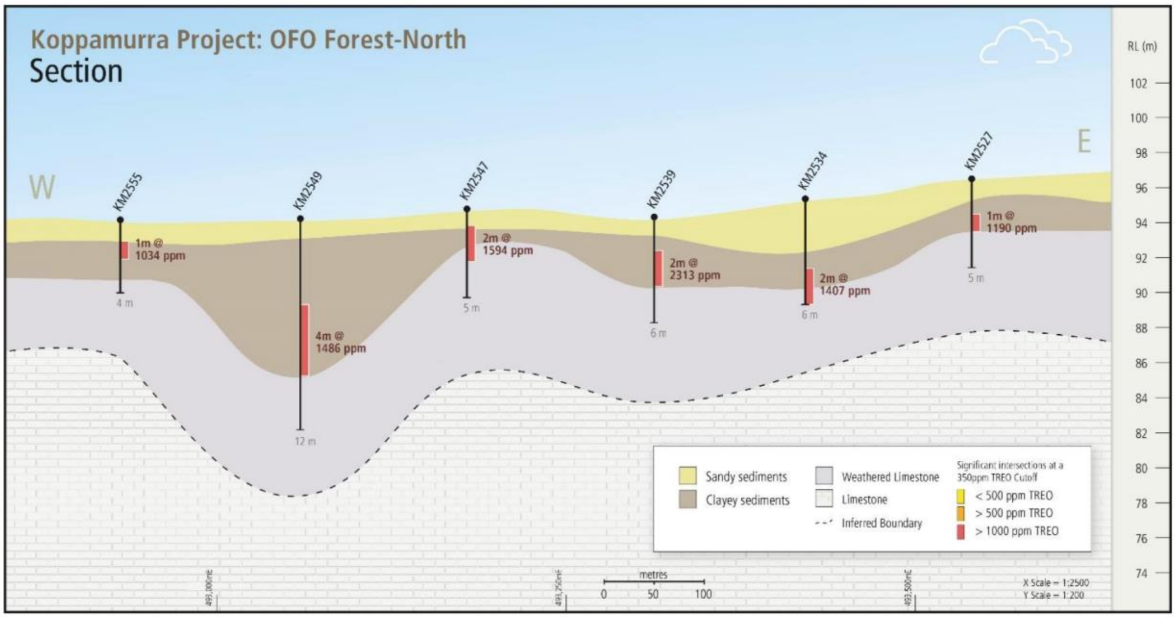


**Figure 2: Cross sectional lithology of OFO Forest-North, demonstrating the shallow nature of the Koppamurra REE mineralisation.**

## Mineralogy

Mineralogical studies were conducted on a composite sample of 74 spatially diverse samples across the Koppamurra deposit, which identified the presence of eight REE bearing minerals. Among these minerals, the carbonate mineral Lanthanite-(Ce), was found to primarily contain the four valuable magnet REE, Neodymium (Nd), Praseodymium (Pr), Dysprosium (Dy) and Terbium (Tb). These four high-value REE bearing minerals were predominantly concentrated in the <20 µm fraction.

The Koppamurra deposit is characterised as an ionic clay deposit, similar to those exploited throughout southern China. Subsequent characterisation has revealed the presence of three distinct phases of REE in the Deposit, in varying proportions.

The ionic (ion-adsorbed) phase of REE is formed through the chemical weathering of REE bearing primary minerals, and subsequent weak adsorption of liberated ions to the surface of secondary minerals. Accordingly, extraction of these REE is achieved through rapid ion exchange desorption, facilitated by pH adjustment using dilute salt solutions, under ambient conditions.

An additional strongly ionically bonded phase of REE is present, which is formed through the chemical weathering or hydrothermal alteration of REE bearing primary minerals. During formation, liberated ions become strongly adsorbed to the surface of secondary minerals, or isomorphous substitution enables the REE to be deposited into the crystal lattice structure of secondary minerals. Accordingly, extraction of these REE is achieved through a weak acidic leach.

A third additional REE phase, the mineral phase is present, in which the REE are naturally present in the crystal lattice structure of primary minerals that are resistant to weathering and alteration. Accordingly, extraction of these REE can only be achieved through energy-intensive cracking or roasting before acidic leaching.

Metallurgical response test work to date on composite samples from the Koppamurra deposit showed up to 77% extraction of the four valuable magnet REE, for a pH 1 leach at ambient conditions. This indicates that processing operations for ion-adsorbed and strongly ionically bonded REE phases can be applied to economically recover REE from the Deposit. Having an understanding of the type and proportion of REE phase/s present in a deposit, as well as their metallurgical behaviour under varying operating conditions, is critical for comprehending the economic and environmental implications of processing operations.

# PROCESSING PLANT OPERATIONS

## Proposed Flowsheet

A simplified depiction of the proposed flowsheet for the economic production of a high-quality specification MREC product is presented in Figure 3. The proposed process initiates with the mechanical mining of shallow mineralised clay, followed by slurry pumping to the processing plant. Due to the fine nature of the ore and the predominant presence of ion-adsorbed and strongly ionically bonded REE phases, the energy intensive methods of cracking and roasting of the ore are not required to enable extraction of the REE. Post slurry pumping, beneficiation is employed to reject gangue minerals and coarse material deficient in REE, leading to an inherent upgrade of the fine material. This fine material undergoes REE extraction via controlled addition of a lixiviant to facilitate desorption of the REE from the clay host. The REE entrained in the liquor are recovered from the solid clay host via solid-liquid separation, followed by neutralisation of the resultant leach residue solids. The resultant liquor, containing the entrained REE, undergoes impurity removal in which the pH of the solution is raised to precipitate out predominantly iron and aluminium. Another solid-liquid separation stage is employed to separate the precipitated solid impurities from the liquor. The resultant solids are consolidated with the neutralised leach residue solids. The pH of the resultant liquor is again raised, to precipitate the REE as a mixed rare earth carbonate solid. Another solid-liquid separation stage is employed to recover the MREC solids, with the recovered liquor recycled as process water, and the MREC solids dried and packaged for shipment to downstream processors.

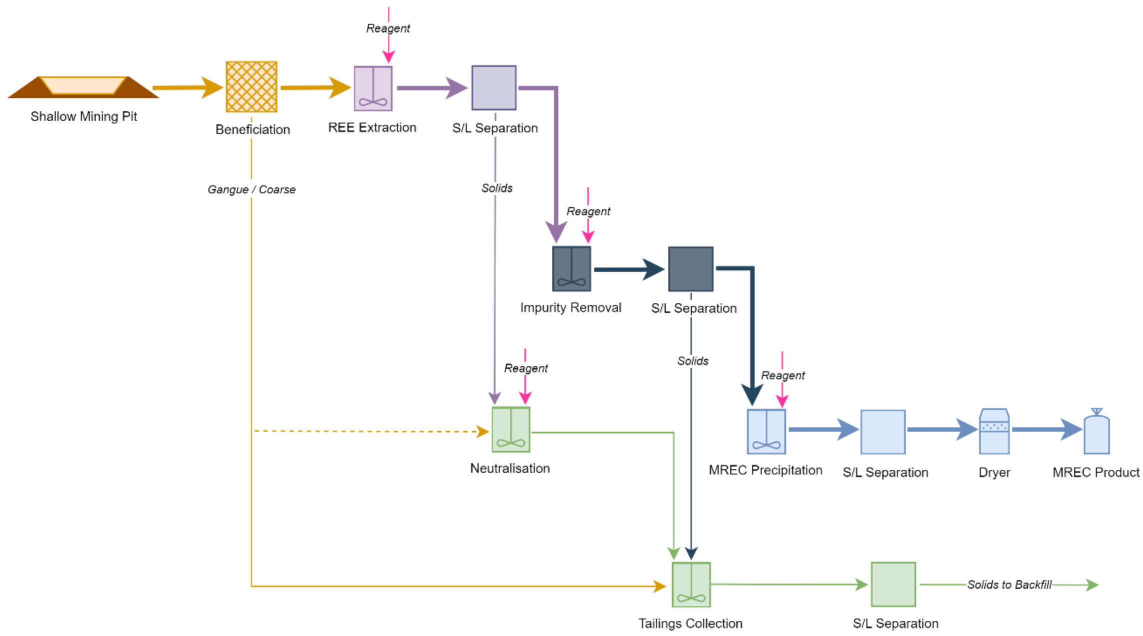


**Figure 3: Proposed MREC production flowsheet for the Koppamurra deposit (simplified).**

## Beneficiation

Several beneficiation methods have been evaluated for the Koppamurra ore, encompassing size classification, attrition, flotation and wet high-intensity magnetic separation (WHIMS). The viability of these methods to upgrade the ore was appraised on a two-fold basis:

- Reducing gangue minerals - to reduce reagent consumption and reduce impurities in the final REE product; and
- Reducing the overall feed mass - to reduce the size of the processing plant.

***Size Classification***

The most recent assay by size analysis was undertaken by ANSTO, on a composite sample generated from spatially diverse drill cores across the deposit. The analysis showed a promising reduction in both gangue minerals and overall feed mass in the <75 µm fraction.

Accordingly, to determine the proportion of extractable REE at given leach conditions, wet screening and subsequent diagnostic leaches was undertaken by ANSTO on ±38 µm and ±75 µm size fractions. Whilst further optimisation test work is required, initial results showed promising extractions of the four valuable magnet REE at a 75 µm size split, for a pH 1 leach at ambient conditions. Such findings warranted an assessment of size classification technologies, with bench-scale sighter test work currently underway using the FLSmidth REFLUX classifier. Insights from this test work will feed into the assessment of the benefits of these single-unit and high-capacity classifiers against other conventional technologies such as a hydrocyclone cluster.

***Attrition***

The Koppamurra Trial Pit revealed a small proportion of excavated ore presenting as large compact clay agglomerates, necessitating further investigation into attritioning technologies such as log washers or low-powered tumble mills. Accordingly, ISO tumble mill sighter tests were undertaken without media on a 35 kg ore charge, whereby extended tumbling motion appeared to have no/limited attritioning behaviour on the clay agglomerates, which remained competent throughout the test. Concurrently, simple in-field dispersion tests involving placement of the clay agglomerates in tap water without agitation were undertaken. These tests revealed a natural dispersion of the agglomerates over time without any form of attrition. As such, further investigation into standalone attritioning technologies was suspended, with future assessments to be undertaken to assess the inherent attritioning and dispersion that will occur during mining and front-end processing units.

***Flotation***

A total of 19 bench-scale rougher flotation tests were undertaken between KYSPYMet and SGS Lakefield, whereby a range of test parameters such as particle size, reagent type (depressant, surfactant, frother, etc) and addition rates and temperature were assessed. Further investigation into flotation viability was suspended as no economic improvement to the grade or mass were established.

***Wet High-Intensity Magnetic Separation***

WHIMS sighter tests were undertaken by SGS Lakefield on a 250 g ore sample, screened at 300 µm. Three passes of the magnet at increasing magnetic strengths, using steel wool as the mattress pad, found there to be no economic improvement to the grade or mass and as such further investigation into WHIMS viability was suspended.

## REE Extraction

The characterisation and extraction potential of the Koppamurra deposit has involved the analysis of more than 200 leach samples by ANSTO and The University of Toronto, encompassing a broad range of leach parameters, as presented below. These leach results represent a significant advancement in the understanding of the Koppamurra deposit and can serve as a valuable resource for further development of the proposed processing flowsheet and further optimisation test work programs.

**Table 1: Range of leach parameters tested by ANSTO and The University of Toronto.**

| *Parameter* | *Minimum* | *Maximum* |
|---|---|---|
| Temperature (°C) | Ambient | 125 |
| Slurry Density (wt%) | 2 | 35 |
| pH | 1 | 5 |
| Duration (h) | 0.5 | 24 |

In addition to the range of leach parameters analysed, an exhaustive analysis of the following nine leach lixiviants has been carried out:

- $CH_3COONH_4$
- $H_2SO_4$
- HCl
- NaCl
- $MgCl_2$
- $MgSO_4$
- NaOH
- $NH_4Cl$
- $(NH_4)_2SO_4$

These lixiviants have been studied both individually and in various combinations, at different molar concentrations, to gain a comprehensive understanding of their leaching potential. Leach programs additionally analysed re-leaching and post-leach washing stages to optimise the recovery of the REE. Parameters tested include the number of washes/re-leaches, ratio of lixiviant to wash water, type of lixiviant, temperature, pH, and more.

Characterisation and extraction potential test work to date has revealed that the Koppamurra deposit is composed of ion-adsorbed and strongly ionically bonded phases of REE. The prevalence of these phases was established through enhanced leach performance at pH 1, in comparison to pH 4, as presented in Figure 4. Further, a third REE mineral phase has been identified, albeit of a limited proportion, through caustic leaches at temperature undertaken by The University of Toronto.

Accordingly, further optimisation test work is being undertaken by ANSTO, to maximise the REE recovery of both the ion-adsorbed and strongly ionically bonded REE, under economically viable test parameters. Recent test work focused on the pH range 1.5 to 2.0, under ambient conditions, yielded a 50% reduction in acid consumption and gangue dissolution, particularly iron and aluminium. Notably, this reduction was achieved whilst maintaining average recoveries of 65% and up to 77% for the four valuable magnet REE, as presented in Figure 4.

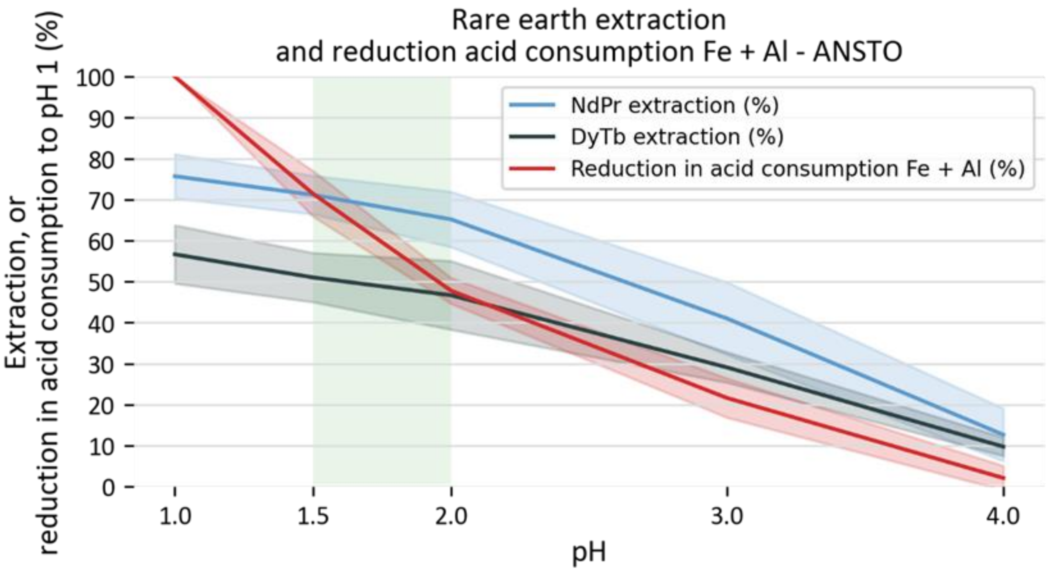


**Figure 4: REE extraction at different pH diagnostic leach tests for samples KM0-241_4 and KM0-234_3.**

Consistent REE extraction results were shown for the spatially diverse samples, CP001 to CP010, across the deposit, as presented in Figure 5. The results highlighted the uniformity of recoveries across the resource composition variation, thereby confirming the proportionate presence of both ion-adsorbed and strongly ionically adsorbed REE phases. These findings have significant implications for the development of a reliable REE recovery method, that is suitable for the whole Koppamurra deposit without the requirement for significant blending of feed ore.

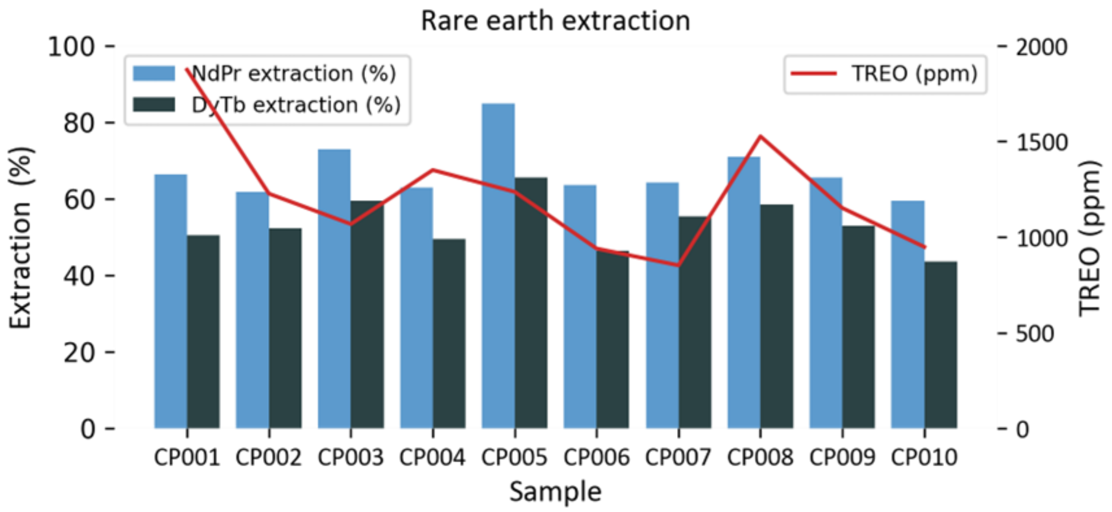


**Figure 5: Valuable magnet REE extraction for the spatially diverse Koppamurra deposit composite samples CP001 to CP010 at pH 1, 6 hours.**

***Solid-Liquid Separation***

Post leach completion, the REE that are entrained in the liquor, are separated from the waste clay host. The solid-liquid separation technologies, that have been assessed to-date, either as a sole technology or in combination with another technology (i.e., thickener followed by a filter press) are presented in Table 2.

**Table 2: Leach residue solid-liquid separation technologies assessed to-date.**

| ***Technology*** | ***Vendor*** | ***Assessment Type*** | ***Sample*** |
|---|---|---|---|
| Thickener | Metso Outotec & GBL Process | Bench-scale test | Leach slurry |
| Plate & Frame Filter | Metso Outotec & GBL Process | Bench-scale test | Leach slurry |
| Belt Filter Press | Phoenix | Bench-scale test | Un-treated ore |
| Screw Press | IFS | Desktop assessment | - |
| Centrifuge | Alfa Laval & GEA | Bench-scale test | Un-treated ore |

Although ongoing testing is still being conducted, thus far, centrifuge and screw press technologies have emerged as the most feasible solution based on all relevant factors, with a particular emphasis on product moisture, capital and operational expenditures, and land rehabilitation potential. As shown in Figure 6, the bench-scale centrifuge tests conducted by Alfa Laval, using an un-treated ore sample, produced a firm and spadable cake, suitable for trucking / conveying, with no free draining water and did not present as ‘sticky’. Ongoing centrifuge test work will assess a range of parameters, including use of an optimal flocculant and a leach residue sample.

**Figure 6: (left to right) Re-slurried composite sample CP008. Re-slurried sample flocculated with Magnafloc 1101. Resultant centrifuge Centrate. Resultant centrifuge cake.**

Concurrently with bench-scale solid-liquid separation test work, a flocculant screening program was undertaken by flocculant supplier, BASF, using leach residue samples from the pilot-scale MREC production tests. The program initially screened nine conventional non-ionic flocculant products, as well as two anionic flocculants from the Rheomax DR range:

- Non-ionic: Magnafloc 10, 333, 338, 351, 155, 1011, 5250, 156, 336
- Anionic: Rheomax 1030, 1050

In general the samples displayed easy flocculation behaviour at a 1:5 volume dilution ratio using pH adjusted tap water, enriched with Magnesium. Among the tested products, the conventional non-ionic agents, Magnafloc 333 and Magnafloc 351, demonstrated a favourable combination of superior supernatant clarity and acceptable settling rates. In contrast, the anionic product, Rheomax 1030, exhibited significantly faster settling rates at higher feed solids and markedly reduced dosage rates, which were approximately half of those required by the conventional agents, as presented in Figure 7. Although the clarity of the supernatant attained using Rheomax 1030 was not proportionate with that achieved by the conventional products, in most scenarios, it would be deemed suitable for the intended application. The optimal utilisation of this flocculant in forthcoming solid-liquid separation assessments is expected to enhance the overall product moisture.

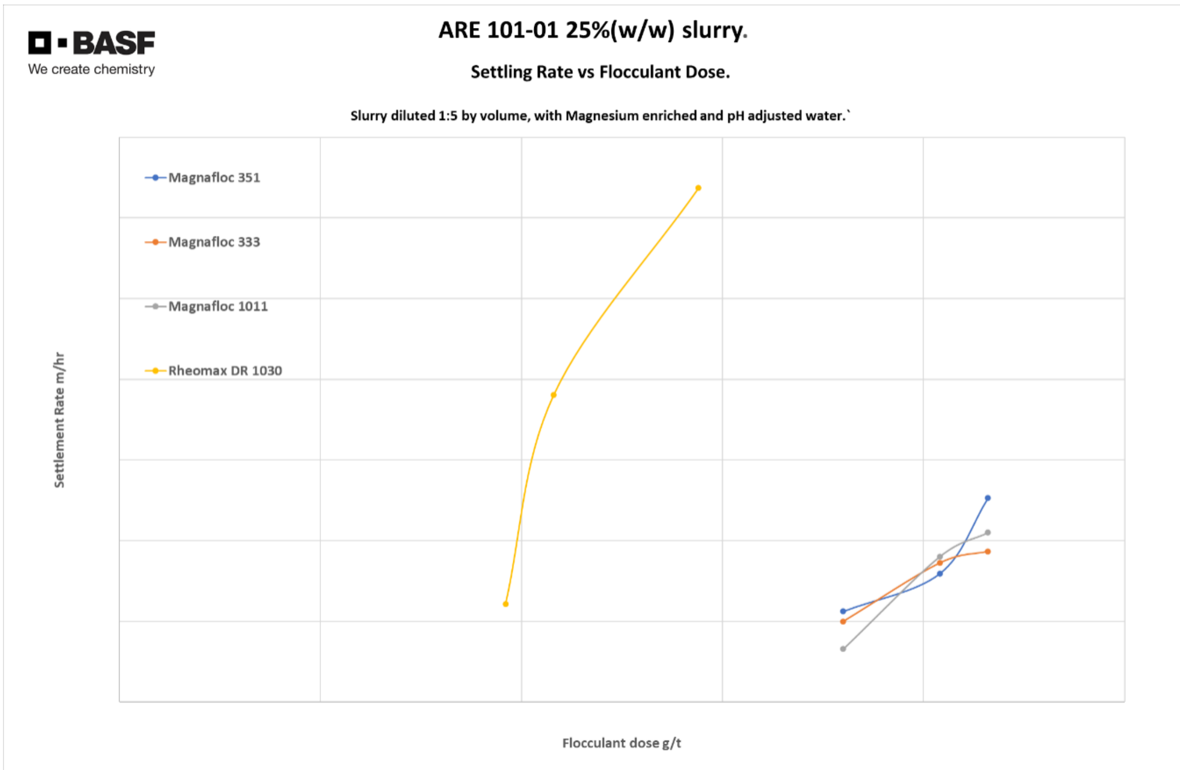


**Figure 7: Settling rate versus flocculant dose for three best performing conventional non-ionic flocculants and one best performing anionic flocculant**

## Impurity Removal

The impurity removal (IR) stage aims to separate the REE entrained in the liquor as solids, from gangue minerals that that ultimately manifest as impurities in the final MREC product. Although several REE processing facilities employ costly and intricate separation techniques such as ion-exchange and solvent extraction, the Koppamurra flowsheet proposes a more economical and straightforward alternative. Specifically, the Koppamurra process entails selective precipitation in conventional tanks at ambient conditions utilising the precipitant ammonium bicarbonate, which elicits an increase in pH. In addition to facilitating impurity precipitation, ammonium bicarbonate also acts as a source of $CO_3^{2-}$ that complexes with REE for the later precipitation of the REE as a carbonate[(4)].

In December 2022, a pilot-scale production program from Koppamurra ore was conducted, involving three IR batch tests, utilising leach liquor volumes ranging from 660-902 L. For two of these batches, a two-stage pH adjustment was employed, whilst a third batch employed a single-stage pH adjustment.

## Mixed Rare Earth Carbonate Precipitation

The MREC stage aims to precipitate the REE as solids, for subsequent solid-liquid separation, drying and packaging for shipment to downstream processors., the MREC stage entails selective precipitation of the REE-laden IR filtrate, which is complexed with $CO_3^{2-}$. This precipitation is carried out in conventional tanks at ambient conditions utilising the precipitant ammonium bicarbonate to elicit an increase in pH.

The December 2022 pilot-scale production program, consisted of three IR filtrate batches with volumes ranging from 620-900 L. Each batch employed a single-stage pH adjustment. The following high-level MREC precipitation results were observed:

- Precipitation, reported as total rare earth elements plus Yttrium (TREY), ranged between 98-99.5% across the three batches.
- Individual REE precipitation for two of the batches, was typically over 98%, with slightly less precipitation observed for all individual REE in one of the three batches.

The positive results obtained from the first production of a mixed rare earth carbonate (MREC) from an Australian ionic clay hosted REE resource have provided valuable insights and avenues for further optimisation test work. In collaboration with Neo Performance Materials (NEO), a renowned producer of high-value rare earth products, AR3 is providing the MREC solids to NEO for product quality assessment. This collaborative effort aims to enhance the efficiency and purity of the Koppamurra REE production process and to further develop the commercial viability of this valuable resource.

## Tailings Management

The proposed Koppamurra flowsheet consolidates tailings material from three process stages:

- Beneficiation - coarse/gangue material as a slurry
- REE Extraction - neutralised leach residue as a slurry
- Impurity Removal - precipitated impurities as a solid

The consolidated tailings will undergo solid-liquid separation, followed by transport back to the mined pit where it will be backfilled into the pit.

In consultation with specialist environmental consultancy, Landloch, leading-practice land management, rehabilitation, and landform design techniques are being assessed for the neutralisation and management of tailings material. Landloch are currently undertaking geochemical and geotechnical assessment of topsoil, overburden clay, un-treated mineralised clay, processed mineralised clay (from the December 2022 pilot-scale production program) and limestone basement samples.

## CONCLUSIONS

The Koppamurra REE deposit has undergone thorough mineralogical assessment and minerals processing test work, leading to the successful production of a mixed rare earth carbonate (MREC) at pilot scale. This remarkable achievement has provided invaluable insights for the design and operational criteria required for larger scale testing of a 500-tonne bulk sample. In addition, pipeline bench-scale test work is currently underway to further optimise particle size separation, solid-liquid separation, impurity removal, and carbonate precipitation. These efforts will contribute to finalising the process flowsheet and provide key inputs for the mining lease application and a scoping study. With the support of a team of expert advisors, AR3 is well-positioned to develop an environmentally sustainable and commercially viable process pathway for economic production of a high-quality specification REE product.

## ACKNOWLEDGEMENTS

The authors would like to thank the board and staff of Australian Rare Earths for the opportunity provided to Wallbridge Gilbert Aztec to work on this pioneering project for South Australia, particularly Acting Managing Director, Mr. Rick Pobjoy. The authors would additionally like to thank the advisory team of technical experts collaborating on the project.

## REFERENCES

1. Statista. (2022). Rare earths: mine production top countries 2022. [online] Available at: https://www.statista.com/statistics/268011/top-countries-in-rare-earth-mine-production/#:~:text=In%202022%2C%20China%20had%20a [Accessed 24 Mar. 2023].
2. Kingsnorth, D. (2022). Rare Earth Ionic Clays - Providing Secure and Diverse HREE Supply to OEMs. [online] Available at: https://az659834.vo.msecnd.net/eventsairseasiaprod/production-eecw-public/e767c52705f54f1db6a203f3a5169e83 [Accessed 24 Mar. 2023].
3. Report, S. (2022). This exciting Australian clay rare earths deposit has just doubled in size. [online] Stockhead. Available at: https://stockhead.com.au/resources/this-exciting-australian-clay-rare-earths-deposit-has-just-doubled-in-size/ [Accessed 21 Mar. 2023].
4. Anawati, J. and Azimi, G. (2022). Separation of rare earth elements from a South American ionic clay lixivium by sequential precipitation. Hydrometallurgy, 213, p.105946.