

### BRISBANE, AUSTRALIA 26 – 28 AUGUST 2024

# **CRITICAL MINERALS** CONFERENCE 2024

**Conference Proceedings** 



# **CRITICAL MINERALS CONFERENCE 2024**

26–28 AUGUST 2024 BRISBANE, AUSTRALIA

The Australasian Institute of Mining and Metallurgy Publication Series No 5/2024



Published by: The Australasian Institute of Mining and Metallurgy Ground Floor, 204 Lygon Street, Carlton Victoria 3053, Australia © The Australasian Institute of Mining and Metallurgy 2024

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ISBN 978-1-922395-30-6

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Vicki Melhuish Conference Program Manager On behalf of the Advisory Committee, I am delighted to welcome you to the AusIMM's Critical Minerals Conference 2024.

We are proud to bring together our professional community to lead the technical conversation on the distinctive challenges of extracting, processing, refining and marketing critical minerals. Finding practical solutions to these challenges will be vital as mines become more complex, grades lower and many deposits remain undeveloped.

Alongside exploring technical challenges, the conference will feature provocative conversations about the commercial, geopolitical and financial realities of operating in this competitive and everchanging international industry. Bringing those two strands together – the technical detail and the big picture – is what makes this conference unique.

The Advisory Committee has worked hard to put together an engaging and relevant programme headlined by outstanding keynote speakers, each with deep industry knowledge, who will offer their perspectives on topics covering the entire critical minerals supply chain.

Our keynotes will be joined by leading technical experts across discovery and development, mineral economics, project investment, ESG and more. With three times more abstracts submitted than we could accommodate, from eminent speakers from around the world, the conference programme will be of high quality and global in its scope with practical takeaways that can be applied to projects and operations.

I would like to thank our speakers, authors and paper reviewers for bringing the programme to life, and our sponsors who make the event possible. I also want to thank the Conference Advisory Committee for giving freely of their time and providing ongoing guidance, as well as the highly professional and dedicated AusIMM team.

Welcome to the Critical Minerals Conference 2024 – we trust you will find it an enjoyable and rewarding event.

Yours faithfully,

Dr Stephen Grocott FAusIMM, Conference Chair, AusIMM Critical Minerals Conference

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### **Abstracts**

### Characterisation of the incongruent dissolution of polyhalite in aqueous environments

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### ABSTRACT

Plants require abundant quantity of potassium, magnesium, calcium and sulfur as nutrients, for growth and development (Patil *et al*, 2020). Polyhalite ( $K_2MgCa_2(SO_4)_{4,2}H_2O$ ) is a natural evaporite mineral with abundant mineral reserve (Wollmann, Freyer and Voigt, 2008). Polyhalite's rich composition of these core nutrients together with low chlorine content, makes polyhalite a suitable source of nutrients for plant fertiliser (Ma et al, 2023). Studies of polyhalite dissolution in water at varying duration (60-240 mins) and temperature (5-40°C) revealed an incongruent dissolution behaviour with a strong dependency on processing time and temperature. Following dissolution, analysis of the liquid filtrate and solid residue using atomic absorption spectroscopy (AAS) and inductively coupled plasma-optical emission spectrometry (ICP-OES) revealed that at higher durations and temperatures, potassium and magnesium concentration increased in liquid filtrate. with a corresponding decrease in these concentrations observed in the solid residue. In contrast, calcium presented a different behaviour associated with concentration declining in liquid filtrate and increasing in the solid residue. Characterisation of the solid residue using powder X-ray diffraction (PXRD) revealed the formation of qypsum (Ca<sub>2</sub>SO<sub>4.2</sub>H<sub>2</sub>O) from leached calcium and sulfate ions. Further studies using Fourier transform-infrared (FT-IR) and Raman spectroscopies showed that gypsum grew at the expense of leached calcium and sulfate ions, with spectra displaying gradual but well-defined increase in gypsum peaks and decrease in polyhalite peaks. The kinetics of the incongruent dissolution behaviour was found to vary with the processing conditions; at short duration (< 60 mins) and low temperature (< 20°C) the solid residue was a mixture of undissolved polyhalite and gypsum. Then, at longer duration (> 60 mins) and higher temperature (> 20°C) gypsum was dominant. Understanding polyhalite leaching in aqueous environments will aid the effective application of polyhalite as a crop nutrition source, optimising the transfer of leached nutrients from the polyhalite to the soil and ultimately aid plant growth.

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Wollmann, G, Freyer, D and Voigt, W, 2008. Polyhalite and its analogous triple salts, *Monatshefte für Chemie – Chemical Monthly*, 139(7):739–745.

### Characterisation of South African coal waste for critical materials recovery

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### ABSTRACT

The escalating demand for Rare Earth Elements (REEs) amidst global supply constraints and geopolitical concerns has intensified the exploration of alternative, sustainable sources beyond conventional mining. South Africa's coal industry, characterised by extensive reserves and a substantial volume of coal waste, presents a promising, yet underexploited, potential for REE recovery. This study aims to characterise the coal waste from several key coalmines in South Africa, evaluating its potential as a secondary source of REEs and other critical raw materials (CRMs). Utilising a combination of analytical techniques, including X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS), and X-ray diffraction (XRD), we assessed the concentration, distribution, and mineralogical associations of critical materials, including REEs, in coal discards and tailings. Results showed total concentrations of REY+Sc elements varying from 108 ppm to 273 ppm. MgO was found in concentrations varying from 0.04 wt per cent to 1.08 wt per cent, while SiO<sub>2</sub> present in SA coal wastes showed concentrations varying from 7.0 wt per cent to 48.0 wt per cent. These findings were compared against the critical materials lists published by the European Union and Australia, highlighting the strategic importance of the identified elements in global supply chains and their relevance to current and future technological advancements. The study also explored potential recovery methodologies, assessing the environmental implications and evaluating the feasibility of employing sustainable extraction and processing technologies to recover these valuable resources from streams without economic value. By comparing SA local findings in South Africa with the critical materials lists of the EU and Australia. this research not only demonstrates the untapped potential of South African coal waste as a significant secondary source of critical materials but also proposes a strategic approach to resource recovery and mine waste valourisation that aligns with global efforts towards a circular economy. This comparative analysis underscores the importance of international cooperation and knowledge exchange in securing the supply of critical materials, offering a path towards sustainable resource management in the coal mining sector.

# Selectivity of magnesite from dolomite during flotation with sodium hexametaphosphate and citric acid

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### ABSTRACT

Magnesium (Mg) has been included as a critical metal on both the European Union and Australian critical mineral lists. Its light weight and high strength to weight ratio (tensile strength 280 MPa) make it crucial to high tech industries. Substantial resources of magnesite (a source of Mg) exist in Australia but known difficulties with processing require the investigation of pathways to production. Magnesite deposits in Tasmania are formed as a partial replacement of dolomite, making dolomite a major gangue mineral. Beneficiation of magnesite, however, is highly dependent on the effectiveness of chemicals (ie collectors, depressants) used to separate it from gangue during flotation recovery. Dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>) and magnesite (MgCO<sub>3</sub>) are known to have similar characteristics such as similar crystal structure, surface composition and physical properties. These similarities inhibit the selectivity of collectors thereby introducing calcium ions from dolomite into the flotation concentrate. This study is focused on evaluating the depression of dolomite with sodium hexametaphosphate (SHMP) and/or citric acid (CA) to improve flotation separation efficiency using samples from the large Arthur River magnesite deposit located in North-west Tasmania and held by GWR Group Limited. During flotation testing, the pH was kept constant while concentrations of SHMP and CA were varied to ascertain optimum dosage for maximum recovery of magnesite in concentrate and minimum recovery of dolomite. Analysis was carried out with calibrated portable X-ray fluorescence (XRF), and automated mineralogy to evaluate the grade, recoveries, and mineralogy of the feed, concentrates and tails. Results to date suggest CA could be employed as a depressant as 50 per cent of the dolomite in the feed material was rejected to tails at the rougher stage with 80-92 per cent recovery of magnesite while SHMP was only able to depress about 10 per cent of the dolomite in the feed sample.

# Lithium geopolitical and socio-environmental dynamics – current and future scenarios

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### ABSTRACT

Lithium is essential to the low carbon technologies necessary for the energy transition because of its applications in energy storage, in particular portable batteries. Its highly concentrated value chains, paired with price volatility and inventory management practices, raised geopolitical concerns, saw the destruction of some demand, and triggered growth in the lithium project pipeline. Likewise, increases in lithium production encouraged debate on the social, environmental, and economic effects and trade-offs of lithium extraction in host provinces. Key lithium producing countries have formulated strategies for their critical minerals sector and cemented geopolitical alliances centred on Critical Raw Materials (CRM). In parallel, battery technologies continue to improve and the potential for sodium ion batteries to displace lithium has fostered discussion and signalled uncertainties. Considering these transformations and uncertainties, what are the future socio-environmental and geopolitical trajectories of lithium value chains? This transdisciplinary paper - integrating socioenvironmental analysis, policy and geopolitical analysis, and mineral economics - studies: i) the current geopolitical and socio-environmental configuration of key lithium supplies, ii) likely geopolitical and socio-environmental scenarios in the medium and long-term, and iii) their implications for lithium producing and consuming countries to play responsible roles in the energy transition. The paper analyses the lithium project pipeline and demand projections, overlaying them with geopolitical alliances and CRM-specific bi-lateral and multilateral initiatives, to formulate medium and long-term geopolitical scenarios. Based on the socio-environmental track record of current and future producers, it identifies likely socio-environmental trends and issues that require attention from producing and consuming countries. It concludes with a reflection on how projected geopolitical and socio-environmental dynamics can interact in future scenarios.

# Exploring circular economy and decarbonisation barriers in Australia's lithium and rare earth elements industry

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### ABSTRACT

The global shift towards achieving a Net-Zero economy is gaining momentum, encompassing a broad spectrum of initiatives ranging from renewable energy technologies, electric vehicles (EVs), to battery energy storage systems. Benefiting from its significant reserves of lithium (Li), a critical component, along with an array of other rare earth elements (REE), Australia is at forefront to lead the change towards clean energy solutions and environmental sustainability. Beyond powering renewable technologies, these minerals play a pivotal role in high-tech industries for manufacturing of a wide range of electronic devices, such as cell phones, tablets, lighter flints, fluorescent lamps, lasers, and super magnets etc, showcasing their versatility and importance in modern society. Specifically, Australia's reputation as a Li powerhouse is underscored by its abundant spodumene reserves, recognised as the world's largest deposits of this critical mineral. Additionally, the nation contributed more than 5 per cent of the world's total REE production. However, the extraction, processing, and disposal of these resources can pose complex environmental, social, and governance challenges that demand innovative solutions.

In such a context, herein, we will critically examine the intersection of Australia's lithium and REEs sectors with circular economy principles, focusing on technological advancements in mineral processing, environmental considerations, recycling, and waste utilisation strategies to achieve sustainable resource management. Aligning to the circular economy principles, the proposed strategies for the establishment of recycling systems for lithium-ion batteries and electronic waste, and the exploration of innovative approaches for waste utilisation and valourisation will also be discussed. Using Li as a case study, a comprehensive framework on waste generation and its recycling and reintegration into the process stream will be presented to illustrate the value addition to the supply chain. This study aims to foster industry partnerships and engage stakeholders in promoting circularity and enhancing the sustainability of Australia's lithium and REEs sectors. Through interdisciplinary collaboration and proactive measures, Australia can harness its resource potential while minimising environmental impact and contributing to global sustainability efforts.

### The infrastructure challenge

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### ABSTRACT

While the Australian Critical Minerals industry is not challenged by the extent of Australia's resource endowment (quality and quantity) nor really its extraction, the path to industry success is critically dependent upon adequate supply chain infrastructure. This might seem obvious, but it is a challenge for Australia's Critical Minerals industry and achieving any appreciable position in a world market.

In this presentation we will consider a sample set of key characteristics important in establishing adequate supply chain infrastructure.

A characterisation of adequate is simply what is needed to support extracted mineral move from a mine to its offtake. As a minimum this includes having adequate – processing and refinement, energy, water, chemicals, production facilities, skills and skilled labour housing, transport – road / rail / ports and airports and technical support – laboratories, R&D etc, much of this does not exist.

Access to these, their existence and development (extent and timing) to support a Critical Minerals industry is lacking. There is little to no existing infrastructure to support the growth anticipated and expected in Australia's Critical Minerals industry. There is little to no investment ready infrastructure opportunities progressed with adequate detail (business case) to entice the levels of investment needed to support any form of modest or broad scale industry development.

Even with government support and accelerated delivery, if we start today progress in this area would see a three to five year study/planning and business case development period, let alone actual delivery, even with government support and accelerated input.

We need government, at the Federal and State levels to take more than a proactive approach to support acceleration of development pathways, in addition to making a level of contribution. Contribution that will at the very least send positive market signals, most significantly to the investment community.

Enabling an environment where there is healthy investment opportunity and engagement will benefit attracting the types of investment good for Australia's mineral wealth and our Critical Minerals industry.

Investment in and the development of suitable supply chain infrastructure will need to consider the extent of capital required to support beyond traditional infrastructure development. It needs to provide for development of premium supply chain infrastructure that will deliver critical minerals that can be delivered in a market with suitable credentials to meet emerging international expectations and standards particularly when we consider the likes of the EU's Passport imperatives.

# Hydro-met solid liquid separation processes and combinations – art or science?

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### ABSTRACT

Hydrometallurgical processes are very common for refining critical minerals and metals. Lithium carbonate and hydroxide conversion, Li DLE, Nickel, as well as Vanadium, Rare Earth and other processing routs encounter multiple and challenging solids liquid separation steps. Leach residue and precipitated impurity removal, product and by-product separation as well as PLS polishing prior to IX or SX to name a few. Challenges arise due to very low solids content and large liquor quantities, requirement to avoid filter aids despite very fine particles, high to very high temperatures, supersaturated liquors of corrosive or toxic components.

This presentation will discuss following topics:

- Filtration basics effecting the outcome.
- To thicken or not to thicken?
- Process combinations:
  - Vacuum filter plus filtrate polishing.
  - o CONTIBAC filter thickening prior to pusher centrifuges.
  - $\circ\,$  Thickener plus underflow filtration by filter press and overflow polishing versus direct filtration.
- Scale-up considerations:
  - Filtration time versus downtime.
  - Cake thickness and cake discharge.
- Parameters effecting filter type and filter size:
  - Slurry properties (Viscosity, Temperature, Corrosiveness, PSD, ...).
  - Scale (multiple filters or not equipment combinations).
  - o Limitations (filter aid or not, flocculants or not).
  - Objective (filtrate clarity, filter cake moisture, cake purity cake washing).

With all those topics being quite universally applicable for different critical minerals processing.

### Building resilient supply chains for the 2035 global EV market

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### ABSTRACT

An overview of:

- How the US' Inflation Reduction Act and the EU's Critical Raw Materials Act seek to eliminate risks associated with China's control over the global battery supply chain.
- Wood Mackenzie's demand forecasts for EVs in individual markets, existing and nextgeneration cathode chemistries, and raw material and refined chemical supply and demand.
- Identifiable investment opportunities in the primary and secondary raw materials space for new entrants.

### Will the next generation HPAL plants be built in Australia

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#### ABSTRACT

Australia had its failures with first generation HPAL plants such as Murrin Murrin, Cawse and Bulong. The second generation plants such as Goro and Ravensthorpe were also problematic. Current nickel prices are at an all time low and even sulfide nickel projects have closed. At the same time Indonesia has built three third generation HPAL projects and is planning seven more on Sulawesi. The usual phases of development, namely feasibility, approval, construction and commissioning have taken place in record time. In Australia we have a number of HPAL projects in the pipeline but banks are negative on funding and the projects are stalled.

Australia has larger reserves of lateritic nickel but we can't compete with Indonesia. This paper looks at why the Indonesians are successful with their HPAL plants and what's holding back plants being developed in Australia. Why have the Indonesians been able to ramp up to capacity in less than 12 months compared to an average of more than five years in the west.

# The new vanadium hydrometallurgical processes yet to be commercialised

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### ABSTRACT

Magnetic separation is the standard route to produce concentrates. Salt roasting to extract vanadium followed by water leaching has been the standard processing route for many years and this locks up the titanium in a glass phase. The cost of suitable sodium salts, availability of capital and increasing energy costs and energy availability are critical factors in determining the viability of aspiring vanadium producers. Alternatively smelting of concentrate to produce pig iron and titanium slag is also used where the vanadium can be recovered in a slag from the pig iron. In this paper, factors influencing the recovery of vanadium are reviewed and emerging processing trends explored particularly hydrometallurgical. The work done to produce titanium rich concentrates exploiting differences in magnetic susceptibility and new hydrometallurgical routes to produce separate vanadium, titanium and iron oxide products are discussed. The new understanding that the vanadium might be locked in the lattice spinel with iron but it can be effectively leached with high recoveries using catalytic chemistry. The growing demand for vanadium electrolyte in Redox Flow Batteries now adds another value added product which can assist vanadium project economics. The important aspects of the processing of titaniferous magnetites have been condensed from the literature, published works, company websites, our own test work and personal communication covering a range of titaniferous magnetites. Reference is made to a number of historical projects and future projects covering traditional process flow sheets and new technology process flow sheets such as TIVAN where titanium pigment, iron oxide and vanadium pentoxide are recovered.

### Enhancing analytical expertise and benchmarking for high purity alumina

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### ABSTRACT

The growing demand for high purity alumina (HPA: >99.99 per cent Al<sub>2</sub>O<sub>3</sub>) in various applications, such as electric vehicle batteries and LED production, necessitates a comprehensive understanding of the impurities present in HPA and their impact on different end uses. From a desktop study, battery separators are concerned with impurities such as Si, Na, Ca, Fe, Cu, and Mg and appear to be limited to  $\leq$ 10 mg/kg to maintain electrical insulation and prevent short-circuiting. On the other hand, LEDs require different impurity profiles, with Ti, Cr, Si, Ca, and Mg potentially included depending on the desired sapphire crystal properties. For achieving a bright white LED, specific limits are set for Cr, Mn, Zn, Pb, and Ni ( $\leq$ 1 mg/kg). This research has benchmarked commercially available HPA based on the type of impurities and to what level of impurity to gain insights into the specific requirements of customers and markets.

This research has also focused on building confidence in analytical methods in terms of the type of analysis method that should be used depending on the target purity level and contaminates (4N: 99.99 per cent versus 5N: 99.999 per cent). This has arisen as there are no standards in the analysis of HPA or the emerging high purity battery materials. Whilst there are numerous techniques to analyse the elemental composition of a sample, ICP-MS and ICP-OES are the most common, largely due to their ability to achieve multi elemental analysis, and high sensitivity. However, another technique that is used, particularly for the analysis of high purity metals is glow discharge mass spectrometry (GD-MS) and has been adopted by industry as a technique for HPA. This study will highlight the pros and cons of each method both from a theoretical and experimental standpoint, which will inform the development of analytical expertise in the context of high purity critical minerals.

### How critical are critical metals and minerals to Australia?

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### **EXTENDED ABSTRACT**

Australia's list of critical minerals all occur in abundance in Australia. So arguably not critical at all for Australians, but critical for our strategic allies and the commodity markets that we deliver into. Australia has all the critical elements but cannot control vital links in the value chain. Australia does not have control of the commodity price cycles in minerals, except perhaps titanium and zircon. As we have seen recently with external pressures on commodity prices, lithium and nickel can be critical eV battery components yet be subject to far greater cyclical price volatility than major metals. This makes feasibility studies fragile, and investors nervous.

Taking a complex-systems thinking approach to modelling these new resources we can have better outcomes. However, a systems-thinking approach will only be transformational if we develop downstream processing, described by CSIRO as a 'once in a lifetime opportunity' to reinvigorate our manufacturing and technology sectors.

All commodity cycles are controlled by the system of supply and demand that has delays and overruns. The feedback loops that cause the cyclicity act even faster for elements that are needed in only small quantities, where oversupply or perceived looming overproduction can happen over short time periods. Already we have seen new designs for eV batteries that use little or no cobalt and less lithium. Salt batteries may become important storage options in the medium term. Technological developments and innovation in batteries is a strong focus of many countries, especially those without their own 'battery metal' resources.

Australia can take a lead in changing this system driven paradigm, by using incentives to guide exploration and mining investment toward long-term wealth not short-term gain. Australia has all the critical elements, but we should take a strategic thinking approach to decide which commodity streams we can excel at, versus those like nickel, that are now controlled by production from one country, Indonesia.

Australia has an official list of 31 Critical Minerals. Some of these we have in abundance. We have 74 per cent of global zircon resources, 65 per cent of global rutile (Ti), 32 per cent of global vanadium and produce 52 per cent of global lithium, 10 per cent of global manganese and already 5 per cent of rare earths. In the strategic metal resources required for the energy transition Australia is number two in the world for copper, and number three for aluminium, number four for tin. Gallium and germanium are recoverable by-products of zinc. Tantalum and tin are by-products of LCT lithium pegmatite mining, whilst cobalt and platinum group elements are already valuable by-products of nickel production and refining. WA1 Resources recent Luni carbonatite discoveries together with pegmatite byproduct columbite, could make Australia a significant producer of niobium, a market currently dominated by Brazil.

At the tail end of the critical mineral list, global markets now and into the medium term for indium, beryllium, bismuth, scandium, tellurium, hafnium, are very small.

For Australia, critical minerals are defined as minerals:

- essential to modern technologies, economies or national security, specifically the priority technologies set out in the Critical Minerals Strategy
- for which Australia has geological potential for resources
- in demand from our strategic international partners
- that are vulnerable to supply chain disruption.

Other countries take different views of what is 'critical'. Canada, a major mineral producer of comparable scale to Australia, has a total list of 34 minerals and metals including recently added 'high-purity' Fe, silicon metal and uranium.

For Canada, critical minerals must meet both of the following criteria:

- the supply chain is threatened
- there is a reasonable chance of the mineral being produced by Canada (*vs being in demand by strategic partners*).

It must also meet one of the following criteria:

- be essential to Canada's economic or national security
- be required for the national transition to a sustainable low-carbon and digital economy
- position Canada as a sustainable and strategic partner within global supply chains.

This list is designed to support three value chains: Advanced Manufacturing, Clean Technologies, Information and Communications Technologies. The Canadian economy is arguably large enough and strategically located next to USA to more readily contemplate in-country downstream processing and manufacture.

We cannot shield ourselves from market forces, nor should we stop research into extraction or recovery technologies for minor metals, but we should be realistic about where we can impact the value chain by focus on a smaller number of geological associated commodity suites where Australia already has endowment, experience and is developing skills, utilising these natural commodity groupings:

- LCT pegmatite suite: Li, Ta, Sn (Nb and possibly Be) batteries and electronics.
- **Carbonatite suite:** REE and Nb for magnets and steels, plus byproduct mica, phosphate, magnetite. Consideration of developing the best ionic clay REE deposits as they are found.
- **Mafic Intrusion associated suites**: V for batteries, Cr for steels plus by-discovery and recovery of PGMs, Ni, Co, Cu.

There is currently no LME premium on 'green' metals. There are big contracts being signed with foreign governments to lock in critical mineral supplies.

Whilst Australia can make a significant contribution to more resilient supply chains at the request of its partners, to generate long-term wealth we should pick mineral groups that are likely to become sustainable industries through all phases of future commodity cycles. This analysis can be done by mapping the complex system that supplies critical minerals from discovery-recovery through the systems of refining and manufacture of end products, within the paradigms set by current and future geopolitics and trade.

There are always potential risks and costs in picking winners and very overt costs in investing in the downstream. There is no protection from forces that breakdown the barriers to make the production of finished products too expensive to sell. However, Australia can take prudent risks in future facing industries that build on our mineral supply capabilities.

### Evaluating circular economy solutions for critical minerals supply

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#### ABSTRACT

The green energy/renewables transition (eg solar, wind, battery, hydrogen and nuclear) is driving demand for specific critical metals, which presents an opportunity to establish emerging mineral supply chains. Elements hosted in Australian geology such as Cobalt (Co), Rare Earths (REE), Rhenium (Re), Scandium (Sc), Tungsten (W), Gallium (Ga), Germanium (Ge), Indium (In), Tellurium (Te), Vanadium (V) and Molybdenum (Mo) are typically associated with the mineralogy of base (copper, zinc, nickel) metal deposits (VMS, porphyry or laterites). Where primary mining is being or has already been undertaken, these valuable by-products in the ore feed may not have been historically targeted or attempts to recover them have underperformed.

Secondary processing with novel flow sheets or new technologies, concurrent to primary mining activities or at end of asset life, poses a unique opportunity to increase domestic resource extraction and expand overall processing capacity for critical minerals. Currently, proposals to reprocess fresh/historical tailings, or spent heaps (to chase a by-product not originally pursued) are generating commercial interest (Araya *et al*, 2021). Additionally, ore rejects/stockpiles of below original cut-off grade material represent potential feedstocks when novel approaches are applied. This presentation explains how options for a 'circular economy' solution to critical mineral supply may be viable from various solid, aqueous or gaseous waste streams (Whitworth *et al*, 2022).

A distinction should be made between activities such as urban mining of e-waste or battery/energy storage systems (BESS) that fully embody circular economy principles by centring on recycling raw materials/metals from end of life/used products and building/construction materials or manufacturing scrap (Giurco *et al*, 2014). In contrast, secondary processing or prospectivity for a mine doesn't follow a true circular life cycle but can reclaim value from various 'neglected' sources of feed, processing plant and smelter/refinery waste streams, even from legacy acid mine drainage (AMD) run-off.

Greater amounts of critical minerals, the raw materials of modern technologies, are needed to meet low-carbon targets and sustainability objectives (Simas, Rocha Aponte and Wiebe, 2022). Feasible options for 'secondary' supply solutions of critical minerals may be economic and support decarbonisation, but these cases are highly dependent on the mine waste and tailings characteristics and the will of operating miners to explore and pursue secondary prospectivity in their commodity pipelines and asset portfolios.

One of the key benefits of secondary mining, is an improved impact to an ecosystem (in terms of less land disturbance, destruction of natural habitats/bio-diversity and water/energy consumption), offsetting those that would be caused by primary mining. Furthermore, cash flow can be generated from both obtaining critical minerals, and from simultaneously extracting some residual value of the original, principal element that remains due to poor past plant performance (owing to a throughput over recovery operating philosophy or unavoidable/intermittent periods of high losses). However, thinking that value can be realised from simply re-directing mine waste/reject material to an existing or a re-start of a former processing facility has already been tested, and shown in most cases to fail. Reject material was originally directed to the non-value stream for a physical or mineralogical reason, and development of a new flow sheet is likely required to achieve an improved outcome. The challenges of designing these new processing plants to accomplish this reprocessing aim include: sub-economic concentrations, large amounts of gangue, marginal economic recovery, weathering issues, flow sheet complexity, significant capital investment needed, challenging materials of selection, extensive test work or piloting requirements, long development timelines and stringent product specifications (Sarker *et al*, 2022). On the other hand, execution timelines to achieving

supply from secondary sources are accelerated compared to greenfield development and in some cases legacy processing infrastructure can be resourcefully repurposed.

It should be noted that the outcome of secondary reprocessing alone from a waste reduction perspective is low, as it does not typically materially reduce final waste volumes. For most commodities mined from secondary sources of ore, only partial grams per ton are extracted and the amount of waste generated may actually increase due to requirements for neutralisation or detoxification. A waste reduction opportunity (volumetric) and improved environmental footprint can be realised from alternate treatment of tailings once handled, which may be enabled by the cash flow derived from sale of the recovered primary and by-products. Typically dewatering of the tailings 2.0 is implemented, however this presents higher operating cost and potential filterability challenges.

A recent MetFest presentation by Glencore concentrator metallurgist titled 'What to do with a slag situation?' inspired a closer look at sludge, slims, slags and acidic leachates as other secondary sources of mineral value, in a similar way that tailings have been touted as rich deposits. The obvious advantage is these streams are considerably liberated and dissolved compared where critical mineral value is contained in in-ground hard rock reserves.

A logistical, technical, environmental, and economic evaluation of multiple secondary processing approaches is key for implementable approaches and successful outcomes. This presentation outlines theorical case studies and reviews applicable technologies, explaining the advantages and disadvantages of each and looks at considerations for success. Australia has an estimated 50 000 or more historic mine sites, and the government released a map of >1000 tailings sites as potential sources of metal, the most prospective of which have been extensively characterised by the University of Queensland' MIWATCH research group. Yet full assessment of the processing/ultimately recovery and NPV of projects requires realistic input from non-academic/non-government entities, based on rigorous metallurgical lab test work and capex/cash flow estimations. These full evaluations aren't being carried out adequately for the number of opportunities that exist, although some grants and federal/state funds are supporting these activities of late.

Past publications focused heavily on identifying the presence and abundance of critical minerals, and some recent reviews provided an overview of metal extraction technologies most suited to recovering the target metals. This has highlighted that the knowledge required by consultants to adequately assess viable extraction options spans hydrometallurgy (pressure/atmospheric/bio-leaching), pyrometallugry and solvometallurgy and are more complex than the beneficiation and concentration techniques conventionally used for base metal production.

The economic drivers impacting success hinge on summation of the cost/complexity/challenges curve against the quantified benefit/bonus cash flow/reduction of liability. After compiling a multi-criteria analysis tool, market price volatility and instability and regional demand/supply were found to be the most influential factors.

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# Recovery of nickel-cobalt mixed hydroxide from laterites through HCI leaching route

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### ABSTRACT

The exploitation of laterite resources for the recovery of nickel and cobalt (Ni/Co) has increased significantly over the last two to three decades due to the depletion of nickel sulfide deposits. Laterite processing has been explored through different mineral acids (sulfuric, nitric, hydrochloric) using different techniques such as heap leaching, atmospheric leaching and high-pressure acid leaching (HPAL). HPAL with sulfuric acid has been successfully established for commercial operations. The nitric and hydrochloric acid routes are mainly explored through atmospheric leaching, due to the more corrosive nature of these acids that obviates the need for pressure. These routes are yet to be established as commercially viable options for reasons that include materials of construction requirements and/or acid cost.

Recently, CSIRO has developed a novel process for nickel laterite processing using hydrochloric acid (HCI) leaching to produce high purity Ni/Co mixed hydroxide. The process has been shown to be applicable to a variety of lateritic ores such limonite, smectite and saprolite, with the leaching stage occurring at atmospheric conditions below 100°C using <25 per cent w/w HCI. The Fe(III) in the pregnant leach liquor is reduced to Fe(II) enabling removal of aluminium/chromium/copper by precipitation (through pH increase). Nickel and cobalt are then precipitated by further increases in pH, along with the majority of Fe(II) to generate a Fe/Ni/Co solid. The presence of ferrous hydroxide in this solid enables partial removal of iron via selective redissolution, after which the residual solid is further treated through selective pH dissolution steps, followed by Fe removal to generate a Ni/Co rich solution for enabling precipitation of high purity mixed hydroxide by lime addition. The Fe/Ni/Co-free process liquor is treated for removal of manganese and magnesium, realising a calcium chloride-rich liquor that, through the addition of sulfuric acid, regenerates HCI for reuse in the leaching stage, along with generation of a high-quality calcium sulfate (anhydrite) precipitate.

## Process to recover high purity vanadium pentoxide from vanadiferrous titanomagnetite concentrate

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### ABSTRACT

Vanadium is a critical mineral which has predominantly been used high-strength steel production (85 per cent of usage), however, is increasingly used in redox flow batteries (currently 2 per cent of use). Its demand is forecast to grow significantly due to the increasing requirement for renewable energy storage systems. Vanadium is commonly derived from concentrates (typically vanadium and titanium-rich magnetite) separated from mined ore, or as a by-product of steelmaking slags. Existing methods for recovering vanadium from vanadiferrous titanomagnetite (VTM) deposits are either by smelting or salt roast processing, neither of which recovers titanium (another critical mineral).

A novel process has recently been developed at CSIRO that enables the recovery of vanadium, titanium and iron from VTM concentrate in one process. Further refinement of the process is in progress in partnership with an Australian company (Tivan Ltd.) who holds a global licence (excluding India) for commercialisation of the technology.

In this process, VTM concentrate leaching occurs under atmospheric conditions below 100°C using 20–22 per cent w/w hydrochloric acid (HCl). Titanium-rich material suitable as a feedstock to the sulfate processing reports to the leach residue. The resulting leach liquor is reduced before pH adjustment facilitates the precipitation of a vanadium and aluminium (V/Al) intermediate that is further processed to yield a >99.8 per cent V<sub>2</sub>O<sub>5</sub> product. After V/Al precipitation, iron remaining in the liquor is recovered as a high iron-grade (>65 per cent), magnetite-rich (>90 per cent) product. After removal of magnesium and manganese, the barren leach solution can be used to regenerate HCl via the addition of sulfuric acid to form high quality anhydrite. The resulting HCl is recycled back to the leaching stage.

# Pyrite reprocessing of critical-metal bearing waste for environmental gain

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### ABSTRACT

Recent estimates of annual global mine waste production, including tailings, have reached as high as 13 billion tonnes (Valenta *et al*, 2023) (in this case, we refer to mine waste as that produced from mining and processing activities and subsequently stored in a waste storage facility such as a tailings dam, integrated waste landform or similar. We do not include other forms of waste from the mining industry, such as wastewater, truck tyres, and other forms of industrial or municipal waste equivalent). Mine waste may contain deleterious elements and may interact with air, water and bacteria to form acids, which are the cause of acid mine drainage (AMD). Mine waste storage facilities, such as tailings dams, must therefore be managed according to strict environmental guidelines, for decades if not longer.

In the case of sulfide ore, a significant component of many tailings dams is pyrite (FeS<sub>2</sub>), which is a significant contributor to AMD, and yet may also contain other metals such as Cu, Co, Ni, Ag and Pt in solid solution. The application of a patented pyrite processing technology by Cobalt Blue Holdings Pty Ltd, to pyrite-rich waste demonstrates the viability of re-mining activities to:

- 1. Extract valuable metals, including critical metals.
- 2. Reduce environmental liabilities through the co-production of elemental sulfur and hematite, both of which are environmentally benign.

Case studies by Cobalt Blue show that environmental liabilities on tailings dams in some Australian states may be reduced by as much as an order of magnitude, whilst simultaneously producing valuable critical and strategic metals such as Co, Ni and Cu, all of which are essential for the energy transition. Combining the value propositions of metal production and liability reduction changes the economics of many mine waste reprocessing opportunities both within Australian and abroad.

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### Impact of mineralogy on economics of the acid bake process route for rare earths

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### ABSTRACT

The sulfuric acid bake route is well established, conventional technology for the processing of rare earth ores/concentrates and represents the preferred process for the majority of current major rare earth producers and many developing projects. The performance of the bake process and the optimal operating parameters vary substantially from project to project, with variations in feed mineralogy being a key contributor. The process, and in particular the baking step, must therefore be tailored to each specific rare earth project. Hitherto, there has been little understanding of these variations or of the fundamentals of the acid bake process.

This work draws on long-standing engagement with industry in acid bake process development combined with substantial investment into fundamental process studies to reveal some of the core chemistry driving the observed performance variations. Impacts of specific key gangue minerals on rare earth recoveries and impurity deportment are quantified and the complex interplay of these effects with process conditions is unravelled. Results from both deleterious and beneficial gangue minerals are presented, and the observed alterations in performance are translated to quantifiable impacts on cost of operation.

The utilisation of this fundamental understanding of bake chemistry to predict bake performance based on feed mineralogy is demonstrated, in addition to manipulation of the feed composition to achieve enhanced performance and ameliorate effects of (typically) deleterious gangue. Finally, key implications for the industry and developing junior projects are discussed.

### Towards increased transparency in critical mineral mining – leveraging the initiative on responsible mining assurance for the global nickel industry

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### ABSTRACT

As technological advancements escalate the demand for critical minerals, transparency in the mining processes becomes imperative. This paper focuses on enhancing transparency in the global nickel industry, including addressing concerns regarding environmental degradation, human rights violations, and opaque supply chains.

The Initiative on Responsible Mining Assurance (IRMA) can be a pivotal tool in this pursuit, offering a comprehensive framework to evaluate and improve the social, environmental, and governance aspects of mining operations. By adopting IRMA standards, stakeholders can address key challenges such as community engagement, biodiversity conservation, and labour rights within the nickel mining sector. Through rigorous assessment criteria and independent verification, IRMA facilitates the establishment of transparent and accountable mining practices.

Drawing on recent developments in the nickel industry, including controversies surrounding deforestation, indigenous land rights, and carbon emissions, this paper analyses the applicability of IRMA standards in addressing these challenges. It examines case studies from nickel mining regions worldwide to illustrate the potential impact of IRMA certification in mitigating environmental harm and fostering sustainable development.

The paper explores the role of multi-stakeholder collaboration in promoting transparency across the nickel supply chain. By engaging governments, corporations, civil society organisations, and local communities, IRMA facilitates dialogue and cooperation towards shared sustainability goals. Through partnerships and knowledge-sharing initiatives, stakeholders can leverage collective expertise to overcome barriers to transparency and accountability in the nickel mining sector.

In conclusion, this paper underscores the critical importance of transparency in the mining of critical minerals, particularly within the context of the global nickel industry. By embracing the Initiative on Responsible Mining Assurance as a tool for accountability and improvement, stakeholders can address pressing environmental and social concerns while safeguarding the long-term sustainability of mineral supply chains. Through collaborative efforts and concerted action, the vision of transparent and responsible nickel mining can be realised, paving the way for a more sustainable future.

## Glycine leaching – a sustainable solution for recovering Cu, Co, and Ni from sulfide minerals

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### ABSTRACT

Nowadays, copper (Cu), nickel (Ni) and cobalt (Co) are considered critical minerals because they play pivotal roles in electronics, renewable energy technologies, transportation, and infrastructure, driving global demand. Despite their widespread occurrence, economically viable deposits are geologically rare, and environmental impacts pose significant challenges to their extraction and processing, leading to concerns about supply security and reliability.

The processing of Cu, Co, and Ni ores requires conventional techniques such as hydrometallurgy and pyrometallurgy, which are energy-intensive and environmentally impactful. Additionally, the depletion of high-grade reserves and exploitation of lower-grade deposits further complicate extraction efforts. This work proposes a sustainable hydrometallurgy process to recover Cu, Co and Ni from sulfide minerals using a non-toxic amino acid. Glycine leaching, a novel eco-friendly approach, has garnered significant attention due to its effectiveness in recovering metals from various ores and waste materials, offering environmentally benign and economically viable alternatives to conventional methods.

Glycine, an amino acid, offers several advantages over conventional leaching agents such as sulfuric acid, including reduced environmental impact, lower energy consumption, and milder operating conditions. The complexation of glycine with metal ions facilitates metal dissolution by forming soluble metal-glycinate complexes, enhancing metal recovery efficiency. Studies have demonstrated the feasibility of glycine leaching for Ni, Co, and Cu from different feed materials, including ores, tailings, and electronic waste, allowing the recycling of glycine. The leaching kinetics and mechanisms of each metal vary depending on factors such as glycine:Ni+Co+Cu molar ratio, temperature, dissolved oxygen (DO) level, stirring intensity, solid content, and pH modifier (ammonia, NaOH, KOH) will be investigated at atmospheric pressure, using sulfide concentrates. The investigation established that the optimum leaching conditions were alkaline pH using NaOH as the modifier, glycine to Cu, Co, and Ni ratio of 6:1, low to moderate oxygen source consumption, stirring speed 300 rev/min, solid content of 30 per cent at ambient to mid-30°C, achieving 82.4 per cent, 82 per cent and 73.4 per cent nickel, cobalt and copper dissolution, respectively.

# The role of Government in securing project approvals for critical minerals

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### ABSTRACT

Critical minerals are essential for the global transition to a low carbon economy. The need for Government to facilitate the switch to a low carbon economy is clear. The role of Government in facilitating mining and processing approvals for critical minerals needs to be clearer.

The role of Government as threefold. Firstly, the planning system needs to be innovative, to recognise this rapid change, to attract investment and cut red-tape. Secondly, Government needs to facilitate the approval process to ensure decisions are strong, fair and quick. Thirdly, Government must ensure that regulation is robust, is workable and results in the best practicable environmental, social and economic outcomes.

Central to delivering these roles is a process of education, design, evaluation and continual evolution to adjust regulatory requirements and process as projects, stakeholder and proponent expectations evolve. Expectations are not static; both Government and industry recognise negotiation and compromise will be needed to transition to a low carbon economy with haste.

To assist government in its roles, industry needs to be smart and understand what is required to receive Government approvals and to operate with a social licence. Again, expectations change; industry must put forward proposals which are developable, sympathetic, adaptable, incorporate sustainable practices and champion a 'going beyond compliance' ethos.

Both sides want the same outcomes. To realise the benefits of a low carbon future, collaboration is key. Communication needs to be effective. Understanding regulation and how it can work for the development is necessary.

At a project scale, early and meaningful engagement with regulators and key decision-makers sets expectations and partnerships are formed. Collaboration not only has the power to deliver a single project, but can facilitate innovative and futuristic outcomes that align with Government-mandated sustainability targets. Strategic alignment with regulators not only propels the journey towards sustainable mining practices but also lends momentum and credibility to the cause.

# Exploring anisotropic effects of grinding media for selective separation of scheelite and fluorite

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### ABSTRACT

Scheelite (CaWO<sub>4</sub>), a primary source of tungsten and a critical mineral, commonly coexists with fluorite (CaF<sub>2</sub>). Similarities in their characteristics complicate flotation separation. Mineral wettability and flotation behaviour depend on the relative proportions and variations of physicochemical properties of the exposed crystal surfaces. Using different grinding media, such as balls and rods, during comminution yields mineral particles with varied shapes, sizes, and surface characteristics due to distinct breakage mechanisms. Due to scheelite's brittleness, the rod mill is suggested to prevent overgrinding. However, its impact on selective flotation from other gangue minerals remains unexplored. This review examines previous studies to explain anisotropic properties resulting from different grinding media during scheelite and fluorite comminution, aiming to leverage subtle surface variations to enhance selective separation. Rod mill particles, with elongated shapes and smoother surfaces, adhere effectively to air bubbles. Their sharp edges improve collision efficiency by breaking water films at mineral-solution interfaces. X-ray diffraction (XRD) and scanning electron microscope (SEM) observations indicated that there are differences in fluorite particle products from both mills. Particles produced using a rod mill possess a higher exposure of more reactive, higher calcium-atom reactivity, and elongated surfaces ({110} and {310}). Monolayer coverage calculations confirmed the high reactivity of the surfaces indicating that oleate treatment (typical collector used for scheelite flotation) achieves complete monolaver coverage on both {110} and {310} surfaces. For scheelite. differences in reactivity of predominant surfaces, {001} in the ball mill and {101} in the rod mill samples, can explain the observed wettability and flotation performance differences of particles. These variations are due to the higher attainable dangling bond density of Ca atoms on {101} surfaces compared to {001}, which have fivefold and sixfold coordination with oxygen respectively. This results in the collector having a greater adsorption energy on the {101} surface (-102 kJ/mol) compared to the {001} surface (-93 kJ/mol).
# Where next for nickel?

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### ABSTRACT

Nickel has endured a difficult period in the last 12 months, with benchmark prices falling by more than 40 per cent through 2023. Pressure on global suppliers is rising with many operational closures announced, with particular concern for Australian companies.

So where next for the market? With less than 30 per cent of demand for battery applications, nickel is facing somewhat of an identity crisis as it is swept along with the electrification and decarbonisation mega-trends, unlike lithium and cobalt where battery demand dominates. Stainless steel currently remains the dominant end use – the global market and pricing benchmarks still revolve around the traditional markets. However, substantial future demand and the developing supply chains are pivoting towards the ever accelerating battery markets. Nickel is at a crossroads.

In 2015, Indonesia accounted for just 5 per cent of supply but as of 2023, produced half of global nickel output and is now the focal point of the market with momentum building downstream in the battery value chain. This demonstrates the rapid growth of the market and the key role the country will play in both the future of the nickel market and the world's shift to electric vehicles, energy storage and a decarbonised world. However, substantial risks remain with sustainability concerns surrounding many Indonesian nickel operations casting a shadow over the country's future role in the energy transition.

This presentation explores where the nickel market will go next, who will be the key players and how market dynamics and policy are expected to shift to support the next chapter in the nickel story.

# An introduction to clay-hosted REE projects in Australia

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### ABSTRACT

Rare earth elements (REEs) are in high demand due to their application in renewable technologies and electromobility. Recent REE exploration has focused on clay-hosted REE deposits that contain a high proportion of valuable heavy REEs (including terbium and dysprosium. Research to date has been largely restricted to clay-hosted REE deposits in China, and little is known about the mineralogy and viability of REE clay projects in Australia.

Clay-hosted REE deposits are typically low-grade and high-tonnage in contrast to hard rock REE deposits. Thirteen Mineral Resource Estimates have been completed in Australia that have a median grade of 840 ppm TREO (total rare earth oxide) and 98 million tonnes (Mt) across all resources. In total, we identified 88 clay-hosted REE projects in Australia, most of which are in the Yilgarn Craton, Albany-Fraser Orogen, and the Gawler Craton with emerging projects in the Delamerian Orogen and NE Queensland.

To address geological, mineralogical, and geochemical knowledge gaps, RSC instigated a research project in June 2023 co-funded by the Minerals Research Institute of WA (MRIWA), RSC, and eight participating exploration companies (Auric Mining, Dreadnought Resources, Golden Mile Resources, HRE, MTM Critical Metals, Mount Ridley Mines, Terrain Minerals, Voltaic Strategic Resources). In this study, we examined the mineralogical and geometallurgical characteristics of 80 samples from eight clay-hosted REE projects using scanning electron microscopy (SEM), X-ray diffraction (XRD), and various geochemical analyses. Here, we present results from four geochemical techniques (ionic leach test, weak-acid digest, four-acid digest, flux fusion analysis) and compare REE abundances with findings from our microcharacterisation study. This holistic approach allows to understand the deportment of REEs within the regolith profiles across different projects and geological conditions.

# Flash calcination of fine spodumene concentrate

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## ABSTRACT

Conventional rotary kilns used in spodumene decrepitation by calcination have difficulties in the processing of fine spodumene concentrates. Fine particles are more susceptible to melting in the kiln, rendering the lithium unrecoverable. The loss of fines as dust is another potential problem. Processing ores in which the spodumene is more disseminated, and the use of flotation to concentrate spodumene, results in finer grained concentrates. It is therefore necessary to develop alternative processes that can handle fine grained spodumene concentrates.

One alternative is flash calcination, where the material freefalls through a vertical shaft kiln. The grains are separated, and the  $\alpha \rightarrow \beta$  spodumene transition occurs rapidly during the descent. A spodumene concentrate containing 6.0 per cent Li<sub>2</sub>O, with a size range of 90 per cent passing 200 µm, was calcined in a Calix reactor, which is a new type of flash calcination kiln. Rapid conversion of  $\alpha$ -spodumene to  $\beta$ -/ $\gamma$ - spodumene was achieved using this new furnace, though multiple passes were needed to achieve good conversion percentages. Four passes at 1050°C resulted in 54 per cent conversion, four passes at 1100°C resulted in 88 per cent conversion, and two passes at 1120°C resulted in 84 per cent conversion. When two different size fractions, -106 µm and +106 µm were treated under the same conditions (one pass, 1100°C) there was minimal difference in the extent of conversion.

Acid baking followed by water leaching of the calcined samples was run under a standard set of conditions: 180 per cent stoichiometric acid requirement, 250°C for 1 hr followed by 2 hrs of leaching in water at 50°C. Lithium extractions correlated closely with the extent of spodumene conversion of the calcined samples as measured by chemical and XRD methods.

# Government grants and incentives – positioning your project for a funding boost

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### ABSTRACT

A significant and growing funding opportunity is available to critical minerals projects through government grants and the R&D Tax Incentive. Over the last 3 years, state and federal governments have awarded over \$100 million in grant funding to critical minerals projects and provided an estimated \$9 billion in tax offsets to Australian companies through the R&D Tax Incentive. Positioning for a share of this funding involves early identification of relevant programs, building a compelling case for funding and navigating technical pitfalls.

Grants provide targeted, non-dilutive funding without any repayment requirement. Successful applications demonstrate alignment with key intentions of the program and highlight broader benefits in other government focus areas such as technology development, job creation and support for economic growth in the regions. Collaboration with strategic international partners is a key theme currently, as Australia seeks to develop sovereign capabilities that complement those of key allies to form a renewable energy superpower.

After publicised scrutiny of R&D Tax Incentive claims caused companies to shy away from the program in the late 2010s, many in the resources industry are now returning to take advantage of the benefit. Cash refunds of 43.5 per cent for smaller companies and tax offsets of 8.5 per cent to 16.5 per cent for larger companies are available on eligible expenditure through the non-competitive self-assessment program. New guidance from AusIndustry and the ATO have clarified eligibility requirements, providing confidence in claim benefits going forward. Technical requirements must be navigated with care, including record-keeping, expenditure tracking, the nature of contractual arrangements and exclusions for ordinary business activities and exploration.

With rising concern over the supply of materials needed to support the energy transition, and fluctuating commodity prices dampening economic incentives, we can expect further government funding to be channelled towards critical minerals projects. Prepare ahead to position your project for this funding boost.

# Closing the gap between Australia's vast mineral endowment and its investable critical minerals projects

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### ABSTRACT

The uneven global distribution of minerals is the outcome of a geological lottery, with the 'Lucky Country' having an abundance of in-demand critical minerals. With trading partners looking to Australia to be a key partner as the global scramble to secure critical minerals continues apace, the strategic importance of Australia's endowment has never been more evident.

Despite the large universe of critical mineral prospects, Australia has relatively few projects in the investment and offtake 'sweet spot'. This is the reality facing those same trading partners.

For example, PwC analysis for lithium and cobalt projects in Australia in 2023 identified five lithium and three cobalt projects when the project universe was filtered to meet the 'sweet spot' criteria for an inbound investor (Table 1).

Step	Filter	Count: lithium	Count: cobalt
1. Identify project universe		79	197
2. Develop the long list	Project stage (resource/reserve defined but not reached FID)	72	39
3. Develop the short list	Offtake available on a 3-to-5-year time frame to first production and acceptable project economics	16	23
4. Develop the priority list	Evaluate the short list against technical, ownership, project and commercial factors, financials, ESG and regulatory	5	3

 TABLE 1

 Illustrative example of filtering to identify investable critical minerals projects.

Projects in the 'sweet spot' are classified as those that: (a) have defined a resource or reserve in compliance with the JORC Code, (b) have not yet reached FID, and (c) have some or all, of the proposed production volume available for offtake.

The presentation will:

- Update and expand the analysis to quantify the number of projects in Australia's critical minerals 'sweet spot'.
- Analyse the data by mineral type, stage of development, capex and rates of return for example.
- Identify the broader trends from the analysis to understand what is happening in the 'sweet spot' and why.
- Evaluate the implications for stakeholders, including major trading partners seeking to invest in critical minerals projects and secure offtake.

# Balancing act – navigating Indonesia's nickel industry strategic development amid decarbonisation efforts

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### ABSTRACT

Indonesia, a global powerhouse in the nickel industry, aims to become a leading supplier of raw materials for electric vehicle (EV) batteries by leveraging its abundant natural resources. With over 20 per cent of the world's nickel reserves and 35 per cent of global production, Indonesia aims to rank among the top three EV battery producers by 2027. Recent government restrictions on low-grade nickel exports have spurred domestic refining capacity and higher value-added exports. However, this growth, supported by local coal-fired captive powerplants, leads to increased greenhouse gas (GHG) emissions, challenging Indonesia's net-zero goals and the sustainability of the global battery supply chain.

Key nickel processing routes in Indonesia include the pyrometallurgical rotary kiln electric furnace (RKEF) and the emerging high-pressure acid leaching technology (HPAL). The RKEF process refines saprolite ores into ferronickel for stainless steel feedstock, while HPAL targets low-grade limonite ores to produce high-purity nickel for EV batteries. This process has recently been deployed in Indonesia and offers a cost competitive advantage to produce high-grade nickel. Both processes rely heavily on fossil fuels, contributing to significant  $CO_2$  emissions.

This study explores solutions to decarbonise the nickel industry and presents a regulatory roadmap for implementation. It showcases two conceptual cases: a brownfield RKEF plant and a greenfield HPAL, illustrating the role of technology in decarbonising nickel processing routes. The study also highlights the emissions intensity of Indonesia's burgeoning nickel refining industry, emphasising the risk of losing competitiveness due to environmental concerns if Indonesia continues to produce nickel with a high carbon footprint, as EV customers are increasingly seeking sustainable raw materials. This research is relevant not only to Indonesia but also to countries where the nickel industry faces environmental, technical, and commercial challenges.

# Resourcing Australia's prosperity – unlocking our future critical mineral potential

### A Heap<sup>1</sup>

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### ABSTRACT

Australia's abundant geological resources are a cornerstone to the country's long-term growth, prosperity, and security. By leveraging our competitive advantage and building sovereign capability, the Australian Government is looking to generate the energy, skills, jobs, technology, and investment that will power our future.

Dr Heap's presentation will provide an overview of the new Resourcing Australia's Prosperity initiative announced in May as part of this year's Federal Budget and to be led by Geoscience Australia. This \$3.4 billion investment over 35 years is designed to position Australia as a global renewable energy leader while striving for net zero emissions by 2050. In delivering this landmark initiative, Geoscience Australia will map the critical minerals and strategic materials, low emissions energy and groundwater resources needed to support our future prosperity.

Andrew will discuss how the suite of geoscience activities at Geoscience Australia are delivering on a range of national priorities and support the outcomes of Resourcing Australia's Prosperity. This includes science and research under the Critical Minerals Research and Development Hub, the international tri-partisan collaboration of the Critical Minerals Mapping Initiative and the recently concluded Exploring for the Future Program.

A focus of the presentation will be on the word-class science, innovative tools, and emerging technologies being developed by Geoscience Australia and how governments, industry, and communities can use them to inform their decision-making and investments.

# How major projects can change the future of critical materials mining

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### ABSTRACT

The conference presentation will focus on *technology*, *sustainability* and *people*. It will delve into the pivotal role of major projects in reshaping the mining industry to meet the global requirement for critical minerals. With a focus on adapting to evolving societal demands and reimagining long-term investments, the talk provides practical insights on attracting partners and talent to expedite the adoption of Industry 5.0 and the broader benefits this will bring to society.

Drawing upon real examples from major mining companies, we will illustrate tangible strategies and success stories. Additionally, growth opportunities will be identified within the mining and metals sector that empower both established players and newcomers, aligning industry expansion requirements and aspirations with global decarbonisation goals. The presentation will also provide a commentary on the strategic opportunity that Australian miners have to develop critical materials in other parts of the world, particularly in Europe.

This comprehensive exploration promises to inspire innovation and transformation in project development and delivery practices in mining to ensure the world has more sustainable access to the material it needs to build a better future for us all.

## Precursor cathode active materials pilot processing and opportunities

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### ABSTRACT

The Future Battery Industries Collaborative Research Centre (FBI-CRC) in conjunction with Curtin University, CSIRO Mineral Resources and 18 industry and government partners set-up Australia's first nickel, cobalt, and manganese (NCM) precursor Cathode Active Materials (pCAM) pilot facility in Western Australia. It became operational in 2022.

The highly automated pCAM pilot plant consists of four parallel production units which can be operated separately, at various scales in either batch or continuous mode to a high level of precision and accuracy. It is possible to monitor the production units around the clock and alter the reaction parameters remotely. Coupled with the highly skilled operational team, comprising of Curtin and CSIRO staff, the pilot facility provides unparalleled capability for high throughput experimentation and simulation of commercial operations to help derisk and expedite future full-scale implementation for pCAM production.

Critical chemical and physical properties were determined in CSIRO's on-site analytical facilities, providing results for timely decision-making and rapid prototyping. These analyses can test for chemical composition/purity (Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Optical Emission Spectrometry (ICP-OES)), crystallite and particle morphology (Scanning Electron Microscopy (SEM) coupled with energy dispersive spectroscopy (EDS)), Particle Size Distribution (PSD), Tap-density, crystal structure (X-ray powder diffraction (XRD)) and surface area and porosity analysis (BET).

The National Battery Testing Centre, hosted by Queensland University of Technology (QUT), calcinated and lithiated the pCAM product and incorporated the now Cathode Active Material (CAM) into batteries for electrochemical testing. Over the past two years of operation, the pCAM pilot plant has successfully produced a number of (standard) NCM precursor products which have been shown to meet and exceed the electro-chemical performance of commercial benchmark products.

## Review of the plasma treatment in extraction of thorium and Rare Earth Elements from complex ores

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### ABSTRACT

Modern day technology such as electronics, magnets, and other high tech equipment all require Rare Earth Elements (REE) due to their unique properties. REE along with Naturally Occurring Radioactive Material (NORM) like thorium and uranium can be found in monazite. However, monazite is often cited as being too difficult, costly and dangerous to work with and is even a banned commodity in some countries. The problem is that conventional chemical digestion methods to recover these rare earth minerals are costly and highly toxic. In many cases this traditional recovery approach has caused significant environmental damaged due to the radioactive waste produced and high quantities of caustic chemicals used, such as heated strong acids. Pre-treatment of monazite with high temperature plasma to chemically 'crack' the material has been shown to enable the extraction the REE using relatively benign weak acids at room temperature. This approach has resulted in high recovery of both the 'light' and 'heavy' REE species. Experiments have shown that using a weak acid allows for the extraction of neodymium with low quantities of cerium and lanthanum, while capturing radioactive species such as thorium and uranium in a residue matrix as they do not leach in weak acids. The thorium and uranium can easily be stored, and if desired, processed separately using stronger acids. The overall ease of leaching plasma treated monazite thus significantly reduces the amount of undesirable caustic chemical and radioactive waste produced during the recovery process. Plasma pre-treatment of monazite therefore provides a mechanism to add high value to REE recovery by reducing recovery costs and environmental impact while also controlling the radioactive components for potential use in downstream nuclear applications.

# Mining for tomorrow – navigating health hazards in the critical mineral supply chain

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# ABSTRACT

While certain critical minerals, such as vanadium, cobalt, manganese and tungsten have established exposure limits recommended by Safe Work Australia, while others such as niobium, scandium and many of the rare earth elements lack such guidelines. Consequently, it is crucial to raise awareness about the need for proper health and safety measures throughout the critical minerals mining sector and supply chain. By proactively identifying and managing health hazards, we can ensure the sustainable development and responsible production of critical minerals, aligning with global environmental goals while safeguarding the well-being of workers and surrounding communities.

Critical minerals mines should undertake comprehensive health risk assessments to determine potential exposures and implement effective management strategies. Significant insights about the characteristics of the dust in coal mining, metals mining and the engineered stone industries have been made in recent years. These include understanding the mineralogical components of the dust, the particle size distributions, particle shapes, and varying agglomeration patterns in the dust. It's been found that the percentage of certain mineralogies can become more concentrated in the respirable fraction of dust that workers are breathing in, making the health hazard of the dust different to the general concentrations of the mineralogies in the mine. This presentation will outline some of these findings and their potential implications for the critical minerals industry and make recommendations for factors to consider when undertaking health risk assessments.

# Clay hosted REE deposits – early characterisation for economics assessment

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## ABSTRACT

Rare earth elements (REE) are critical for new and emerging technologies used for the carbon-free energy transition. Some REE occurrences are concentrated to economically viable grades within clay horizons that have developed over weathered REE-rich parental rocks, for example, granites. The extraction economics for clay-hosted REE are directly related to the specific REE that are present and how these exist in clay deposits. From most economically viable to more challenging, the REE can occur as ionically adsorbed, chemisorbed, or as colloid particles on the clay surface, and in relict minerals inherited from the clay protolith. Further, REE can be found as a combination of the above types in various degrees adding to their complexity. They can occur at different stratigraphic depths of the clav deposit within both *in situ* and transported horizons that display vertical and lateral changes in extent and thickness. CSIRO Mineral Resources and industry partners are currently investigating several Australian clay-hosted REE prospects using multiscale and multidisciplinary approaches involving synthesis of metallurgical analysis for recovery with various microscopy analysis techniques, geochemistry, geophysics, infrared reflectance spectroscopy (colloquially hyperspectral), hydrogeochemistry, and regolith landform evolution analysis combined with advanced computer analytics. With the early-stage synthesis of existing data, we aim to delineate the prospects and to outline the mineralogical properties of the ore domains within the clay deposit stratigraphy. Specifically, we are looking for features that are salient to the beneficiation processes in order to aid the industry partners in their economic assessment of their prospects. We will present early findings from multidisciplinary characterisation of clay-hosted REE deposits in south-western West Australia and discuss the pros and cons of various methods that were applied in the process of characterisation.

# XplorelQ – successfully using machine learning in mineral exploration

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### ABSTRACT

Exploration expenditure has significantly increased since 2010, as the industry has shifted its focus to deeper domains as readily available discoveries become progressively exhausted. However, during this period, the industry discovery rate has decreased by more than 50 per cent, raising the question of whether our targeting process is fully optimised. In 2016, the SGS Geological Services team won the Integra Goldrush Challenge by employing an innovative combination of mineralised vector load in a block model, which was then filtered through machine learning algorithms to generate the next generation of exploration targets. This challenge has sparked interest among many explorers regarding the efficient use of new technologies for any type of deposit.

Over the past decade, the mining industry has adapted various types of algorithms, such as decision trees and stumps boosting enhanced with domain adaptation, for targeting purposes on different global projects. Phylogenetic algorithms have also been integrated into the toolbox to address questions related to geological uncertainties and rock classification using complex geochemical data sets. These applications are diverse in the mining industry, ranging from exploration targeting to block model ore classification to processing plant reconciliation. This presentation will primarily focus on exploration targeting, showcasing three successful case studies in the Gold, PGE, and Oil and Gas industries, utilising different algorithms and software. The discussion will also touch upon the limitations of the technique, the challenges that lie ahead and the importance of innovation in future mineral deposit discovery.

## A sustainable approach for lithium metal production – LithSonic<sup>™</sup>: current technology development status

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## ABSTRACT

Lithium metal holds immense promise as a next-generation anode material for lithium batteries, enabling significantly higher energy densities. However, the challenge lies in reliably obtaining highpurity metallic lithium, and the prevalent industrial electrolytic process poses several issues, importantly the environmental concerns chiefly stemming from the emission of toxic chlorine gas. Addressing this challenge is critical to accommodate the escalating demand for lithium metal and safeguard the supply chains of sovereign nations.

CSIRO has patented LithSonic<sup>™</sup> process, an innovative and sustainable approach for lithium metal production. The process utilises carbothermic reduction of lithium oxide to produce lithium metal vapor, followed by supersonic cooling via a 'de Laval' nozzle – the overall reaction is given in Equation 1. This rapid quenching minimises the reversion reaction by freezing lithium metal vapour to metal powder in its non-equilibrium state. Compared to the existing electrolysis process, LithSonic<sup>™</sup> offers several advantages over the industrial electrolysis technique, especially significant environmental benefits.

$$Li_2O_{(s)} + C_{(s)} \to CO_{(g)} + 2Li_{(g)}$$
 (1)

This paper provides an update for LtihSonic<sup>™</sup> technology development. At this stage, laboratoryscale investigations are underway for the process to be validated and demonstrated at the kilogram scale. This current research focuses on developing fundamental understanding of the reduction process via investigations into the melt and gaseous chemistry and behaviour at elevated temperatures. The thermodynamic modelling work coupled with small-scale experiments is employed to achieve this understanding and enable the optimal process conditions to be established. The study is aimed to gain crucial insights for process development and scale-up. Additionally, the process is being modelled and tested at laboratory-scale for compatibility with alternative feedstocks, thereby expanding the potential applications of LithSonic<sup>™</sup> technology across diverse scenarios. These findings are facilitating the advancements in lithium metal production and hold significant implications for the future of high-performance lithium battery technology.

# Creating a sustainable vanadium industry in Queensland – primary mining and recycling

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### ABSTRACT

Vanadium is a critical new-economy mineral needed for the transition to renewable energy. Australia hosts the second largest vanadium resource globally, following China, but there is no sovereign production. On-shore processing plants near prospective mines will help retain jobs and capital in Australia.

QEM Limited (ASX: QEM) is a publicly listed company focused on the exploration and development of its flagship multi commodity Julia Creek Project, covering 250 km<sup>2</sup> in the Julia Creek area of North-West Queensland.

The company's vanadium project is a unique world-class resource with the potential to utilise and deliver innovative and sustainable energy solutions. In response to a global vanadium deficit, QEM strives to become a leading producer of high purity vanadium pentoxide to the swiftly growing energy storage sector.

QEM is taking innovative steps to power the Julia Creek Project sustainably. QEM has prioritised renewable energy for the Project, aiming to power mining processes and green hydrogen production using 100 per cent renewable sources. The overall project represents a significant step towards sustainable critical minerals production.

QEM has also engaged with The University of Queensland (UQ) for a Circular Economy project, upcycling vanadium-bearing spent catalysts into high-purity vanadium pentoxide ( $V_2O_5$ ).

To progress the responsible growth of a nascent Queensland vanadium industry, will require an innovative approach, circular economy initiatives, and commitment to sustainability.

# Recovery of critical metals from copper tailings – a Queensland case study

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## ABSTRACT

Whilst interest in copper in mine waste has grown, there is lack of fundamental knowledge on Co minerals and their processing. Cobalt recovery efficiency is generally low due to its complex mineralogy, fine particle size and content in a given slurry feed. This paper focuses on: i) determining Co tailings tenor at a mine site in north-west Qld, and ii) testing floatability of Co and Cu from two types of tailing feeds- fresh slurry tailings (ST) and stored old tailings (SOT). Specifically, xanthate collectors, activator and pH were used to test the efficacy for concentrating Co and Cu.

Co grade in the tailings was 0.05 wt per cent while Cu was 0.15 wt per cent. Quartz was the major gangue mineral that accounted for 70 per cent of the tailings with traces of calcium minerals (calcite, apatite) and iron-oxide minerals are also present in the mine tailing sample. About 6 wt per cent of pyrite was observed in the SOT sample while ST had 2–4 wt per cent pyrite (MLA). Oxide and sulfides minerals are dominantly free liberated with low abundance of mineral locking. Co was 100 per cent associated with pyrite.

Flotation produced different results for ST and SOT feeds because of mineralogical variability with SOT feed containing more Co than ST. Potassium isopropyl xanthate (PIPX) exhibited favourable flotation for SOT feed while sodium ethyl xanthate (SEX) was favourable to ST feed. The activator, CuSO<sub>4</sub>, had a slight improvement for Co recovery, however a higher dosage, 200 g/t, was detrimental to concentrating the target minerals. The pH had the most significant effect for Co recovery using PIPX collector when floating SOT and ST feed. Lastly, copper recoveries were significantly low due to their finer particle size resulting in poor floatability. Due to this observation, carrier flotation method was carried out to enhance fine particle recovery by attaching fines to coarse carrier particles and results are discussed. The JOGMEC-SMI-DoR partnership are continuing to evaluate critical metal recovery from Queensland tailings.

# Natural gamma response to indicate REE

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### ABSTRACT

Natural gamma is extensively used as a downhole wire-line logging method for detecting naturally occurring gamma radiation from rock or sediment. Different rock types emit varying amounts of gamma radiation, making the data valuable for distinguishing 'fingerprints' that can assist formation evaluation and sedimentary resource models.

Seeking rare earth elements (REE) in the coal measures, typically delivered through volcanic mechanisms during coal measure formation, we explored the full suite of available downhole data. REE are commonly adsorbed by clays, hence we focused on high gamma traces that would indicate clay-rich or tuffaceous sediments. We have used natural gamma logs for ~20 boreholes in the Bowen Basin, Queensland, and found that high gamma responses, mainly associated with tuffs, correlate with high REE concentrations. Further, we have considered the collocation of heavy radioactive (gamma producing) elements with REE and discussed the results here.

Given the encouraging results of our preliminary study, we plan to further explore the use of preexisting gamma logs and identify REE opportunities in non-coal sedimentary situations.

## Scheelite processing challenges and opportunities – an example from Kara Magnetite-Scheelite Mine, Tasmania

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## ABSTRACT

Tungsten (W) has been classified as a critical metal in Australia, as well as the European Union (EU), United States of America (USA), and Japan. Scheelite has become the main global supply of tungsten due to the exhaustion of easily extractable and processed wolframite. Two emerging industrial applications that are projected to boost tungsten consumption in the future are its use in Li-ion batteries and as tungsten powders for additive manufacturing. The Kara magnetite-scheelite mine in north-western Tasmania contains critical metal resources, particularly scheelite. Processing scheelite can be challenging because it is often found in low-grade (0.2–1.3 per cent WO<sub>3</sub>); is brittle thus resulting in the production of fine particles during comminution ~20 per cent that can be easily transported to the tailings; and similar surface characteristics between scheelite easily using typical flotation techniques. Scheelite is usually processed by froth flotation. Consequently, an attempt has been made to recover scheelite at coarse particle size of +150  $\mu$ m to +425  $\mu$ m using a conventional flotation cell (CFC) by optimising operating parameters such as pulp agitation, reagent dosages and pH. The optimum conditions were agitation 900 rev/min, 5 ml/L of collector dosage, 6 mL/L depressant dosage and pH 9.5.

It was established that it is feasible to float scheelite at a coarse particle size of up to +425  $\mu$ m with an optimal recovery of 98 per cent. The application of such froth flotation techniques could reduce the formation of fines particles during comminution, environmental impact, energy consumption, and processing costs.

# From minerals to materials – Government R&D initiatives to support Australia's critical minerals mid-stream processing capabilities and opportunities

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### ABSTRACT

Australia's critical minerals resource endowment and mining credentials position us well to capitalise on the international demand for minerals needed to support the energy transition. But realising the value will require new capabilities and technologies to refine and process minerals and manufacture materials needed to support our 'Future Made in Australia' ambitions.

Recent Government investment in R&D is helping Australia chart this course and identify our innovation strengths and gaps when it comes to processing critical minerals.

- The Australian Critical Minerals R&D Hub is a \$50.5 m initiative which brings together Australia's leading science agencies ANSTO, CSIRO and Geoscience. This program is funding seven priority collaborative critical minerals research projects which are tackling some of the most challenging technical bottlenecks for the sector.
- The CSIRO's new report 'From minerals to materials: Assessment of Australia's critical minerals mid-stream processing capabilities' assesses current state of Australian capability across the value chains of five economically and strategically important critical minerals (lithium, cobalt, silicon, rare earth elements and graphite), with a strong focus on processing and value-add opportunities and recycling of energy technologies.
- This report provides unique and valuable data on Australia's innovation capability to support
  sustainable and cost-competitive critical minerals processing, to guide decisions by industry,
  government and research sectors. It also showcases Australia's technical strengths with
  potential international investors and identifies complementarities across supply chains with
  international partners.

# Towards greener lithium production – eco-friendly flow sheet innovations

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### ABSTRACT

This study investigates an innovative approach to enhance lithium ore beneficiation by integrating HydroFloat technology and sustainability principles into the processing flow sheet. The focus is on pre-concentrating coarse spodumene particles from pegmatite ores and addressing the main challenges prevalent in conventional flotation methods such as poor selectivity and high energy consumption. Despite Australia's significant role in global lithium production, efficient flotation separation remains challenging due to similarities in physicochemical properties between spodumene and associated gangue minerals.

Processing plants whose operations involve fine lithium ores beneficiation methods heavily rely on energy-intensive comminution, where approximately 75 per cent of mining sector energy consumption is attributed to crushing and grinding. Furthermore, the concomitant flotation recoveries of the values are often less than desirable. Recent findings highlight the potential of the HydroFloat for enhanced coarse particle flotation recovery, demonstrating up to a 35 per cent reduction in energy input as compared with conventional flotation cells. This facilitates an economic shift in grind size and aligns with the industry's focus on sustainable mining practices and ore processing operations. To tackle these challenges, the study focuses on the optimisation of coarse particle flotation of grind size, surface chemistry, chemical pre-treatment methods, reagent mix, and pulp pH, a more productive, cost-effective, and environmentally friendly flow sheet for spodumene beneficiation is developed.

Furthermore, the study explores the environmental benefits of HydroFloat, including reduced consumption of process water and chemicals, and proposes strategies for water quality management and flotation wastewater reuse.

# Production of lithium sulfate from spodumene processing, does it make sense?

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### ABSTRACT

Australia is currently the world's biggest producer of spodumene mineral concentrate, from which is derived >50 per cent of the world's lithium production. The vast majority of this spodumene is exported (primarily to China), where it is processed through to lithium carbonate or hydroxide for the use in the manufacture of lithium ion batteries.

Currently, only a small fraction of Australia's spodumene production is refined to lithium hydroxide onshore (ie Tianqi in Kwinana and Albemarle at Kemerton since 2022, both in Western Australia). However, considerable investment in recent years from both the Australian Government and private sector has sought to increase the amount of spodumene refining that is performed in Australia. This has been driven by both economic and security considerations, the arguments for which are outlined in the Australian Government's Critical Minerals Strategy 2023–2030.

The refining of spodumene to battery grade lithium hydroxide is expensive and technically challenging. For this reason, there has been growing interest from lithium project developers in producing more easily obtained 'midstream' lithium chemicals, that contain a higher lithium grade and value compared to the parent spodumene concentrate, and which can be refined to battery grade lithium chemicals elsewhere.

Lithium carbonate is one such midstream lithium chemical widely used in the processing of brines and to a lesser extent hard rock resources. An arguably more suitable midstream lithium chemical from spodumene would be lithium sulfate.

This presentation will discuss what a spodumene to lithium sulfate flow sheet could look like, the pros and cons of this chemical intermediate over alternatives (eg  $Li_2CO_3$  and  $Li_3PO_4$ ), and what factors favour the economics of producing lithium sulfate over a business-as-usual spodumene concentrate product.

## Extractive hydrometallurgy for critical metals recovery

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### ABSTRACT

Extractive hydrometallurgy has a long history in contributing to the Australian resources economy. Export metal commodities involving hydrometallurgical processing are valued at approximately \$60 B/a and include gold, lithium, copper, alumina, nickel, zinc, uranium, cobalt and silver. According to the Australian Government's Critical Minerals Strategy 2023–2030, it is essential to build-up advance sustainable extractive processes by recovering valuable metals from waste and critical minerals using innovative hydrometallurgical techniques which cover leaching, solution separations and purification, as well as product recovery. This work will cover some research highlights from the University of Queensland hydrometallurgy research group considering metallurgical process residues as feed for critical metals recovery and utilisation, such as recovery critical metals from bauxite residue (Gao *et al*, 2024; Peng *et al*, 2023; Wang *et al*, 2023a), synthesis of zeolites from leached spodumene (Wang *et al*, 2023b; Gao *et al*, 2022) and rare earth recovery from uranium process residue (Whitworth *et al*, 2022; Vaughan *et al*, 2021). The research addresses resource scarcity and environmental concerns and liabilities associated with industrial waste.

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# The double edged sword of EV demand

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### ABSTRACT

The first rechargeable lithium-ion battery (LiB) was conceived in the 1970s and commercialised in portable devices throughout the 1990s and early 2000s. At the same time, LiBs were beginning to find use in electric vehicles (EVs), first in Tesla's Roadster, the world's first production all-electric sports car. In 2012, Tesla began production of the Model S, a full-size electric luxury sedan. In 2015, Tesla released the Model X, a full-size electric luxury SUV. That same year, 196 countries/regions committed to the Paris Agreement, which would seek to limit emissions of greenhouse gases, including those from the transportation sector. By 2016, enhanced performance and environmental regulation had culminated in pushing EVs to become the main end use of LiBs. By 2018, the main end-use for lithium was LiBs, no longer dominated by things like ceramics, grease and pharmaceuticals.

In this presentation, we argue that LiBs will continue to dominate the EV landscape, now complicated by sodium-ion (Na-ion/NiB) batteries, resurgent due to briefly unsustainably high lithium prices. We will also explore the possibility for higher lithium demand and market opportunities presented by lithium metal and its role in solid-state batteries (SSB), the first of which are being deployed in China as early as this year. Finally, we will explore how geopolitics and emissions legislation have shaped each of these key themes, and how it will continue to do so in the years ahead.

# Novel crystallisation process for high-purity lithium hydroxide monohydrate

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### ABSTRACT

Lithium chemicals are in high demand due to the rise of electromobility and the surging need for lithium ion batteries. The two main lithium chemicals used as a lithium source in the cathode active material are lithium carbonate and lithium hydroxide. Lithium hydroxide is typically produced as lithium hydroxide monohydrate (LiOH.H<sub>2</sub>O, LHM) for desired battery applications. However, specifications for lithium hydroxide are more stringent than those for lithium carbonate, thus the production of battery-grade material requires more purification steps. In addition, LHM is a delicate substance and has to be handled in a controlled atmosphere due to its tendency to take up  $CO_2$  from the air, resulting in its conversion to lithium carbonate and a limited shelf life.

This presentation outlines the synthesis of LHM using a novel crystallisation approach that enhances the purity of the product by meticulously controlling parameters such as concentration, pH, and temperature. Through this process, impurities are effectively minimised, ensuring the production of LiOH.H<sub>2</sub>O with exceptional chemical homogeneity and electrochemical stability. Furthermore, this presentation underscores the sustainability aspect of this proprietary crystallisation process, emphasizing its scalability and eco-friendliness.

# Developing Australia's ionic clay and clay-hosted rare earth deposits

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## ABSTRACT

The Rare Earth Elements (REE, defined here as the lanthanides and yttrium) are critical to many green technologies. In particular, the so-called magnet REE (Pr, Nd, Tb and Dy) are in high demand for applications in electric vehicles and wind turbines. These technologies are set for significant growth, supported by the global drive towards net zero emissions, demand for renewable energy, electrification of transport and the geopolitical push for diversification of supply chains.

The REE are conventionally mined from hard rock deposits containing bastnaesite, monazite and xenotime, and 'ion adsorbed' or 'ionic clay' deposits (IAD). The IAD, while lower grade, are typically enriched in the more valuable heavy REE (Tb and Dy) and require less chemical/energy intensive processing conditions than hard rock deposits. The IAD are the predominant global source of the HREE, and mined mainly in China and Myanmar, which historically have operated under less stringent regulatory and environmental standards.

In recent years, there have been numerous discoveries in Australia of clay-hosted rare earth deposits (CHRED), with varying components of adsorbed rare earths together with primary/secondary rare earth mineralisation. The processing routes for the CHREDs with low adsorbed REE content are not currently well defined.

The ADARER Project (Accelerating Development of Australia's Rare Earth Resources), funded by the Commonwealth Government, is one of the projects operated under the umbrella of the recently established National Critical Minerals Research and Development Hub, which brings together the expertise of three science agencies, namely ANSTO, CSIRO and Geoscience Australia (GA). The project's objective is to accelerate the discovery, extraction and processing of REE from Australian, CHREDs and IADs type deposits.

This paper outlines ANSTO's contribution to the project, which seeks to develop simple, low-cost processes that cover the whole spectrum of the Australian clay deposits, and the integration with existing REE separation technologies.

## Development of smart(er) flow sheet for beneficiating rare earth minerals bearing heavy mineral sand ores

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### ABSTRACT

The industrial, economic, and political importance of rare earth elements continue to increase globally, since the set of these 17 chemical elements are vital for many important electronic products and critical to support transition to green energy technologies. A common source of the rare earth elements includes 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 REEbearing heavy minerals sand ores originating from Australia. The diverse range of characteristics affects their amenability to beneficiation techniques and the impact of the unique properties of each ore type on the resultant beneficiation flow sheets developed considering these differences are examined.

In addition, whilst the metallurgical, operational, and economic advantages of using gravity spiral separators for beneficiating Heavy Mineral Sands, and therefore monazite and xenotime, are well recognised (Burt, 1999), smarter techniques are necessary for the continued success of mineral processing operations, due to the dwindling of easy-to-process ore sources and hazards associated with concentrating radioactive monazite. This paper will therefore concentrate on recent work completed to expand the applicable size ranges that can be successfully treated by gravity separators as well as explore the synergic advantages of utilising other complementary wet processing techniques.

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# The optimisation of PGM recovery from a low-grade ore

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## ABSTRACT

Since the discovery of Merensky in 1924 there has been continuous laborious ingenuity focused on improving the efficiency of Platinum Group Metals (PGM) recovery, this having been brought on by ongoing scarcity of the readily recoverable PGMs. The reality of the situation throughout the years also led to alternative ore expeditions such as UGs and MGs. The latter required extensive technological improvements as far as the PGM mineral processing infrastructure is concerned. The introduction of UGs and MGs PGM flotation marked a significant advancement in PGM recovery techniques. The enhanced technological capabilities enabled the extraction of PGM and Base Metals sulfides from low-grade Merensky, UG2, and mixed ores. However, blending ores without proper testing or mineralogical analysis can adversely impact recovery rates and concentrate purity. This is attributed to the intricate nature of the mineral compositions in mixed ores, underscoring the critical importance of mineralogical analysis and laboratory-scale testing before blending.

This body work of uses various deterministic and analytical techniques and instruments such as fire assay, ICP (inductively Coupled Plasma), QMSCAN and TIMA. Therefore mentioned techniques and instruments were used to determine the surface mineralogy and composition of the low-grade ore. The 2 g/t PGM ore was treated and tested using numerous standardised metallurgical techniques. The treatment involved laboratory scale crushing and milling phase, and baseline testing involved batch floating using 2I Denver flotation cells at 48, 60 and 80 per cent passing 75 microns.

# Improving the discovery potential of High Purity Silica in Australia

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### ABSTRACT

High Purity Silica (HPS) is the principal raw material in the production of silicon used to manufacture high technology products including semiconductors and solar cells. Quartz (SiO<sub>2</sub>) is the most abundant silica mineral in the Earth's crust; however, economic deposits of high purity quartz (HPQ; SiO<sub>2</sub> >99.995 per cent) are rare. Rapid acceleration towards reaching net zero emissions has seen a parallel increase in demand for the discovery of new HPQ deposits for downstream processing. As a part of the Australian Critical Minerals Research and Development Hub, Geoscience Australia is addressing this demand by generating the first mineral systems model and accompanying national scale mineral potential map to help explorers accelerate discovery.

Two new mineral systems models are being developed for: i) all pegmatite types and, ii) metamorphically-derived hydrothermal quartz veins. The two mineral systems are combined into key components, including geodynamic and geological setting, geodynamic drivers and fluid drivers. Each of the components have been subsequently converted into discrete mappable layers as part of the GIS-based process of generating a combined national mineral prospectivity map for deposit-scale accumulations of silica and quartz. A new, first generation, mineral prospectivity map has been developed for the combined pegmatite and hydrothermal quartz mineral system and, has already highlighted the massive potential in Australia for hosting both types of HPS occurrences at economically viable scales.

The mineral potential map has already been used to define a suite of sample locations in which to help define the best source for HPS. Further, we are undertaking the first national scale sampling and analytical geochemistry campaign to examine the impact of mineral systems on quartz purity and develop the Explorers' Toolbox – an industry applicable, best practice guideline for the characterisation of potential HPS deposits in Australia.

# Evaluating the selectivity of thiol collectors on froth flotation of PGMbearing ores

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## ABSTRACT

The present study explored the impact of thiol collectors on the flotation process of platinum group metals (PGMs) ores. Froth flotation tests were conducted utilising sodium isobutyl xanthate (SIBX), sodium ethyl xanthate (SEX), potassium ethyl xanthate (PEX), and sodium isopropyl xanthate (SIPX) at concentrations ranging from 40 to 120 g/t. Excellent recoveries exceeding 90 per cent were achieved during rougher flotation tests employing these collectors at various dosages, underscoring their strong selectivity towards both ore types. The dosages of these collectors were tracked via UV-Vis analysis in solution over time at a consistent pH, revealing substantial mineral-collector interactions at 300 nm. Thiol collectors (SIPX, SEX, SIBX, and PAX) exhibited selectivity towards PGMs and BMS, yielding comparable cumulative recoveries. Moreover, the structural composition of these collectors significantly influenced flotation recovery, with iso-alkyl xanthate (SIBX) demonstrating superior consistency in achieving maximum cumulative recovery across various dosages compared to other xanthates.

## Exploration for critical metals under cover in the Madura Province – Western Australia

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### ABSTRACT

The Madura Province in Western Australia stretching over 50 000 km<sup>2</sup> and represents an underexplored greenfield area where ore deposits have not yet been discovered. The Proterozoic basement rocks in this province are buried beneath c 200-800 m of Cretaceous clastics of the Bight Basin and Eocene limestones of the Eucla Basin. The presence of thick cover and the lack of outcrops challenge mineral exploration efforts, and assay analyses are unlikely to capture the chemical dispersion of metals from the basement through cover. However, sampling across the Cretaceous-Eocene and Cretaceous-basement unconformities for indicator minerals has uncovered numerous grains of detrital pyrite, pyrrhotite, chalcopyrite, pentlandite, sphalerite, cobaltite, galena and Bi-Se tellurides. This suggests the occurrence of prospective sulfide-rich rocks in the region. In addition to the detrital sulfides, diagenetic/hydrothermal pyrite, sphalerite, and galena have also been observed in the Cretaceous carbonaceous sediments. The composition and abundance of detrital sulfide grains vary substantially, with pentlandite predominating in one area, while chalcopyrite is more abundant in another. Trace element compositions indicate that the chalcopyrite is likely derived from epithermal or skarn deposits. Sphalerite occurs in two distinct populations; the first is rich in Ga, Ge. Se. As, In, Sn. Sb. Pb, Tl, Ni, Co, Bi, and Mo, vet shows depletions in Cu, Cd, and Pd compared to the second type, suggesting different sources. Detrital sulfide grains display single or composite fabrics and subangular shapes, which may indicate they have been transported over short distances from nearby Ni-Cu mineralisation. The elevated content of detrital sulfides at the unconformities suggests the presence of nearby basement palaeohighs as the main source of detrital sulfides. Therefore, targeting unconformities for indicator mineral analyses along with the basement palaeotopography mapping could be an effective exploration tool to vector toward mineralisation and reduce the cost of deeper drilling programs.

## A novel approach towards cobalt extraction from spent Lithium-ion Batteries using selective leaching and electrowinning

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### ABSTRACT

Lithium-ion batteries (LIBs) are becoming increasingly popular for energy storage applications, but improved recycling methods are needed to recover lithium and cobalt once the batteries have reached end-of-life. Mineral acids, such as sulfuric acid, were utilised in conventional recycling techniques for leaching or pyrometallurgical operations. These extraction methods have been shown to be both toxic and energy-intensive. This study investigates using deep eutectic solvents (DES) as alternative leaching agents to selectively extract cobalt (Co) from spent LIBs. A DES was synthesised by combining myristic acid ( $CH_3(CH_2)_{12}COOH$ ) with tetra-ethyl ammonium chloride ([N(CH<sub>2</sub>CH<sub>3</sub>)<sub>4</sub>]<sup>+</sup>Cl<sup>-</sup>)(TEAC) salt to produce an ionic liquid, ie DES, with tuneable properties. After the LIBs had been discharged and dismantled, the material that contained cobalt in the cathode powder underwent a process of leaching using an optimised DES solution of myristic acid:TEAC at molar ratios of 1:1. A maximum Co extraction efficiency of 87 per cent was achieved when leaching at 150°C for 180 mins under 600 rev/min agitation. The extracted cobalt from leachate was subsequently retrieved using the process of electrowinning. The goal was to develop a novel, nonhazardous DES leaching system that can efficiently extract Co from spent LIBs. Outcomes were analysed via characterisation techniques like Atomic Absorption Spectroscopy (AAS) and Fourier Transform Infrared Spectroscopy (FTIR). By utilising this sustainable method, it may be possible to enhance the recycling of critical battery materials.

# Development of new technologies for processing low-grade sulfide critical minerals

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### ABSTRACT

Australian sulfide deposits contain significant value of critical, strategic, and precious metals. However, in some instances realising this value is hampered by low-grades, complex mineralogy and poor recovery utilising conventional technology. To support Australian industry, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) is actively developing novel hydrometallurgical processing systems for economically extracting maximum value from these deposits. As part of this technological development process, the Australian Government Critical Minerals Office (CMO) has funded selected activities for trialling one promising technology – electrolytically driven *in situ* oxidant generation in leach solutions. This process can operate on an intermittent basis and thus has the potential to be powered exclusively using renewable energy.

Whilst initially developed as a targeted process to extract copper from chalcopyrite in existing heap leach operations, focus has also extended to treatment of other critical mineral-containing materials that currently are unable to be processed economically. This technology was evaluated at laboratory scale across such a selected group of Australian deposit and sulfidic tailing samples. The process demonstrated significant advantages in comparison to conventional hydrometallurgical flow sheet options, including: (i) improved gangue rejection through operation at elevated pH, (ii) close to complete extraction of value from sulfidic minerals, and (iii) rapid extraction of value. This novel process can be readily integrated with existing unit processes, common flow sheet configurations and does not require exotic or unproven technology.

The work program funded by this CMO grant identified several prospective applications of this technology, including the recovery of value from an Australian nickel-cobalt deposit that cannot be effectively processed using conventional technology. If this technology is realised, it has the potential to unlock considerable value from this deposit (A\$5B metal value) and others. The current presentation will outline this technology and the opportunities it offers.

# The role of Industry 4.0 in the mining industry

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### ABSTRACT

The advent of Industry 4.0, characterised by the integration of digital technologies and advanced automation, has instigated a profound transformation across industrial sectors worldwide. This paradigm shift signifies a departure from conventional manufacturing and production methods towards interconnected systems, data-driven decision-making, and enhanced operational efficiency. Within the mining industry, renowned for its inherent complexities and operational challenges, the incorporation of Industry 4.0 technologies represents a pivotal opportunity for innovation and optimisation. These technologies encompass a spectrum of digital solutions, including the Internet of Things (IoT), artificial intelligence (AI), robotics, and digital twins, each offering unique capabilities to address the sector's multifaceted demands. Industry 4.0 innovations are reshaping mining exploration, where IoT sensors and UAVs deliver real-time geological insights, while digital twins optimise resource prospecting, slashing costs and enhancing accuracy. In extraction, Al-driven automation ensures safer, more productive operations, employing autonomous vehicles and robotic systems for precision tasks. Throughout processing, digital twins facilitate predictive maintenance and workflow optimisation, identifying inefficiencies to minimise downtime and maximise resource utilisation. These advancements herald a new era of efficiency and sustainability in the mining industry, driven by the seamless integration of cutting-edge technologies. Moreover, the implications of Industry 4.0 extend beyond operational realms, encompassing environmental stewardship, supply chain management, and stakeholder engagement. Through the integration of digital solutions, mining companies can enhance sustainability practices, ensure transparency along the supply chain, and foster positive relationships with local communities. This academic research endeavours to explore the transformative potential of Industry 4.0 within the mining industry, elucidating the diverse applications of advanced technologies across the entirety of the mining life cycle. By examining the nuanced roles and impacts of these technologies within each operational phase, this study aims to provide insights that inform strategic decision-making and facilitate the adoption of innovative practices in modern mining operations.

# Pyrometallurgical options to reduce e-waste and recover critical metals

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### ABSTRACT

According to Australia's Critical Minerals Strategy 2023-2030, it should promote itself as a world leader in ESG performance by 'adopting renewable fuel, reducing energy requirements, ... for example through recycling and reprocessing materials'. Significant amount of e-waste will be produced in the same period. E-waste contains precious metals and metals of strategic interest for energy transition: copper, zinc, nickel, cobalt, tin, PGMs at concentrations higher than in primary ores. Furthermore, the Department of Climate Change, Energy, the Environment and Water is currently developing the 'Regulation for small electrical products and solar photovoltaic system waste', which will essentially restrict the disposal of e-waste in landfill and introduce liability for corporations that import or manufacture electronics or PV systems. The rapid rise of PV waste is of particular concern from environmental point of view since no standard economically viable methods exist for its recycling. The fees collected from importer/manufacturers are intended to facilitate the collection, sorting, disassembling, or shredding. The companies extracting critical minerals can benefit from preprocessed recycled materials both economically, and in terms of reputation. particularly if they choose to do metal refining in Australia. In the presentation, we demonstrate the case study of the pyrometallurgical options for the co-treatment of printed circuit boards and solar PV waste with either: 1) copper concentrate using the existing infrastructure of Mount ISA copper smelter, or 2) recycled low-grade copper and copper-contaminated iron, using small-scale urbanbased smelting technology. Case studies consist of process simulation using advanced FactSage™ thermodynamic modelling and laboratory scale equilibration.

# Improving bioleaching efficiency of critical elements from bauxite residue

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### ABSTRACT

Australia is the second largest producer of alumina in the world with more than 20 Mt (million tonnes) produced in 2022 and generates annually 30 Mt of bauxite residue, as a by-product of the alumina refinery process (Australian Aluminium Council Ltd, 2024; Scullett-Dean et al, 2022). Currently, only 2-3 per cent of the 150 Mt of bauxite residue produced worldwide is reused, and almost all residue is stored in disposal areas (Di Carlo, Boullemant and Courtney, 2019). Bauxite residue contains a wide range of critical minerals such as rare-earths elements, gallium, and germanium. Global demand of critical minerals has increased over the years because they are essential for development of cleaner technologies, however the energy intensive extraction process generates large amounts of hazardous waste (Čížková et al, 2019). Biomining is arising as a method for sustainable and costefficient extraction of these minerals. Extraction of critical minerals from bauxite residue via bioleaching with organic acid producing organisms has been proposed for this investigation. Filamentous fungi strains isolated from bauxite residue across various mine sites were selected as candidate micro-organisms: A. niger, P. oxalicum and P. tricolor. The growth and tolerance response of A. niger has been investigated in high concentrations of La, Dy, Ga, and Ge, showing that A. niger can grow on concentrations of up to 20 mM, 5 mM, 5 mM, and 5 mM, respectively. Adaptative laboratory evolution and genetic engineering techniques will be conducted to increase the organic acid production and bioleaching efficiency and to obtain a heavy metal and alkaline pH tolerant organism. Bioinformatics and 'multi-omics' research combined with metabolic network modelling will be integrated to examine the molecular underpinnings of bioleaching optimisation. This research could develop a novel strategy for an environmentally sustainable, scalable, and industrially feasible process for critical minerals extraction and alumina refinery by-product valourisation.

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## What is the investment community seeking from climate-related financial disclosures under ASRS and ISSB? An opportunity for critical minerals as leading players in decarbonisation

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### ABSTRACT

The incoming mandatory climate disclosure requirements have been described as 'the biggest changes to financial reporting and disclosure standards in a generation' (Longo, 2024). Driven by the global investment community, these changes will require disclosure on the transition companies need to make by 2050, including considerations of net zero, the impact climate risk will have on financial performance, and the opportunities these changes present. Reports will be aligned with or contained in a company's financial report. These are no longer just Environment, Social and Governance (ESG) reports, these are reports on how aspects of climate change financially impact the business and how they are managed. Ultimately, climate-related financial disclosures will enable the global investor community to assess the climate performance of the assets in which they are investing.

The critical minerals industry will need to disclose in line with these requirements. As a burgeoning industry featuring in the decarbonisation of economies, boards should consider how they can best leverage the Australian Sustainability Reporting Standard (ASRS) and International Sustainability Standards Board's (ISSB) requirements to drive engagement up and down value chains, and profile the industry's role and value.

The ISSB's work is backed by the G7, the G20, IOSCO, the Financial Stability Board, African Finance Ministers and by Finance Ministers and Central Bank Governors from over 40 jurisdictions. The number of jurisdictions that have mandated, or are considering mandating ISSB aligned disclosures, continues to grow. More than 20 jurisdictions globally are considering, or have mandated, reporting in line with ISSB requirements (International Financial Reporting Standards (IFRS) Foundation, 2024a). These jurisdictions account for:

- nearly 55 per cent of global GDP
- more than 40 per cent of global market capitalisation
- more than half of global greenhouse gas emissions (IFRS Foundation, 2024b).

### New, broad and detailed – the insights investors need

Mandatory reporting requirements are extensive, and well beyond what most companies typically report. These include financial quantification associated with:

- Scope 1 and scope 2 greenhouse gas emissions. These are emissions from your owned assets, and emissions associated with the energy they consume.
- Scope 3 emissions, which arise as you 'do business'. For example emissions associated with the transport of product from site to customers, or the emissions from the production of reagents consumed in your process.
- Your net zero pathway, and how your site will change over time to a final permutation where it gives rise to no, or almost no, greenhouse gas emissions. These plans will need to be completed, costed and planned out.
- Your progress against your net zero pathway.
- How your company will transition all of its assets to a carbon free future.
- A clear understanding of the climate resilience of all assets, including the financial impacts of different climate scenarios (or degrees of warming) on your operations.

Businesses will need to link scope 1, 2 and 3 emissions, a transition plan, a net zero plan, and climate resilience to financial outcomes out to 2030, 2040 and 2050. Boards require a transparent, evidence-based and auditable approach to calculating the financial impact of material climate risks and opportunities. The work encompasses directors, risk, finance, ESG, legal and operations.

The critical minerals sector will need to assess their performance across the breadth of the requirements of ASRS or ISSB aligned reporting. Of interest for developing projects is the ability to address, and minimise, their greenhouse gas emissions, and engage with the breadth of climate impacts that the project is likely to face at inception – to design out the issues, and exploit any opportunities that are identified on a site by site basis. In our presentation we will discuss case studies of how mining companies have addressed some of these risks and built out opportunities to enable improved financial performance.

#### The importance of your value chain

The boundary for reporting does not begin and end with a financial control boundary – the focus is on the value chain which, for many companies, remains challenging to manage.

However, quantification is not the end game. The end game is to reduce emissions and thereby risks, including costs and exposure to transition challenges. It is here that critical minerals have a huge opportunity, as suppliers to the technologies that will deliver a carbon reduced economy by 2050. Global mandatory disclosure will build the business case for critical minerals products. The critical minerals industry needs to unpack the requirements of global reporting regimes so that they are able to reflect their performance, and that of their product, to best effect on the global stage.

We will discuss the reporting frameworks and highlight how critical minerals can best make input to these to leverage opportunities and manage risks. The introduction of global mandatory reporting could, to a great extent, help critical minerals to sell themselves.

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# Application of vertical wet high intensity magnetic separators in critical mineral processing

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## ABSTRACT

The Vertical Wet High Intensity Magnetic Separator (VWHIMS) is a high intensity electrical magnetic separation equipment that utilises a blend of magnetic force, pulsating fluid, and gravity to process minerals. Its cutting-edge features are integrated into a design that employs a unique vertical configuration, pulsation mechanism, and specialised matrix materials to deliver optimal outcomes. The primary purpose of the Vertical WHIMS in mineral processing is to segregate magnetic particles from non-magnetic ones, enhancing the magnetic material grade or eliminating magnetic material contaminants from non-magnetic substances.

Manufactured by LONGi Magnet Co. Ltd, the LGS VWHIMS boasts innovative features such as a magnetic coil design, patented oil cooling system, and automatic control, making it widely applicable across various minerals., such as, hematite, including lithium, manganese, titanium iron ore, chromite, rare earth, phosphate ore, quartz, and feldspar, etc.

This paper provides an overview of the development journey of WHIMS, operational principles, different models of LONGi LGS VWHIMS, and its typical applications in some critical minerals processing.

# The India Australia New Policy Proposal (NPP) – unlocking critical minerals

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## ABSTRACT

Both India and Australia are aiming to secure their domestic Critical Minerals supply chains by ramping up mineral exploration, processing, and manufacturing strategies. The Indian Ministry of Mines has identified 30 elements as critical for the country and has forged a strategic partnership with Australia under a New Policy Proposal (NPP) agreement for Critical Minerals. Given the geological similarities to areas containing high mineral endowment and exploration challenges shared by Australia and India, leveraging the expertise of CSIRO in Critical Minerals research holds significant opportunity to boost mineral exploration and extraction efforts in India. This collaboration aims to enable a stable domestic supply of vital minerals to meet India's expanding industrial demands, as well developing new exploration tools that are applicable within Australia.

Several commodities and target areas have been collectively identified for investigation to unlock their economic potential. These include:

- 1. Ultramafic-hosted Cr-PGE(-Ni-Co) and their lateritic derivatives in Odisha and Karnataka.
- 2. Carbonatite-hosted REE deposits in Rajasthan and Meghalaya.
- 3. LCT pegmatites in Rajasthan.

Exploratory initiatives in these selected regions are guided by a collaborative, multidisciplinary and multi-scale methodology. This entails implementation of techniques for crustal scale imaging, lithological and mineral mapping through advanced airborne geophysical and hyperspectral surveys. Ground-based investigations aligned with a Mineral Systems framework are envisioned, integrating disciplines such as structural geology, whole-rock/mineral geochemistry and petro-mineralogical characterisation to construct comprehensive genetic models. These models will be compared with those of Australia to develop tools for enhanced exploration strategies within both nations.

## The critical choices required to seize Australia's unique opportunity

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### ABSTRACT

Australia has a chance to generate more than \$170 billion in gross domestic product (GDP) and create almost 330 000 jobs by 2040, if we capitalise on our first-class endowment of critical minerals and other energy transition materials.

PwC research reveals mining companies are well positioned to increase exploration, discovery and development of critical minerals projects.

However, this opportunity will only be realised if the country thinks differently and acts now. It is a race, and while market movement shows strong growth in the mid-tier critical minerals sector, more needs to be done to ensure we capitalise on a narrowing window of opportunity.

By considering four alternative futures for Australia's critical minerals sector, our presentation will explore a range of policy choices that could help Australia maximise the opportunity.

The scenarios range from maintaining market position; value adding; shaping international markets; and under the last and most beneficial situation, building capabilities and international market share.

The presentation will explore critical choices around:

- funding and incentives to significantly increase exploration activity
- infrastructure to support and incentivise critical minerals investments
- direct market interventions to address potential market failures
- collaboration across both industry and geographies
- untangling regulation to accelerate critical minerals supply
- access to talent and skills to deliver critical minerals projects.

These choices are critically important, with PwC analysis finding the additional GDP opportunity presented by critical minerals could also deliver up to \$50 billion in additional tax revenue to the governments of Australia.

In addition, the presentation will comment on opportunities the mining industry has to better demonstrate its positive impact on society.

# Critical raw materials sustainability, traceability and provenance verification – Australian pilot of the UN/CEFACT Project

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## ABSTRACT

The increasing range of sustainability reporting requirements and compliance regulations drive the standardisation imperative for critical mineral traceability and provenance verification. This imperative is further fuelled by the escalating global demand for critical minerals within the context of ensuring a secure and resilient supply chain.

The UN/CEFACT Critical Raw Materials Traceability and Sustainability Project (CRM Project) offers the supply chain traceability and sustainability reporting tools for national policy makers, critical mineral industry actors to respond to business, regulatory, governmental and consumer requirements for higher quality sustainability and conformity reporting information. The project is the foundational initiative of the emerging UN Transparency Protocol and delivers a efficient and scalable protocol to provide interoperability between traceability tools and a core library for sustainability reporting needed for CRM supply chain actors with a consideration to the confidentiality of sensitive information.

The protocol data includes three key components (product, traceability event, and conformity) to enable a supplier to access a market or get a premium price. This involves identifying practices to enhance compatibility, aiming to establish a framework for international data exchange to foster trust and traceability throughout the cross-border supply chain with developed interoperability standards, and ensure guarantee of origin (provenance verification) for compliance regulations. The project provenance verification framework is supported by a material fingerprinting tool developed by the Future Battery Industries CRC Trusted Supply Chain project, which utilises comprehensive physical and geochemical characterisation of battery minerals and materials to identify and validate the provenance through the battery supply chain.

The Critical Raw Material Transparency Protocol is ready for industry, technology and producer collaborations, and currently being implemented through pilot project focused on the Congolese cobalt, Australian Lithium and Canadian Copper to materially demonstrate due diligence, guarantee of origin and sustainability reporting compliance respectively.

## DLE completes the circle for lithium brine

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## ABSTRACT

Direct Lithium Extraction (DLE) describes a range of emerging technologies to remove lithium from brine sources. The 'Direct' part of DLE refers to the ability to extract lithium without time-consuming and water-wasting evapoconcentration steps. Major DLE methods include sorption, ion exchange, solvent extraction, membranes and electrochemical. While these approaches differ in process, they share common goals like reduced processing time, increased recovery, and minimised water loss.

Conventional evaporation methods may not recover even 60 per cent of the lithium while taking a year or more for the brine to work its way through the process. Most of the water is lost through evaporation. By contrast, DLE works on time frames of hours to days to recover 80 per cent to 90 per cent of the lithium with minimal water loss. DLE also opens up new sources of lithium such as geothermal or oil-field brines that are impractical to process using conventional evaporation methods.

Adoption of DLE could close major gaps in the circularity of lithium brine operations. Reduced processing time allows DLE operations to effectively adjust to demand. Increased recovery means more lithium can reach the market without increasing the amount of brine pumped. Processing geothermal and oil-field brines represents added value for what is otherwise a waste fluid.

A key DLE benefit is reduced water loss. The majority of spent DLE brine can be returned to the aquifer, maintaining the hydrologic balance and minimising potential impacts on fresh-water resources. A portion of the spent brine can be purified for use in the extraction process, further reducing impacts on scarce water resources.

Several DLE projects been piloted. DLE has advanced beyond proof-of-concept to the point where scaling to commercial operation is the next challenge. A DLE operation will be fundamentally different than current facilities, coming closer to the ideal of circular lithium brine mining.

# Environmental and cost comparison of different spodumene concentration processes

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### ABSTRACT

The world needs more raw materials for the growing sustainable economy, for lithium it is expected that the demand will increase by 400 per cent by 2050. Few know the variability in the environmental impacts and costs of existing and emerging raw material production assets, and it is expected that when using the same technology for lithium production, costs and environmental impacts will only increase as the highest quality resources are currently being mined.

FLSmidth (FLS) has been looking into alternative methods for spodumene concentrate production as part of the lithium shake-up project. Minviro Australia and FLS have worked together to understand the climate change and water use impacts and costs of producing spodumene concentrate via the lithium shake-up project, in comparison with conventional wet stack and dry stack lithium processes. As part of this process, three different flow sheets were compared.

The FLS Shakeup option (vertical roller mill with dry stack tailings) has a clear potential for reduced climate change and water use impacts whilst in parallel, having lower costs compared to conventional production with dry stack tailings and marginally higher costs compared to conventional production with wet stack tailings. This suggests that the flow sheet developed by FLS as part of the lithium shake-up project is a superior option, especially in light of emerging carbon penalties, taxes and sustainability concerns.

## Critical minerals - a road worth travelling, but it might be a bumpy ride

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### ABSTRACT

The Australian Government has designated 31 minerals to be *critical minerals*, including platinum group elements and rare earth elements. Each critical mineral might have three or more global markets, considering the downstream value chain, so there are around 100 global markets to consider. What distinguishes a critical mineral from an ordinary mineral, is one or more significant market flaws. A common flaw is too much market concentration, for example the dominance of China as a buyer or seller. There are however other flaws, such as high barriers to entry, poor availability of market information, heterogenous products and the market impacts of co-production in many cases. In addition, new substitutes are emerging for many critical minerals, leading to the potential for disruptive falls in demand. These factors combined, add to the potential for volatile and unpredictable commodity prices, especially in the short and medium term. No wonder it can be challenging to finance critical minerals projects.

Major mining companies might have the financial strength to push through these challenges, but most critical minerals markets are currently too small to be of interest to them. This leaves the challenge of bringing on new supply to mid-tier and small cap companies. Clearly the challenges are enormous, but the potential rewards are also enormous. Although commodity prices are likely to be volatile and unpredictable in the short and medium term, for many critical minerals, the long-term trend for demand is strongly positive. This is because many critical minerals find application in the growing markets for net-zero technologies, and high-tech defence. The companies that can navigate the challenges can set themselves on a path to long-term growth. In this presentation, I will examine these challenges in more detail, and suggest how companies can help themselves, and sometimes collaborate, to win.

## Conquering the challenges in commercialising great tech

#### R Williamson<sup>1</sup>

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#### ABSTRACT

While Solvent Extraction (SX) has been a well-established technique for extracting metals, Alpha HPA has uniquely adapted it to aluminium purification. The use of our Smart SX technology is transformative in the production of HPA as a sustainable alternative to traditional HPA production methods, setting a new industry standard for a 70 per cent reduced carbon footprint HPA product. This decarbonised approach offers a sustainable alternative to traditional methods, with HPA applications spanning various decarbonisation technologies such as lithium-ion batteries and LED lighting.

But how did we go from an idea and a technology that works in a beaker to commercialising and leveraging the technology to be the cornerstone of our business? Why do so many great ideas and technologies never see the light of day? We will discuss the process of commercialisation of Solvent Extraction for aluminium purification developed by Alpha HPA as a case study and potentially a framework for others to consider.

The presentation will give an initial overview of the technology, why Alpha HPA focused on significantly lowering carbon emissions for HPA, what this meant for the technology and how it was adapted, and what pitfalls of technology development needed to be avoided.

Drawing from Alpha HPA's experience, emphasis is placed on protecting intellectual property, navigating risks, and understanding market dynamics to drive technology development forward. The journey from laboratory-scale experimentation to industrial-scale implementation is fraught with uncertainties and complexities.

Through anecdotes and real-world examples, we will illustrate the strategic decisions, partnerships, and adaptations that were instrumental in Alpha HPA's journey towards commercialisation. By sharing these experiences, we aim to provide valuable insights and guidance for other innovators seeking to translate groundbreaking ideas into impactful solutions in the global marketplace.

## The circular reference of sales and funding

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### ABSTRACT

Navigating the complex realm of project funding within the critical minerals and advanced materials processing industries requires a nuanced understanding of key investment drivers. Alpha HPA, a pioneer in sustainable high-purity aluminium production, has learnt to navigate the intricacies involved in securing funding, especially amidst the challenges posed by sale contracts within these specialised sectors.

Addressing the conundrum of financing companies operating within opaque markets with intricate customer specifications and lengthy qualification processes presents a formidable task. How does one validate a product when the commercial plant is yet to be established, yet its qualification is pivotal to success?

This presentation aims to provide insights into these pressing questions, shedding light on innovative financing solutions that have proven successful. Additionally, it emphasises the significance of strategic partnerships and market positioning in attracting investment. Using Alpha HPA's firsthand experiences, the presentation delves into the critical factors that investors evaluate when assessing opportunities in these sectors.

Key focal points include the role of off-take agreements and long-term contracts in ensuring revenue certainty and mitigating market risks. Alpha HPA's experience has highlighted the importance of communicating accurately technology readiness levels and pilot-scale demonstration to reduce perceived investment risks, facilitate product qualification, and attract investment for a precommercial project.

Successfully navigating project funding in the critical minerals and advanced materials space demands an integrated approach combining financial innovation, strategic alliances, and technological advancements. By offering practical insights, this presentation endeavours to empower industry stakeholders with the knowledge needed to drive sustainable investment within this vital sector.

# Utilising Cyclowash<sup>™</sup> technology to reduce fines reporting to hydrocyclone underflow

#### M J Wright<sup>1</sup>

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### ABSTRACT

Cyclowash<sup>™</sup> is an elution device that is exclusive to the FLSmidth KREBS<sup>®</sup> Hydrocyclone product. It utilises the injection of an elutriation liquor - typically water - to induce a second stage of classification slightly above the theoretical plane intersecting the cyclone axis below which all particles, both solids and liquids, will report to the hydrocyclone underflow despite any possible interference from additional forces introduced. The gain from this second stage separation is to displace the entrained fine particles - characteristically sub #400 mesh - typically carried with the water reporting to the underflow causing the classifying phenomenon of short circuiting. The mining industry is experiencing a positive drive towards safer tailings dam construction; high fines content in the dam wall material can be detrimental to its stability and drainage properties. Without desliming of this material, the dam is at risk of minor to major collapses which can be devastating to the surrounding areas. Previous test work using KREBS® gMAX6 hydrocyclone with Cyclowash™ resulted in an average reduction from ~14.6 per cent sub #400 mesh feed recovery to the underflow to ~9.1 per cent without any major sacrifice of the underflow density. Contextualising this recovery difference of ~5.5 per cent in terms of a 400 MTPH solids throughput, this is an additional recovery of 22 MTPH solids of sub #400 mesh to the hydrocyclone overflow - equivalent to 176 000 MTPY solids. The recovery of this quantity of sub #400 mesh utilising Cyclowash™ cannot only make substantial differences to the sustainability of a mine's tailings dam but could potentially positively affect a grinding circuit through the reduction of recirculating fines. Pending ongoing research results. the recirculating fines reduction induced by Cyclowash™ on hydrocyclones classifying mill discharge may possibly increase the overall circuit capacity, consequently increasing throughput as well.

## Key trends in technology - an analysis using patent data

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#### ABSTRACT

As Australia looks to increase its supply of critical minerals, investing in new technologies will become increasingly important. The mining sector remains one of the greatest contributors to the Australian economy, accounting for ~15 per cent of our GDP in 2023. For Australia to fully realise its potential as a supplier and producer of critical minerals, it is also important to understand the state of development of its technology.

Using patent data, we explore and identify emerging trends in critical minerals both locally and globally. We create topographical maps of patent data to show us the parts of the supply chain which are attracting the most innovation and those which will require further development. This enables us to pinpoint gaps in research areas. These gaps correspond to less competitive areas with regard to R&D and/or IP filing. The gaps can also correspond to vital sections of the supply chain which require development.

We also look at emerging trends in technology for different critical minerals to identify the trajectory of innovation. This helps us to understand how technologies related to the exploitation of critical minerals such as mining, ore processing, refining etc are changing over time.

Finally, as companies look to add value to critical minerals, strategic partnerships between major players will become more crucial. We map the activity of competitors, which can help to identify potential research or commercialisation partners.

From our analysis, key recommendations are presented in which we show the 'hot' areas for innovation and identify crucial gaps that need to be filled to ensure that critical mineral supply can keep pace with demand.

# The battery materials challenge – sodium sulfate: an economic analysis of valourisation technologies

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## ABSTRACT

Sodium sulfate is a byproduct from the production of battery materials such as metal sulfates (NiSO<sub>4</sub>, CoSO<sub>4</sub>, MnSO<sub>4</sub>), lithium hydroxide, and pCAM (precursor cathode active material). The recycling of end-of-life batteries also produce significant amounts of sodium sulfate. Given the low cost of sodium sulfate and the rapidly rising demand for battery materials, the supply of sodium sulfate is expected to surpass the demand in the near future, making it difficult for facilities to secure off-take agreements for the by-product. Disposal of the material poses a financial cost and an environmental concern, thus there is a need to develop a process to convert sodium sulfate to a higher value product. Furthermore, given the lack of regulation around the discharge of sodium sulfate, the necessity of valourisation may be driven by more stringent environmental regulations.

The economics of three processes to valourise sodium sulfate are presented. The Glaserite flow sheet and Hatch's proprietary ion exchange flow sheet converts sodium sulfate to potassium sulfate (SOP) and sodium chloride using potassium chloride (MOP) as a reagent. While both MOP and SOP are fertilisers, SOP is used for chloride sensitive crops and holds a price premium to MOP. Additionally, the use of bipolar electrodialysis (BPED) to valourise sodium sulfate to sodium hydroxide and sulfuric acid is considered. However, the quality of the acid and base, and the limitations posed by impurities have a major impact on the feasibility of the process. A capital cost estimate for each process is developed and compared. Additionally, the operating cost for each flow sheet is developed and compared using reagent and utility rates from different regions.

# Green and efficient tungsten extraction via direct solvent extraction in alkaline medium

#### L Zeng<sup>1</sup> and K Barnard<sup>2</sup>

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### ABSTRACT

Tungsten is ranked by British Geological Surveys, US Department of Defence, the European Commission and Australia as a 'critical' mineral due to its economic importance, supply risk and inability to be substituted. However, the vast majority of tungsten mining and processing occurs in China. Australia ranks second for world economic resources of tungsten (Hughes, 2020) although current production is modest with only WO<sub>3</sub> concentrate being sold from two operating mines. A substantial opportunity exists for downstream hydrometallurgical processing of tungsten in Australia by converting scheelite and/or wolframite ores to ammonium paratungstate (APT  $(NH_4)_{10}(H_2W_{12}O_{42}) \cdot 4H_2O)$ . In the present work, the current technologies and existing problems of tungsten hydrometallurgy have been summarised and compared. To overcome drawbacks of current processes, a new process for APT production from caustic leach solutions of scheelite and/or wolframite based on direct solvent extraction (DSX) is presented. The principle, flow sheet and characteristics are introduced in detail. The results indicated that the new technology has wide applicability to the treatment of alkaline leach solutions arising from different tungsten ores generated via either autoclave soda leaching or caustic soda leaching. After leaching, the sodium tungstaterich solution (Na<sub>2</sub>WO<sub>4</sub>) was readily transformed to ammonium tungstate solution ((NH<sub>4</sub>)<sub>2</sub>WO<sub>4</sub>) in the DSX process, while P. As and Si impurities remained in the raffinate. The raffinate solution can be returned to the leaching step directly (for scheelite leaching) or after conversion to a caustic sodarich solution with lime (for wolframite leaching), realising the recycling of alkali and water. Compared to traditional processes, the new process exhibits advantages of high recovery of WO3 (>98.5 per cent) and low consumption of chemicals resulting in an estimated 40 per cent decrease in operational cost.

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## A novel vibration energy harvester for self-powered sensors at mine sites

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### ABSTRACT

Critical minerals are the building blocks of our modern world, essential for everything from smartphones to clean energy technologies. However, extracting critical minerals is becoming increasingly challenging due to dwindling accessible deposits and growing environmental and social concerns. To deal with these issues, Mine Internet of Things (MIoT) is introduced into critical mineral mining operations to improve productivity and safety. Sensor nodes play important roles in a MIoT system, which are responsible for data collection and data transmission. However, securing enduring power sources for sensor nodes poses a substantial challenge in the implementation of MIoT. As operating machines at the mine site continuously produce vibrations, piezoelectric vibration energy harvesting technique can be considered as a feasible approach for developing self-powered sensors, where dissipated vibration energy is converted into electrical energy based on piezoelectric mechanism. This presentation presents a novel piezoelectric vibration energy harvester designed to capture vibration energy from operating machines at the mine site characterised by low vibration frequencies. Experimental results indicate that when subjected to a stable vibration source with an RMS acceleration of 0.346 g and a frequency of 25 Hz, the proposed energy harvester can successfully power a temperature and humidity sensor node. Simultaneously, the collected temperature and humidity data can be transmitted to the computer through BLE wireless connectivity every 3:30 mins.

# Process for battery grade nickel and cobalt sulfate products from mixed hydroxide precipitate

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## ABSTRACT

Nickel laterite is becoming an important ore source for the preparation of battery grade nickel sulfate and cobalt sulfate as lithium battery precursor materials due to the depletion of nickel sulfide deposits. Current commercial hydrometallurgical processes produce intermediate products: mixed sulfide precipitate (MSP) and mixed hydroxide precipitate (MHP). In comparison to MSP, MHP contains relatively high amounts of impurities. The purification of MHP usually involves the (costly) extraction of nickel, typically by solvent extraction, leaving relatively small amounts of impurities such as alkali and alkaline earth metal ions in the pregnant leach solution.

CSIRO has developed a novel process for separating nickel and cobalt from crude nickel and/or cobalt bearing materials including MHP through the removal of the impurities. The process comprises treating a crude nickel material to remove iron and aluminium, and alkali metal ions (if needed), and then sequential solvent extraction steps to remove other impurities (eg Zn, Cu, Mn and Ca). Cobalt is then recovered, and magnesium is separated, leaving nickel in the raffinate (purified nickel liquor) suitable for crystallisation of battery grade nickel sulfate. Battery grade cobalt sulfate is obtained separately after stripping the cobalt-loaded organic stream. This process has been demonstrated at laboratory scale.

## Purification process for battery grade manganese sulfate

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## ABSTRACT

High purity manganese sulfate monohydrate (HPMSM) is a critical precursor material for the synthesis of various lithium battery cathodes for improved stability, safety, and energy density and reduced material costs. Conventional routes for the production of HPMSM via electrolytic manganese metal (EMM), high purity EMM (HPEMM) or electrolytic manganese dioxide (EMD) are energy intensive, while the direct routes from manganese ores require the challenging separation of manganese from calcium and magnesium in the leach solutions.

The current methods for manganese purification practised in China (a major producer of HPMSM) include highly toxic, polluting fluoride precipitation, solubility-based crystallisation with low selectivity and efficiency, and direct solvent extraction (SX). Various SX extractants and synergistic SX (SSX) systems have been studied; however, all of the SX processes suffer from one or more issues including: use of expensive organic reagents, low loading capacity, efficiency and selectivity, high solubility of organic extractants in aqueous solution and thus loss of extractant, and chemical instability of some synergist reagents in the SX process making them unsuitable for commercial applications.

In response to the need for a simple and robust SX process suitable for generating high purity manganese products, CSIRO has recently developed a novel SX process using a non-expensive, non-synergistic reagent system arranged in a simple extract-scrub-strip configuration with a small number of stages at practical organic to aqueous (O/A) volume ratios. The process, which features high loading capacity, high selectivity and high throughput, is suitable for the purification of various leach solutions containing high concentrations of manganese, calcium and magnesium. This CSIRO-developed system has been demonstrated at laboratory scale to produce nearly saturated manganese sulfate liquor containing little or no Ca, Mg, Na/K/NH<sub>4+</sub>. Such a solution will require little or no evaporation for production of HPMSM, ultrahigh purity manganese sulfate (UPMSM) or greater than 99.99 per cent purity products.

# **Papers**

## Sustainable beneficiation of hard rock lithium ores – aiming at zerowaste from single to multi metal/mineral processing: a case study

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### ABSTRACT

Lithium (Li) occurs naturally in various geological settings around the world. The most common lithium-bearing minerals are spodumene, lepidolite, and petalite, which are typically found in igneous rocks, pegmatites, and sedimentary deposits. According to the International Energy Agency (IEA), lithium demand will increase more than 40 times in less than 20 years.

Lithium (Li) plays a critical role in various industries and applications due to its unique properties. Some significant uses of lithium are batteries, electronics, automotive, aerospace, glass and ceramics, pharmaceutical, among others.

Spodumene is the most common lithium-bearing mineral. It is a pyroxene mineral that contains lithium aluminium inosilicate (inosilicates are inorganic compounds that have structures characterised by silicate tetrahedrons (each of which consists of a central silicon atom surrounded by four oxygen atoms at the corners of a tetrahedron) arranged in chains (https://www.britannica. com/science/inosilicate)). Spodumene is usually found in lithium pegmatite deposits and can occur in massive, granular, or crystalline forms. Lithium has good recycling potential, and recycling of lithium-ion batteries and other lithium-containing products reduces environmental impacts associated with traditional mining (*viz* urban mining).

The extracted lithium ore involves crushing, grinding, and separating the ore to remove impurities and increase the lithium concentration. This can be done through physicochemical methods, such as gravity separation, magnetic separation, or froth flotation, depending on the characteristics of the ore. Flotation, dense medium separation (DMS) and magnetic separation are the main beneficiation approaches used for hard rocks ores. Note that the close similarity in chemical and physical properties between lithium minerals and associated gangue minerals makes the beneficiation of lithium minerals from ores challenging.

This contribution addresses the separation approach used with a side stream of lithium ore processing from a mine in Portugal. The work consisted of an ore characterisation (ie chemical, mineralogical and screen size profile) and dense medium separation testing. The focus of the study has been on defining boundary conditions and process configuration at laboratory scale. The state-of-the-art indicates that DMS studies of Li-bearing ores are limited. Consequently, this work will help expand the use of DMS for lithium hard rock ores. In addition, the metric design to quantify performance is traceable, precise, and consistent. It goes without saying that as soon as the process configuration is established, the upscaling of it will be developed. The purpose of the project is to establish an integrated, sustainable extraction approach (zero-waste) to recover lithium from pegmatite deposits.

### INTRODUCTION

Lithium (Li) occurs naturally in various geological settings around the world. The most common lithium-bearing minerals are spodumene, lepidolite, and petalite, which are typically found in igneous rocks, pegmatites, and sedimentary deposits. According to the International Energy Agency (IEA), lithium demand will increase more than 40 times in less than 20 years.

Lithium (Li) plays a critical role in various industries and applications due to its unique properties. Some significant uses of lithium are batteries, electronics, automotive, aerospace, glass and ceramics, pharmaceutical, among others. Spodumene is the most common lithium-bearing mineral. It is a pyroxene mineral that contains lithium aluminium inosilicate. Spodumene is usually found in lithium pegmatite deposits and can occur in massive, granular, or crystalline forms. FIG **1** shows a diagram of the spodumene mineral and its primary components (*viz* lithium oxide, aluminium oxide and silicon dioxide). This figure also indicates the stoichiometry of spodumene formation, ie by combining 1 mole of  $Li_2O$ , 1 mole of  $Al_2O_3$  and 4 moles of  $SiO_2$ , these components generate 4 moles of spodumene (LiAlSi<sub>2</sub>O<sub>6</sub>). FIG **1** provides a general description of the Element-to-Mineral Conversion (EMC) approach which is a type of chemical-mineral mass balance quantification method to infer modal mineralogy for the different mineral components present in the ore.



**FIG 1** – Conversion of elemental assays to mineral quantities. Element-to-Mineral Conversion (EMC) is a type of chemical-mineral mass balance quantification method (Cupido, 2021).

It goes without saying that mineralogical characterisation is a 'must' sort of characterisation in order to determine effectively the hard rock lithium ore processing approach.

Lithium has good recycling potential, and recycling of lithium-ion batteries and other lithiumcontaining products reduces environmental impacts associated with traditional mining (*viz* urban mining). This recycling potential is the future of mining, ie smarter, greener and more sustainable way to access critical raw materials (ie in a scenery of decreasing ore grades, scarce water supply and costly energy).

### **PROPOSED SEPARATION APPROACH**

The extracted lithium ore involves crushing, grinding, and separating the ore to remove impurities and increase the lithium enrichment. This can be done through physicochemical methods, such as gravity separation, magnetic separation, and/or froth flotation, depending on the characteristics of the ore. Flotation, dense medium separation (DMS) and magnetic separation are the main beneficiation approaches used for hard rocks ores. Note that the close similarity in chemical and physical properties between lithium minerals and associated gangue minerals makes the beneficiation of lithium minerals from ores challenging.

FIG **2** presents a proposed flow sheet for spodumene beneficiation. The circuit considers a screening, dense medium separation (DMS) and flotation stages. FIG **2** also indicates that the fate of mica and feldspar must be addressed to achieve zero waste and develop a sustainable beneficiation approach.



FIG 2 – A proposed flow sheet for spodumene beneficiation (Gibson *et al*, 2021; Pillay *et al*, 2022). The circuit considers a screening, dense medium separation (DMS) and flotation stages. The figure also indicates that mica and feldspar must be addressed to achieve zero waste.

Every single unit operation helps access the value (spodumene) in the ore (Tadesse et al, 2019). Briefly, a short description of these techniques is provided:

**Screening separation** is commonly utilised to quickly and effectively sort out values from gangue based on particle size, shape and density.

**Dense media separation (DMS)** or heavy media separation exploits the difference in specific gravity between the valuable minerals and gangue minerals and is commonly used in the separation of spodumene from other gangue silicates. Note that spodumene sinks (ie concentrate), while gangue minerals float (ie tailings or less valuable materials).

**Flotation** is commonly used to process lithium bearing minerals such as spodumene. When the density difference between valuable mineral and gangue mineral is small, flotation is the ideal separation approach to be used. Note that depending upon mineralogical assemblage either reverse or direct flotation may be carried out. Several factors may influence selective flotation which must be considered carefully based on the ore characteristics.

FIG **2** depicts that the screening section produces undersize and oversize streams. The oversize stream feeds the dense media separation stage which consists of two sub-stages (sort of primary separation followed by a cleaner). On the other hand, the undersize stream mixes up with one of the waste streams of the DMS (ie Float 2). The combination of these streams forms the flotation feed.

As a result, FIG **2** generates two types of spodumene concentrates, *viz* spodumene DMS concentrate and spodumene flotation concentrate. It is also important to highlight that mica and feldspar must be addressed to have a sustainable beneficiation approach.

FIG **2** clearly shows that all the separation stages (ie screening, DMS and flotation) have got a common thread which is the density. Density is a property of all matter: solids, liquid and gases. It is also important to distinguish bulk density which is the measure the mass of solids in relation to the volume of the solids and the pores. Having briefly described density, it is now possible to contextualise the spodumene beneficiation approach through a density scale as the one shown in FIG **3**. This scale positions all the separation processes according to density separation ranges. For instance, screening starts off at 2200 kg/m<sup>3</sup>, DMS covers a density range between 2500 through 3100 kg/m<sup>3</sup>, and flotation separation (ie based on flotation aggregate density) occurs at the density range of 100 through 500 kg/m<sup>3</sup>.





FIG **3** also depicts the separation diagrams (ie recovery [valuable] versus yield [mass recovery]; Note that this contribution considers YIELD = Mass Recovery = Weight Recovery) for the different separation approaches used in the flow sheet. The diagrams show the diagonal lines of NO SEPARATION and the actual separation curves for screening, DMS and flotation.

Note that selectivity for screening depends on the screen opening (#). Nonetheless, selectivity for DMS is achieved by the medium density (ie selectivity increases as the medium density increases). At the same time, flotation selectivity is obtained by effective collision of hydrophobic particles (ie sufficient level of liberation) with air bubbles of the right bubble size proportion (*viz* 1:10 = particle: bubble). This, in turn, produces flotation aggregates of the appropriate density to be separated out under first order kinetic conditions.

### **RESULTS AND DISCUSSION**

FIG **4** provides a summary of the separation diagrams described in FIG **3**. The flow sheet's separation diagram (TOTAL) is also shown in FIG **4**. Based on the ore characteristics, it is observed that the overall separation performance achieved is about 54 per cent recovery with yield of ~17 per cent. In addition, the obtained enrichment ratio corresponded to 3.2 times.



**FIG 4** – Total separation diagram for circuit configuration (see FIG **2**), which is a result of previous stages. These stages are screening, dense medium separation (DMS), and flotation. Note that screening is a sorting stage.

Lastly, FIG **5** summarises performance separation results (ie recovery) as a function of particle size for screening, DMS and flotation processes.



**FIG 5** – Spodumene recovery as a function particle size for all the unit operations presented in FIG **2**.

It is observed that the screening stage is a 'sorting stage', ie it achieves a low recovery, but it separates out unwanted material that may impact adversely DMS performance. DMS stage shows a clear separation performance which is strongly associated with the screen opening and medium density. Lastly, flotation presents a separation profile which shows an optimum at the intermediate region of particle sizes. It can also be observed that at fine and coarse particle sizes, separation performance decreases. In conclusion, depending upon the driving forces of the three separation approaches and the mineralogical characteristics of the ore, separation performance may be optimised by manipulating key attributes of the processes and managing ore attributes.

### **CONCLUDING REMARKS**

This contribution addressed the separation approach used with a hard rock lithium ore processing from a Mine in Portugal. The work consisted of an ore characterisation (ie chemical, mineralogical and screen size profile) and dense medium separation testing. The focus of the study was to define the boundary conditions and process configuration at laboratory scale. The state-of-the-art indicates that DMS studies of Li-bearing ores are limited. Consequently, it is believed this work will help improve the use of DMS and flotation for hard rock lithium ores. In addition, the metric design to quantify performance is traceable, precise, and consistent. It goes without saying that as soon as the process configuration is established, the upscaling of it will be developed. The purpose of the project was to design a well-integrated, sustainable extraction approach (zero-waste) to recover lithium from pegmatite deposits.

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## Critical minerals – economic complexity and Australia's downfall

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## ABSTRACT

Australia is the lucky country, a country that has created a reliance on selling raw products that disadvantage us from an economic complexity point of view. In 2021, Australia was ranked the lowest in economic complexity indicators (ECI) in trade value compared to countries of a similar GDP (https://oec.world/en/profile/country/aus) according to Observatory of Economic Complexity (OEC). In the last 20 years Australia has dwindled from the 33rd to 82nd position in the ECI ranking. Take a moment to consider this.

Australia is consciously extracting its natural resources to supply other countries with the materials required to manufacture intermediate and end products. Then we buy these processed goods back at a large inequality to the balance of trade. The most significant export trade products are unprocessed raw goods. Closures of smelters and refineries in Australia as a result of aging infrastructure or operating costs are exacerbating the issue. Government support for developing downstream processing options and products have been completely overlooked until recent times.

Indonesia created an international uproar by banning sales of raw mineral products in 2014, their aim was to increase the value of minerals for export and preserve the country's resource supplies (USAID, 2013). Indonesia now has a stranglehold on nickel metal supply. Oman while having few metal mines of its own, developed special economic zones. For example, the Sohar Free Trade Zone has attracted 14 foreign companies, who have invested in metals, minerals and logistics. This includes Sohar Aluminium's smelter with downstream aluminium rolling plants, and an antimony and gold roasting plant (Sohar Port and Freezone, 2020). Large gypsum resources have been used to feed large gypsum dry wall product plants. Limestone is being mined and converted to clinker with cheap power from oil and gas and shipped to India from deep-water ports.

This paper will examine the role of governments in developing downstream mineral processing facilities for critical minerals and the lessons Australia could learn from growing economies around the world. Can Australia afford not to secure our children's future through enhanced economic complexity?

## INTRODUCTION

Governments play a critical part in how a country can potentially transform itself from a source of raw product to a multi commodity complex export trade balance. Australia has historically been known as a country rich in produce and raw minerals that are fed to our trading partners to enrich and re-export at significant trade imbalance. The Australia of the 1960s and 1970s was a burgeoning player in the Oceania region with a strong manufacturing industry (eg Newcastle and South Australian steel, Victorian car makers, mining technology development) (Quince and Kesteven, 2020). Manufacturing was 29 per cent of GDP in 1960 (Anderson, 2020). However, the trade protectionism in place since the federation in 1901 was slowly dismantled in 1973 with a 25 per cent across the board cut in tariffs, followed by dismantling of all protections in the mid-1980s (Anderson, 2020). This resulted in unsustainable competitive cost disadvantages for companies operating in Australia, by 1990 manufacturing had slid to only 15 per cent of GDP.

Australian industry has been impacted from cost pressures (wage, transport and utility) and significant competition from South-east Asian and other developing countries that have extracted market share. In the past two decades, China grew from being specialised in 16 per cent of technological capacities to a huge 94 per cent. India has also increased its areas of scientific specialisation from 42 per cent to 68 per cent and Colombia from 7 per cent to 21 per cent (WIPO, 2024).

## ECONOMIC COMPLEXITY

Australia has several challenges to overcome if they are to remain relevant in the coming decades. One measure of a country's ability to weather future headwinds is to increase the level of economic complexity. Economic complexity as a measure is the innovation, creativity and technological value added to raw products. The Observatory of Economic Complexity (OEC) currently designed and developed by Datawheel LLC was originally a research project (Simoes and Hildago, 2011) at the Massachusetts Institute of Technology. The OEC tracks worldwide trade movements through country import and export data. This is used to establish which countries are moving from raw product to mid and end use product through adding processing and technology, like iron ore to steel to ships, or rare earths to neodymium magnets to wind farm generators. Australia against a suite of comparable trade partners in the world is the lowest in complexity (Figure 1).



**FIG 1** – ECI (Trade) ranking by country for Australia (high is the lowest complexity) Source: OEC 2024.

The export value is dominated by the raw mineral product group most of which is coal, iron ore and petroleum gas (Figures 2 and 3) with vegetable products second and gold metal third. The first manufactured export occurs at position 30 in the list of items with therapeutic appliances.



**FIG 2** – Top 10 Australian export trade product value by group and per centage. Retrieved from: <a href="https://oec.world/en/profile/country/aus>">https://oec.world/en/profile/country/aus></a>.



**FIG 3** – Top 10 mineral products value by per centage of total trade. Retrieved from: <a href="https://oec.world/en/profile/country/aus">https://oec.world/en/profile/country/aus</a>>.

The World Intellectual Property Organisation (WIPO) examines the trademark industry and recognises that industrial policymaking is critical in developing markets. It sees many developing and least developed countries, who are increasingly targeting economic diversification – and the innovation, creativity and technology required to achieve it – as a means of securing supply chains, addressing national and international challenges and driving sustainable growth (WIPO, 2024).

Australia expects competition from China, Japan, Korea and Indonesia. However emerging countries like Oman and Saudi Arabia, backed by petroleum wealth, are making calculated changes to their mineral economies by moving from oil producers and processors to developing mineral resources and upgrading them through special economic allowances and taxation concessions to become high value product generators.

Driven by a desire to diversify, the Omani wealth funds and government have developed special economic zones based on deep water port access. This enables overseas companies to develop processing facilities to value add to raw products whether from in-country materials or imported raw products (eg bauxite). The Public Authority for Special Economic Zones and Free Zones was established in August 2020 by Royal Decree to oversee the Special Economic Zones (opaz.gov.om). Several economic free trade zones including the Sohar Free Zone and port has since its establishment in 2010, become one of the Gulf Cooperation Council's (GCC) largest and most successful industrial zones, together with the Sohar Port there is a combined investment of over USD27 billion. Businesses that establish in these zones enjoy free trade zone benefits, such as exemptions from tax duties on the import and export of goods, exemptions from personal income tax, no compulsory amount of minimum share capital to meet, full foreign ownership, and a tax holiday from corporate tax rates for up to 25 years (Sohar Port and Freezone, 2020; Tetra Consultants, 2024).

The Kingdom of Saudi Arabia (the Kingdom), always a world power based on its petroleum asset wealth, has turned its hand definitively to its mineral wealth. The Kingdom's Vision 2030 focus is firmly on the increasing development and processing of its raw products. To achieve this objective, the Kingdom is implementing a variety of sectoral structural reforms. They seek to stimulate private sector investment by intensifying exploration, building a comprehensive database of the Kingdom's resources, reviewing the licensing procedures for extraction, investing in infrastructure, developing funding methods and establishing Saudi centres of excellence (Lean, Muller and Purves, 2021).

## AUSTRALIA – A WORLD POWER

Australia is in a technological desert from an economic diversity point of view. Let's put that aside for now and look at the opportunities available if they are proactive. We have world-class deposits in iron ore, bauxite, copper, gold, uranium, lead, zinc, lithium, tantalum to name a few. We have the mining skills to be efficient in our mining processes we do however lack the manufacturing capacity to upgrade our products. As Lynas Rare Earths boss Amanda Lacaze rather eloquently stated recently 'Australia's advantage in terms of its resource endowment is really significant, but as well as that, I really hate it when we get the 'world's quarry' sort of commentary going on, because we are indeed the world leaders in mining, in terms of safety, in terms of sustainability, in our approach to the way that we mine and we should be proud of this, we should not think that it is some sort of second-class activity — it is not a bunch of boofheads driving tractors, pushing dirt around. It is a high-tech industry in and of its own right'.

Economic diversification is a challenging process. Difficult questions are asked of policymakers about what areas to support, what not to support, and where untapped potential lies. It also requires the flexibility to move swiftly and seamlessly into new areas of specialisation, as well as the focus to build new often complex innovation capabilities (WIPO, 2024).

University course options in geoscience and mining engineering degrees are reducing as universities convert high-cost degree courses (such as geoscience) to courses that are taken up more by overseas students. Graduates in mining engineering steadily decreased from 2015 to 2020 as shown in Figure 4. Knights (2020) suggests a minimum of 160 mining engineering graduates a year are required. The Mining Council of Australia (MCA) has issued papers in 1998 and the Australian Geoscience Council Inc. (AGC) in 2022 (MCA, 1998; Cohen, 2022) showing the decline in numbers of graduates and entrants to geoscience and mining engineering since a peak in the 2010s

(Figure 5). BDO (2022) state research that Gen Z population are sceptical that the natural resources industry can offer them a career with security or progression. Of the students interviewed by BDO (2022), 58 per cent believe poor environmental, social and governance (ESG) credentials is one of the biggest drawbacks to pursuing a career in natural resources. A generational (1970s and 1980s) media stance of anti-mining and anti-nuclear has only recently given way to the progressive critical minerals debate. Open questioning of nuclear policies to feed the electrification/battery needs and reduce carbon output is opening people's opinions on mining. This along with prime-time advertising by the mining majors highlighting the benefits of mining is making some impact on turning the tide.



Graduates in Mining Engineering from four year degree

**FIG 4** – Australian university mining graduates by university by year. Source: AusIMM (2021) adapted from Knights (2020) and Cohen (2022).



**FIG 5** – Australian university geoscience enrolments by year. Source: AusIMM (2021) adapted from Knights (2020) and Cohen (2022).

The closure of many schools' further limit opportunities for the STEM students to add to the mining future built on the back of the baby boomer era scientists. Ian Fitzsimons as Professor of Geology at Curtin University in a letter to the editor of MiningNews in 2020 (Fitzsimons, 2020) stated that 'Australia has a long and proud record of supplying highly-skilled and well-rounded geoscience graduates to the world, particularly in the field of mineral and energy resources, but this reputation is at risk unless we can agree on the core knowledge and skills that qualify someone as a professional geoscientist'. When a geology or earth science degree can contain as little as 25 per cent geoscience content it is little wonder our graduates require significant post graduate upskilling.

In the United States (US) the Center for Strategic and International Studies recently stated: 'More than half the current domestic mining workforce will need to... retire and [be] replaced by 2029

(roughly 221 000 workers). This number stands in stark contrast to the total of just 327 degrees awarded in 2020 in mining and mineral engineering and a 39 per cent net drop in graduations in the United States since 2016' (Senate Committee on Energy and Natural Resources, 2023).

## **RECENT DEVELOPMENTS**

The Department of Industry, Science, Energy and Resources (DISER) announcements of a Critical Mineral Strategy (DISER, 2022) has a stated claim to build sovereign capabilities in critical mineral processing. The stated claim is that the Federal Government will support the sector across communication, coordination, regulation and financial support. Grants already in place to the value of \$243.6 million have been issued to rare earth, battery technology and high-purity alumina production companies.

Queensland Government has developed the Queensland Critical Minerals and Battery Technology Fund (The State of Queensland, 2023) with an investment of \$170 million to support Australian businesses. This will allow global competition by enhancing the extraction and processing of critical minerals in Queensland, thus accelerating the development of battery technologies and production of precursor or advanced materials in Queensland. Through grants and or equity investment Queensland companies have an opportunity to derisk investment in high technology value added processes. The government also needs to provide the certainty of development approvals beyond initial funding promises.

#### CONCLUSION

Overseas countries like Oman are generating greater product diversity in country by developing Free Trade Zones that incentivise investment through tax holidays, no duties, no minimum capital requirements and allowance of 100 per cent foreign ownership. Saudi Arabia has turned around a closed-door exploration and mining sector by enacting into law transparent and guaranteed land access along with a national industrial development and logistics program. Clear pathways to development are available, where in Australia green and red tape can mean a standard development pipeline of discovery to mine can take 10–15 years.

Australia has the undeveloped land to build as many manufacturing sites as it needs. However, there are significant hurdles to be overcome including energy availability and cost, infrastructure (be it port or rail), and workforce at rates that are cost-effective. Fulfilling these requirements is not easy or quick, but sitting back and enjoying the benefits of large export or royalty windfalls without using them to build our future is a failure to plan by Government. The Association of Mining and Exploration companies (AMEC) produced a submission (AMEC, 2023) to the South Australian Department of Industry, Science and Resources recommending development of a critical minerals processing hub to process demonstration-size quantities of critical minerals. If the Federal and State governments are serious about advancing the economic complexity of Australia, then manufacturing of downstream products using these high-end technological requirement metals should be efficiently developed in a timely manner.

The Australian education system is not recognising the enormous role that STEM subject skills has in developing our future in mining and manufacturing. If we lose our competitive edge in mining the 71 per cent of export trade value is at risk. Developing the right tools and skills for our educators to market geoscience and mining to the youth of today can only benefit the future of our single most important export value sector. The US Senate in July 2024 approved the Mining Schools Act of 2023 to establish grants, recruitment, studies and research projects related to the production of minerals.

We are at a tipping point right now, and Australia needs to make considered decisions in developing its resources beyond just shipping them offshore. Funding and investment confidence needs to continue beyond this year's election in Queensland. The future of Australia as first world country depends on developing plans to maintain our relevance in the world beyond a raw product supplier.

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## Process simulation of a nanofiltration, ion exchange, and electrodialysis flow sheet for lithium production using fundamental thermodynamic modelling

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## ABSTRACT

As the world moves towards reducing reliance on fossil fuels via increased electrification, battery metals will play an increasingly important role. Lithium is expected to play a key role in this transition.

Conventional processes for producing lithium required for batteries involve evaporation in large ponds for the production of concentrated Li-bearing brines. In recent years, there has been significant interest in membrane-based processes for preconcentration and purification of lithium brines. Furthermore, electrochemical processes such as electrodialysis have garnered attention as a means for direct production of lithium hydroxide from concentrated brines.

In this work, a conceptual process model is presented which evaluates nanofiltration, direct lithium extraction, and electrodialysis for the production of lithium hydroxide brine from raw feed brine. The models are based upon fundamental thermodynamics, utilising both commercially available thermodynamic software and open literature data. Using the models, operating parameters and brine feed chemistry can be varied to understand their impact on the overall process.

The thermodynamic modelling software, AQSOL, is used within SysCAD via the Thermodynamic Calculation Engines interface. AQSOL uses the extended UNIQUAC thermodynamic model for estimation of activity of solutes in salt solutions over a wide range of temperatures. Solubility of salt hydrates and double salts are calculated. AQSOL calculations embedded in the overall process model allow prediction of solution properties, including osmotic pressure and conductivity, as well as scaling propensity.

The thermodynamic modelling package, PHREEQC, is also used within SysCAD via the Thermodynamic Calculation Engines interface. In addition to having additional data for a large number of relevant solids, this package includes ion exchange functionality which is used for modelling of the direct lithium extraction technology.

### INTRODUCTION

There is significant interest in new processes for lithium production which have the potential to produce less solid waste, consume less water, and have a lower land footprint than conventional production routes. Some of these new processes involve the use of membrane technology for the separation of lithium from other elements commonly hosted in a deposit. Direct Lithium Extraction (DLE) technology is also receiving significant attention due to its potential for efficient isolation of lithium from other host elements in production brines.

New functionality in SysCAD, a process simulation platform used extensively in mineral processing, has been developed to allow first principles modelling of these important unit operations. Using the Thermodynamic Calculation Engine interface, membrane and DLE processes are modelled from first principles and these models can be used to predict overall performance as well as scaling propensity. SysCAD was used to evaluate a conceptual flow sheet involving nanofiltration, ion exchange, and bipolar electrodialysis for the production of lithium hydroxide from brine.

A key drawback of membrane and DLE technology is the sensitivity to mineral scaling. Because of this, pretreatment of the feeds is often required for these technologies, which can significantly affect their capital and operating costs. Solubility prediction is very important for determining the feasibility of such processes. These chemical equilibrium calculations are accomplished via the SysCAD

Thermodynamic Calculation Engines interface, which currently connects seamlessly to several equilibrium packages, namely AQSOL, PHREEQC, OLI, and ChemApp.

### OVERALL PLANT MODEL

The overall plant model is presented as a high-level block diagram in FIG **1**. Feed brine is passed through nanofiltration to remove divalent ions, such as magnesium. The cleaned brine is then pH-adjusted using hydrochloric acid solution prior to direct lithium extraction. Hydrochloric acid solution is also used for elution of the loaded DLE resin. The acidic eluate from DLE is then neutralised using recycled LiOH product. The neutralised lithium chloride feed is then provided to bipolar electrodialysis for the production of lithium hydroxide and hydrochloric acid. In this diagram, only high level details are shown. Individual process circuits are described later in this report.





### EQUILIBRIUM MODEL

### AQSOL Software

Salt precipitation and ionic activities used for determining electrode polarisation are calculated with AQSOL software. In this work a specific AQSOL package, AQSOL037 is used. This version contains the following ions and species:  $H_2O$ , Li<sup>+</sup>, Na<sup>+</sup>, K<sup>+</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup>, Fe<sup>2+</sup>, Mn<sup>2+</sup>, Fe<sup>3+</sup>, Al<sup>3+</sup>/AlO<sup>2-</sup>, H<sup>+</sup>, Cl<sup>-</sup>, HSO<sub>4</sub><sup>-</sup>/SO<sub>4</sub><sup>2-</sup>, OH<sup>-</sup>, CO<sub>2</sub>(aq)/HCO<sub>3</sub><sup>-</sup>/CO<sub>3</sub><sup>2-</sup>, H<sub>3</sub>BO<sub>3</sub>/B<sub>4</sub>O<sub>7</sub><sup>2-</sup>/BO<sup>2-</sup>, SiO<sub>2</sub>/SiO<sub>3</sub><sup>2-</sup>, O<sub>2</sub>(aq), H<sub>2</sub>(aq) and Cl<sub>2</sub>(aq). All solid phases and gases known to form from these aqueous species are also included in the software.

AQSOL software is based on the Extended UNIQUAC model, a thermodynamic model for electrolyte solutions proposed by Thomsen, Rasmussen and Gani (1996) and Thomsen (2005). The model consists of a UNIQUAC term for short range interactions and a Debye-Hückel term for long range interactions between species. UNIQUAC is a local composition activity coefficient model developed by Abrams and Prausnitz (1975), while the Debye-Hückel term was developed by Debye and Hückel (1923). This model uses only a few parameters and is therefore very robust and suitable for process simulation. The required model parameters are two size parameters for each species and an interaction parameter for each species pair. The model parameters were determined from a large databank of experimental data published in the open literature.

In AQSOL software, speciation equilibria, solid-liquid equilibria and vapor liquid-equilibria are dealt with through the general equation:

$$\ln K = -\frac{\Delta G^0}{RT} = \sum v_i \ln a_i$$

*K* is the equilibrium constant,  $\Delta G^0$  is the increment in standard state Gibbs energy in the equilibrium process,  $a_i$  is the activity, and  $v_i$  is the stoichiometric coefficient of species *i*. *R* is the gas constant and *T* is the temperature in Kelvin. Standard state Gibbs energy values for aqueous species are obtained from the NIST Chemistry WebBook (National Institute of Standards and Technology, 2023) when available. The corresponding values for anhydrous and hydrated salts are determined from experimental data during parameter fitting. Equations for each of the three types of equilibria are solved simultaneously to determine the composition of the aqueous phase, the amount and type of solids precipitating at thermodynamic equilibrium, and the vapor pressure of the solution. AQSOL software does not take pressure as an input and does not determine the amount of gases evaporating.

The accuracy of phase equilibrium calculation with AQSOL is demonstrated in Figures 2 and 3. Figure 2 displays the solubility isotherm for the LiCl-KCl-H<sub>2</sub>O system calculated with AQSOL software at 50°C. Experimental data by Plyushchev and Kuznetsova (1959) is plotted in the diagram for comparison with the calculated isotherm. Figure 3 displays the solubility diagram for the Li<sub>2</sub>SO4-MgSO<sub>4</sub>-H<sub>2</sub>O system at 75°C calculated with AQSOL software. Experimental data by Lepeshkov and Romashova (1960) and Li, Guo and Zhu (2021) are plotted in the diagram for comparison with the calculated isotherms.



**FIG 2** – Phase diagram for the LiCl-KCl-H<sub>2</sub>O system at 50°C calculated with AQSOL software and plotted with experimental data from Plyushchev and Kuznetsova (1959).



**FIG 3** – Phase diagram for the Li<sub>2</sub>SO<sub>4</sub>-MgSO<sub>4</sub>-H<sub>2</sub>O system at 75°C calculated with AQSOL software and plotted with experimental data from Lepeshkov and Romashova (1960) and Li, Guo and Zhu (2021).

#### PHREEQC Software

PHREEQC is developed by the United States Geological Survey (Parkhurst and Appelo, 2024). The Pitzer.dat database, distributed with PHREEQC, includes solution equilibrium data for 17 elements. Importantly, it includes data for lithium, potassium, sodium, magnesium, calcium, silica, chloride, and sulfate.

PHREEQC includes an ion exchange feature, called the 'Exchange' functionality. It allows calculation of ion exchange equilibrium, and this feature was used specifically for simulation of Direct Lithium Extraction. See the PHREEQC online help files for additional information.

The database structure in PHREEQC is open text, making it a relatively simple exercise to add additional chemistry and data. Furthermore, the SysCAD-PHREEQC interface features a data-fitting function which allows for automated adjustments of equilibrium constants in the PHREEQC database. Examples of the use of this functionality are provided elsewhere (Heppner, 2021, 2022).

The PHREEQC Pitzer.dat database is suitable for lithium-bearing muriate of potash brines, as shown in FIG **4**.



FIG 4 – Comparison of NaCl and KCl solubility predicted by PHREEQC using the Pitzer.dat database to d'Ans (1952).

#### NANOFILTRATION MODEL

Nanofiltration has been investigated by many authors for the removal of divalent metals, such as magnesium, from lithium-bearing brines (Yang *et al*, 2024; Sun *et al*, 2021; Liu *et al*, 2023, 2024; amongst others). The nanofiltration model is a semi-empirical model that allows specification of ionic permeability of different ions in solution. These permeabilities can be determined from ionic diffusivity, test work, and/or membrane vendor specifications. Rejection efficiencies greater than 90 per cent have been reported for magnesium using suitable membranes (Li *et al*, 2019).

In this work, permeabilities were calculated from measured permeances for sea water in an NFAL (Alfa Laval, Polyamide) membrane, as reported by Hubach *et al* (2023). Flux of an ion,  $J_i$ , was calculated from the following equation:

$$J_i = P_i \Delta m_i$$

Here,  $\Delta m_i$  is the concentration difference across the membrane (in molal) and  $P_i$  is the permeance of the i<sup>th</sup> ion. The ionic permeation as a fraction of the feed was then calculated:

$$Perm_i = \frac{J_i A_{membrane}}{F_i}$$

Water transfer through the membrane is calculated based upon applied pressure. Water flux is adjusted such that the osmotic pressure difference across the membrane is equal to the applied pressure. This assumes that there is sufficient membrane area such that water flux equilibrium is achieved.

The nanofiltration circuit model implemented in SysCAD is shown in FIG 5.


FIG 5 – Nanofiltration circuit model in SysCAD.

# DIRECT LITHIUM EXTRACTION MODEL

Direct Lithium Extraction (DLE) is an emerging technology for the isolation of lithium from its host brine. The mechanism can be either direct absorption or ion exchange (Farahbakhsh *et al*, 2024). In this work, a conceptual model of ion exchange DLE was developed by defining a set of exchange reactions in the PHREEQC Pitzer database. Here, the DLE cation exchange site is represented by Dle<sup>-</sup>:

$$H^+ + Dle^- = HDle$$
  
 $Li^+ + Dle^- = LiDle$ 

Several reactions for other alkaline metals ( $A^+$ ) and alkaline earth metals ( $Ae^{2+}$ ) were also defined:

$$A^{+} + Dle^{-} = ADle$$
$$Ae^{2+} + 2Dle^{-} = Ae(Dle)_{2}$$

DLE technology is stated to be highly selective for lithium. Therefore, equilibrium constant values for these reactions were adjusted such that the affinity of the exchange sites were much higher for lithium and acid than other larger metals. This was done because isotherm data was not available for data fitting.

With appropriate isotherm data, equilibrium constants for each of these reactions can be obtained. A recommended approach is to generate pure salt isotherms for a known resin form, eg LiCl on HDIe. Doing these tests for all metals allows for individual calculation of equilibrium constants, resulting in a competitive adsorption model. Such a model is suitable for a wider range of operating conditions compared to an isotherm generated for a production brine. Examples of this type of data fitting are provided by Heppner (2021, 2022).

The DLE model is presented in FIG **6**. The circuit includes pH adjustment, loading, elution, and washing. pH adjustment of the circuit feed is included in the model for the purpose of optimisation of

lithium loading and minimisation of scale formation in the column. It is well known that pH is important for the loading of lithium onto DLE resins (Li *et al*, 2023; Zhang *et al*, 2023). The resin recycle rate is adjusted to minimise lithium losses to the barren solution. The rectangle/triangle repeated units within each column are AQSOL reactors followed by solid/liquid separators. Each of these reactor/separator pairs represent a 'slice' in the column, allowing for calculation of the lithium concentration profile within each column.



FIG 6 – Direct Lithium Extraction circuit model in SysCAD.

# **BIPOLAR ELECTRODIALYSIS MODEL**

Bipolar electrodialysis is used for the direct production of lithium hydroxide. It has the added benefit of acid production which may be used for DLE elution. In a bipolar electrodialysis unit, membranes are arranged in the following pattern: bipolar – anion exchange – cation exchange, with a final bipolar membrane isolating the cathode. A simplified diagram of a single stack bipolar electrodialysis unit is presented in FIG **7**.

Bipolar membranes are set in reverse bias to reject ions from the adjacent chambers, ie the cation exchange side of the membrane faces the anion exchange membrane chamber, and *vice versa*. Due to this reverse bias, current in a bipolar membrane is carried largely by the catalytic dissociation of water which occurs within the middle layer of the membrane. Several papers have been published on this topic (González, Grágeda and Ushak, 2023; Koter and Warszawski, 2005; Pärnamäe *et al*, 2021; amongst others). See these references and others for further information on the bipolar membrane process.



**FIG 7** – Simplified diagram of bipolar electrodialysis model (single stack) showing the movement of major ions.

Mass transport in the electrodialysis unit occurs due to gradients in concentration and electrical potential, ie:

$$N_j = -z_j \frac{D_j}{RT} C_j \nabla \varphi - D_j \nabla C_j$$

For transport within membranes, the equation is adapted to account for tortuosity of the ionic migration/diffusion path as well as repulsion due to Donnan exclusion. It is modified to be:

$$N_j = -z_j \frac{D_j^{eff}}{RT} C_j \nabla \varphi - D_j^{eff} \nabla C_j$$

. .

where:

$$D_j^{eff} = D_j f_k$$

In this equation,  $f_k$  is a scaling factor for the k<sup>th</sup> membrane which reduces the effective diffusivity of each ion. In the above equation, the potential gradient across the membrane,  $\nabla \varphi$ , is solved iteratively to estimate the transfer of each ion across the membrane considering both migration and diffusion.

At any point in the electrodialysis unit, the current density is carried by the movement of ions:

$$i_{applied} = F \sum_{j} z_{j} N_{j}$$

Substitution of the membrane flux equation into the above expression of current continuity, followed by algebraic manipulation, results in an expression of Ohm's Law:

$$\nabla \varphi = -\frac{i_{applied} + i_{dp}}{\kappa}$$

Here,  $\kappa$  and  $i_{dp}$  are the solution conductivity and diffusion potential current density, respectively:

$$\kappa = \frac{F^2}{RT} \sum_j z_j^2 D_j^{eff} C_j$$
$$i_{dp} = F \sum_j z_j D_j^{eff} \nabla C_j$$

The diffusion potential current density,  $i_{dp}$ , is equal and opposite to the current density arising from diffusion transport. Thus, diffusion potential acts to maintain solution electroneutrality. Because ions have different diffusion rates, unhindered diffusion would result in charge separation, which is physically impossible. This is described in greater detail by Newman and Balsara (2021).

It is advantageous for a constant current system, such as electrodialysis, to rewrite the flux equation in terms of current, not potential, thereby allowing direct calculation of the ionic fluxes from the applied current density:

$$N_{j} = z_{j} \frac{D_{j}^{eff}}{RT} C_{j} \frac{i_{applied} + i_{dp}}{\kappa} - D_{j}^{eff} \nabla C_{j}$$

Conservation of charge across each channel and membrane allows calculation of migration-diffusion flux of all ions across the electrodialysis unit. A mass balance on each channel, combined with equations of ionic flux for each adjacent membrane, provides a means to calculate the distribution of each ion across the entire electrodialysis unit.

Water transfer across membranes is calculated by osmosis and electro-osmosis (Filippov and Shkirskaya, 2022). Coefficients for water transport are a function of water concentration gradient and applied current, ie:

$$J_w = k_o \nabla C_w + k_{eo} I$$

Water transport is an important consideration for electrodialysis as it reduces the effectiveness for concentrated brines (Pärnamäe *et al*, 2021).

At the anode and cathode, electrochemical reactions occur which typically produce gases, ie oxygen and chlorine at the anode, and hydrogen at the cathode. The extent to which these reactions proceed depends on the applied current to the unit and the availability of reagents for individual reactions. The current-potential relationship at the electrode is calculated using the Butler-Volmer equation combined with the Nernst equation. Mass transfer limitations are also considered. See Dickinson and Wain (2020) for a review of the Butler-Volmer equation.

Overall potential drop across the unit is calculated by a sum of all resistances across membranes and solution channels:

$$\Delta E = E_a - E_c + i \sum_{j=1}^{N_{stacks}} \left( \frac{t_{c,bp,j}}{\kappa_{bp,j}} + \frac{t_{c,ax,j}}{\kappa_{ax,j}} + \frac{t_{c,cx,j}}{\kappa_{cx,j}} + R_{bp,j} + R_{ax,j} + R_{cx,j} \right) + i R_{bp,cathode} + \frac{t_{c,bp,cathode}}{\kappa_{bp,cathode}}$$

Here,  $t_{c,bp,j}$  is the channel thickness on the anode side of the bipolar membrane,  $t_{c,ax,j}$  is the channel thickness on the anode side of the anion exchange membrane, and  $t_{c,cx,j}$  is the channel thickness on the anode side of the cation exchange membrane.  $R_{bp,j}$ ,  $R_{ax,j}$ , and  $R_{cx,j}$  are the membrane resistances for the bipolar, anion exchange, and cation exchange membranes, respectively.  $R_{bp,cathode}$  is the final bipolar membrane resistances are a function of both membrane properties and the adjacent electrolyte solutions (Veerman *et al*, 2023). In all cases,  $\kappa$  is the solution conductivity, with the subscripts having the same meaning.

With knowledge of the potential drop and the applied current, power requirements for the unit can be calculated:

$$P = iA\Delta E$$

The bipolar electrodialysis unit model in SysCAD is presented in FIG 8.



FIG 8 - Electrodialysis unit model in SysCAD.

# MODEL APPLICATION

In this work, a conceptual process was presented which utilised nanofiltration, direct lithium extraction, and bipolar electrodialysis for the production of lithium hydroxide. Use of the model for a specific application would require adjustment of various parameters to match the performance of a real system. Bench, pilot scale, and/or plant data can be incorporated into this model through refinement of adjustable parameters. Some adjustable parameters in the model include:

- Permeability of different ions in the nanofiltration circuit.
- Equilibrium constants for different reactions in the direct lithium extraction circuit.
- Tortuosity and Donnan exclusion factors, and electrical resistance of the anion exchange, cation exchange, and bipolar membranes in the electrodialysis circuit.
- Saturation index factors in the AQSOL and PHREEQC interfaces, allowing for supersaturation/undersaturation kinetic effects.

The list shown above is not comprehensive. There are many input parameters in this model enabling refinement of the model predictions based upon physical properties for specific systems.

# CONCLUSIONS

Sophisticated models have been developed for the evaluation of three major new lithium extraction technologies. These models consider mass transfer as well as chemical equilibrium. Thermodynamic calculations are incorporated using the AQSOL software and the PHREEQC software via the Thermodynamic Calculation Engines Interface in SysCAD.

The use of thermodynamic models for solubility allows for prediction of stream properties as well as scaling propensity. This capability is important for evaluating the feasibility of membrane-based processes, as well as direct lithium extraction.

The model is fundamental in its approach to mass transport and chemical equilibrium. This approach provides a strong theoretical basis from which tuning parameters can be applied to account for membrane properties, kinetics, and other factors.

Use of this model for design would require additional project-specific parameters and physical properties to enable validation of the model predictions against bench, pilot, and/or operational plant data. These parameters could be obtained from vendor specifications, open literature data, test work campaigns, and other sources.

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# Design considerations for the metal dissolution process for production of battery grade metal sulfates

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# ABSTRACT

The demand for battery-grade metal sulfates, which are key materials for lithium-ion battery manufacturing, is continually growing due to the rapid expansion of the EV market. One important pathway to help meet this demand is via a metal dissolution process, which involves the dissolution of nearly pure metals (eg Ni, Co) or alloys containing these critical metals, and subsequent leachate purification. This is a proven and viable approach that offers producers an opportunity to enter the battery market faster compared to producing metal sulfates from primary or intermediate sources. This paper discusses the important process design considerations for each major block flow in the metal dissolution process, including:

- 1. Material handling of raw metal or alloy feed.
- 2. Metal dissolution reactor circuit.
- 3. Neutralisation.
- 4. Purification.
- 5. Metal hydroxide precipitation.
- 6. (Optionally) Crystallisation.

By addressing these design considerations, and de-risking through test work and process modelling, the performance and costs can be optimised, thereby enhancing the competitiveness in the rapidly evolving battery market.

# INTRODUCTION

Global trends in climate change and sustainability continue to push the decarbonisation of transportation via electrification and the shift from fossil fuels to renewable power in the electricity grid. Lithium-ion batteries (LiBs) are arguably the core enabling technology to facilitate this energy transition. Processes that produce battery-grade metal sulfates are highly sought after due to the expansive growth in rechargeable battery production. One pathway to meet the industry demand immediately is via a metal dissolution process, which involves the dissolution of nearly pure metals (eg Ni, Co) or alloys containing these critical metals, and subsequent purification and recovery via hydrometallurgical processing. A simplified block flow diagram of this process is shown in Figure 1.



**FIG 1** – Block flow diagram of a metal dissolution plant.

An extensive test work program was run by Hatch to study the key parameters that drive the nickel dissolution process and its stability including acidity, pH, acid concentration, oxidant concentration, superficial velocity, temperature, and dissolved metal strength. Additionally, test work programs to design the purification and recovery process to ensure battery-grade nickel sulfate specifications are met were completed. The purpose of these test work programs was to assist with the path to commercialisation of the metal dissolution plant by informing the design and scale-up of the unit operations.

# MATERIAL HANDLING OF METAL OR ALLOY FEED

Material handling systems are integral components of commercial plant design and must be designed correctly to ensure stable and safe operations. For metal dissolution plants, considerations must be made for criteria such as plant throughput, size of feed, shape of feed, and ventilation requirements, among others. Plant throughput of a metal dissolution plant determines the quantity and size of material handling units, and the level of automation required. It is possible to have more manual types of material handling equipment such as a forklift paired with a drum lifter for smaller plant throughputs, as refilling the dissolution reactor will not be a very frequent operation. However, for larger throughputs, a manual operation will be more challenging and require more personnel to complete the task.

The size and shape of the metal or alloy feed also impacts the type of material handling equipment that can be used. Standard equipment typically requires the material is less than 5 cm which means custom equipment must be designed for cut cathodes larger in size (ie 10 × 10 cm cathodes). Additionally, the sharp edges of cut cathodes may not be suitable for standard material handling equipment in which case customised equipment would be designed or a manual operation can be considered as noted above.

# METAL DISSOLUTION

In designing a metal dissolution reactor, it is critical to understand the chemistry and the process stability to optimise the kinetics and ensure efficient operation. Nickel dissolution is an oxidative dissolution reaction, where the solid nickel in elemental state converts to an ionic state. Sulfuric acid solution is a common and preferred lixiviant for nickel dissolution as it directly produces the sulfate salt. The nickel dissolution reaction can be completed through an addition of strong oxidant, such as hydrogen peroxide for example, to enhance the reaction kinetics and eliminate hydrogen gas generation as per the following reaction:

$$Ni_{(s)} + H_2SO_{4(aq)} + H_2O_{2(aq)} \rightarrow NiSO_{4(aq)} + 2H_2O_{(l)}$$
(1)

The parameters that drive the nickel dissolution rate and the stability of the above reaction in a packed bed reactor were studied through a test work program completed by Hatch to assist with derisking the process and scaling-up to the commercial operation. These parameters include temperature, hydrogen peroxide concentration, dissolved nickel concentration, superficial velocity, hydrogen peroxide to acid ratio, and pH. It was found that superficial velocity, hydrogen peroxide concentration are the key levers that drive the nickel dissolution rate, while the relative effect of temperature is smaller. This indicates that the overall dissolution rate is largely mass transfer limited.

It is important to note that although higher hydrogen peroxide and lower dissolved nickel concentrations increase the overall dissolution rate and reduce the reactor sizing requirements, the balance of plant must also be considered. A higher residual hydrogen peroxide concentration in the pregnant leach solution (PLS) that goes to downstream for further treatment results in higher losses of hydrogen peroxide reagent and therefore higher operating costs. A lower dissolved nickel concentration will increase the volumetric PLS flow rate (to achieve the same nickel production rate) and hence the size of the unit operations downstream of the dissolution circuit and therefore the capital cost. Additionally, a lower concentration of nickel sulfate in solution will increase the required evaporation rate in the crystallisation circuit and result in an adverse effect on the operating and capital costs if nickel sulfate crystals are being produced. Therefore, it is critical to consider the entire operation of a metal dissolution plant to determine which levers for dissolution can be manipulated without impacting the balance of plant. The dissolution circuit should be operated at a dissolved nickel concentration such that a sufficient dissolution rate is maintained and the nickel concentration to the balance of plant does not pose a risk of saturation or crystallisation at the solution handling temperatures.

Parameters impacting the stability of the dissolution process were also studied as part of the test work program. It was observed that hydrogen peroxide decomposition occurred when the stability criteria was not maintained. Three criteria were found that impact the stability of the process; these include terminal acid concentration and pH, as well as the molar ratio of hydrogen peroxide and sulfuric acid in solution. It is generally recommended that a pH below 1.5–2.0 is maintained at the outlet of the dissolution reactor to eliminate the risk of hydrogen peroxide decomposition. Additionally, operating temperatures below 85°C are recommended as accelerated decomposition is observed for hydrogen peroxide at higher temperatures. The operating range for the metal dissolution reactor for sulfuric acid and hydrogen peroxide concentrations is shown on Figure 2.



FIG 2 – Operating range of metal dissolution reactor for temperatures between 60–85°C.

Enclosure and ventilation requirements also need to be considered for metal or alloy feeds where hydrogen gas generation can occur. The reactors must be designed to allow for sufficient air inflow in the freeboard such that hydrogen gas concentrations are well below the explosive limits

(25 per cent of lower flammability limit for hydrogen gas). This is required as it is difficult to completely isolate the reactors from any air ingress with the material handling equipment.

A dissolution test work program was also previously completed on a Ni/Co/Mn alloy and showed many similar dissolution characteristics as nickel (Gray *et al*, 2023). Therefore, many conclusions captured in this paper may be equally applicable for the dissolution of other metals (eg Co) and multi-component alloys.

# **REFINING AND RECOVERY**

The acidic pregnant leach solution (PLS) leaving dissolution is high in desired product metal, but also contains impurities from the original feed. Most metal feeds have higher levels of impurities than is acceptable in most battery-grade metal sulfate specifications, due to the stringent specifications required. Therefore, the impurities from the PLS must be selectively removed for a battery grade salt to be produced. Purification steps must be developed with consideration of the feed material and identification of the elements of concern. It is possible to first determine the estimated product composition if no purification is performed and compare this composition to the product specification to determine the elements of concern.

For this test work program, LME Grade Ni (ASTM specification B39–79 (2023) – minimum 99.80 per cent purity) was considered for the overall plant feed composition, and the flow sheet was designed to produce battery-grade nickel sulfate. Elements of concern in LME Grade Ni include, among others, Cu, Fe, Mn, and Zn. Removal of these cationic elements is well understood in hydrometallurgical flow sheets, however this test work program aimed to de-risk the challenges presented by the very high Ni concentration (>100 g/L) and low initial impurities concentration with an even lower final target concentration in the product. Additionally, the small projected product premium over the feed material cost ensures that operating costs and nickel losses throughout the process must be minimised.

Purification of the nickel sulfate solution is done in three main steps:

- 1. Neutralisation.
- 2. Purification.
- 3. Crystallisation.

#### **Neutralisation**

Neutralisation serves multiple purposes. First, the liquor leaving dissolution is acidic (pH of 1.5–2.0). If this acidic solution was directly fed to the Crystallisation circuit, where water is evaporated, acid concentration would further increase and result in a highly acidic solution which would necessitate expensive materials of construction. Therefore, it is desirable to increase pH before crystallisation. Raising pH is beneficial for ion exchange (IX) as well, as the operating conditions for many applicable IX resins to selectively remove impurities from Ni are less acidic than the dissolution liquor. Furthermore, raising the pH also serves to precipitate some of the impurities as hydroxides, and this reduces the load on the IX circuit.

Neutralisation methods can include the use of a common basic reagent such as NaOH, produced basic metal salts such as nickel hydroxide or basic nickel carbonate, or nickel powder. The use of NaOH for neutralisation is advantageous as it is widely available. However, neutralisation using NaOH introduces a significant amount of Na directly to the PLS as an impurity. Using precipitated basic metal salts such as Ni(OH)<sub>2</sub> to perform the neutralisation step prevents this contamination of the PLS and also slightly raises the Ni concentration. In this method, the bleed from crystallisation is recovered using a patented process (Fraser *et al*, 2021) in which nickel precipitates as a basic compound (eg Ni(OH)<sub>2</sub> precipitated by NaOH addition). Effective washing of the Ni(OH)<sub>2</sub> becomes critical to remove the Na contained in the entrained liquor and prevent it from entering the main process stream.

The use of nickel powder as a neutralising agent can be beneficial as:

• reagent consumption is reduced

- high concentrations of new impurities are not added to the process
- high quantities of waste products such as Na<sub>2</sub>SO<sub>4</sub> are not produced
- residual hydrogen peroxide from dissolution is consumed
- additional nickel sulfate is produced.

However, it requires the addition of nickel powder handling equipment. Furthermore, as the hydrogen peroxide is consumed, hydrogen gas may be generated as per the reaction shown below. Therefore, correctly sized ventilation systems must be in place to ensure safe operation and any hydrogen gas produced remains below the explosive limits.

$$Ni_{(s)} + H_2SO_{4(aq)} \rightarrow NiSO_{4(aq)} + H_{2(g)}$$
(2)

# Purification

Ion exchange is known to be an effective method for removing the majority of divalent and trivalent cationic elements down to very low concentrations. This is necessary for producing a clean feed to the crystallisation circuit to produce a high-quality product with minimal bleed. However, IX has multiple drawbacks in addition to the capital cost. First, for each mole of impurity loaded, at least one mole of acid and one mole of base must be spent to strip and then regenerate the resin. The use of a base to maintain pH during loading of the IX columns also results in addition of an impurity to the system, such as Na from the base NaOH. Finally, while IX conditions can be chosen to selectively remove impurities from the nickel rich liquor, there will always be co-loading of nickel with the impurities. This co-loading is a source of nickel loss for the process. Therefore, it is beneficial to reduce the load on IX, where possible, by first removing higher concentration impurities upstream by precipitation.

# Crystallisation

Crystallisation involves evaporation of water to increase the concentration of nickel sulfate in solution beyond the solubility limit, causing it to crystallise. Further evaporation drives further crystallisation of nickel, while the impurities (ideally) remain in solution. While crystallisation is a recovery step, it can also serve as a purification step when correctly designed. As nickel is crystallised, it remains approximately at the solubility limit in solution while the impurity concentrations in solution continue to rise. For this reason, a bleed must be taken from the crystalliser to limit the build-up of impurities. While increasing the bleed rate is one solution to limiting impurity concentrations, this can also result in greater nickel loss and increase operating costs.

It can be advantageous if crystallisation is eliminated by directly feeding the purified nickel sulfate solution to precursor cathode active materials (pCAM). This is because the pCAM producer typically redissolves the nickel sulfate hexahydrate salt at the front end of their flow sheet. The metal dissolution plant would need to be in close proximately to pCAM producers for this option to be feasible. This allows simplification of the overall process, reduces operating and capital cost, and footprint of a metal dissolution plant. The drawback, however, is that the crystallisation step can act as a purification step for the nickel sulfate and removal of crystallisation may increase the concentration of some impurities reporting to pCAM production. If further purification of the PLS is not necessary for the pCAM producer to accept it, then significant capital and operating expenses can be saved by elimination of the crystallisation step.

# Experimental work

As with many hydrometallurgical flow sheets, each of the above process steps are heavily influenced by the operation of the other steps due to the effect of recirculation. Test work was conducted on each step to select the desired conditions.

Test work for neutralisation and impurity removal focused on the selection of the optimum terminal pH to maximise removal of impurities while minimising nickel loss and residence time. While iron is effectively removed at most pH levels considered, Cu removal increases significantly as pH 5 is approached or exceeded. As expected, impurities such as Ca, which typically precipitate at higher pH than nickel, are not removed as shown in Figure 3.



FIG 3 – Final concentration of Fe, Cu, and Ca at varied final pH.

While selection of a pH greater than 5 is desirable for reducing the Cu concentration before IX, the maximum pH achievable is ultimately limited by the solubility of nickel. This is due to both the desire to limit nickel precipitation from solution, but also a result of the use of nickel hydroxide as the base reagent. It was found during the test work that the rate of the nickel hydroxide dissolution and resulting pH increase of the solution is reduced significantly as pH 5 is approached and exceeded. This can be seen in Figure 4, which shows pH versus time for one of the tests where the target final pH was greater than 5. For the test shown in Figure 4, additional base was added after ~40 mins. The impact of this addition on the rate curve is unclear since the initial base addition was already in excess of the acid neutralisation requirement so the additional base simply increased the excess. At the end of this test there was significant nickel residue recovered by filtration in a Buchner funnel. Therefore, increasing Cu removal, by targeting a pH of 5+, is associated with longer residence time and increased nickel loss.



FIG 4 – Plot of pH versus time for one test where the target final pH was >5.

A test work program for ion exchange was developed to compare different IX resins to select the preferred resin and pH for selective removal of the target elements, with minimised co-loading of nickel. This involves performing an equilibrium rate test and an equilibrium capacity test to generate adsorption isotherms for each impurity. The IX test plan follows the methodology described by DuPont (2019). This experimental work is still ongoing and is not presented in this paper.

For crystallisation tests, a synthetic feed was generated based on simulation results to represent a conservative estimated feed composition. As part of the test program for crystallisation, a small 1 L batch evaporative crystalliser equipped with a Metller Tolado EasyMax probe was used to produce nickel sulfate hexahydrate as the final product. The crystallisation was conducted at 50°C, under vacuum, and the evaporation rate was set to produce the target size crystals similar to industrial scale productions. The final crystals were harvested, dried, and characterised using X-ray diffraction

(XRD) and inductively coupled plasma – optical emission spectroscopy (ICP-OES) for their final composition. The final crystals met typical battery grade specifications for almost all elements and indicated which elements must be further removed upstream by ion exchange (eg Cu) for battery grade specification to be met. This provides a performance target for the ion exchange test work and crystallisation of the IX treated solution can be performed once available.

Test work for nickel hydroxide precipitation with NaOH addressed the selection of the optimum terminal pH as well as conditions such as pH steps, residence time per step, feed nickel and NaOH concentration, and seed ratio to help develop good quality crystals that can be washed effectively. Precipitation of Ni(OH)<sub>2</sub> using 50 per cent NaOH in a single step, with no seed, resulted in a very thick slurry that was difficult to pump and had very ineffective washing of the filter cake. Alternatively, precipitation of Ni(OH)<sub>2</sub> following a similar methodology as described by Sist (2004) resulted in a much higher quality cake with effective washing of Na.

One additional challenge encountered throughout this work was that the typical limits of detection for some elements of interest were comparable to or exceeded the target final concentrations in some steps, due to the stringent specifications for battery-grade metal sulfates. This made it challenging to confirm that the targets had been met and difficult to compare the results of different test runs. This is primarily due to the high concentration of nickel which can interfere with detection of the low concentration impurities. Significant effort was required to optimise the ICP-OES procedures to produce accurate, usable results. Continued further advancement of procedures for determining trace impurity concentrations in high concentration Ni solutions is likely required to improve understanding of this space.

# PROCESS MODELLING AND TEST WORK

Process modelling simulation tools are widely used in plant design to complete mass and energy balances and run various case studies to evaluate the effect of changing multiple parameters. Initial inputs to the process models can be derived from literature, know-how, or test work for similar feeds and impurities prior to running test work programs for the exact feed and impurities. The outputs from the model can inform the test work program of the inputs and generation of synthetic solutions, if required. Using synthetic solutions for the various process steps allows for the parallel testing of the steps which can reduce schedule time. Alternatively, a staged approach can be used where test work is completed on one process step and the results are analysed and inputted into the process model to inform the test work program of the inputs to the subsequent stage. This approach can result in a longer schedule, but it can result in a lower cost for the test work program as repeat tests may not be required.

# SCALE-UP CONSIDERATIONS

Factors to consider for scale-up are the individual technology challenges and risks associated with new processes, components, process integrations or combinations of these. Test work is a key component of de-risking and scaling up new technologies as indicated by the sections above. Findings from Gordon and Kumar (2014) show that each technology is unique with respect to its scale-up challenges. Their review of new technology scale-ups for packed bed processes in the iron and steel industry show that different technologies, processes, and pieces of equipment all have different critical scale-up parameters and recommended scale-up factors. For instance, cylindrical furnaces have different critical parameters than rectangular or angular furnaces. As such, to ensure optimal performance, it is essential to identify the critical scale-up parameter(s) of the processes and equipment when scaling up a technology.

In the roadmap to commercialisation, Technology Readiness Level (TRL) is a scale often used to represent the overall level of development of a technology. TRLs are assigned based on a scale of 1 (lowest level, basic principles reported) to 9 (commercially implemented). Some broad definitions of each TRL can be found in Table 1.

#### TABLE 1

Example of TRL scale and general definitions (US Department of Energy, 2015).

TRL	Definition
1	Basic principles reported
2	Technology concept and/or application formulated
3	Experimental and analytical critical function and/or characteristic proof of concept
4	Component or proof-of-concept validation in laboratory environment
5	Component or pilot validation in relevant environment
6	Engineering/pilot scale similar (prototypical) system validation in relevant environment
7	Full-scale, similar (prototypical) system demonstrated in relevant environment
8	Actual system completed and qualified through test and demonstration
9	Actual system operated over the full range of expected conditions

While an overall measure is too broad to be helpful in creating a commercialisation path, this scale can be applied to various sub-systems or elements of the technology to assess the current level and the level that could be attained through various validation methods such as bench scale, pilot plants, and demonstration plants. It is recommended that a TRL is provided for each subsystem using the weakest link methodology; the minimum TRL of the topics within that subsystem dictates its overall TRL. It should be noted that not all elements evaluated need to be fully demonstrated as contingencies (additional equipment or design margins) can address the technical risk in certain cases. There are however elements of high importance that represent the highest risk which need to be demonstrated in an integrated way at a scale that's indicative of the intended commercial operation.

A guideline for scale-up is the size of the unit operation increases by a factor of 10 for each level of demonstration (bench scale  $\rightarrow$  pilot plant  $\rightarrow$  demonstration plant  $\rightarrow$  commercial operation). Examples of scale-up factors for various hydrometallurgical operations are provided in Table 2. As noted above, this serves only as a guideline, and each unit operation will have a unique scale-up factor.

Type of Facility	Name/Operation	Commercial Scale-up Factor
Large plant-scale test facility	Codelco BioCop demo plant	Single line 1:1
Large integrated pilot	LionOre Activox NiCu leach/refinery	170:1
plant or demonstration plant	Inco VBN Ni refinery modules to site	100:1
	QIT UGS HCI leach reactor	65:1
	CVRD UHC Chalco high pressure acid leach	25:1
Small integrated pilot	BHP Gag Island Laterite Ni high pressure acid leach	>1000:1
plant	WMT Activox P/P	>3000:1
Bench scale lab work	BHP San Felipe Laterite Ni high pressure acid leach	>1000:1
	WMC Pinares Laterite Ni high pressure acid leach	>1000:1
	BHP Ravensthorpe Ni high pressure acid leach	>1000:1

#### TABLE 2

Examples of Scale-up Factors for Hydrometallurgical Operations.

In addition to scale-up factors, the experimental equipment must be designed using the correct sizing requirements. Some equipment require that the correct aspect ratios are maintained in the experimental set-up. For example, for ion exchange columns it is recommended to maintain a resin bed height to diameter ratio of 4:1 to 10:1 for any experimental set-up to allow for correct scale-up to the commercial operation.

#### CONCLUSIONS

This paper summarised the engineering work that was completed to de-risk and scale-up metal dissolution plants. These steps included designing and implementing test work programs for metal dissolution, neutralisation, purification, and crystallisation for overall flow sheet development. Additionally, scale-up considerations were provided to ensure successful implementation to a commercial operation.

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# Graphite - the sleeping giant

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# ABSTRACT

Graphite is recognised globally as a critical mineral as a result of its unique position in the battery anode market and the risk to the global graphite supply chain. China dominates supply, producing 98 per cent of the world's refined graphite for the lithium-ion battery market. On December 1st 2023, China implemented export permits for graphite production, effectively controlling the global supply chain and limiting graphite availability to the rest of the world.

Graphinex is a graphite Battery Anode Material (BAM) manufacturer whose strategy is to disrupt China's dominance by becoming a fully integrated global supplier in Queensland, from mine to market. We are focused on developing our world-class Esmeralda graphite deposit in North Queensland and constructing and operating Australia's first full-scale graphite refinery in Townsville, further enhancing Townsville's reputation as a Critical Minerals Hub.

Graphinex completed a Scoping Study in November 2023 with the aim of producing BAM from the Esmeralda orebody. Purified Spheronised Graphite (PSG) was produced at a purity of 99.97 per cent graphite that met physical and chemical specifications for battery manufacturers.

The PSG was then sent to the University of Queensland (UQ) to coat with High Purity Alumina (HPA) from Vecco Group and conduct battery testing. Twenty lithium-ion coin cells were made with the Esmeralda graphite as the anode. All exceeded charge/discharge specifications, reaching theoretical values at the first attempt. After six months of cycling, the batteries have shown little degradation.

This paper will give a brief overview of the role of graphite as a battery anode and a summary of the global graphite market. It will then focus on the steps that Graphinex has underway to develop the Esmeralda graphite deposit and also the Townsville Battery Anode Refinery. It will present the results of the Scoping Study and battery performance test work at UQ.

# INTRODUCTION

Graphite has a major role to play in the global energy transition. It is used extensively to make anodes, the negatively charged electrodes in various battery systems, most notably lithium-ion batteries (see Figure 1).





Graphite's layered structure, composed of hexagonally arranged carbon atoms, offers spaces, or intercalation sites, to accommodate and store lithium ions during the charging process. This intercalation mechanism contributes to the battery's energy storage capacity. Graphite's excellent conductivity also facilitates the efficient flow of electrons in the battery circuit, which is crucial for the power output. Its stability and resilience under repeated cycles of charge and discharge ensure a good lifespan for the battery.

Most attention has been placed on cathode chemistry to tailor the battery's performance, aiming for improved capacity or volumetric capacity, cost or stability depending on the battery application. Yet, for the anode, there has been comparatively less attention due to the dominance of natural or synthetic graphite in this space.

Some 98 per cent of anode materials in lithium-ion batteries are based on graphite chemistry due to the low cost, abundance, high energy density and long cycle life achievable with graphite anodes. Many other anode candidates have been postulated, including silicon, silicon-graphite, lithium metal, and other metallic sulfides and oxides, but all have their drawbacks and cannot yet match the overall performance of graphite (Zhang *et al*, 2020). Another commercially viable substitute for graphite is unlikely to eventuate in the next 10–15 years, given the stringent qualification of materials required by battery manufacturers.

The two sources of graphite production are from mined natural graphite and from manufactured synthetic graphite. Synthetic graphite is derived from the high-temperature treatment of petrochemical coke. It has poor environmental credentials and has a questionable role in the push for decarbonisation. This paper will focus solely on the production of natural graphite.

# The market for graphite

Graphite is recognised globally as a critical mineral. Governments have realised that graphite is an essential component for technologies such as electric vehicles, computers, smartphones etc and that the implications for scarcity of supply could disrupt economies and national security.

Traditionally, graphite has not commanded the same publicity as critical minerals peers like lithium, vanadium and cobalt, but it is graphite's importance in battery production and electrification that is set to drive global demand. This is why graphite is the sleeping giant – of all the components in a lithium-ion battery, the biggest volume is graphite, which makes up 95 per cent of the battery anode. It can take 50–100 kg of graphite to make a single battery – up to ten times more graphite than lithium.

#### Supply side

The risk for the global graphite supply chain is that China is the dominant producer. In 2024, China has produced 72 per cent of the world's natural graphite and 98 per cent of the spherical graphite required for battery anodes (Benchmark Mineral Intelligence, 2024). As the leading exporter of graphite, China has considerable influence over setting global graphite prices. On December 1st 2023, China implemented an export permit system on graphite, limiting the availability of graphite battery anode material outside of China, in turn disrupting the global supply chain.

Although China dominates supply, it holds just 15.8 per cent of global reserves, sourcing much of its feedstock from Africa. Australia has significant reserves of graphite in Queensland, South and Western Australia, suggesting huge potential for supply diversification.

#### Demand side

Analysts forecast that demand for graphite will be strong, driven by rapid growth in global battery production, particularly in electric vehicle uptake, which is estimated to grow from 8.8 M vehicles sold in 2020 to 60.5 M vehicle sales in 2030 (Macquarie Research, 2023). Given the rapid rise in demand, coupled with Chinese supply constraints, the market is expected to absorb the current graphite supply surplus and quickly move into deficit next year. By 2030, it is forecast that graphite supply will be 1 Mt in deficit and as much as 8 Mt in deficit by 2040 (see Figure 2, Macquarie Research, 2023).



FIG 2 – Market deficit forecast beginning in 2025 (Macquarie Research, 2023).

The demand for graphite is set to eclipse that of lithium, cobalt and nickel, with the projected number of new mines and tonnages by 2035 shown on the following page (see Figure 3, Benchmark Mineral Intelligence, 2024).



**FIG 3** – Critical minerals deficit from 2022 to 2035 (source: Benchmark Mineral Intelligence, Sept 2022).

# Pricing

With a deficit in supply looming in 2025, the price of natural graphite is expected to rise next year. In the medium to longer term, despite the larger deficit, it is unlikely that graphite prices will skyrocket. New producers around the world will come into production and fill some of the void. There is also likely to be greater competition from synthetic graphite, notwithstanding the poor ESG credentials of its high-temperature manufacture from petroleum pitch (Benchmark Mineral Intelligence, 2024).

# **GRAPHINEX – AUSTRALIA'S NEXT BATTERY ANODE MATERIAL SUPPLIER**

Graphinex is on track to be one of Australia's first mine-to-market graphite producers and a new supplier of Battery Anode Material (BAM) to global battery manufacturers. Graphinex has nine graphite tenements in Queensland, Australia. Our portfolio includes the flagship Esmeralda project, located near Croydon, which has an Inferred Resource of 34 Mt @ 7.2 per cent graphite for a contained graphite resource of 2.45 Mt, making it Queensland's largest graphite deposit. An extensive drilling campaign began in June 2024 to further increase and likely upgrade this resource to become one of Australia's largest and one of the world's most significant graphite deposits.

Unlike most of the world's other graphite deposits, which are sedimentary in nature, the Esmeralda deposit is volcanic, with graphite hosted within altered granite as veins or blebs. This unique geology offers several advantages over traditional sedimentary graphite:

- The volcanic nature of Esmeralda means that high temperatures on formation burnt off the organic volatiles (coal, oil/shales etc), with very low levels of 0.15–0.2 per cent present. Typically, graphite contains 0.5–1.0 per cent organic volatile compounds. These compounds add to operating expenses by consuming reagents and need to be removed from the BAM.
- The graphite is fine-grained. Sedimentary graphite is usually coarse-flaked, but for battery applications, the finer the graphite particle, the better. Esmeralda ore contains graphite with a mean particle size,  $d_{50}$  of 25 µm.
- The deposit will be well-suited to hard rock mining, with an open pit operation planned.

# Scoping study – processing and refining

Graphinex began a Scoping Study in January 2023, with 340 kg of Esmeralda drill core shipped to the specialist German metallurgical laboratory, Pro-Graphite. This core was metallurgically tested, and in November 2023, Purified Spheronised Graphite (PSG) was produced from the Esmeralda orebody at a purity of 99.97 per cent graphite that met physical and chemical specifications for battery manufacturers. From this work, the processing and refining flow sheets were developed and optimised.

#### Processing plant – Croydon region

The concentrator has been designed to upgrade 7 per cent graphitic ROM feed to 95 per cent graphite concentrate. It consists of the following unit operations:

- Comminution circuit:
  - $_{\odot}$  Two-stage crush to reduce the top size of the ore to minus 5 mm.
  - o Primary and secondary milling to generate a particle size of 300–600 μm for flotation.
- Flotation circuit:
  - Initial stages of flotation roughing and scavenging provide a significant upgrade to flotation feed. Any graphite not recovered in these stages will be reporting to the final tails.
  - Rougher and scavenger concentrates report to the cleaning circuit. These are multiple stages of flotation and regrind to liberate and remove gangue minerals and further upgrade the graphite to a saleable final concentrate.
- Dewatering:

- The concentrate is filtered, dried, sized and bagged in preparation for transport to Townsville for refining.
- Tailings:
  - Options being considered are thickened tailings sent to a conventional Tailings Storage Facility or a dry-stacking operation.

#### Demonstration plant/refinery – Townsville

The first step to building a refinery will be to build a Demonstration Plant. This will be used to validate the refining process and to prove technical and commercial viability. The Demonstration Plant will be a 300 t/a operation designed to upgrade the 95 per cent graphite concentrate to 99.95 per cent BAM and to produce a sufficient quantity of BAM for marketing to off-takers for qualification or to conduct in-house battery test work. Graphinex has recently secured a site in Townsville for this plant and will begin construction in Q4 2024.

The Demonstration Plant will be a stepping stone to building a larger 30 kt/a PSG refinery later this decade. Depending on the reserve identified at Esmeralda in the coming drill campaigns, an expansion case to build a 100 kt/a PSG refinery will also be considered.

The Demonstration Plant and Refinery both integrate the following unit processes:

- Micronising further milling to reduce the particle size to  $14-16 \mu m$ .
- Spheronising shaping of the micronised particle into a sphere.
- Purification the removal of impurities such as iron, silica, aluminium and calcium by alkaline roasting followed by a sulfuric acid leach. This provides the final upgrade to produce a marketable PSG.
- Coating to improve the electrochemical properties of the graphite anode.

For the first few charge and discharge cycles, when the electrolyte contacts the anode, reactions occur in the electrolyte, forming decomposition products. In lithium-ion batteries, compounds such as LiF, Li<sub>2</sub>O, LiCl and Li<sub>2</sub>CO<sub>3</sub> are formed in a few nanometre-thick layers called the Solid Electrolyte Interface (SEI). The SEI layer is important because it protects the anode from further decomposition and also prevents the consumption of the electrolyte. An effective SEI layer provides long life, good cycling ability, high performance, and safety and stability for a battery.

Coating graphite with High Purity Alumina (HPA) in atomic layers offers control and stability of SEI growth due to the slow electron transfer rate. HPA-coated graphite offers the following advantages over raw graphite:

- The coating blocks direct contact of electrons with electrolyte, preventing electrolyte degradation.
- HPA is conductive, allowing ions from the electrolyte to flow to the anode and back again.
- It is chemically stable and does not react with the electrolyte.
- It is mechanically stable and can withstand stresses of expansion and contraction during charging and discharging cycles.
- It can maintain stability across various operating temperatures.

Graphinex is partnered with the Vecco Group to supply HPA for the coating stage.

#### Battery manufacturer's specifications

It is difficult to obtain battery specifications – the physical and chemical properties of the graphite – from manufacturers, as this is fundamental to the performance of the battery and is generally proprietary knowledge. The uncoated PSG should broadly conform to the specifications in Table 1. Esmeralda graphite specifications have also been tabled for comparison.

Parameter	Units	Battery spec value	Esmeralda value
d <sub>50</sub>	μm	14–16	14–15
d <sub>10</sub>	μm	10–12	10–11
d <sub>90</sub>	μm	23–25	23–24
d <sub>90</sub> /d <sub>10</sub> ratio		2.1–2.9	2.5
Tap density	g/mL	≥0.9	0.9
BET surface area	m²/g	≤6.0	6.0
Purity	Total graphitic content (%)	99.95	>99.97
Fe	ppm	<30	11.4
Si	ppm	<40	6.5
AI	ppm	<15	2.9
Са	ppm	<20	12.5
Cr	ppm	<15	0.1
Cu	ppm	<30	0.3
Ni	ppm	<30	2.0
Zn	ppm	<30	0.1

TABLE 1

Typical physical and chemical specifications for PSG (source: Wave International, 2023).

### Battery test work with Esmeralda graphite anodes

In November 2023, Graphinex entered into a research agreement with UQ to conduct battery test work. Twenty lithium-ion coin cells were prepared using Esmeralda graphite as the battery anode. Four cells were prepared as a baseline with raw PSG, while the remaining 16 were prepared with HPA-coating of varying thickness, four cells each of 0.5 wt per cent, 1.0 wt per cent, 1.5 wt per cent and 2.0 wt per cent. Scanning electron microscope (SEM) images are shown in Figures 4 and 5.



**FIG 4** – SEM images of Esmeralda Uncoated Purified Spherical Graphite with particle size shown in the second image (resolution is ×500 left, ×1000 middle, ×2000 right).



**FIG 5** – SEM images of Esmeralda PSG (resolution left to right, ×5000, ×10 000, ×20 000, ×50 000).

Results to date have been outstanding. The specification for the specific capacity of a lithium-ion battery, or the amount of charge that can be stored, is typically 330 mAh/g. The industry standard is 355 mAh/g, with a theoretical value of 372 mAh/g achievable. Two of the coin cells, coated with 1.0 wt per cent of HPA, have reached above theoretical capacity, 399.2 and 381.5 mAh/g.

These batteries have now been cycling for six months and show little sign of degradation, pointing to a long-life battery that shows a good stability and safety profile (see Figure 6).



**FIG 6** – (a) Charge/discharge curves of 1 wt per cent HPA-coated graphite, (b) long-term cycling performance profile.

# **CONCLUSIONS AND NEXT STEPS**

Metallurgical test work has proven that Esmeralda graphite can be processed and refined to produce high-quality BAM, with battery test work at UQ showing high-performing battery anodes.

The next steps for Graphinex will be:

- Complete the current drilling campaign to define and upgrade the Esmeralda graphite resource and to provide bulk samples for further metallurgical test work.
- Complete a Pre-Feasibility Study in Q4 2024 considering geology, mining and processing components at the Esmeralda site.
- Begin planning and designing the Demonstration Plant, which is due to operate in 2025.
- Continue battery test work at UQ to optimise coating and anode composition to create the nextgeneration anode. This will include the industry-standard pitch coating, polydopamine and other potential coatings.

# ACKNOWLEDGEMENTS

The author acknowledges Graphinex for allowing them to publish this paper, particularly the Managing Director, Art Malone, who has been the visionary behind Graphinex's successes to date.

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# The MTM sulfation roast process for critical metals

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# ABSTRACT

MINETOMETAL is developing technology for recovering critical metals from complex sulfide concentrates and recycled materials. The technology is based on sulfation roasting followed by selective alkaline leaching and precipitation. The current work is primarily aimed at copper concentrates which have unacceptable levels of problem impurities such as arsenic and radionuclides.

Arsenic is present in many copper orebodies and is a large and growing problem in copper production. The amount present far exceeds the arsenic demand, so copper producers have an issue of how to recover the copper and fix the arsenic in an inert form for disposal. In addition, countries such as China and Japan now limit the arsenic concentration in copper and other concentrates being imported and the limit set is likely to decrease further in the future. Very few custom smelters will now accept high arsenic in concentrates which is a serious problem for miners without an integrated smelter.

MINETOMETAL is developing a new process based on sulfation roasting with lime additions to recover the copper from high arsenic concentrates and fix the arsenic as inert ferric arsenate suitable for disposal. The lime roasting reacts the sulfur present to sulfates and gives strongly oxidising roasting conditions where the arsenic forms cupric arsenate and is not volatilised. This avoids the environmental issue of gaseous arsenic oxides and the need for an acid plant and an outlet for sulfuric acid.

The calcine from the roaster is leached in ammonia/ammonium chloride liquor to dissolve most of the copper which is then precipitated out to give cupric oxide suitable for gaseous reduction to metal. The insoluble cupric arsenate in the residue is leached in dilute sulfuric acid to recover the remainder of the copper and enable precipitation of an inert ferric arsenate.

The behaviour of other metals is also being investigated. Uranium has been found to remain in the residue as do related metals such as lead. Metals that are known to form sulfates under sulfation roasting conditions such as cobalt, nickel and rare earths can potentially be recovered from the calcine using selective leaching and precipitation. A similar approach can be used for the recovery of metals from recycling of complex materials such as lithium – ion batteries and manufacturing scrap.

Conceptual flow sheets have been developed for a wide range of metals and potential feedstocks. These are based on known chemistry, but most have not yet been tested experimentally.

# INTRODUCTION

The current processes for the critical metals tend to focus on the feed materials rich in individual metals rather than treating complex mixtures. Despite many years of work the industry still struggles with processing complex feed materials containing problem impurities even for major metals such as copper.

The current dominant process for copper metal is through mining sulfide ores and producing a copper concentrate via comminution and flotation. The concentrates are smelted at high temperatures to make an impure blister copper. This is then electro refined to give high purity metal and to recover other valuable components especially gold and silver. The sulfur is converted to sulfuric acid for sale or use in heap leaching.

Copper smelting is mature technology and highly efficient for large tonnages of clean high-grade concentrates. It is less well suited to complex materials and those with problem impurities such as arsenic and radionuclides. This is a serious problem for miners without access to an integrated

smelter where the impurities can add penalties, and even prevent sale, of the concentrates. Several countries now have import limits on arsenic content. The miners seldom receive any payment for metals other than copper and gold.

There have been many attempts over the last 50 years to find an efficient, low-cost hydrometallurgical process as an alternative to large smelters with their high CAPEX. There has been some success for chalcocite concentrates with two medium scale plants being built but there have only been small tonnage demonstration plants for chalcopyrite concentrates. The processes developed have mainly focused on using an oxidative acidic leach to dissolve the copper followed by solvent extraction and electrowinning.

There have also been attempts to use ammonia leaching but these also needed the high-cost solvent extraction – electrowinning steps and had issues with ammonia recovery and managing sulfate buildup in the system. Neither the acid nor ammonia processes have been able to compete economically with existing smelters.

# **DEVELOPING THE MTM SULFATION ROAST PROCESS**

# Background

The basis for the current development work is the MTM Copper Process (Shaw, 2022a, 2022b) which has been extended to target more complex materials. In that process lime roasting is used to fix the sulfur in a calcine as a mix of copper oxide and copper sulfate which can then be selectively leached with ammonia-ammonium chloride liquor. The copper is then precipitated as copper oxide/copper hydroxide by ammonia stripping and cooling.

The process economics are reasonable, and early studies suggest better than acid-based processes which include solvent extraction – electrowinning, but the CAPEX required means the process is unlikely to be competitive with current TC/RC charges from smelting. MINETOMETAL has therefore focused on expanding the technology to apply it to materials that are not well suited to smelting.

# Chemistry

The key to the process is using low temperature, atmosphere-controlled, roasting of sulfide containing feed materials to convert all the target metals into leachable compounds. A second important feature is predominantly using neutral and/or alkaline leaching to recover the metals. The important reactions are given below:

- Copper Sulfides
   Copper Sulfate Copper Oxide
- Copper Arsenic Sulfides 
   Copper Arsenate
- Iron Sulfides
   Iron Oxide (Hematite)
- Cobalt Sulfide
   Cobalt Sulfate
- Molybdenum Sulfide 
   Molybdenum Trioxide
- Nickel Sulfide
   Mickel Sulfate
- Rare Earth Minerals
   Sulfates with limited oxide
- Lithium Carbonate/Metal 
   Lithium Sulfate
- Manganese Oxide/Metal 
   Manganese Sulfate
- Calcium Oxide
   Calcium Sulfate

The other important chemistry underpinning the process is the differential solubility of the sulfates and oxides with varying pH and the solubility behaviour of copper in ammonia – ammonium chloride. Figure 1 shows the solubilities of many of the metals of interest in the pH range from strongly acidic (pH=0) through to moderately alkaline (pH=10). Molybdenum and Lithium are not included as they are both highly soluble in concentrated caustic soda.



FIG 1 – Metal ion solubility versus pH at 25°C.

Figure 2 shows the behaviour of copper in ammonia – ammonium chloride liquor which is the basis of the MTM Copper Process. Leaching in high ammonia liquor ( $\sim$ 3 M NH<sub>3</sub>) at  $\sim$ 60°C then stripping off part of the ammonia and cooling the liquor enables the copper to be recovered as pure copper oxide and/or copper hydroxy chloride. Copper hydroxy chloride can be hydrolysed to copper oxide using ammonium hydroxide. The copper oxide is readily reduced in hydrogen and/or SYNGAS at >200°C or can be blended with concentrate and sold.



FIG 2 – Copper ion solubility versus NH<sub>3</sub> g/L.

#### Copper arsenic ore

Much of the current development work is aimed at concentrates with elevated arsenic levels. Arsenic is a major problem in the copper industry as it typically reports in the ore as enargite ( $Cu_3AsS_4$ ) or tennantite ( $Cu_{12}As_4S_{13}$ ) which are difficult to separate from minerals such as chalcopyrite ( $CuFeS_2$ ) and bornite ( $Cu_5FeS_4$ ). Selective flotation can give low and high arsenic concentrates but processing the high arsenic concentrate is difficult. There are a range of approaches (Yamazaki, 2018) but none are ideal for miners without an integrated smelter.

The MTM Process uses lime roasting of the concentrate in air at around 600°C to oxidise the sulfides and control the arsenic behaviour. Figure 3 shows the behaviour of sulfur and arsenic when roasting

an enargite and pyrite rich concentrate containing 9 per cent As, 25 per cent Cu and 38 per cent S. Calcium is very efficient at preventing the arsenic volatilising while minimising the loss of sulfur consistent with the work of Bartlett and Huang (1973).



FIG 3 – Sulfur and Arsenic volatilisation versus Ca/S Molar ratio.

Table 1 shows the behaviour of the individual minerals during lime roasting of the concentrates based on XRD and nodal analyses. The XRD shows copper present as copper oxy sulfate and copper sulfate and the iron is all hematite. The Enargite calcine XRD traces showed no arsenic phases and lower levels of copper minerals than expected. This confirms the arsenic mainly forms copper arsenate consistent with published work (Chambers, 2012).

	Chalcopyrite/Bornite		Enargi	te
Mineral	Concentrate	Calcine	Concentrate	Calcine
CuFeS <sub>2</sub> (%)	33.5	-	-	-
Cu₅FeS₄ (%)	31.1	-	-	-
FeS <sub>2</sub> (%)	10.5	-	40	-
CuS (%)	3.4	-	-	
$Fe_2O_3(\%)$	16.8	27.2	-	13
CaSO <sub>4</sub> (%)	-	38.8	-	48
$Cu_3AsS_4(\%)$	-	-	52	-
Cu <sub>3</sub> (AsO <sub>4</sub> ) <sub>2</sub>				15
CuSO <sub>4</sub> (%)	-	18	-	4
CuO.CuSO <sub>4</sub> (%)	-	9	-	14

 TABLE 1

 Copper. Iron and Arsenic minerals in concentrate and calcine.

The MTM Copper Process uses ammonia – ammonium chloride leaching to dissolve the copper present as sulfates and oxides and then recover the copper by precipitation from the liquor. This avoids iron dissolution which was a problem in much of the early roast – leach – electrowinning work and the need for solvent extraction. An arsenic treatment step has been added to give a full process flow sheet as shown in Figure 4.



**FIG 4** – Flow sheet for high arsenic copper concentrate.

The arsenate phases present in the calcine do not leach in the ammonia – ammonium chloride so extra processing is required to recover the copper and fix the arsenic into an inert iron arsenate for disposal, as shown in Figure 4. The copper arsenate readily leaches in dilute sulfuric acid leaving an arsenic and copper free residue suitable for further processing to recover gold and silver if they are present. Table 2 shows results for multistage leaching of the calcine. These results confirm that the copper in the calcine is a mix of water-soluble copper sulfate (~25 per cent), ammonia – ammonium chloride soluble copper oxide (~34 per cent) and acid soluble copper arsenate (~40 per cent).

<b>TABLE 2</b> Cumulative metal extraction in leach liquors.				iors.	
Metal	H₂O	NH₃/NH₄CI	H₂SO₄ 2%	H <sub>2</sub> SO <sub>4</sub> 5%	-
Copper (%)	25	59	94	99	
Arsenic (%)	0.5	2.7	96	99	
Iron (%)	0	0	17	34	

The work on producing an inert iron arsenate for disposal is ongoing but published work by Demopulos (2005) and others has shown arsenic can be precipitated from this liquor as iron arsenate by raising the pH to around 2 with lime. This iron arsenate precipitate is returned to the roaster to improve the crystallinity and hence stability.

There are several options for recovering the copper from the acid solution ranging from conventional solvent extraction – electrowinning through to precipitation as sulfide or hydroxide. The preferred low CAPEX option is using lime to precipitate the copper in a mixed gypsum – copper hydroxide solid which can then be recycled within the process most probably to the roaster in a mix with the iron arsenate.

A conceptual engineering design has been developed based on this flow sheet and been used to estimate current CAPEX and OPEX for a 25 000 t/a copper plant treating a 9 per cent Arsenic concentrate in Australia. The costs given in Table 3 have been estimated by MINETOMETAL based on a prefeasibility study for the related MTM Zinc Technology supplemented by published data and some input from an external engineering group. A 40 per cent contingency has been applied to the CAPEX estimate given the early development stage of the work.

CAPEX and OPEX for a 25 000 tpa copper plant.			
CAPEX	US\$	OPEX	US\$/t Cu
Roaster	26	Natural Gas	40
Leach – Crystallisation	40	Electricity	35
Copper Reduction	20	Lime	260
Gold Plant	8	Reagents	80
Total Installed Cost	94	Labour	140
Contingency (40%)	38	Maintenance	48
Total	132	Contingency	83
\$/t copper	5280	\$/t copper	686

TABLE 3

The process steps are all high intensity requiring much less equipment than processes such as those using bio-oxidation which require long residence time leaching, separate neutralisation and solvent extraction and electrowinning. The roasting step is already used for copper – cobalt concentrates (Guntner and Hammerschmidt, 2012) and the process uses conventional hydrometallurgical equipment and there are no high pressure or temperature steps. This allows common plastics to be used to overcome corrosion issues with the ammonium chloride. The arsenic fixation stage adds only a small amount to the CAPEX estimated previously for the MTM Copper Process.

The MTM Process avoids the high electricity cost for electrowinning but does require energy for ammonia stripping and gaseous reductant for the copper oxide reduction. With higher sulfur feeds (>30 per cent) most of the thermal energy required can be obtained from the roaster. The calcium required to fix the sulfur is the dominant variable cost and depends heavily on the copper and sulfur assays in the feed. The costs in Table 3 have assumed a Cu/S ratio in the feed of 0.8 and the use of lime rather than limestone. The arsenic fixation step requires sulfuric acid and lime/limestone which adds ~\$400/t of arsenic in the feed. For the 9 per cent arsenic concentrate used in the experimental work this equates to ~\$125/t of copper produced or around 18 per cent of the total OPEX.

MINETOMETAL's study suggests the CAPEX is lower and the OPEX comparable to acid based hydrometallurgical processes but the CAPEX needed means that the process is not competitive with the current TC/RC's for clean concentrates. The primary target for the MTM Process is concentrates with unacceptable arsenic levels and is especially suited to deposits where flotation enables a high arsenic concentrate to be separated from the ore. The MTM process is not sensitive to arsenic grade and can readily handle up to 10 per cent arsenic in the feed.

The approach is very different to that of the Toowong Process (MacDonald, Molver and Pepper, 2018) and of using inert roasting to volatilise arsenic (Safarzadeh and Miller, 2016). The MTM process fixes the arsenic directly as iron arsenate and the copper reports as a product rather than an upgraded sulfide concentrate. We do not have sufficient information on those processes to make meaningful economic comparisons but avoiding volatilisation and directly making iron arsenate are both environmentally attractive.

# Copper ores with radionuclides

The behaviour of radionuclide elements, or their indicators, was studied through sulfation roasting of South Australian concentrate in developing the MTM Copper Process. The three elements tracked, uranium, lead and cerium all reported to the final residue rather than the copper product. The levels studied were too low to warrant recovering them as products. The work suggests that the process can be used to treat these concentrates to recover the copper and leave the unwanted elements in the residue for disposal.

# **Complex mixed metal materials**

There has been considerable work on using ammonia – ammonium salts to process mixed concentrates and battery scrap (Wang *et al*, 2020; Biswas *et al*, 2023). MINETOMETAL has coupled that with thermodynamic studies on sulfation roasting to develop flow sheets on using this combination to recover individual metals from a range of complex mixed metal feeds. The work is at an early stage and no physical experiments have yet been carried. The chemistry of the individual metals suggests they can be separated and recovered. This is discussed below based on roasting and solubility information given in Table 1 and Figure 1, and on published work.

- Copper roasts to a copper sulfate copper oxide mix. The copper in the calcine is soluble in NH<sub>3</sub>/NH<sub>4</sub>Cl and the copper sulfate is soluble at pH < ~5.5.</li>
- Iron roasts to hematite which is insoluble at pH > 2 and in  $NH_3/NH_4CI$ .
- Nickel roasts to nickel sulfate which is soluble in  $NH_3/NH_4Cl$  and at  $pH < \sim 6.8$ .
- Cobalt roasts to cobalt sulfate which is soluble in  $NH_3/NH_4Cl$  and at  $pH < \sim 7.5$ .
- Molybdenum roasts to molybdenum trioxide. Soluble in caustic soda at high pH.
- Lithium roasts to lithium sulfate which is highly soluble in water and caustic soda. Can precipitate as insoluble lithium carbonate.
- Rare Earth elements There is limited data, but sulfate baking is used to disrupt the bastnasite (CeCO<sub>3</sub>F) and monazite ((Ce,La,Nd,Th)(PO<sub>4</sub>,SiO<sub>4</sub>)) to give soluble sulfates.

A conceptual flow sheet has been developed for processing feed containing a mix of these metals. The version shown in Figure 5 treats a mix of black mass from lithium – ion battery scrap blended with a complex copper-cobalt-nickel sulfide concentrate. The concentrate provides the sulfur needed for the sulfation roasting. A simpler flow sheet is possible for just treating concentrate and the experimental program will be studying both options.



FIG 5 – Flow sheet for a complex feed material.

The blended feed is roasted and the calcine subject to selective leaching steps to recover the metals. Leaching the calcine in caustic soda dissolves lithium present leaving base metals in the residue. A neutral (pH 6–8) leach dissolves cobalt and nickel present and the copper rich residue is processed using the ammonia – ammonium chloride based MTM Copper Process.

The recovery of the individual metals from the liquors, and the preferred flow sheet, can vary depending on the amount of each metal present. For low concentrations and/or small tonnages precipitating the cobalt and nickel as a mixed sulfide is likely to be preferable to using solvent extraction for separation. Including anaerobic bioreactors can provide  $H_2S$  for the sulfide precipitation and a means of regenerating magnesium carbonate for use in precipitating lithium carbonate.

The next step in developing this further is to confirm that the roasting step can give the desired calcine. The known thermodynamics suggests that roasting at around 600–650°C in air with some added lime to control the sulfur dioxide atmosphere can give these reactions, but mixed systems do not always behave as expected during roasting. Once the roasting behaviour is better established work will be undertaken on processing the calcine.

# **CONCLUSIONS AND FUTURE PLANS**

MINETOMETAL is continuing to develop the technology with further laboratory work. The immediate focus is the work on copper arsenic concentrates and the arsenic precipitation step. We are planning to move to larger scale laboratory work and pilot plant testing to fully prove the process and provide data for more rigorous engineering and costing. Work on the more complex materials is ongoing but somewhat limited by current staff availability.

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