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An evaluation of conventional spodumene concentrator flow sheets

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ABSTRACT

This paper investigates the merits of three common flow sheets used for the concentration of spodumene hosted in pegmatites for sale/use in the downstream lithium supply chain and summarises the key drivers, including mineralogy and lithology, which have historically dictated flow sheet selection methodologies for a given pegmatite resource.

The three 'conventional' flow sheets deployed for concentration of spodumene are: dense medium separation (DMS) only flow sheets, whole of ore flotation flow sheets, and hybrid flow sheets comprised of both DMS and flotation unit processes.

Aspects of orebody interpretation that affect flow sheet selection methodology are discussed. Mean and variable components of the orebody, lithology, liberation size and key contaminants are considered.

The trade-offs of each flow sheet are compared and contrasted by assessing key dimensions of lithia recovery, product quality, capital cost intensity, operating cost intensity, project development schedules/factors/risks, environmental factors, and carbon intensity.

Improved understanding of the trade-offs inherent in each flow sheet selection can inform asset owners and financiers alike in valuation of spodumene assets (risk adjusted economic models) and improved development decisions including staged development.

In closing, the authors briefly explore some questions about where potential 'unconventional' spodumene and downstream lithium conversion flow sheets may evolve toward and what this may imply for spodumene producers: past, present, and future.

Value chain life cycle – from planning to the end user

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ABSTRACT

Australia's contribution to the development and increase in response to global Critical Minerals demand is delivered through several key areas and initiatives. Key amongst these is an imperative that Australian governments and industry unite and take ownership of a premium secure supply chain. Ownership that addresses mineral supply stewardship from resource development planning, through mining, production, processing and delivery, offtake end user consumption, and consideration of product recovery and reuse.

End user manufacturers are demanding a 'green' product with secure delivery and 'traceable' or verifiable credentials. A product demonstrating secure green credentials across the entire supply chain with surety in material management and delivery is essential.

A supply chain that securely traces material through to consumption, results in the delivery of a mineral product that can demand a premium. The application of a critical mineral material stewardship lens and process across the value chain provides a key differentiator in supporting the success of Australian critical mineral product.

Technology options including blockchain management can support critical mineral product security and 'tag' green credentials providing offtake end users confidence that the material is 'clean and green'.

Understanding the role each party can play across each step of critical mineral resource development, along the value chain, and through delivery 'gate' to the user is fundamental in delivering a strong supply chain product from Australia with guaranteed security.

GHD will provide a summary of strategies and risks in implementing critical mineral supply chain security and material credentials, and potential benefits secure supply chain success brings to a company's business model, and what this supply chain will look like.

Zinc carborane all-solid-state batteries – possibility or pipe-dream?

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ABSTRACT

The need for efficient, safe and cheap batteries has created interest in solid inorganic electrolytes for all-solid-state batteries. By avoiding the toxic and flammable components that are present in lead-acid and lithium-ion batteries, solid-state batteries are inherently safer, can retain greater energy density, and enable alternative battery chemistries. This is further amplified by using a multivalent metal cation and metal anode, such as zinc. Zinc is the 23rd most abundant element in the earth's crust and is relatively low cost (2844.1 USD/ton) (London Metal Exchange, 2021a) compared to lithium (11 750 USD/ton as $LiOH{\cdot}H_2O$ (56.5%) (London Metal Exchange, 2021b). Previous research into zinc solid-state batteries (ZSSB) has relied heavily on polymer based aqueous Zn-ion electrolytes which have high ionic conductivities (10^{-1}–10^{-2} S/cm) at room temperature (Huang *et al*, 2019). However, aqueous zinc electrolytes are limited, with a narrow electrochemical window, dendrite formation, corrosion and passivation by water on the zinc metal anode surface. Using an inorganic solid-state salt as the electrolyte could increase the electrochemical window and overcome these limitations. Metal boranes have shown great promise as solid-state electrolytes in proposed Li-ion batteries (Hansen *et al*, 2016). A zinc-salt of the monocarborane anion, $CB_{11}H_{12}$ – ($Zn(CB_{11}H_{12})_2$) has been synthesised and characterised. $Zn(CB_{11}H_{12})_2$ shows a high ionic conductivity in comparison to its $ZnB_{12}H_{12}$ analogue at 100°C (10^{-5} and 10^{-8} respectively) as well as non-borate inorganic compound $ZnPS_3$ (10^{-7} at 60°C) (Martinolich *et al*, 2019). While this performance is not currently as high as the lithium and sodium salts, it does show potential into what a fully all solid-state zinc battery could be. Future modification of the zinc borane salt offers the possibility to enhance the conductivity and performance towards a more desired operational window.

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De-risking the repurposing of industrial residues towards a circular economy

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ABSTRACT

In addressing the urgent needs of industry and Government regulatory agencies to enable the beneficial reuse of mine/industrial residues in a responsibly ethical, socio-economic and environmentally safe manner, the application of the 'LEAF Tools' approach can inform the de-risking of residue repurposing.

'LEAF (Leaching Environmental Assessment Framework) Tools' is a collection of laboratory leaching tests, data management and modelling tools developed and validated by the European Union and USA EPA to assess the environmental impact of repurposing residue materials and by-products. The LEAF Tools can be applied to a wide range of waste-derived materials and by-products from industrial processes, including water treatment and mineral processing residues.

Through full geochemical characterisation (including LEAF testing) of the residue and local soils, performing LeachXS modelling of virtual material applications over a wide range of local soil types can more efficiently inform the optimisation of repurposed residue applications. Applications of residue include soil amendment, clean fill, road construction, building and construction products. In soil amelioration and agronomy applications, the LEAF approach can help optimise application rates that will better inform field and pot trials, leading to more efficient and cost-effective trials.

This paper will present how the application of LEAF Tools can help the lithium battery and energy metals industry and government authorities to assess the potential environmental impact of repurposing industrial residue and by-products.

Shortage of basic raw materials for construction, landfill and poor quality of soils are issues of significant environmental, economic and social importance to Australia and many nations around the world. The repurposing of industrial residues addresses these issues and provides potential benefits of reducing environmental impacts and assisting the sustainability of many land uses. It also addresses the issue on the growing industrial residue volumes. This will also provide economic benefit and reduced environmental impact for industry, agriculture and the wider community.

Ultra-pure battery compounds – the hunt for the last ppm's of impurity

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ABSTRACT

The global demand for lithium and other battery related compounds like cobalt, nickel and manganese is evolving. Next to the sheer quantity of lithium compounds required, also the quality plays a more and more important role as this is understood as a major driver for the efficiency, lifetime, and safety of lithium-ion batteries.

The main sources of primary lithium are ores like spodumene on the one hand and salt brines on the other hand. Secondary lithium from recycled batteries will, and must, play a stronger role in the future as a more circular economy needs to be established for lithium and the other battery-related compounds. From all sources, whether primary or secondary, the raw material is impure. Depending on the source of the raw material a specific impurity profile is given. However, the final product should be ultra-pure with regards to different impurities like sodium, potassium, magnesium or calcium. Most of such impurities are not allowed to exceed 1–100 ppm, depending on the specific impurity and manufacturer's product specification.

A key understanding of the behaviour of all relevant single impurities is essential for the process design from a certain feed stock to the ultra-pure product. After involving certain upstream treatment steps like precipitation, filtration, extraction, or ion exchange, normally crystallisation is the final step ending up in a processed solid battery-related compound like lithium hydroxide and lithium carbonate or the sulfates of cobalt, nickel and manganese.

Crystallisation thereby is very selective; however, a different mechanism applies for the different impurities. For impurities which are only concentrated in the mother liquor, efficient washing techniques may be sufficient to deplete the undesired side compounds below any pre-defined limit. Other impurities could co-crystallise or even form so-called solid solutions which is understood as integration of impurities into the crystal lattice of the product. This complicates the process design; however, specific process set-ups are developed to overcome the constraints described before.

GEA designed, supplied, and installed several production plants for most of the applicable battery related compounds. Next to the installed references, extensive experience of numerous laboratory developments makes GEA one of the most reliable companies worldwide for processes for the production of battery-related compounds.

Development of novel flotation collectors for the beneficiation of spodumene

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ABSTRACT

The demand for lithium has increased exponentially in recent years. This demand is being fuelled by the need for energy storage in many electronic devices and mostly due to the increasing demand for electric vehicle battery storage. Traditionally, lithium has been almost exclusively extracted from salt brines. Spodumene is the main hard rock lithium bearing mineral from which chemical grade lithium carbonate and lithium hydroxide are produced. Gravity concentration and flotation are the main methods of concentrating spodumene to chemical grade, with flotation mainly suitable for processing relatively finer and lower grade ores for which gravity concentration is uneconomical. Flotation is mainly carried out using a variety of fatty acids as collectors. Though cheap and economical, fatty acids:

- have slow adsorption kinetics onto the spodumene surface
- require very long conditioning times
- conditioning even at temperatures up to 50°C
- are relatively unselective and require very large dosages.

BASF has developed a non-fatty acid collector for spodumene flotation that is very selective against iron, silica and alumina-based minerals. The new collector achieved rougher lithia grade of 5.2% compared to 3.7% for fatty acid when tested without proper desliming and magnetic separation. With proper magnetic separation and slimes removed – actual plant feed – BASF collector achieved concentrate grade greater than 6.5% in the rougher test compared with just 5% for fatty acid. Additionally, up to 70% of lithia was recovered in 4 minutes of flotation after conditioning for 5 minutes compared to only 40% recovered in 4 minutes of flotation after conditioning for 15 minutes with fatty acid, which represents improved kinetics.

The effects of hydrothermal alteration on spodumene colour – implications for ore assessment

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ABSTRACT

Alterations of spodumene ($LiAlSi_2O_6$) under hydrothermal conditions results in variable colouration of the mineral. This colour classification is used by the Li-mining industry for the assessment of ore quality.

Here, we use this colour grading scheme, ie white, grey, yellow, green and dark green, for samples from the Bald Hill mine in the Eastern Goldfields to investigate mineralogical and chemical changes associated with the alteration of spodumene. White and grey spodumenes contain flaky primary muscovite. Yellow specimens host fine-grained, µm-sized secondary muscovite veins distributed along cleavage planes. Assemblages of spodumene + muscovite + cookeite ($LiAl_4(Si_3Al)O_{10}(OH)_8$) + quartz ± microcline and muscovite + cookeite are characteristic of green and dark green samples, respectively. The chemical composition of spodumene remains stochiometric in all specimens. Supported by textural characteristics, four types of muscovite can be distinguished based on their chemistry:

1. Primary muscovite yields low Li_2O (0.09 wt.%) and MgO (0.02 wt.%) as well as high Fe_2O_3 (1.02 wt.%).
2. Veins of secondary muscovite in yellow specimens are enriched in Li_2O (1.25 wt.%) and depleted in Fe_2O_3 (0.65 wt.%).
3. Green and dark green specimens contain two types of secondary muscovite replacing spodumene. Type-1 contains more Li_2O (up to 0.93 wt.%) compared to Type-2 that is enriched in Fe_2O_3 (2.08 wt.%) and MgO (4.01 wt.%).
4. Cookeite is predominantly associated with Type-2 muscovite and comprises up to 3.67 wt.% Li_2O, 4.62 wt.% Fe_2O_3 and 2.86 wt.% MgO.

Mineral paragenesis and chemical compositions indicate that the breakdown of microcline provided K for the crystallisation of all secondary muscovites during the hydrothermal replacement of spodumene. Enrichment of Type-2 muscovite and cookeite in Fe and Mg suggests that fluids interacted with the mafic country rock prior to spodumene alteration. Based on the presented data, the colouration of spodumene provides an improved ore quality assessment due to the fast prediction of mineralogical changes and the degree of alteration.

HPGR's success with new lithium projects

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ABSTRACT

High Pressure Grinding Rolls (HPGR) is a newcomer to crushing circuits and offers energy savings, lower media wear and recovery gains, which makes it hard to resist compared to conventional crushing circuits. HPGR has now been used with great success with some of the new lithium projects for hard and highly abrasive spodumene ore. HPGR is well suited to spodumene ores causing breakage along crystal boundaries and achieving fine crush sizes particularly well suited to Dense Media Separation.

The laboratory small-scale and pilot testing is well established and reliable. Scale up and design predictability is reliable. From an operational aspect the ability to change operating pressures and screen apertures offers significant operational flexibility not offered by a SAG mill. In addition, the rolls life has greatly increased due to innovation, and change out times have shortened. The reliability of HPGR has been shown to be equal to SAG mills. The advantages of wear life, energy consumption and flexibility to crush size at a number of sites is referred to. HPGR's inclusion in new flow sheets has proven to be relevant to battery metals compared to the older flow sheets and has become the new standard.

Green nickel and cobalt recovery and production of their battery chemicals from various primary resources

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ABSTRACT

The WA School of Mines at Curtin University has led the research into the green extraction of nickel and cobalt from a range of sulfide and oxide (primary and secondary) resources, and the subsequent recovery of the metals from solution using a highly selective leach approach. The patented technology will be discussed in relation to the performance of this technology to ores, concentrates, and tailings and process intermediates. The technology utilises an alkaline glycine approach, in conjunction with an oxidant and which may have additional catalysts to selectively recover nickel and cobalt from a diverse range of resources in an environmentally friendly approach that eliminates the need for aggressive acids, high pressure or smelting and converting (and associated flue-gas treatment). It will be shown that recoveries for nickel of more than 85% can be obtained on disseminated nickel sulfide ore, greater than 93% on concentrates and greater than 50% on tailings within practical and feasible residence times. The paper will also present some options for the refining of mixed hydroxide precipitate purification derived from laterite processing. Metal contaminants such as Si, Mg, Fe, Cr, Al, and Mn are essentially eliminated during the leach providing clean leachates of glycine-chelated Ni, Co, Cu, Zn. Depending on the concentrations of metals in solution, either ion exchange or solvent extraction may be used to recover pay metals. The pay metals are subsequently stripped into a sulfuric acid medium and separated in a conventional sulfate based aqueous system to produce crystallisable sulfate salts of nickel, cobalt and, if present in sufficient quantities, copper. Should precious metals such as Pt, Pd and Au be present the technology can, with minor modification allow for their recovery as well. The technology allows high selective recovery at atmospheric pressure, mild (ambient or slightly above) temperatures, and using non-exotic materials of construction combined with a safe working environment.

Water resource challenges for battery and rare earth mineral resources

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ABSTRACT

Lithium resources, both within Australia and abroad, face water resource limitations. Lithium brine deposits, which are often in desert settings, face water resource issues associated with local fresh water supplies. These limitations can also result in local obstacles to upstream processing and manufacturing resulting in it occurring at distal locations, far from the deposit and often not within the country of origin of the resource.

Likewise, hard rock lithium deposits, more commonly targeted in Australia, are often hosted in what would be considered to be, poor aquifers and small-scale excavations. This hydrogeological environment also extends to other battery minerals and rare earth elements across Australia.

The resultant small-scale associated dewatering from these poor aquifers requires operations to expand their water supply options beyond mine dewatering to borefields and surface water catchments thereby increasing reliance on rainfall recharge making water security a key operational challenge to many of Australia's battery and rare earth mineral resources.

How much of a challenge this becomes, is commonly driven by how much value add/upstream processing is intended to be applied locally. The more upstream processing we intend to do in Australia, or within the country of origin of a resource, the more we need to consider availability and reliability of water resources. This applies to not just the operational mining considerations, but also in the processing, manufacture and provision of both battery and rare earth minerals to the Australian and international markets.

Getting serious about reducing the carbon footprint of battery metals – where to focus

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ABSTRACT

CSIRO's critical energy metals mission is focused on delivering the greenest feedstocks to the world's gigafactories. There are four key areas of focus including: direct routes metals and chemicals, higher performing natural graphite, recycling, and next generation batteries. There is a clear environmental rationale for these focus areas and this presentation will reveal CSIRO's own research findings to justify these areas and help the industry prioritise its carbon reduction targets in the battery metal space. For example, nickel laterites are likely to be a preferred source of new nickel – yet HPAL is energy intensive. Nickel sulfate could contribute to 50% of the total battery cell's CO_2 footprint. Alternatives to this process will be discussed. Similarly, natural graphite does not perform as well as synthetic – yet we must find a way to fix this to eliminate synthetic versions based on coking coal. Recycling will become vital, yet there are hurdles to making this economic and the timing of the opportunity as well as new technology required to improve economics will be discussed.

Acid leaching of base metals and separation of nickel and cobalt from a smectite ore

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ABSTRACT

As a result of the increasing demand for rechargeable batteries for electric vehicles, the demand and price for nickel and cobalt has increased in recent years. Smectite is a major lateritic ore in which nickel and cobalt are distributed in smectite, nontronite and iron/manganese minerals. Only a few studies have been reported for the leaching of smectite/nontronite type ores in the presence or absence of reducing agents such as SO_2 in H_2SO_4 solutions (Topkaya and Buyukakinci, 2009; Das and de Lange, 2011; Senanayake *et al*, 2015). Poor selectivity for nickel and cobalt leaching, high impurity levels of iron, aluminium, chromium, magnesium, and undesirable free acid content in post-leach liquor are foremost drawbacks of atmospheric acid leaching (AAL). This study reports a comprehensive mineralogical analysis of an iron-rich smectite ore of West Australian origin, consisting of nontronite and goethite as the main minerals along with amorphous phases using a combination of chemical analysis and characterisation techniques (ICP-OES/XRF, XRD/QXRD, QEMSCAN, SEM/EDS). An extensive diagnostic leaching indicated the effect of mineral speciation and elemental distribution within the ore on leachability and the need for strong acid for breaking the oxide/silicate lattice in smectite. Acid leaching with 4.5 mol dm_{-3} H_2SO_4 at 25% solids and 97°C over 6 hours gave the best leaching efficiencies of 99% Ni, 96% Co, 89% Mn, 90% Fe, >99% Al and Mg, and 50% Cr. Pregnant leach liquors from AAL were used in solution purification, separation and recovery using mixed-hydroxide precipitation (MHP) and ion-exchange (IX) techniques. The composition of MHP (26–37% Ni and 2–5% Co) produced using magnesia/lime is close to previously published results (Topkaya and Kose, 2011). The IX separation based on adsorption onto DOWEX resin (M4195) and elution with sulfuric acid shows the potential for developing an integrated flow sheet based on leaching, precipitation and ion-exchange.

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Geothermal lithium – the final frontier of deep decarbonisation

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ABSTRACT

Geothermal lithium chemical compounds for battery manufacturing are a compelling option for deep decarbonisation of the industrial economy.

In this presentation, we quantify this decarbonisation opportunity. This includes the results of prospective life cycle assessment (LCA) models for two geothermal lithium projects in development. Due to their ability to produce low CO_2 intense power and lithium simultaneously, we find that the lowest CO_2 intensity lithium chemicals in 2030 will likely come from geothermal lithium operations, if they are built.

We compare geothermal brine projects to evaporative brine projects, another low CO_2 source of lithium compounds. Not needing to evaporate the water from the brine means that geothermal lithium consumes ~100× less energy than evaporative brine processes (both very low carbon energy sources). And because geothermal energy is ~100× more dense on the surface of the Earth, it means overall ~10 000× more lithium can be produced from the same square metre of Earth in a geothermal lithium project compared to an evaporation pond.

Supply chain stakeholders like cathode manufacturers should help these projects get built if their customers value low embodied emissions of EV manufacturing.

Lithium manganese ferro phosphate – the next generation of lithium-ion batteries

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ABSTRACT

Lithium ferro phosphate (LFP) batteries have many characteristics which are superior to the more common lithium-ion batteries that contain nickel (Ni) and cobalt (Co). They have only one critical metal, lithium, have a low manufacturing cost, wide operating temperature range, good thermal stability and supreme safety. LFP could be the perfect battery if it were not for their lower energy density – about 30% less than their Ni/Co bearing counterparts. The 'olivine' crystal structure, that imparts the superior characteristics to LFP is retained if other metals are substituted for iron in the lattice. The addition of such metals can improve battery performance. In particular, the addition of manganese results in an increase in energy density of up to 25% resulting in a battery that is much more acceptable to those consumers suffering from range anxiety, is economical to manufacture and is very safe.

Lithium Australia's subsidiary, VSPC Ltd, has successfully produced lithium manganese ferro phosphate (LMFP) cathode powders that capture the advantages of LFP but have an energy density close to that of the spinel structured Ni/Co cathode powders. LMFP is the next generation of cathode material and is now available for commercial testing.

Developing substituted metal boranes as solid-state ion conductors

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ABSTRACT

Energy storage devices are vital to the world we live in and will form a large part of our future into the digital age. As a result, research into battery technology is intensifying in order to produce cheaper, more efficient and safer batteries. Solid-state electrolytes have been developed as an alternative to traditional liquid electrolytes as safer options with a higher energy density (Zhuiykov *et al*, 2002). Group 1 metal salts of *closo*-borane anions have been shown to have high ion conductivity with the 12-vertex carborane ($CB_{11}H_{12-}$) showing particular promise (Hansen *et al*, 2016; Franken *et al*, 2001). This reduces the symmetry within the anion and also creates a dipole within the molecule. The ion conductivity of the lithium carborane salt ($LiCB_{11}H_{12}$) is far improved to the unsubstituted $Li_2B_{12}H_{12}$. Creating a charge dipole within the anion increases the ion conductivity, so increasing this dipole by using other heteroatoms, such as heavier group 14 elements like lead and tin (instead of carbon) could increase the ion conductivity. The main aim of this research is to synthesise, characterise and develop stanna – and plumbaborane salts ($B_{11}H_{11}Sn_{2-}$, $B_{11}H_{11}Pb_{2-}$) as ion conductors. These anions were paired with a variety of metal cations to investigate their ion conductivity and consequently as future battery materials. $Li_2B_{11}H_{11}Pb{\bullet}xH_2O$ shows high ion conductivity of above 1 mS/cm between 90–120°C and $Li_2B_{11}H_{11}Sn{\bullet}xH_2O$ see equally excellent performance between 100–150°C. Other metal cation salts were also synthesised, however, these compounds showed lower ion conductivity with $Na_2B_{11}H_{11}Sn$ (0.2 mS/cm at 170°C) and $K_2B_{11}H_{11}Sn$ (1 μS/cm at 90°C) showing particular promise. This performance is slightly worse than the carborane ($LiCB_{11}H_{12}$) possibly due to the coulombic attraction of the divalent $B_{11}H_{11}Pb/Sn_2$ – anion to the respective cation. However, they an improvement on the unsubstituted $Li_2B_{12}H_{12}$ at increased temperatures so this class of novel compounds show promise as possible ion conductors.

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Supplementary Cementitious Materials Part 4: Pozzolans – Manufactured

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ABSTRACT

Late 2019, the Australasian Pozzolan Association received approval from Standards Australia to develop a new Joint Standards Australia/Standards New Zealand through the Committee BD-031, Supplementary Cementitious Materials. This new Standard, *Supplementary Cementitious Materials Part 4: Pozzolans – Manufactured*, will be complimentary to the existing series AS 3582 Part 1: Fly ash, Part 2: Slag–Ground granulated blast-furnace and Part 3: Amorphous silica. The Standard uses a similar structure.

Pozzolans include a broad category of materials, both naturally occurring, processed natural materials, and by-products of various manufacturing processes. All can be generally defined as having the following common characteristics; being mainly siliceous or silico-aluminous or dicalcium silicates material that will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds having cementitious properties.

Objectives in creating this Standard relate to encouraging resource efficiency, that is, to facilitate the beneficial use of manufactured pozzolans as mineral resources within a modern circular economy, using well-defined standards to provide market confidence in the resource use.

Whilst natural pozzolan sources are well understood, there is an emerging class of manufactured pozzolans arising from various non-metallurgical and mineral processing industries which warrants greater attention given ‘Circular Economy’ drivers to maximise mineral resource use.

We will discuss the standard development process considered, where appropriate, existing international, national and relevant standards, coupled with publicly published research and extensive testing program of the Australasian Pozzolan Association. In summary, the new Standard is expected to include: new classes of materials, definitions, sources, specified requirements, testing methods and product conformity requirements in the normative section.

Techno-economic assessment of electric vehicle charging solutions for rural WA

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ABSTRACT

This study provides a comprehensive techno-economic assessment for alternative EV charging solutions for rural locations in WA, specifically roadhouses. This project aims to assist in the execution of an 'Electric Highway' across WA which will demonstrate the development of EV technology and infrastructure, challenging negative attitudes and stimulating EV uptake rates. The solutions explored include conventional methods such as the use of grid power supply and solar, with the addition of battery storage systems, as well as the use of diesel generators as a stand-alone power system, utilising either diesel or waste vegetable oil.

The project evaluates and models both Capital Cost of equipment, as well as Operating Costs, comparing hardware and connection costs, supply charges and electricity tariffs, and differences between grid connection, battery buffered grid, solar array and battery, diesel, and waste vegetable oil operating costs. These Capital and Operating Costs have been used to model the 10-year Life Cycle Costs of each solution. Cost data was modelled based on existing 50 kW DC public charging systems in WA recently installed in rural areas of WA with known costs, as well as commercial electric transport charging projects. Cost estimates were modelled for 10 locations in WA, which demonstrate install and operational costs for a variety of site characteristics. The cost model created has also been presented in an excel document which allows potential stakeholders of EV charging locations to input site characteristics and estimate associated costs for the site.

The use of unprocessed waste vegetable oil has been analysed to outline its viability for EV charging in the current context. An assessment of engine performance and energy density of vegetable oil has been carried out to confirm the performance of waste vegetable oil use in a diesel generator and provide relevant data for modelling. These cost comparisons indicate that not only is waste vegetable oil use feasible but the most cost competitive of solutions.

Effect of staged-grinding and sieving on Li deportment in a calcined spodumene ore

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ABSTRACT

Lithium extraction from hard rock ores involves higher capital and operating expenses than that from brines. A significant contribution to processing costs is in energy consumption during grinding. There is the potential for grinding costs to be reduced using calcination before grinding as the process reduces spodumene hardness markedly due to the conversion of the α to β phase. There is also the potential for waste rejection prior to grinding resulting from the impact of calcination. This work investigates the impact of different modes of grinding on the potential to upgrade the lithium content in the finer fraction of the mill discharge. The results showed that while staged grinding resulted in 89% lithium recovery of the finest size fractions (-600 μm) relative to 65% over the same time for continuous grinding, this was associated with a far higher mass retention. The grade of the finest size fraction in the case of the continuous grinding was 1.7 times more than that in the case of the staged-grinding. This work shows the potential of using different grinding modes to maximise lithium grade and recovery.

ESG supply chain resilience – a short-term and long-term approach

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ABSTRACT

The mining sector is being both pushed and pulled towards a number of ESG targets globally, but companies are still struggling with the lack of clear guidance and requirements, regarding ESG policy and implementation and the ever-adapting ideologies and competing interests of the end consumer.

For an ESG approach to be genuinely effective, support corporate strategy and ultimately minimise company ESG management exposure, it is imperative that strategy also consider an organisations' supply chain from mine planning and exploration all the way through to manufacturing, end consumer and disposal – recycling/recovery, completing the full life cycle of the product.

The EU Carbon Trading Scheme; Equator Principals; the London Stock Exchange; the GRI; the IIE; and the ICMM are just a few of the industry bodies providing guidance and setting expectations. Along with global financial institutions such as the World Bank, IFC and broader investment community focus on ESG performance and 'metrics' presents an unparalleled level of demand on business.

Rare Earth and Battery Mineral mining companies require a clear and intuitive process that supports ESG values and increases resilience of their supply chain and the 'green' product imperative.

GHD has developed a simple dashboard which supports mining companies and OEMs develop a 'balanced ESG' approach to utilise when approaching/considering ESG opportunities. A 'step-by-step' guide that starts at project inception and prevails through to the end user, and beyond.

Pathway to decarbonisation – achieving carbon neutrality by 2035

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ABSTRACT

IGO acknowledges the changing global climate and accepts the position expressed by the Intergovernmental Panel on Climate Change that continued emissions of greenhouse gases will cause further global warming that could lead to catastrophic economic and social consequences. Similarly, IGO are uniquely positioned to take advantage of the global focus on decarbonisation and energy transition, with strong market opportunities for our nickel, copper, cobalt and lithium concentrates in energy storage and renewable energy.

The ongoing challenge for companies such as ours is clear: mining practices impact on the climate in ways that are increasingly unacceptable to civil society. While many things slowed down due to the pandemic in 2020, the focus on climate change and commitments to reduce emissions definitely heated up.

In FY2020, IGO released our climate change policy, aspiring to carbon neutrality by 2035. This paper and subsequent presentation will address how will we achieve this. IGO's pathway to decarbonisation and carbon neutrality is built on three pillars:

1. Emissions reduction roadmap – execute projects at our Nova Operation that will decarbonise our direct emissions. We will talk through the projects that form part of this roadmap, including how we prioritise under strategic, commercial and technical criteria. Part of this roadmap is also focused on our material scope 3 emissions, and how we can reduce and influence upstream and downstream.

2. Internal carbon price – we will use an internal carbon price to enable and fast track emission reduction projects. Our carbon price allows IGO to price operational emissions and create a centralised decarbonisation fund, to fund low carbon investments and technology.

3. Natural solutions offset strategy – we are investing in carbon abatement projects within our communities to offset the emissions we cannot reduce. We are partnering with organisations to develop new methodologies that are not currently established under the Clean Energy Regulator legislation.

Overview of lithium recovery from hard rocks using fluorochemical processes

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ABSTRACT

In the last decade, fluorine-based methods have been actively reported for lithium extraction from its hard rock resources. Owing to the minerals' silicate nature, hydrogen fluoride (HF) has been showing powerful leachability to lithium. However, the direct use of HF also brings safety and environmental concerns. To address this, different sources of HF have been used such as the combination of fluorite (CaF_2) and sulfuric acid to *in situ* generate HF. Also, fit-for-purpose reactors, inducing continuous tubular reactor (CTR), has been reported to reduce the risks of HF release and enhance metals extraction. When lithium and other metals are extracted from the hard rocks, the downstream purification and recovery brings many differences and also similarities, compared with that from traditional sulfuric acid roasting. For example, fluorine will need to be removed and recycled for both environmental and economic reasons.

This study, therefore, provides an overview of using fluorochemical processes to recover lithium from its hard rocks, including spodumene and lepidolite. The fluorine-based methods for extraction and the following downstream purification reported in the last 10 years will be focused on and analysed, including the authors' experiences. The suggestions of fluorochemical processes for future development will also be addressed.

It is expected that, as a review specialising in fluorochemical processes, this study can provide insights and bring discussions for this specific and still developing area.

Extract lithium from spent lithium-ion battery leachate using CYANEX 272 – experimental and thermodynamic studies

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ABSTRACT

Due to the revolutionary growth of green energy storage and electric vehicles, the supply chain of critical metals required for lithium-ion batteries is under pressure from a spike in global demand. Circular economies provide promising relief whereby end-of-life lithium-ion batteries are recycled to manufacture new batteries. Solvent extraction is an essential separation technology after pre-treatment, shredding and leaching of the batteries in the recycling industry. CYANEX 272, a commonly used extractant for the Co and Ni mining industries, was tested in laboratory-based trials for this purpose. The results indicate that lithium can be extracted *from synthetic leach solutions* at pH values between 5.5–8.0. This finding enables the separation and purification of metals using only one solvent. It not only avoids contamination from different solvents but also simplifies the recycling process. However, due to the weaker affinity between lithium and the extractant, only 50% of lithium can be extracted at one extraction stage.

To further understand the mechanism of lithium extraction, a new heterogeneous equilibrium model was developed and experimentally validated. Rather than using standard slope analysis, the model uses a new approach to determine the stoichiometric ratio. This model can also predict the extraction performance over a range of operating conditions. The impact from pH, other metals and extractant content is significant, while the impact from temperature, leachate ionic strength and modifier content is minimal.

Greenbushes past, present and future

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ABSTRACT

A brief view of the past, present and future of spodumene production from the Greenbushes orebody.

Greenbushes is closing in on its 40th anniversary of spodumene mining and production. Commencing in 1983 with a converted tantalum pilot plant producing a flotation concentrate for the glass and ceramic industry, to the present day as the world's largest and lowest cost spodumene producer boasting three active pits, three processing plants and two crushing plants. Future growth plans are already in the construction phase which will see Talison maintain its number one spot in the market providing lithium for the battery market for many years to come.

Extraction of lithium from lepidolite and *α*-spodumene by sodium bisulfate roasting, water leaching and precipitation as lithium phosphate

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ABSTRACT

This paper presents the extraction of lithium from *α*-spodumene and lepidolite of 3.58% and 2.37% Li (w/w), from Greenbushes (Western Australia) and Minas Gerais (Brazil), respectively. Characterisation of the solids (feed concentrate and reaction products) was performed using XRD, SEM-EDS, FTIR and Raman spectroscopy. The ICP-MS analysed the elemental composition of the leach liquors and digested solids. Results from TG-DSC analysis of feed material and XRD scans of solids justified the thermodynamic modelling of chemical reactions using HSC software package. The roasting of lepidolite at 500°C and *α*-spodumene at 1000°C with $NaHSO_4$ followed by water leaching yielded 96% and 80% of Li extraction, respectively. Purification of the lepidolite leach liquor by adjusting the solution pH to 9.0 using caustic soda resulted in the precipitation of cryolite ($NaAlF_6$) as a primary phase. Spodumene leach liquor did not require purification before lithium recovery due to low impurity content. Precipitation of lithium phosphate from the lepidolite and spodumene leach liquors recovered about 93% lithium. Addition of lime to Li_3PO_4 produced 98% $LiOH{\cdot}H_2O$ with 99.7% conversion.

Novel applications of electrodialysis in hydrometallurgical processing of battery minerals

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ABSTRACT

Global market demand for battery precursor chemicals and energy metals—which are the key ingredients required to produce modern batteries—is increasing every year. This is reflected by the recent trend of many established and new companies looking at commercial production of these key ingredients for batteries. In addition, many research groups are working on improving the existing production processes or seeking breakthrough processing technologies. This rapid ramp-up has unsurprisingly revealed limitations in the conventional hydrometallurgical processing methods for producing precursor chemicals of sufficiently high purity for battery application, which is hindering producers' ability to sustainably meet battery-grade product specifications in an economically viable manner. Electrodialysis is emerging as an attractive alternative technology for the hydrometallurgical processing of battery precursor minerals. It is demonstrating potential as a continuous production technology for high purity compounds, as well as reduction of reagent consumption and elimination of certain effluents from the processing flow sheet. It is a mature technology that has been applied on an industrial scale for more than 60 years in other applications. Recently it has been shown to be a suitable technology at the laboratory scale for the hydrometallurgical production of battery chemical precursors such as lithium and vanadium. This presentation will provide a brief review of recent studies and demonstrations related to the application of electrodialysis in hydrometallurgical processing of battery minerals. In particular, the effects of using different electrodes, ion exchange membranes, systems, impurities in the electrolyte, cell configurations and other key factors will be reviewed. The results of the research and development work conducted at Murdoch University by the Hydrometallurgy Research Group (HRG) (previously known as MPI) will also be discussed.

Changing cathode chemistries driving critical battery material outlooks

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ABSTRACT

Car manufacturers globally are continuously updating their outlook on not only EV adaptation and sales but also on the consumer's changing requirements for larger, longer-range batteries. These updates are based not only on changing consumer expectations but also on a broader range of vehicle models being offered, economics of production as well as the value proposition to the consumer in terms of price and sustainability.

The battery and cathode supply chains are responding to these requirements in a variety of ways, with battery manufacturing companies committing large amounts of capital to increase capacity. In addition, ongoing research into ways to push the boundaries of what existing chemistries can deliver in terms of energy density is ongoing.

In recent months, LFP battery chemistry has moved from being a mainly Chinese market focused chemistry to emerge as a serious contender for part of the global market outside China. This growth is happening alongside continued growth for high nickel chemistries which will support the higher end of the vehicle market.

This changing landscape is constantly challenging existing outlooks for which type, and amount of lithium compound will be required as well as the demand for cobalt and nickel.

Roskill will cover the EV outlook in terms of market penetration as well as our outlook on which battery chemistries will be deployed in the coming decade. The presentation will conclude with an up-to-date demand outlook of lithium carbonate, lithium hydroxide, cobalt and nickel as well as a comprehensive outlook on supply of these critical raw materials and potential supply deficits.

Australia – growing an upstream lithium-ion economy

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ABSTRACT

Lithium and its main compounds, lithium carbonate, chloride and hydroxide, have numerous remarkable properties, making them essential to many critical technologies such as Li-ion batteries. These batteries are the technology of choice for electric vehicle (EV) manufacturers who are racing to meet consumer expectations, as well as government-imposed regulations. Already, indicators suggest 2021 will be another milestone year for EV adoption, with strong orders already exposing shortfalls in pockets of the battery supply chain. Importantly, out of the 211 Li-ion Megafactories Benchmark is currently tracking on a monthly basis, 156 are Chinese, 22 are European and 12 are in the USA. At the same time, battery megafactories and gigafactories are becoming the embodiment of a country's industrial and political ambition, meaning that we are bound to see a larger pipeline emerge in the USA and Europe. Concerns from consumers, regulators and EV manufacturers around supply security, mineral criticality, as well as environmental, social and governance (ESG) issues means that new supply relationships will increasingly be formed with these factors placed under consideration. At the same time, supply takes a number of years to come online, with even more time needed to develop and qualify products that are fit for purpose. Low levels of investment during recent low-price environments means that a supply deficit could occur as early as this year. Indeed, a market deficit of a few thousand tonnes in 2015 took almost 3 years to address, pushing prices to all-time highs. In Australia, lithium supply is expected to grow by over 100% to 2025, but it is unlikely to be enough. In this presentation we will explore the future for EV manufacturers and their relationships with upstream production, and will delve deeper into lithium supply globally, with a special focus on Australia.

Formation and alteration of Li-bearing micas in pegmatite at Lepidolite Hill, Western Australia

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ABSTRACT

The chemical and isotopic composition of micas is widely used as an indicator helping to elucidate the formation processes of ore deposits. Here, Li-bearing micas, from Lepidolite Hill (Western Australia) have been examined to decipher the behaviour of lithium during formation and subsequent alteration of pegmatite under hydrothermal conditions. Samples were collected along the profile starting from the contact between pegmatite and the ultramafic host (dark brown micas) to the quartz-rich core of the pegmatite (bright pink micas). A ~10 cm thick layer of dark micas has formed at the contact between pegmatite and ultramafic rocks. Pink micas are intergrown with massive feldspar and quartz.

Based on the microscopic observations and XRD, SEM-EDS, EPMA analyses the micas were classified as lepidolite (polylithionite, trilithionite), muscovite, zinnwaldite, and phlogopite series. BSE images and EPMA quantitative elemental mapping revealed that the distribution of minor and major elements in all micas is heterogeneous; ie zoning. The estimated concentration of Li_2O in micas varies from 3.26 to 8.41 wt.% at the contact and in the core, respectively. Further from pegmatite-ultramafic contact, the micas are depleted in Fe (<5.41 wt.% FeO) and Mg (<4.32 wt.% MgO), and enriched in Mn (0.70–5.23 wt.% MnO) and Al (3.26–36 wt.% Al_2O_3). The presence of Cs (~0.213 wt.% Cs_2O) and Rb (~2.45 wt.% Rb_2O) enriched rims in all micas indicates late alteration by hydrothermal fluids. The identified mineralogical and chemical signatures of micas at Lepidolite Hill revealed deposit scale circulation of hydrothermal fluids that produced well defined zones enriched in Li, Cs, and Rb.

The impact of residual stress on the cyclability of thin-film silicon anodes for lithium-ion batteries

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ABSTRACT

Silicon is one of the outstanding candidates for replacing the commonly used carbon anode material in lithium-ion batteries (LIBs) because of its high specific capacity, 4200 mAh/g (ie up to 11 times higher than carbon). Unfortunately, the widespread use of silicon has been hindered by the large volume expansion produced during charge/discharge cycling as well as its high resistivity. Film stress has been found to impact the electrochemical and cycling performance of silicon anodes. The stress can arise from two sources, namely: (1) residual stress resulting from the deposition process during anode fabrication; and (2) mechanical stress resulting from the large volume expansion during the lithiation/delithiation process. Most of the focus within the literature has been centred on mechanical stress. Residual stress has been largely ignored, underestimated, or considered negligible, without any rigorous experimental evidence to support the claims.

In this work, silicon thin-films have a wide range of residual stress and electronic resistivity were produced using magnetron sputtering, a physical vapour deposition (PVD) technique. In order to study the impact of residual stress on the electrochemical and cycling performance of silicon films, three sets of silicon thin-films were used as anodes and assembled into half cells. Each set consisted of a pair of films having essentially the same resistivity, density, thickness, and amount of oxidation, but possessing distinctly different residual stresses. The comparisons between the films were based on the charge/discharge cycling and cyclic voltammetry measurements. Contrary to the popular belief within the literature, films with high compressive residual-stress produced enhanced electrochemical performance and cycling stability. The work offers an informed and definitive understanding of the role that residual film stress plays in PVD Si anodes, which will improve silicon-based thin-film anode design.

Producing high-purity battery-grade materials using crystallisation

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ABSTRACT

The safety and performance of lithium-ion batteries is greatly affected by impurities in the precursor chemicals. Consequently, the specifications for their purity are very stringent. Battery manufacturers seeking greater safety and higher performance are now pushing for even higher purity standards which are not possible to achieve with traditional crystallisation techniques. To achieve these new purity targets the innovations in crystalliser design are required which at the same time deliver sustainable operation at lower cost.

Each battery precursor material is different in terms of its chemistry, associated impurities, and crystallisation behaviour. Therefore, the operating conditions and the design of the crystallisation plant should be tailored to the specific requirements for each material.

This paper describes the crystallisation techniques, processes and salient design features associated with producing battery-grade nickel sulfate, cobalt sulfate and lithium hydroxide products. It compares the crystalliser design features, operating conditions and critical design parameters required to achieve the desired product purity.

Advanced supercapattery materials for enhanced electrochemical energy storage

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ABSTRACT

Supercapattery (supercapa + ttery term originated from the few letters in words such as supercapacitor and battery, respectively) is an energy storage device that couples the merits of the electrochemical characteristics from the secondary battery and supercapacitors into a single device. To mitigate the detrimental impact of carbon emissions and to utilise renewable sources in places of fossil resources, efficient energy storage is vital to fully realise the intermittent sources such as sunlight, wind and tide. Various materials for batteries and supercapacitors have been reported in the literature but in this work, a link to supercapattery electrode materials design, synthesis and tuning the materials with the need to promote electrode processes and electrochemical reactions for storing and releasing the ions from the aqueous electrolyte have been contributed.

Reversible storing (charging) and releasing (discharging) of ions stems from the optimised electrode material that facilitates the ion transport kinetics and enhances material stability. Recently, mixed metal oxides have been examined to maximise the electrochemical storage performance, but pristine materials tend to be poor conductors. Binary metal oxides (BMOs) with chosen dopants are emerging for energy storage purpose as it demonstrates good redox behaviour, wide potential window, improved conductivity and improved stability. A unique class of binary metal molybdate in the presence of suitable dopants has been examined for supercapattery studies.

We have studied dopants such as zinc (Zn) and gadolinium (Gd) and its effect on binary metal molybdates to enhance the storage performance. Our experimental results showed the electrochemical performance of the doped electrode material exhibited enhanced storage capacity. Zinc (Zn) as a dopant in nickel molybdate ($NiMoO_4$) exhibited a 15% improvement in the energy storage capacity when compared to the pristine material. Extending our studies to gadolinium (Gd) as a dopant in bismuth molybdate (Bi_2MoO_6) improved the capacity twice (from 77 mAh g^{-1} to 153 mAh g^{-1}). A detailed electrochemical insight of the binary metal molybdate and to tackle the challenges of storing more energy with inexpensive cost employing green hydrothermal technique will be presented at the conference.

Lithium boron-hydrogen salts as battery electrolytes

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ABSTRACT

Lithium-ion batteries are the most common carrier of energy that is used to power the majority of portable electronic devices, which also currently lead the market in rechargeable batteries. They exhibit high power density, long cycle life and the ability to quickly charge (Yan *et al*, 2020). However, the development of new technologies requires batteries that possess higher energy storage capacity, less toxicity and lighter components. These requirements have led to extensive research in the development of all-solid-state-batteries (ASSBs). The energy density of a battery cell can be increased with the use of solid electrolytes, as they are compatible with alternative electrode materials, eg lithium metal. Lithium has a low standard half-cell potential (−3.04 V versus standard hydrogen electrode) and a high theoretical capacity (3860 $mAh \cdot g^{-1}$), thus the energy density of the battery can be increased significantly (Kim *et al*, 2019). Metal boron-hydrogen compounds are considered as promising solid electrolyte candidates for the development of all-solid-state batteries, owing to the high ionic conductivity. In particular, *nido*-boranes, boron-hydrogen anions with a nest-like structure, adopt a disordered structural polymorph at elevated temperatures, which leads to superionic conductivity (Tang *et al*, 2017; Souza *et al*, 2021). In this study, derivatives of hydrated lithium *nido*-boranes compounds, $LiB_{11}H_{14} \cdot (H_2O)_n$, were synthesised and their ionic conductivity was investigated at different temperatures. They exhibit a Li^+ conductivity in the order of 10^{-6} S/cm at room temperature, however upon heating, a sudden increase in ionic conductivity occurs, and they reach 10^{-2} S/cm at 70°C, close to what is observed for the currently used ionic liquid electrolytes. Moreover, they also exhibit electrochemical stability above 2.0 V against Li^+/Li at 30°C. These outcomes bring great perspectives for the use of lithium boron-hydrogen salts as electrolytes for the next generation of batteries.

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The role of mineral processing in low-carbon critical battery metals production

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ABSTRACT

The significance of this study is to challenge the association of conventional mineral processing with energy – and carbon-intensive minerals and metal production. The mining industry is contending with increased scrutiny from external stakeholders to improve its environmental credentials where a legacy of high pollution and poor natural resource management poses serious socio-sustainability challenges to the production of the key metals critical in the manufacture of clean energy storage technologies. The IGO Nickel Sulfate ('NS') project is a case study that exemplifies the importance of conventional mineral processing for the integrated production of low-carbon nickel sulfate for the clean energy storage market.

This paper details the test work programs and strategies employed at the Nova Nickel ('Nova') concentrator that enabled the production of a tailored sulfide nickel concentrate suitable as feedstock to a low-temperature pressure oxidation (LTPOX) process to produce a high-quality, low-carbon nickel sulfate product. The program generated four tonnes of high-grade sulfide nickel concentrate with a reduced sulfur:nickel ratio from 2.4 to 1.6 through the improved rejection of pyrrhotite by flotation, using appropriate reagents and regrinding of the intermediate concentrates. The reduction in the sulfur:nickel ratio of the sulfide nickel concentrate yielded several benefits to the environmental credentials of the IGO NS project – equivalent to the reduction in the mass of sulfur to be oxidised. These included a reduction in oxygen production requirements, autoclave quench water requirements, neutralisation reagent requirements, and tailings mass and storage requirements.

By leveraging existing site assets with proactive innovative strategies, the importance of conventional mineral processing to low-carbon critical battery metals production is reinforced.

Mineralogical characterisation of the LCT pegmatites using TIMA and LIBS automated mineralogy techniques

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ABSTRACT

Spodumene is the most valuable Li-bearing mineral present in the LCT pegmatites. Depending on the type of the orebody, it can either present fine-grained mosaics or forms large crystals that are coarsely intergrown with quartz, albite and potassium feldspar. Spodumene can be pink, green, grey, white and translucent and the colour is related to the elemental impurities and the mineral inclusions. Apart from spodumene, lithium is distributed in many other minerals, including micas, tourmaline, beryl, garnet and phosphate minerals. Due to high number of deleterious elements and overall low Li content, they are often considered as unwanted gangue minerals. On the other hand, processing out mica and other Li-bearing gangues could significantly lower the lithium grades in the final product.

Laser Induced Breakdown Spectroscopy (LIBS) from ELEMISSION allows for a rapid and accurate quantitative mineral analysis of large sample specimens including drill cores, rock chips and sand fractions (±1 mm). Unlike the X-ray based techniques, it can directly identify the areas enriched in lithium and define which minerals contribute to the Li concentration in the analysed sample. By understanding the mineral assemblage, informed decisions can be made about the origin and extraction of the valuable mineral.

TIMA automated mineralogy X-ray based technique from Tescan is commonly used for the mineral liberation studies of the crushed ore and metallurgical stream samples. The acquired X-ray spectra are compared with a pre-defined mineral library that includes spodumene and many other minerals. Quantitative mineralogical data are used to optimise process flow sheet for griding, flotation and leaching strategies to get the best quality product.

Short-term outlook for EVs and battery materials

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ABSTRACT

The year 2020 had been billed as a revolutionary year for battery markets and electrification – a prediction that turned out to be true, but not in the way many had planned. Now those markets and the raw materials that supply them are set to charge into 2021 with a new kind of momentum, with new chemistries being pushed forward and the pandemic acting as a catalyst for governments around the world to do more to address global challenges such as climate change. It remains to be seen which technological advances will actually gain traction commercially, and with the metals sector adjusting to competing requirements, will 2021 manage to deliver the rate of progress that many are hoping for? Looking at leading markets, by far the most compelling motivator for European electrification is the penalties incurred by carmakers if they exceed carbon targets for their fleet. European carmakers have seized on the opportunity to move into the new space, with several flagship models scheduled to hit the market in 2021 after their recent unveiling. Looking to Asia, China is moving to boost overall vehicle sales at the start of its 14th five-year plan in 2021. Local governments will encourage residents in rural areas to buy trucks, and will offer subsidies to residents who sell old high-emission vehicles to buy new, low-emission models. Last year, China revised its EV credit scheme, aiming to encourage carmakers to produce EVs and reduce output of vehicles that use fossil fuels. The new program will raise the NEV credit to 14% in 2021, 16% in 2022 and 18% in 2023 – up from 10% in 2019 and 12% in 2020. China has also pledged to keep subsidies in place until at least 2022. Argus Consulting forecasts that EV sales in China will rise by 35% to over 1.3 million in 2021 – a resurgence of growth following a tough year.

Separation of graphite and cathode materials from spent lithium-ion batteries using flotation technology

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ABSTRACT

Since the introduction of the lithium-ion batteries (LIBs) technology in 1991, the market for lithium-ion cells has been driven by the high demand for portable electronic devices and more recently by the electric car industry. However, if spent LIBs are sent to landfill, this is harmful for the environment and also wasteful due to the loss of valuable cathode materials and graphite. For this reason, several physical and chemical recycling technologies have been proposed to recover these valuable materials. Amongst these, froth flotation technology is a cost-effective candidate for separation of the graphite fraction from the lithium metal oxides in spent LIBs due to the hydrophobicity of graphite.

Because of the chemical complexity of LIBs, an exhaustive metallurgical analysis is carried out. These analyses include particle size analysis, scanning electron microscopy, X-ray diffraction, X-ray fluorescence, chemical analysis, contact angle analysis and mineral liberation analysis before and after roasting under controlled conditions.

In order to get a better understanding of the flotation process for spent LIBs when graphite and cathode materials are completely liberated, an experimental study is conducted using binary mixtures of high-purity graphite and lithium cobalt oxide ($LiCoO_2$) battery grade. This study includes analyses of the contact angle of these materials and flotation trials using mixtures at different aeration rates and pH conditions. Flotation results show good recoveries (up to 75%) in one rougher stage for graphite with a moderate entrainment degree of $LiCoO_2$ particles (grades up to 14% in graphite concentrates) depending on processing conditions. This analysis using binary mixtures acts as a benchmark for comparison with flotation trials using electrode materials from commercial spent lithium-ion batteries.

Using machine learning and transfer learning techniques for state of health estimation of lithium-ion batteries

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ABSTRACT

Lithium-ion (Li-ion) rechargeable batteries have gained traction in recent years due to their outstanding cycling efficiencies and power densities with lower costs, and have been extensively used in various applications ranging from portable electronics and medical devices, to electric vehicles and grid-scale energy storage systems. Accurate estimation of the state of health (SOH) of Li-ion batteries is crucial to warrant their safety and reliability in use. Except for the traditional model-based methods for online capacity estimation, data-driving approaches using machine learning (ML) are fast-growing in the field, which relies more on experimental data while knowledge about the battery working principles is less required. Traditional ML methods such as neural networks, support vector machines, and ensemble learning methods have been exploited to extract features intelligently and find out the dependent relationship therein. Such models are built on the assumption that large amounts of data are readily used for training. However, in real-world applications, collecting newly long-term cycling data especially for different operating environments is time-consuming and expensive. To overcome this challenge, we will introduce the concept of Transfer Learning, which is one of the most promising techniques in ML that features in dealing with small training data, how it works, and its potential in the Li-ion field.

From concept to reality – the discovery of the McDermitt Lithium Deposit

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ABSTRACT

The lithium market has experienced a significant uplift in the last 12 months, driven by the global political and social push for electrification of the transport sector. A crucial component for the Electric Vehicle revolution is the lithium required for battery production. The United States currently produces 5000 t/a lithium carbonate equivalent (LCE) with demand forecast to reach 350 000 t/a LCE by 2030.

Lithium is currently produced from two main types of deposits – brine and hard rock. Sediment-hosted lithium deposits represent a third and emerging type which are lower grade than hard rock but very large and mineable at relatively low cost. Until recently, sediment-hosted deposits were considered unfeasible due to a perception that lithium was bound too tightly in the clay lattice to be extracted economically, but studies now support multiple potential options for processing.

In 2018, Jindalee Resources identified ground in Oregon and Nevada prospective for sediment-hosted lithium. The first drill program in 2018 at the McDermitt Project was successful in confirming the concept, and subsequently 29 drill holes have confirmed thick zones of flat lying lithium mineralisation from surface over an area approximately 25 km^2. In just three years McDermitt has advanced from a conceptual target to 10.1 million tonnes of contained LCE in Indicated and Inferred Mineral Resource.

Developing McDermitt will be challenging, as there are currently no operating mines of this type in the world. However, the project also presents a great opportunity due to its size, location and the predicted demand for lithium. Challenging the status quo and thinking outside the box are still important criteria to exploration success and in this case the reward has been the delineation of the largest lithium deposit in the United States.

Mineralogical investigations of Li-pegmatites in Western Australia and implications for process optimisation

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ABSTRACT

Lithium is a key component in the production of rechargeable batteries for use in a wide range of products including portable electronic devices (mobile phones), e-bikes/scooters and energy storage systems. However, electric and hybrid vehicles exert the strongest demand, accounting for ~70% of Li end-use applications in 2020, which is forecast to increase to ~90% by 2031 (Roskill, 2021). With Western Australia currently producing nearly 49% of global Li output in 2020 (USGS, 2021), understanding the mineralogical controls of both economic (Li, Nb, Ta) and deleterious element (F, Mn) distribution is essential in optimising the design and development of LCT pegmatites to meet this increase. To that end, a 2-year Minerals Research Institute of Western Australia (MRIWA) project (M532), supported by industry and GSWA, was carried out with the aim of developing a geometallurgical framework for WA lithium pegmatite deposits, leading to improved efficiencies in exploration, mineral beneficiation and processing techniques. This work presents some of the key research findings of the M532 project, which encompassed petrology, mineralogy, geochemistry and geochronology of LCT-pegmatites from the Yilgarn (Murchison, Goldfields, Southern and Southwest regions) and Pilbara Cratons. This research demonstrated that pegmatite mineralogy has important implications for process optimisation. For example, hydrothermal alteration of spodumene preferentially leaches Li from the spodumene structure as well as introduces contaminants such as K, Mg, Rb and F hosted by secondary, Li-bearing mica ('sericite') as a network of fine-scaled, fracture and cleavage-controlled veining. Thermal decomposition of the sericitic veining under calcine roasting conditions, can potentially result in the formation of a melt phase that forms liquid coatings along fractures and fills pore spaces. This can partially encapsulate the decrepitated spodumene and effectively removes the Li in the core from being leached, thus reducing overall recovery.

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Modelling metals demand for a transition to electric vehicles using a stocks and flows framework

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ABSTRACT

This presentation explores the impacts that electric vehicles (EVs), and their changing battery requirements, have on demand for cobalt, nickel, and lithium, under three related scenarios involving limited changes in both EV technology and EV life cycles over time.

A Physical Stocks and Flows Framework (PSFF) is used. PSFFs enable a user to keep track of the physical supply and demand dynamics of a scenario in a manner that ensures the model is coherent, and that analysis based on it remains internally consistent.

One insight from the modelling is how different the outlook for these three battery metals may be, even under the same scenario, particularly with regard to timing. Cobalt, for example, may be a short-term opportunity only. Nickel experiences a longer demand window but is nevertheless quite constrained. Lithium appears to have an extended and bright future under most scenarios.

A PSFF also facilitates modelling of the highly disparate impact that alternative developments in the 'circular economy' would have on demand for these metals. One key insight is that primary nickel and cobalt producers could have a very strong interest in encouraging the rehabilitation of ex-EV batteries for 'second-life' applications. This contrasts directly with the strong negative effects that the alternative (direct scrapping and recycling) would have on their prospects.

The main goals of the presentation are to: 1) demonstrate how even a few simple variations in assumptions around how the transition to EVs will play out will have very different implications for demand of individual metals; and 2) demonstrate the value of a PSFF for identifying opportunities and as a risk management tool.

Ultrasonochemical synthesis of iron oxide nanopowders as li-ion battery anode material

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ABSTRACT

Current global problems of climate challenges have highlighted the importance of self-sustainable energy production and utilisation. Electricity is an essential energy for everyone in daily life, which powers homes, transportation, activities, jobs and communication. A portable energy storage device becomes an area of interest for researchers in many years, to provide energy for everyone at any time. Among the other rechargeable batteries, the lithium-ion battery (LIB) has been paid much attention due to its high energy density, stable cycling performance and lower self-discharge. To optimise these properties, the electrode material plays an important role as an active material for the electrochemical reaction.

In recent years, transition metal oxides have become the most favourable material due to their ease of handling and high capacities (Fang, Bresser and Passerini, 2020). Our research has been focusing on employing iron oxide (α-Fe_2O_3) nanoparticles as LIB anode. Previous studies show that α-Fe_2O_3 nanoparticle has a promising capacity by 1187.1 mAh/g (Li *et al*, 2019), 937 mAh/g (Wu *et al*, 2019), and 800 mAh/g (Luo *et al*, 2019). However, the fabrication processes are complicated and not cost-effective for commercial application (Yu *et al*, 2018) and thus, it remains challenging for the industrial stage.

In this research, we utilise an eco-friendly ultrasound-assisted synthesis technique as it is well-known as a facile, low-cost, and eco-friendly technique for nanostructure synthesis (Chatel, 2018; Poinern *et al*, 2009). We used advanced characterisation including X-ray powder diffraction (XRD) and Fourier transform infrared spectroscopy (FTIR) to observe the phase purity, transmission electron microscopy (TEM) to determine the particle size and morphology, thermogravimetric analysis (TGA) to investigate the particle stability at high temperature, and finally cyclic voltammetry (CV) to study the electrochemical performance.

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An overview of two enhanced hydromet processes for cost-effective recycling of LIB cathode materials

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ABSTRACT

Hydrometallurgy is an important method for recovering valuable materials from waste lithium-ion batteries (LIBs). But in the traditional leaching process, the valuable metals in spent cathode materials are individually recovered in separate steps. This increases the cost and complexity of the process, impacting its economic viability. Reducing the number of steps has obvious economic and feasibility advantages.

In this paper, overviews of two enhanced hydromet processes are presented. Both processes reduce the number of steps required to recover the valuable metals from spent LIBs, and have undergone or are undergoing industrial implementation in China. Variations on the processes are also discussed.

The first process reduces the number of process steps by co-extracting the transition metals in a single step, followed by their co-precipitation as regenerated cathode precursor materials. After being separated from the lithium, the transition metals are extracted and crystal-controlled growth technology is used to produce spherical nickel-cobalt-manganese hydroxide precursor materials. The lithium in the raffinate is recovered by carbonate precipitation to form lithium carbonate. The regenerated lithium carbonate and the nickel-cobalt-manganese hydroxide are mixed and sintered to produce ternary lithium-ion battery cathode materials, realising a cost-effective closed-circuit recycling process for lithium-ion battery cathode materials.

The second process uses waste graphite as a reducing agent to reduce cobalt (+3) and other elements in the cathode material to a low-valence state (+2) through roasting, and converts lithium to lithium carbonate. After this reductive process, transition metals and lithium can be easily leached at a lower temperature using less acid and other reagents. This process also adds environmental value by making full use of the energy and reducing properties of waste graphite, by treating waste with waste, and by reducing the acid mist and acid wastewater produced by the traditional leaching process.