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*Including*  
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## Lithium Processing Keynote

### INNOVATION REQUIRED TO MEET FUTURE LITHIUM DEMAND

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#### ABSTRACT

With a seemingly insatiable demand for lithium-ion batteries accelerating globally, we, as a wasteful society, discharge more lithium to waste than ever enters the supply chain.

Within the supply chain itself, lithium has become a disposable commodity, a large proportion of it ultimately relegated to landfill.

Meanwhile, much lithium not actually entering the supply chain is lost to inappropriate processing technologies or a dearth of meaningful attempts to recover any when it is associated with other commodities, such as tin and tantalum. And all of this occurs in the shadow of potential supply shortages.

The solution to ethical and sustainable lithium supply lies in better resource utilisation and effective recycling.

There are several elements to better resource utilisation. With respect to hard-rock sources of lithium, different styles of mineralisation can be exploited, among them greisen, clays and waste discharge streams containing lithium micas. In the case of lithium brines, yield can be improved using chemical processes that recover lithium more efficiently than via evaporation ponds.

Within the supply chain itself, lithium can be recycled by way of hydrometallurgical rather than pyrometallurgical techniques, since the latter discharge lithium to useless slag or flue gas.

Unutilised opportunities to improve efficiencies throughout the lithium cycle (as in the production of lithium-ion batteries) are outlined in this paper.

*Keywords: lithium, sustainable, ethical, clay, brine, greisen, recycling, LieNA<sup>®</sup>, SiLeach<sup>®</sup>*

## INTRODUCTION

Worldwide, a seemingly insatiable demand for lithium-ion batteries (LIBs) in energy distribution applications is driving a revolution in lithium production, with demand rising as for few other commodities. Government agencies in many countries have intensified that demand by legislating for a range of clean-energy initiatives that, presently, can only be fulfilled using LIBs. Energy policies are aimed not only at weaning consumers away from vehicles powered by internal combustion engines (ICEs) but also dismantling coal-fired power stations and replacing them with sources of renewable energy and energy storage systems (ESSs)

Original equipment manufacturers (OEMs) have committed to a battery-dependent future and, to meet societal needs, the battery industry's resolve has contributed to growth from a production base of 19 gigawatt hours (GWh) in 2010 to an installed capacity of 285 GWh in 2019, with major expansion planned across Europe and Asia. Currently, about 70 LIB production plants are on the drawing board and, once these are established, they should take installed annual capacity to around 1.5 terawatt hours (TWh) in less than a decade <sup>(1)</sup>.

Thus the battery manufacturing landscape is changing rapidly, a trend that will see the much touted Tesla Gigafactory 1 in the US <sup>(2)</sup> dwarfed by single production facilities the capacities of which exceed – by a factor of three <sup>(3)</sup> – that which was considered revolutionary only a few years ago. Commitments to these facilities are costed at hundreds of billions of dollars, meaning LIBs are now firmly established as a long-term component of the energy industry. Commercially, then, the LIB industry is past the point of no return in terms of the massive capital investment involved. That, however, does not mean LIBs will cease to evolve; nor does it mean the battery landscape will be devoid of LIB substitutes. What is clear, nevertheless, is that we are locked into lithium's long-term domination as a means of transferring energy at cell level within committed battery architectures.

A strong alliance between OEMs and LIB producers will see the expansion of LIB use in Asia, Europe and the Americas as production capacity increases from GWh to TWh annually.

It seems that the future of LIBs in mobile energy applications is assured, but what of ESSs? Eventually, lithium capacity for use in ESSs could eclipse that for electric vehicles (EVs) as the world transitions to renewable energy – but can current battery architecture fulfil these needs? Already there are many competing technologies for ESSs, including vanadium flow, zinc redox and, of course, lead-acid batteries but, given the duty requirements of such systems, right now LIBs offer the best combinations with which to meet operating specifications and cost. And, as mass production of LIBs for EV applications further reduces the cost of such vehicles, there is the potential for LIBs to become embedded in grid-scale ESSs in the longer term.

Despite this accelerating demand for lithium, however, large quantities continue to be discharged in mining waste streams or lost via inefficient processing, with both scenarios equating to sub-optimal resource utilisation. Indeed, there is some concern as to whether the minerals industry as it stands can meet projected demand for lithium, with cumulative annual growth rates for LIB applications forecast at around 19% or higher. Meanwhile, the mining industry maintains its culture of 'more of the same', including profligate waste, and downstream consumers continue to discard spent product, turning municipal landfill sites into the battery mines of the future.

The alternatives to such wasteful practices involve:

- better use of available resources;
- exploitation of alternative lithium sources, and
- recycling of LIBs to recover *all* the metals they contain.

## THE ABUNDANCE OF LITHIUM

Lithium is the 25<sup>th</sup> most abundant element on Earth. Its fractionation by geological processes enhances its ubiquity in the continental crust (compared to its abundance globally). As the continental crust evolves, lithium concentrations in the more volatile fraction of silicic magmas increase. Lithium is preferentially expelled in violent explosive events as magmatic flows, ejecta and magmatic fluids. The resulting deposits, preserved in a number of locations along the Andean/Rockies mountain chain in the Americas, appear as rhyolites, tuffs and clays.

Lithium's moderate incompatibility as a trace element means it also concentrates in sediments during erosion cycles, not as a primary mineral but as a component of clays. Subduction and the re-melting of continental sedimentary materials are nature's lithium recycling plan. Subsequent erosion and weathering cycles discharge lithium (it being very soluble) into the oceans. Indeed, lithium's solubility during weathering cycles is such that no secondary lithium minerals occur, except as clays and evaporates; indeed, its preponderance in the arid lake systems of the so-called 'Lithium Triangle' (the confluence of Chile, Bolivia and Argentina) is a prominent example of the latter.

To put global lithium distribution into perspective, and to ponder some potential sources of long-term supply, it's worth looking at how lithium is partitioned overall (Table 1).

**Table 1. Common lithium abundances**

Source	Concentration (ppm)
Seawater	0.17
Chondrites	1.5
Oceanic crust	2
Continental crust	20
Argillites	Up to 100
Oilfield brines	150 – 300
Salars	200 – 2700
Greisen	1000 – 2000
Lithium clays and tuffs	1000 – 3000
Lithium-cesium-tantalum pegmatites	2000 – 8000
Spent LIBs	40,000 – 70,000

## LITHIUM DEMAND

Today's common LIB chemistries consume approximately 700 grams of lithium per kWh of storage capacity. It's expected that around 1.5 TWh per annum of LIB production capacity will be installed by 2028, so it is easy to see how lithium supply constraints could arise. Such capacity will require about 700,000 tonnes per annum (tpa) of lithium annually (i.e. 3.6 million tpa of lithium carbonate equivalent (LCE)). Given that current levels of production are barely above 200,000 tpa LCE, an increase in lithium chemical production in the order of 15-fold will be required over the next 10 years to meet future demand. It is interesting to note that this volume equates to the roughly 50 million new EVs that will have to be produced annually to replace the ICEs that will be outlawed in many jurisdictions by 2030.

Despite the rapid escalation in production of lithium concentrate currently occurring in Australia, it's unlikely that new concentrate production can meet demand in the longer term. Satisfying consumer demand for lithium will thus require much greater resource utilisation (improved recoveries), as well as the exploitation of less conventional sources.

## THE RECOVERY DILEMMA

### Hard-rock Deposits

Historically, lithium was mined from pegmatite deposits in North Carolina, Zimbabwe, Portugal, Brazil and China. With the advent of cheaper lithium production from brines in South America (and to a lesser extent China) in the 1980s, however, hard-rock production in the aforementioned countries dwindled. Then, from the 1990s on, production of spodumene concentrate came to be dominated by the Greenbushes mine in Western Australia – a situation that persisted until the commissioning of new production in that Australian state by the likes of Galaxy, Pilbara Minerals, Altura, Minres, Neometals, etc.

More recent developments in Western Australia (Wadgina, Pilgangora, Mt Marion, Bald Hill, Mt Cattlin and Earl Grey), as well as the expansion of Greenbushes, will result in considerable extra lithium feed, as will new projects in Canada and southern Africa, but requirements are still likely to outstrip supply in the longer term.

To date, spodumene deposits mined have shown yields to commercial lithium concentrate of 50-70%, with some operations targeting optimised recoveries of 75%. But where is the rest reporting?

Often, lithium pegmatites are characterised by complex mineralogy, with the lithium occurring in more than one mineral phase. Product specifications for commercial spodumene concentrates preclude other lithium-mineral contaminants, meaning that lithium micas, petalite, amblygonite, eucryptite, etc. are rejected as tailings. Under some circumstances this can lead to lithium losses of as high as 30%. The situation is exacerbated by the requirement to meet quality specifications for commercially traded spodumene concentrates. Moreover, not only is liberation (to achieve chemical specifications) an issue but the specified particle size for conventional 'converter' feed also reduces yield, the principal factor being the need for acceptable sizing to feed counter-current rotary kilns.

## **Brine Production**

While there are many types of lithium-bearing brines, including oilfield brines, geothermal brines and continental brines, commercial lithium production from such sources is currently confined to the processing of continental brines – lithium recovery is usually achieved by pumping the brines into evaporation ponds, then progressively evaporating them and precipitating unwanted components. Once the brine that remains contains a high enough concentration of lithium (5-6%) to warrant chemical processing, it is removed from the ponds as a solution and processed in a lithium recovery plant to produce lithium carbonate by precipitation.

Generally there is no requirement for the evaporation ponds to be lined, given that they sit above the aquifer from which the brine is pumped. While leakage is of little environmental concern, it does result in high lithium losses, especially since solar evaporation can take from 18 months to 2 years to achieve the required outcome. During that period, rain and flooding can also have a marked impact on production. Thus, lithium extraction from brines via conventional processes is inherently inefficient; indeed, the poor lithium yield from brines is comparable to that of hard-rock operations.

## **Unconventional Sources**

Lithium has been recorded in more than a hundred naturally occurring mineral species and, due to its high solubility, is a common component of a wide range of water sources derived from both meteoric and magmatic origins. Apart from spodumene, petalite and brines (the latter, as noted, being currently exploited in both the Lithium Triangle and China), most other occurrences of lithium are either at grades too low to be commercially viable or exhibit challenging metallurgy, which also makes operating costs uncompetitive. Nonetheless, research and development activities to improve lithium extraction/recovery techniques and create a more sustainable resource base are ongoing.

Although in the past lithium micas – mainly lepidolite and zinnwaldite – have been exploited for lithium production, low grades and metallurgical recoveries have presented competitive challenges; thus, global utilisation of such materials for lithium production has been limited. That said, lithium mica mineralisation is extensive, so research to resolve these challenges is also ongoing.

Another lithium occurrence that can be classified as unconventional is the giant Rio Tinto-controlled Jadar deposit in Serbia. There, the lithium mineralisation occurs as jadarite, a lithium borosilicate discovered in 2004. In fact, Jadar is the only known occurrence of such mineralisation. While little with respect to production strategies is known, commercial output is anticipated in 2023.

## **THE NATURE OF UNCONVENTIONAL SOURCES OF LITHIUM**

### **Geothermal and Oilfield Brines**

There have been numerous studies on the recovery of lithium from geothermal and oilfield brines. Most commonly, the solution phase is the target carrier, although the sludge and scale that precipitate as a result of changes in pressure and temperature have also been evaluated. Among the recovery techniques investigated are ion exchange (IX), adsorption, membrane filtration and precipitation <sup>(4)</sup>.

That said, the low concentrations of lithium within such sources present a challenge from both a processing point of view and also, in the case of oilfield brines, the expense of pumping from great depths. Despite these difficulties, attempts have been made to recover lithium from geothermal

brines in Japan and New Zealand. More recently, bids to recover lithium and other metals from the Salton Sea geothermal field in the United States (where lithium could be considered a by-product of geothermal power) have proved unsuccessful.

In Britain, the Cornish tin belt contains numerous high-level peralkaline intrusions, exemplified by the fluorine-rich leucogranite of the St Austell pluton. These intrusives – a source of tin and copper in the region – contain many volatile and incompatible elements, including lithium. High geothermal gradients result in the hot springs often encountered in mine workings; they probably comprise a mix of magmatic fluids and ground water, circulated by the underlying heat source. Such symbiosis has led to recent assessments of mine water as a potentially commercial source of lithium, as well as prompting regional exploration for other lithium brine occurrences <sup>(5)</sup>.

## Lithium Clays

Recently lithium clays, albeit low in grade in comparison with more conventional hard-rock lithium deposits, have garnered considerable attention. Deposits in Mexico (e.g. Bacanora's Sonora and Lithium Australia's Electra deposits) have been metallurgically assessed, with future production from the region anticipated. Other lithium clay deposits – among them Rhyolite Ridge in Esmeralda County, Nevada – contain lithium and boron in a thick sequence of volcanogenic sediments <sup>(6)</sup>.

As noted, lithium clay deposits present unique challenges in that they are of a low grade; moreover, proposed flow sheets for lithium recovery in such instances are often energy-intensive. Lithium production from deposits with recoverable boron may be the subject of restrictions if boron markets limit by-product credits and in so doing limit the scale of production. Indeed, B:Li ratios as high as 10 make reliance on boron markets a key consideration for commercial development. Although not a clay deposit, Rio Tinto's Serbian Jadar project will be the subject of similar commercial considerations, because it can be considered a boron deposit with a lithium credit (Resource 135 Mt @ 1.86% Li<sub>2</sub>O and 15.4% B<sub>2</sub>O<sub>3</sub>).

## Seawater

Despite seawater containing very low concentrations of lithium (generally around 0.17 ppm), it too has attracted some interest as potentially commercial lithium feed in recent times <sup>(7)</sup>. Recovering lithium from seawater would not be as challenging as the tantalising but unlikely prospect of extracting gold (concentrations of about 0.000004 ppm) from the same medium, as the amount of lithium in solution can be boosted by way of evaporation, adsorption and electro dialysis, followed by purification and precipitation of lithium carbonate <sup>(8)</sup>.

Also with respect to seawater, commercially viable lithium recovery may be achieved where the water contains higher initial concentrations of lithium, in which case recovery is more competitive and so more favourable than for brines, which – ironically – were targeted in the first place to resolve extraction problems. If the recovery issues for seawater can be resolved, its commercial advantages will centre on location and its ubiquity. In fact, exploiting seawater as a source of lithium could resolve much in the way of political uncertainty and security risks and in so doing enhance sustainability.

## Spent Lithium-Ion Batteries

Worldwide, the enthusiastic adoption of LIBs, particularly for portable power, is very environmentally concerning, in that only around 9% of spent batteries are recycled to keep them out of landfill and recover the valuable metals they contain. (In Australia, the recycling rate is even worse: < 3%.) In fact, the huge amount of batteries discarded globally represents a potentially significant resource.

At present Belgium, South Korea, China and Canada recycle the greatest amount of batteries, with the metals these contain generally recovered by smelting. However, this involves pyrometallurgical processes that are highly inefficient in recovering lithium, the extreme volatility of which means it is usually lost in flux or off-gas. Flux is not generally reprocessed, being used instead as aggregates and fillers, which precludes the reuse of the lithium. Research into the recovery of lithium through condensation of smelter off-gas, however, is currently underway.

With such inherent shortfalls in the pyrometallurgical processing of spent LIBs, hydrometallurgical recovery of the metals they contain seems a more obvious choice for resolving the entire recycling dilemma.

## Lithium Micas

Lithium is present as a trace element in a number of phyllosilicate groups or, in the case of lepidolite and zinnwaldite, in percentage concentrations. Lepidolite is found in lithium-cesium-tantalum (LCT) pegmatite, in gneisses and in greisen. The paragenesis of the latter is as residual magmatic fluids crystallising within the roof of highly volatile granitic magmas. If the magmatic fluids are expelled from the magma chamber along brittle failures in surrounding country rock, pegmatites – possibly of the LCT type – are formed.

Lithium micas, and lepidolite in particular, are commonly associated with tin, tantalum and tungsten mineralisation and, where such mineralisation is mined, are discarded as waste.

Although it is stoichiometrically possible for lepidolite to contain nearly 8% Li<sub>2</sub>O (lithium oxide), the percentage is usually much lower. Indeed the nature of the concentrates produced from deposits with lepidolite as a major component can be quite variable. Lepidolite often occurs as mixed-layer aggregates, where it may be intimately associated with muscovite-like micas; this precludes the recovery of clean concentrates, which from a commercial viewpoint means that producing concentrates with grades exceeding 4% Li<sub>2</sub>O is difficult.

Zinnwaldite – which occurs in similar geological environments to lepidolite but seems more common in greisenised granite cupolas than pegmatites – generally contains lower concentrations of Li<sub>2</sub>O.

Where lithium micas are processed to produce lithium chemicals, this has until now been achieved by way of the same conventional 'conversion' processes used to recover lithium from spodumene. Such processes begin with roasting and, in the case of micas, the production of hydrogen fluoride (HF), as the micas contain 3-7 percentage-by-weight of fluorine. Quite apart from the fact that HF production involves safety issues, there is the necessity for specialised materials of construction. So, while simplistically these conversion processes involve energy and reagent consumption similar to those for the refining of spodumene, the feed grade for lithium micas is about half, meaning the operating cost per unit of lithium chemical produced is roughly doubled.

Less conventional approaches to recovering lithium from micas have led to many alternative pyrometallurgical flow sheets. Roasting with sulphates and carbonates prior to acid leaching, for instance, is the approach adopted for feasibility studies into the processing of zinnwaldite from the Czech Republic (Cinovec) and Germany (Zinnwald)<sup>(9)</sup>. Other, similar solutions to recovering lithium from clays have also been investigated.

To summarise, then, the challenges inherent in the pyrometallurgical processing of micas to recover lithium include:

- high energy consumption;
- control of fluorine, and
- the need for specialised materials of construction,

which strongly suggest that a hydrometallurgical approach may be more viable.

## UNREALISED OPPORTUNITIES

The global abundance of lithium described in Table 1, indicates how, and where, improvements to lithium supply are likely to occur.

Without radical departures from current processing technologies, lithium supply will most probably be enhanced by greater exploitation of known sources and material discarded during the processing of other resources. The best targets, then, are:

- waste generated during the processing of spodumene;
- the lithium micas found in pegmatites and greisen, and
- spent LIBs.



In line with a major push by consumers and legislators for greater sustainability overall, as well as greater protection of the environment, the ubiquity of the aforementioned sources renders each an ideal focus in the quest for improvement.

## Spodumene Tailings

Given the ways in which spodumene mineral separation circuits perform, and how commercial concentrates are currently produced, most pegmatite orebodies offer only a low lithium yield. Partly, the issue revolves around the product specifications for spodumene conversion in China (and soon Australia), which involves spodumene concentrates being fed into rotary kilns for the first stage of the lithium extraction process. The kilns convert  $\alpha$ -spodumene (unreactive with sulphuric acid) to  $\beta$ -spodumene, from which the lithium is recovered by a sulphation bake and subsequent water leach. The lithium is extracted as a sulphate solution, which is then purified prior to the manufacture of lithium carbonate or lithium hydroxide.

Although well established, such 'conversion' processes have a number of shortfalls: not only are they energy-intensive but feed rates are dependent on particle size (as gas flow is counter-current to the flow of concentrates being converted from  $\alpha$  to  $\beta$ -spodumene). Relatively coarse feed material is best for such systems, but producers must deal with trade-offs that include:

- liberation;
- concentrate purity, and
- product size specifications.

To date, trade in spodumene concentrates has been a 'buyers' market', with China dominating downstream conversion activities and the production of lithium chemicals. However, that will change as refining facilities in Australia (among them Tianqi, Albemarle, Minres and SQM/Kidman) come online. Although these companies should have greater flexibility in terms of product specifications, from a practical point of view the refining will still entail commercial trade-offs, in that much of the fine spodumene will be discharged to tailings.

Lithium Australia has been working with ANSTO Minerals to not only solve the fine-spodumene dilemma but also develop a less energy-intensive alternative to conventional conversion processes. To that end, the company has developed the LieNA<sup>®</sup> process<sup>(10)</sup>, a caustic digest of spodumene. In effect, it generates a phase change analogous to conventional 'conversion' processes, but it occurs in solution rather than in a furnace.

During the LieNA<sup>®</sup> process, fine spodumene is fed into an autoclave, where it reacts with caustic soda to form a synthetic lithium sodalite. Most of the lithium partitions into the newly formed sodalite, which is recovered via a simple solid/liquid separation step. The lithium within the sodalite is weakly bound, so an exchange reaction that substitutes H<sup>+</sup> for Li<sup>+</sup> allows it to be recovered from the solid by leaching in weak acid. A simplified pictorial flow sheet is provided in Figure 1.

The LieNA<sup>®</sup> process, rather than being *sensitive* to fine spodumene, *requires* fine spodumene as a feed source to achieve acceptable kinetics.

So, what are the ramifications of a process designed to recover lithium from fine spodumene? If we assume that Western Australian spodumene concentrate production will soon eclipse 5 million tpa (Mtpa), and that the average recovery will result in a fine discharge of 1.7 Mtpa of spodumene (of which 75% is recoverable), that leaves around 1.3 Mtpa spodumene fines available for processing via LieNA<sup>®</sup>. That quantity of fines could produce about 170,000 tpa LCE. Such is the waste inherent in the lithium industry! Adoption of a LieNA<sup>®</sup> processing strategy could also allow utilisation of many years' worth of stored tailings containing fine spodumene.

The ability to process such sources of fine spodumene would create a new market for concentrate producers, allowing them to better utilise resources. That in turn would improve sustainability and help meet the rapidly escalating demand for lithium.

Lithium Australia seeks partners to assist in evaluating the recovery of lithium from fine spodumene in both current tailings discharges and historic tailings in storage facilities.

## LieNA<sup>®</sup> process steps

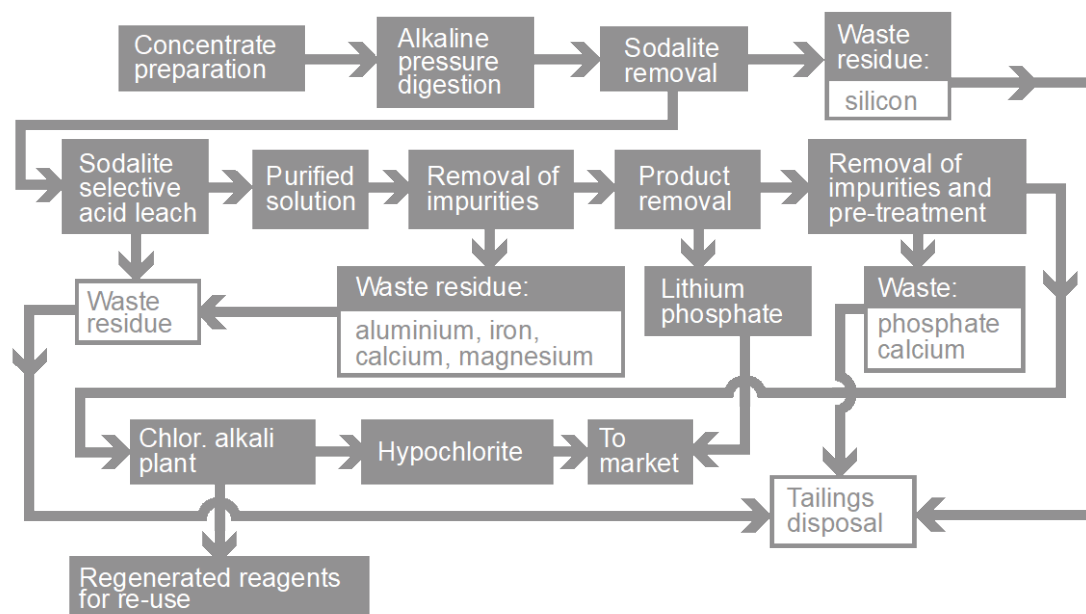


Figure 1. Simplified LieNA<sup>®</sup> flow chart.

### The Lithium Miccas

As discussed, lithium miccas are a most abundant group of lithium minerals. Although they can and have been processed using conventional 'conversion' techniques, this has proved commercially uncompetitive compared to using spodumene concentrates as a feed source. In the early 2000s in China, there were some attempts to reinvigorate this approach but they failed. Now, however, increasing lithium prices have rekindled interest and a small number of conversion facilities have been built in that country. While it is not possible to employ the same processing technology as that used for spodumene with an operating cost that remains competitive, other factors may be driving the resurgence. Clearly the high prices for lithium chemicals help, but the source and cost of feed materials may be far more important drivers. Benefitting most from the processing of lithium miccas involves taking advantage of that material's low value, in that it is considered a 'waste' product, one that would generally be discarded.

Ideally, the production of lithium chemicals from a cheap feed source like miccas should be by way of processing routes that involve:

- low energy consumption, and
- by-product credits.

Such parameters are desirable in that they improve the commercial outcome for processing low-grade concentrates.

Hydrometallurgical approaches provide the option of low energy consumption and an opportunity to recover valuable by-products. While various studies on various types of strong acid have been undertaken, sulphuric acid is the most attractive option, being cheap and readily available. The downside of using any strong acid as a lixiviant is the quantity required, since the cations released on digestion of the mica must be maintained in solution, balanced by the acid's anion.

Miccas have variable chemistry (complex solid solution series). Most target miccas contain more than 10% potassium oxide, which can be recovered as sulphate of potash. Although miccas are low in sodium, other alkalis – in the form of rubidium and cesium – may be present, and these too can be recovered as by-products.

In addition to the LieNA<sup>®</sup> process, Lithium Australia has been developing its SiLeach<sup>®</sup> process for several years in partnership with ANSTO Minerals <sup>(11)</sup>. SiLeach<sup>®</sup> is a sulphuric acid digest kinetically

enhanced by the addition of calcium fluoride. Enhanced kinetics mean the process can occur in smaller reaction vessels. The elegant SiLeach® flowsheet (Figure 2) takes an unconventional approach to enhancing kinetics and the recovery of lithium. Lithium carbonate at the pH usually required for precipitation has a relatively high solubility. Evaporation to increase the tenor of the lithium in solution is a common method of achieving the levels of lithium that allow precipitation to occur. Although evaporators/crystallisers can be used for this, they are capital-intensive and operating costs are high. Lithium Australia's alternative is to precipitate lithium as lithium phosphate, which has a very low solubility, eliminating the need for evaporators to recover the lithium.

## SiLeach® process steps

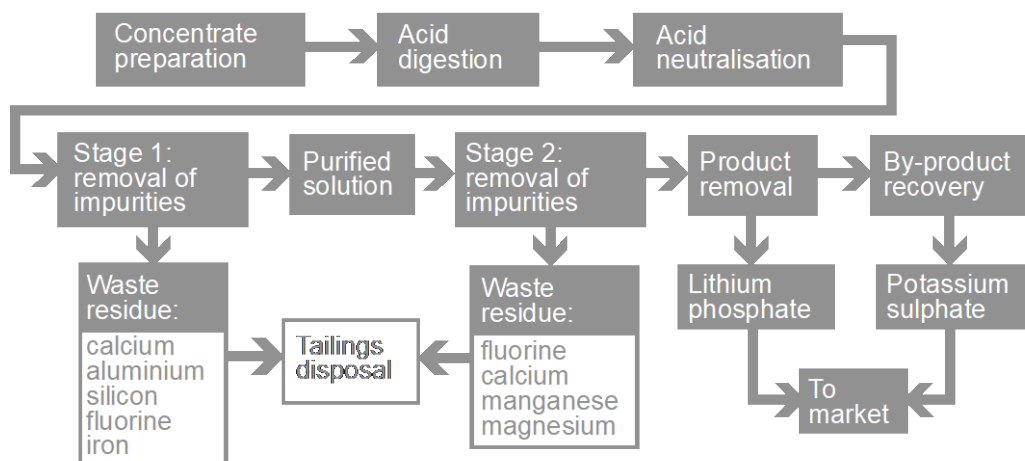


Figure 2. Simplified SiLeach® flow chart.

Precipitation of the lithium as a phosphate resolves some of the expensive water-balance issues encountered with more conventional lithium carbonate precipitation. Moreover, there is a direct path to cathode powder production, with the patented processes of Lithium Australia's wholly owned subsidiary VSPC Limited being used to generate lithium-iron-phosphate powders (LFP) <sup>(12)</sup>. The powders created are now being tested by battery producers in China, Japan and South Korea.

The techniques Lithium Australia has developed for the precipitation of lithium phosphate may also be applicable to lithium recovery from brines <sup>(12)</sup>: eliminating the need for evaporation ponds would lessen capital input, improve residence times, potentially recover more lithium and reduce the environmental footprint of such operations.

### Processing Spent Batteries

Pyrometallurgical processing of spent batteries can efficiently recover nickel, copper, cobalt and manganese from LIBs but not the lithium, shortages of which could inhibit unconstrained expansion of the battery market. Nor does pyrometallurgical processing recover graphite from LIBs. Moreover, volatilisation of the complex polymers in the binders and separators found in LIBs presents an atmospheric emission risk.

A potential alternative to the downsides associated with pyrometallurgical processing of spent LIBs is thus a hydrometallurgical approach. The bulk chemistry of a mixture of LIBs bears a strong resemblance to that of a high-cobalt lateritic nickel deposit, albeit the bulk of the components in the former occur as metals – copper, aluminium, tin and iron as components of the steel casings, and nickel, manganese, cobalt, lithium and aluminium in the spinel (the backbone of the cathode). All can be dissolved in acid to produce a solution of sulphates, chlorides, nitrates, etc.

Again, considerations of cost and efficiency point to the use of sulphuric acid as a lixiviant, with subsequent recovery of metals from the battery materials as sulphate solutions. A combination of precipitation, solvent extraction, IX and other conventional metal-extraction techniques can be used to separate those contained metals. An alternative is to readjust the metal ratios of the solution by adding specific ionic species and directly precipitating cathode powders.

Dissolving cathode materials without any thermal treatment is difficult, since the binding material in the cathode – a complex organic polymer, usually polyvinylidene difluoride – is designed to allow

the passage of lithium ions but restrain larger ions. However, it can be accomplished with organic solvents. A more practical solution, however, is low-level thermal treatment, which can sufficiently degrade the binder without any loss of lithium. Subsequent dissolution of the cathode material with sulphuric acid means that all metals in the LIBs can be extracted as sulphates in solution.

It may seem that the key to efficient LIB recycling is product preparation prior to hydrometallurgical recovery, but that is not the case. The greatest challenge remains logistics – collecting enough batteries to ensure a viable enterprise. An inability to aggregate the feed for recycling plants is the main reason that LIB recycling rates remain so low.

Lithium Australia is investing in the logistical infrastructure necessary to recycle LIBs through its partnership with Envirostream Australia <sup>(13)</sup>, which supports recycling nationwide and will apply its collection know-how to other jurisdictions in due course.

## CONCLUSION

The rapidly rising demand for LIBs will create a mismatch in the critical metal supply chain. With 1.5 TWh per annum of installed battery production capacity planned for the next 10 years, it is difficult to determine how the need for critical metals will be met. Primary lithium supplies are unlikely to match demand requirements unless the industry improves both efficiency and resource utilisation.

While some unconventional sources of lithium, including seawater, could prove a seemingly infinite resource, commercial practicality may prevent them becoming an industry saviour. The vast quantities of waste discharged during tantalum, tin and tungsten mining operations, on the other hand, often contain associated lithium micas. Such waste is an obvious target, since mining and some processing costs are already covered by exploitation of the primary minerals. That said, efficient processing technologies such as SiLeach<sup>®</sup> are required to turn this opportunity into a practical source of certain critical metals. Improved processing efficiency could even lead to the lithium in such mining operations becoming the primary target, with tin (or other metals) seen as by- or co-products.

Spodumene mining and concentrate production are other areas in which a change of processing technology could allow for much greater resource utilisation and the production of considerably more lithium for each tonne of ore extracted. Technologies like LieNA<sup>®</sup>, with their potential to improve recoveries and utilise material unsuitable for conventional lithium 'converters', present the industry with a great opportunity. Implementing such processing philosophies could provide the battery industry with far greater amounts of lithium chemicals without increasing mine production.

Finally, it is incumbent upon all of us to gain maximum benefit from the world's resources while also protecting the environment. That means preventing spent batteries – and both the metals and toxins they contain – from being consigned to landfill and ultimately affecting the water table. The solution, of course, is to recycle all LIBs, rebirthing the valuable materials they contain. Globally, the LIB industry must aspire to achieving the recycling levels of the lead-acid battery industry. Recoveries beyond 90% should be the aim, rather than the more than 90% disposal that is presently the case.

We sit at the brink of a new age in energy management, where ethical and sustainable supply is paramount, to not only meet demand but also protect our planet for future generations. There are many ways to achieve these goals, and seizing presently unrealised opportunities will give the LIB industry a platform upon which these goals can be achieved.

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