Pioneering recycling technology for end of life lead-acid batteries

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Aurelius

FENIX

Lead-Acid Battery Recycling – a different way

Circular Economy team Aurelius Environmental is piloting a green, low-cost and highly efficient hydrometallurgical process for the recycling of lead-acid battery paste.

Founded in 2014, Aurelius Environmental Limited is a visionary and innovative waste management and recycling company. The team is working primarily, but not exclusively, on lead-acid battery and lithium-ion battery waste streams.

Our company's mission is to bring about a revolution in recycling. We are thinking of waste and the cities of the future as ecosystems having endless possibilities. Our vision is a web of industries, where one stream's waste is another stream's feedstock – bridging linear and wasteful processes to create circular, energy-efficient, non-polluting, zero-waste industries. We want to add economic and societal value in all markets in which we operate, promoting sensible and sustainable technologies which are 'best fit' for the local jurisdictions in which they are deployed.

Our stepping stone towards this vision is a technology for the recycling of lead-acid battery paste. Invented by Professor Vasant Kumar at the University of Cambridge in 2006, the technology promises to deliver significant improvements to the lead recycling/secondary lead industry, as well as the lead-acid battery itself. In partnership with the University of Cambridge, we are developing, piloting and scaling-up the technology as a potential alternative to waste battery paste desulphurisation and/or smelting.

Dubbed FenixPb, our hydrometallurgical process is a zero-emission, low-carbon footprint, energy-yielding process which delivers a step-change in the lead-acid battery recycling industry.

Where we are

At Aurelius we have extensive knowledge of the waste and recycling industry. We have a proven track record as an established waste management business that accepts, processes and recycles over 10,000 tonnes of waste lead-acid batteries *per annum*. Our forecast for 2019 is to surpass 15,000 tonnes and to deliver sophisticated but affordable battery breaking systems to the market.

These battery breaking systems, some of which are built in-house at Aurelius, automate the battery breaking process and separate battery components for further recycling while minimising personnel exposure to lead. They are ideal for SME companies which cannot afford to invest over £1m for a sophisticated battery breaker.

The principal technology behind the battery paste-treatment step, trademarked in the UK, EU and overseas as Fenix^{Pb}, was invented by Professor Kumar at the University of Cambridge. In 2016 it was licensed exclusively to Aurelius for further development, piloting and scaling up. We have an active partnership with the University of Cambridge and Professor Kumar which includes two Post-Doctoral Researchers, an Engineering and Physical Sciences Research Council (EPSRC) Fellow and a Process Engineer (who is a PhD graduate from the same group) working on our research and development projects.

Our piloting efforts are supported by three major grants: two Innovate UK awards (UK/Brazil Newton Fund and Open Programme), and the prestigious Horizon 2020 (Phase 2) SME Instrument. In total we have raised to date more than £2.5m in grant funding, while our annual turnover which exceeds £10m is also used to fund our technology and innovation.

Aurelius Environmental

Scaling-up sustainable resources

Industry Overview

The success of our patent process lies in its low cost, scalability, and ability to produce battery-ready products which exceed current market expectations. Fenix^{Pb} therefore benefits from a combination of superior green credentials and advanced material performance.

The active component of new lead-acid batteries is leady oxide – a combination of lead oxide (PbO) and free metallic lead (Pb). When the battery reaches the end of its life, the lead oxide has been typically converted to lead sulphate, $PbSO_4$. Therefore, waste lead-acid battery paste contains firstly lead sulphate, and secondly free metallic lead, residual lead oxide and some lead dioxide, PbO_2.

The incumbent industry recycles these materials in a furnace at 1,100°C – a process known as smelting, which produces lead ingot. The ingot is then processed by battery manufacturers; this entails melting it down and oxidising via the Barton-pot or ball-mill methods to manufacture fresh leady oxide. And such is the circular economy of the battery paste: it starts from PbO, which becomes $PbSO_4$, which is then converted to lead ingot, and finally used to manufacture new PbO.

Our process is different in that it converted waste battery paste directly to leady oxide, without producing or handling an intermediate ingot. In doing so we reduce the number of processing steps and costs. Crucially, we utilise water (i.e. hydrometallurgy) rather than fire (i.e. pyrometallurgy) to process the paste. For these reasons, Fenix^{Pb} delivers important environmental benefits including:

1) Reducing the carbon dioxide emissions by at least 80%;
2) Eliminating noxious gases (including sulphur dioxide and nitrogen dioxide) with no added costs;
3) Reducing slag by more than 50%, and in some cases more than 75% (for example in comparison to smelting whole lead-acid batteries); and
4) Releasing, rather than consuming, energy of the order of 400 mWh per 1,000 tonnes of battery throughput.

The generation of battery-ready lead oxide, as opposed to manufacturing lead oxide from lead ingot, is an important step change in the lead-acid battery industry. First, it reduces the cost and improves the logistics of leady oxide production. Second, it enables the battery industry to use its own waste directly for the manufacturing of battery paste – 'from waste to paste', as we like to say with less or no reliance on LME-priced lead metal sourced from the open market.

But the recycling process is not the only innovation brought about by this technology. In the laboratory, we have been able to demonstrate batteries manufactured from our advanced leady oxide can increase energy density by approximately 30%. This is because our hydrometallurgical process affords nanostructured particles: essentially, it's a leady oxide whose particle size distribution is not only smaller, but also more consistent in comparison to traditional leady oxides.

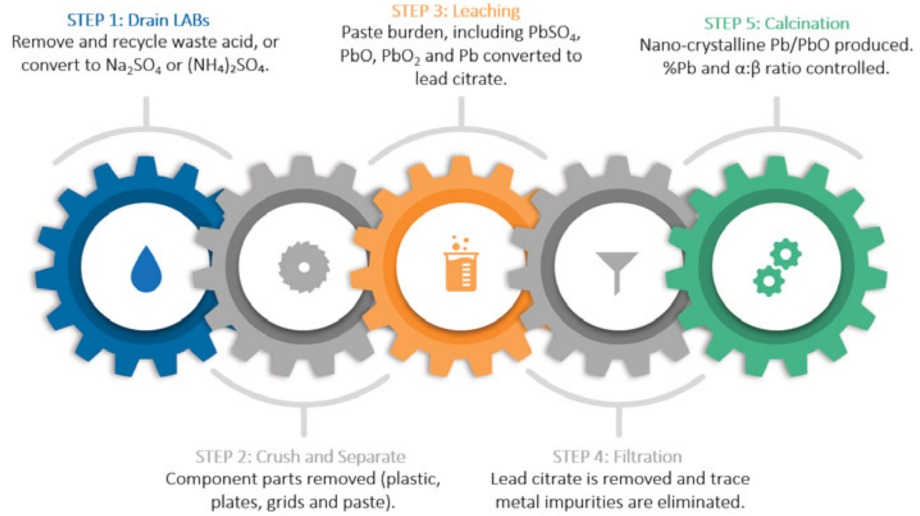
Moreover, we are able to control the proportion of free metallic lead (as a percentage of the total paste by weight) and the ratio between the alpha and beta lead oxides. These innovations pave the way for development of a next-generation lead-acid battery, as well as next-generation recycling with hydrometallurgy at its core.

The recycling of lead metal is a colossal business. In 2013, global secondary lead production rose to an impressive 6.1 million tonnes (source: ILA). Today, secondary lead production accounts for more than half of all lead produced throughout the world – with the US reporting more than 80% and Europe over 60%. Lead-acid batteries are the primary application for all of this lead.

In Europe and the US, almost 100% of used lead-acid batteries are recycled. This impressive statistic is evidence that lead as a material is one of the world's most successfully recycled commodities. Indeed, lead metal is recycled indefinitely with no loss of quality – and lead-acid batteries have become one of the world's most successfully recycled consumer products (source: ECOBAT, BCI). Unlike many other recyclable products, the value of lead means that recycling is economically viable and hence sustainable.

The global lead-acid battery market is forecast to reach $84bn by 2025, driven largely by expansion of the automotive industry in developing countries including Brazil (source: Markets & Markets). More batteries on the road means an ever-increasing amount of battery waste, so our process for the recycling of lead-acid battery paste could not be more timely.

The recycling of lead batteries via current methods is energy intensive and wasteful. In some parts of the world it produces 'smelter smoke' – a toxic mixture of sulphur dioxide, nitrogen dioxide and very often lead metal particles. For this reason, although the lead-acid battery itself is a perfect example of a successful circular economy, the recycling processes used on this product are in dire need of improvement and innovation.



Perhaps it's ironic that recycling any material, lead including, is born from our human desire to achieve a sustainable economy. Indeed, pyrometallurgy may be a successful and reliable process, making the circular economy of lead a reality for over a century now, but it comes at a heavy cost to the environment. The recycling of lead has come a long way, but this isn't enough.

With Fenix^{Pb}, we aim to deliver a truly sustainable and low-cost recycling industry for the lead-acid battery – whilst improving the economic and environmental footprints, and bringing to the market a next-generation, high energy density lead-acid battery.

Fenix^{Pb} – towards sustainable green recycling

Fenix^{Pb} uses refined mechanical separation and a patented hydrometallurgical process to afford a proprietary leady oxide battery paste. In terms of its environmental credentials, the process brings about the following:

1) **No harmful emissions.**
Unlike smelting, our lead recycling chemistry does not release any noxious gases including sulphur dioxide and nitrogen dioxide. In fact, the process can be used as a desulphurisation method even in the classic production of lead ingot.

2) **Significantly reduced carbon footprint.**
Our process reduces the carbon dioxide emissions by 80-89% compared to pyrometallurgy. In addition, we are currently investigating an exciting new process to capture and re-use some of our carbon dioxide emissions.

3) **Reduction in slag**
Compared to smelting whole lead-acid batteries, Fenix^{Pb} reduces slag by a minimum of 50% and in some cases 75%.

4) **Energy is a product of the reaction.**
Our chemistry is highly exothermic, releasing (rather than consuming) energy of the order of 400 mWh per

1,000 tonnes throughput. Whereas smelting consumes anything from 2-10 kWh energy per kilogram of battery scrap, our process consumes (on average) a mere 50 Wh per kilogram. To put this figure into perspective, the specific energy of a lead-acid battery is around 33-42 Wh per kilogram.

5) 'Waste to paste'
Instead of producing lead ingot, Fenix^{Pb} delivers a battery-ready leady oxide directly from spent paste. Therefore, the downstream reprocessing of lead to manufacture lead oxide is avoided, leading to cost savings and improved logistics.

Our battery-ready leady oxide is not only the product of a revolutionary process; it is in itself a revolutionary product bringing us closer to a next-generation lead-acid battery.

Laboratory tests carried out at the University of Cambridge have shown that batteries produced from our leady oxide are on average 30% more energy dense. This innovation is largely due to the particle size.

Fenix^{Pb} leady oxide is nanostructured, which means that particles are much smaller in comparison to Barton-pot and ball-mill oxides (which are of the micrometre scale). In the case of Fenix^{Pb}, the particle size distribution is also narrower and more reproducible. This is important because, generally speaking, smaller particles and greater chemical homogeneity or uniformity translate to superior electrochemical performance.

However, this is not the only innovation. Our process also enables fine-tuning of the leady oxide as follows:

1) By controlling the percentage of free metallic lead (%Pb); and

2) By controlling the ratio between the alpha and beta lead oxide.

The ability to control the ratio between alpha and beta oxide is particularly important. This level of control could bring about a revolution in the battery-making process – enabling production of fine-tuned pastes for specific battery applications (for example where faster discharge or better cycling may be required).

How does it work?

Our technology is based on an ambient temperature hydrometallurgical process – replacing the comparatively hot, high-energy processes used in pyrometallurgy. The main steps involved, carried out on the segregated and neutralised spent battery paste, are as follows.

1) Leaching/Crystallisation
Non-toxic carboxylic acids are added to the neutralised paste. Through a series of physical and mechanical processing steps, the entire lead burden (which includes lead sulphate, lead oxide, lead dioxide and free metallic lead) is converted to a lead organic salt. Crystallisation of this salt occurs with zero loss of lead.

2) Calcination/Combustion
The organic lead salt is heated at 300-400°C to remove organics and release lead. The product from this process is lead oxide with a tuneable amount of free metallic lead. During this process, only carbon dioxide and water are released. The combustion process is exothermic, releasing on average 400 mWh per 1,000 tonnes of battery throughput. The organic component serves as fuel for the combustion, assisting further calcination and lowering the energy cost whilst liberating lead and lead oxide.

The degree of oxidation depends on operating conditions. Indeed, by varying the calcination conditions it is possible to tune the ratio between the alpha and beta lead oxides. Importantly, all particles (whether lead or lead oxide) are produced in nanocrystalline form – this explains why our leady oxide is associated with an uplift in the energy density.

Target market

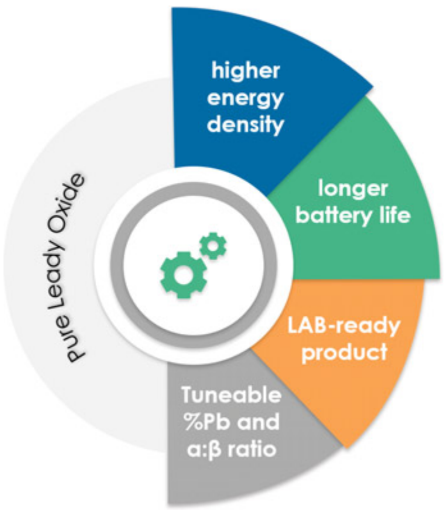
Lead is a globally traded commodity with a worldwide market value in excess of $20bn. Coupled with rising global demand, recycled lead makes up over 50% of all lead produced worldwide. There are no economic alternatives to lead batteries for starting, lighting and ignition in automotive applications, and lead-acid batteries continue to offer the cheapest and most reliable source of energy for many old, new and emerging technologies.

Extremely high growth rates in lead consumption are forecast in emerging markets for decades to come. Yet capital costs for installing pyrometallurgical process plants with full environmental control for the recycling of lead are high. This leads to so-called 'informal sector' recycling, in some parts of the world, where the escape of lead to the environment causes pollution and poisoning of local communities.

A new, environmentally friendly, low-capital cost process will have major global impact. Our technology can deliver this and so much more as it improves efficiency, lowers cost and enables economic and safe recycling anywhere in the world. For every 10,000 tonnes of batteries processed we expect to generate between $2.5m and $5m more gross profit than smelting. Because our capital expenditure is low, we are economically viable with relatively small processing capacities. We can potentially operate a profitable business in a remote area or closer to the source of waste batteries.

Our process delivers important environmental benefits including a reduction in the carbon footprint (by 80-89%), elimination of noxious gases and a significant drop in the energy costs and slag. It produces battery-ready leady oxide directly from scrap, eliminating the production and downstream reprocessing of lead ingot (for the synthesis of battery paste). Our leady oxide is also a technological revolution; as a nanostructured material, with a fine-tuned ratio of alpha to beta lead oxide, we are seeing in the laboratory energy density uplifts of the order of 30%.

At Aurelius Environmental, we seek to set up our own recycling facilities but will also evaluate joint ventures and licensing arrangements. With our UK pilot plant due to open in late 2018, we are paving the way for companies around the world to join us on our mission to deliver next-generation recycling – with corporate responsibility and sustainability for a brighter future.



Aurelius, LABs and the Circular Economy

Some claim that the end of the Oil Age is within sight. Governments around the world are setting ambitious targets for electric vehicles (EVs). In the UK, plans have been announced to phase out sales of new petrol and diesel vehicles by 2040. JP Morgan estimates that electric cars would take 35% of the global market by 2025.

Despite these statistics, the global lead-acid battery (LAB) market is forecast to reach $84bn by 2025 (source: Markets & Markets). LABs are used in automobiles for starting, lighting and ignition – but you'd be excused for not knowing that lead metal has one of the highest recycling rates in the world. In fact, according to EUROBAT, the lead battery is one of the most successfully recycled consumer products.

The lead battery has been on an incredible journey since being invented in 1859 by the French physicist Gaston Planté. To put this timescale into perspective, it was around ten years before the invention of the mechanical generators of electricity. The earliest LABs were therefore charged by Daniell cells or Bunsen cells. It was not until 1925 that half of all homes in the US had electric power – around 66 years after LABs were invented.

And yet, despite the significant technological advancements of the 20th and early 21st centuries, LABs continue to dominate as the most safe, reliable, low-cost and recyclable energy storage solution to the market.

The recycling of lead batteries has likewise been on an incredible journey. Today, this recycling infrastructure is one of the world's best examples of a circular economy – and amazingly it all started at a time when recycling and the circular economy were not even buzzwords. But despite these successes, the industry as a whole is in dire need of innovation due to pollution concerns and pressure from competing technologies.

At Aurelius we want to revolutionise recycling. We are thinking of waste and Cities of the future as ecosystems having endless possibilities. Our vision is a web of industries, where one stream's waste is another stream's feedstock – bridging linear and wasteful processes to create circular, energy-efficient, non-polluting, zero-waste industries. We want to add economic and societal value in all markets in which we operate, promoting sensible and sustainable technologies which are 'best fit' for the local jurisdictions in which they are deployed.

Our innovative technology for the recycling of LAB paste will deliver important environmental benefits: including a reduction in the carbon footprint (by more than 80%), elimination of noxious gases (at no added cost) and significant reduction in energy use and slag. But this is just the beginning – over the course of the next 12-24 months, we will pilot and deliver complementary technologies working in synergy to enhance the circular economies of multiple waste streams.

For example, electrolyte waste from the lead batteries is normally drained and neutralised to produce sodium sulphate or ammonium sulphate. Our plan is to change this; we want to open a sulphuric acid recycling plant – enabling clean-up of the acid through filtration and flocculation processes. The clean sulphuric acid can be used directly in industry. This plant, which is due to open by late 2019, will reduce the cost of electrolyte treatment by £40 per tonne while preventing the emission of 85kg carbon dioxide per tonne of electrolyte treated.

The clean acid can also be used to manufacture reagent for our battery paste recycling process – enhancing further the circular economy of secondary lead batteries.

Throughout 2019 and 2020, we will also pilot biotechnological processes for the treatment of municipal waste and carbon capture. The goal of these projects is to convert waste, including but not limited to waste destined for landfill, into feedstock for our battery paste recycling technology. This could reduce the cost of manufacturing battery-ready leady oxide, whilst increasing the number of waste streams circulating within our industry.

In some of these cases the recycled battery acid can be used as an ingredient. Also, the energy released during our calcination process for the production of lead oxide (approximately 400 mWh per 1,000 tonnes of battery throughput) can be potentially captured and used in a parallel process. Our activities and progress in these areas will be reported through a series of six special reports in *Government Europa Quarterly*.

We aspire to work with like-minded companies and individuals where value added opportunities to any market can be realised.

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