A Natural “Industrial Ecology” Based Solution for Spent Potlining
Closing the loop for aluminium in the circular economy

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Summary

In the natural world, the waste from one species is the food for another species. In the same way, industrial resources can be optimized by looking at how ecological systems operate. This article describes how the principles of “Industrial Ecology” are used to realise a safe, sustainable solution for spent potlining (SPL). This solution sees all of the SPL detoxified and refined into products that have genuine value in energy intensive industries. The solution has been proven over fifteen years with more than 180,000 tonnes of SPL from four aluminium smelters completely transformed, with no residual materials, and sold in a developed market.

The SPL Situation

Primary aluminium smelters are faced with increasing expectations that they will find alternatives to landfilling and/or long-term storage of hazardous waste materials such as SPL. SPL is hazardous because of the presence of cyanide compounds, soluble fluoride and an alarming potential to combine with moisture and generate explosive gases[1]. This material is subject to close regulatory control including the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal [2].

In its raw form, SPL varies in size from fine dust to lumps of up to one metre (**Figure 1**). It typically presents a wide range in mineral and chemical composition as different materials in the pot lining are mixed together.

Over the typical life of a pot (five to eight years), materials such as aluminium metal, calcium, fluorides and sodium infiltrate the cathode lining and cause it to deteriorate.

Complex chemical reactions result in the formation of various carbides, nitrides and cyanide within the pot linings. When the linings are removed from the pot, the resulting SPL also contains aluminium metal and sodium metal. SPL readily absorbs atmospheric water, which reacts with these components. The explosive gases evolved are methane, ammonia and hydrogen.

Pawlek[3] noted that about 25kg of SPL results from each tonne of aluminium metal produced and that while in the past, most of the SPL has gone to landfill, “*this practice must change if the industry wants to claim a reasonable degree of sustainability and environmentally tolerable emissions.”*

Figure 1 – Raw SPL

As alternatives to landfill, various methods for treatment of SPL have been well researched and described in the literature [3] [4] [5]. Drawbacks associated with most methods include one or more of the following:

- Not all of the SPL can be processed (e.g. the carbon SPL can be handled but not the refractory SPL or vice versa)
- The SPL brings unwanted hazards (e.g. where the nepheline in the refractory portion of SPL provides an attractive flux for clay brick making but the fluorides may present environmental, health and safety concerns)
- There are residual waste materials without ready disposal options other than landfill.

The industrial landscape is also rapidly changing with new commercial standards emerging for the purpose of scrutinizing sustainable manufacturing methods. For example the Aluminium Stewardship Initiative (ASI) Standard Version 1 (December 2014) states under Criterion 6.7 for Spent Pot Lining (SPL):

> “The smelter shall maximize recycling of carbon and refractory parts from SPL, and will demonstrate that they continuously review alternative options to land filling of SPL. SPLs shall not be discharged to fresh water or marine environments.” [6]

The Industrial Ecology Hope

In a natural ecosystem, the waste of one species is food for other species. Tibbs[7] explains that Industrial Ecology uses the natural environment as a model for solving environmental problems and that "… *the key to creating industrial ecosystems is to re-conceptualize waste as products*."

Fiksel[8] describes the concept of Industrial Ecology as providing *"…a useful systems perspective to support sustainable development while assuring shareholder value creation*." Erkmann[9] provides a more comprehensive statement of the scope of Industrial Ecology:

> *"Industrial Ecology does not just address issues of pollution and environment, but considers as equally important, technologies, process economics, the inter-relationships of business, financing, overall government policy and the entire spectrum of issues that are involved in the management of commercial enterprises*."

A particular boost to the emergence of Industrial Ecology came with a 1989 article in Scientific American by Frosch and Gallopoulos,[10] who put forward the concept of an industrial ecosystem as a more integrated concept than the traditional industrial model of raw materials being used to make products for sale and waste to be disposed of. They further observed that *"corporate and public attitudes must change to favor the ecosystem approach, and government regulations must become more flexible so as not to unduly hinder recycling and other strategies for waste minimization*."

Applying Industrial Ecology principles to the situation for SPL leads to the question: "where is the value in SPL?"

Manufacturers of energy intensive products such as cement and clay bricks are faced with increasing energy costs and societal expectation of reduction in carbon dioxide emissions.[11] [12] SPL is rich in particular substances that have beneficial energy saving and carbon dioxide emission reduction properties when used in cement and clay brick manufacture. The key valuable constituents in SPL are:

- carbon as a source of thermal energy
- sodium that acts as a **flux**
- fluorine that acts as a **mineraliser** for cement
- alumina and silica that are useful raw materials.

A **flux** is a substance that lowers the temperature at which solid materials enter a liquid phase and/or increases the quantity of liquid at a given temperature. For the clay brick industry, Sodium is an effective flux, lowering the firing temperature required to achieve a given quality of clay brick product and delivering energy savings and CO_2 emission reductions.[13] [14] [15]

A **mineraliser** is a substance that accelerates reaction rates and promotes the formation of desired materials; in cement clinker, this results in a higher quality product with reduced residence time and less energy needs.[16] [17]

Fluorine is a widely used and effective mineraliser.[5] [16] Sodium contributes to the clinker melt through its fluxing properties. Sodium also leads to a beneficially more reactive clinker where the clinker raw materials have low to moderate alkali levels. Sodium can be used to balance the important alkali/sulphur ratio in production circumstances where the clinker plant has excessive sulphur levels (e.g. from using petroleum coke as fuel).

However, the hazards associated with SPL and the highly variable nature of the material have thwarted realisation of these benefits.[18] [19] Simply adding crushed raw SPL to cement kilns can actually degrade cement process performance due to the wide fluctuations in chemical constituents.

The Promise of a Spent Pot Lining Solution

Given the SPL situation, the regulatory environment and community concerns, a long term sustainable and cost-effective solution must be found for SPL reduction, re-use or recycling. Aluminium smelters are improving pot lining technology to extend the life of pots, but reducing SPL generation does not solve the present storage and landfill issue. Also the volume of SPL will continue to increase as demand for aluminium increases.

The opportunities for re-use and recycling inherent in the Industrial Ecology framework allow a solution to be formulated around:

(a) increasing interest in energy savings and CO_2 emission reduction in the cement and clay brick industries

(b) knowledge that chemicals and minerals in SPL and other residual materials from primary aluminium smelting could enable substantial gains in energy and CO_2 emission reduction for these industries.

The Industrial Ecology framework is instrumental in formulating the design of an SPL solution and sets the tone for engagement with aluminium smelters, regulatory agencies, community stakeholders and potential markets. SPL can then be viewed as a valuable resource to be “mined” for economic and environmental benefit, with wide regulatory and community support.

The objectives and strategies formulated to realise this solution are:

OBJECTIVES	STRATEGIES
• 100% beneficial use of SPL with no residue • Low cost of SPL re-processing • Lower energy consumption and greenhouse gas emissions for manufacturing products such as cement and clay bricks • Positive impact on the environment.	1. Secure support of regulatory agencies, environmental groups and community stakeholder groups through effective communication and education in Industrial Ecology principles 2. Develop and commercialise a chemical process to eliminate the explosive gas and cyanide hazards at the smelter, so that only refined products are shipped from the smelter, not hazardous waste materials 3. Use industrial mineral trading and marketing to identify target markets, support the products and promote and distribute products. Encourage industries to move away from hazardous waste processing fees and issues and to see the economic value in SPL-derived products 4. Gain classification of SPL-derived products as safe to transport and use. Thus the refined products are not subject to Basel Convention protocols and meet the by-product requirements of the EU directive on waste[20] 5. Establish and maintain integrity of the SPL solution by ensuring all materials are accounted for and by involving only reputable and trustworthy service providers and end-use customers.

SPL Processing Model

Design of a process to enable SPL recovery, detoxification and manufacture of valuable products follows from the objectives and strategies outlined above. A simplified flowsheet is shown in Figure 2.

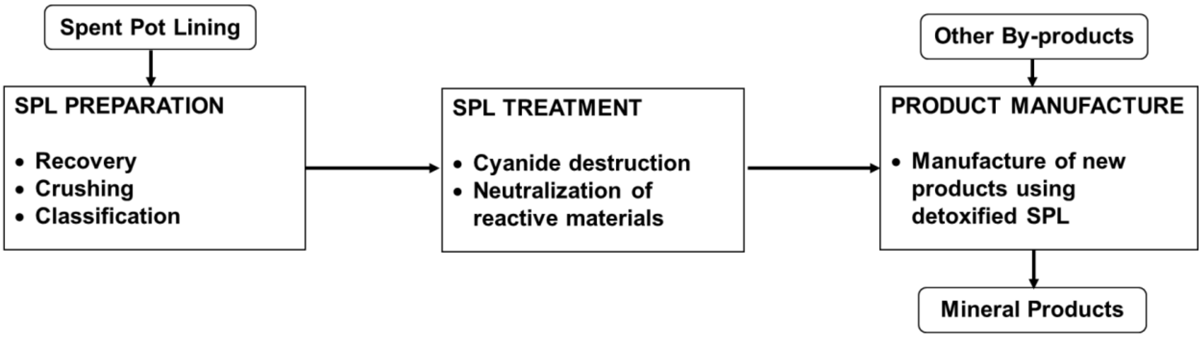

Figure 2 – SPL Processing Flow Diagram

SPL Preparation involves (a) recovery of material from storage or directly from pots; (b) segregation of aluminium metal, carbon materials and refractory materials; (c) sorting into like material streams and (d) crushing and size classification.

The cyanide and explosion hazards in SPL are eliminated through the **SPL Treatment** process. Cyanide destruction is achieved by thermal oxidation i.e. heating the material in the presence of oxygen. Neutralisation of the reactive materials is achieved by bringing on the reactions that generate the explosive gases in a controlled environment such that no more gas can be generated. The Treatment Process becomes almost self-sustaining by re-using the gases generated to heat the raw materials. No residual materials are produced.

Mineral products with beneficial fluxing and mineralising properties are **manufactured** by refining the detoxified SPL material. Other smelter by-products can be added at this point.

An Industrial Ecosystem

Like ecosystems in the natural world, a solution based on Industrial Ecology principles must fit within a framework that optimises resources. The SPL solution is based on a multi-party ecosystem (Figure 3) which integrates the physical components of the system with an enabling platform comprising:

- the technology to detoxify SPL
- the technology to use the products in cement and clay brick manufacture
- regulatory approvals for technology and products
- trading of refined products
- optimised marketing and logistics of products
- research knowledge to support innovation and use of the products.

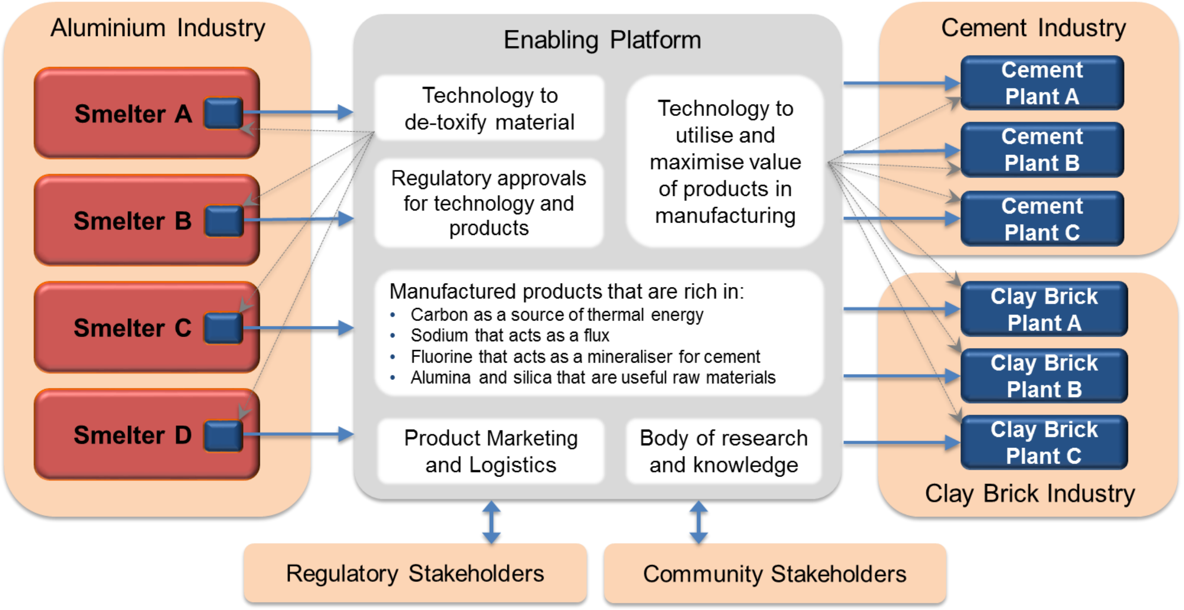

Figure 3 – Industrial Ecosystem for SPL

Case Study

The system described above has been developed by Regain Materials over a period of fifteen years. Regain has provided SPL treatment services for four aluminium smelters in Australia. More than 180,000 tonnes of SPL have been processed through this system.

The process is based on site next to the raw material (SPL) which is detoxified and refined before being shipped outside the smelter boundary. All SPL is used and there are no residual materials. Regain's refined products are used in cement plants and/or clay brick plants in Australia, China, Philippines, Thailand, Morocco, Ecuador, Costa Rica and El Salvador. Regain's products have been classified as safe to export and import by governmental and/or environmental regulators in all of these countries.

Market development has been a key enabler for the success of the technology. Cement and clay brick manufacturers accept that quality-controlled products derived from SPL are valuable to their business, so they are not seeking rent for processing hazardous waste.

The innovation and uniqueness of Regain's SPL detoxification technology has been recognised internationally with patents granted in Australia, Canada, USA, New Zealand, South Africa and UAE.

To validate the Industrial Ecology concept, a Lifecycle Analysis (LCA) was conducted to determine the net effects of treating SPL for the purpose of downstream utilization[21]. The results confirmed net benefits for emissions and energy savings, as shown in **Table 1** below:

Table 1 - Summary of Emission and Energy Aspects for One Tonne of SPL

Description	GHG Emission	Thermal Energy	Electrical Energy
SPL Processing	0.2 t CO2e	1.5 GJ	50 kWh
Savings from SPL Usage	4.2 t CO2e	17.5 GJ	400 kWh
Net	**4.0 t CO2e**	**16.0 GJ**	**350 kWh**

Conclusion - Closing the Loop in the Circular Economy

Regulatory and societal pressures for material stewardship are growing, in the resource-conscious Circular Economy. The aluminium process has the potential to become fully sustainable, if Spent Potlining can be completely re-used. The described solution for SPL is an innovative model of environmental sustainability with gains for the aluminium industry, for end-users of products and for the environment.

This transformation of SPL can be achieved safely within an Industrial Ecosystem by:

1. De-toxifying to eliminate the cyanide and explosive gas hazards in the SPL materials making them safe to transport and use
2. Refining the de-toxified SPL material into quality-controlled products that use the valuable chemicals and minerals to deliver energy savings and CO_2 emission reductions in cement and clay brick industries
3. Certifying that the refined products do not require waste regulation (e.g. Basel Convention protocols) because they are no longer a hazardous waste.

This solution has demonstrated its success as a model of Industrial Ecology, with more than 180,000 tonnes of first-cut and second-cut SPL transformed from a hazardous waste into valuable products, with no residual materials. The principles of Industrial Ecology can engage and educate industry, regulators and the community in helping to close the loop for the aluminium industry with a safe, sustainable SPL solution.

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