SUSTAINABLE PRACTICES IN SPENT POTLINER - AN INDUSTRIAL ECOLOGY APPROACH

P. J. Black[1], B. J. Cooper[1]
[1] Regain Services Pty Ltd, PO Box 6919, Melbourne 3004, Victoria, Australia

Keywords: Spent Potliner, Environment, Hazardous Waste

Abstract

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 paper describes how the principles of "Industrial Ecology" are integrated into a safe, sustainable solution for hazardous spent potliner (SPL) from the aluminum reduction process. All of the SPL can be detoxified at the source and refined into products which retain the valuable chemicals and minerals in an accessible form. These products have genuine value in energy intensive industries and a Life Cycle Analysis shows a net environmental benefit can be achieved. This approach has been proven over 12 years and market demand is presently greater than supply.

Introduction

An ecosystem is a natural system consisting of all plants, animals and microorganisms (biotic factors) in an area functioning together with all the non-living physical (abiotic) factors of the environment (Christopherson 1997) [1]. Central to the ecosystem concept is the idea that living organisms are continually engaged in a set of relationships with every other element constituting the environment in which they exist [2].

More simply, it is both living and non-living things that interact with each other. Crucially, an organism cannot live completely on its own without involving another species of organism.

In natural ecosystems a multitude of symbiotic and synergistic effects are constantly taking place. Life, death, energy consumption and exhaustion and resource utilization are indicators that the system is healthy and performing. In such an ecosystem, the waste of one species is food for other species.

Man can create "Industrial Ecosystems" that are artificial representations of natural ecosystems for exactly the same purpose: to combine and optimize resources used by each species for the synergistic benefits of the entire population. Hence the concept of Industrial Ecology.

Tibbs [3] 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 [4] describes the concept of Industrial Ecology as providing *"…a useful systems perspective to support sustainable development while assuring shareholder value creation."* Erkmann [5] explains that Industrial Ecology principles solve much more than just pollution and environmental issues: they consider *"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 [6], 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."*

Defining aluminum processes as part of an Industrial Ecosystem leads to the question: how does Spent Potliner, one of the major waste streams from aluminum metal making, fit into this ecosystem?

The SPL Situation

Primary aluminum 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 [7]. This material is subject to close regulatory control including the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal [8].

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.

Figure 1 Raw Spent Potliner

Over the typical life of a pot (five to eight years), materials such as aluminum 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 aluminum metal and sodium metal. These components of SPL readily react with water, including atmospheric water, to generate explosive gases including hydrogen and methane.

Pawlek [9] noted that about 25kg of SPL results from each tonne of aluminum 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."*

There are potential environmental liabilities if leachate from landfills escapes to the environment. For this reason, landfilling of unreacted SPL is prohibited in many regulatory jurisdictions. Godin *et. al.* [10] describe a study aimed at identifying a site remediation option that would minimize overall environmental impacts for a landfill containing 100,000 cubic meters of SPL. The study was based on a comparative lifecycle assessment (LCA) and modelling of contaminant transport in groundwater. The study makes the observation that: a) avoiding environmental impacts by placing the SPL in a secure landfill depended on the assumption that confinement of the waste material would be perfect and b) that if concerns about the quality of the long term confinement are considered, then total destruction of the SPL would be required to avoid adverse environmental impacts.

The 2006 Canadian National Guidelines for Hazardous Waste Landfills makes the observation that "*the contaminating lifespan of some hazardous wastes pose significant challenges to landfill design and operation"*, and further that *"the limited service lives of (engineered) components are an important consideration in the facility design"* [11]. The hazardous chemicals in SPL are stable [12] and if stored under dry conditions have effectively an unlimited contaminating lifespan. Aldrich [13] sets out an approach to predicting long term liability costs in landfill of hazardous wastes, and states *"unless one assumes that a manmade structure will never fail, these safeguards cannot eliminate financial liability for the waste."*

As alternatives to landfill, various methods for treatment of SPL have been well researched and described in the literature [9, 14, 15]. 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.

SPL and the Industrial Ecology Principle

The industrial landscape is rapidly changing with recognition by consumers of the requirement for resource conservation, through movements such as the Circular Economy. The Circular Economy could be thought of as a collection of Industrial Ecosystems. New commercial standards are emerging for the purpose of scrutinizing sustainable manufacturing methods, ensuring "Green" or "Circular" practices. For example the Aluminum Stewardship Initiative (ASI) Standard Version 1 (December 2014) states under Criterion 6.7 for Spent Pot Lining (SPL) [16]:

"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."

Given the current stocks of SPL around the world, the regulatory consciousness around landfill issues and community concerns, a long term sustainable and cost-effective solution must be found for SPL reduction, re-use or recycling. Aluminum smelters are improving pot lining technology to extend the life of pots [17], but reducing the rate of SPL generation does not solve the present storage and landfill issue. Also the overall volume of SPL will continue to increase as demand for aluminum increases.

If we accept that the aluminum smelting process can be classified as part of an Industrial Ecosystem, then applying Industrial Ecology principles to the situation for SPL leads to the question: "what is the optimal approach to re-use of hazardous SPL?"

This question may be answered with another – "what would happen to such a toxic waste in a natural ecosystem?"

Firstly, the introduction of the waste would cause problems in the ecosystem, perhaps resulting in population reduction as various methods were tried but failed to deal with the waste. Then a natural process of adaptation would lead to an optimum situation as one or another species found optimum ways to process elements of the resource. An example is the way that mangrove plants adapt to deal with salt [18].

The aluminum industry must interact with other species in the industrial ecosystem to survive. This is exemplified by the inability to develop an economical internal recycling loop for SPL in more than 40 years of serious attempts [19]. Working together with other "Industrial Species" as a combined ecosystem could optimize the resource utilization so that many industrial populations may benefit synergistically.

In a different species within our "aluminum industrial ecology", 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 [20, 21]. 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 for cement manufacture are:

- carbon as a source of thermal energy
- sodium that acts as a flux, lowering the temperature at which solid materials enter a liquid phase [22, 23, 24]
- fluorine that acts as a mineralizer for cement, accelerating reaction rates and promoting the formation of desired materials [15, 25, 26]
- alumina and silica as useful raw materials.

Fluorine is a widely used and effective mineralizer [25]. 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 realization of these benefits [19, 27]. Simply adding crushed raw SPL to cement kilns can actually degrade cement process performance due to the wide fluctuations in chemical constituents [15]. So the aluminum/cement ecosystem must adapt to make the most of the benefits.

Table I Objectives and Strategies for SPL Processing

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 the products. Encourage industries to move away from hazardous waste processing fees and handling 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 [28] 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.

The Design of an SPL Solution

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

The objectives and strategies formulated to realize this promise are listed in Table 1.

Design of a process to enable SPL recovery, detoxification and manufacture of valuable products follows from the objectives and strategies outlined in Table 1. A simplified flowsheet is shown in Figure 2.

SPL Preparation involves (a) recovery of material from storage or directly from pots; (b) segregation of aluminum 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. Neutralization of the reactive compounds 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 destroy Cyanide by thermal oxidation i.e. heating the material in the presence of oxygen. No residual materials are produced because there are no other chemical processes or additives.

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

The SPL Industrial Ecosystem

Like ecosystems in the natural world, a solution based on Industrial Ecology principles must fit within a coherent framework that optimizes 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:

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

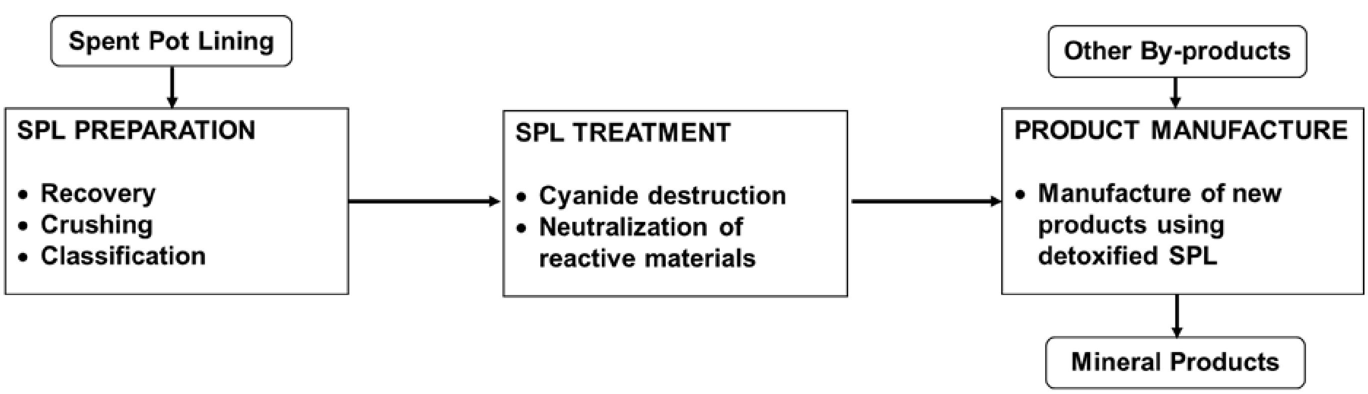

Figure 2 SPL Processing Flow Diagram

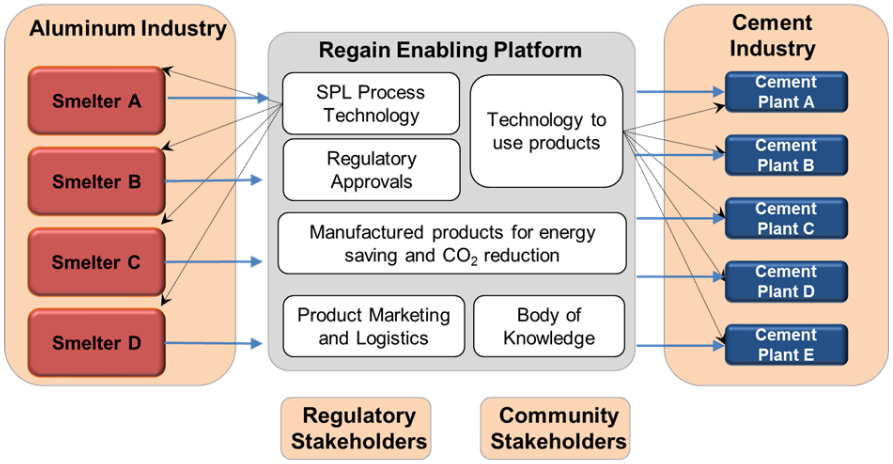

Figure 3 Industrial Ecosystem for SPL

Case Study

The system described above has been developed over a period of fifteen years, providing SPL treatment services for four aluminum smelters in Australia. More than 200,000 tonnes of SPL have been processed through this system and sold to customers as refined products.

The process is typically based on the smelter site near the raw material (SPL). The SPL is detoxified and refined before being shipped outside the smelter boundary. All SPL is used and there are no residual materials. Refined products are used successfully in cement plants and/or clay brick plants in Australia, China, Philippines, Thailand, Morocco, Ecuador, Costa Rica and El Salvador. The refined products have been classified as safe to export and import by governments and/or environmental regulators in all of these countries. The innovation and uniqueness of this SPL detoxification technology has been recognized internationally with patents granted in Australia, Canada, USA, New Zealand, South Africa and UAE.

The success of the solution has been enabled by developing technical expertise on how to maximize the potential value of SPL, designing products tailored for downstream industries, and optimizing the market for the products. Around a quarter of all cement manufacturers can add 2% of quality-controlled products derived from SPL to optimize their production, without seeking rent for handling hazardous waste. With 1 million tonnes of aluminum smelter SPL generated globally each year, and 4 billion tonnes of cement clinker, the cement industry can absorb the generation of SPL by the aluminum industry many times over.

To validate the Industrial Ecology concept, a Lifecycle Assessment (LCA) was conducted on the system of SPL processing, product transport and consumption in a cement plant [29]. The results confirmed net benefits in emissions reduction and energy savings, as shown in Table 2 below.

This approach to dealing with SPL is a mature system. Progressive cost reductions have been realized resulting from the benefits accruing from the technology learning curve, continuous improvement, economies of scale and revenues from sale of refined products (see Figure 4). The costs to a smelter of transforming SPL under this Industrial Ecology approach are now less than the typical liabilities associated with SPL in landfill due to the long term contaminating lifespan and the ongoing landfill remediation requirements [30, 31, 32].

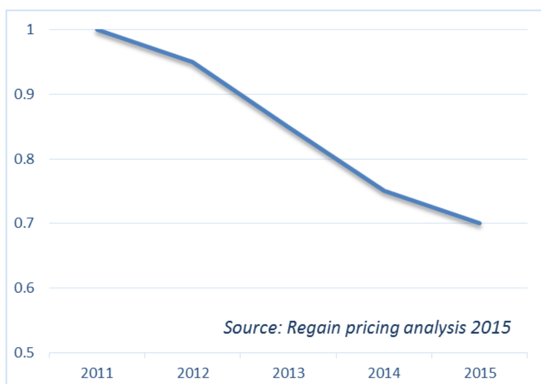

Figure 4 SPL Solution Price Index - Constant 2011 USD Price Level

Table II Summary of Emission and Energy Aspects for One Metric Tonne of SPL

Description	GHG Emission	Thermal Energy	Electrical Energy
SPL Processing	0.2 t CO_2e	1.5 GJ	50 kWh
Savings from SPL-Derived Product Usage	4.2 t CO_2e	17.5 GJ	400 kWh
Net Benefit	**4.0 t CO_2e**	**16.0 GJ**	**350 kWh**

Conclusion

There is a finite resource pool on planet Earth. Understanding natural systems can help us to optimize the value of materials from all possible sources. Regulatory and societal pressures for material stewardship are growing in response to new technologies and our understanding about the impact of industrial progress on the Earth's fragile ecosystem.

While SPL is a tough problem for the aluminum industry, transformation and beneficial re-use of this resource 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 re-use in other industries
2. Refining the de-toxified SPL material into quality-controlled products that use the valuable chemicals and minerals to deliver energy savings and CO2 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.

A transformation process is described for SPL that has demonstrated success as an innovative model of Industrial Ecology, with net cost benefits for smelters. More than 200,000 tonnes of first-cut and second-cut SPL have been transformed at smelter sites into valuable products which are completely consumed in a developed market. The principles of Industrial Ecology make an environmentally and economically sound argument for industry, regulators and the community to consider SPL as a resource for the future.

REFERENCES

1. Christopherson, Robert W. *Geosystems: An Introduction to Physical Geography*, 3rd Edition, Prentice Hall Inc. 1997
2. *Ecosystem Concept*, from http://www.ecosystems.ws/ecosystem_concept.htm Nature Worldwide: Ecosystems - World Institute for Conservation & Environment (WICE) – accessed August 2015
3. H. B. C. Tibbs, *Industrial ecology: an environmental agenda for industry*, Global Business Network, 1993
4. J. Fiksel *Sustainable development through industrial ecology*, http://eco-nomics.com/images/SD_through_Industrial_Ecology.PDF, First published as a chapter in Eds. R. L.Lankey and P. T. Anastas, Advancing Sustainability Through Green Chemistry and Engineering, American Chemical Society, 2002
5. S. Erkman, *Industrial ecology: a new perspective on the future of the industrial system*. "President's lecture", Assemblée de la Société Suisse de Pneumologie, Geneva, 2001 at http://www.ncbi.nlm.nih.gov/pubmed/11759173
6. R. Frosch and N. Gallopoulos, *Strategies for manufacturing*, Scientific American (Special Edition, September 1989)
7. *Flammable gas causes explosion*, Loss Prevention Case Studies, www.shipownersclub.com, The Shipowners' Protection Limited, 2010, 19 - 20
8. Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal
9. R. P. Pawlek, *Spent potlining: an update*, Light Metals 2012, ed. C. E. Suarez, The Minerals, Metals and Materials Society, 2012
10. Godin, J-F. Ménard, S. Hains, L. Deschênes and R. Samson, *Combined use of life cycle assessment and groundwater transport modelling to support contaminated site management*, Human and Ecological Risk Assessment: An International Journal, 10(6), 2004, 1099-1116.
11. National Guidelines for Hazardous Waste Landfills, Canadian Council of Ministers of the Environment, 2006
12. D. Dzombak, R. Ghosh, G. Wong-Chong, *Cyanide in Water and Soil - Chemistry, Risk, and Management*, CRC Press, 2006
13. J. R. Aldrich, *Expected Value Estimates of the Long-Term Liability from Landfilling Hazardous Waste*, J. Air & Water Manage. Assoc. 44:800-803, 1994
14. G. Hollywell and R. Breault, *An overview of useful methods to treat, recover, or recycle spent potlining*, The Journal of the Minerals, Metals & Materials Society, 65(11), 2013, 1441-1451.
15. M. Sørlie and H. Øye, *Cathodes in aluminium electrolysis*, Dusseldorf: Aluminium-Verlag Marketing and Kommunication, 2010.
16. Aluminium Stewardship Initiative (ASI) Performance Standard Version 1 (December 2014) Part 1: Principles and Criteria, ASI via International Union for the Conservation of Nature (IUCN), 2014
17. International Aluminium Institute (IAI) website *Aluminium Facts – Emissions and Waste* http://primary.world-aluminium.org/aluminium-facts/emissions-waste.html accessed August 2015
18. *Mangrove Ecosystems – Where the Land and Sea Intertwine* http://www.bsu.edu/eft/belize/p/libm/adaptations.html - accessed September 2015
19. H. A. Øye, *Treatment of spent potlining in aluminium electrolysis, a major engineering and environmental challenge*, Energia Vol. 5, No.1, Centre for Applied Energy Research, University of Kentucky,1994
20. *Cement roadmap targets – CO2 emission reductions*, The International Energy Agency, http://www.iea.org/publications/freepublications/publication/Cement_Roadmap_targets_viewing.pdf, 2012
21. *Energy Saving Concepts for the European Ceramic Industry*, Intelligent Energy Europe, 2009
22. A. S. Smith, *To demonstrate the commercial viability of incorporating ground glass in bricks with reduced*

energy emissions and energy savings, The Waste and Resources Action Program, 2004.

23. R. Kirby, *Potential energy saving from the use of recycled glass in brick manufacturing*, Centre for Environmental Economic Development, California Department of Conservation, 2006
24. W. Goldfinch, *A new paradigm for the brick industry*, presentation to Think Brick Australia, (Australian clay brick industry body), 2009
25. V. Johansen and J. Bhatty, *Fluxes and Mineralizers in Clinkering Process*, Innovations in Portland Cement Manufacturing, Portland Cement Association 2011
26. L. Hills, V. Johansen and F. Miller, *Solving raw material challenges*, Construction Technologies Laboratories Inc. Cement Industry Technical Conference, 2002
27. *Beneficial Reuse of Spent Potliner Waste*, Cement Industry Environmental Consortium (CIEC), Ongoing Research, www.cieconline.net/Res/Research.htm
28. *Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain directives* Official Journal of the European Union, November 2008, page 305/11
29. B. Cooper, *Considerations for Dealing with Spent Potlining*, Proc. 11th Australasian Aluminium Smelting Technology Conference, 6-11 Dec 2014, Eds. B Welch, M Skyllas-Kazacos, UNSW School of Chemical Engineering, 2014
30. Testa, Stephen M. *Geological Aspects of Hazardous Waste Management*, CRC Press, 1994
31. *Economic Assessment of the Revised LDR Treatment Standards for Spent Aluminum Potliner (K088)*, Prepared for U.S. EPA Office of Solid Waste and Emergency Response, DPRA Incorporated, 2000
32. *Implementation of the Basel Convention: The Costs of Inaction*, Non-Paper Submitted Under Agenda Item 7 (i) - Resource Mobilization and Sustainable Financing, Ninth Meeting of the Conference of the Parties, 23-27 June 2008, Bali; Basel Convention, 2008