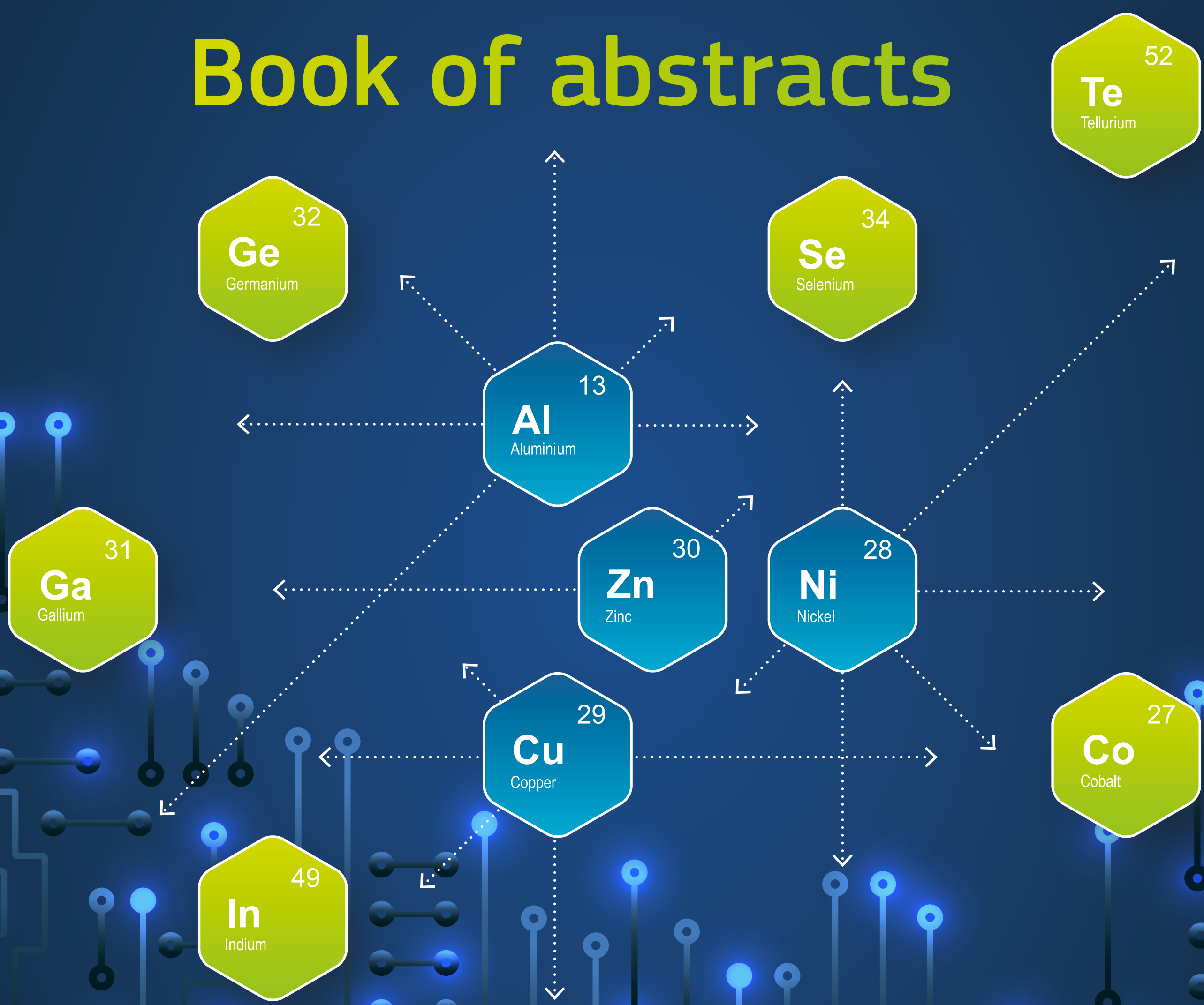
European Commission

Exchange of good practices on **metal by-products recovery**

Technology and policy challenges

Book of abstracts



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PDF copy of this Book of Abstracts and presentations available online in the website of the European Innovation Partnership (EIP) on Raw Materials.
https://ec.europa.eu/growth/tools-databases/eip-raw-materials/en

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The European Union Strategy for Raw Materials

Minerals, metals and raw materials in general are essential for the functioning and progress of modern societies. Raw materials are the foundation on which our economy is built, and a sustainable supply of raw materials is essential for maintaining and improving our quality of life.

In response to the key role of raw materials and the current and future challenges in this field, the European Union has launched various actions in recent years. In 2008, the European Commission (EC) submitted the **'Raw Materials Initiative'**. This initiative, which defines a series of policies and integrated strategies that can help the sustainable supply of raw materials for the European economy, is based on three pillars. The first pillar aims to ensure for Europe a sustainable access to raw materials from third countries. The second seeks to promote the supply of raw materials within the Union. Finally, the third pillar covers the promotion of recycling and resource efficiency.

Everybody can see the growing use of increasingly sophisticated products and devices. Modern technologies and services usually depend on raw materials that are difficult to obtain either due to scarcity in nature, difficult extraction or geopolitical reasons. In response to this, and based on a detailed expert report, the EC published in 2010 the first **List of Critical Raw Materials (CRM) for the European Union**. CRM are those important for the value chain and with a particularly high risk of supply shortage. The last criticality assessment was carried out in 2013, when 20 raw materials were identified as critical. The next exercise is planned for 2016.

The EC proposed in 2012 the creation of a **European Innovation Partnership** (EIP) in the field of raw materials. Through this partnership and its **Strategic Implementation Plan** (SIP, adopted in 2013), there is now a much clearer idea of the research and innovation priorities in different sectors of raw materials, from prospecting to extraction, processing, recycling and substitution, including environmental, social or health aspects. The final objectives of the EIP are to reduce imports, promote production in Europe and exports, and put Europe at the forefront in each stage of the value chain by 2020.

Many measures promoted by the EC should be complemented by actions from Member States, industry, academics, researchers and civil society in general. In this regard, the EC launched in 2013 the first **Call for Commitments**. A commitment is a joint undertaking by several partners, who commit to carrying out activities that will contribute to achieving by 2020 the objectives set out in the SIP. At this moment, approximately 800 partners from very different sectors got together in 80 raw materials commitments, which cover the three-pillar structure of the EIP (technological and non-technological aspects, as well as international cooperation). The **second Call for Commitments** will open in end-2015, and new calls are planned for 2017 and 2019. All stakeholders are invited to participate.

Some of the actions proposed in the SIP are being implemented in the framework of the Programme **'Horizon 2020'** (H2020). The **raw materials part of H2020 is placed under the 'Societal Challenge 5** – Climate Action, Environment, Resource Efficiency and Raw Materials' (SC5) and has a budget of nearly EUR 600 million over the period 2014-2020. H2020 calls on raw materials aim to maximise the positive impacts of the EIP actions across the raw materials value chain and achieve its targets, including 10 innovative pilot actions, finding 3 substitutes for critical raw materials, creating innovation friendly regulatory framework, and developing a proactive international cooperation strategy. The 28 proposals (with around 400 participants) selected in the calls of SC5 and 'Waste Focus Area' for the first programming period (2014-2015) create a very promising basis for achieving the EIP objectives and targets. The new **work programme 2016-2017 of H2020** contains 16 raw materials topics under the SC5 with a budget of more than EUR 140 million, and several topics in other parts of H2020 directly contributing to the raw materials policy. In this period, the first large innovative pilot actions will be launched to demonstrate viability of cost-effective, environmentally sound and safe production of primary and secondary raw materials and unlocking a substantial volume of key raw materials within the EU.

Last but not least, a new main actor has recently arrived to the field of raw materials in Europe. A 'spin-off' of the EIP on Raw Materials under Horizon 2020, the **Knowledge and Innovation Community (KIC) on Raw Materials**, launched by the European Institute of Innovation & Technology (EIT) starts now to work at full speed. Addressing sustainable exploration, extraction, processing, recycling and substitution, the KIC will integrate all three sides of the 'knowledge triangle' – i.e. higher education, research and business – bringing together leading players from all these dimensions.

For further information on EU Raw Materials Policy, please consult:
http://ec.europa.eu/growth/sectors/raw-materials/index_en.htm

The International Conference 'Exchange of good practices on metal by-products recovery – technology and policy challenges'

This conference aims at increasing the ability of the raw material industry to supply the economy with vital raw materials by exploiting a higher share of a potentially significant, but currently underexploited source of raw materials: the 'metal by-products'. Ore bodies of major metals such as copper or nickel usually contain metallic raw materials at low concentrations that accompany the major element. These **accompanying elements** or **'metal by-products' are often not properly recovered** during the mineral processing and metallurgical treatment of ores, so they finish diluted in major elements, in slags or wasted, not being properly valued.

Most significantly for the EU, many of these minor metals are scarce or have strategic economic importance, and usually they figure in the list of CRM for the EU. Many **by-product metals play a fundamental role on the competitiveness of the manufacturing sector and on innovations in high-tech sectors** such as renewable energy, telecommunications, information technology or defence industry. Recycling of secondary raw materials (e.g. mining and industrial waste and residues, scrap, complex end-of-life products) faces similar non-optimal recovery rates of strategic/high-value elements contained in low concentrations. The recent 'Study of By-Products of Copper, Lead, Zinc and Nickel', supported by the EC, confirmed the **opportunities** that can be reaped by **improving the metal by-products recovery rates** achieved in the raw material industry.

This conference tackles the technology challenges but also the policies and regulatory framework apt **to promote the recovery of metal by-products**. This aim is pursued by bringing together **leading stakeholders in the field** from industry, research and academia, as well as trade experts and relevant policy-makers. This event provides an excellent opportunity to share experiences, exchange good practices and present existing examples across the whole value chain. A specific session informing about the relevant raw material topics under H2020 aims to encourage multidisciplinary cooperation (at European and international levels) in research and innovation, and a round table will serve to wrap-up the main conclusions.

This volume collects the **abstracts of the presentations and posters received from world-class experts** and shows the latest developments on the recovery of metal by-products. Several abstracts illustrate how the challenges for the recovery of metal by-products are complex and diverse. Accordingly, the **ways to overcome those challenges have multiple origins and reproduce well the three-pillar structure of the EIP:** solutions can come from sustainable technological developments, but better-informed decision making by both policy–makers and companies is also essential. For that, strategies for improving the knowledge base and better understanding the markets can play an important role. Additionally, promotion of skills and multidisciplinary cooperation across the value chain, usually at international level, will be required.

This conference fits well within some of the major challenges for European and global societies for the next decades. For example: many metals recovered as by-products are key for the development of a digital economy and society, and mining, mineral processing and metallurgy can also play a major contribution to an improved resource efficiency and the achievement of a circular economy.

We hope you enjoy the conference.

Unit C2 Resource Efficiency and Raw Materials
Directorate-General for Internal Market, Industry,
Entrepreneurship and SMEs (DG GROWTH)
European Commission

The Partnership Instrument, Introduction by the Service for Foreign Policy Instruments (FPI) of the European Commission

The Partnership Instrument (PI) is one of the funding instruments that enable the EU to take part in shaping global change and promote its core values. It is one of several instruments included in the EU's budget for 2014-2020 as a means of financing the Union's external action.

Projecting EU interests abroad

The PI finances activities in a number of areas of key interest to the Union. This funding supports the external dimension of EU internal policies – in areas such as competitiveness, research and innovation, as well as migration – and helps to address major global challenges such as energy security, climate change and environmental protection. As one of its main orientations, it contributes to the external projection of the Europe 2020 Strategy.

The PI also deals with specific aspects of the EU's economic diplomacy with a view to improving access to third-country markets by boosting trade, investment and business opportunities for European companies. It encourages public diplomacy, people-to-people contacts, academic and think tank cooperation and outreach activities.

Widening the scope of the EU's cooperation

The EU's interaction with many countries around the world focuses on development cooperation. The PI offers a different approach to established models of development cooperation by promoting policy cooperation with countries of strategic interest to the EU. In particular, it allows the EU to establish a wider political dialogue with emerging partners. It also supports the EU's relations with countries that are no longer eligible for bilateral development aid.

The Partnership Instrument and Raw Materials Initiative

By-products conference

FPI4 has supported under the impulse given by the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROWTH), a two-day event focused on the exchange of good practices between the EU and third countries on the recovery of metal by-products during raw materials processing. The event is structured in several sessions with oral presentations, a poster session and a round table session. It has a strong technical character, but policy challenges and international policy dialogues will be also covered.

EU-Canada Mineral Investment Facility

The general objective of this action is to support the Raw Materials Initiative objective of guaranteeing access to a secure and sustainable supply of raw materials for the EU industry. The feasibility study, which will encompass associated events and stakeholder dialogue, should analyse the current state-of-play of cooperation between the EU and Canada on the mining sector and related technology and services, and conclude how to better boost and structure this cooperation and whether this could be achieved through the establishment of a mineral investment facility (MIF) between the EU and Canada; examine all options within the context of the EU-Canada relationship in the field of raw materials; and make a proposal on the best design of the MIF.

Speaker abstracts

Enhanced recovery of metal by-products: current challenges and future trends

Element cycles and criticality: a focus on by-product metals

Keywords
- critical metals
- recycling

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More than half of all metals are produced largely as by-products. Because these metals are not traded on public metal exchanges, their markets are opaque. In this talk I will discuss some of the particular characteristics of these by-product metals: their typical uses, their potentials for substitution, and their rates of end-of-life recycling. I will then demonstrate some results of a recent assessment on metal criticality, and what that work shows for the by-product metals generally. It is metals characterised by being largely by-products, having geographically concentrated production, with few opportunities for substitution, and with very low rates of end-of-life recycling, that may be at the greatest risk of supply constraints in the coming decades.

'Hitchhiker' metals as by-products

Keywords
- rare metals
- rare earths
- geology
- 'attractors'
- 'hitch-hikers'
- prices
- life cycle
- recovery
- functions
- recycling

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The technologies primarily responsible for economic growth in the industrialised countries – information and telecommunications technology and renewable energy – have created important new uses for a number of geologically rare metals, some of which were mere curiosities in the past. Most of them not mined for their own sake (gold, the platinum group metals and the rare earths are exceptions) but are found mainly in the ores of the major industrial metals such as aluminium, copper, zinc and nickel. We call these major metals 'attractors' and the rare accompanying metals 'hitch-hikers'. The key implication is that rising prices do not necessarily call forth greater output because that would normally require greater output of the attractor metal. We trace some of the geological relationships and the functional uses of these metals. Some of these metals appear to be irreplaceable in the sense that there are no known substitutes for them in their current functional uses. By-product recovery (and recycling) will be increasingly important, notwithstanding a number of barriers.

Challenges in quantifying the conversion of mineral resources to production of by-product and critical metals

Keywords
- mineral resources
- mining
- environmental impacts
- rare earth elements

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There are several metals which are used in abundance across the world (e.g. Fe, Cu, Zn, Al, Ni, Pb) for buildings, transport, heavy industry, consumer goods, and so on. For the remaining metals, such as In, Ga, rare earth elements (REEs) or Te (amongst many), their use has been relatively minor – but this has changed significantly in the past few decades as new uses have been developed in renewable energy (solar photovoltaic panels, wind turbines), consumer electronics (especially colour screens), specialty metal alloys or energy efficiency and pollution control technologies. Many of these metals are invariably found as secondary products to the main metals of interest to a mining company – and so little is published or known on how much of such metals are globally extractable from such mineral resources.

When planning a new mine, a company typically examines the most direct route to a reliably profitable project – and this invariably focuses on the dominant value and easily recovered metals (Cu, Au, Zn, Fe, Al, etc.) and they typically ignore a wide range of possible other metals which may also occur – such as In in Zn or Sn deposits, Ga in Al (bauxite) deposits, Te in some Au deposits, REEs in some Cu deposits. Such metals, which have a low proportion of the output value from a mine, are typically termed 'by-products' and published data is often very limited on their extent in mineral resources, ore processing and smelting-refining. For most by-product metals, their production tends to be concentrated in the smelters and refineries which process concentrates from such mines, and often only a very small number of these sites produce specific by-product metals globally.

Globally, many by-product metals are often dominated by very few countries and/or mines, this leads to concerns over market supply (monopoly) risks as well as significant uncertainties on how much of these metals are recoverable given the paucity of published data. It is a common mistake, however, to confuse mineral resources with supply as well as lack of accurate mineral resource estimates with resource depletion (i.e. scarcity). Based on the known mineral resources of the primary host metals (e.g. Cu, Zn, Al), it is reasonable to expect that the mineral resources of almost all by-product metals are very large and can conceivably meet future demands for decades.

This presentation will examine the following aspects of the material flows of by-product metals:
- the current and future roles of mineral resources codes in better quantifying by-products;
- case studies of estimating global mineral resources of selected metals (In, REEs, Co); and
- analyses of the recovery efficiency during mining and milling of selected by-products.

Overall, the presentation will provide significant insights into the current challenges in estimating recoverable global mineral resources of various 'by-product' metals for future societal needs, as well as suggest possible methods and strategies for improving the knowledge base to inform community, government and industry policy needs.

Metal by-products. A focus on market and applications

OAKDENE HOLLINS
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By-product metals – the challenges and advantages of minor metal production

Keywords
- by-product dynamics
- critical raw materials

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Raw material supply, including by-production, is a topic that has received considerable attention in recent years. This is a result of concerns over continuing access to certain raw materials, particularly those linked to important technologies and economies. As a consequence, several studies by governments and businesses have sought to identify which are the most 'critical' raw materials to them, where supply issues could occur, and what mitigation options exist.

Metal by-products are often highlighted within these analyses, as they are essential to the function of many products. The importance to technologies is frequently combined with a concentrated supply, as a consequence of low production volumes. For by-products, the reliance on another metal for supply is often perceived as an additional risk, however this is not always true and wider factors need considering. Therefore, understanding the production and market dynamics for these metals is crucial to understanding where concerns are real. By-production also provides a mitigation path if issues occur with these materials, as well as an opportunity to increase supply through better exploitation of resources.

As well as technical aspects, challenges also exists in understanding the production characteristics of by-products, and therefore identifying where opportunities for developing more resilient supply exist. By-product markets are often small and opaque when compared to some of the main metals. Therefore increasing understanding in these markets is important in developing supply.

In this talk, the speaker will discuss by-production in the context of raw materials supply and 'criticality', and outline some of the changes to the supply that have occurred over recent times. Selected data and results from a recent study on by-production will be presented, for example: developments in supply, shifts in prices, or increased demand due to application growth. This will provide important contextual information for those wishing to understand the significance of metal by-production, and the challenges and issues it presents.

Minor metals – essential elements for today's world

Keywords
- MMTA
- minor metals
- aerospace
- automotive
- medical
- optics
- consumer electronics
- catalysts
- batteries
- renewable energy
- critical raw materials
- trade

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The Minor Metals Trade Association (MMTA) was founded in 1973 in a period when 'by-product' metals were just starting to be used in growing mass applications. From just seven elements covered at the outset – antimony, magnesium, nickel (not then traded on the LME and still regarded as a minor metal), cadmium, bismuth, selenium and mercury, the scope of minor metals trade activity today has increased dramatically, and the association now covers a total of 49 elements. In those early days, it was necessary to establish clear trading rules, and so the MMTA was formed to guide and inform those involved in the nascent minor metals industry. Today's MMTA is made up of consumers, producers, traders and service companies, who are engaged in the minor metals industry in all its forms.

Minor metals are defined as those metals, predominantly by-product metals, which are not exchange traded. They are lower volume, often high value metals, critical to a multitude of sectors. Industries that have led the application of minor metals – and thus also the trade in them – include aerospace, automotive, medical, optics, consumer electronics, catalysts, batteries and a host of technological applications that we have come to identify with the modern world, such as renewable energy technologies.

This presentation will provide an overview of the importance of by-product minor metals in a range of different applications, as well as some of the current challenges faced by these elements.

Several short examples will give an idea of the importance of minor metals:

- **Cobalt**, primarily a by-product of copper and nickel production, is an essential element of many applications: its high temperature strength and corrosion resistance make it an essential alloying element for jet engine and electrical power generation turbines, as well as in replacement joints, in cutting and drilling tools, and permanent magnets for ABS breaking systems in automobiles. It is also used in pigments, semi-conductors and solar and wind power technologies.
- **Indium** is mined as a by-product of zinc, lead, tin and copper. It is used in flat screen displays and a range of other mechanical and electronics applications.
- **Bismuth** is a by-product of lead and copper production and is used as an alloy in some galvanisation processes, in ceramic glazes and pigments, pharmaceuticals and make-ups.
- **Gallium** is found in trace amounts in zinc and bauxite. Its main use is in the manufacture of gallium arsenide, used in electronics, particularly in radio frequency chipsets in mobile and satellite communications, in display screen LEDs, automotive and lighting applications, as well as sensors in avionic, space and defence systems.

The MMTA works together with and on behalf of its members, to promote the importance of minor metals and inform on the issues affecting their trade, availability and use.

By-product metals: mastering these mysterious markets

Keywords
- rhenium
- scandium
- tellurium
- gallium

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Greater interest has been levied on by-product metals over the last decade, driven by increased demand from high-tech applications and more recently as a source of additional revenue for primary metal producers whose core markets have been subjected to lower pricing/profitability. Outside of the trade, and in all likelihood within it, reliable published market intelligence is lacking. Much like the market for the metals themselves, this a function of supply and demand, with primary metal smelters treating by-product metals as a side business and refiners increasingly focussed in China or on supplying particular grades/markets/customers on regular business. High-level overviews driven by 'critical' material analyses in recent years have failed to capture the true picture, and can be misleading. Confusion, especially around supply (a lack of clarity on mined, intermediate or refined output) and demand (misleading country-level data used in the global context), has been compounded by FYME (Fanya) and other investment and stock building activity distorting the market. Roskill has seen a renaissance in by-product metal market research interest, especially for rare and electronic metals, but bridging the gap between its multi-client reports dating back to the early 1990s and the situation today has been challenging. Using the examples of rhenium, scandium, gallium and tellurium, Roskill's presentation will give an overview of some of the pitfalls faced in by-product metal market analysis and how these have been overcome through different approaches.

The majority of primary rhenium supply comes as a by-product of a by-product, rhenium being extracted during molybdenum roasting following separation from copper concentrates/tailings. This ~60tpy market is dominated by use in superalloys, specifically single crystal turbine blades in aero-engines and industrial gas turbines (IGT). Output is concentrated at three producers (Molymet, Freeport and KGHM) with the majority of their output on long-term contracts with the ultimate users (GE, Pratt & Whitney and Rolls Royce). To mitigate supply risk following a price spike in 2011, these users became savvier about their rhenium 'units', increasing external (scrap) and internal (revert) collection practices, stockpiling and recycling. Coincidentally, the availability of scrap increased dramatically from the late 2000s as rhenium-bearing aeroengines manufactured from the late 1980s started to be decommissioned. Using historical cumulative consumption, paired with information on scrap flows, Roskill has analysed secondary rhenium availability and shown how that stream could balance future requirements given potential limitations on primary output.

Scandium is an even smaller market than rhenium, with less than 10t produced and consumed annually, but bares many similarities to the larger global market (600t) for tellurium. Both of these by-product metals, scandium being sourced largely from rare earth processing and tellurium from copper smelting, have seen demand patterns changed by new technology – scandium-based solid oxide fuel cells and cadmium-telluride solar cells – dominated by just two companies: Bloom Energy and First Solar. The raw material requirements of these tech companies fundamentally changed the previous metallurgy-dominated applications, whose users could no longer compete on price as demand escalated. These tech companies have also been savvy in securing future needs by entering into long-term contracts and stockpiling. Given the very recent commercial development and >20-year lifespan of CdTe cells, and potential rapid increase in tellurium demand in a renewable energy future, Roskill analysed the elasticity of copper smelting supply to understand potential future availability of tellurium should demand increase. The potential for greater scandium output in the future relies on alternative by-product streams (largely nickel and niobium) or better capture in existing metal streams (bauxite and titanium dioxide) and Roskill has reviewed the potential from both sides.

Despite gallium featuring high on the EU's critical raw material assessment of supply risk given China's dominance, potential alternative supply is possible given that gallium contained in bauxite mined in 2013 totalled about 12kt with hundreds of tonnes also contained in sphalerite ore used in zinc production. In gallium, supply patterns are more an issue of cost than potential, an element of the industry often missed in CRM analyses. Jumping on expectations of perceived high levels of demand growth, Chinese gallium output rose strongly in 2009-2011 as bauxite processors installed extraction equipment and refiners opened or expanded capacity, resulting in high stock levels, much of which was subsequently sold onto the Fanya Metal Exchange in 2013 and which now holds more than half a year's demand in stock. Roskill has analysed the historical shift in output, as well as potential additional sources of gallium, to understand why supply has shifted from west to east and whether it could return.

Technology challenges and solutions for the enhanced recovery of metal by-products in various non-ferrous metals

Innovative use of characterisation methods and extractive metallurgy for by-product recovery at ERAMET Group

Keywords
- mineralogy
- ore processing
- hydrometallurgy
- pyrometallurgy

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ERAMET is a mining and metallurgical group, represented all over the world by its mining operations and processing plants. It is continuously aiming to create and increase product and market value. An essential part of this is created by product recovery optimisation resulting at the same time in maximising income and minimising expenditure and labour-related efforts.

In order to reach its objectives, every step will be analysed and illustrations will be provided through existing processes or projects still under development.

Mineralogy is a fundamental tool to provide ideas and potential solutions for by-product recovery. As for main elements, the following processes will strongly depend on the location and the nature of the phases containing the elements. Systematic use of statistical analyses using a Scanning Electron Microscope coupled with in-house developed databases can identify the nature of interesting mineral phases, and their textural relationships indicating more rapidly which means will be needed for more efficient mineral beneficiation decisions.

Mineral processing is closely linked to the mineralogical analysis and can facilitate further treatment by using any available beneficiation technology (e.g. density separation, screening, magnetic separation, flotation, etc.) in an appropriate logic. For example, in our new Tizir Grande Cote plant in Senegal, a detailed analysis of mineral phases in heavy mineral sands allowed us to identify the potential recovery of zircon in addition to initial titanium resources, through appropriate densimetric separation coupled with Wet High Intensity Magnetic Separation, providing a significant addition in value to the product.

Hydrometallurgy is a fantastic tool to separate different elements in a deposit step-by-step. ERAMET has been working on developing an extraction process for niobium production in its Maboumine project in Gabon. Through an aggressive leaching and fine-tuned thermo-precipitation, it has been possible to separate rare earths and uranium containing solution from niobium main flow. Later on, by using an innovative solvent extraction route, tantalum was separated from niobium, adding significant value while requiring small additional equipment and reactive consumption compared to the requirements of the entire process.

Pyrometallurgy can also create very interesting conditions to recycle valuable elements that are already commercialised. For instance, a specific treatment through Silico-Aluminothermy Process allows bear chemicals to produce ferro vanadium and ferro molybdenum from processed catalysts and by-product of operating mines.

It is thus clearly shown that ERAMET has developed and keeps working on bringing additional value to existing operations and projects under development, through innovative use of characterisation methods and appropriate developments of extractive metallurgy based on mineral processing, hydrometallurgy and pyrometallurgy.

Addressing obstacles to implementing multi-metal projects

Keywords
- multi-metals
- constraints

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The presentation focuses on two aspects of by-product metal production – impediments to resource utilisation often encountered and how, to some extent, these can be alleviated by removing upstream process constraints.

Simply put ... Imaginative, multi-metal projects often are not implemented. Why?

The presentation deliberately refers to South African experience and examples. However, these examples are considered to be equally applicable to the European and global environments.

The obstacles to implementation of multi-metal projects are suggested to be often due to the risks associated with complicated processes, the lack of investor enthusiasm for this type of project, the danger of management distraction from the primary metal/s and the difficulties of simultaneous optimisation of multiple metal production. The failure of the South African PALMAG project, intended to simultaneously recover potassium, magnesium, aluminium and fluorine from phlogopite, and taken to very large pilot plant scale in 1997 at a development cost well in excess of EUR 80 million in today's money, is cited as an example.

Some of these obstacles can only be addressed by keeping them firmly in mind at the time of developing the production process. Aiming for maximum simplicity in process design, adoption of the most reliable technology possible, adopting easily 'bolt-on' (and 'bolt-off') processes for each of the by-products, and recognising and addressing investor concerns can alleviate reservations to some extent.

The typical research approach of developing new technology to more efficiently recover numerous by-products from a resource is recognised as being valuable. However, it is suggested that an additional, complimentary and valuable area of research is to develop technology which, when applied downstream, has the effect of relaxing constraints otherwise imposed on upstream processes. Relaxing these process constraints has a progressive beneficial effect all the way upstream, to the point where the ore resource can be more fully utilised. ConRoast® and BIOX® are cited as examples of this type of technology – where most value is derived from the beneficial upstream effect derived from constraint relaxation, rather than a saving in capital or operating costs or an improved metal recovery directly associated with that technology.

These relaxed upstream constraints can also facilitate exploitation of hitherto uneconomic ore resources, of which several exist in Europe and its potential supply markets. These ore resources often contain substantial quantities of associated by-product metals (several of which are defined by the European Commission to be 'critical raw materials') which could be recovered. Tin, often associated with indium, tungsten and tantalum, is cited as such an example. If technology can be developed which is capable of economically smelting and refining tin concentrate grades substantially lower than the current norm, the opportunity arises to open up currently sub-economic ore resources, thereby enhancing the feasibility of by-product production and increasing security of supply through European production of the associated CRM by-products.

Maximising recovery of useful metals from ores: the challenge

Keywords
- mineral processing
- pyrometallurgy
- hydrometallurgy
- resource
- reserve

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Many ore resources never become ore reserves. Under modern classification systems, e.g. JORC, resources can only be considered as reserves after a number of 'modifying factors' have been assessed and, where necessary, addressed. A reserve is only quoted once there is confidence that the deposit can be mined economically and there is a known and economically viable processing strategy to extract the metal (or mineral) of interest. Reserves will not be (and cannot be) quoted where there has been either no test-work or an economically viable processing route has not been defined. Typically there are three (or more) distinct processing steps involved in the mining of metals, a mineral processing step (concentration stage) producing an intermediary product which passes to an extractive metallurgical step (smelting using pyrometallurgy or leaching using hydrometallurgy) which is often followed by a refinery stage (using either pyrometallurgy or electrometallurgy) to produce a high purity product.

The challenge facing the industry is to ensure that the most effective resource utilisation can be adopted, recovering as many products (and by-products) as possible from the ore – effectively turning all resources into reserves. Ultimately this would involve zero-waste, as all components of the ore would be recovered for beneficial use, although clearly this is an economic as well as technological issue.

Mineral processing effectively separates one mineral constituent from another, thereby making subsequent extraction steps easier (less energy required, enhanced separation efficiency and hence product quality). However, different metals (minerals) may have competing requirements for mineral processing and, to maximise the recovery of a particular component, may adversely affect the recovery of a more minor constituent of the ore. Downstream processing requirements often dictate the mineral processing strategy, where potentially valuable by-products are often considered as deleterious penalty elements.

This presentation looks at some of the specific challenges facing Europe by way of case studies:

- Recovery of gold and antimony from sulfidic ores;
- Removal and recovery of zinc and lead from fluorspar; and
- Recovery of by-products, especially indium from tin ores.

An underlying issue facing Europe is a skills shortage in mineral processing and extractive metallurgy – recognised by the European Commission and being addressed through programmes such as H2020 – and the lack, in particular, of pilot scale pyrometallurgical test facilities. These will need to be addressed to ensure European resources become reserves.

NIKKELVERK
A GLENCORE COMPANY

Recovery of by-products from primary and secondary raw materials in a polymetallic nickel refinery

Keywords
| nickel
| recycling
| zero harm

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Glencore Nikkelverk in Norway is an integrated unit in a global value chain which processes both primary and secondary materials.

Together with its sister company, 'Sudbury smelter operations' in Canada, Nikkelverk represents both traditional underground mining as well as recycling of materials, often referred to as 'urban mining'.

From the ore originating from Glencore's own nickel mines in Canada, Nikkelverk recovers the following by-products along with nickel: copper, cobalt, sulfur as sulfuric acid, silver, gold plus platinum group metals, and selenium.

All the by-products, except for selenium and silver, are recovered to a high degree of purity as finished products at the Nikkelverk site which maximises metal and by-product recovery.

Secondary materials such as batteries, super alloy scraps and catalysts are recycled via the smelter in Canada following recovery of cobalt as finished metals for sale at the refinery in Norway.

Under the objective of 'zero waste' the energy in the acid plant generated from exothermic chemical reactions is recovered as hot water and utilised in the district heating system in the town of Kristiansand where the refinery is located.

'Zero harm' during the materials processing is the primary objective and includes processing of materials in a safe and environmentally friendly way. No material is purchased without a full elemental scan to identify deleterious elements such as beryllium and PCBs. Elemental scans are repeated on all inbound lots after contracting to ensure compliance.

Supply of precious metals: a focus on key supply trends

Keywords
• platinum group metals

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Platinum Group Metals (PGMs) are recovered through both underground and open pit mining from polymetallic sulfide ores containing PGMs, nickel, copper and other metals:

- platinum (Pt), palladium (Pd), rhodium (Rh) and ruthenium (Ru) are the most prevalent of the six PGMs, with iridium (Ir), and osmium (Os) found in much smaller quantities but mined concurrently
- gold is often associated with PGM deposits and treated as part of a family – with platinum, palladium and rhodium – collectively known as '4E'
- nickel and copper are the most prevalent base metals
- chromite (used to derive chrome) is another significant by-product
- silver and cobalt are also found in trace quantities
- selenium, tellurrium and bismuth can and are sometimes recovered in trace quantities

World PGM reserves total about 3 200 M oz (c. 200 years at the current rate of production), and are found in relatively few areas of the world: South Africa (88 %), Russia (8 %), North America (2 %), Zimbabwe (1 %) and rest of world (1 %).

South Africa (SA) is the source of over 60 % of newly mined PGMs and over 80 % for platinum. PGM mining in South Africa is located in the Bushveld Complex in three regions commonly referred to as the Western, Eastern, and Northern Limbs. The Bushveld Complex includes three distinct mineral-bearing strata known as reefs:

- The Merensky Reef, the source of most current SA production, contains relatively higher PGM grades and ratios of platinum (vs palladium)
- The UG2 Reef, a chromite-rich reef, is more consistent, but lacks Merensky's high yield of gold, copper and nickel by-products. UG2 ore may contain as much as twice the PGM reserves as Merensky and Platreef
- Platreef is a wider reef with lower PGM values, but higher base metal content

It is getting harder to remain profitable (the 'running hard to stand still' effect) for mainly two reasons:

- Mines are getting deeper with trickier geology
- Society is demanding a fair share of the profit pool in an industry suffering from poor economics

The future of technology in PGM mining is focused on creating a step change in mining extraction processes and the use of critical resources such as water and energy.

Enhanced recovery of metal by-products. A focus on copper value chain

RioTinto

By-products recovery via integrated copper operations at Rio Tinto Kennecott

Keywords
- copper
- molybdenum
- gold
- silver
- selenium
- lead
- rhenium
- sulfuric acid
- co-generated power

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Rio Tinto Kennecott (RTK) is a fully integrated mining, concentrating, smelting and refining company committed to practicing sustainable development in every facet of its business. Nearly everything people do today relies on materials that are mined from operations like RTK. Cell phones, computers, cars, plumbing and jewellery are just a few of the many benefits enjoyed because of these products. As the second largest copper producer in the United States, RTK comprises 15 to 25 % of the annual US copper supply.

The presentation will provide an overview of the RTK integrated copper value stream and technologies used for recovery of valuable by-products. Examples include molybdenum recovery from copper ores; gold, silver, lead and selenium recovery from copper anode tank house slimes; rhenium recovery from smelter off-gases; advanced cementation to recover copper from acidic mine waters; sulfuric acid production from copper smelting; and electricity production (co-generation) from recovery of waste heat and gases from smelting.

Further value stream integration will bring opportunities for recovery of other by-products from mine ore bodies, and here RTK have conducted studies relating to extraction and recovery of tellurium, bismuth, antinomy, platinum, palladium, and lithium.

Sustainable development is integral to the company's success as a fully integrated producer of copper and by-products, and this will also be discussed in the presentation. For example, a significant portion of the gold and silver produced by RTK makes its way into jewellery, and in 2012 the Responsible Jewelry Council announced that Rio Tinto plc was the first mining company to achieve certification by meeting the highest ethical, social and environmental standards established by the RJC's Member Certification system. International computer chip manufacturers have also 'benchmarked' RTK for greater understanding of sustainable business practices such as 'end-to-end' product stewardship of precious metals which are used in consumer electronics.

To further unlock the value of by-products also requires new and detailed 'ore body knowledge' as it all starts with knowing what is in the ground and how best to recover valuable metals and by-products economically. Although a challenge, it is also a great opportunity for our industry to sustainably contribute to the material needs of society.

Outotec

By-products recovery technologies in primary non-ferrous metals production

Keywords
- copper
- zinc
- precious metals
- tellurium
- selenium

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Outotec offers leading technology solutions and services for the processing of copper, nickel, zinc, lead, gold, silver, and platinum group metals at all stages in the value chain from ore to metal. We provide energy-efficient and cost-effective methods based on extensive R&D and proprietary process equipment, together with life cycle services which ensure sustainable operations. Depending on the concentrate mineralogy, various hydrometallurgical and pyrometallurgical process solutions are possible, and recovery of valuable by-products including sulfuric acid and precious metals is feasible. As an example, process flow sheets in primary copper production are presented showing recovery of metal by-products.

ecometales LIMITED

Value recovery and environmentally suitable process for treating residues from copper smelting and refinery

Keywords
- arsenic
- flue dust
- copper refinery
- Chile
- minor metals

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In current operations and new mining projects, the grade of the copper ore mined has been decreasing. At the same time, there has been an increase of the impurities such as As/Sb/Pb/etc. content in the concentrates. Due to the content of these contaminant elements, the copper concentrates are penalised, becoming difficult to trade or process.

Raw materials – exporting countries usually focus on a few products, like Chile on copper; depending on the mineralogy, also molybdenum, gold and silver are recovered from very simple processes. Other elements, which can be found in the concentrates from smelter and refinery processes, are not always considered valuable but rather as dirty residues which affect the environment. In developed countries more and more by-products are recovered from those facilities, such as PGMs elements, Te/Se and many others. Additionally, the higher efficiency for recovering minor materials implies a higher level of contaminants capture. In the current scenario, in which environmentally friendly processes are a driver of the industry, both processes are required. You can't export dirty concentrates for environmental reasons, and you have to recover almost everything, for economic reasons. The EU, China and Asia, for example, have established high restriction in the copper concentrates quality related to As content (<0,5 % As in the copper concentrates).

With these two requirements, the focus shall be to clean the process and recover the valuable by-products on site, or at least as close as possible. To clean the process is the most important step; if Europe or China do not accept imported copper concentrates with high As content (but also Ag/Au/PGMs), then treating these issues at the origin will help recover the valuable metals and also the adequate handling/disposal of the impurities.

EcoMetales Limited (ECL) is a 100 % Codelco subsidiary that operates a plant for processing flue dust and copper refinery effluent. A typical flue dust sample contains Ge, Sb, Ag, Bi and Pb. Our facilities are located in a strategic location, 35 km northeast of Calama. Up to today EcoMetales has processed more than 300 000 tonnes of residues recovering 54 000 tonnes of copper. The arsenic is deposited as escorodite, a stable arsenic compound, after a proprietary process, (AAA) in our facilities. Our plant has a capacity for treating 8 000 tonnes of As per year.

HATCH

Research on metal by-product recovery – methods for enhancing industry exploitation

Keywords
- hydrometallurgy
- profitability
- capital costs
- operating costs
- solvent extraction
- ion exchange

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Many collaborative projects involve academic partners and industry partners to develop new technology or to exploit a resource or facility. Most academic partners have different motivations and attitudes compared to industry partners. Whereas academic partners tend to focus on topics such as providing opportunities for PhD and post-doctoral study, improving their personal standing and the prestige of their institutions, and publishing application based papers on their work, industry partners are in the business of making money, and see the exploitation of collaborative research project outcomes as a means of making money. To this end, collaborative research must be focussed at providing technologies or solutions that may have economic, industrial application.

A case study on applied research about metal by-product recovery is used to show how academic research can be focussed to enhance the usefulness thereof to industry. The research program in this case study was aimed at developing a practical flowsheet for by-product recovery, apart from recovering copper as the main pay metal. The potential by-product recovery flowsheets consisted of a range of unit operations. An industrial partner analysed those possible by-product recovery flowsheets which had originally been considered as applied research targets, for their respective incremental operating costs and incremental capital costs on an industrial scale. These costs were compared with incremental revenues from these by-product recovery flowsheets to provide an indication of their potential industrial exploitation, i.e. their ability to contribute to the business of making money. These comparisons clearly show that the potential economic value (i.e. revenue minus processing costs) of an individual by-product directly impacts the choices of the unit operations that should be considered for a collaborative applied research project. Generally, unit operations that demand exotic materials of construction on industrial scale, such as crystallisation, or unit operations that involve large temperature changes or high pressure, such as pressure oxidation or pressure reduction, can only be considered as research topics for by-products that are available in relative large concentrations or that have high associated revenues.

A mine, whether underground or in-situ, and a processing plant can be part of a greater circular economy, provided the correct processing flowsheet is used. Should the recovery of a by-product be considered not economically feasible, then recycled material can potentially be introduced to increase throughputs to more economic levels. Ideally, these analyses should be performed ahead of or right at the start of the research project so that the chances are higher for the research project outcomes to lead to industrial application, thereby maximising the potential for exploitation by industry partners.

Enhanced recovery of metal by-products from secondary raw materials

Metallurgical infrastructure: a key enabler of a circular economy

Keywords
- system integrated metal production
- process metallurgy
- flowsheets
- technology

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A robust and adaptive metallurgical infrastructure are key to extracting as many elements from dynamically changing product compositions as possible. Therefore, the focus will be on the metallurgical infrastructure that is required to recover by-products, minor and critical elements from a variety of feeds.

The detail and deep process metallurgical knowledge that is required to systemically fully understand resource efficiency in the context of a circular economy will also be discussed and 'design for resource efficiency' (DfRE) and 'design for recycling' (DfR) elaborated on. Specifically, the understanding of product-centric recycling is highlighted, setting it apart from the usual material-centric recycling approaches that cannot quantify resource efficiency, as it does not capture the complex non-linear thermodynamics of metal recovery of elements and compounds from complex feeds. The latter material-centric approach focuses more on bulk materials and therefore inherently limit the maximal recovery of by-products, technologically critical and minor elements in particular and these limitations will be discussed.

The base metals – copper, cobalt, lead, nickel, tin, and zinc – and their processing infrastructure all play a crucial part in present society. Critical processing flow sheets and technology that maximise the recovery of valuable elements will be shown and also elaborated on by applying a simulation basis. These base metal infrastructures are linked in concert to form the crucial carrier metals for the sustainable circular economy society termed the 'web of metals' (WoM) or in a more modern paradigm 'system integrated metal production' (SIMP) (or the process metallurgical 'Internet-of-Things' (IoT)). Thus this presentation examines the special and crucial role base metals and their metallurgical processing infrastructure have in acting as enablers in any recycling efforts, as they carry and release important and vital minor elements. Above all, the precious metals (PM) and platinum group metals (PGM) are key economic enablers for the economic viability of recycling as well as the metallurgical infrastructure (SIMP/IoT). In summary, of importance is not only the criticality of elements but also the criticality of the metallurgical infrastructure and technology that enables the economically viable recovery of elements and compounds from complex products and materials.

Treatments of secondary raw materials in non-ferrous smelters in Japan

Keywords
- non-ferrous smelters
- secondary raw materials
- copper smelters
- lead smelters
- zinc smelters

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Copper, lead, and zinc smelters are widely used in the non-ferrous smelting industry in Japan. In these smelters, imported mineral concentrates obtained from dressing ores are treated to produce refined metals. The concentrates of sulfide minerals containing iron are treated to remove sulfur, iron, and other minor impurities in order to recover objective metals that are then refined to obtain purified metals. The copper, lead, and zinc concentrates contain other valuable elements such as gold (Au), silver (Ag), platinum group precious metals (Pt, Pd, Rh, etc.), selenium (Se), tellurium (Te), antimony (Sb), bismuth (Bi), nickel (Ni), tin (Sn), indium (In), and gallium (Ga). These elements are also recovered from the intermediate products in non-ferrous smelters.

With the recent international competition for resource acquisition, the non-ferrous smelting industry in Japan has been forced to use low-grade concentrates. Further, there are increasingly stricter environmental regulations on the use of particular elements and substances. Therefore, for the sustainable development of the domestic non-ferrous smelting industry, it is very important to efficiently recover and stabilise environmental load elements such as arsenic (As), cadmium (Cd), and mercury (Hg) from intermediate products in non-ferrous smelters. Non-ferrous smelters are designed to be efficient for controlling various elements with impurities. Thus, the non-ferrous smelting industry plays an important role in the recovery of valuable metals and in the control of environmental load elements through treatment of secondary raw materials and industrial wastes. This industry is therefore becoming widely recognised as indispensable for resource circulation in Japan.

For example, printed circuit boards containing high-quality Au and Cu are an important secondary raw material in copper smelters. Automobile shredder residues containing waste plastics and lower amounts of valuable metals are incinerated in copper smelting facilities. Industrial wastes such as sludges containing heavy metals are melted and sulfurised to produce copper matte for subsequent copper smelting. In zinc smelters, crude zinc oxide, which is produced from the electric arc furnace (EAF) dust generated from steel scrap recycling, is an important secondary raw material. Japan's non-ferrous smelting industry also includes hydrometallurgical zinc smelters primarily treating mainly zinc concentrates and pyrometallurgical zinc smelters (ISP) actively treating secondary raw materials containing various impurities. These processes are indispensable for domestic resource circulation. Lead smelters such as blast furnaces are important in the treatment of intermediate products generated in copper and zinc smelters. Lead blast furnaces are also suited for treating various industrial wastes in order to recover valuable metals through the control several phases such as molten lead, speiss, matte, slag, and gas.

Thus, the non-ferrous smelting industry is crucial for Japan's resource circulation system for waste treatment and the recovery of valuable metals. However, this will require the establishment of more organic linkage among copper, lead and zinc smelters for the efficient interchange of smelting intermediary compounds.

umicore Precious Metals Refining

By-product metal recovery @ Umicore – from smelter by-products to post-consumer products and everything in between

Keywords
- by-product treatment
- recycling
- manufacturing residues
- rechargeable batteries
- e-waste
- non-ferrous metals

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Umicore is a global materials technology and recycling company. Its mission making 'materials for a better life'. The overarching business approach consists of two parts: Transforming metals into high tech materials for clean technologies and closing the materials loop by recycling production scrap and end-of-life products by using deep understanding of metallurgy, engineering and material science. The material portfolio includes many of the so-called by-product elements of which some are listed as critical raw materials, as well as base metals. Or to be specific: Co, Ni, Cu, Zn, Ga, Ge, As, Se, Ru, Rh, Pd, In, Sn, Sb, Te, Ta, W, Re, Ir, Pt, Au, Pb, Bi, La, Ce, Pr, Nd, Ag. 28 in total. Each of them has its own specificities and supply chain. One thing they have in common: most of them are by-product elements and their recovery and recycling is complex. Umicore has state-of-the-art processes to make this happen, which will be illustrated with a number of examples.

- Minor metal recovery from non-ferrous (primary) smelter by-products at Umicore in Hoboken, Belgium. Using a multi-process flowsheet and the properties of copper, lead and nickel as carrier metals to facilitate the separation and recovery of 17 different elements from smelter by-products. The presence of base and precious metals are the economic drivers for treatment of the by-products and so allow the recovery of other minor metals both from an economic as well as technical perspective, as the cost of recovery of the minor elements is often higher than their economic value. The recovery of the different metals happens in an environmentally sound and sustainable manner. The existing 350 000 tonne processing capacity will be expanded to 500 000 tonnes/year in the coming years.
- Rhenium recycling from superalloys: recycling of rhenium from superalloys used for jet engines is key in securing ongoing supply of rhenium as well as keeping rhenium prices more stable. Umicore provides recycling services for scraps generated at alloy melters and during casting as well as for end-of-life turbine blades. Ni and Co are also recycled out of this process, and Umicore transforms them further into Ni – and Co chemicals.
- Cobalt and tantalum recycling from hard metal scrap: hard metal is used in the production of diamond tools and high performance tools. During production of hard metal itself, the products and at end-of-life scraps arise. Umicore is recycling those streams for Co and Ta, and transforms the recycled Co further into Co powders for the hard metal industry and Co chemicals.
- Germanium
- Minor metal recovery from industrial and post-consumer waste. Recycling of metals from WEEE (printed circuit boards), catalysts and rechargeable batteries.

BRAVO – Bauxite Residue and Aluminium Valorisation Operations

Keywords
- bauxite
- residue
- alumina
- valorisation
- BRAVO

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From a total aluminium metal supply of 13.2 million tonnes in 2011, 35 % was produced by European primary smelters, 30 % was net-imported and 34 % was recycled by European refiners and remelters. This metal was processed into 4.5 million tonnes rolled products, 3.0 million tonnes extruded products, 3.2 million tonnes of castings, and another 1.2 million tonnes is produced in the form of wire, slugs, powder and other applications. The aluminium industry in Europe directly employs around 255 000 people [European Aluminium Association].

In spite of increasing global demand for aluminium, since 2003 ten primary aluminium smelters have closed in the EU, while none have opened or are planned to open. Therefore, a new Commission study looks at the situation in the aluminium sector. Former European Commission Vice President Antonio Tajani, Commissioner for Industry and Entrepreneurship, said, 'Restoring the aluminium industry to competitiveness is an urgent issue. We need to carefully consider the effects of all relevant EU policies on this sector' [EC – MEMO/13/954 06/11/2013]. European competitiveness in this sector is imperative to both stabilise and reduce EU dependency on imports, promote production and protect jobs.

In addition to this situation, the safe environmental management of by-products and wastes from the aluminium value chain is critical and includes bauxite residue from alumina refining which is normally landfilled.

In the event of improper disposal of bauxite residue in rivers or lakes, there are fatal environmental hazards. The rain water runoff from the red mud landfills increases river and stream water alkalinity which will convert lands into alkali soils when used for irrigation purpose. In October 2010, approximately 1 000 000 m^3 of red mud from an alumina plant near Kolontár, Hungary was accidentally released into the surrounding countryside. The Ajka alumina plant accident killed ten people and contaminating a large area.

Currently, some European plants are slated to be closed because their bauxite residue landfills are filled and governments are unwilling to give authorisation to build new ones. A report published in 2010 by the International Aluminium Institute states that storage volume reduction and revaluation of waste residues is a main strategic goal of the industry (>20 % by 2025).

BRAVO, a newly sanctioned European Innovation Partnership's Raw Materials Commitment with over 35 international partners across the value chain of the aluminium sector believes this represents the opportunity to increase the competitiveness of the aluminium sector in Europe and be at the forefront of resource efficient technologies via metal recovery from the residue itself as well as addressing the technologies for reusing the bulk volume of the residue.

This presentation will review the challenges as well as approaches and methodologies being undertaken by the BRAVO partnership to address the metal recovery opportunity from bauxite residue.

SOLVAY latest developments in 'rare earth recovery' from urban mines

Keywords
- rare earth
- hydrometallurgy
- solvent extraction
- recycling
- mining

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During the past decade, SOLVAY has acquired a unique experience in recovery of rare earth from urban mines and more generally in purification of rare earth concentrates from various origins. SOLVAY launched in 2007 a large program of research and development concerning 'rare earth recycling'. Among all materials screened technically and economically, significant progress have been achieved concerning end-of-life phosphors from lamps, nickel hydrides batteries as well as tailing from magnet manufacturers. This program has resulted in particular in 2012 by the investment of two industrial units devoted to concentration of rare earth from end-of-life phosphors in La Rochelle and Saint Fons sites in France. These two complementary units have been associated to the unique capabilities of La Rochelle plant for rare earth separation with solvent extraction technique as well as the historical know-how regarding manufacturing of phosphor precursors. During the presentation, a general overview will be given about the rare earth market dynamic, highlighting recent evolution regarding the Chinese situation, as well as the global resource. Criteria for selection of promising streams at the start of the program will be explained. Lessons learnt and last progress on rare earth recovery from urban mines, secondary mines and primary mines will be shared.

Poster abstracts

Biomining – an innovative strategy to recover metals from secondary resources

Keywords
- metal recovery
- waste incineration residues
- metalophytes

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The exploration of novel technologies for metal recovery gains more importance, as primary resources get scarce and expensive. New technologies should be efficient and less energy consuming, also supporting a low carbon economy. The present series of projects investigate the utilisation of secondary resources like waste incineration ashes and other waste streams for bio-based metal recovery. In one project, metal hyperaccumulating plant species were grown on diverse industrial wastes that have been amended to suit plant growth. Such metal hyperaccumulators possess the ability to extract metals from their substrates, translocate and accumulate them in different parts of the plant. Within a field trial at the Viennese landfill metal accumulating plants were grown on waste incineration residues to check feasibility and to gather high amounts of biomass. This metal-enriched biomass is further treated with gentle techniques to recover metals in their pure form. Other strategies that will be investigated include microorganisms, peptides and polymers, algae and cyanobacteria, and biosorption and rhizofiltration techniques to concentrate metals in biomass. Associated projects are the BIO-ORE project (Austria FFG, project no. 8389609), Bergwerk Pflanze (FFG, project no. 843643) and GRecoMet (FFG, in evaluation). Applications for H2020 will be undertaken in the next rounds.

Metal recovery by reductive melting of red mud

Keywords
- red mud
- critical raw materials
- reductive smelting
- rare earth metals
- recovery

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The alumina production from bauxite via the Bayer process is accompanied with a huge amount of a residue. This so called red mud is currently only deposited and mainly consists of Fe2O3 (47 %), Al2O3 (15 %) and TiO2 (11 %). However, elements that are classified by the EC as critical raw materials due to their high economic importance and high supply risk are also present in this red mud such as Ga, Ge, Nb and rare earths (REE). Those critical raw materials are irreplaceable for applications in high-technology fields (permanent magnets, catalytic converters, LED, laser, etc.) but the current recycling rate is in many cases negligible. Carbothermic fusion of red mud in the temperature range 1400-1600°C was investigated in graphite crucibles without further additives. The products were Cr- and V-containing pig iron and Al- and Ti-rich slags. Metal phase and slag were separated from each other by mechanical post treatment. The slag consisted of Al- and Ti-rich compartments with a clear phase boundary. The mineral titanium phase was identified as TiC. It was possible to separate Ti from the Al-phase by leaching with nitric acid. Furthermore, reductive fusion of red mud was tested in a pilot-scale electric arc furnace.

RELAX: reductive bioleaching for extracting metals from oxidised ores

Keywords
- biomining
- bioleaching
- bioprocessing
- laterite
- nickel
- cobalt

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Laterites deposits are characterised by the presence of two distinct horizons: a limonite zone near the surface and a lower saprolite zone. Due to the lack of economic and robust process the limonitic part remains often untreated and is stockpiled on site. RELAX project proposes the development of an innovative biohydrometallurgical process for the recovery of metals (Ni, Co, Cu, ...) associated to limonitic laterite ores. It is based on the bacterial catalysis of the reductive dissolution of goethite, the most prominent host mineral in limonite. This mechanism involves chemolithotrophic bacteria which can grow using FeIII as an electron acceptor in the absence of oxygen under mild acid and temperature conditions. This reductive biocatalytic process provides the opportunity to supplant classical hydrometallurgical processing routes operating at high temperature and pressure. RELAX relies on an interdisciplinary European consortium bringing together world-leading experts from various areas of hydrometallurgy and bioprocessing. This collaboration aims at optimising the performances of the reductive bioleaching and integrating this biological mechanism in a global hydrometallurgical strategy for metal production. This new bioleaching procedure which involves soft operating conditions is expected to improve the economics of laterites processing while reducing its environmental impacts.

Novel methods for metal collection combined to online detection

Keywords
- CH Collector
- metal collection
- on-line measuring
- geopolymers
- automated systems

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University of Eastern Finland (UEF) developed a novel resin-free ion exchanger (CH Collector, (commercialised by Chemec Oy) to collect metals from aqueous solutions (AS). Material is non-toxic and regenerable over number of cycles, and cost effective compared to other related materials. CH Collector enables selective collection of metal ions, e.g. U, Pb, Y, Th and Sc, since collection is pH dependent. Among this material, Chemec also offers NT-products used as depressants of industrial minerals, Fe and other metals. Geopolymers (GP), developed by KAMK, are novel green and low-cost cation exchangers prepared from industrial side products. GP improves significantly the sorption capacity of raw materials. KAMK have prepared highly active, regenerable and potential GP sorbents to recovery metal from AQs. CEMIS-Oulu has developed a novel approach to measure trace concentration of toxic metals (Co, Ni, Pb, and Hg) down to the ppb-level in real time from ASs. The method is based on an innovative Hg-free nano-scale electro-chemical sensor also passing heavy field tests. In the near future, the techniques above will be tested together in pilot and production scale studies. The target is to develop an on-line system to purify ASs automatically. These products, CEMIS technology together with lab analyses and R&D from UEF are strong team for solving many heavy and REE metal challenges.

The supply of sustainable raw materials in the EU rely on copper as a key driver for multi-metal ore recovery and enabler of metal-mix recycling

Keywords
- copper extraction
- copper recycling
- resource efficiency
- copper value chain
- industrial symbiosis

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Europe has a very energy and resource efficient copper industry directly employing around 50 000 people. With a world class smelting and refining sector, European companies continue to pioneer many of the world's leading metallurgical processing and environmental protection technologies. The EU's six refined copper producers operate a heterogeneous set of production processes reflecting a diversity of technologies and varying raw material sources – e.g. proximity to EU mine sites, the imports of copper blister and concentrates, and complex, multi-metal bearing scrap and by-products. Most of the European copper installations are also multi-metallic in their end product offerings.

The starting point in the recovery chain is the copper ore body that contains many metal-containing compounds, including molybdenum, precious metals and rare earths. Copper is also the main element (>60 %) in a broad range of alloys. With copper being the 'carrier' in many metallurgical refining and recycling streams, copper smelters processing either concentrates (primary) and/or recycled (secondary) raw materials will, in addition to copper, produce other metals, such as for e.g. gold, lead, tin and precious metals.
Copper manufacturing and recycling facilities in Europe developed an intelligent combination of different metallurgical processes for recovering a wider range of metals, and act as a successful industrial symbiosis.
ECI's poster will outline the challenges faced today in the recovery value chain, invite for discussion and, hopefully pave the way to potential solutions.

By-product status: implications for reserve estimates

Keywords
- minor metals
- resources
- exploration
- minerals processing
- abiotic resource depletion

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Because there is no active exploration and little process technology development for metals when their by-production fully satisfies demand, by-product resources and reserves are consistently underestimated. Assessment methods that take resource or reserve estimates as inputs tend therefore to exaggerate supply risks associated with by-products. For the same reason, claims as to whether current by-products will ever be economically mined as a main product could be highly speculative.

InsPyro, a knowledge centre for high-temperature metal processes

Keywords
- knowledge centre
- modelling
- thermodynamics
- experimental set-ups
- process development

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InsPyro improves metallurgical processes by research-based industrial projects and services and develops new sustainable high-temperature processes in cooperation with its customers. It has substantial experience with the recovery of metals from by-products and has cooperated in several projects on critical metals.

SIMORGH project: biological metal recovery from secondary resources with encapsulated biomass

Keywords
- biohydrometallurgy
- copper
- bioleaching
- cell encapsulation
- secondary resources

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Biohydrometallurgy is an emerging technology for metal recovery from secondary resources. Based on well-established know how for copper-ores refinery and precious metal biomining, the microbial assisted leaching offers new opportunities for heavy and precious metals recovery from electronic wastes, end-of-life vehicles, spent catalyst, etc. The eco-friendly nature of biohydrometallurgy is obviously supported by mild operating conditions (low pressure and temperature, reduced chemicals). In the SIMORGH R&D project funded by Belgium's Walloon Region and supported by. Hydrometal s.a, an innovative approach implementing 'biomass encapsulation' is adapted to 'niche resources' from automotive industry, amongst other resources, presenting intrinsic iron-, low copper-content and which are not recycled due to low profit with conventional technology. The development will offer an economic and environmental sustainable alternative to landfills with selected poly-metallic industrial wastes. The SIMORGH process (system with immobilised micro-organisms for hydrometallurgy, Pat. Appl. EP2813586A1) has shown its advantages in comparison with planktonic cultures in terms of biomass protection against harsh medium conditions and in efficiency in copper recovery from brake-pads dust. The technology will be applied to primary wastes (anodic sludge) and to rare-earth metals recovery from NdFeB magnets.

Mineral processing and extractive metallurgy for mining and recycling: the PROMETIA Association

Keywords
- mineral processing
- extractive metallurgy
- secondary waste
- recycling
- innovation

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The PROMETIA Association promotes the development of innovative processes for recovering metals from primary and secondary resources. Today mining and industrial by-products represent a huge opportunity for Europe. The poster presents the position of the association in the value chain of these metals.

Mobile hydrometallurgy to recover rare and precious metals from WEEE

Keywords
- WEEE
- hydrometallurgy
- critical metals
- recovery

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Because of the increasing resource scarcity, the EC projects HydroWEEE (2009 – 2012) and HydroWEEE Demo (2012-2016) have dealt with the recovery of rare and precious metals from WEEE, including lamps and spent batteries. The idea has been to develop a mobile plant using hydrometallurgical processes to extract metals like yttrium, indium, lithium, cobalt, zinc, copper, gold, silver, nickel, lead, and tin in high purity (above 95 %). By making this plant mobile (in a container) several SMEs can benefit from the same plant at different times and therefore limit necessary quantities of waste as well as investment. By making the processes universal, several fractions (lamps, CRTs, LCDs, printed circuit boards and Li-batteries) can be treated in the same mobile plant in batches. This reduces the minimum quantity per fraction per recycler even more. These innovative processes are currently being demonstrated in two industrial plants (one stationary and one mobile) in order to test the performance and prove the viability of the processes from an integrated point of view (technical, economical, operational, and social) including the assessment of risks (including to health) and benefits to society and the environment. This will help make SMEs much more competitive and reverse the general trend to bigger companies.

Purification of phosphogypsum from 226Ra and heavy metals for its further utilisation in construction: technological utopia or reality?

Keywords
- phosphogypsum
- purification
- radium
- heavy metals
- construction

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Phosphogypsum (PG) is a waste product of the phosphate fertilizer industry. Because mainly of 226Ra and heavy metals, the use of PG in construction is impractical and 85 % of PG produced worldwide is dumped in the stacks, where it poses environmental and human health hazards. The known purification approaches failed to produce a breakthrough in the industry, and remained confined to the laboratory, largely due to cost considerations. The method suggested at the Technion is based on mixing hot PG suspension containing special chemical reagents to extract the impurities. The best results achieved demonstrated reduction of 226Ra content by an order of magnitude. The author, together with his colleagues from the new COST TU1301 Action NORM4BUILDING, seeks a cooperation with academic and industrial partners in order to compare the given approach with alternative purification methods for further implementation on a larger scale. An important step would be to estimate an economic efficiency of the process. One of the possibilities discussed now in the COST Action would be to create a consortium of the academy and industry for submitting a joint research proposal to one of the next Horizon2020 calls. The brain storming between the experts from academy and industry dealing with the uses of phosphogypsum in construction is set for mid-March 2016 in Paris.

UCT PRAGUE

Li and Rb recovery from industrial by-products in the Czech Republic

Keywords
- lithium
- rubidium
- zinnwaldite
- extraction

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By-products from mineral processing of Sn-W ores and from production of feldspar raw materials, used in glass and ceramics industries contain high Li and Rb content in the form of the zinnwaldite mineral. Improved separation and extraction methods were developed and verified at the lab scale in order to obtain high-purity zinnwaldite concentrate from the by-products and to maximise Li and Rb extraction into solutions. Lithium carbonate was obtained from the leach liquors by carbonate precipitation and Rb was separated by selective precipitation of rubidium alum. A magnetic separation process was applied to recover calcium hydroxide from leach residues, which can be reused in sintering in order to minimise the consumption of additives.

Magnesium recovery from exhausted brine

Keywords
- brine disposal
- magnesium
- mineral recovery
- salt works
- reactive crystallisation

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Mg and MgCO3 are among the 20 EU critical raw materials. Interestingly, Mg can be found at very high concentration in brines generated as waste stream from salt works. Literature works have demonstrated the feasibility of Mg extraction from brines [1–3] by reactive precipitation, for the production of Mg(OH)2. Here we present an overview of the experimental campaigns carried out using exhausted brine from real salt works (Italy) to produce Mg(OH)2 with high purity and conversion. Lab – and pilot-scale batch and semi-continuous CSTR crystallisers were developed and tested, eventually leading to a continuous process by a quasi-PFR pilot reactor. Different alkaline solutions have been adopted in order to analyse their influence on the process, looking in particular at the product purity (affected by possible by-products co-precipitation) but also at the economic profitability. A late development focused on the development of a membrane crystalliser reactor using ionic exchange membranes (CrIEM) [4]. In the CrIEM the precipitation reaction occurs avoiding the direct contact between feed brine and alkaline solution, thus allowing in principle the use of any alkaline species, minimising the risk of by-products co-precipitation. In preliminary tests 99.5 % pure Mg(OH)2 was produced using cheap reactant, opening room for the development of a novel and economically profitable process.

Removal of cytostatic platinum compounds and recovery of precious metal from aqueous wastestreams

Keywords
- platinum
- cytostatics
- wastewater
- biomaterials
- adsorption

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Over the last decades, a strong anthropogenic increase in platinum concentrations in the environment is observed. In understanding the complete loop of platinum contamination, it is important to track the sources. While catalytic converters used in cars and industry contribute to elevated levels in vegetation and soils, hospitals intensely discard platinum from their effluents to surface waters. Since the discovery of its cytostatic properties by Rosenberg, cisplatin and other platinum coordinating compounds such as carboplatin and more recently oxaliplatin are extensively used in chemotherapy for cancer treatment. After ingestion and interaction with DNA, the drugs are biodegraded and excreted by patients through urine – either in hospital or at home – and remain mostly untreated. Removal and detoxification of cytostatic drugs is of critical importance for the environment and can be associated with economic benefits. In a screening step, several natural wood-based materials and dried microalgal biological flocs have been tested for their sorption efficiency towards cytostatic platinum compounds (CPC). Although large variations between platinum species, good overall sorption capacities were found for biomaterials. Especially biochar (59.6 % relative platinum removal) and chitosan (55.9 %) excel.

Vanadium recovery from steel slag leachates by ion exchange: Multidisciplinary research investigating the science of recovery and its political economic context investigations

Keywords
- steel slag
- vanadium
- recovery
- environmental remediation
- policy

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This multidisciplinary research project is investigating steel slag, a problem waste that produces highly alkaline leachate and is a source of environmentally hazardous, but potentially valuable, metals such as vanadium. The management and monitoring of legacy and current steel slag is therefore an expensive liability. At the high pH ranges associated with slag leachate V is mobile and toxic. Laboratory tests indicate that ion exchange resins are an effective means for V removal and recovery at relevant pH levels. The maximum adsorption capacity was greatest for pH 11.5 (49 mg V g-1 resin). The average recovery of V was 70 %, and there was no efficiency loss from the anion exchange resin after 20 reuses. No resin exhaustion was reached in column tests (after 90 L of steel leachate). This process of recovery of V from steel slag, provides opportunities for its

environmentally safe reuse in other sectors. This innovative project analyses the political and economic constraints that hinder the utilisation of our novel approach for resource recovery and removal of metals from alkaline waste. Investigation of relevant national and international policy for waste and associated liabilities is in progress. Ongoing interviews with stakeholders indicate complex issues of ownership and potential conflicts of interest between those associated with proposed and current uses of the slag.

Challenges in the recovery of critical metals from waste electrical and electronic equipment

Keywords
- pre-concentration
- electronic scrap
- physical separation
- hydrometallurgy
- eddy currents

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Critical raw materials are highly used in electrical and electronic equipment (EEE). Once the EEE become waste, it is complicated to recover the critical raw materials because they appear in low concentration in a large number of small scattered fractions. A classical post-shredder sorting (eddy current separator, density separation, ...) does not allow for an efficient pre-concentration. Some specific recovery technologies (selective leaching, ...) exist or are being developed, but are often too expensive to be used in industrial application. Currently, in Belgium, for most recycling companies, a separation of some flows (e.g. printed circuit boards) must be made before shredding. This separation process might be improved by removing selectively the components with high critical metals content. This is the case, for example, for tantalum which is present in large amounts in capacitors on printed circuit boards and which might be easily detected. In this poster, we will review some pre- and post-shredding separation processes. For each separation process, we will highlight the barriers for a successful implementation and the benefits regarding the recovery of metals.

The potential of deep eutectic solvent ionic liquids for recovery of Te, Bi and Sb from gold ores

Keywords
- Te
- Bi
- Sb
- gold ore
- deep eutectic solvent

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Gold ores, and concentrates from them, often contain high enrichments of scarce or critical elements such as Te, Bi and Sb, but these elements are not always recovered, or can incur smelter penalties and as such, are not prioritised for recovery. Recovery of these elements along with the gold would add value and secure supply. Ionic liquids are anhydrous salts that are liquid at low temperature. They are powerful solvents and electrolytes with potential for high selectivity in both dissolution and recovery. Deep eutectic solvents (DES) are a form of ionic liquid that are mixtures of salts such as choline chloride with hydrogen-bond donors such as urea. DESs are environmentally benign, yet chemically stable and, furthermore, the components are already produced in large quantities at low cost. Gold, as electrum, dissolves rapidly by oxidation in DES at 50°C and recovery of the gold by electrodeposition has been demonstrated (Abbott et al. 2015). Hessite (Ag2Te) dissolves as rapidly as electrum and

tellurobismuthite (Bi2Te3) and stibnite (Sb2S3) also dissolve. Base metal sulphides such as galena and chalcopyrite dissolve slowly, whereas pyrite and sphalerite are insoluble. Thus there is good discrimination in dissolution behaviour between the base metal sulfides/pyrite gangue and the Au, Ag, Te, Bi and Sb minerals, suggesting the potential to recover all these elements from gold ores.

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TeaSe: by-product assessment and recovery

Keywords
- tellurium
- selenium
- gold
- copper

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Tellurium and selenium: cycling and recovery ('TeaSe') is a ~ EUR 3 million research project funded by the UK Natural Environment Research Council as part of the Security of Supply of Minerals (SOS) programme. It involves researchers from UK universities and global companies in mining, metal processing, sales, and end-use. Our focus is on the geological processes which control Te and Se mobilisation and concentration in potential resources, and the potential for recovery using novel methods. This project showcases the potential approach to enhance the recovery of by-products from existing ore streams, and the untapped waste streams produced simultaneously. Our approach is to understand the fundamental geochemical and mineralogical controls on Te and Se to improve our ability to identify resources at regional, deposit, and mineral scales. A significant portion of our project is dedicated to metal recovery by microbiological processing and deep eutectic solvent ionic liquids. Our goals are to improve the discovery and recovery of by-products from major ore streams (Au, Cu), maintain or improve recovery of primary ore metals, and minimise the environmental impact of mining and processing. This approach can be expanded to a wider range of elements that occur as by-products: indeed, many of them will be associated within the same ores.

Sustainability assessment of rare earth elements (REEs) beneficiation in the mining industry and use in materials development using sustainability assessment tools

Keywords
- rare earth elements (REEs)
- sustainability assessment
- critical metals
- recovery

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REEs belong to a class of metals known as critical metals. Critical metals have their title because of their huge importance globally, making the demand for them high. Typically REE substitutes are not readily available, they have a low recycling rate and they are at risk of low supply. The aim of sustainability assessment is to guide decision makers in determining what actions to take and what actions to forego in order to attain a sustainable society. The goal of this research is to demonstrate that sustainability assessment of the potential recovery routes of REE can lead to a sustainable beneficiation process of REEs. The sustainability assessment tool (SAT) utilised in this research has been derived from a combination of indicators obtained from: green chemistry; global reporting initiatives (mining and metal sector supplement); life cycle assessment; towards sustainable mining and seven questions to sustainability. The result obtained from the SAT tool will be used as a guide to provide substitutes to critical metals currently being exploited for the production purposes and also to substitute primary materials with secondary materials. Sustainability assessment is needed in all stages of REEs' life cycle from its extraction, beneficiation, usage, end-of-life and disposal phase.

UNIVERSITY *of York*

Closing the loop of precious metals: Starbon® for selective metal adsorption and subsequent catalysis

Keywords
- metal
- separation
- recovery
- carbons
- mesoporous

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There is a growing awareness of the criticality of elements utilised in chemical products and consumer goods. Some low carbon technologies now rely on Platinum Group Metals (PGM's) and other precious elements. Elemental reserves are rapidly depleting and are being quickly dispersed throughout our environment. Many of these important unique elements have low recycling rates and recapture is challenging or costly. As such, it is essential to develop new sustainable routes for the use and recovery of these elements. Polysaccharides including starch are non-toxic, biodegradable, possess polyfunctionality and are found in nearly every geographical location on the planet. The development of tuneable, nano-structured and mesoporous carbons derived from waste polysaccharides will open new doors to adsorbents. The surface chemistry, functionality and surface polarity of these materials can be controlled through varying the temperature of preparation, thus making them ideally suited for the recovery of a wide variety of elements. Herein, we present polysaccharide-derived mesoporous carbonaceous materials (Starbon®) which are able to selectively adsorb precious metals and separate them from a mixture containing other earth abundant metals. These materials can then be used as effective catalysts in the heck reaction.

Keyword index

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