

# (Re)mining Extractive Waste:

## a new business?



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## PREFACE

Since the earliest days of the Industrial Revolution, the primary mining and metal processing industry has been landfilling and/or stockpiling vast quantities of waste. This waste type, termed “extractive waste”, is considered as one of the largest waste streams in Europe. Specific precautions need to be taken when dealing with “sulphidic mine tailings”, as during the oxidation of residual sulphides, acidic waters are generated. These can result in the release of residual heavy metals to surface and ground waters. Especially in the case of historical mining sites, pre-dating the EU Extractive Waste Directive, this can cause problems, as these sites generally lack the required environmental protection.

Given the ambition to move towards a more circular economy, the question arises as to whether this extractive waste problem cannot be transformed into a resource-recovery opportunity, as these “tailings” can still contain valuable metals and minerals. Put differently, can the (re)mining of extractive waste become a new business?

The answer is that, in fact, the (re)mining of extractive waste is already an established business, albeit not a very extended one so far. Reprocessing of tailings is a common practice in the mining industry, driven by rising metal prices and the progressive improvement of metal-extraction technologies. What was waste in the past can become a valuable resource today. Nevertheless, only for a small fraction of tailing deposits is reprocessing considered to be economic when considering the contained metal value only.

In recent years, however, there is an increasing interest in the reprocessing of tailings. Several factors contribute to this. First, many of the raw materials termed as “critical raw materials” for the EU have been discarded in waste fractions in the past, as at the time when they were mined in association

with base or precious metals, they were not of interest. For these critical raw materials, extractive waste might become an important resource.

Second, in the EU, the mining sector has to cope with an image of being a very dirty and polluting industry, and even if this does not correspond to reality in 2022, it is very difficult to start-up mining activity or to obtain a so-called social-license-to-operate for a mine and the associated tailings storage facilities. Multiple accidents of tailings-dam breakages have even worsened the situation. Tailings management is therefore becoming an increasingly important part of a mining operation. Enhanced tailings processing or reprocessing is considered to be an important aspect of tailings management, as it can improve the environmental properties of tailings (e.g., through desulphurization or increased metal removal) and reduce the risks associated with tailing-dam stability (e.g., through dewatering and dry stacking). When the bulk fraction of the tailings can be valorized, the need to install tailings storage facilities can even be completely eliminated.

Third, there is an increasing interest in using tailings as a secondary raw material in the construction sector. As with all industries, the construction industry is driven to improve its sustainability and to lower its carbon footprint. The use of secondary raw materials, such as tailings, is considered to be a key factor in this. In addition, in certain populated areas, there is a scarcity in raw materials, such as sand. As the enhanced processing or reprocessing of tailings results in a reduction of the metal and sulphide content, tailings become progressively “cleaner”, allowing many tailing deposits to match the criteria to be used as a raw material for the construction industry, for the production of sand, aggregates, cement, concrete and ceramics.

Against this background, the 2-day symposium “(Re)Mining extractive waste: a new business?” gathers leading experts in the field of mining and/or remining of extractive waste. The target public includes industry,

academia, policy makers and civil society. This book of abstracts offers a total of 55 abstracts, grouped according to the four thematic sections, highlighting different aspects of the (re)processing of extractive waste: (1) Mapping, resource estimation & geometallurgy; (2) Multi-criteria assessment, policy and Social License to Operate; (3) Metal and mineral recovery; (4) Bulk mineral matrix valorization. The latest evolutions in the field, novel concepts and business cases are presented, including case studies from both historical and active mining sites. Drivers for (re)mining and remaining bottlenecks are discussed in order to take a step further towards tailings (re)mining as a new business and as an integral part of sustainable tailings & raw materials management.



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The H2020 NEMO project is formally acknowledged for its financial support.

## ORGANISERS

### **H2020 NEMO project**



The NEMO project “Near-zero-waste recycling of low-grade sulphidic mining waste for critical-metal, mineral and construction raw-material production in a circular economy” is an EU H2020 Innovation Action project. Using a “4 PILOTS – 3 case-studies” concept, NEMO develops, demonstrates and exploits new ways to valorise sulphidic mining waste. The three cases are the Sotkamo Ni-Zn-Cu-Co mine in Finland, the Cu-Zn-Au Luikonlahti processing facility in Finland and the Tara Zn-Pb mine in Ireland; the 4 pilots are located at key points in the near-zero-waste flowsheet, encompassing the recovery of valuable and critical metals, the safe concentration of hazardous elements, the removal of sulphur as sulphate salts, while using the residual mineral fraction in cement, concrete and construction products. NEMO has established an interdisciplinary consortium, including 8 industrial partners (2 mining, 4 engineering, 1 machine manufacturing & 1 construction material company), 4 research institutes, 2 universities and 1 civil-society group. NEMO’s near-zero-waste technology will provide the EU with both direct and long-term, indirect advantages. The former, range from new resources (e.g., base metals: Cu, Zn, Ni, Au; critical metals: Co, Sc, Nd, Y, Sb; SCM and aggregates etc.), CO<sub>2</sub> savings from metal recovery and the replacement of ordinary Portland cement), new job creation, new revenues from the multiplication of the former benefits, while eradicating acid-mine drainage and other environmental issues, and ensuring an enhanced dialogue between industry and civil society, to obtain and maintain the social license to operate mines in EU.

More info <https://h2020-nemo.eu/>

## H2020 ETN SULTAN project

SULTAN, the “European Training Network for the Remediation and Reprocessing of Sulfidic Mining Waste Sites”, provides the first-



ever training programme dedicated to the reprocessing of tailings. SULTAN has pooled the interdisciplinary and intersectoral expertise of leading EIT RawMaterials members, world-leading mining and chemical companies, covering all the links in the tailings-reprocessing value chain. SULTAN trains 15 early-stage researchers (ESRs) in the different aspects of sulphidic tailings re-processing. It develops cutting-edge methodologies to assess the resource potential of Europe’s main tailings families and explores eco-friendly mining chemicals to be used in advanced metal-extraction/recovery set-ups. SULTAN not only recovers the metals but also valorises the cleaned tailing residues in circular-economy applications, including inorganic polymers, green cements and ceramics. A novel environmental assessment methodology is developed. SULTAN’s 15 ESRs also benefit from a unique soft-skills training programme and maximize the impact of their research through dissemination and exploitation. This will kick-start their careers as highly employable professionals in the EU’s tailings reprocessing/remediation sector, as well as for geological surveys, teaching and scientific organizations, and public bodies.

More info on <https://etn-sultan.eu/>



## **KU Leuven Institute for Sustainable Metals and Minerals (SIM<sup>2</sup> KU Leuven)**

SIM<sup>2</sup> KU Leuven unites the KU Leuven research groups working on sustainable metals and minerals in an interdisciplinary framework. SIM<sup>2</sup> KU Leuven's mission is "to develop, organize



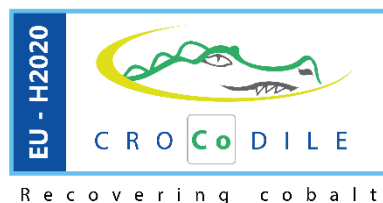
and implement problem-driven, science-deep research and future-oriented education, contributing to the environmentally friendly production and recycling of metals, minerals and engineered materials, supporting the transition to a climate-friendly, circular economy. SIM<sup>2</sup> KU Leuven therefore designs, researches and exploits selective and efficient processes for the exploration, extraction, recovery, recycling and refining of (base and critical) metals and minerals, as well as for the upcycling of primary and secondary resources. SIM<sup>2</sup> KU Leuven assesses and advances the environmental gains and the economic feasibility of the developed flow sheets. To support the social license to operate for the associated industrial activities, SIM<sup>2</sup> KU Leuven pro-actively engages with external stakeholders, including civil-society groups and local communities.

More info on <https://kuleuven.sim2.be/>

## With the support of

### H2020 Crocodile project

The H2020 Innovation Action CROCODILE project showcases innovative metallurgical systems based on advanced pyro-, hydro-, bio-, iono- and electrometallurgy technologies for the recovery of cobalt and the production of cobalt



metal and upstream products from a wide variety of secondary and primary European resources. CROCODILE demonstrates the synergetic approaches and the integration of the innovative metallurgical systems within existing recovery processes of cobalt from primary and secondary sources at different locations in Europe, to enhance their efficiency, improve their economic and environmental values, and provides a zero-waste strategy for important waste streams rich in cobalt, such as batteries. Additionally, CROCODILE produces a first-of-a-kind economically and environmentally viable mobile commercial metallurgical system based on advanced hydrometallurgical and electrochemical technologies able to produce cobalt metal from black mass containing cobalt from different sources of waste streams, such as spent batteries and catalysts.

More info on <https://h2020-crocodile.eu/>

### H2020 Tarantula project

The H2020 research and innovation project Tarantula “Recovery of Tungsten, Niobium and Tantalum occurring as by-products in mining and processing waste streams” aims



to develop a toolkit of novel, efficient and flexible metallurgical technologies

with high selectivity and recovery rates with respect to W, Nb and Ta. As such, the project promotes (i) a sustainable annual supply of secondary W at an amount equivalent to 50% of the EU's current W primary production, (ii) the exploitation of Ta content equivalent to at least 120% of the EU's annual demand (iii) the exploitation of Nb content equivalent to at least 5% of the EU's annual demand.

More info on <https://h2020-tarantula.eu/>

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Prof. Dr.-Ing. Daniel Goldmann is the Chairman of the board of CUTEC Clausthal Research Center for Environmental Technologies; Director of the Institute of Mineral and Waste Processing, Waste Disposal and Geomechanics; and Head of the Department of Mineral and Waste Processing at TU Clausthal. His scientific focus is on flotation, mechanical and hydrometallurgical processing of complex, metal-bearing waste streams and ores, especially critical raw materials; recycling strategies for and in complex structures of advanced circular economy.



### **Anders Sand, Boliden**

Anders Sand (D.Sc., Docent, QP) is a Research Manager at Boliden Mines.

Anders has about 15 years of experience in senior academic and corporate positions in the mining industry, with his main field of expertise in the mineral-processing technology. At Boliden he has held positions as Process Manager, Manager of the Process Technology R&D Programme and currently as Research Manager. He

holds a D.Sc. degree in Chemical Engineering from Åbo Akademi University, Finland and is Docent in Mineral Processing at Luleå University of Technology, Sweden.



### **Max Frenzel, HZDR**

Max Frenzel is Group Leader in Geometallurgy at the Helmholtz-Institute Freiberg for Resource Technology. He obtained his M.Sci. degree in 2012 from the University of Cambridge, UK, followed by a Ph.D. degree in 2016 from TU Bergakademie Freiberg, Germany. His research covers relevant aspects of the formation, modelling, and exploitation of mineral deposits, as well as the modelling of raw-material supply chains.



### **Mafalda Oliveira, SOMINCOR-Lundin Mining, Neves Corvo mine, Castro Verde, Portugal**

Dr Mafalda Oliveira has a geology degree from the University of Oporto (FCUP). She is the head of the Department of Dams, Tailings, Mining Waste and Water at Somincor–Lundin Mining. She is a member of national committees, international professional societies and standards committees (CEN/TC396, Working Group 6, Earthworks Part 7). She is a member of the Tailings Work Group, as an expert representing ANIET and SOMINCOR in Euromines, for the Revision of Best Available Techniques for the management of tailings and waste rock in the mining industry.



**Alexandra Escobar, Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal**

Alexandra Escobar is a geological engineer with over 10 years of experience in different areas of economic geology: geological modelling, resources estimation and technical, economic and legal valorisation of mining properties. In addition, she has 4+ years of international experience in geometallurgical characterization of industrial and metallic minerals and critical raw materials in England and France (Portuguese and German deposits). She has taken the role of main research engineer in the recovery of critical minerals from old tailings dumps and from primary raw materials.



**Maria NYBERG, European Commission**

Maria NYBERG, European Commission, DG for Internal Market, Industry, Entrepreneurship and SMEs, unit 'Energy Intensive Industries and Raw Materials' where she works as a policy officer responsible for policy on sustainability and secondary raw materials and framework conditions for primary raw materials. The aim is to support industrial competitiveness in the twin green and digital transition, including circularity aspects, through access to responsible and sustainable raw materials. Maria has a master's degree in International Relations, Johns Hopkins University School of Advanced International Studies (S.A.I.S.), Bologna, Italy and a degree in Business and Economics, Luleå University of Technology, Sweden.



### **Ville Heikkinen, Terrafame**

Ville Heikkinen is a Research Manager at the Terrafame Sotkamo mine and holds an MSc in physical chemistry, graduated from the University of Oulu, Finland. Ville has 18 years of experience in R&D and operations in the hydrometallurgical industry. He has worked with the Terrafame process for 16 years, involving positions in R&D, metals recovery and bioleaching.



### **Anne-Gwénaëlle Guezennec, BRGM**

Dr Anne-Gwénaëlle Guezennec is an expert in biohydrometallurgy and more specifically in bioleaching process design. Her research work focuses on three main areas: the characterization of mass and energy transfer in bioleaching reactors and their influence on micro-organism activities; the design of innovative bioreactors; the adaptation of bioleaching processes to unconventional resources such as electronic waste, complex mining wastes, lateritic resources. She has developed a novel and original research methodology relying on the association of innovative numerical modelling and multiscale experimental approaches to study the complex interactions occurring in a bioleaching reactor between the microbes and the G/L/S phases.





**Srećko Bevandić, KU Leuven**

Srećko Bevandić is a geoscientist with an interest in geometallurgy, mining geology and circular economy. Since 2019, he has been working on the EU H2020 MSCA-ITN-ETN SULTAN project dealing with the remediation and reprocessing of sulfidic mining waste sites. His focus is on assessing the potential of mining waste as an alternative deposit type (Plombières tailing pond), supplying the metal and ceramic industries with critical and strategic raw materials. His expertise includes economic evaluations of metals, the conversion of geological data into mining data, bulk and in-depth characterization of different materials and the interpretation of complex data.



**Rosie Blannin, HZDR**

Rosie Blannin is a geologist and resource engineer from the UK. Her work focuses on sampling and geometallurgical characterisation and the geostatistical modelling of tailings deposits, as well as scanning-electron-microscope-based automated-image analysis. She is currently completing her PhD as part of the SULTAN European Training Network.



### **Lugas Raka Adrianto, ETH Zurich**

Raka has diverse backgrounds in sustainability topics for the past 6 years, covering renewable energy, waste management, and optimal chemical industry operations. Until recently, he has been working in the metal/mining sectors and sees how equally vital this industry is for the global low-carbon economy. Since 2019, Raka has been a research assistant/PhD researcher at the chair of ecological system design (ESD) at ETH Zurich, working on environmental assessments of mine tailings management employing life cycle assessment approaches within the H2020 SULTAN project. In collaboration with the emerging process design experts in the projects, his work aims to identify trade-offs between environmental benefits and the costs of mine-waste reprocessing in one of the untapped resource potentials in Europe and beyond.



### **Andreas Hoppe, Thyssenkrupp**

Andreas Hoppe is a research engineer at ThyssenKrupp Industrial Solutions, Germany. He studied energy and plant engineering and received his PhD from Technische Universität Braunschweig, Germany in 2005. He has more than 15 years of experience in the cement and ore processing industry with a focus on the development of pyroprocessing concepts including cement production and ore refinement.



### **Thomas Lapauw, ResourceFull**

ir Thomas Lapauw obtained a master's degree in materials science at KU Leuven in 2013. During his doctoral thesis, he studied intensively the synthesis of high-temperature ceramics for nuclear applications. Since 2018, he is active at ResourceFull as CTO where he returned to room-temperature chemistry to develop ecologically friendly building materials and enthusiastically committed himself to a more sustainable and circular construction world.



### **Arne Peys, VITO**

Arne has received a master's and a doctoral degree in materials engineering from KU Leuven. During these studies, his interest in metallurgy was transformed into a love for the valorisation of industrial by-products. His PhD, awarded in 2018, focused on the reaction mechanisms for alkali-activation of iron-rich slags that can be used as a sustainable cementitious binder. Since 2019, he is working at VITO to transform a wide variety of mineral residues in cement and concrete constituents. He manages the research in a few projects and tries to understand and communicate about how industrial residues can be used in construction materials.



### **Hilde Chambart, Wienerberger**

A geologist from KU Leuven, Hilde has been working at Wienerberger since 1989. Head of the central R&D lab for roof tiles in Kortrijk (Belgium) since 2009. Also Head of the central R&D lab for facing bricks in Beerse (Belgium) since 2014.



## **Francisco Veiga Simão, Wienerberger**

Francisco Veiga Simão is a Portuguese geoscientist with an entrepreneurial mind-set and a passion for the circular economy. He holds a BSc in geology and an MSc in geosciences with a specialisation in geological resources from the University of Coimbra, Portugal. During his graduate studies he also attended the University of Oviedo, Spain, and the University Centre in Svalbard, Norway. Currently, he works at



Wienerberger NV, Belgium, as an early-stage researcher (ESR12) in the EU-H2020-MSCA-ITN-ETN-SULTAN project and is a PhD researcher at the Catholic University of Leuven, Belgium. His research is focused on the sustainable use of (cleaned) sulphidic mining waste in building ceramics. He helped to found a Portuguese start-up company called Geonatour, which does geological consulting jobs and promotes geodiversity through a mobile application. He worked as an intern geologist in a Portuguese technology start-up company called Primelayer, where he did consultancy jobs on e-waste management. He was also a co-founder of an entrepreneurial project called WEEE-DO aiming to maximise the efficiency of the collection, reuse, and recycling of electronic waste in Utrecht, The Netherlands. Recently, he co-founded the Energy and Climate Forum, a Portuguese NGO focused on promoting and supporting climate-resilient and sustainable projects around nine Portuguese-speaking countries (Angola, Brazil, Cape Verde, Guinea-Bissau, Equatorial Guinea, Mozambique, Portugal, São Tomé and Príncipe, and East-Timor).

## **REMINING OF THE HISTORICAL RAMMELSBERG TAILING POND, GERMANY: HISTORY, CURRENT STATUS AND LESSONS LEARNT**

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### **Introduction**

This abstract is based on several own publications on this topic, complemented by some actual findings and developments.

The historical Rammelsberg tailing pond, situated at the site named Bollrich, contains approximately 7 million tons of flotation tailings of the closed Rammelsberg mine, where a high-grade massive sulfide ore (Cu-Zn-Pb) was mined. Within the research project REWITA, a reprocessing approach including flotation and hydrometallurgy was investigated in 2015–2018 with the aim to recover valuable metals like Pb, Zn, Cu, Au, Ag, Co, In and Ga, as well as pyrite and barite, and to develop a remining and a remediation process for this site. Besides the development of remining and reprocessing technologies, geotechnical and legal aspects as well as risk potentials have been explored. The outcomes of this first project gave an indication that with respect to the geotechnical stability of the dam, not only the before-mentioned constituents, making up around 45 % by weight of the overall tailings mass should be removed, but also the mineral phases derived from waste rock and gangue minerals making up around 55 % by weight. Due to the forthcoming end of the coal-fired power plants, the ashes from these plants, used in cement and concrete production, will vanish and must be replaced. Mineral phases from the fine-ground host rock of the processed ore, made up of shale and some gangue phases of the orebody, show a promising composition. Since 2021 the follow up project REMINTA has been addressing this point and, in addition, sociotechnical questions with respect to the acceptance of remining activities by the public.

### **History and status**

The Rammelsberg ore deposit was mined until 1988. The submarine synsedimentary exhalative ore deposit had been exploited for at least 1000 years due to its high copper, lead, zinc, silver and gold concentrations. The main production period started in the late 1930s. The flotation tailings were collected in a tailing pond since 1938. Since its construction, the pond has also been used for flood control. Additionally, neutralized acid mine drainage (AMD) from the closed mine has been pumped into the pond. The dam is constructed in an

upstream way, meaning that the upper dam is founded on older tailing material. Furthermore, karst has been observed in proximity.

Based on old production data, historical drill hole data on tailing materials and new samplings, the deposit has been analyzed and modelled in the research project REWITA. The material consists of roughly 55 % inert material (carbonatic gangue, dominated by ankerite and silicate gangue phases from Wissenbach shale), 25 % barite and 20 % sulfides. The main major and minor metals of interest as well as elements with negative environmental potential are found in the sulfidic phases according to a comprehensive correlation calculation and validation by electron microprobe. Key value elements are Ba/barite (14.5/24.6 %), Zn (1.4 %) and Pb (1.2 %), Cu (0.15 %). Furthermore, some critical or highly valuable elements include Co (199 ppm), Ag (31 ppm), Ga (24 ppm) and In (6 ppm). Harmful trace elements are for example Cd (30 ppm), As (700 ppm), Tl (66 ppm).

Based on the different analyses from old production as well as geographical data and former drilling campaigns, a comprehensive 3D block-based model of the deposit was elaborated. The tailing pond shows a relatively homogenous structure, except for an increase of barite towards the bottom of the tailings due to changes in mineral processing.

## **Frame conditions and major challenges**

Usually, the infrastructure at tailing ponds is better than in green-field operations, considerably lowering initial project costs. Also, costs for mining and grinding might be greatly reduced. On the downside, the ore quality and quantity are considerably lower than in the corresponding ore deposit due to prior mineral extraction, alteration and, possibly, contamination.

The legal situation is usually different, when comparing conventional and anthropogenic deposits, and may include additional legal obligations. For example, in Germany, tailing facilities are affected by the Federal Mining Act, but can also fall into waste legislation. Tailing reprocessing projects may, as in the case of the Bolrich tailing pond, benefit strongly from existing rights, permits and licences as new applications may be very time-consuming. Especially in densely populated areas with high environmental requirements and social participation, the application outcome always remains unknown.

Resource efficiency contributes to the fact that primary resources are limited and can be exploited only once. A sustainable mining practice considers this by responsible exploitation planning. Considering the re-mining of tailings, the resource efficiency is very high because the benefit from the original deposits is raised, and additional mining is circumvented.

Economic performance is undoubtedly the most considered aspect of traditional mining project planning. In contrast to traditional mining, the avoided costs (see section safety, environment) through tailing re-mining should be assessed together with the value of the contained minerals to estimate the actual added value. Regarding prior target minerals, the ore content has been lowered significantly due to prior processing. However, tailings may

still contain elements that have either significantly risen in value and/or demand or were not recovered before due to technical limitations.

An operation can only be sustainable if it has the “social-license-to-operate”. This refers to the acceptance and approval by the local community, which is related to social risks and benefits. The term of trust represents a central element of the debate. Tailings are directly related to previous or ongoing mining projects. The social acceptance of re-mining and reprocessing is influenced by the relationship of the community to the operation, subject and operator. In the case of the Bollrich, public opinion is in favor of the project due to planned job creation, revival of old mining traditions and remediation.

Safety should have the highest priority in mining operations for business and ethical reasons. A continuous risk assessment based on the current state of the art represents an instrument to maximize the safety of the facility. Whereas safety is usually defined as work safety, here it is of even higher importance to focus on dam stability due to several accidents and their tremendous impacts in the past. In this respect, tailing dam safety is also strongly connected with community safety and environment. As mentioned above, the dam of the Bollrich tailing is erected upstream, making it vulnerable to material liquification and movements. Due to its usage as a rainwater-retention basin, lacking base sealing and karst, dam stability might decrease in the future. A possible mandatory removal of the material could have a driving impact on processing and beneficiation profitability.

Environmental sustainability is the last corner stone of the introduced sustainability concept. In the case of sulfidic tailings, attention must be given to the generation of AMD and the mobilization of harmful substances. Regarding the Bollrich tailing pond, approximately 19.3 % of the material is sulfidic (most of it the easily oxidized pyrite), bearing a large AMD potential. Furthermore, lead and other highly toxic heavy metals are present and could be mobilized under specific conditions. Though no risk has been reported yet, climate change might also lead to changes here.

## **Findings and lessons learned**

Based on these considerations, a re-mining and reprocessing strategy has been defined and elaborated. It could be shown that a combination of flotation, bioleaching and chemical leaching will open the doors for an efficient technical solution for the processing of such a material. It could be shown that the potentially valuable and harmful elements can be removed and concentrated. The resulting residue volume and hazard potential can be massively reduced.

Nevertheless, dealing with tailing ponds is a multi-dimensional task. New approaches, trying to address all relevant dimensions in a systematic way are under development, based on the UNFC United Nations Framework Classification for Resources. Further work on the Rammelsberg tailing pond is ongoing, with the aim to get to a final overall approach as a starting point for operations of re-mining.

## **THE ROLE OF REMINING: STATUS AND FUTURE PROSPECTS AT BOLIDEN MINES**

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### **Introduction**

Since the launch of the EU Raw Materials Initiative in 2008 and EU's Strategic Implementation Plan on Raw Materials in 2013 as well as through many policy initiatives at the Member State level during the last decade, the need has been recognized to reduce dependency on raw-material imports. The sourcing was broadly targeting to secure domestic supply through primary as well as secondary sources, in parallel with initiatives towards substitution<sup>1-4</sup>. Since 2011 the European Commission maintains a list of critical raw materials, with economic importance and supply risk as key parameters<sup>5-6</sup>.

Over recent years, however, there has been a shift within EU policy towards increased emphasis on recycling, reprocessing and substitution, rather than development of primary resources. Regardless of the focus on primary or secondary sourcing, European mineral and metal producers such as Boliden have a key role in the raw-materials ecosystem and supplying metals to our society.

Boliden is active both in primary base-metal production, as well as recycling of electronic scrap, batteries and industrial intermediates. A vast number of projects within the company have been pursued to identify by-product potentials both from ores and processing residues, including reprocessing of tailings.

### **The mining industry and reprocessing**

It should be recognized that reprocessing is not a new concept, but rather an integrated part of the minerals and metals value chain and therefore also works in synergy with the mining industry and oftentimes also concentrator operations. Recycling companies use identical types of separation methods and unit operations as in processing of primary resources.

To mention one example of historic reprocessing, tailings from the Outokumpu area in Finland was processed at the Keretti concentrator 1982–1988, extracting residual copper, sulphur and cobalt<sup>6-7</sup>. As an example of reprocessing in the metallurgical industry, a concentrator was started up in 1966 near the Harjavalta smelter in Finland for the reprocessing of slags<sup>7-8</sup>. This operation, then run by Outokumpu, was acquired by Boliden in



2004. Also, the Boliden concentrator in Sweden has a separate production line for reprocessing slag from the nearby Rönnskär smelter since the early 1990s.

It is likely that reprocessing of mine tailings will increase in the future, based on higher strain on resource availability, the development of new process technology and the green transition. For instance, iron sulphides, which are one of the more problematic residues of mining, might prove to become a highly sought after resource as fossil fuels are phased out and there will be a lack of raw material for sulphuric acid production.

## **Recent projects and prospects at Boliden**

Boliden has recently reviewed the potentials for the reprocessing of tailings and other mine residues in the Boliden area, constituting part of the Skellefte mining district in northern Sweden with some 30 historic mine sites. Approximately 3–3.5Mt of residues have been identified, containing up to 9% Zn, 2g/t Au and 60 g/t Ag. Economic evaluations show a positive project NPV with approximately €10m estimated net income. In the first stage, the Korea dam project, residues near the Boliden concentrator were reprocessed using a combination of gravimetry, flotation and leaching, with average recoveries of 60% Zn, 73% Au and 72% Ag. The project also resulted in environmental benefits and has allowed land reclamation planning to start.

An ongoing project, also subject of investigation within NEMO, is the Luikonlahti high-sulphur tailings in the Outokumpu district of Finland. The Co and Ni content of the tailings have been confirmed to 0.7% and 0.4%, respectively, which at current market prices are approaching an in-situ value of €1 billion. Reprocessing of these residues alone, could supply about 10% of current EU Co demand over 10 years. Comparable potentials may exist in the valorisation of other high-sulphur tailings at the Boliden Kevitsa and Boliden Aitik mines.

Besides metal extraction, there have been several recent initiatives for developing construction materials from tailings and waste rock, including cement activation, filler in concrete and aggregates production. This is also one of the focus areas of NEMO, evaluating the potential of using tailings from the Boliden Tara mine. Relevant to the topic of iron sulphides, Boliden is collaborating with the Swedish mining company LKAB in the ReeMAP project<sup>9</sup>. Here, LKAB strives to commission a fertilizer plant with apatite tailings as feedstock. Other by-products would include REEs, residing in the apatite matrix, and gypsum. Pyrite from Boliden tailings would provide energy in the process, be converted to sulphuric acid for the fertilizer production and additionally generate direct reduced iron as a by-product.

## **Concluding remarks**

From the policy perspective at the EU-level, as well as in raw-material strategies at the Member State level, there is a general trend in support of reprocessing and other means of raw-material extraction from residues. Economic and technical constraints, often due to lack

of economies of scale, high CAPEX as well as long and costly permitting processes remain the most typical challenges. Thus far, however, there have been few policy initiatives providing concrete support for reprocessing initiatives.

The mining industry has a long history of reprocessing tailings and other types of processing residues such as smelter slags. The preconditions are that residual value is present to a sufficient extent, both in terms of grade and total amount, that suitable processing technology and infrastructure is available or that their costs can be carried by the project. Additionally, the permitting required or legal framework should not involve risk and unpredictability prohibitive to the project. Based on these constraints, the economics of reprocessing activities are more often than not too challenging, which is why there are still relatively few examples of such operations.

Even though reprocessing of residues will not be sufficient in covering any significant part of EU's raw-material needs for most metals, these sources are still highly relevant from the sustainability perspective, through maximising resource efficiency and ideally also reducing environmental impacts as well as supporting social licence to operate. An added potential is that historic mining residues may contain critical but low tonnage raw materials essential for modern technology and the green transition.

## References

1. The Raw Materials Initiative – Meeting our critical Needs for Growth and Jobs in Europe (2008). Communication from the Commission to the European Parliament and the Council, SEC(2008) 2741, COM/2008/0699 final.
2. Strategic Implementation Plan for the European Innovation Partnership on Raw Materials - Part 1 (2013). <https://ec.europa.eu/growth/system/files/2021-10/eip-sip-part-1.pdf>. Downloaded 2022-02-25.
3. Strategic Implementation Plan for the European Innovation Partnership on Raw Materials - Part 2 (2013). <https://ec.europa.eu/growth/system/files/2021-10/eip-sip-part-2.pdf>. Downloaded 2022-02-25.
4. A Review of National Resource Strategies and Research (2012). Department of Environment, Food and Rural Affairs. <http://www.defra.gov.uk>. Downloaded 2014-01-16.
5. Blengini, G., Mathieux, F., Mancini, L., Nyberg, M., Viegas, H. (Eds.) (2019). Recovery of critical and other raw materials from mining waste and landfills – State of play of existing practices, JRC Science for Policy Report, ISBN 978-92-76-08568-3.
6. Tackling the Challenges in Commodity Markets and on Raw Materials (2011). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM/2011/0025.
7. Concentrators of Outokumpu Oy Finland (1982). Outokumpu, Pariset Oy, Helsinki, Finland.

Toropainen, V. (2006). Yhteenveto sulfidimalmikaivostoiminnasta Suomessa ja toiminnassa muodostuvista sivutuotteista sekä niiden ympäristövaikutuksia, GTK Report S 49/0000/2006/2, Kuopio, Finland.

8. Today's waste becomes tomorrow's resource (2022). LKAB ReeMAP, <https://ree-map.com>

*SESSION 1*

*Mapping, resource estimation  
& geometallurgy*

*Chair: Philippe Muchez, KU Leuven*

## **RESOURCE ESTIMATION AND GEOMETALLURGY OF TAILINGS PONDS: AN OVERVIEW**

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### **Abstract**

Rapidly increasing volumes of mine tailings generated by the global mining industry are of major concern for the coming century. Not only does the storage of these materials significantly increase the land use of many mining operations, but it also represents a major environmental hazard due to the often-high contents of toxic elements, small grain sizes, and sometimes high acid-generating potential of the tailings. Efforts to re-mine and re-process tailings provide a promising avenue in addressing this issue. For optimal results, these efforts should be designed around detailed knowledge of the specific materials they wish to target: their mineralogy, particle and grain sizes, and particle microstructure, as well as the spatial distribution of these properties within the tailings dams.

While many mines continuously collect data on tailings streams, this information is generally incomplete with respect to relevant properties: it is focussed on bulk chemistry, density, and particle size distributions, but not mineralogy and particle microstructure. Furthermore, sedimentary style deposition processes in the tailings dams generally lead to the spatial segregation of different components of the tailings stream, such that knowledge of what kind of material was deposited and when is still insufficient to infer actual material distribution within the dam. Finally, further modifications of relevant properties may occur due to weathering.

For these reasons, it is generally necessary that tailings dams are sampled and characterised in detail before re-mining and re-processing operations are planned, and that this information is translated into the expected behaviour of the materials in the planned operations. This contribution provides a general overview of the current state of the art in the methods and tools, which are relevant for this purpose, as well as potential future developments in this field.

## **Perspectives on tailings (re)mining at the Neves Corvo deposit, Portugal: valorisation of the Cerro do Lobo Tailings Storage Facility, challenges and opportunities**

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The implementation of exigent procedures and standards for the development of tailings storage facilities (TSF) aims to increase safety quality, to minimize the risk of failure, and to mitigate environmental impacts. Furthermore, with new technologies emerging in the mining industry, and the evaluation of secondary raw materials as possible sources of critical and high-tech metals, and/or as a way of increasing the recovery of additional base metals, companies have started to characterize and to classify their tailings as potential resources for future (re)mining.

The Neves Corvo mine was discovered in 1977 and started its operations in 1989 with tailings dumping in a downstream constructed dam with a sub-aqueous disposal system. By the end of 2010, tailings disposal was changed from sub-aqueous to sub-aerial thickened tailings deposition, to increase the tailings-dam capacity, which currently extends the active lifetime of the mine to 11 years. Since then, detailed geochemical, geotechnical, and mineralogical monitoring has been conducted, aiming at the characterization and optimization of the mining residues.

From 2010 till the end of 2020, the Neves Corvo mine has accumulated around 10 million tonnes of waste rock and 18.6 million tonnes of thickened tailings. These mining residues are stored at the Cerro do Lobo Tailings Management Facility (Cerro do Lobo TMF), which completes a tailings tonnage of 48.6 million tonnes since the beginning of the operation in 1989 (30 million tonnes are slurry tailings).

The thickened tailings are composed of 66% solids on average. Chemical analysis has shown copper and zinc grades in the waste rock ranging between 0.3 and 0.9% Cu, and 0.4% and 1.1% Zn, and concentrations up to 0.3% and 0.4% of copper and zinc, respectively, in the tailings. A recent drilling campaign at the Cerro do Lobo TSF has shown maximum copper grades up to 3% wt. and zinc grades up to 2.1% wt. at depths of approximately 16–17 m. 3D modelling and geostatistical analysis will contribute to the pre-feasibility study of the future mining potential.

The combination of all variables evaluated at the Cerro do Lobo TSF (pH, conductivity, salinity, humidity, chemical-metal content) with the monitoring parameters for stability and safety (local friction, pore shoulder and tip resistance), together with the on-going geochemical and mineralogical characterization research is aimed to provide predictive indicators of secondary sources of raw-materials with subsequent resource estimation and valorisation of mining extractive techniques and re-processing technologies.

This study is part of WP1 of ETN-SULTAN project (H2020) - European Training Network for the remediation and reprocessing of sulfidic mining waste sites. Publication supported by FCT- Project UIDB/50019/2020 - Instituto Dom Luiz.

## **X-RAY ORE SORTING FOR HISTORIC TUNGSTEN MINE WASTE TRANSFORMATION AND NEW GEOLOGICAL APPROACH FOR MT CARBINE TUNGSTEN**

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### **Abstract**

Mine waste materials and low-grade stockpiles, without the application of innovative technologies, remain economically unviable for reprocessing. However, if characterised and processed optimally using advanced technologies, these materials represent significant new resources of critical metals.

With this in mind, in 2019, CRONIMET, a Germa, leading high-value-metal recycler and trader, partnered with Australian EQ Resources (EQR) to resume activities on EQR Mt Carbine (MtC) Tungsten deposit, with the reprocessing of the historical tailings dump and, specifically discussed in this abstract, mine waste stockpile.



**Figure 1:** Mt Carbine historical 12MT Low-Grade Stockpile – courtesy of EQ Resources



Through a multidisciplinary approach, with the integration of specialized partners – including TOMRA, the University of Queensland, Sustainable Minerals Institute and DAS Mining Solutions – the project aimed at characterizing the MtC mine waste material and confirm its amenability to sorting.

The project started with the site geological and geometallurgical characterization, and the installation on site of a pilot X-ray sorter. Understanding physical controls on separation efficiency during pilot tests allowed predictive geometallurgical models to be developed. The pilot sorter also led to 20+ times upgrade of feedstock, meaning that only 5% of the sorter feed material requires crushing (the most energy-consuming process step) prior to further gravity beneficiation, a wet process, in which water requirement will also be reduced by up to 20 times. This is now allowing the project to enter an industrialization phase with the mid-term aim being to convert the MtC deposit into a world-class tungsten-producing asset.



**Figure 2:** Pilot X-ray sorter installed in Mt Carbine – courtesy of EQ Resources

The project's long-term development is also ensured with in-situ resources being revisited through additional drilling, and re-interpretation of the historical drill core, with the target to maximize the resource utilization and minimize the project footprint, thanks to modern and efficient mining techniques.

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## METALS WITHOUT MINING: BUCHANS RIVER DELTA REHABILITATION PROJECT, NEWFOUNDLAND AND LABRADOR, CANADA

**Mark Thorpe, John Walsh, Monty Reed, Will Upshaw**

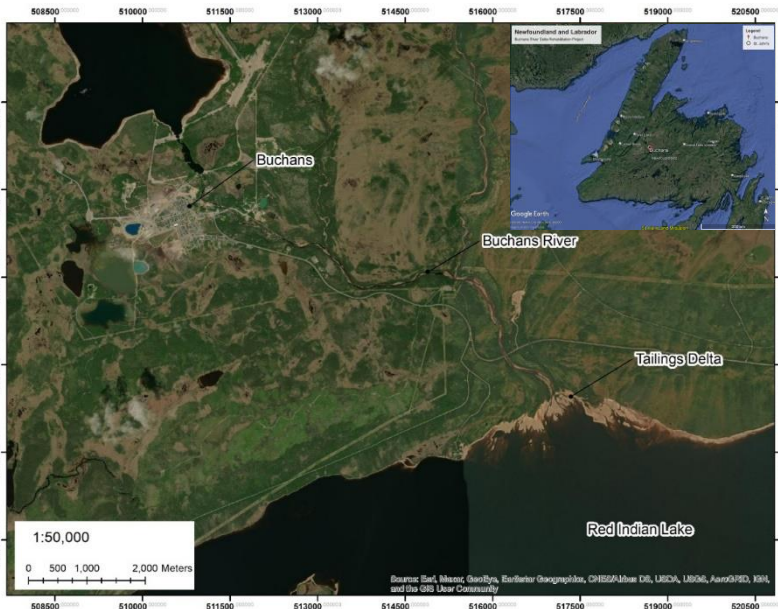
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### Abstract

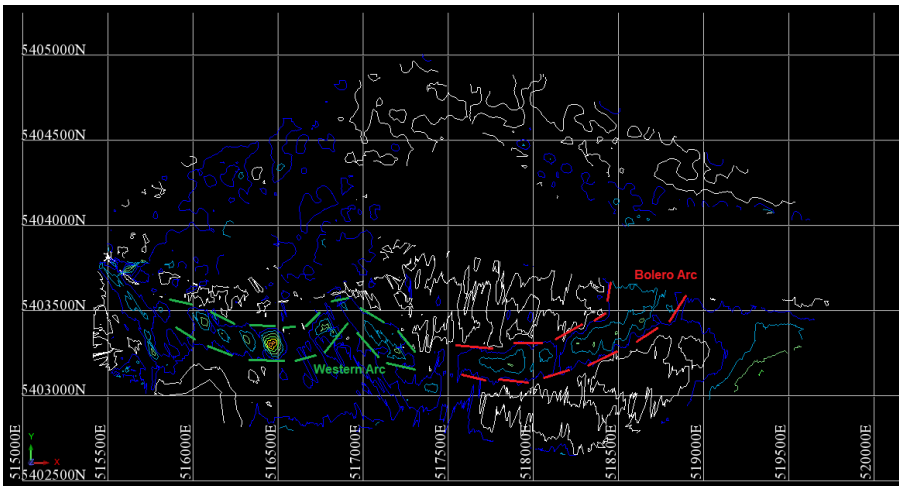
The Buchans Mining camp in Buchans, Newfoundland and Labrador, Canada operated from the mid-1920s to about 1986. During that time, over 16 million tonnes of ore were produced, the tailings from which were, from 1926 to about 1965, dumped into the Buchans River. The tailings flowed down the Buchans River into Red Indian Lake and formed a delta (Figure 1).



**Figure 1:** Buchans Mine in Newfoundland and Labrador

EnviroGold Global (NVRO) has obtained the rights to reprocess the metal-contaminated tailings from the delta, which is located in an area of Newfoundland suffering from a lack of employment and investment. Samples of the material from the delta have been analysed in the GMR Laboratory in Vancouver, showing concentrations of ~1.6% and ~7% for lead and zinc, respectively.

These metals have been leaching into a salmon lake for about 100 years, such that the Buchans River is no longer a salmon river. Using ground-penetrating radar, NVRO assessed the thickness of THE tailings within the Buchans River Delta. The preliminary results are presented in Figure 2.



**Figure 2:** Preliminary tailing thicknesses from the ground-penetrating radar study at the Buchans River Delta, Newfoundland and Labrador

The application for environmental approval for coring the tailings in the Western Arc (Figure 2) will be submitted to the Government of Newfoundland and Labrador. Coring for confirmation of the resource is anticipated in Q1 2022. Additional samples will be collected for ongoing metallurgical testing in Q1 2022. The paper will present the history of the project, the social and environmental benefits of the project, the results of the project to date (tailings resource and metallurgical testing) and the applicability of the work to other tailings deltas around the world.

## **Advanced X-ray-based 3D structural and chemical characterisation of ores**

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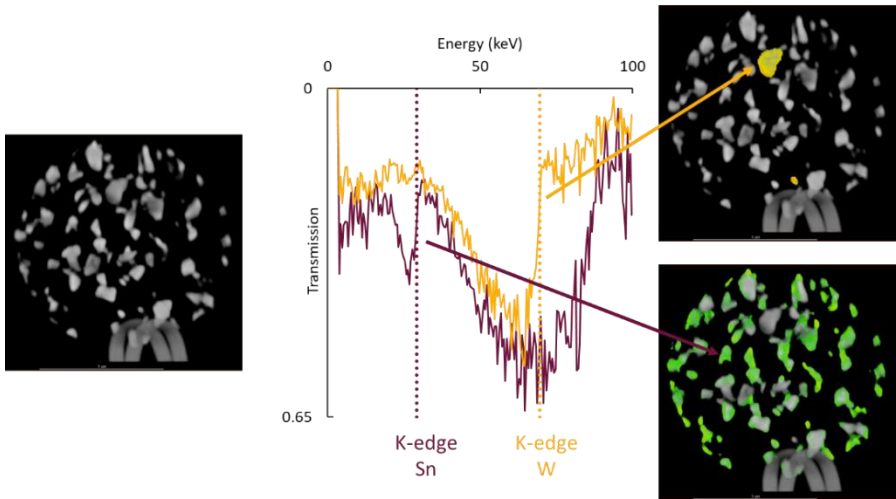
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### **Abstract**

Understanding the 3D distribution of elements within mineralised rocks is crucial for understanding the formation of mineral deposits and developing efficient extraction methods<sup>1,2</sup>. X-ray microtomography (micro-CT) has established itself as an important tool to non-destructively characterise a wide range of materials, including ores and building materials, over the years<sup>2</sup>. However, traditional micro-CT imaging still only provides an indirect insight into the chemistry of a material<sup>2</sup>. To address this challenge, a continuous effort is being undertaken at the Ghent University Centre for X-Ray Tomography (UGCT) to develop workflows and to bring techniques previously only available at the synchrotron to the lab, where they can be used on a routine basis on a wide range of samples<sup>1,3-5</sup>.

Here, we show how lab-based hyperspectral CT, a technique based on the difference in X-ray absorption energy of elements present within the sample<sup>6</sup>, can be used to differentiate between different mineral grains in mineralised samples. The association between specific elements and mineral phases and specific rock textures can then be studied in 3D, giving an important insight into the formation process for the different minerals of potential economic interest. By complementing the capabilities of 3D hyperspectral CT and 2D scanning-electron-microscopy-based energy-dispersive spectroscopy (SEM-EDS), a correlative workflow can be created to characterise materials that are crucial for the energy transition and a circular economy.



**Figure 1:** Differentiation between cassiterite ( $\text{SnO}_2$ ) and ferberite ( $\text{FeWO}_4$ ) from the identification of chemical compounds in the hyperspectral data.

## References

1. Sittner J, Godinho JRA, Renno AD, et al. Spectral X-ray computed micro tomography: 3-dimensional chemical imaging. *X-Ray Spectrom.* 2021;50(2):92-105. doi:10.1002/xrs.3200
2. Withers PJ, Bouman C, Carmignato S, et al. X-ray computed tomography. *Nat Rev Methods Primers.* 2021;1(1):18. doi:10.1038/s43586-021-00015-4
3. Laforce B, Goderis S, Vekemans B, Van Hoorebeke L, Vincze L. The Herakles 3D X-ray Scanner: Concept, Characterization and Application Complementary to Synchrotron Radiation Based Experiments. *Microsc Microanal.* 2018;24(S2):242-243. doi:10.1017/S1431927618013557
4. Van Assche F, Vanheule S, Van Hoorebeke L, Boone MN. The Spectral X-ray Imaging Data Acquisition (SpeXIDAQ) Framework. *Sensors.* 2021;21(2):563. doi:10.3390/s21020563
5. Boone MN, Garrevoet J, Tack P, et al. High spectral and spatial resolution X-ray transmission radiography and tomography using a Color X-ray Camera. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.* 2014;735:644-648. doi:10.1016/j.nima.2013.10.044
6. Egan CK, Jacques SDM, Wilson MD, et al. 3D chemical imaging in the laboratory by hyperspectral X-ray computed tomography. *Sci Rep.* 2015;5(1):15979. doi:10.1038/srep15979

## **A DESK-BASED SCREENING APPROACH COMPLIANT WITH THE UNFC TO IDENTIFY THE RAW-MATERIALS RECOVERY POTENTIAL FROM BASE-METAL TAILINGS**

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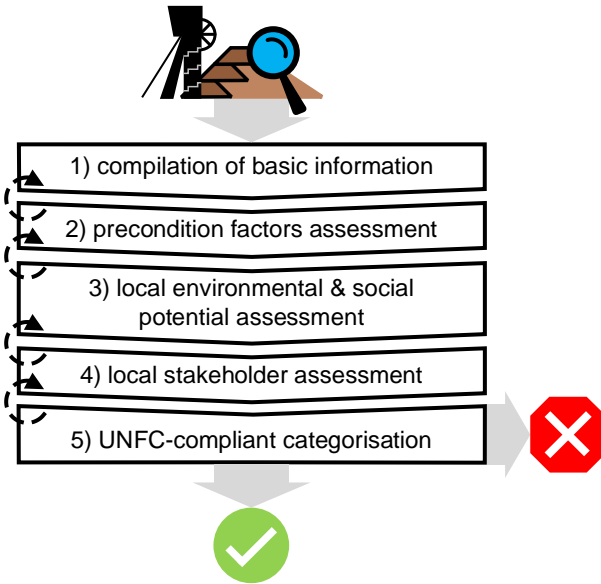
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### **Abstract**

In general, the first assessment of a natural raw-materials (RMs) deposit is performed within a reconnaissance exploration. Geological mapping of an area on a regional scale aims to identify economically exploitable mineral occurrences for further investigation<sup>1</sup>. For anthropogenic RMs, such as base-metal tailings, there is no similar procedure to quickly identify potentially viable recovery projects. Hence, we propose a desk-based approach for a systematic screening of tailings-storage facilities (TSFs) in 5 steps (cf., Figure 1). It makes it possible to evaluate whether a particular TSF meets the criteria for a more advanced study, including costly on-site exploration. The user of the approach is guided in compiling the information that is available at the local level in a structured manner. Aspects related to a TSF's content, physical structure, surroundings, potential environmental and social impacts, and potentially affected stakeholders are considered. A comparison of base metals stored in ores and in tailings shows that the latter are at the interface of natural and anthropogenic RMs, which requires a consideration of sustainability aspects. However, these aspects are not sufficiently addressed in the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) classification code. In contrast, the United Nations Framework Classification of Resources (UNFC) addresses all dimensions of sustainability, *i.e.*, social and environmental aspects alongside economic ones. Therefore, an approach compliant with the UNFC was developed. It is tested with the TSF Bollrich (Germany), which is situated in a complex location close to different stakeholders. The investigation is based on publicly accessible information. It shows that the TSF meets the criteria for a more advanced study, and that the TSF's environmental and social impacts can be two of the main drivers. Overall, the developed approach is suitable for identifying the potentials of and barriers to RMs recovery at the local level, and for screening the TSF inventory at the national level.



**Figure 1:** Five steps of a UNFC-compliant approach for a desk-based systematic screening of tailings-storage facilities to identify a potentially viable RMs recovery project<sup>2</sup>. The dotted lines indicate possible iterative steps.

## References

1. M. Ilich, "On the use of geological exploration data in mineral projects", *J. Environ. Geol.*, **2** 61–63 (2018).
2. R. Suppes and S. Heuss-Aßbichler, "How to Identify Potentials and Barriers of Raw Materials Recovery from Tailings? Part I: A UNFC-Compliant Screening Approach for Site Selection", *Resources*, **10** 26 (2021).



## **A SUSTAINABILITY-ASSESSMENT APPROACH COMPLIANT WITH THE UNFC FOR ON-SITE EXPLORATION DATA TO IDENTIFY THE RAW-MATERIALS RECOVERY POTENTIAL FROM BASE-METAL TAILINGS**

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### **Abstract**

In the primary-mining industry, a prospective raw-materials (RMs) deposit identified by reconnaissance exploration is investigated on site to provide data for a first techno-economic assessment<sup>1</sup>. The exploration of base-metal tailings using an approach focused on techno-economic aspects can overlook relevant issues. These issues can impact economic competitiveness and they are also essential for the overall evaluation of the project, including potential risks. Therefore, a holistic assessment and classification approach is required in an early project-development phase. The United Nations Framework Classification for Resources (UNFC) concept provides information about all the dimensions of sustainability, *i.e.*, social and environmental aspects alongside economic ones. Furthermore, it enables a transparent comparison of the different types of RM sources. We developed an approach compliant with the UNFC to evaluate RMs recovery from base-metal tailings based on on-site exploration data in three steps<sup>2</sup>: (1) the project is defined, including potential valorisation scenarios and the general information for a knowledge base is summarised; (2) the project's development status is assessed in terms of geological, technical, economic, environmental, social and legal aspects; and (3) the overall project and subprojects for individual RMs recovery are rated. For a quick overview, the assessment results are summarised in a heatmap-like categorisation matrix. This form of visualisation enables a quick comparison of different studies. The approach is tested with the tailings-storage facility Bollrich (Germany) based on on-site data obtained from a large research project<sup>3</sup>. It is shown that the developed approach helps to identify sustainability aspects at the local level, and the potentials and barriers for further project development. The transparent visualisation of the results can be a basis for a communication between all the involved stakeholders in their search for a mutually acceptable solution.

## References

1. M. B. Revuelta, *Mineral Resources*, Springer International Publishing Cham, 2018.
2. R. Suppes and S. Heuss-Aßbichler, "How to Identify Potentials and Barriers of Raw Materials Recovery from Tailings? Part II: A Practical UNFC-Compliant Approach to Assess Project Sustainability with On-Site Exploration Data", *Resources*, **10** (11) 110 (2021).
3. D. Goldmann, T. Zeller, T. Niewisch, L. Klesse, U. Kammer, C. Poggendorf, J. Stöbich, *Recycling of mine processing wastes for the extraction of economically strategic metals using the example of tailings at the Bollrich in Goslar (REWITA): final report*, TU Clausthal: Clausthal-Zellerfeld, 2019.

*SESSION 2*

# Multi-criteria assessment, policy and social license to operate

Chair: Peter Tom Jones, KU Leuven

**EU policy for sustainable raw materials for the green and digital transition  
with A special focus on (re)mining extractive waste**

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## **ECONOMIC EVALUATION OF RESOURCES FOR COMMERCIALISATION OR RE-COMMERCIALISATION**

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### **Abstract**

There are many aspects to resource evaluation that need to be addressed to determine the feasibility of a particular project. This is particularly true when considering an old or abandoned site. The aspects for evaluation include many topics and tools. Very broadly, they include social (acceptance and permission to operate from society), environmental and financial accounting and analysis, along with statistical analyses of the resource. In addition, mining properties that have been in production for many years have both advantages and disadvantages when it comes to resource and reserve evaluation.

Several benefits are available from the reprocessing of tailings or other wastes when this is done in some environments. These are, in no particular order, a net positive income, improvement of the environment of the area, improvement in the social conditions of the indigenous people, and the improvement of the perception of the area globally.

There is a global demand for metals, and many have been deemed critical to our modern world. For the EU alone, there could be a need for up to 18 times more lithium and 5 times more cobalt to meet the 2030 target and up to 60 times more lithium and 15 times more cobalt to meet the 2050 target, compared to current supplies of these metals.

By applying modern recovery methods to the tailings there can be a significant improvement in the economics of what was previously considered as waste as well as a method for remediating a tailings issue in an economic way, which if not profitable, is at least economically neutral. Additionally, there is an opportunity to minimize the environmental impact and improve the perception of both the mining company and the industry.

## **RECOMINE: SUSTAINABLE SOLUTIONS FOR MINE WASTE**

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### **Abstract**

After the reunification of Germany, ore mining in Saxony was discontinued for economic and ecological reasons. What remained were numerous contaminated sites. Some of these sites cause considerable environmental problems, with remediation efforts ongoing to date. Remediation, however, focuses exclusively on the storage and immobilization of pollutants. It requires ongoing control and maintenance, ultimately translating into eternity costs for society. At the same time, the demand for raw materials by modern societies is constantly increasing. Increasing electromobility or the increased use of renewable energies requires the increasing production of raw materials worldwide. Raw-materials production, in turn, is energy intensive and is once again associated with lasting negative impacts on the environment. Therefore, it appears only sensible to explore all possibilities to extract raw materials from industrial residues (waste rock piles, tailings, slags, ashes) of past generations as an avenue to supplement current raw-material requirements. The Recomine alliance was thus established three years ago in the border region between Germany and the Czech Republic to jointly develop the technologies needed for the treatment of industrial residues remaining from historic mining, mineral processing and extractive metallurgy. The goals of environmental protection and raw-material extraction are weighed equally in the search for holistic solutions that will minimize pollution, while also enabling raw-material extraction. To this end, the regional alliance of more than 70 partners from industry and academia is setting up five field-test sites. At these sites, technological innovations can be tested on a pilot scale in a real-world environment. It is the goal of the Recomine alliance partners to make an important contribution to technologies and holistic concepts that can then be applied by industry and society in current efforts to rehabilitate historic sites and rendering future raw-materials extraction and beneficiation more sustainable.

## **LCA OF TAILINGS MANAGEMENT: CURRENT STATUS, POTENTIALS AND CHALLENGES**

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### **Abstract**

A life-cycle assessment (LCA) has been increasingly implemented in past decades to support tailings management in doing less harm to the environment and improving resource efficiency. This study explores 28 LCA publications applied to tailings management, considering disposal, use in the construction sector and reprocessing for metal recovery. It analyses i) the current status of LCA practices (distinguishing the classic four LCA steps: goal and scope definition, life-cycle inventory (LCI), impact assessment and interpretation), ii) the potentials of LCA, in particular in terms of support to decision-making, and iii) the challenges that we are still faced with.

According to the literature on LCA results, tailings' final disposal is an environmental hotspot in the production of several metals and manufactured goods, in particular regarding the human-toxicity and eco-toxicity impact categories, which are very sensitive to metals' mobility. Moreover, tailings use in the construction sector globally is better than classic routes, while the environmental performance of reprocessing still needs to be further explored.

Uncertainty in LCI modelling is still a core issue to be addressed to refine further the conclusions of LCA studies. This is particularly key at an early stage of process development, for which LCA is aimed at steering processes towards environmentally preferable outcomes. Moreover, the accounting for resource inaccessibility and potential dissipation in LCA, recently a hot-topic in the LCA community, is particularly promising to support more resource-efficient solutions for tailings' management.

Finally, this study concludes with a suggested "path to follow" for the LCA of tailings' management to deliver more robust (i.e., representative, complete and consistent) results as a support to sound decision-making.

## **RESPONSIBLE TAILING MANAGEMENT: MAKING THE SOCIAL LICENSE TO OPERATE TANGIBLE**

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### **Abstract**

For a long time, the management of mining residues was not a focal point of the mining industry. Most recently, the need to engage more with the management of tailings came to the fore and the call for including a social licence to operate (SLO) became more prominent<sup>1,2</sup>. Since its emergence in the mid-1990s, the SLO concept has become widespread in the mining industry and various approaches have been developed and applied<sup>3</sup>. In 2020 the ICMM, UNEP and PRI published the “Global Industry Standard on Tailings Management” that suggests a standardised approach to tailing management with a strong focus on risk reduction and responsible risk management throughout the whole tailings-facility lifecycle, including closure and post-closure<sup>4</sup>. Within the standard, ideas are taken up that tie in with the SLO concept<sup>4</sup>. However, a detailed procedure for how to identify context-dependent factors related to gaining or sustaining a SLO in the context of tailing management is so far missing.

In this presentation we will address this gap and present preliminary results from our research. Factors specific to the geographical and social context that intervene with the relationship remining tailing-pond projects build with the local community are discussed. These factors are, for example, local experiences with large-scale recycling projects, the local perception of tailing ponds as a place for sport and leisure or the specific meaning of the local mining history. This research is part of the REMINTA project, which focuses on remining of the historical Rammelsberg tailing pond in Germany as one possible option for tailing management. Based on a social scientific research approach we aim to develop a general guideline that facilitates the engagement of tailing-management projects with local communities and thus, gaining a SLO.

### **References**

1. Goerke-Mallet, P., T. rudolph, J.F. Brune and J. Kretschmann, „The importance of Social Licence to Operate fort he Mining Life Cycle“, *Mining report Glückauf* **165** (49) 323-332 (2020).



2. Owen, J.R., D. Kemp, É. Lèbre, K. Svobodova and G. Pérez Murillo, „Catastrophic tailings dam failures and disaster risk disclosure.“ *Int. J. Disaster Risk Reduct*, **42** 101361 (2020).
3. Moffat, K. and A. Zhang, “The paths to social licence to operate: An integrative model explaining community acceptance of mining.”, *Resour. Policy*, **39** 61-70 (2014).
4. Global Tailings Review (International Council on Mining and Metals [ICMM], United Nations Environment Programme [UNEP], Principles for Responsible Investment [PRI]), “Global Industry Standard on Tailings Management”, URL: <https://globaltailingsreview.org/>, 2020.

## **THE POTENTIAL FOR IMPROVING GOLD ARTISANAL MINING PRACTICES IN SUDAN**

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### **Abstract**

The Government of Sudan attempted to control its artisanal and informal mining activities that account for about 85% of total gold production (2010–2018)<sup>1</sup>. At the same time, there are more than 1 million miners and 4 million dependents directly benefiting from the activity<sup>1</sup>. Moreover, Sudan's mercury release is considered to be the highest in Africa, with 108 tons of mercury being released<sup>2</sup>. Additionally, artisanal mining in Sudan has brought land-conflict issues that may hinder the mining industry. With the aim of resolving these issues, the government has tried to implement several policies to reduce the negative impact and to control the activity. However, one of the potential policies that could improve and formalize artisanal mining is to allow large companies to buy the miners' ore before it is processed by amalgamation, by offering attractive prices to the miners. Consequently, a mercury-free gold-recovery method is adopted that maximizes the returns for the government, companies and miners. Thus, the ore will be processed only once by more cost-effective and environment-friendly methods. This paper aims to address the potential benefits of this policy and to highlight the expected challenges of the implementation to improve the overall process.

### **References**

1. Bakr, A. (2018). Smart artisanal gold mining from a Sudanese perspective. *Biomedical Journal of Scientific and Technical Research*.
2. UNEP (2018), Technical Background Report to the Global Mercury Assessment 2018

## **PROSPECTIVE LIFE-CYCLE ASSESSMENT OF ALTERNATIVE MINE-WASTE REPROCESSING: A CASE STUDY OF COPPER TAILINGS**

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### **Abstract**

The production of copper with traditional approaches generates a considerable amount of mine waste called tailings. This waste is often landfilled in impoundment storages, which require careful monitoring to prevent the risk of contamination. Among new mitigation strategies, one solution is the implementation of a circular economy in mining: minimizing environmental loads caused by tailings' deposition, while recovering secondary resources. When properly treated, copper tailings can be a valuable source of secondary metals and building materials. While this initially appeared beneficial, it is important to transparently quantify the pros and cons of the proposed disposal alternatives with a standardized accounting method, since the valorisation of tailing materials requires further processing. This helps to validate the sustainability claims of such strategies through systems-thinking approaches. Therefore, the goal of this study is to understand the potential environmental impacts of emerging copper-tailings management using a prospective life-cycle assessment (LCA).

Benefitting from continuous interactions with researchers who design the processes in the EU Horizon 2020 SULTAN project (<https://etn-sultan.eu/>), we develop LCA models that can parameterize multiple reprocessing routes of copper tailings. We also adapt process-based LCA by integrating prospective elements in the analysis, such as the bottom-up modelling of foreground systems and future background data, such as for energy supply.

Our results suggest that the valorisation of bulk residues as building materials is crucial to obtaining positive environmental benefits for all alternative routes. Also, this study contributes to the identification of environmental bottlenecks and critical levers of the copper tailings' reprocessing and reuse, highlighting key optimisation areas for improving overall end-of-life management in the mining industry.

## **THE BIORECOVER PROJECT: RE-MINING BIOTECHNOLOGIES TO CREATE NOVEL CRITICAL-RAW-MATERIAL VALUE CHAINS**

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### **Abstract**

BIORECOVER aims at developing and piloting integrated biotechnological processes capable of treating mining waste streams and selectively extracting target metals with the goal of developing a new, sustainable re-mining process based on biotechnology. Specifically, the project is investigating techniques to recover rare-earth elements from bauxite residues, magnesium from low-grade magnesite ores, and platinum-group metals from low-grade platinum ores. The EU H2020 project involves fourteen international partners from mining, microbiology, chemistry, engineering, metallurgy, sustainable process development, as well as CRM end-users<sup>1</sup>.

To bridge the gap between research results and industrial exploitation, the project includes a study of the impact of its novel biotechnologies on the raw-materials value chains in question. The study has mapped out the existing value chains of scandium, yttrium, platinum and magnesium, and the key European stakeholders working with these materials. It includes an analysis of the financial performance of major corporate commodity producers and consumers to provide insights into different actors pricing power and the ability to extract economic rent at different links along each chain. Moreover, the study draws upon expert interviews to explore the major governance mechanisms and public policies structuring each material's value chain, and the critical success factors considered during negotiations between suppliers and clients. This research provides insights into how value chains can be expected to take up the project's re-mining innovations. Finally, new value chains for target materials are hypothesized to account for the ways that re-mining using novel biotechnologies could transform relations between stakeholders and lead to changes in their business models.

### **References**

1. A. Alcasabas, F. Massingberd-Mundy, B. Breeze, M. Ruiz-Pérez, C. Martínez-García, "BIORECOVER New bio-based technologies for recapture of Critical Raw Materials" , 2021

## **ENVIRONMENTAL IMPACT OF CLEANED SULPHIDIC MINE WASTE INTEGRATED INTO CONSTRUCTION MATERIALS**

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### **Abstract**

Proper management and storage of mine waste, e.g., tailings and waste rock, is one of the main issues that mining industries face. Additionally, there are many historical mining deposits that may, even centuries later, still leach contaminants into the environment. One solution to minimise the risks associated with the waste, with also potential economic benefits, is valorisation. After recovering valuable metals and removing hazardous contaminants, the remaining residue can be valorised into green construction materials, such as alkali-activated materials (AAMs), ceramics, or cements. In the present study, the characteristics of mine waste originating from three different sites were compared with metal(loid)s leaching from cleaned mine waste and green construction materials containing (cleaned and uncleaned) mine waste. Emphasis was given to the mobilisation of metal(loid)s from the mine waste and construction materials under different conditions, through a series of leaching tests. The leaching tests were applied to either mimic neutral conditions in nature, conditions in a landfill (end of life), or extreme pH conditions. Most of the original mine waste samples contained high levels of Pb, Zn, and As, which decreased in most cases via cleaning methods such as bioleaching with acidophilic bacteria or flotation. Based on the leaching studies, several AAMs, ceramics, and cements/clinkers effectively immobilised metals (e.g., Pb and Zn). Also, longer curing times of the AAM generally improved the immobilisation of metal(loid)s. For ceramics, the temperature at which the test pieces were fired, also played a major role in decreasing the mobility of some metal(loid)s, while increasing the mobility of others (e.g., As, potentially via the structural rearrangement of As and Fe). Overall, through this detailed characterisation, the environmental impacts from the mine waste and the downstream products were assessed, determining viable valorisation methods to close the circular-economy loop.

## **A CIRCULAR-ECONOMY APPROACH TO THE VALORIZATION OF RARE EARTHS GENERATED IN ALLUVIAL MINING BY QUANTIFYING ENVIRONMENTAL IMPACTS THROUGH LIFE-CYCLE ANALYSIS**

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### **Abstract**

The growing global consumption of goods and services due to population growth, higher living standards, and economic growth results in **the** increased extraction of natural resources, including primary metals. This despite the great efforts of society to use resources more efficiently, to progress to a circular economy (CE) and to dematerialize, **i.e.**, to reduce the amounts of energy and materials required for some economic function, with the objective of reducing environmental impacts and maximizing the use of renewable resources.

The mining, minerals processing and metals production sector, like other industrial sectors, are under increasing pressure to reduce not only the energy sources they consume, but also the waste released into the air, soil and water. Because of this, production systems **must** become more sustainable, sustainable energy resources **must** be used and **the** improved treatment of waste streams is required. The CE goal is the maintenance of materials in a useful state in products as long as possible, avoiding material losses, dissipation or hibernation, and emissions to the environment.

In Colombia, the waste from the alluvial mining of ore and platinum generates nine million tonnes per year of waste products, including black sands, containing minerals of interest such as monazite, which contain rare earth elements (REEs) such as lanthanum, cerium and praseodymium that have great application in communications, LED screens, electric cars, among others. The black sands are currently not used to obtain REEs, which encourages the sector to give added value to said waste generated in the region.

The research performed aimed to evaluate the environmental impacts from alluvial mining from cradle to gate; that is, from the prospecting and extraction stage, and the refining

process until gold ingots are produced. Additionally, routes for the recovery of REEs from the black sand derived from alluvial gold mining were analysed in environmental terms. Life Cycle Analysis is implemented as a tool for evaluating the environmental sustainability of production processes to identify the environmental impacts of the selected black sands valorisation route to propose more sustainable production patterns that allow a better disposal, use and recovery of the waste generated.

*SESSION 3*

# Metal and Mineral Recovery I

Chair: Valérie Cappuyns, KU Leuven, KU Leuven



## **BIOLEACHING AS A CORE TECHNOLOGY FOR THE TREATMENT OF LOW-GRADE METAL-CONTAINING TAILINGS: HEAP- AND POND-LEACHING DEVELOPMENTS IN THE NEMO PROJECT**

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### **Abstract**

The Terrafame Sotkamo mine is using bioheapleaching for the metal extraction from the Talvivaara deposit ore. The precursors of the host rocks were deposited 2.1–1.9 million years ago in a stratified marine basin. Characteristic features of the ore are high concentrations of organic carbon and sulphur, with median values of 7.6% and 8.2%, respectively. The main sulphides of the Talvivaara ore are pyrrhotite, pyrite, sphalerite, chalcocopyrite and pentlandite.<sup>1</sup>

The Terrafame production process consists of open-pit mining, four-stage crushing, agglomeration, heap stacking and reclaiming, heap leaching in two stages and metals recovery, ending in upgrading nickel and cobalt sulphides into battery chemicals.

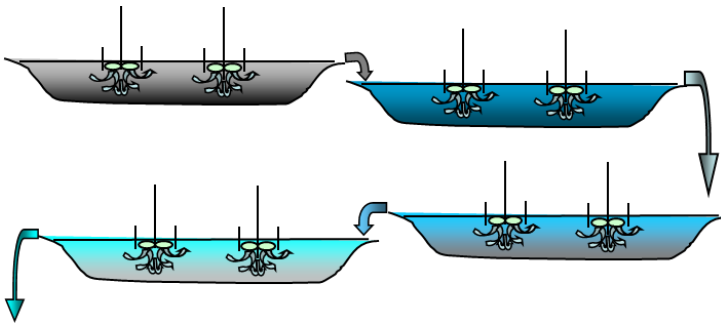
In bioheapleaching the crushed ore is stacked in a heap that is aerated and irrigated to oxidize sulphide minerals and dissolve valuable metals into solution as sulphates. The heaps are irrigated with an acidic (pH ~ 2.0) solution and aerated to enhance the chemical and biological oxidation process. Metal-containing pregnant leach solution (PLS) is partly recirculated back to irrigate the primary pads and partly fed to the metals production plant, where the metals are extracted from the solution by precipitating them as sulphides. After the metals-recovery process, the nickel-, cobalt-, copper- and zinc-free raffinate solution is used as a feed solution in the secondary leaching phase, where the primary leached ore is leached further and finally buried if no other use for the material is found.

Bioleaching of the pyrite-rich ore is challenging due to the need for very oxidising conditions for the pyrite mineral to leach. Also, the high iron content in the ore is producing a lot of secondary material, hindering the leaching more and more over time, thus making the total leaching of the ore very difficult.

In the Nemo project, Terrafame is researching the total leaching and enhancing the knowledge of leaching of the black shist ore with secondary-leaching pilot-scale heaps. The goal is to use the ore metal's potential as much as is feasible and thus help the mine closure work or further use of the leached material, for which some possible methods are being researched in other work packages of the Nemo project.

This pilot work shows the potential for bioleaching of the secondary ore, but also points out some challenging aspects in the total Terrafame operation for the very sensitive bioleaching process.

In parallel with the pilot work performed by Terrafame, another concept of bioleaching process is being developed in the NEMO project by BRGM as a compromise between conventional bioleaching heap and stirred-tank reactors (STRs). This new technology involves ponds where pulp suspension and gas-liquid mass transfer are achieved with floating agitators (see Figure 1). The objective is to reduce the investments costs compared to STR technology, while maintaining the same kinetics and recovery yields. In NEMO, this concept has been tested at the pilot scale using the same material (secondary ore) as the one used in the Terrafame pilot heap.



**Figure 1.** Schematic view of the bioleaching pond concept

The pilot has been designed to mimic the bioleaching-pond concept in the BRGM pilot process hall. It is composed of a stainless-steel tank with a working volume of 1800L and a floating agitator. The tank is thermostated by means of a water jacket maintained at the desired temperature with a cryo-thermostat. The floating agitator was built on the model of TurboxAL agitators designed by MRM and Air Liquide for water-treatment applications. The dimensions of the industrial agitator were divided by four for the purpose of the study (diameter: 750mm, height: 850 mm). The agitator performs pulp mixing, together with gas injection. During the project, around five tons of materials were reprocessed in this bioreactor. The main parameter that was tested was the solid concentration, which was varied between 20 and 30% (w/w). The extraction yield for Ni, Co and Zn was between 80% and 100% for a residence time of 10 days, whatever the solid concentration. In conventional

bioleaching STR, the solid concentration is usually below 20% to avoid any bacterial damage or mass-transfer issue. It is likely that the progressive increase of the solid concentration from 20 to 30% made it possible to maintain the bioleaching performance thanks to the adaptation of the bacteria. No mass-transfer issue was encountered: the oxygen was in excess and the solid concentration in the reactor was homogeneous.

The pilot testing was complemented by numerical approaches to support the technology upscaling and to check the ability of the system to self-control the temperature. Bioleaching reactions are significantly exothermic and thus the temperature must be carefully controlled to maintain the biological activity. In contrast to conventional stirred-tank reactors, the temperature in industrial ponds cannot be regulated with heat exchangers. On a pilot scale, it is difficult to test the capability of the system to reach the right temperature without any temperature control because of the small size of the equipment. In such cases, numerical modelling is a powerful tool to simulate the full-scale system. In the first step, computational fluid dynamics was used to model the hydrodynamics of the system and to define the volume of influence of a single agitator, the number of floating agitators and the mechanical power dissipated into the fluid. Then, a heat-balance model was developed to characterize the impact of each heat-transfer component (operating and environmental conditions) on the temperature regulation. From the CFD simulation, the geometry of the pond on an industrial scale was designed and the heat balance was simulated for the Sotkamo case study. The results show that the temperature can be maintained in a suitable range (40° to 50°C), compatible with a high bacterial activity.

The literature devoted to bioleaching development rarely proposes a comparison of different types of bioleaching reactors with the same substrates. The work performed by Terrafame and BRGM in the NEMO project is one of the first attempts to benchmark two bioleaching technologies, i.e., heap and pond with mechanical stirring, to study their advantages and drawbacks. The use of pilot equipment makes it possible to build a set of consistent data that will be further used to perform an economic and environmental assessment of both technologies.

## References

1. Multiphase evolution in the black-shale-hosted Ni–Cu–Zn–Co deposit at Talvivaara, Finland  
Kirsti Loukola-Ruskeeniemi, Hannu Lahtinen

## **Extraction of cobalt and nickel from a sulfidic mining residue via stirred-tank bioleaching: A pilot operation**

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### **Abstract**

The extraction of metallic values from sulfidic mining residues has recently become an interesting field for process development, with clear benefits both from the economic and environmental perspectives. There is a wide range of hydro and pyrometallurgical process options available for the oxidation of the residues, the extraction of the valuables as well as the purification and production of final products. While the technologies of many of these process options are generally well known, material-specific questions such as reaction kinetics, the formation of new residues and their characteristics, detailed process variables, etc., require pilot operations designed to simulate full-scale operations as closely as possible. It is often after pilot operations that the full feasibility of a flowsheet can be determined.

In this project, a series of processes for the production of cobalt (Co) and nickel (Ni) sulphides from Boliden's Luikonlahti (Finland) mine residues was piloted. The pilot flowsheet, which was developed after sequential desktop and laboratory investigations, consisted of fine grinding, bioleaching, iron removal, bulk hydroxide precipitation, re-dissolution of bulk hydroxides, solution purification and finally the production of mixed Co and Ni sulphides. A continuous stirred-tank bioleaching process was set up and performed on a scale of 3.5 m<sup>3</sup>. Recoveries of up to 90% could be attained during 7 days of retention time. Boliden's patented two-stage process was operated to treat 5 m<sup>3</sup> of the leach solution for iron removal and producing representative iron-gypsum residues for environmental analyses. Downstream processes for the purification and production of final products, including CuS, ZnS and (Co-Ni)S, were also operated and the effect of process parameters such as pH on the separation and purity of different products were studied during a continuous sulphide-precipitation process. The pilot operation resulted in invaluable know-how for different processes as well as insights into the quality of the products and other side-streams and residues, which can be used for recycling or deposition purposes. The pilot operation also served to provide samples to other parallel projects that were carried out within EU-funded Horizon 2020 NEMO project.

## **TWO-STAGE LEACHING OF MINE TAILINGS: RECOVERING IRON AND SULPHUR TOGETHER WITH VALUABLE BASE METALS?**

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### **Introduction**

Hydrometallurgical technologies provide new possibilities for treating secondary streams, including mine tailings. However, in existing flowsheets, complex mineralogy with a high diversity of elements may generate challenges in leaching, especially in later leachate purification and metals recovery. With sulphidic mine tailings, the challenge is the high iron and sulphur contents, generating a highly concentrated ferric sulphate leachate with significantly lower target-metal concentrations in oxidative leaching circuits. Iron and the majority of the sulphate are then precipitated to a solid residue, typically with a very high volume. Then, valuable metals are recovered. In this conventional flowsheet, iron and sulphur are lost.

In this research, a two-stage leaching process is applied for high-sulphur mine tailings, containing pyrite (53 wt %), pyrrhotite (24 wt %) and valuable metals of cobalt, nickel, zinc and copper (each < 1 wt %). The first leaching stage targets pyrrhotite leaching, utilising non-oxidative sulphuric acid leaching. In optimal conditions, this stage results in the rapid conversion of pyrrhotite-based sulphur to hydrogen sulphide gas, which can be collected from the process. Collected hydrogen sulphide can be used in later metals-recovery steps if sulphide precipitation is applied. Another possibility is to use the Claus process to convert hydrogen sulphide to an elemental sulphur product. The iron incorporated into pyrrhotite is dissolved in the non-oxidative leaching and can possibly be recovered as ferrous sulphate after leachate purification by crystallization. Alternatively, if the desire is to decrease the freshwater intake, the ferrous sulphate leachate can be directly used as process water for the second leaching stage. The second leaching stage in the process utilises oxidative leaching to liberate valuable metals into the product leachate, allowing their later recovery.

### **Results**

The first leaching stage was studied in batch-mode screening tests to find the optimal parameters for the non-oxidative leaching of pyrrhotite. Then, continuous-mode validation tests were conducted on a bench-pilot scale. It was seen that when applying 90 °C and

process retention time of 106 minutes, pyrrhotite dissolution was practically complete and resulted in acid consumption of 427 kg/t (expressed as kg of 95 % sulphuric acid per ton of feed). Due to the major hydrogen sulphide production, dissolution of target metals was minor, and thus the leach residue contained the valuable metals after pyrrhotite removal. The obtained ferrous sulphate solution had approximately 22 g/L iron content as ferrous sulphate, and < 0.8 g/L calcium and magnesium impurities. The zinc, nickel and silica impurities were < 0.3 g/L. The hydrogen sulphide gas production was higher than required by the later cobalt, nickel, zinc and copper sulphide precipitation.

The second leaching stage was studied utilising tank-bioleaching technology. In the conducted study, the first leaching stage outputs were used; ferrous sulphate leachate served as process water, and the residual solid was the solid feed. No significant differences were observed in bioleaching performance between native high-sulphur tailings and acid-leached tailings. The leaching yields were generally >80 % for cobalt and nickel, >90 % for zinc and >50 % for copper.

## METALS-RECOVERY PROCESS FOR A PREGNANT LEACH SOLUTION FROM TAILINGS BIOLEACHING

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### Introduction

The bioleaching process of secondary streams, such as sulphur-containing tailings, has gained much interest for recovering valuable metals. The pregnant leach solution (PLS) obtained from a bioleaching process contains large amounts of iron, in both ferric and ferrous form. However, the obtained product leachate is practically always dominated by unwanted elements, such as iron and sulphur, while the valuable metal concentrations remain low. Moreover, certain toxic elements, for example, arsenic and cadmium, require careful management in leachate purification. Multiple process considerations are available for the iron removal. In low-temperature processing, ferric hydroxide precipitation remains as one alternative<sup>1</sup>. Sulphide precipitation is a conventional solution-purification method that can be utilised as a selective precipitation method for copper, cadmium and zinc removal with the low co-precipitation of nickel and cobalt<sup>2-3</sup>.

### A hydrometallurgical metal-recovery process for product leachate from tailings bioleaching

This research examines leachate purification and metal recovery for a product leachate obtained from the tank bioleaching of high-sulphide tailings. The product leachate contained mainly ferric iron, and other elements, mainly zinc, copper, nickel and cobalt. In addition, the solution contained other impurities, such as cadmium and arsenic. The PLS's elemental analysis is presented in Table 1.

**Table 1.** Elemental analysis of selected metals for the PLS from the tank bioleaching process.

Material	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Co (mg/L)	Fe (mg/L)	Ni (mg/L)	Zn (mg/L)
PLS	90	2.5	251	761.0	55000	310.0	1160.0

As the product leachate contains ferric sulphate, the first step after bioleaching and liquid-solid separation is iron removal via chemical precipitation. Of the many possible precipitate types, bioleaching is typically linked with iron hydroxide and gypsum production, due to the low operating temperature that prevents efficient jarosite or goethite precipitations. This study examined preliminary operating values with screening experiments in batch mode, followed by a continuous-mode pilot campaign to validate the results.

Due to the selected final recovery process, which is direct nickel-cobalt SX, the pre-treatment was executed in two consecutive stages. The first stage was the iron removal, where the iron was firstly precipitated as a hydroxide by calcium carbonate. The final pH adjustment prior to the second stage was conducted with ammonia addition, which prevented losses of Co and Ni to the solids and effectively lowered iron ions concentration. It was seen that in continuous mode, >99 % of the iron was removed with a residual concentration of 0.9 mg/L. Iron precipitation was also seen to be effective in arsenic capture and stabilization; the arsenic removal was 100 % (below the detection limit). Varying losses for valuable metals (Cu, Zn, Ni, Co) are typically reported during iron removal, either as co-precipitation or due to poor washing. In our study, continuous mode achieved low losses, approximately 5–10 %. Thus, the iron hydroxide precipitation can be considered as a rather selective sub-process. However, a considerable quantity of reagents was consumed in the iron removal (125 kg  $\text{CaCO}_3$  / $\text{1m}^3$  of and 0.75L  $\text{NH}_3$  / $\text{1m}^3$ ), and a lot of iron hydroxide and gypsum was produced. These factors might be one of the main economic challenges of a complete hydrometallurgical treatment.

After the iron removal, copper and zinc were precipitated as sulphides using hydrogen sulphide gas. Sulphide precipitation is known to be an extremely rapid and, typically, a highly selective method. Even copper and zinc can be precipitated separately, here the mixed product was prepared as the copper concentration was very low compared to the zinc, and thus it can most likely be tolerated in the zinc process plant. Again, the work protocol was first to determine the optimal parameters with batch-mode screening tests and then proceed to the continuous-mode pilot campaign of sulphide precipitation. The feed solution for the sulphide precipitation contained only traces of iron, minor amounts of copper and cadmium and <1 g/L of zinc, nickel and cobalt. The continuous-mode sulphide precipitation, completed at 35°C and with 10 minutes of active retention time, resulted in very high yields for zinc (99.0%), copper (>99.9%) and cadmium (>99.9%), with relatively low co-precipitations of nickel (2.5 %) and cobalt (3.7%). Therefore, the precipitation was very selective. The corresponding  $\text{H}_2\text{S}$  consumption of the process was 1.3 L per L of solution.

Table 2 presents an elemental analysis of selected metals for the zinc sulphide precipitation overflow that was prepared for the direct nickel-cobalt solvent-extraction research.



**Table 2.** Selected metal's elemental analysis of the zinc sulphide precipitation overflow. "UD"=Under detection limit

Material	As (mg/L)	Cd (mg/L)	Cu (mg/L)	Co (mg/L)	Fe (mg/L)	Fe <sup>+++</sup> (mg/L)	Ni (mg/L)	Zn (mg/L)
PLS	UD	UD	UD	732.0	0.52	UD	302.0	8.5

## References

1. J. Monhemius, "The iron elephant: A brief history of hydrometallurgists' struggles with element no. 26", *CIM Journal*, **8**(4) 197-206 (2017).
2. A.E. Lewis, "Review of the metal sulphide precipitation", *Hydrometallurgy*, **104**(2) 222-234 (2010).
3. T. Tuominen & P. Grönqvist, "Hydrogen Sulfide as a Hydrometallurgical Reagent", *Erzmetall: Journal for Exploration, Mining and Metallurgy*, **22** B81-6 (1969).

## **INTRODUCTION OF NUMERICAL APPROACHES TO SUPPORT THE DEVELOPMENT OF THE POND BIOLEACHING UNIT**

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### **Abstract**

In the frame of the H2020 NEMO project, bioleaching was used to recover metals from mining residues. A new bioreactor concept, consisting of ponds where pulp suspension and gas-liquid mass transfer are achieved with floating agitators, was studied at a pilot scale on the two case studies considered in the project. Complementary numerical approaches were then developed to simulate and benchmark several process scenarios as well as to support further up-scaling of this concept. First, computational fluid dynamics (CFD) was used to model the hydrodynamics of the system and to define the volume of influence of a single agitator, the number of floating agitators and the mechanical power dissipated into the fluid. It was then applied to the Sotkamo and Aïtik mining residues.

A model was then developed and solved using MatLab software to quantify the contribution of the operating and environmental conditions to the heat balance and their influence on the pond temperature. Various scenarios were simulated (equatorial and sub-arctic climates, sulfide concentration, pond geometries). At the industrial scale, the environmental conditions have little influence on the heat balance, which is mainly dominated by the reaction enthalpy. It was also demonstrated that the temperature could be maintained in a suitable range (between 40 and 50°C) by controlling the fresh-pulp inlet conditions (flow rate, temperature) and the aeration capacities (flow rate, oxygen partial pressure), even at low sulfide concentration (between 5 and 10 %).

Finally, a model based on Syscad was developed to simulate the flowsheet of the process and take into account the recirculation loop that could not be studied experimentally. As the solid was composed of various mineral phases, the use of such a model, based on the kinetics experimentally obtained, was also able to provide data for economic and environmental assessments.

## **INTEGRATED INNOVATIVE PILOT SYSTEM FOR CRITICAL-RAW-MATERIALS RECOVERY FROM MINE WASTES IN A CIRCULAR-ECONOMY CONTEXT**

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### **Abstract**

Critical raw materials (CRMs) are crucial to Europe's economy. They form a strong industrial base, producing a broad range of goods and applications used in everyday life and modern technologies. CRMs are needed for significant economic and strategic sectors, for example, manufacturing batteries, construction tools, sensors and electronic devices, medical devices, metals, automotive, defence or renewable energy sectors. However, limited supply and the difficult substitution of CRMs is a growing concern within the EU and across the globe.<sup>1</sup>

The RAWMINA project aims to develop and to demonstrate the RAWMINA pilot system: an industrially scalable and flexible innovative pilot in continuous operation for mine waste (MW) valorisation, achieving 95% recovery rate and 95% selectivity for CRMs (Co, Sb, Ge, W), and 80–90% recovery rate and 95% selectivity for Au, Ag and Fe-based high-value products, whilst re-utilising 90% of the water. RAWMINA will implement and standardize an innovative energy-, water- and cost-effective pilot system able to treat up to 100–150 kg MW/day in an industrial demonstration (TRL7), including efficient and robust process control.

To achieve these aims, RAWMINA activities include MW sampling, MW dressing and characterization, upscaling of innovative technologies such as continuous bioleaching coupled with the alkaline leaching of bioleaching residues, iron removal with magnetic separation and CRMs' selective recovery through a combination of nanofibrous composite materials and electrocoagulation processes from unexploited/underexploited metal-containing materials.

Pilot design, integrated system engineering & demonstration with MW of diverse geological compositions from EU and non-EU mine sites will demonstrate flexibility and adaptability to different mine-waste compositions and metal grades.

RAWMINA will improve EU competitiveness and create added value in RMs' processing, refining and equipment manufacturing by developing a new circular business model as an alternative to the traditional linear mining economy.

The techno-economic and sustainability assessment, social impact and exploitation of the pilot system will be evaluated to ensure market penetration, technology export and circular business plan. Finally, RAWMINA will create a unique community, called the "CRM Recovery Helix", to maximise clustering and dissemination to all the relevant stakeholders.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement n° 958252.

## References

1. EC, 2018. Report on Critical Raw Materials and the Circular Economy. <https://op.europa.eu/es/publication-detail/-/publication/d1be1b43-e18f-11e8-b690-01aa75ed71a1/language-en>

## **AN INNOVATIVE BIOCHEMICAL ROUTE TO RECOVER COBALT FROM LATERITIC MINING WASTE**

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### **Abstract**

The demand for cobalt (Co) and nickel (Ni) is expected to grow steadily over the next decade. Around 60% of the world's Ni reserves are contained in lateritic ores, which also contain significant amounts of Co<sup>1</sup>. Laterite deposits are characterized by the presence of two distinct horizons: (i) an upper limonite zone where Ni content usually varies between 1 and 2% and which also has significant quantities of Co; (ii) a lower saprolite zone with Ni content varying between 3 and 5%. The saprolitic ore is usually treated via a pyrometallurgical reduction, whereas the limonitic ore is traditionally processed through pressure acid leaching (PAL), which has often proven to be very costly and plagued by technical challenges<sup>2</sup>. Currently, Ni extracted from laterites mainly derives from saprolite ores, while the associated limonite ores are usually stockpiled or considered as mining waste. However, this stockpiled material represents a vast unlocked resource.

Recent work has demonstrated that Ni and Co can be extracted from limonite by using acidophilic bacteria in anoxic conditions, mild acid (pH 1.8) and at ambient temperature (30°C). This method is called “reductive bioleaching” or “bioleaching in reverse gear”<sup>3,4</sup>. The H2020 CROCODILE research project aims to demonstrate combined innovative metallurgical options for the recovery of Co from primary and secondary sources. Within the CROCODILE project reductive bioleaching has been applied to limonite from New Caledonia. The leaching mechanisms were investigated and have been optimised to design a demonstration plant at the pilot scale.

### **References**

1. Mudd, G.M., Jowitt, S.M.: A detailed assessment of global nickel resource trends and endowments. *Economic Geology* 109, 1813–1841 (2014).
2. Asselin, E.: Thermochemistry of the Fe-Ni-Co-NH<sub>3</sub>-H<sub>2</sub>O system. *Min. Met. Proc.* 28, 169–175 (2011)

3. Hallberg K., Grail B.M., du Plessis C.A., Johnson D.B.: Reductive dissolution of ferric iron minerals: a new approach for bioprocessing nickel laterites. *Min. Eng.* 24, 620–624 (2011)
4. Johnson D.B., Grail, B.M., Hallberg, K.: A New direction for biomining: extraction of metals by reductive dissolution of oxidized ores. *Minerals* 3, 49–58 (2013)

## **Redox-Controlled Bioleaching: a Generic Approach for Extracting and Recovering Metals from Oxidised and Reduced Mineral Wastes**

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### **Abstract**

Waste materials generated and disposed of at metal mine sites include low metal-grade waste rock, tailings produced by froth flotation and metal-rich overburden layers (such as limonite zones at laterite mines) that are not suitable for processing using available technologies. Quite often, these waste materials contain concentrations of critical and other metals that make them attractive for reprocessing using bioleaching technologies, which has the important secondary benefit that this can eliminate or greatly reduce the threat that these wastes pose to the surrounding environments.

We have developed and tested a variety of biotechnological strategies for extracting and recovering metals from both solid and aqueous mine wastes. These include: (i) sulfur-enhanced oxidative bioleaching of sulfidic mine tailings<sup>1</sup>; (ii) sulfur-enhanced reductive dissolution of oxidised limonitic wastes<sup>2</sup>; (iii) redox-controlled partial oxidation of pyrrhotite waste to limit acid generation and recover nickel: (iv) selective recovery of transition metals from streams draining “natural biominerals”<sup>3</sup>. Examples will be given of all four applications.

### **References**

1. C. Falagán, B. M. Grail and D.B. Johnson, “New approaches for extracting and recovering metals from mine tailings”, *Miner. Eng.* **106** 71-78 (2016).
2. A. L. Santos, A. Dybowska, P. F. Schofield, R. J. Herrington and D. B. Johnson, “Sulfur-enhanced reductive bioprocessing of cobalt-bearing materials for base metals recovery”, *Hydrometallurgy*, 195 105396 (2020).
3. D. B. Johnson, “The Evolution, Current Status, and Future Prospects of Using Biotechnologies in the Mineral Extraction and Metal Recovery Sectors”, *Minerals*, **8** 343 (2018).

## **FUTURE SMART MINING: HOW ARCHAEA CAN ENHANCE VALUABLES RECOVERY AND INCREASE THE VALORISATION POTENTIAL OF MINE TAILINGS**

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### **Abstract**

Global mining operations generate 5–7 billion metric tons of tailings annually; mostly disposed rather than valorised. These substantial amounts have increased concerns regarding their ecological and environmental impacts such as the occupation of large areas of land, the generation of windblown dust, and the contamination of surface and underground water. Additionally, these tailings still contain unrecovered valuables, mostly for economic reasons. Over the past years, the mining industry has been subjected to increased environmental principles. As a consequence, besides waste rock and water management, tailings management and enhanced recovery have become progressively important factors for ecologic and economic reasons.

An alternative (or additional) method for valuables recovery from ores and tailings is bioleaching – the extraction of metals and minerals through microorganisms. Recently, many thermophilic bacteria and archaea have been isolated, characterised, and used for extracting metals, at least on a laboratory scale. To make bioleaching economically feasible on a large scale, the proper combination of micro-organisms and strains, as well as the selection of operational conditions, are essential and often require extensive research. Archaea exist in a broad range of habitats and are recognized as a major part of global ecosystems. Acidophilic archaea display a strong potential for the extraction of metals from various ores.

When applying bioleaching for the extraction of valuables as an additional process to regular mineral processing operations, the remaining tailings show an increased surface area: strongly simplified they look like Swiss cheese. If the remaining mineralogical matrix is rich in, e.g., aluminosilicates, these tailings can be an excellent precursor for geopolymers or supplementary cementitious materials. Thus, bioleaching not only enhances mineral processing but also increases the valorisation potential of the remaining tailings.



## References

1. R. Obenaus-Emler, M. Illikainen, M. Falah, P. Kinnunen, K. Heiskanen, "Geopolymers from mining tailings for more sustainable raw material supply", *MATEC Web of Conferences* **274**, 05001, RICON17, doi: 10.1051/mateconf/201927405001 (2019).
2. R. Obenaus-Emler, M. Falah, M. Illikainen, „Assessment of mine tailings as precursors for alkali-activated materials for on-site applications”, *Construction and Building Materials*, **246**, <https://doi.org/10.1016/j.conbuildmat.2020.118470> (2020).
3. E.R. Donati, C. Castro, M.S. Urbieto, "Thermophilic microorganisms in biomining", *World Journal of Microbiology and Biotechnology*, **32** (179), <https://doi.org/10.1007/s11274-016-2140-2> (2016).

## **(Bio)leaching of stockpiled iron-rich laterite in percolators**

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### **Abstract**

The Barro Alto mine (Goias, Brazil) is supplying a ferronickel smelter with raw material from its Ni-Co lateritic deposit. This deposit consists of an iron-rich limonitic layer at the top, which cannot be processed in the ferronickel smelter, and a magnesium-rich saprolitic layer, which is processed in the smelter. Limonitic material, with approximately 1.3 % of Ni and 0.1 % of Co, is excavated and deposited on a stockpile. The aim of this research was to investigate bioleaching in comparison to the chemical leaching of Ni and Co from the stockpiled limonitic material in percolators. Leaching experiments were conducted in small columns (50 cm height) in recirculation mode by application of the following lixivants: 1-M sulphuric acid, 1-M sulphuric acid with addition of 7 g/L ferrous sulphate and a liquid culture of sulphur-oxidizing bacteria, namely *Acidithiobacillus thiooxidans*. Before leaching, lateritic material was agglomerated in a drum agglomerator using sulphuric acid as a binder. Sulphur for the bioleaching experiments was mixed with lateritic material, and the mixture of sulphur and laterite was then agglomerated. The leaching degrees of Ni and Co in columns with 1-M sulphuric acid reached 39 % and 18 %, respectively; in columns amended with ferrous iron the Ni and Co extractions were 49 % and 73 %, respectively, proving the crucial role of ferrous iron in the efficient leaching of cobalt. During the bioleaching experiment, the pH was increasing, indicating that the approach to bioleaching of laterites in percolators needs some changes. Different and more successful bioleaching experiments were carried out and the first data will be presented.

## BIOLEACHING OF METAL(LOID)S FROM TWO SULPHIDIC MINE WASTES BY ACIDOPHILIC CONSORTIUM

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### Abstract

Sulfidic mine waste usually contains elevated amounts of metal(loid)s and can constitute significant environmental hazards such as acid mine drainage, especially when poorly managed. Reprocessing of mine waste could contribute to the ever-growing global demands for raw materials, as well as reduce the environmental impact posed by mining waste. Biomining is a global biotechnology that facilitates the extraction of metal(loid)s by harnessing the inherent abilities of some micro-organisms to catalyse the oxidative dissolution of *sulphide* minerals. This technique can be used to treat mining residues due to its competitive cost-effectiveness for the processing of low-grade ores, in addition to its minimal carbon footprints, in comparison to other extractive metallurgies such as pyrometallurgy. An acidophilic consortium containing various acidophilic bacteria and archaea was used to extract metal(loid)s from fresh waste rock and tailing samples from the Neves Corvo mine, Portugal. Over 70 % of the total Zn, Co, In, As and Cd contents were solubilized from both mine wastes by the acidophilic consortium. However, only 30 and 20 % of the total Cu content were recovered from the waste rock and tailing samples, respectively. Mineralogical characterizations of the bioleaching residues using X-ray diffraction (XRD) and mineral liberation analysis (MLA) revealed the formation of new minerals, especially jarosite, after bioleaching. Most of the biogenic jarosite formed after bioleaching was co-precipitated with other elements such as Cu and Pb. In conclusion, *the* bioprocessing of the mine wastes led to the simultaneous recovery of valuable and hazardous metal(loid)s, thereby achieving both economic and environmental benefits. Further research will investigate subsequent valorisation of the bioleaching residues into various circular-economy applications such as green cement, inorganic polymer, and ceramics.



*SESSION 4*

# Metal & Mineral Recovery II

Chair: Jarno Makinen

## **REMINING OF TAILINGS IN EUROPE: AN INTERDISCIPLINARY APPROACH AND LESSONS FROM THREE CASE STUDIES**

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## Abstract

The SULTAN European Training Network for the Remediation and Reprocessing of Sulfidic Mining Waste Sites focuses on developing novel methods for the 3D modelling of tailings, recovery/removal of valuable and hazardous metals, and the use of tailings in construction materials, as applied to three tailing storage facility (TSF) case studies.

The Plombières TSF, in East Belgium, is a by-product of the pyrometallurgical processing of Mississippi valley-type ores. The TSF contains 4 different types of mine waste: soil, metallurgical waste, brown and yellow tailings. Mineralogical and geochemical methods, such as Mineral Liberation Analyser (MLA), Electron Probe Micro-Analyser, and X-ray fluorescence, were employed to collect the key data (e.g modal mineralogy, mineral deportment, grade) required to assess the valorisation potential of the Plombières mine wastes.

The Davidschacht TSF, in the Freiberg mining district, Germany, was deposited in the 1950-60s, from the processing of the polymetallic hydrothermal vein ores. Geostatistical modelling of the TSF was performed to investigate the tonnages of valuable (Zn, Pb, Cu, In) and hazardous (As, Cd) metals. Multiple simulations were produced to optimise the sampling of tailings deposits. The mineralogy and texture of the tailings was assessed with MLA and modelled to evaluate the potential for metal recovery and Acid Mine Drainage production.

The Neves Corvo mine currently generates both waste rock and tailings residues from the active mining of high-grade Cu-(Pb)-Zn deposits of the Iberian Pyrite Belt. At present, the waste rock and the pyritic tailings from Cu and Zn processing plants are co-deposited in the Cerro de Lobo TSF. With each waste having distinct properties, several novel processing methods were investigated to assess different waste treatment routes. The results were compiled in a series of potential technological flow sheets to evaluate the feasibility of reprocessing and improve waste management at the current or similar sites.

The SULTAN project has shown that the potential benefits of reprocessing sulfidic wastes are manifold: reduction of the volume of wastes deposited, mitigation of environmental hazards, recovery of valuable metals, and valorisation of residues in industrial materials. Innovations come from the end-to-end assessment methodology for comprehensive appraisals of mine wastes, highlighting the significance of collaborative and interdisciplinary research.

## **TRANSFORMING AN ENVIRONMENTAL LIABILITY INTO A RESOURCE-RECOVERY OPPORTUNITY: THE CHVALETICE MANGANESE PROJECT**

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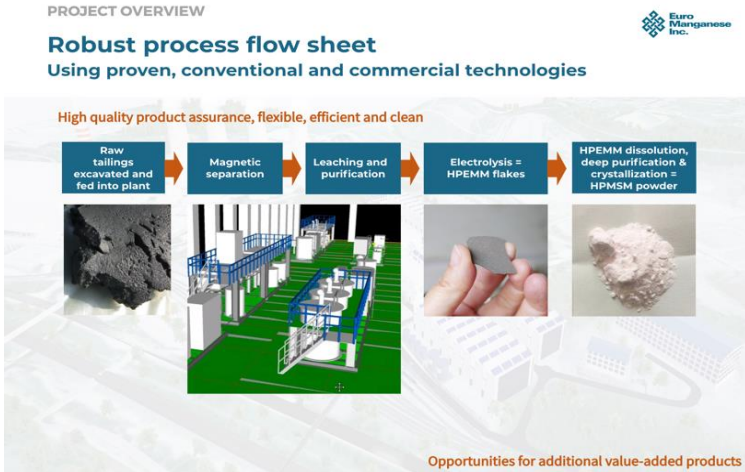
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### **Abstract**

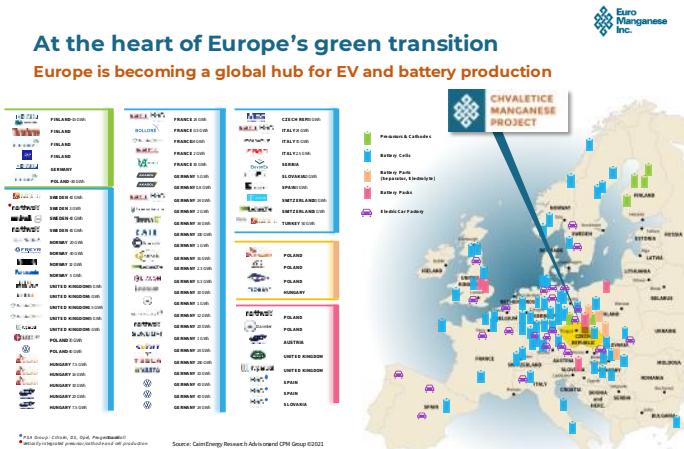
As the EU pursues its vision of decarbonization and a circular economy, the value of extractive-waste valorisation through sustainable resource and raw-materials management is more important than ever.

Euro Manganese Inc. (EMN) is a Canadian battery-materials company whose principal focus is the development of the Chvaletice Manganese Project. Strategically located in the heart of Europe, the project is designed to recycle valuable raw materials from extractive-waste streams and historical industrial residues to produce high-purity manganese, an essential component of batteries for electric vehicle. Our goal is to attain the maximum resource optimization from the tailings and create a strong, local, sustainable battery-raw-material supply chain.

In this session, EMN CEO Matthew James, a corporate executive with extensive experience in the natural resources, will discuss how the Chvaletice project stands to become the only primary producer of battery-grade manganese products in the world's fastest-growing EV market, while complying with modern Czech and European Union environmental laws and standards. At the same time as the project supports the EU's green goals, it will clean up a longstanding source of groundwater pollution and bring economic and social benefits to local communities. EMN has earned the trust and cooperation of regulatory agencies, community stakeholders and all levels of government, and has proactively engaged local residents throughout the development of the project.



**Figure 1:** Process showing the re-mining of extractive waste to produce high-purity manganese



**Figure 2:** Potential customers/offtakers for high-purity manganese production from the Chvaletice Manganese Project, strategically located in the heart of Europe



## LEACHING OF COPPER FROM CHRYSOCOLLA USING MONOETHANOLAMINE–AMMONIUM SALT SYSTEMS

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### Abstract

Oxidized copper ores are primarily comprised of oxide (e.g., tenorite, cuprite), carbonate (e.g., malachite, azurite) and silicate (e.g., chrysocolla) mineral phases. Chrysocolla, an ill-defined copper silicate with the general formula  $(\text{Cu,Al})_2\text{H}_2\text{Si}_2\text{O}_5(\text{OH})_4 \cdot n\text{H}_2\text{O}$ , is a common mineral in some oxidized copper deposits. It contains approximately 34 wt% of copper and offers potential economic value that currently is not being utilized because of difficulties in its beneficiation and metallurgical processing. Chrysocolla does not respond well to conventional flotation, and although it is easy to dissolve in sulfuric acid, its dissolution also leads to the formation of silica gel that causes problems during separation and the subsequent solvent-extraction process. Therefore, leaching in alkaline media, such as in ammonia, is more practical.

In this study, we have investigated solvometallurgical leaching based on mono-ethanolamine (MEA) lixiviants to extract copper from high-grade chrysocolla ore. Because of its high boiling point (170 °C), leaching in MEA can be performed at higher temperatures than leaching in aqueous ammonia, preventing evaporation losses. Being a bifunctional solvent, MEA holds both an amine and a hydroxyl functionality, which are available to coordinate copper ions. A series of preliminary leaching tests with MEA and different ammonium salts (i.e., chloride, carbonate, sulfate salts) showed that the MEA–NH<sub>4</sub>Cl lixiviant gave the best copper-leaching efficiencies (35%). Leaching optimization was carried out in 3-M MEA–NH<sub>4</sub>Cl by varying leaching times, temperatures and contacts. The results showed that the leaching rate was relatively slow and that the prolonged leaching time did not significantly affect the leaching efficiency. The conducted second leaching contact ruled out the possibility of lixiviant saturation, but the leaching efficiency remained low. Furthermore, the leaching temperature was found to be the decisive parameter; by increasing the temperature to 80 °C, 82% of the copper could be dissolved via single-contact leaching of 3 hours at a liquid-to-solid ratio of 10. It is hypothesized that the amine functional group of the MEA molecule forms a positively charged copper-ammine complex, while the chloride of the ammonium salt subsequently acts as a complex-stabilizing counter anion.

## **TOWARDS MORE SUSTAINABLE MINERAL PROCESSES: CELLULOSE NANOCRYSTALS AS A COLLECTOR IN FROTH FLOTATION**

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### **Abstract**

The development of green chemicals from renewable resources originates from great ecological and economic interests to overcome the inherent environmental and health problems associated with traditional petroleum-derived mining chemicals. Thiol collectors (mostly xanthates) are typically used as flotation chemicals for sulfidic minerals, while amine collectors are used for silicates. Cellulose is a renewable and sustainable biopolymer, which has the potential to mitigate many drawbacks related to the current mining chemicals. Especially, nanocelluloses have many appealing characteristics, such as a high surface area and tailorable surface chemistry, and they can be produced in high yield from abundant biomass resources. In the present work, cellulose nanocrystals (CNCs) were functionalized using aqueous silylation reactions to introduce an amine group on the CNC surface having affinity towards silica surfaces, or a thiol group having affinity towards sulfidic minerals. The CNCs' functionalization and reaction conditions were optimized and micro-flotation tests were carried out in a Hallimond tube to investigate the floatability of pure quartz or pyrite both with the green CNCs and commercial collectors. In addition, interactions between the functionalized CNCs and the selected pure minerals were detected via atomic force microscopy and the wettability of mineral surfaces was revealed via contact-angle measurements.

## **A Continuous Scandium supply from TiO<sub>2</sub> and bauxite residues: ScaVanger and Scaleup projects**

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### **Abstract**

New businesses will be created through the recently funded EIT upscaling projects (budget €6 million) ScaVanger (2021–2024, [www.scavanger.eu](http://www.scavanger.eu)) and Scaleup (2022–2024). These projects aim to bring three scandium (Sc) products to the market and create the Scavanger start-up company: 1. Sc-hydroxides; 2. Sc-oxides and fluorides; 3. AlSc alloys in mass production to supply small-scale specialized AlScMg producers. Feasibility studies were conducted during the H2020 SCALE project ([www.scaletechnology.eu](http://www.scaletechnology.eu)). Sc oxide production from TiO<sub>2</sub>-production and bauxite residues was demonstrated at pilot scale.

European Sc resources are residues from TiO<sub>2</sub> pigment (total 1.5 million tonnes per year) and from alumina production (7–8 million tonnes per year) at MYTILINEOS S.A, Greece. The upscaling of metallurgical processing to pre-industrial production will be performed. Scandium production will start up-ramping in 2025 at a TiO<sub>2</sub> plant and at Mytilineos S.A. Forty-five tons of Sc per year equivalent to Sc oxide will be produced for the EU market, a significant step to Europe's independence from the 100% Sc imports.

Europe can become a leader in the growing market applications covering the entire value chain when a continuous Sc supply is ensured: Sc is increasingly used in energy-storage systems (solid-oxide fuel cells, SOFC) and for green hydrogen production in solid-oxide electrolyzer cells (SOEC). Scandium is also increasingly used in the aluminium production and refining industries for manufacturing lightweight alloys such as AlMgSc sheets for marine and space constructions, liquified petroleum gas (LPG) container vessels, windmill blades and for 3D printing. AlScN piezoelectric films for energy generation are important compounds for 5G applications. The Sc market is expected to increase from 25 tons per year of Sc<sub>2</sub>O<sub>3</sub> in 2020 to 350 tons per year in 2026 and 1,100 tons per year in 2031.

ScaVanger's ecological and economic processing includes acid and water recycling, as well as metal recoveries during the cleaning process. This converts residue to valuable products that are economically and ecologically friendly.



## THE VALORE PROJECT: VANADIUM AND GALLIUM RECOVERY FROM BAYER LIQUOR

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### Abstract

Both vanadium (V) and gallium (Ga) are critical metals for the development of novel technologies such as batteries and 5G applications. However, the production capacity of both metals in Europe is limited to non-existent. At the moment, the highly alkaline Bayer Liquor from the aluminium industry is the main production source of Ga today. This stream also contains high V concentrations, which hampers the recovery of Ga, as current technologies co-extract V and Ga.

The EIT upscaling project VALORE (2022–2024, [www.kic-valore.eu](http://www.kic-valore.eu)) has as its main objective the development of an innovative metallurgical process that enables the separate extraction and valorisation of purified V and Ga as side products from the Bayer process in alumina refineries. The core of the VALORE innovation is a novel solid-phase extraction material with high alkaline resistance and selectivity towards V, which was developed during the H2020 Chromic project.

Using the selective recovery of V from the Bayer liquor, prior to Ga extraction, VALORE will solve two major problems simultaneously:

- 1) tapping into a new source of V supply (for which Europe is 100% dependent on imports);
- 2) making Ga extraction from high-V Bayer liquor more economically viable and environmentally friendly.

The innovative metallurgical process will be demonstrated on a pilot scale (TRL7) in a V/Ga extraction pilot built by MEAB on the site of the MYTILINEOS Alumina refinery in Agios Nikolaos (Greece). The aim is to generate 98.5% pure  $V_2O_5$  and  $GaCl_3$  of purity 4N to 5N, to be subsequently precipitated as  $Ga(OH)_3$  of GaAs.

The VALORE project connects players over the whole material value chain: from sorbent production (BASF, VITO), metal separation (MYTILINEOS, MEAB) and refining (VITO, MEAB, KTH). The VALORE project closely collaborates with the Scavanger project, which is co-producing vanadium from  $TiO_2$ -pigment production residues besides scandium ([www.scavanger.eu](http://www.scavanger.eu)).

## **RECOVERY OF VALUABLE METALS FROM DILUTE HYDROMETALLURGICAL LEACHATES BY ION FLOTATION**

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### **Abstract**

The development of novel techniques for the recovery of valuable metals from dilute aqueous solutions is essential for the exploitation of low-grade metal resources, such as tailings and slags. Solvent extraction is unable to treat dilute feeds due to the high extractant losses. Ion flotation is a gas-liquid separation technique that is based on differences in the surface activity and is capable of recovering metals from dilute aqueous solutions. In this technique the solution to be treated is sparged with gas bubbles and surfactants are added to generate a mobile gas-liquid interface. The oppositely charged targeted metals are adsorbed to this interface due to interactions with the hydrophilic head of the surfactants. Due to its simplicity and fast operation, the technique has attracted researchers' attention as an alternative hydrometallurgical metal recovery or removal operation. Nevertheless, current advances are limited to the metal recovery from dilute synthetic solutions and neglect the regeneration and reusability of the surfactants. As a consequence, the industrial implementation of ion flotation to hydrometallurgical operations is limited. In this work, the efficiency of ion flotation was evaluated under realistic conditions for the recovery of copper and lead from dilute copper-zinc ammoniacal and lead-zinc chloride leachates. Based on the experimental results it was possible to selectively and quantitatively concentrate copper over zinc to the foam phase with sodium dodecyl sulfate and lead over zinc with cetyltrimethylammonium bromide. Additionally, a novel solvometallurgical technique was developed for the recovery of copper from the foam phase as a precipitate and the regeneration and reuse of sodium dodecyl sulfate to a new ion-flotation cycle. The results are very promising, as they clearly indicate that the technique of ion flotation can be used as a metal-recovery operation in real hydrometallurgical leachates.

## **AQUEOUS LEACHING OF TUNGSTEN FROM SCHEELITE AFTER MW-ASSISTED FUSION WITH A LOW-MELTING EUTECTIC ALKALI HYDROXIDE SALT SYSTEM**

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### **Abstract**

Extraction of tungsten (W) from scheelite ( $\text{CaWO}_4$ ) is important to process tungsten resources, including low-grade ores or tailings, by metallurgical companies. The core step in the flowsheet of the conventional industrial processing of scheelite is to efficiently convert  $\text{CaWO}_4$  into sodium tungstate ( $\text{Na}_2\text{WO}_4$ ). Fusion (alkaline roasting) is a promising technique to form and recover metal oxyanions from (waste) materials.

An alternative two-step process to extract tungsten from medium-grade (3.67 wt.% of W) scheelite pre-concentrate was developed. In a first step, the  $\text{CaWO}_4$  was converted into more soluble alkali tungstates [ $\text{Na}_2\text{WO}_4$ ,  $\text{K}_2\text{WO}_4$  and/or  $\text{K}_3\text{Na}(\text{WO}_4)_2$ ] by fusion with a low-melting eutectic alkali hydroxide salt system consisting of an equimolar mixture of sodium hydroxide (NaOH) and potassium hydroxide (KOH). Fusion is performed via microwave (MW) assisted heating instead of conventional heating to enable fast and volumetric heating, thereby lowering reaction times. The use of a low-melting eutectic alkali salt mixture allows to lower the reaction temperature. After fusion, in a second step, the (cooled) MW-fused mass is brought into contact with water to leach the soluble tungstate salt. Fusion and leaching parameters were optimised, and W phase transformations monitored.

Under optimal conditions, MW-assisted fusion of medium-grade scheelite pre-concentrate with an equimolar Na-/KOH mixture (with ratio ore:salt = 1:1) at 200 °C for 30 min leaches ca. 90% of W into water (L/S = 10) at 25 °C after 30 min. The low-melting eutectic salt system allowed for  $\text{CaWO}_4$  to react at 200 °C and the main matrix elements (Al, Ca, Fe) displayed limited dissolution (<5%) during leaching. The procedure was also validated on low-grade scheelite tailings, yielding high W leachability.

### **Acknowledgements**

The authors acknowledge the Horizon 2020 TARANTULA project Grant Agreement n° 821159 which aims to develop novel, efficient and flexible metallurgical technologies with high selectivity and recovery rates with respect to W, Nb and Ta (more information on [www.h2020-tarantula.eu](http://www.h2020-tarantula.eu)).

## CONCENTRATION AND LEACHING OF RARE EARTHS FROM MOROCCAN PHOSPHOGYPSUM

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### Abstract

The rare-earth elements (REEs) are a class of metallic elements, considered as an important strategic resource, as they are found in several key green-technology products like smartphones, computers, flat-screen televisions and hybrid cars. The complexity of the mining and extraction process along with its environmental consequences, due to the mildly radio-active slurry tailings and the toxic acids involved, leaves REE manufacturers vulnerable to supply shortages. China produced more than 85% of the world's supply over the last two decades.<sup>1</sup> At the beginning of the current decade, Chinese export quotas led to a price surge, making some of these elements more valuable than gold. Therefore, it is of utmost importance to find new sources and to develop new green processes to address the increasing market demand for these elements.<sup>2</sup> Moroccan phosphogypsum, which is the main by-product of the phosphate industry, contains several added-value elements including REEs. Therefore, phosphogypsum could be considered as a secondary resource of REEs since, for each ton of phosphoric acid produced, 4.5 to 5 tons of phosphogypsum are generated.<sup>3</sup> The current study investigates the leaching of REEs from phosphogypsum. Systematic leaching processes, using various solutions under various operating conditions, were performed. It was found that salt solutions led to REE enrichment in the residue due to phosphogypsum dissolution, whereas pH-dependent leaching allowed a better dissolution of such elements in the liquid phase.

### References

1. J. Su, R. Xu, S. Ni, F. Li, X. Sun, "A cost-effective process for recovering thorium and rare earths from radioactive residues", *Journal of Cleaner Production*, vol 254, 2020.



2. C. Tunsu, Y. Menard, D. Eriksen, C. Ekberg, M. Petranikova, "Recovery of critical materials from mine tailings: A comparative study of the solvent extraction of rare earths using acidic, solvating and mixed extractant systems", *Journal of Cleaner Production*, vol. 218, p. 425–427, 2018.

3. S. Wu, L. Wang, L. Zhao, P. Zhang, H. El-Shall, B. Moudgil, X. Huang, L. Zhang, "Recovery of rare earth elements from phosphate rock by hydrometallurgical processes A critical review", *Chem. Eng. J.*, vol. 335, p. 774–800, 2018.

## **GREEN PROCESS FOR THE RECOVERY OF RARE-EARTH ELEMENTS FROM PHOSPHATE BY-PRODUCTS**

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### **Abstract**

The rare-earth elements (REEs) are the lanthanide-group elements plus yttrium and scandium. They are known for their exceptional physicochemical properties. Currently, the extensive use of these metals is dramatically increasing since they are involved in a wide range of advanced technologies such as green and renewable energies, phosphor lighting materials, glass polishing, petroleum refining, catalysis, permanent magnets in electric and hybrid cars, smart phones, etc.<sup>1</sup> To reduce the environmental challenges associated with REE mining, several countries are investigating in the extraction of REEs from industrial residues and other secondary resources.<sup>1,2</sup>

Phosphogypsum (PG) is a by-product generated from the phosphate industry with an annual production of more than 280 million tonnes worldwide. This industrial waste is associated with a promising amount of REEs. As a result, many processes have been developed in the world for the recovery of REEs from PG. However, the presence of diverse impurities is a major limitation for extending the developed processes to an industrial scale.<sup>3,4</sup> In the present work, REEs were selectively leached from PG using green acids as the leaching agents. The approach was designed to extract the desired elements without dissolving the host mineral. The optimized leaching process was also modelled using the shrinking-core theory to assess the kinetics of the system and to determine the predominant mechanisms. Finally, the proposed approach could be an efficient strategy for producing REE solutions, which could facilitate the incoming advanced separation processes for the recovery of commercial grade REE concentrates.

## References

1. J. Ait Brahim, S. Ait Hak, B. Achiou, R. Boulif, R. Beniazza, R. Benhida, Kinetics and mechanisms of leaching of rare earth elements from secondary resources, *Miner. Eng.* 177 (2022) 107351. <https://doi.org/10.1016/j.mineng.2021.107351>.
2. J. Ait Brahim, S. Ait Hak, B. Achiou, R. Beniazza, R. Benhida, Towards Green and Sustainable Processing of Phosphogypsum, in: *Advances in Green Materials Engineering*, Springer, 2021 (Accepted).
3. C.R. Cánovas, S. Chapron, G. Arrachart, S. Pellet-Rostaing, Leaching of rare earth elements (REEs) and impurities from phosphogypsum: A preliminary insight for further recovery of critical raw materials, *Journal of Cleaner Production.* 219 (2019) 225–235. <https://doi.org/10.1016/j.jclepro.2019.02.104>.
4. M. Walawalkar, C.K. Nichol, G. Azimi, Process investigation of the acid leaching of rare earth elements from phosphogypsum using HCl, HNO<sub>3</sub>, and H<sub>2</sub>SO<sub>4</sub>, *Hydrometallurgy.* 166 (2016) 195–204. <https://doi.org/10.1016/j.hydromet.2016.06.008>.

## **A PRESSURE-LEACHING PROCESS FOR SULPHIDE TAILINGS USING A NEUTRAL MEDIUM: COMPARISON BETWEEN OXYGEN AND AIR OXIDATION**

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### **Abstract**

Sulphidic mine tailings are among the largest mining wastes on Earth and are prone to producing acid mine drainage (AMD). Therefore, pollution reduction, waste minimisation, and recycling end-of-life products (ELPs) have become a major focus of millennials' interests. Waste is, at the same time, a problem and an opportunity.

The aim of this study is the advanced removal of sulphur from mine tailings via oxygen and air oxidation in neutral media. Air or oxygen flows – both oxidant agents – supply the system with enough oxygen to trigger and assist oxidation reactions. The generated sulphuric acid solubilises the metals of interest from the solid mass at low/moderate temperatures and pressures.

The main technological process is pressure leaching in neutral media (water) using air or oxygen at 120–155°C and 4–8 atm.

More than 96% of the sulphur was removed from pyrites in one stage using oxygen as an oxidising agent. The use of oxygen showed a 7% higher efficiency than the results obtained when using air. The removal of sulphur in this process could support further processes to reduce mining waste, recover valuable products (like residual metals) and by-products (like inert waste material for construction applications), or reduce the environmental impact of mine tailings that undergo oxidation.

### **Acknowledgements**

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## **VALORISATION OF THE IRON PRECIPITATE OBTAINED BY HYDROLYTIC PRECIPITATION**

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### **Abstract**

The pressure leaching of pyrite concentrates in an autoclave results in sulphidic solutions, representing a particular problem. To reduce the environmental impact of these type of residues and increase the leachate value, a hydrometallurgical process was used. From this solution, the precipitation of iron with calcium carbonate leads to an iron precipitate mixed with gypsum. This mixture has no use and must be dumped. To benefit from the valuable metal, iron is selectively separated by precipitation with  $\text{Na}_2\text{CO}_3$ . Iron oxides obtained by hydrolytic precipitation from sulphidic solutions were further separated, purified, and concentrated to achieve a commercial iron-containing by-product. To be able to be used in the steel industry, the iron precipitate (without sulphur) must be treated to increase the iron content. The following conditions must be met for the steel industry. Fe concentration: min = 55%; maximum content of non-ferrous metals: Cu = 0.05%; Pb = 0.02%; Zn = 0.06%; As = 0.13% S = 0.04%. In addition, it must be in the form of pellets with the following characteristics: 95% with diameter 10–15 mm, and 5% under 10 mm and with compression and shock resistance.

This paper is part of the “NEMO” project, which has received funding from the European Union’s EU Framework Programme for Research and Innovation Horizon 2020 under Grant Agreement No. 776846 -<https://h2020-nemo.eu/>.

## LEACHING EFFICIENCY OF METALS FROM MINE TAILINGS BY ACIDIC AND SALT MEDIA

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### Abstract

Mining activities generate a large amount of solid waste each year. So-called mine tailings are finely ground waste from ore extraction, and are usually stored long term under dam facilities. However, there are environmental risks associated mainly with the contamination of soils and groundwaters, and with dam failures. Nevertheless, these tailings can still contain valuable metals that can be removed and employed in different industrial sectors. One solution to treat this residue is to apply hydrometallurgical methods to leach such metals in a solid-liquid system. Furthermore, several studies have indicated the importance of the presence of chloride ions in the leaching solutions. An alternative to this, is the replacement of fresh water by saltwater sources, which is especially important in regions where fresh water is scarce. The present work aimed to investigate the leaching of three metals (copper, zinc, and lead) from a fresh mine tailings. Through a design of experiments the leaching efficiency of two acidic media in the presence of sodium chloride as the main salt source was studied. Both hydrochloric and sulphuric acids showed great capacity to leach the three target metals at atmospheric pressure and mid-high temperatures. However, due to the presence of sulphate ions in the sulphuric acid medium, two-stage leaching was necessary to obtain soluble lead in solution. Additionally, increasing the leaching time significantly enhanced the amount of leached metals. Furthermore, tests with artificial seawater-based media showed comparable results with those containing sodium-chloride-based media. This indicates that the use of seawater in leaching processes may be a suitable substitute for fresh water. Therefore, the use of acidic routes along with alternative chloride sources such as seawater are appropriate for use as leach solutions.

## RECOVERY OF CU-ZN-PB-SULFIDES FROM MINE TAILINGS THROUGH FLOTATION

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### Abstract

Mineral-processing plants generate a considerable amount of residues, also called tailings, which are usually stored in massive ponds. The management and storage of such volumes of material are challenging and the environmental and health risks increase when it comes to residues containing sulfide minerals. In the present study, flotation was used to enable a collective recovery of sulfide minerals contained in tailings with a large amount of ultrafine particles. The aim was to generate two product streams, with high and low sulfides content. For that, bench-scale experiments were performed using an innovative approach, which combined conventional flotation and floc-flotation (flotation of flocs of targeted minerals). The studied tailings originate from a sulfidic mining site in Europe and contained a high grade of pyrite and low grades of chalcopyrite, galena, and sphalerite. Initially, the material was split into two fractions due to its relatively wide particle size distribution. The coarser particles underwent conventional flotation, while the finer particles were treated either by using the conventional or the floc-flotation approach. The process developed using conventional flotation enabled high recoveries of Cu and Zn sulfides along with pyrite, regardless of the fraction utilized. For Pb, the recovery was higher in the coarse particles route and there was a depletion of Pb in the concentrate of the finer particles route. The use of floc-flotation allowed a higher recovery and a slightly higher grade for Pb; however, there was no improvement for Cu and Zn. To selectively flocculate the sulfide minerals and thereafter enhance the flotation was challenging in many ways (e.g., change in froth properties, increasing entrainment of gangue minerals). Overall, the development of a route to recover ultrafine sulfide minerals from tailings was assessed and proved to be promising. However, further investigations are needed with respect to the use of selective agglomeration.

## LITHIUM EXTRACTION FROM NATURAL BRINES THROUGH MEMBRANE ELECTROLYSIS WITH LIMITED WASTE GENERATION

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### Abstract

The demand for lithium, a key component in batteries, is skyrocketing, and its price multiplied by 9 in only a year. Argentina, Chile and Bolivia contain approximately 56% of the total lithium reserves globally, where lithium is present in salt lakes at about 1 g/L. Other ions like  $Mg^{2+}$  (3.1 g/L),  $Ca^{2+}$  (0.6 g/L), B (1.5 g/L),  $K^+$  (14.2 g/L) and mainly  $Na^+$  (102 g/L) are present in large quantities, resulting in a saturated salt solution. The state-of-the-art processes for lithium extraction consume large quantities of chemicals and generate enormous amounts of waste (115 ton per ton LiOH), only to be landfilled<sup>1</sup>. In addition, 30–50% of the initial lithium is lost in the waste in every extraction cycle, which lasts 1.5 to 2 yr. The processes are also accompanied by large water and CO<sub>2</sub> footprint and the destruction of ecosystems<sup>2</sup>. As an alternative, a membrane-electrolysis-based process was designed to recover lithium in a fast process where the majority of the generated waste is valorised as a by-product. The natural brine is first pre-treated by an ion-exchange resin to extract the boron from the synthetic brine, followed by the extraction of  $Mg^{2+}$  and  $Ca^{2+}$  by a membrane electrolysis unit<sup>3,4</sup>. Next, the brine is sent to the cathodic compartment of a membrane electrolysis cell, where the chloride ions are separated from the natural brine. In the catholyte, an alkaline mixture of NaOH, LiOH and KOH is generated (pH > 14) that is subsequently sent to a crystallizer. Here, CO<sub>2</sub> gas is absorbed in the alkaline solution and will acidify the solution gradually (until pH = 12). At the optimum pH, 74.9% of the initial Li is recovered as Li<sub>2</sub>CO<sub>3</sub>



with a purity of 96.8% in a single crystallization step. In a second crystallizer, more CO<sub>2</sub> is absorbed in the alkaline solution and the pH is lowered to 8.5 to recover 28% of the initial Na as NaHCO<sub>3</sub>, without any additional treatment by an electrolyser. The left-over solution can be treated further to produce process water or can be sent back to the natural reservoir.

## References

1. Flexer, V., Baspineiro, C. F., & Galli, C. I. (2018). Lithium recovery from brines: A vital raw material for green energies with a potential environmental impact in its mining and processing. *Science of the Total Environment*, 639, 1188-1204.
2. Dry, M. (2018). Extraction of Lithium from Brine—Old and New Chemistry. In *Extraction 2018* (pp. 2225-2234). Springer, Cham.
3. Bonin, L., Deduytsche, D., Wolthers, M., Flexer, V., & Rabaey, K. (2021). Boron extraction using selective ion exchange resins enables effective magnesium recovery from lithium rich brines with minimal lithium loss. *Separation and Purification Technology*, 275, 119177.
4. Nieto, C. H. D., Palacios, N. A., Verbeeck, K., PrévotEAU, A., Rabaey, K., & Flexer, V. (2019). Membrane electrolysis for the removal of Mg<sup>2+</sup> and Ca<sup>2+</sup> from lithium rich brines. *Water research*, 154, 117-124.

## **Sustainable REE, Co supply from magnet recycling: closing the loop and the EIT DysCOVERY project**

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### **Abstract**

DysCOVERY's business model is based on the extraction of rare-earth elements (Nd, Dy, Sm) Co and Fe from end-of-life permanent magnets. These elements will feed the REE market, in particular to manufacture new permanent magnets partially from recycled materials. Monolithos (<https://monolithos-catalysts.gr/en/>) Greece will build a new plant, starting in 2025, and recycle 630 t/a EoL material, enhancing EU recycling capacity by minimum 23 %, to produce magnet-specification metals (300 t/a), commercialised 30% lower than current market prices.

The DysCOVERY project (2022–2024; €3.2 million) contributes to the European Raw Materials Alliance (ERMA) and the European Battery Alliance (EBA). Its future business is part of the ACTION PLAN of the ERMA TASK FORCE on permanent magnets and motors to increase the permanent-magnet recycling capacity in the EU from about 500 t/a at present up to 7000 t/a in 2030. Increasing the EU REE extraction capacity and recycling to produce new magnets/products is indispensable. Currently, Europe imports 16,000 t of magnets per year (ERMA Task force Magnets and motor action plan, 2021). Moreover, the Chinese supply chain does not necessarily meet EU environmental and societal standards. In 2020, each wind turbine consumed 4 t of NdFeB magnets and 95% of EVs containing NdFeB magnets in their motors. The growing EV market is a key indicator, with an expected increase of the permanent magnet demand to about 50 kt in 2030. All recycling projects and companies launched so far by the EU combine an estimated capacity of 1500–2000 t/a in the EU by 2025.

The DysCOVERY project proposes an innovative and sustainable hydrometallurgical processing route consisting of a greener hydrogen-free leaching process, coupled with extraction chromatography metal separation and molten-salt electrolysis for the metal/alloy production.



*Partners*



## **TUNGSTATE SOLID-PHASE EXTRACTION USING LAYERED DOUBLE-HYDROXIDE FIBERS**

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### **Abstract**

During the extraction of tungsten from ores, highly alkaline streams are generated. Therefore, the present study focuses on the solid-phase extraction of tungstate ( $\text{WO}_3^{2-}$ ) from alkaline streams by ion-exchange with layered double-hydroxide (LDH) powders and shaped into fibers.

Layered double hydroxides (LDHs) are a family of anionic clays having positive layers and negative exchangeable interlayer species. SoA LDH compositions, e.g., MgAl-LDH or ZnAl-LDH, are not stable in such alkaline environments, and when used for the recovery of W from alkaline leachates, metals are leached from the LDH structure. Therefore, LDHs with new compositions were designed to be able to withstand the highly alkaline conditions and to enhance their exchange features for W recovery. In particular, La-doped LDHs were synthesized. Sorption tests were conducted to study the leaching and adsorption behaviour as a function of the LDH composition and alkalinity of the W-containing solutions. The results showed that La doping provides the necessary alkaline stability during sorption testing and additionally increases the sorption capacity towards W recovery.

For practical handling, the synthesized powders were extruded into fibres with different diameters and the sorption kinetics indicated the occurrence of some diffusion limitations in the first stage of adsorption, while the desorption step is overall not affected by the fibre thickness. The study demonstrates the applicability of the newly developed LDH-containing fibres for W recovery in a continuous adsorption/desorption process.

## **Acknowledgements**

The authors acknowledge the Horizon 2020 TARANTULA project (Grant Agreement n° 821159) which aims to develop novel, efficient and flexible metallurgical technologies with high selectivity and recovery rates with respect to W, Nb and Ta (more information on [www.h2020-tarantula.eu](http://www.h2020-tarantula.eu)).

## PHYSICALLY UPGRADING LATERITIC MINE WASTE PRIOR TO BIOPROCESSING FOR COBALT RECOVERY

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### Abstract

The Fe-oxide-rich limonitic component of laterite deposits is usually discarded as mine waste to provide access to the high-grade silicate-rich units below. Although limonites contain only low concentrations of Co and Ni they are volumetrically enormous, leading to hundreds of thousands up to millions of tonnes of Co, Ni, and other critical metals being stockpiled as waste. Low-impact, low-cost processing technologies such as atmospheric heap leaching<sup>1</sup> and bioprocessing [e.g., 2] have been shown to successfully process these materials and recover this lost resource.

Within the H2020 CROCODILE project<sup>3</sup> we have been testing the relative benefits of pre-processing two mineralogically distinct limonites from New Caledonia. Using gravimetric sieving we have separated a limonite from Penamax into 7 different size fractions and a limonite from Tiébaghi into 6 distinct size fractions. The size fractionation ranges from < 50 µm up to >2 mm. To further concentrate the Co density separation using a Mozley table was performed on the Penamax 100 – 400 µm size fraction.

These size fractionated and enriched samples have been analysed for bulk properties, including chemistry and mineralogy, and mineralogical properties including mineral chemistry, modal mineralogy and grain-scale texture. For both limonites the concentration of cobalt increases as the particle size increases with >50 and >8 times more cobalt in the largest size fraction compared to the smallest size fraction in the Penamax and Tiébaghi limonites respectively. Along with these increases in cobalt are substantial decreases in Fe<sub>2</sub>O<sub>3</sub>. Mineralogically, the primary host phase for cobalt increases from 0.04% in the smallest size fraction to 23% in the largest for the Penamax limonite and from 0.85% to 53% for the Tiébaghi limonite. Use of the Mozley table concentrated the Co in the light fraction and enabled the production of an enriched material with a final Co content of 2.4%.

The full range of mineralogical and chemical changes associated with the pre-processing will be described along with the distribution of potentially toxic species that may significantly hinder the bioprocessing technology<sup>4</sup>.

## References

1. A. Oxley, M.E. Smith and O. Y. Caceras, "Why heap leach nickel laterites?", *Minerals Engineering*, **88** 53-60 (2016).
2. A. L. Santos, A. Dybowska, P. F. Schofield, R. J. Herrington and D. B. Johnson, "Sulfur-enhanced reductive bioprocessing of cobalt-bearing materials for base metals recovery", *Hydrometallurgy*, 195 105396 (2020).
3. Crocodile, the first of a kind commercial compact system for the efficient recovery of cobalt designed with novel integrated leading technologies. <https://h2020-crocodile.eu/>
4. A. L. Santos, A. Dybowska, P. F. Schofield, R. J. Herrington and D. B. Johnson, "Chromium (VI) inhibition of low pH bioleaching of limonitic nickel-cobalt ore" *Frontiers in microbiology*, 12:802991 (2022).

## **TUNGSTEN RECOVERY FROM W-TAILINGS: CONCENTRATION TESTS AND PRELIMINARY BIOLEACHING RESULTS**

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### **Abstract**

In the frame of the H2020 RAWMINA project (Grant Agreement n° 958252), the recovery of critical raw materials such as tungsten (W) in mining waste is evaluated by various innovative (bio)hydrometallurgy techniques.

As a first step, the recovery of W from W-mining waste is carried out by applying mineral processing techniques, after which it is bioleached to treat the sulfide content and reduce acidity in the final residue. A representative sample (500 kg) was sampled on a mine site in Portugal and prepared at the BRGM facilities to obtain homogenised sub-samples according to well-established procedures: drying, crushing, grinding, splitting.

Concentration tests have been performed by gravimetric separation, taking advantage of the scheelite density ( $5.9\text{--}6.1\text{ g/cm}^3$ ). The first pre-treatment step was the classification in four particle size fractions ( $< 100\text{ }\mu\text{m}$ ;  $100\text{--}250\text{ }\mu\text{m}$ ;  $250\text{--}500\text{ }\mu\text{m}$ ;  $500\text{ }\mu\text{m}$  to  $1\text{ mm}$ ); since scheelite was observed in particle sizes up to  $1\text{ mm}$  by UV shortwave radiation (blue spots of scheelite are bright fluorescence). Then, a separation step was carried out using a gravimetric Mozley table on a  $100\text{ g}$  sample. The W content in the concentrate product was increased 10 fold (from around  $2000\text{ ppm}$  to  $2\text{--}5\text{ wt}\%$ ), as quantified by portable XRF technology. The W concentration in a  $50\text{ kg}$  sample was evaluated using a shaking table on the coarser fractions ( $> 100\text{ }\mu\text{m}$ ) and a similar W concentration as in the smaller sample was observed. A multi gravity separator (MGS Mozley) technique will also be applied to treat fine fraction ( $< 100\text{ }\mu\text{m}$ ). Then, an optimal flowsheet of the concentration process will be established.

Bioleaching tests are currently being performed on shake flasks to adapt a selected acidophile microbial consortium to the bioleaching of W-concentrated samples. The next steps include the inoculation of 2-L reactors with the adapted microbial consortium and a progressive increase of the pulp density in batch experiments to bioleach sulfides and provide sulfide-free samples.

In subsequent steps in the RAWMINA project, alkaline leaching will be applied, followed by the selective recovery of W using nanofibrous composite materials and electrowinning.



*SESSION 5*

# Bulk Matrix Valorisation

Chair: Priya Perumal, Oulu University

## **DEMONSTRATION OF THE USE OF MINE TAILINGS IN CEMENT AND CONCRETE: FROM BIN TO BIG-BAG**

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### **Introduction**

Given that the world is only 8.6% circular, a massive fraction of the 100 billion tonnes of materials consumed every year need to be mined.<sup>1</sup> This amount is expected to almost double by 2060.<sup>2</sup> The legacy of waste materials that this scenario brings along in the current state of commercially applied flowsheets is of unseen proportions. However, hope is found in the match between one of the most abundant waste streams and the largest materials-consuming industry: the nature of mine tailings promises a useful contribution to the production of cement and concrete.

The annual volume of mining waste in the EU accounts for approximately 700 Mt/year.<sup>3</sup> When compared to the volumes of cement (176 Mt<sup>4</sup>) and aggregates (2826 Mt<sup>5</sup>) that are produced in 2019 in the EU, the mining waste seems to be a realistic resource on a volume basis. However, tailings that can cause environmental hazards in the vicinity of their storage facility can also cause environmental problems in a concrete. The most well-known problems with tailings are the presence of sulphides and heavy metals. While these are the cause of acid mine drainage<sup>6</sup>, in concrete sulphides can cause internal sulphate attack<sup>8</sup> and residual heavy metals might leach to the environment. These issues are not present in all tailings. Furthermore, projects like H2020 NEMO develop bioleaching processes to lower the sulphide and heavy-metal content.<sup>9</sup> Such a process simultaneously targets the recovery of valuable metals and cleaning. The mineral matrix of the tailings is left low in metals and void of sulphides, ready to be used in cement and concrete.

### **Tailings in cement and concrete**

Tailings have already been milled to a powder to enable the mineral processing that separates the metal concentrates from the excavated ores. Their physical nature is therefore similar to cement and the use as filler or supplementary cementitious material (SCM) in

cement is the most self-evident application. Whether any reactivity is observed as SCM depends on the mineralogy of the specific tailings, which varies dramatically between mine sites, even if the same commodity is mined. Some tailings might contain a small amount of clay phases which can be activated by calcination,<sup>8,11</sup> while others merely contain phases that are known as inert fillers in cement chemistry.<sup>8,12</sup> However, even when used as inert filler, the tailings can be beneficiated in significant replacement levels in high-quality concrete products.<sup>13</sup>

Reconsidering the volume of tailings produced and cement consumed each year, the necessity of a parallel application arises; the aggregate sector can fill this role. Artificial coarse aggregates can be manufactured from fine tailings using a granulation (a.k.a. agglomeration) process. With the addition of a small amount of cement powders are snowballed in a pan granulator or high-intensity mixer, resulting in hardened granules.<sup>14</sup>

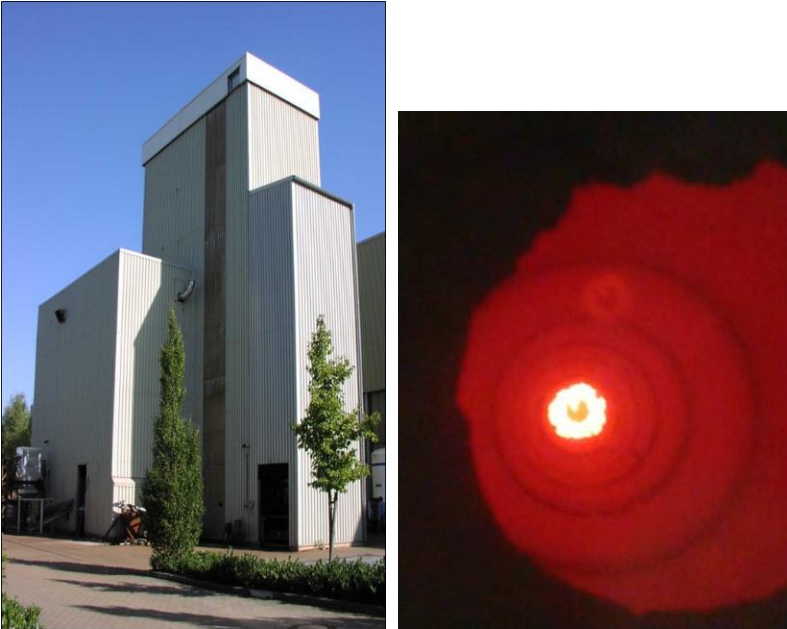
## Upscaling and demonstration in H2020 NEMO

Matrix valorisation in the NEMO project targets the upscaling of the use of tailings from the Boliden Tara mine as filler and artificial aggregate. The 20 tonnes of material are sourced from the tailing storage facility, dried and packed into big-bags (Figure 1). The material was mainly composed of limestone and quartz, and is thus expected to act as an inert filler in the studied applications.



**Figure 1:** Freshly sourced tailings from the storage facility at Boliden Tara (left) and sun-dried tailings in big bags at Thyssenkrupp (right).

The calcination process at Thyssenkrupp's demonstration plant was applied on 10 tonnes of the material to oxidise the sulfides (Figure 2). Stable operation of the calciner was obtained and the desired phase transformations were confirmed using X-ray diffraction.



**Figure 2:** 500 kg/hour demonstration plant at Thyssenkrupp (left) and inside view of the calciner loop (right).

The calcined tailings are being tested as filler in 3 types of concrete products shown in Figure 3: in the paver production, ready-mix concrete and in self-compacting concrete for prefab. Laboratory test samples with the desired properties for the envisioned applications could be obtained by ResourceFull using at least 20 wt% of cement replacement. Pavers were already successfully produced in an industrial environment.



**Figure 3:** Demonstration production of pavers (left), ready-mix concrete (middle) and self-compacting concrete (right).

The production of artificial aggregates was carried out at VITO's 1-tonne/day granulation pilot. A powder mixture with 5 wt% of CEM III/B (95 wt% of tailings) resulted in granules with appropriate properties for use in concrete products.



**Figure 4:** Granulation and concrete production pilot at VITO (left) focused image of the Eirich mixer after granulation (right).

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## References

1. M. de Wit, J. Hoogzaad, C. von Daniels, *The Circularity Gap Report*, Circle Economy, 2020.
2. OECD, *Global Material Resources Outlook to 2060*, OECD Publishing, Paris, 2019.
3. European Innovation Partnership on Raw Materials, “Raw Materials Scoreboard 2018”.
4. CEMBUREAU, “Key facts & figures”, accessed 9 February 2022, available online at: <https://cembureau.eu/about-our-industry/key-facts-figures/>
5. European Aggregates Association (UEPG), “Estimates of Aggregates Production – 2019 Data”, accessed 9 February 2022, available online at: <https://uepg.eu/pages/figures>.
6. M. C. Moncur, C. J. Ptacek, D. W. Blowes and J. L. Jambor, “Release, transport and attenuation of metals from an old tailings impoundment”, *Applied Geochemistry*, **20** (3) 639-659 (2005).
7. N. P. Martins, S. Srivastava, F. V. Simão, H. Niu, P. Perumal, R. Snellings, M. Illikainen, H. Chambart and G. Habert, “Exploring the Potential for Utilization of Medium and Highly Sulfidic Mine Tailings in Construction Materials: A Review”, *Sustainability*, **13** (21) 12150 (2021).
8. J. Mäkinen, M. Salo, M. Khoshkoo, J.-E. Sundkvist and P. Kinnunen, “Bioleaching of cobalt from sulfide mining tailings; a mini-pilot study”, *Hydrometallurgy*, **196** 105418 (2020).
9. F. Vargas, M. Lopez, “Development of a new supplementary cementitious material from the activation of copper tailings: Mechanical performance and analysis of factors”, *Journal of Cleaner Production*, **182** 427-436 (2018).
10. O. Celik, I. Y. Elbeyli and S. Piskin, “Utilization of gold tailings as an additive in Portland cement”, *Waste Manag. Res.*, **24** 215-224 (2006).
11. X. Wang, R. Yu, Z. Shui, Z. Zhao, Q. Song, B. Yang and D. Fan, “Development of a novel cleaner construction product: Ultra-high performance concrete incorporating lead-zinc tailings”, *Journal of Cleaner Production*, **196** 172-182 (2018).
12. M. Gesoglu, E. Güneyisi and H. O. Oz, “Properties of lightweight aggregates produced with cold-bonding pelletization of fly ash and ground granulated blast furnace slag”, *Materials and Structures*, **45** 1535-1546 (2012).

## FROM MINE WASTE TO CERAMIC RESOURCE

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### **Abstract**

Waste materials should be seen as potential resources, which can help decreasing the pressure on the primary-raw-materials sector and the external market dependence. A material's passport, where the full characterisation and valorisation routes of waste materials can be given, is a must to shift towards a more circular approach within the raw-materials sector and boost industrial symbiosis. On the one hand, construction and demolition waste is currently considered as the biggest waste stream in the EU27, followed by mining and quarrying waste, with their associated environmental, health, and social hazards. On the other hand, natural resources scarcity, due to the fast-growing world population, induces the need to find alternative material sources to supply the global demand for technological and building materials. Therefore, turning mine waste into a recyclable resource could help reduce the associated hazards of mine-waste disposal and, at the same time, minimising the pressure on natural resources' exploration used for building and construction applications.

The purpose of this study was to evaluate the potential valorisation of (clean) sulphidic mining waste materials, tailings from Plombières and Freiberg (inactive mines) and waste rock from Neves Corvo (active mine), in ceramic roof tiles, inner-wall blocks, pavers, and facing bricks, taking into account their production processes (shaping, drying, and firing), product quality (technical, aesthetical, and chemical), and environmental performance (service life, second life, and end-of-life). After a detailed physical, mineralogical, chemical, thermal, and environmental characterisation of the mining waste materials, one company-specific blend for each ceramic product type has been modified on a lab scale, by partly/totally replacing primary raw materials by mining waste residues (5-40 wt%). The production processes included shaping (vacuum-extrusion for roof tiles and blocks, and hand-moulding for pavers and bricks), drying (industrial/lab dryer), and firing in lab electric kilns at different temperatures, depending on the product type. Technical (drying and firing

shrinkage, water absorption, and E-modulus strength), aesthetical (firing colour and efflorescence), and chemical (total C/S, and soluble ions) properties of the test specimens have been assessed and compared with the standard. The environmental performance tests, considering the products' service life (diffusion leaching test), 2<sup>nd</sup>-life usage (column leaching test), and/or end-of-life (batch leaching test), were performed on the fired bodies and compared to Flemish and European regulatory limits to assure environmental compliance. Finally, a cradle-to-gate LCA was performed to assess the environmental impact of the fired ceramics over their lifecycle from raw-materials extraction to the factory gate.

The results show that, from all the assessed mining-waste materials, Plombières yellow tailing material can be used directly to partly/totally replace primary raw materials in ceramic blends for roof tiles (5 wt%), blocks (10 wt%), pavers (10 and 20 wt%), and facing bricks (20 and 40 wt%), without any pre-treatment. The test specimens for each studied ceramic product, using Plombières tailing material, followed production standards, product quality requirements and showed compliance with environmental regulations, even considering a 2<sup>nd</sup>-life scenario where demolished tailing-derived ceramics can be recycled or downcycled as aggregates. The uncleaned and even the cleaned Freiberg tailing and both Neves Corvo waste rock materials are not yet suitable for the studied ceramic blends mainly due to their high sulphur and hazardous metal(loid)s content, which induced aesthetical (Figure 1) and chemical-environmental problems of the fired ceramic bodies.

## **Acknowledgements**

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## **Ore-sand: addressing the global sustainability challenges of mine tailings and sand**

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### **Abstract**

The demand for sand and other aggregates – the most used solid materials globally – has tripled over the last two decades to reach an estimated 50 Bt per year<sup>0,0</sup>. Despite being recognised as a strategic resource for sustainable development, the environmental problems associated with their supply, in particular sand extraction from dynamic environments including the riverine, coastal and marine environment, remain largely unaddressed and unresolved in many places around the world<sup>0,0</sup>.

Efforts towards responsible sand sourcing should include the use of a diverse mix of more sustainable sources of sand (e.g., construction and demolition waste, steel slag, and fly ash). However, on a global scale very few alternatives can substitute a significant share of the global demand. One of the promising alternatives at scale is sand sourced as a co-product or by-product from processing of mineral ores.

The deliberate recovery of alternative aggregates from mineral ores is often disregarded. Yet, it offers the possibility of addressing two global sustainability challenges: the sand sustainability challenge and mine waste. Most recent changes in mining, environmental and waste policy mean that large volumes of mine waste, in particular tailings, now need to be treated differently in many places in the world<sup>0</sup>. Innovations like the recovery of ‘ore-sand’ could become an important part of future mineral processing and sustainable infrastructure projects.

Ore-sand is a type of processed sand sourced as a co-product or by-product of mineral ores<sup>0</sup>. It requires considering aggregates being equally important products, meeting their specifications during mineral processing rather than trying to repurpose existing reject materials. The recovery of ore-sand from old mine waste could also be possible, especially when combined with valuable minerals recovery and mined-land rehabilitation.

This presentation will overview global opportunities with ore-sands, and present the findings from an ongoing research project, using Vale sand – a by-product from iron ore mining and one of the first examples of ore-sand – as a case-study.



**Figure 1:** Vale sand stocking yard and transportation at Brucutu (iron ore) mine, Minas Gerais, Brazil (left), and sample collected for testing and analysis (right).

## References

1. UNEP, 2019. Sand and sustainability: Finding new solutions for environmental governance of global sand resources : synthesis for policy makers. United Nations Environment Programme, Nairobi.
2. UNEP, 2022. Sand and sustainability: 10 strategic recommendations to avert a crisis. GRID-Geneva, United Nations Environment Programme, Geneva, Switzerland.
3. Peduzzi, P., 2014. Sand, rarer than one thinks. *Environmental Development*, 11, 208-218.
4. Torres, A., Simoni, M.U., Keiding, J.K., Müller, D.B., zu Ermgassen, S.O., Liu, J., Jaeger, J.A., Winter, M., Lambin, E.F., 2021. Sustainability of the global sand system in the Anthropocene. *One Earth* 4, 639-650.
5. Wijepala, U., Jayakody, S., Zimar, A., Jayasinghe, J., Jayasena, W., 2019. Characterization of the properties of manufactured sand and natural river sand, 7th International Symposium on Advances in Civil and Environmental Engineering Practices for Sustainable Development (ACEPS - 2019).
6. Franks, D.M., Stringer, M., Torres-Cruz, L.A., Baker, E., Valenta, R., Thygesen, K., Matthews, A., Howchin, J., Barrie, S., 2021. Tailings facility disclosures reveal stability risks. *Scientific Reports* 11, 5353.
7. Golev, A., Gallagher, L., Vander Velpen, A., Lynggaard, J.R., Friot, D., Stringer, M., Chuah, S., Arbelaez-Ruiz, D., Mazzinghy, D., Moura, L., Peduzzi, P., Franks, D.M., 2022. Ore-sand: A potential new solution to the mine tailings and global sand sustainability crises. Final Report. The University of Queensland & University of Geneva.

## **MINE-WASTE VALORISATION IN MOROCCO: OPPORTUNITIES AND CHALLENGES**

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### **Abstract**

The reprocessing and retreatment of mine waste is a key sustainable solution to manage mine waste and to recover the remaining high-value products. Many studies around the world have demonstrated the large interest in recovering the residual metals and the use of mine waste in other applications such as the construction sector. In this project, a special accent will be given to the current management practices of mine waste in Morocco as well as the possible opportunities related to metals recovery and the reuse of mine waste coming from different mining activities. Different mine-waste categories are targeted: phosphate waste rocks and tailings, coal waste rocks, zinc and silver tailings. The goal is to suggest more sustainable management methods and to explore new future opportunities related to the re-use and reprocessing of these wastes. Some possible high-value-added products from these types of waste are suggested based on their characteristics, location and volume.

## **INTRODUCING THE PROJECT: MINE TAILINGS REPROCESSING, REVALORIZATION AND RISK REDUCTION CONNECTING INNOVATIONS IN METAL RECOVERY, GEOPOLYMERIZATION, CERAMICS & SEALING LAYERS (TailingR<sup>3</sup>2Green)**

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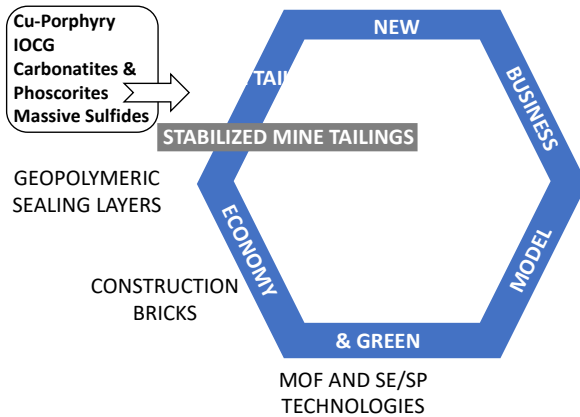
### **Abstract**

TailingR<sup>3</sup>2Green's ultimate goal is to develop a new business model based on a circular and zero-toxic approach to revalorize and reuse mine tailings while minimizing their environmental impact. This green-economy and zero-toxic approach will lead to (1) the full bio-recovery of critical raw materials such as REE and Co diluted in secondary sources such as mine tailings; (2) the revalorization of mineral by-products as construction bricks and (3) mine tailings sealing by an in-situ geopolymerization process to create sealing layers that will prevent water percolation and pollutant lixiviation to the surrounding ecosystems (Figure 1). The TailingR<sup>3</sup>2Green approach is flexible and adaptable to the geochemical and mineralogical nature of the mine tailings, and in parallel, it has been designed to maximize the economic gain while minimizing the environmental impact.

TailingR<sup>3</sup>2Green will decode the key geochemical and mineralogical nature of mine tailings to shape a highly intensive and green (bio)leaching and preconditioning process that will

allow their posterior geopolymerization and sealing. Specific and detailed efforts will be deployed to identify new business models for mine tailing's revalorization, connecting the outputs of the project with relevant actors of the socio-economic tissue within and outside the EU.

The innovative and circular approach pursued in the project will have concrete and measurable direct and side impacts, being (1) greener mining-technology development; (2) secondary CRE resources' revalorization; (3) business opportunities thanks to the mineral by-products reshaping; (4) securing CRE supply for the EU; and (5) gaining the trust of the society regarding the need for the future of green mining and a transition to green energy and a circular society.



**Figure 1:** Project TailingR<sup>3</sup>2Green main stages and expected outcomes.

## **VALORISATION OF MINING WASTES AS SECONDARY RAW MATERIALS FOR ALKALI ACTIVATION**

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### **Abstract**

The mining industry generates millions of tonnes of waste all over the world, which poses potential risks to the environment and human activities. It is estimated that almost 65% of the waste produced in EU is mineral waste. Examples are waste rock and tailings that are stored in temporary stockpiles and impoundments near mining sites. Only a small part of this waste is backfilled in the mines as cement pastes. The challenge lies in the valorisation of this waste into high-value-added materials. In the past decades, the research on alternative cementitious binders focuses on developing green materials. Alkali-activated materials (AAMs) show promising properties and have a lower carbon footprint compared to traditional construction materials. Normally, raw materials rich in aluminosilicates are candidates for alkali activation. However, as most mining waste is crystalline, aluminosilicates are not soluble under alkaline conditions. It is therefore essential to enhance the chemical reactivity of mining waste, preferably with pre-treatment methods, more efficient and greener than thermal treatment. In this study, mechanochemical activation was carried out on both mine tailings and mining waste rock rich in aluminosilicates and/or carbonates. The results indicate that structural collapse induced by intensive grinding can increase Si and Al solubility, allowing the formation of alkali-activated materials based solely on mine waste. Apart from an intrinsic reactivity improvement, blending with other reactive precursors, such as metakaolin and blast-furnace slag improved the mechanical properties of the building materials produced. Tailings are complex in nature with diverse physical and chemical properties and therefore the role of tailings in binders is hard to define. New reaction products can be formed if tailings are reactive, whilst the inert parts of the tailings hardly participates in the geopolymerization reactions. Nevertheless, inert components can also affect the hydration process and other physical properties like porosity of the final products. In the present research, alkali-activated materials based solely on mining waste were developed. In addition, blends of mine tailings with other raw materials were also developed. The influence of mine tailings on the properties of the end products was also investigated.



In 1978 some 400 families were evacuated from Geamana, Romania, and their village was replaced by a tailing pond from the Roşia Poieni copper mine. Painting entitled *Under* (oil on canvas) by Romana Ogrin