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From metal-containing industrial waste towards circular economy of metals: European Training Network SOCRATES

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It is becoming ever more clear that the natural resources – especially metals – are fast depleting from the Earth crust. Therefore, secondary sources like industrial residues, waste and side-streams could potentially act as more sustainable critical metal supply. This approach is in the very heart of the circular economy principles and actually from that point of view, European countries have “inherited” a large quantity of industrial waste (e.g., tailings, sludges, slags and ashes), i.e. a potential raw material “mines” for metals, since the industrialization. With this motivation, the European Training Network for the sustainable, zero-waste valorization of critical-metal-containing industrial process residues “SOCRATES” has been launched in January 2017 in the framework of the Marie Skłodowska-Curie Action (MSCA-ETN).

The objective of the project is two-fold: 1) to provide new scientific insights into recycling and sustainable processing of materials and 2) to train new experts of metal recycling and processing when 15 Early Stage Researchers (ESRs) pursue their doctoral degrees within the scope of the project (Figure 1). The outcomes of the SOCRATES project will offer comprehension to the process residues valorization, with a focus on critical metals recovery, production of catalysts and inorganic polymers and integrated assessment of process sustainability. Whether we discuss about catalyst production or metal recovery from sludges, it is obvious that electrochemistry, surface science and process engineering play critical roles and it can be seen also in the training of early stage researchers.

SOCRATES brings together organizations from academia, industry and research sector (Table 1) and actually, the unique combination of SOCRATES partners spans through the entire metal supply chain. The universities within the SOCRATES consortium are among Europe’s leaders in extractive metallurgy research and transfer of knowledge to new generations of scientists is the main goal of this program.

Each of four scientific work packages (WPs, Figure 2) of SOCRATES is dedicated to one step in value chain – namely, metal extraction from industrial residues (WP1), metal recovery from process solutions (WP2), residual matrix valorization into high value-added products (WP3) and integrated assessment of newly developed technologies (WP4).

WP1 focuses on advanced metal-extraction technology combinations, ranging from plasma-, hydro- to solvometallurgical unit operations. The development of a plasma-driven metal extraction methods have great potential to effectively separate metals that will lead to minimizing costs, emissions mitigation, safer and cleaner by-products. Solvometallurgy is based on organic solvents instead of aqueous solvents; here the surface chemistry and physics play a critical role in the organic-aqueous interface. With the development of new biocompatible solvometallurgical leaching methods, efficient recovery of targeted elements is envisaged. The development of deep eutectic solvents is a novel approach in extractive metallurgy, still industrially not widely applied.

Searching for novel methods of metals removal from aqueous solutions is one of priorities for WP2. Emerging interest for extraction of minor quantities of valuable metals from complex impure hydrometallurgical solutions is drawn to electrochemical methods as no additional chemical reagents are required and the recovery can be precisely controlled by applying favorable process conditions. The fundamental electrochemistry knowledge of very complex, multi-metal solutions is in the core of this WP. Solvent extraction is another important mass transfer operation in hydrometallurgy. Components of this process are diluents and extractants and their properties play an important role in extraction of metals from both primary and secondary sources. The conventional extraction methods, which have been in use for decades, require prolonged extraction times and relatively large quantities of solvent. Therefore, intensification of the extraction process by application of techniques like ultrasound and microwaves is included in scope of SOCRATES.

In order to provide zero-waste solutions, WP3 develops technologies to turn the mineral matrix discarded in extraction process into engineered products, focusing on supplementary cementitious materials, inorganic polymers and catalysts. By adding an extra processing step, the properties of the residues are adjusted, broadening the range of suitable by-products, and increasing their valorization potential.

WP4 develops and applies integrated system-analysis methods. Advanced characterization of metallurgical products and residues would facilitate the understanding of minerals and metals department within the processing route and contribute to process optimization and development. The research projects in this WP is also targeted at defining a sustainability indicator for assessment of the developed processes, which takes into account various aspects, such as economical, technical, environmental, political etc.

Aalto University's research group of Hydrometallurgy and Corrosion is involved in SOCRATES together with Outotec Research Center in Pori, Finland. Professor Mari Lundström supervises two ESRs working on leaching and electrochemical recovery of critical/valuable metals in cyanide-free solutions. The

research is focused on leaching kinetics of metal dissolution and selective electrowinning of metals from complex impure solutions. The objective of leaching studies is to develop and optimize hydrometallurgical process for valuable metals (such as Au, Ni and Co from copper flotation tailings), producing solutions suitable for electrometallurgical metal recovery, and the final goal is to develop an integrated process for continuous leaching and electrometallurgical recovery. The target is to find the most energy efficient metal recovery route with the lowest investment costs in such a way that very low concentrations of metals can be recovered from process solutions. Proposed electrometallurgical method is based on oxidation-reduction reaction between gold and less noble metals, occurring spontaneously at ambient conditions, and already by now gold recovery has exceeded 75%.

As mentioned earlier, in addition to new scientific input to the field, the SOCRATES project concentrates also on educating new experts for the metal recovery and sustainable processing, and thus network events with specific training courses are organized every year. For example, the latest workshop was hosted by Outotec Research Center in Pori, Finland (4-8th September 2017) and it covered topics like state-of-art in gold hydrometallurgy, industry's response to growing lithium demand and the challenges and opportunities found in recovering metals from zinc production residues. In addition to traditional lectures, SOCRATES wants to provide also more hands-on feeling to the respective industries and thus, visits to the Boliden Copper Electrorefinery and the Outotec Pilot Plant were part of the training event.

No single shareholder (from neither academy nor industry) can solve the complexity of metal scarcity, and thus, ambitious projects combining metal processing experts without boundaries are urgently needed. However, it is not only the current experts and the shared knowledge between them, which is crucial, but also the transfer of all this knowledge to the younger, early-stage researchers is necessary. In the end, all the "big problems" – like climate change, limited natural resources, etc. – are something which will demand also cross-generation debate and discussion, and when it comes to sustainable metal processing and recycling, the SOCRATES project is looking at future challenges with the eyes of 15 eager and enthusiastic early-stage researchers. It is clear that electrochemistry will play a big role in the future recovery of minor concentrations of valuable metals from complex hydrometallurgical process solutions. This is where Aalto University and Outotec will take the role of providing the best advantage point for ESRs for the development of latest innovations.

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Table 1. Participants of SOCRATES consortium

Organization	Country
Aalto University	Finland
KU Leuven	Belgium
TU Bergakademie Freiberg	Germany
University Bonn	Germany
University of Leicester	United Kingdom
Utrecht University	The Netherlands
AVR	The Netherlands
Boliden Kokkola	Finland
Kerneos	France
Metallo	Belgium
Outotec	Finland
Umicore	Belgium
VTT Technical Research Center of Finland	Finland

Figure 1. Scope of the SOCRATES project in the metals value chain

Figure 2. Overview of the SOCRATES work packages