Welcome to Phoenix

We’re pleased to welcome the mineral processing community to the 9th International Symposium on Hydrometallurgy honoring J. Brent Hiskey. You’ll find a focused compilation of the significant advances in hydrometallurgical processing for today’s highly relevant topics such as the transition for clean energy production and more efficient, environmentally friendly methodologies. Dig into all the learning, networking and community that this important symposium has to offer.

Organizing Committee

Jaeheon Lee, Co-Chair
Associate Professor, Dept. of Mining Engineering
*Colorado School of Mines*

R. Nick Gow, Co-Chair
Senior Study Manager
*Paterson & Cooke USA Ltd*

Michael Free, TMS Representative
Professor and Chair, Dept. of Materials Science and Engineering, College of Engineering
*University of Utah*

Gisele Azimi, CIM Representative
Professor, Dept. of Chemical Engineering & Applied Chemistry
*University of Toronto*

Georgios Kolliopoulos
Assistant Professor, Dept. of Mining, Metallurgical and Materials Engineering
*Université Laval*
# Agenda

## Saturday, August 26, 2023

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<td>8:00 am - Noon</td>
<td>Short Course: Solvent Extraction Technology Applied to Metals Recovery (ticketed)</td>
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<td>Noon - 1:00 pm</td>
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<td>Technical Sessions: Metal Extraction</td>
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<td>2:00 pm - 5:00 pm</td>
<td>Technical Sessions: Rate Earths/Critical Minerals</td>
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<td>3:30 pm - 4:00 pm</td>
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**Tuesday, August 29, 2023**

**Wednesday, August 30, 2023**

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Plenary Session

Monday, August 28, 2023  
9:00 am – Noon

Sponsored by Atlas Materials  
Frank Lloyd Wright Ballroom E

9:00 am  
Conference Chair, Jaeheon Lee, Colorado School of Mines  
Welcoming Comments

9:10 am  
John O. Marsden, President, Metallurgium  
Chalcopyrite Leaching – Searching for the Copper Grail

The search for a method to effectively recover copper from chalcopyrite through hydrometallurgy has been ongoing for half a century. This effort has gained momentum in recent years as copper ore grades have declined and orebody complexity has increased. This presentation examines the potential for extensive commercial application of leaching technology and discusses the critical success criteria.

John Marsden is president of Metallurgium, a consulting engineering firm specializing in the extraction and recovery of copper, gold, silver and related minerals. He is a graduate of the Royal School of Mines, Imperial College, London, and a registered Professional Engineer in the USA. Prior to starting Metallurgium in 2009, he held various senior operations and technical positions with Freeport-McMoRan, their predecessor Phelps Dodge Corporation, and with Consolidated Gold Fields. He has spent over 40 years working on the design and optimization of leading copper and gold operations worldwide. He holds 13 US patents and has published over 50 technical papers.

9:50 am  
David Dreisinger, CTO, Atlas Materials Co and Chair, University of British Columbia  
The Atlas Materials Process for Carbon Negative Nickel and Cobalt Recovery from Laterites

Atlas Materials has developed a process for extraction of nickel and cobalt from saprolite ores to meet the growing demand for nickel and cobalt salts for lithium-ion battery manufacture to enable the electric vehicle transition in the global transport sector. Saprolite ores are milled in a sodium chloride brine solution and then leached using hydrochloric acid addition. The silica residue from leaching may be used as a supplemental cementitious material. Iron and aluminum are removed by pH adjustment with olivine addition. Nickel and cobalt are precipitated as a mixed hydroxide product. Manganese is removed by oxidation and pH adjustment to form a manganese product (+25% Mn content). Magnesium is precipitated as magnesium hydroxide. The final brine solution is recirculated to leaching or directed to chlor-alkali processing to produce hydrochloric acid and sodium hydroxide. The mixed hydroxide product (MHP) can be converted to high purity nickel sulfate salt for the lithium-ion battery market.

David completed his B.A.Sc. and Ph.D. in Metallurgical Engineering at Queen’s University at Kingston. Since 1984, David has worked at the University of British Columbia in Vancouver, Canada and holds the position of Professor and Chair, Industrial Research Chair in Hydrometallurgy. David has worked closely with industry to develop and commercialize technology. David has received a number of professional awards including the Sherritt Hydrometallurgy Award (METSOC), the EPD Science Award (TMS), the Wadsworth Award (AIME) and the INCO Medal (CIM). David is a Fellow of CIM, Engineers Canada and the Canadian Academy of Engineering.
10:45 am  K. Marc LeVier  
**Are All Those R&D Expenditures Necessary – How to Build a Successful Mining Company for the Future**

Hydrometallurgical technology has slowly and methodically advanced over the past 50 years in knowledge and application. Research & Development has played a key role in the advancement and remains a critical factor in innovation and building successful mining companies. With a focus on personal experiences in precious metal and rare earth ores, base case examples are provided along with an eye to the future of Hydrometallurgy and the mining industry.

K. Marc LeVier is a metallurgical engineer who has worked in many process mineral systems with mining companies and engineered equipment suppliers. LeVier retired from Newmont Mining Corporation after 22 years of leading the Newmont Metallurgical R&D Team. He went on to be CEO, President & Director of two junior mining companies who were developing rare earth mineral deposits. LeVier has worked on multiple international projects in base metals, iron ore, precious metals, and energy fuels including uranium, thorium and coal. LeVier is a SME Fellow, Honor of Legion Member, and the 2023 SME President.

11:25 am  J. Brent Hiskey, Professor Emeritus of Mining and Geological Engineering, University of Arizona  
**Hydrometallurgy: Infinite and Sustainable Possibilities**

J. Brent Hiskey is Professor Emeritus of Mining and Geological Engineering in the College of Engineering at the University of Arizona. From 1999-2010 he served as Associate Dean for Research and Administration in the University of Arizona College of Engineering. Prior to joining the University of Arizona in 1984, he was manager of metallurgical research at Kennecott’s Process Technology Center. Hiskey received a BS in metallurgical engineering (1967), MS (1971), and PhD (1973) from the University of Utah. He has held research positions with US Steel and Alcoa and was an assistant professor in metallurgical engineering at the New Mexico Institute of Mining and Technology. Hiskey has edited or coedited a number of books: Gold and Silver Leaching, Recovery and Economics; Au and Ag - Heap and Dump Leaching Practice; and Interfacing Technologies in Solution Mining. In 1993, he edited the SME/TMS book Hydrometallurgy: Fundamentals, Technology and Innovation. Hiskey received the SME Arthur F. Taggart award in 1974, and was the 1993 recipient of the AIME James Douglas Gold Medal, which recognized his achievements in chemical metallurgy. In 1994, he was elected a Distinguished Member of the Society for Mining, Metallurgy and Exploration (SME). He received the SME Milton E. Wadsworth Extractive Metallurgy Award in 2003. He was awarded the The Minerals, Metals & Materials Society EPD Distinguished Lecture Award in 2010. Hiskey was elected to the National Academy of Engineering, Class of 1997.
1:30 pm
Atmospheric Tank Leaching of Chalcopyrite Concentrate in Ferric Sulfate Media

R. Kurniawan, W. Liu, and D. B. Dreisinger, Department of Materials Engineering, University of British Columbia, Vancouver, BC

Chalcopyrite leaching at atmospheric conditions exhibits slow kinetics and poor leaching efficiency. This has been attributed to the formation of passivating layers on chalcopyrite surface hindering further oxidation of the mineral. Various strategies have been developed to overcome passivation, such as increasing leaching temperature and pressure, use of chloride media, increasing mineral surface area by fine grinding, use of microorganisms, and the addition of additives or catalysts. This research aims to develop a catalyzed atmospheric tank leaching process to leach chalcopyrite concentrate in ferric sulfate media. A series of stirred reactor tests was carried out to determine the effects of different parameters on the effectiveness of this process. The experimental results show that the kinetics of copper dissolution could be greatly enhanced in the presence of the catalyst.

2:00 pm
Evaluating the Use of a Dynamic Model to Predict Direct Copper Electrowinning Tankhouse Performance

Suné Grobbelaar, Department of Chemical Engineering, Stellenbosch University; Christie Dorfling, Department of Chemical Engineering, Stellenbosch University; Margreth Tadie, Department of Chemical Engineering, Stellenbosch University

A dynamic model can be coupled with advanced control strategies to improve the efficiency of tankhouses employing resource-intensive direct copper electrowinning. Consequently, a high-fidelity, dynamic model that captures the complex fundamental chemistry associated with the variable electrolyte composition present in direct copper electrowinning was developed. A self-updating parameter-fitting approach was incorporated to calibrate the model for use on tankhouse-specific data. Validation of the model was performed using industrial electrowinning data. This paper presents the findings, challenges, and opportunities associated with the application of the model to industrial case-study data obtained from a direct copper electrowinning tankhouse.
2:30 pm
Precious Metals Refinery Transformation – Piloting as a Basis for Success
Christoph Ziegler, Aurubis AG, Hamburg, Germany; Leslie Bryson, Aurubis AG, Hamburg, Germany

Aurubis is considering upgrading its precious metals refinery. Developed internally, the current process is based on a Möbius type silver electrolysis and a combined nitric/chloride gold refining and platinum group metals (PGM) solution production. A future refinery shall be based on a direct chloride leach of the silver anode slimes and a subsequent treatment of the resulting gold/PGM solution and silver chloride residue. For this purpose we developed a full flowsheet based on lab scale results. In this paper we present how we planned, built and operated a pilot plant for this flowsheet. Furthermore, we will discuss the importance of an early definition of scope and success criteria. Finally, the results of the piloting were transformed into process design criteria that are the basis of a feasibility engineering.

3:00 pm
Optimization of Silver Electrorefining at Aurubis
Leslie Bryson, Aurubis AG, Hamburg, Germany; Christoph Ziegler, Aurubis AG, Hamburg, Germany

Aurubis is considering the upgrade of its precious metal refinery. Developed and optimized over the years, input to the current process is based on cast silver anodes feeding a Möbius type silver electrolysis section. It has been envisaged that the future refinery shall continue to incorporate a Möbius based silver electrorefinery, however at unprecedented higher PGM contents and operating current densities. These modifications aim at the development of a silver-based Precious Metals refinery with a higher degree of flexibility and lower CAPEX and working capital. In this paper we will discuss these new developments along with the design and operation of a pilot plant used to validate design criteria. These design criteria have been considered in the basis of a feasibility engineering study.

3:30 – 4:00 pm  Coffee Break
Sponsored by M3 Engineering

4:00 pm
Improving the Rate of Recovery from Copper Leach Residue with the Addition of a Wetting Aid: A Metallurgical and Geophysical Study

Ore grades have been shown to be decreasing globally, forcing more mining operations to increase the annual throughput of ore to maintain metal production targets. A leaching aid has been developed with the goal of increasing the kinetic rate and overall metal recovery in heap-leaching processes. This investigation utilizes electrical resistivity testing to investigate the conductivity of an active leach pad before and after the addition of a leaching aid and discusses the changes observed in the geophysical and metallurgical data following its addition, as well as the implications of those results.

4:30 pm
Performance Evaluation of Modified Biopolymers as Acid Suppressants in Copper Electrowinning
Marcio Ribeiro, W-Tech Technologies Ltd; Peter So, W-Tech Technologies Ltd; Patrick Wong, W-Tech Technologies Ltd

Sulfuric acid mist is released during the electrowinning of copper. Among several techniques applied to
suppress acid mist formation, fluoroalkyl based products have been the most chemistry type used worldwide. In this paper, modified biopolymers were tested as alternative surfactants to reduce acid mist in copper electrowinning. Two products, Biopolymer NCB and Biopolymer LB, were tested in laboratory to determine their effects on acid mist suppression. Both products lead to over 90% reduction of sulfuric acid mist with no significant impact on current efficiency. The two products were recommended for a commercial field test.

5:00 pm

Leaching Metals from Phyllosilicate Ores

Isabel Barton, University of Arizona Department of Mining & Geological Engineering; Maxwell Drexler, Rio Tinto Inc.; Molly Radwany, Freeport-McMoRan Inc.; Pierre-Marie Zanetta, Univ Jean Monnet, Saint-Etienne, France

Phyllosilicate minerals are important ores of V, Zn, Ni, and sometimes Cu. This paper uses phyllosilicate crystal chemistry, leaching experiments, and transmission electron microscopy to examine metals’ three distinct modes of occurrence and leachability in these ores. (1) Adsorbed metals can be liberated via exchange with solution cations, depending on chemical conditions and phyllosilicate type. (2) Crystallographically contained metals are partially leachable, typically at elevated temperatures, if they are in octahedral or higher coordination. (3) V, Ni, Cu, and possibly other metals, form discrete nanometer-scale inclusions within phyllosilicates whose leachability is mostly controlled by their mineralogy, not the phyllosilicate host’s.

Rare Earths/Critical Minerals

Frank Lloyd Wright Ballroom CD
Sponsored by Atlas Materials

Chair: Jaeheon Lee, Colorado School of Mines

2:00 pm

Temperature Dependence of Biooxidation of Coal-Based Pyrite

Kitsel Lusted, University of Utah; Prasenjit Podder, University of Utah; Joel Ilunga, University of Utah; Kara Sorenson, University of Utah; Prashant Sarwat, University of Utah; Michael Free, University of Utah

Rare earth elements have properties that make them useful in advanced electronics, magnets, and batteries. However, they are difficult to isolate from their constituent elements, which results in an environmentally costly operation to refine them. An environmentally friendly alternative extraction method involves biooxidation which uses bacteria to generate acid and ferric ions from pyrite to free the REEs from chemically bonded constituents. Because bacteria are living creatures, one of the most important factors to consider when running a bioreactor is the operating temperature. This study involved testing and analysis of the temperature dependence of biooxidation using pyrite concentrated from coal waste. The temperature was varied from 25°C to 40°C. Acid production in the bioreactor was monitored with pH measurements and bacterial oxidation was measured using the oxidation-reduction potential (ORP) of the system. Bacterial vitality was monitored by periodic ferrous oxidation tests which quantitatively assessed the biooxidation rate. The ferrous biooxidation rate (BOR) was evaluated using the Michaelis-Menten or Monod kinetic equations. Elemental and volumetric mass balances were done after each parameter. Pyrite recoveries were analyzed using energy-dispersive x-ray spectroscopy (EDS), scanning electron microscope (SEM) analysis, and x-ray diffraction (XRD). Additionally, bacteria species analysis showed that Leptospirillum ferriphilum was the dominant bacteria species, showing divergence from the original Acidithiobacillus ferroxidaans culture. Analysis showed that 35°C had the lowest pH, highest ORP, and highest BOR, while 40°C caused bacterial death.
2:30 pm

**Hydrometallurgical Treatment of Copper Flash Smelter Dusts via Ammoniacal Leaching**

Joseph Trouba, Colorado School of Mines, Kroll Institute of Extractive Metallurgy; Corby Anderson, Colorado School of Mines, Kroll Institute of Extractive Metallurgy

Copper smelter flue dusts contain appreciable quantities of Cu, which would represent a substantial financial loss if not recovered. The presence of deleterious elements including Bi, As, and Pb limits the ability to recycle dusts back into the smelter as it inhibits downstream operations. Disposal of dusts also presents a challenge, due to the toxic elements As and Cd. A hydrometallurgical method involving ammoniacal leaching for treatment of dusts addressing these challenges is presented. This method also provides improved potential for recovery of minerals critical to thin film photovoltaic applications including Cd and In.

3:00 pm

**Sequential Leaching of Nevada Sedimentary Claystones for Subsequent Selective Lithium Extraction**

Angela Tita, Department of Mining and Metallurgical Engineering, University of Nevada, Reno; Pengbo Chu, Department of Mining and Metallurgical Engineering, University of Nevada, Reno

To meet the current high demand for lithium, new sources of lithium are needed. A Nevada sedimentary claystone containing lithium was analyzed for its composition, phase transformation, and leaching efficiency for lithium extraction through a 5-step sequential (step-by-step) leaching. Methods such as XRD, SEM, AAS, and ICP-MS were used to characterize the clay and its resulting products. The study found that the clay consisted mainly of compounds of Ca, Al, Mg, Fe, K, and Na, as well as Li having 1188 ppm. In the first step trace element extraction was performed using MgCl2, which positively impacted the second step for calcite removal. In the second step, about 50% of Ca was removed in 5 hours at room temperature with 1M sodium acetate, which was an indication that some of the Ca was associated with the carbonate-bound fraction. In the third step, the temperature was applied at 96oC with hydroxylamine hydrochloride in acetic acid. Under these conditions, less than 20% of the Fe was removed, which suggested that the Fe is barely associated with the Fe-oxide bound fraction. The last step (residual step) made use of aqua regia, aiming at attacking the silicate matrix. At this step, most of the metal ions were released. The results showed that most of the metal ions were situated in the crystalline matrix (residual fraction).

3:30 – 4:00 pm  Coffee Break

4:00 pm

**Intra-Lanthanide Separation Processes Using Neutral Diglycolamide Extractants**

Kevin L. Lyon, Idaho National Laboratory, Idaho Falls ID, USA; Santa Jansone-Popova, Oak Ridge National Laboratory, Oak Ridge TN, USA; Derek M. Brigham, Oak Ridge National Laboratory, Oak Ridge TN, USA; Mitchell R. Greenhalgh, Idaho National Laboratory, Idaho Falls ID, USA; Amy K. Welty, Idaho National Laboratory, Idaho Falls ID, USA; Melissa M. Warner, Idaho National Laboratory, Idaho Falls ID, USA; Bruce A. Moyer, Oak Ridge National Laboratory, Oak Ridge TN, USA

Separation of individual rare earth elements (REE) is often regarded as the most difficult processing step in the production of high-purity rare earth oxides for end-use technology applications due to their inherent chemical similarities. Current industrial REE separation practices utilize solvent extraction with organophosphorus extractants, a complex process plagued by poor adjacent-lanthanide selectivity, excessive chemical reagent consumption, and adverse environmental impacts. Consequently, research efforts within the Critical Materials
Institute (CMI) are aimed at the development of alternative REE separation technologies that improve economic viability and environmental sustainability to enable domestic supply diversification. Recent efforts have focused on electroneutral solvating diglycolamide (DGA) extractants as an alternative method for the separation and purification of critical rare earth elements. DGAs offer distinct advantages over traditional phosphonic acid extractants used in separations including elimination of saponification to achieve high recovery in a solvent extraction cascade and improved adjacent-lanthanide separation factors, ultimately requiring fewer solvent extraction stages to facilitate the required separations. Novel DGA extractants have been synthesized and tested to maintain high intra-lanthanide selectivity, high organic-phase loading capacity, and proper phase dispersion behavior for high throughput separations. In this paper, solvent extraction cascade design principles have been tested using the well-known DGA N,N,N',N'-tetraoctyldiglycolamide as the first test case to validate separation performance in counter-current solvent extraction equipment to obtain high degrees of REE recovery and purity. Finally, challenges and ongoing research associated with this family of neutral extractants are evaluated within the context of domestic rare earth oxide production from bastnaesite ore.

4:30 pm
Enhancing the Recovery of Rare Earths and Phosphate Enriched By-Product from Monazite Ore via Sulfuric Acid Baking with Additives
Tarek Mohammed, College of Science, Technology, Engineering and Mathematics, Murdoch University; Andro Tomas, College of Science, Technology, Engineering and Mathematics, Murdoch University; Gamini Senanayake, College of Science, Technology, Engineering and Mathematics, Murdoch University; Wensheng Zhang, Hydrometallurgy Innovation, CSIRO Mineral Resources

Monazite, a rare earth phosphate mineral, is the second most important primary source of REEs for increasing demand in modern technologies. Current technologies for processing monazite ore using sulfuric acid are primarily focused on REE recovery. However, these technologies result in the loss of phosphorus in waste streams, which impedes downstream REE recovery processes. Therefore, there is a need for efficient processing methods that could recover both REEs and phosphorus from monazite ore. This study presents a method for recovering both REEs and phosphorus as iron phosphate battery precursor from monazite ore by sulfuric acid baking with the addition of sulfate salts. The leaching efficiency of REEs and P varied depending on the additives used, with the highest efficiencies observed for the ferric sulfate system. As the temperature increased, the leaching efficiency of REEs and P decreased when baking with no additive. However, the addition of ferric sulfate salt to the baking reactants improved leaching efficiency of REEs and favourably enriched P in the residue for subsequent processing as battery precursor (FePO4). The XRD confirmed the successful constraining of P and Fe in the residue while more than 95% REEs were selectively leached. The results suggest that this method can be a promising alternative to conventional methods for processing monazite ore. An integrated flowsheet was proposed to produce a marketable REO product of over 99% purity.

5:00 pm
The Use of Hydrogen Peroxide to Inhibit Silicon Co-Extraction with Iron During Slag Leaching-M2-6
Michael Caplan, Kroll Institute for Extractive Metallurgy, Colorado School of Mines; Corby Anderson, Kroll Institute for Extractive Metallurgy, Colorado School of Mines; Erik Spiller, Kroll Institute for Extractive Metallurgy, Colorado School of Mines; Roberto Huamani, Universidad Nacional de San Agustin de Arequipa

The extraction of silicon and iron commonly pose problems during hydrometallurgical leaching. These problems generally arise during downstream processing where iron can co-extract with target elements and silicon-based gels can hinder processing. This work presents a mechanism by which hydrogen peroxide can be used to suppress iron and silicon extraction during leaching of pyrometallurgical slags with sulfuric
acid. Ferro-silicates are common in slags, therefore the extraction of iron and silicon by leaching in slags is linked. By increasing the oxidizing environment during leaching, the thermodynamically favored iron bearing species becomes solid. This reduces the degradation of the ferro-silicates in slag, which reduced the silicon available for extraction. This work supports this mechanism by leaching a mixture of copper reverberatory slag and lead blast furnace slag with sulfuric acid and hydrogen peroxide. The presence of hydrogen peroxide suppressed the extraction of both iron and silicon.

Tuesday, August 29, 2023 8:30 am

**Metal Extraction**

*Frank Lloyd Wright Ballroom AB*

*Chair: Jaeheon Lee, Colorado School of Mines*

**8:30 am**

**Use of Activated Carbon as Copper Substitutes During Cobalt Cementation for Zinc Electrolyte Purification**

*Hanggoo Kim, Dakyeong Baek, Yoojin Lim, Kyoungkeun Yoo, , Department of Energy and Resources Engineering, National Korea Maritime & Ocean University, Busan, Republic of Korea*

In zinc hydrometallurgy, zinc electrolyte must be purified before electrowinning process to produce high-purity Zn metal. Cobalt ions have been removed through cementation process with Zn dust, where Cu and Sb ions were added to the cementation process as cementation activators. Because this precipitate consists of Zn dust, Cu, Sb, and Co, A complex recovery process will be required to recover each metal such as Zn, Cu, Sb, and Co. In the present study, Cu was substituted with activated carbon, which has been found to be conductor, the cementation process was performed using Zn dust, activated carbon, and Sb ions. The Co ions can be removed successfully when Zn dust, activated carbon, and Sb ions were added to the leach solution. When the precipitate powders were sieved, the activated carbon and Zn dust with Co-Sb precipitate, and most of Co was observed in the Zn dust.

**9:00 am**

**High Performance Liquid Chromatography Analytical Method Development for Reduced Sulfur Species Quantification in Cyanide Leach Solutions**

*N. Duru, University of Nevada, Reno; C. Nesbitt, University of Nevada, Reno*

Development of an accurate analytical method for sulfur species in cyanide leaching units of gold ores where sulfur speciation occurs has important role to explain the metal recovery deviations. This study presents the development steps of high-performance liquid chromatography (HPLC) method to analyze reduced sulfur species thiocyanate (SCN-), thiosulfate (S2O32-), trithionate (S3O62-), tetrathionate (S4O62-) in cyanide leaching circuits for gold ores. HPLC method developed has resulted in precise quantification of target sulfur species in leach solutions. Method development and validation results were illustrated on analytical graphs contains each species’ peak number, retention time (min), type, width (min), area (mAU*s), height (mAU), area distribution (%) of the peak.
10:00 am

**Ammonium Thiosulfate Leaching of Gold with Magnesium Hydroxide and Its Effect on the Consumption of Thiosulfate**

Sujin Chae, Queen’s University; Farzaneh Sadri, University of Alberta; Yeonuk Choi, Queen’s University; Ahmad Ghahreman, Queen’s University

Thiosulfate gold leaching is a promising alternative to cyanidation though it still has to be improved due to the significant reagent consumption caused by its decomposition. The purpose of this study is to mitigate thiosulfate consumption. The key to this study is the cycle in which ammonia vaporizes and the lowered pH is restored by the dissolution of magnesium hydroxide. Mg(OH)₂, which has low solubility in alkaline solutions, has the potential to benefit gold leaching by preserving a pH that is favorable to gold extraction.

In this study, the effects of pH, magnesium, copper, and thiosulfate concentration were evaluated. The test adjustment using NH₄OH had higher Au recovery than using Ca(OH)₂ though, Ca(OH)₂ is still suggested to be an alternative that can reduce the amount of ammonia. Gold concentration increased with 0.01 M of Mg(OH)₂, but there was no discernible improvement with further addition. Thiosulfate showed enhanced gold leaching when increasing from 0.5 to 2.0 M. Up to 1.0 mM, copper concentration had a favorable impact on the concentration of Au, but after that point, it had the opposite effect. The optimal gold extraction condition in this study was thiosulfate 0.2 M, Mg(OH)₂ 0.01 M, Cu 1 mM, pH 10.0, leaching 70.5% gold, which is comparable to 66.5% obtained by cyanide leaching.

10:30 am

**Suppression of Ammonium Thiosulfate Gold Leaching in the Presence of Arsenopyrite and a Pretreatment to Improve Gold Extraction**

Takunda Joseph Mhandu, Hokkaido University; Sohta Hamatsu, Hokkaido University; Sanghee Jeon, Akita University; Ilhwan Park, Hokkaido University; Mayumi Ito, Hokkaido University; Naoki Hiroyoshi, Hokkaido University

The use of thiosulfate to extract gold from refractory ores is promising because of its non-toxicity and high selectivity. Arsenopyrite is a major gold carrier mineral in refractory gold ores and known to hinder gold extraction due to high consumption of lixiviant. Hence, this study investigated the effects of arsenopyrite on gold leaching in ammonium thiosulfate solutions and found that gold extraction after leaching gold powder in the presence of arsenopyrite for 24 h was suppressed because of the unwanted decomposition of thiosulfate on the surface of arsenopyrite. To address this problem, this study investigated the use of ammonia solution containing cupric ions pretreatment and confirmed that gold dissolution was improved in the subsequent ammonium thiosulfate leaching.

11:00 am

**Modern Testing Methodologies in Hydrometallurgical Research to Better Understand Stockpile Chemistries and its role in Copper Mining**

Elizabeth Glenn, University of Arizona

As the demand for copper continues to increase, the industry is challenged to find innovative solutions for maximizing production. Solutions are often found in the various opportunities afforded in the hydrometallurgical practices found on mine sites across the globe. In many ways, these processes have remained greatly unchanged through history, however recent pressure affords an opportunity to
expand on metallurgical research and development and find inventive ways to break down the process, and better understand it. This discussion is to explore and define modern methodologies and sciences in hydrometallurgy that contextualize the chemistry that occurs within stockpiles and analyzes it for the benefit of production.

11:30 am

Microbial Pretreatment of Preg-Robbing Carlin-Type Carbonaceous Ore

Anthony Kaah, McEwen Mining, Nevada

Gold deposits in northern Nevada have the occurrence of carbonaceous material that tends to adsorb leached gold in a phenomenon called preg-robbing. Processing of carbonaceous ore requires the use of a Roasting facility to combust the organic carbon into CO2 and CO. For heap leach operations, having carbonaceous ore on the leach pad causes a reduction in gold recovery. Bacterial pretreatment of carbonaceous ore was successful in reducing the preg-robbing potential of carbonaceous ore samples from the Eureka trend in Nevada. The conditions for the pretreatment are as follows:

- Sample particle size of 85% passing 75 microns (200 mesh)
- 40% solids slurry
- 6.5 to 7.5 pH
- Temperature maintained between 37 OC to 40 OC
- 30 L/min air addition
- 24 hours residence time

For a carbonaceous ore sample, a preg-robbing reduction of 74% (94.2% to 24.6% preg-robbing) was achieved at 24 hours. Under similar conditions, another carbonaceous ore sample achieved a preg-robbing reduction of 77.3% (95.3% to 21.6% preg-robbing) at 6 hours and 78.1% preg-robbing reduction at 24 hours. This processing method could be an alternate method for pretreating carbonaceous ore for both Milling and Heap leach operations.

Recovery/Recycling

Frank Lloyd Wright Ballroom CD

Chair: Georgios Kolliopoulos, Université Laval, Québec, QC, Canada

8:30 am

Recovery of Valuable Metals from LIBs Black Mass by Nickel Pre-Loaded Extractants

Yeon-Chul Cho, Daejin University; Ki-Hun Kim, Daejin University; Junmo Ahn, Jeonbuk National University; Jaewoo Ahn, Daejin University

Recycling of valuable metals from waste Li-ion batteries(LIBs) has recently attracted significant attention. A leaching solution obtained by leaching LIBs black mass with sulfuric acid contains copper, aluminum, manganese, cobalt and nickel. In order to remove Cu, Al and Mn from the leaching solution and recover Co and Ni, experimental work was performed using solvent extraction with Ni-D2EHPA and Ni-PC88A as extractants. The effects of various process parameters on pre-loading and extraction were investigated. Based on experimental designs, the parameters with the largest effects on the process performance were determined to be organic phase saponification, nickel concentration and phase ratio for pre-loading.
9:00 am

**Imaging Spectroscopy from Unmanned Aerial System (UAS) for Monitoring Heap Leach Pad Operations**

Jinping He, Dean Riley, Isabel Barton, University of Arizona, Tucson, AZ

Unmanned Aerial Systems flying imaging spectrometers are a potential solution for hydrometallurgy operations to monitor heap leach pad operations, maintenance, and design. Heap leach pads are active geochemical systems and mapping mineralogical changes with background confusers such as pipes, ponded lixiviant, and other materials makes it difficult for ground truth sampling. We are using unsupervised learning with subject matter expertise and matched filtering to improve material mapping on leach pads. Early results indicate that mapping background materials as well as constraining the analytical methodology to the individual leach pads improves computational performance and allows for comparative analysis between leach pads.

9:30 – 10:00 am

Coffee Break

10:00 am

**Recycling of Bauxite Residue (Red Mud) for Recovery of Metallic Values**

Himanshu Tanvar, Material Science and Engineering, Worcester Polytechnic Institute; Brajendra Mishra, Material Science and Engineering, Worcester Polytechnic Institute

Bauxite residue is an industrial by-product generated during alumina production through the Bayer process. The worldwide stockpiles of bauxite residue are expected to reach 10 billion tons by 2050 if not processed effectively. Limited industrial-scale processing (3-4 %) of bauxite residue is mainly due to complex physical and chemical characteristics. High alkalinity and multiple elements make the recycling process complicated and expensive. The following work presents a hydrometallurgical approach for effectively recycling bauxite residue to recover high-purity metal oxide products, including magnetite, alumina, titanium dioxide, and scandium oxide. A pyrometallurgical method based on smelting for recovery of pig iron and subsequent processing of slag for value recovery is also discussed. A comparative analysis of hydro and pyrometallurgical processes is carried out to highlight the key differences and potential for large-scale application.

10:30 am

**Metal Leaching from Spent LIBs Using Deep Eutectic Solvents**

Yeongran Hong, Jaeoon Lee, Eunjin Jung, Hyung Sub Eum, Younwoo Park, Go-Gi Lee, Industrial Materials Research Group, Research Institute of Industrail Science and Technology, Pohang, Korea

Current technologies for the valuable metal recovery from spent LIBs are limited in terms of environmental point of view due to the use of strong acids, alkalis and organic solvents. Deep Eutectic Solvents (DESs) are a class of ionic liquids which can be formed by simply mixing hydrogen bond donors and acceptors above their eutectic temperatures. In this study, the DESs were applied to extract the valuable metals such as nickel, cobalt, lithium and manganese from black mass of the spent LIBs. The composition of DESs and the reaction conditions were explored to achieve eco-friendly metal leaching.
11:00 am

Solvometallurgical Recycling of Lithium-Ion Battery Components

Halimeh Askari Sabzkoohi, Université Laval, Québec, Canada; Georgios Kolliopoulos, Université Laval, Québec, Canada

E-waste generation, including spent lithium-ion batteries (LIBs), is a significant problem facing the world that can be turned into a critical and strategic metal recycling opportunity. Although hydrometallurgy offers a sustainable pathway to extract and recover these metals, the extensive use of aqueous solutions generates toxic effluents and raises concerns over the social acceptability of such projects. In this study, we report on a new solvometallurgical process paradigm to recover metals from lithium-ion battery components using green selective anhydrous solvents, namely deep eutectic solvents. Our approach promises to minimize water use and effluent generation in process circuits, thus improving the overall efficiency of metal recycling processes.

Tuesday, August 29, 2023

2:00 pm

Plant Practice

Chair: Junmo Ahn, Jeonbuk National University

2:00 pm

Reverse Osmosis Treatment of In-Situ Copper Leach Solution

Lingyu Zhang, Florence Copper, LLC

This paper summarizes the development of Reverse Osmosis treatment to concentrate low grade copper leach solution which produces high quality permeate for use as electrowinning process make up water. The demand for sustainability in the copper hydrometallurgy process is to increase sharply due to the water crisis especially in desert area like Arizona and the significant growth of copper usage in electrical industries such as semiconductor or electrical car manufacturing. A review of RO plant optimization practices including acid RO design, fouling and scaling problems, pH control, multimedia filter management strategies, membrane selection, and clean in place frequency is given in this paper.

3:00 – 3:30 pm

Coffee Break

Metal Extraction

Frank Lloyd Wright Ballroom AB
3:30 pm

Extraction of Critical Elements from Sulfuric Acid Solutions
Weston C Hartzell, Missouri University of Science and Technology, Rolla, MO; Michael S Moats, Missouri University of Science and Technology, Rolla, MO

To address the supply risk of critical semiconducting materials, sustainable resources need to be developed. A zinc leach residue originating from electric arc furnace dust contains gallium (Ga), germanium (Ge), and indium (In). The residue can be leached with sulfuric acid to extract Ga, Ge, and In into an aqueous solution, however a process is needed to separate and concentrate these elements for recovery. The extraction of these critical elements from sulfuric acid solutions were examined using commercially available solvent extraction extractants and ion exchange resins. Distribution ratios and separation factors of these products are reported. A potential flowsheet to recover these critical electronic elements from a zinc leach residue is presented.

4:00 pm

Kupferglimmer – Its Identification and Leaching in Copper Anode Slimes
Shijie Wang, Coeur Mining, Inc., Chicago, IL

Kupferglimmer is a copper-nickel-antimony oxide phase contained in some copper anode slimes. It is difficult to effectively leach copper from kupferglimmer due to its refractory nature. This paper identifies and analyzes kupferglimmer for the first time as a needle-shape mineral in slime samples. This paper presents the mineralogy results, describes how to leach kupferglimmer during slimes processing, and shows the kupferglimmer composition before and after the leach.

4:30 pm

Stabilization of Arsenic Byproduct from Decopperization Process to Scorodite Using Methanesulfonic Acid
Junmo Ahn, The Department of Mineral Resources & Energy Engineering, Jeonbuk National University, Jeonju, South Korea; Jiajia Wu, The Department of Mining & Geological Engineering, University of Arizona, Tucson, AZ, USA; Jaewoo Ahn, The Department of Advanced Materials Science and Engineering, Daejin University, Pocheon, South Korea; Jaeheon Lee, The Department of Mining Engineering, Colorado School of Mines, Golden, CO, USA

Arsenic (As) is a toxic byproduct from copper smelter. Arsenic immobilization is critical to prevent detrimental impacts on the environment. Arsenic compounds from decopperization requires to be dissolved and stabilized into scorodite. However, conventional lixiviant, H2SO4 limits As leaching, so methanesulfonic acid (MSA), an alternative lixiviant was investigated for arsenic leaching and scorodite crystallization. Results of arsenic trioxide leaching show that arsenic extraction with MSA was above 90% at 80oC within 4 hours. In addition, arsenic removal in scorodite was 98% at 80oC, and scorodite was successfully crystallized at MSA medium of pH 0.5. Overall, MSA was proven to be an alternative lixiviant to treat arsenic byproduct and feasible to precipitate arsenic into scorodite in MSA medium.
5:00 pm
Copper Extraction from Chalcopyrite in Various Hydrometallurgical Systems

Jaeyeon Kim, Department of Mining Engineering, Colorado School of Mines; Kroll Institute for Extractive Metallurgy, Colorado School of Mines; Junmo Ahn, Department of Mineral Resources and Energy Engineering, Chonbuk National University; Jaeheon Lee, Department of Mining Engineering, Colorado School of Mines; Kroll Institute for Extractive Metallurgy, Colorado School of Mines

Copper sulfide concentrate leaching, particularly chalcopyrite or other primary copper sulfides, has been investigated as an alternative to the conventional smelting. The grand challenge for copper industry is to improve copper extraction from the primary sulfides such as chalcopyrite. A newly developed method using activated carbon showed almost 99% copper extraction from a chalcopyrite concentrate containing 85% chalcopyrite and 8% pyrite. The system used sulfuric acid and ferric ion as a stock solution with activated carbon as an additive. In the absence of the activated carbon, only 19.2% copper extraction was observed for 96 hours at 65°. With 10 g/L activated carbon increased the copper extraction up to 98% for 48 hours at 65° in 10 g/L H2SO4. The activation energy of the H2SO4-activated carbon leaching system was 127.47 kJ/mol from the 25-65° temperature range, indicating the reaction is controlled by the chemical reaction. The system enhanced the copper extraction without surface passivation under the conditions used because the solution potential has been maintained lower than 640 mV vs. SHE. This leaching system is also compatible with the current solvent extraction and electrowinning process without any modification.

Separation Technology & Energy
Frank Lloyd Wright Ballroom CD

2:00 pm
On the Feasibility of Forward Osmosis and Freeze Concentration: A Process Simulation and Cost Analysis

Runlin Yuan, Chemical Engineering & Applied Chemistry, Institute for Water Innovation, University of Toronto; Vladimiros G. Papangelakis, Chemical Engineering & Applied Chemistry, Institute for Water Innovation, University of Toronto

Forward osmosis and freeze concentration (FO-FC) is a hybrid membrane-thermal process for water recovery. To fully understand its energy savings compared to conventional evaporative technologies, a thermodynamic process model was built using the OLI Flowsheet software. By simulating the operating conditions of a realistic FO-FC process and incorporating some basic heat integration, the energy cost was calculated to be 19 kWh/m3. It was also shown that the FC unit must be able to produce high purity ice otherwise the chemical cost of replenishing the lost draw solute can be prohibitive to the FO-FC process.
2:30 pm  
**Rare Earth Elements Separation Principles and Methods**  
*Michael L. Free, University of Utah; Prashant K. Sarswat, University of Utah*

Rare earth elements are critical to many modern devices. REEs are not as rare in ores as many common elements, but many of them are rare in applications because of their cost and availability. Much of their low market availability and relatively high cost are related to their similarities in properties, which make them difficult to separate. This paper provides a brief overview of various fundamental principles, such as reaction free energies, equilibrium constants, and electrochemical potentials as well as application methods that can be used to separate rare earth elements. The principles that establish what is possible in terms of extraction, separation, and recovery of rare earth elements and critical elements are based on the atomic level properties of the elements as well as the processing methods with related time, temperature, and mass transport parameter effects. Correspondingly, the main tools for separating elements are generally related to selective complexation, precipitation, oxidation/reduction, and mass transport.

3:00 – 3:30 pm  
**Coffee Break**

3:30 pm  
**Copper Refinery and Impurity Control**  
*Bradford C. Wesstrom, Freeport – McMoRan Copper & Gold, El Paso Refinery, El Paso, Texas*

Copper refining requires the removal of impurities that can build up in the electrolyte. This is typically done by removing a small amount of electrolyte from the refinery. This paper will cover the control methods used at the Freeport McMoRan Refinery in El Paso, Texas for these soluble electrolyte impurities.

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**Environment/Waste Treatment**  
*Frank Lloyd Wright Ballroom CD*

Chair: Mike Free, University of Utah, Salt Lake City, UT

4:00 pm  
**Assessing the Suitability of Mine Tailings as a Geopolymer Precursor Material for Subsurface Engineered Barriers for In-Situ Recovery Operations**  
*Godfrey Mawire, Curtin University, Commonwealth Scientific and Industrial Research Organisation; Robbie McDonald, Commonwealth Scientific and Industrial Research Organisation; Lionel Esteban Commonwealth Scientific and Industrial Research Organisation; Abhijit Mukherjee, Curtin University; Navdeep Dhami, Curtin University*

Introducing artificial barriers to contain lixiviants within in-situ recovery operations is critical for economic and environmental reasons. Geopolymers which offer high acid resistance and rapid strength development were investigated as barrier materials. A range of mix designs were used to study tailings from two sites, CMT1 and CMT2. The reaction stages were quantitatively analysed with isothermal calorimetry. Under representative of subsurface pressure and temperature conditions, all permeability measurements were made at 3.5 MPa confining pressure (or 1.72 MPa effective pressure) and 22°C; and converted into apparent hydraulic conductivity assuming water physical properties at the subsurface pressure and temperature conditions. The best hydraulic conductivity was found at 2.74×10^{-11} m/s for CMT1 and 3.62×10^{-11} m/s for CMT2 corresponding to a period ~ 1150 and 875 years respectively to displace lixiviants through 1-meter of such artificial barrier.
4:30 pm
Sustainable Water Recovery from Hydrometallurgical Effluents Using Gas Hydrate Based Desalination-29 OR 30
Seyed Mohammad Montazeri, Department of Mining, Metallurgical, and Materials Engineering, Université Laval, Québec, Canada; Georgios Kolliopoulos, Department of Mining, Metallurgical, and Materials Engineering, Université Laval, Québec, Canada

Hydrometallurgical processes generate large volumes of aqueous effluents. These effluents are deposited in tailings ponds, after being treated to remove impurities and recover water for reuse in process circuits. Effluent desalination is key to attain a zero liquid discharge future in the industry. In this study, we report on hydrate based desalination (HBD), which is an innovative, energy-efficient, and sustainable desalination technology, capable to treat hydrometallurgical effluents to recover water in the form of gas hydrates by consuming CO₂, which is a harmful greenhouse gas. Therefore, HBD meets the criteria of an eco-friendly effluent treatment technology, especially compared to conventional methods.

5:00 pm
In Pursuit of Zero Discharge: Forward Osmosis and Freeze Concentration for Hydrometallurgical Wastewater Recycling
Noel Devaere, University of Toronto; Vladimiros Papangelakis, University of Toronto

To address the growing need for improved water capture for recycling in the hydrometallurgical industry, we are developing a hybrid process to treat aqueous wastes and intermediate streams by Forward Osmosis (FO) and Freeze Concentration (FC). The proposed FO-FC process has energy advantages over traditional precipitation and evaporative technologies, particularly for cold climates. This work describes the FO-FC proof-of-concept results and developments to date.

5:30 pm
A Novel Process for Synthesis of TiO₂ and Application for the Photocatalytic Remediation of Water
Trenin Bayless, Gary Wilson, Courtney Young, Department of Metallurgical and Materials Engineering, Montana Tech, Butte, MT

A novel process for synthesizing carbon-doped TiO₂ at ambient temperature has been studied as a potential alternative to other techniques. During the synthesis, titanium tetrachloride (TiCl₄), commonly referred to as “tickle” (i.e., TiCl), is exposed to UV radiation in an oxidizing environment to precipitate TiO₂ particles. The study investigated the impact of the absence and presence of different UV wavelengths, oxygen source, and either carbon tetrachloride (CCl₄) or graphene-oxide as carbon-doping agents. Characterization was accomplished using UV-vis spectroscopy, Raman spectroscopy, calorimetry, scanning electron microscopy (SEM), and X-ray diffraction (XRD). Bandgaps were therefore determined along with the presence of anatase and rutile. Photocatalytic activity was measured by comparing the rates at which azo dye was degraded under UV as measured by its colorimetric intensity. The dye was used as a substitute for organic contamination. It was found that UV exposure favors synthesis through the oxygen-rich route while depressing production through the routes deprived of oxygen. The preliminary production of an anatase TiO₂ supports future research into scaling and methods of improving efficiency.
Wednesday, August 30, 2023

Rare Earths/Critical Minerals

Frank Lloyd Wright Ballroom AB

Chair: R. Nick Gow, Patterson & Cooke USA LTD

8:30 am

Fluoride-Free Processing of Columbite Concentrate for Selective Recovery of Niobium and Tantalum Oxides

Himanshu Tanvar, Material Science and Engineering, Worcester Polytechnic Institute; Brajendra Mishra, Material Science and Engineering, Worcester Polytechnic Institute

The industrial processes for extracting niobium and tantalum oxides depend highly on hydrofluoric acid. This work focuses on developing an alternative fluoride-free approach based on alkali treatment and solvent extraction. The application of microwaves in thermal treatment with potassium hydroxide shows positive outcomes of rapid processing with a high reaction rate and recovery. The microwave alkali treatment produces a water-soluble complex of niobium and tantalum separated in a downstream solvent extraction process using methyltrioctylammonium chloride as an extractant. Finally, niobium oxide and tantalum-rich mixed oxide with >98% purity were prepared after microwave treatment and solvent extraction.

9:00 am

Fluoride Control and Flowsheet Development for the Hydrometallurgical Processing of Bastnaesite Concentrates

Austin Rich, Corby Anderson, and Brock O’Kelley, Colorado School of Mines

Rare Earth Elements (REEs) are materials which are critical to the landscape of modern and evolving technology. In the United States, these elements often occur in bastnaesite ore, which has been historically mined and processed at the Mountain Pass mine. The most recent leaching process used on the Mountain Pass bastnaesite ore achieved a REE recovery of 55-60%. As a result of the poor recovery values, the Critical Materials Institute (CMI) commissioned an investigation on leaching recovery improvement. Colligan et al. showed that a decreased slurry density could yield leaching REE recovery values greater than 80%, and as high as 97%. However, this method still required improvement, as the leaching of such a low percentage of solids left large concentrations of hydrochloric acid in the residual leach liquor. This acid could be recycled for further leaching, which would result in much better process economics than using a new batch of acid per leach. It was ultimately found that any recycling of the solution would cause the fluoride from previous batch leaches to react with fresh bastnaesite, which would form insoluble Rare Earth Fluoride and decrease process REE recovery. Therefore, this study was conducted to develop a process which could remove the fluoride from the process solution, thus mitigating its detrimental effects. To achieve this goal, analytical procedures were developed to quantify fluoride in both solid and liquid REE-bearing matrices.

9:30 – 10:00 am Coffee Break
10:00 am

**Potential of Total Recycling Valuable Materials from Light-Emitting Diodes Module by Pre-Treatment Using Heating and Resin Decomposition**

Seunghyun Kim, Department of Integrated Energy and Infra System, Kangwon National University, Kangwon-do, Republic of Korea; Ha Bich Trinh, Department of Integrated Energy and Infra System, Kangwon National University, Kangwon-do, Republic of Korea; Taehun Son, Department of Integrated Energy and Infra System, Kangwon National University, Kangwon-do, Republic of Korea; Jaeryeong Lee, Department of Integrated Energy and Infra System, Kangwon National University, Kangwon-do, Republic of Korea

The recycling of LED lamps is important to reclaim the valuable materials and prevent the pollution problem. Herein, a process was investigated to recycle all the constituents from the LED modules. Firstly, the LED package and the printed circuit board of LED module were completely separated at 250 oC for 15 min. The further decomposition of resin was studied in suitable solvents: (i) epoxy resin coated on PCB in polyethylene glycol and sodium hydroxide, and (ii) silicon resin from LED package in N-methyl-2-pyrrolidone and N,N-Dimethylformamide. The remained encapsulant was subsequently processed to recovery gallium and other valuable metals.

10:30 am

**Selective Recovery of Rare Earths and Phosphate By-Product from Iron-Rich Monazite Ore by Roastings and Water Leaching**

Tarek Mohammed, College of Science, Technology, Engineering and Mathematics, Murdoch University; Gamini Senanayake, College of Science, Technology, Engineering and Mathematics, Murdoch University; Wensheng Zhang, Hydrometallurgy Innovation, CSIRO Mineral Resources

The demand for rare earth elements (REEs) has increased with the rise of modern technologies. However, current practices of processing monazite ore pose sustainability challenges. These practices involve the use of concentrated acids, which result in the discharge of acidic effluents containing dissolved gangue minerals and require energy-intensive high temperature operations. To address these challenges, a novel approach has been proposed in this study. The proposed method involves roasting the ore with NaOH, which yields water leachable Na3PO4 as a by-product that can be used in the production of fertilizer. The dephosphorized ore is then further roasted with NH4Cl, followed by water leaching, resulting in over 95% REEs recovery and merely 2% Fe. Additionally, the proposed method yields a high-purity RE2O3 product with over 99% purity, making it a promising alternative to conventional methods for processing monazite ore of high iron content. The proposed method offers numerous benefits and can contribute to the development of eco-friendly technology while promoting sustainable practices in the mining industry.

11:00

**Development of Solvent Extraction Technology for Lithium Recovery from Low-Concentration Lithium Solutions**

Go-Gi Lee, Eunjin Jung, Hyung Sub Eum, Yeongran Hong, Younwoo Park, Jaehoon Lee, Chang-Keun Chun, Industrial Materials Research Group, Research Institute of Industrial Science and Technology, Pohang, Korea

The demand for lithium resources has greatly increased in recent years due to the fast growing markets for lithium ion batteries and their use in portable devices and electric vehicles. In this regard, extensive efforts have been made to develop a technology for recovering lithium from low concentration lithium solutions. In this study, NaOH and LiOH were simultaneously used as saponification agents, and the recovery efficiencies of lithium were maximized by adjusting the ratio of aqueous and organic phases. The stabilization time of the solvent extraction process was minimized through the qualitative and quantitative analysis. The continuous extraction process was operated for more than 150 hours. Finally,
a highly concentrated solution containing more than 30 g/L of lithium was obtained to realize a circular economy of lithium resources.

**Rare Earths/Critical Minerals**

*Frank Lloyd Wright Ballroom CD*

*Chair: Gisele Azimi, University of Toronto, Toronto, ON, Canada*

**8:30 am**

**Separation of Rare Earth Elements Using Electrodialysis**

Gisele Azimi, Laboratory for Strategic Materials, Department of Chemical Engineering and Applied Chemistry, University of Toronto, Canada. Lingyang Ding, Laboratory for Strategic Materials, Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Canada

Rare earth elements (REEs) are widely utilized in advanced green technologies including permanent magnets for wind turbines and electric vehicles. The REE processing involves leaching followed by separation and purification. Conventional methods for REE separation are precipitation, ion exchange, and solvent extraction. Recently, the electrodialysis method has gained increasing interest as an effective separation method. Electrodialysis offers several advantages including simple, continuous, and multi-stages operation. Chelating agents are used to provide additional selectivity in this method. Here, the electrodialysis method with Hydroxyethyl ethylenediaminetriacetic acid chelating agent is applied to separate cerium-lanthanum from praseodymium-neodymium as two groups. A separation model is developed to simulate the separation characteristics of REEs. Using the model, the optimum ratio of HEDTA to neodymium that results in highest product purity and yield is determined.

**Recovery/Recycling**

*Frank Lloyd Wright Ballroom CD*

**9:00 am**

**Infrared Assisted Dissolution as a New Solubilization Method for Critical Metals in Different E-Waste Streams**

Mélodie Bonin, Chemistry department, Université Laval; Frédéric-Georges Fontaine, Chemistry department, Université Laval; Dominic Larivière, Chemistry department, Université Laval

Focused infrared digestion (FIRD) was evaluated as a new heating strategy for the solubilization of rare earth elements, which are considered as critical elements in many countries, in electronic waste (e-waste). Two different e-waste streams were investigated: neodymium magnets (Nd magnets) and fluorescent lamp phosphors (FLPs). Parameters relevant to digestion method, such as the nature and concentration of acids used and the solid/liquid ratio are discussed. The FIRD method is compared to more conventional digestion approaches such as hot plate, microwave, and alkaline fusion. For the magnets, FIRD is faster than hot plate and more convenient than microwave and alkaline dissolution. Investigation regarding the pros and cons of FIRD for the recycling of FLPs is still ongoing.

**9:30 – 10:00 am**

*Coffee Break*
10:00 am
**Palladium Pressure Leaching Kinetics in Chloride Medium, from Printed Circuit Boards, in a Pressure Reactor**

Guadalupe Martínez-Ballesteros, Chemical Engineering and Metallurgy Department, University of Sonora, Hermosillo, Sonora, México; Jesús Leobardo Valenzuela-García, Chemical Engineering and Metallurgy Department, University of Sonora, Hermosillo, Sonora, México; Patricia Guerrero-Germán, Chemical Engineering and Metallurgy Department, University of Sonora, Hermosillo, Sonora, México; María Mercedes Salazar-Campoy, Chemical Engineering and Metallurgy Department, University of Sonora, Hermosillo, Sonora, México; Agustín Gómez-Alvarez, Chemical Engineering and Metallurgy Department, University of Sonora, Hermosillo, Sonora México

The recovery of palladium (Pd) by recycling printed circuit boards (PCBs) has attracted attention in recent years because this metal is found in low concentrations in the earth’s crust and the demand for it increases day by day due to its chemical and physical properties. Currently, the extraction of Pd from waste PCBs through an efficient and ecological process remains a challenge. In the present study, palladium leaching was carried out in a PARR titanium reactor with a capacity of 1 L with an acid leaching agent under pressure from printed circuit boards, using \([\text{NaCl}]=0.017 \, \text{M}, \, [\text{NaClO}]= 0.067 \, \text{M}\) and varying the concentration of hydrochloric acid, pressure, and temperature, obtaining the best extraction results when using a pressure = 0.34 MPa, temperature = 70 °C and \([\text{HCl}]= 4 \, \text{M}\), with a recovery greater than 93% Pd, this was based on the thermodynamic analysis of the Pd-Cl-H2O system. In addition, the study of the extraction kinetics was carried out to know the leaching reaction mechanism, which was carried out at 0.34 MPa, 20% solids, 600 rpm, varying the temperature (40, 50, 60, and 70 °C) and different reaction times (from 10 to 120 min). Obtaining an activation energy (Ea) less than 1 kJ/mol, the mechanism is diffusion through the product layer and an extraction greater than 93% of Pd at 70 °C and 120 min.

10:30 am
**Hydrometallurgical Recovery and Process Optimization of Rare Earth Fluoride from Recycled Magnets**

Mitchell Harvey, Price Sarfo, Courtney Young, Department of Metallurgical and Materials Engineering, Montana Tech, Butte, MT

Magnets containing substantial quantities of rare earth elements are currently one of the most sought-after commodities because of their strategic importance. Recycling these rare earth magnets after their life span has been identified to be a unique approach for mitigating environmental issues that originate from mining and also for sustaining natural resources. The approach is hydrometallurgical, with leaching and precipitation followed by separation and recovery of neodymium (Nd), praseodymium (Pr) and dysprosium (Dy) in the form of rare earth fluorides (REF) as the final product. The methodology is specifically comprised of sulfuric acid (H2SO4) leaching and ammonium hydroxide (NH4OH) precipitation followed by reacting the filtrate with ammonium bifluoride (NH4F-HF) to yield the REF. Additional filtering also produces ammonium sulfate ((NH4)2SO4) as a byproduct fertilizer. Quantitative and qualitative evaluations by means of XRD, ICP and TGA-DSC to determine decomposition of ammonium jarosite, which is an impurity in the recovery process were performed. Additionally, conditional and response variables were used in a surface-response model to optimize REF production from end-of-life magnets. A REF recovery of 56.2% with a REF purity of 62.4% was found to be optimal.
11:00 am

**Agglomeration Scale: A Method to Improve Leaching Performance**

Arnaldo Guzman, Sara Swiokla Korsikas, and Toren Olson, HydroGeoSense, Inc., and Yuri O. Zepeda, Compañía Minera Lomas Bayas, Ltd

Ore agglomeration has been used as part of the heap leaching process for the last 40 years. However, industrial experience shows that the lack of a universal agglomeration standard has limited the benefits of this, otherwise, valuable unit process. The more complex the ore, in terms of the nature and relative abundance of fines (< 74 µm), the more important that the agglomeration product satisfies some minimal requirements (Guzman et al, 2013). This paper presents an agglomeration scale which identifies the quality standards for agglomerates and documents the resulting mechanical, physical, and hydraulic (hydrodynamic) behavior associated with each level on the agglomeration scale. The hydrodynamic properties of an agglomeration product are critical for the proper design of a leaching operation and, as shown in this paper, can be used to select the optimal pretreatment method for a given ore sample. Agglomeration as a unit process not only allows better conditioning of the hydrodynamic behavior of the ore; but it also creates an opportunity for optimized delivery of reagents to kick-start the leaching process which may ultimately improve the economic performance of leaching. Industrial case data is used to demonstrate the shortfalls associated with low quality agglomeration and the benefits of improved agglomeration which range from enhanced porous structure (better percolation and drainage characteristics); to better metallurgical response (faster kinetics and higher metal recovery). Proper agglomeration has been used to render otherwise untreatable ores into valuable leaching resources.

11:30 am

**A Sustainable Method to Recover the Critical Metals from Spent Lithium-Ion Batteries by Glycine and Sodium Metabisulfite in a Near-Neutral Solution**

Jiajia Wu, University of Arizona, Tucson, AZ and Jaeheon Lee, Colorado School of Mines, Golden, CO

A green leaching system consisting of glycine and sodium metabisulfite was proposed to recover critical metals from spent lithium-ion batteries (LIBs). The preliminary leaching study using synthetic LiCoO2 revealed that metal extraction was 99.9% for cobalt and 99.8% for lithium under optimal conditions. Following metal dissolution, cobalt was separated using an acidification-precipitation technique involving oxalic acid as the precipitant, and glycine was recycled into the leaching step. This leaching system operates at near-neutral conditions and is cost-effective compared with the conventional method, making it an economical alternative for recycling spent LiBs.
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