Arizona State Mine Inspector

Committed to Safety. Protecting the lives of Arizona Miners.

OPPORTUNITY STATEMENT: Reprocessing Copper Mine Tailings

BACKGROUND: Historically copper is one of the most economically important metals mined in Arizona and Arizona leads the nation in copper production. The future demand for copper is expected to increase from between 275-350% by 2050*. The demand is being driven by modern societal needs in telecommunication, renewable energy, electric vehicles, electric grid expansion, etc. Although the demand is expected to increase significantly over the coming decades, the future supply is at risk due to the lower number of new and high-quality deposits. In general, copper mining is mostly conducted in open pits and generates significant quantities of tailings (mixture of fine-grained solid materials remaining after extraction of recoverable metals and minerals and water used in the process). Production of ore needs to be excavated, crushed, concentrated and then extracted using different methods, depending on the nature of the ore. Historical extraction processes produce large quantities of tailings, which contain potentially strategic and valuable minerals. In addition, declining ore grades in primary deposits have led to the idea of reprocessing of mine tailings, particularly from old and abandoned mines, as a potential secondary source of some critical metals and minerals. Many waste tailings contain high-levels of strategic and valuable metals such as, cadmium, iron, zinc and lead. Innovative and improved reprocessing methods, especially in old or abandoned mine, could be cost effective due to the fact that many "older" tailing piles have higher concentrations of valuable metals and minerals than newer mines. In addition, reprocessing of mine tailings may significantly reduce costs, as the ore has already been mined, crushed and partially processed. By removing valuable and problematic metals and minerals from the tailings this could lead to reduced human expose via wind dispersion and seepage into the ground water. In addition, many of these metals and minerals are critical to the economic and national security of the United States.

OPPORTUNITY: The opportunity is for Arizona to develop and lead the world in copper tailings reprocessing to recover strategic and valuable minerals via research that leads to innovative, environmentally beneficial and cost-effective reprocessing technologies.

* Ayman Elshkaki, T.E. Graedel, Luca Ciacci, Barbara K. Reck, "Copper demand, supply, and associated energy use to 2050", Global Environmental Change, Volume 39, 2016, Pages 305-315

REPROCESSING COPPER MINE TAILINGS: *CRITICAL MINERALS RECOVERY FROM PAST, CURRENT, AND FUTURE COPPER MINE TAILINGS*

Lead Principal Investigator and Team:

Building on existing ABOR initiatives (Arizona Abandoned Mine Lands project), a long history of working with mining companies throughout the state, and longstanding records of excellence in mining, geology, environmental science, remote sensing, and extractive metallurgy, this interdisciplinary project will draw on the expertise of a total of 13 faculty and staff in 9 departments across all 3 Arizona public universities.

Task Team Leaders	Department	Institution
Principal Investigator: Isabel Barton; Project Liaison: Misael Cabrera*	Mining & Geological Engineering, School for Mining & Mineral Resources	UArizona
Task 1 Satellite Scanning: Phil Christensen	Earth & Space Exploration	ASU
Task 1 UAV Scanning: Chris Edwards	Astronomy & Planetary Science	NAU
Task 1 Data Compilation and Field Sampling: Carson Richardson, Julie Neilson	Arizona Geological Survey, Environmental Science	UArizona
Task 2 Sample Analysis: Mark Barton, Pierre Herckes	Molecular Sciences, Geosciences & Lowell IMR	UArizona, ASU
Task 2 Extraction Testing: Jinhong Zhang, Raina Maier, Pierre Herckes	Mining & Geological Engineering, Environmental Sciences, Molecular Sciences	UArizona, ASU
Task 3 Techno-Economic Analysis: Hongyue Jin	Systems & Industrial Engineering	UArizona

*Project Liaison labor will not be billed to the grant.

Proposal Description, Proposal Advantages and Benefits to Arizona Citizens

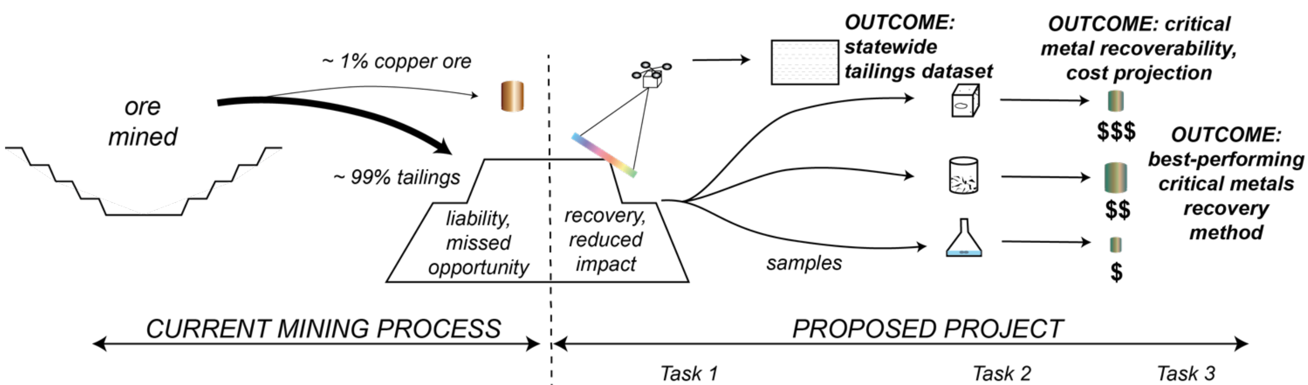
In response to the request from the State Mine Inspector, we propose to assess the critical metal content of copper mine tailings across Arizona and develop pathways to recover metals that are not currently considered in copper mining. This can create economic opportunities through recovery of critical resources, help meet national demand for these elements, and reduce environmental and related liabilities posed by copper mine tailings. The extraordinary volumes and the breadth of materials of interest make (re)processing copper tailings a world-class challenge and opportunity for Arizona.

Tailings (re)processing research is an opportunity for a major investment in critical metals. Discovery and testing of critical metal resources by conventional means requires many years and typically costs $10-100M for exploration surveying, drilling, logging, and testing - on a single deposit. Even then, deposits discovered may never be mined due to decade+ permitting timelines, land/water use concerns, and the $1-5B capital investment commonly required for each new mine. Assessing Arizona's tailings-hosted critical metals resource and developing viable means of extraction thus has huge potential for savings over the cost to find (let alone extract) them, as well as mitigating tailings-related liabilities and reducing US dependence on foreign sources. With 10 sub-projects spanning discovery, characterization, extraction, and techno-economic assessment; coverage across Arizona of hundreds of copper-bearing tailing impoundments; and compilation and organization of many dimensions and perhaps a petabyte of data, this large-scale interdisciplinary project represents a massive first step toward making use of a massive (but undeveloped) potential resource.

Arizona has produced ~70 M tons of copper since large-scale mining began in the late 19th century and contains at least another 280 M tons yet to be mined. Current production is ~0.75 M tons per year, and is projected to increase in future as demand soars, potentially quadrupling by 2050. Since every ton of copper produced requires mining and processing roughly 250 tons of rock, the past century of major mining has generated an estimated 17.5 B tons of tailings (i.e., nearly 10 cubic km of finely ground, copper-depleted waste rock), with upwards of 200 M tons now added annually and more to come as more copper is mined.

Many tailings, particularly from historic mining, contain uncertain but appreciable concentrations of critical elements such as zinc, cadmium, lead, rare earths, cobalt, lithium, and others. These are both critical elements for US high-tech manufacturing (green energy, semiconductors) and are damaging to the environment. Consequently, better treatment of historic and modern copper tailings represents an enormous opportunity to recover critical elements, while also adding value by reducing economic and environmental liabilities and mitigating associated public concerns. This challenge will only increase going forward as more copper mining produces more tailings. Finding solutions now for reprocessing existing tailings for critical mineral recovery will thus be as or more important in dealing with the much larger amounts that will be generated in coming decades. To address the large and growing copper tailings challenge, we have assembled a multidisciplinary team of experts from all three Arizona public universities, with a long history of working with Arizona mining companies on geology, metallurgy, and environmental research. In collaboration with them, our team will:

(1) Assess the types, volumes, fluxes, and critical/hazardous metal contents of copper tailings in the state;
(2) Test standard and novel/unconventional methods of recovering these critical metals by (re)processing the tailings; and
(3) Assess the tested methods to identify which performs best at recovering critical metals in an economically, technically, and environmentally sound manner.



Schematic diagram of proposed work

Characterization is the required first step, since differences in original ore types and processing methods over time have resulted in a wide and mostly unknown variety of copper mine tailings around Arizona. Task 1 will generate the <u>first systematic evaluation of the locations, volumes, types, and estimated critical metal resources</u> contained in Arizona's copper mine tailings. Based on that, Tasks 2 and 3 will examine a suite of different methods for processing copper mine tailings to extract critical and hazardous metals, along with technical and economic assessments of each and a comparison of all methods. This will pave the way for later, field-scale pilot tests.

This proposal leverages the multidisciplinary expertise, world-class facilities, and industry and government partnerships across Arizona's three public universities in mining, resource geology, remote sensing, extractive metallurgy, and environmental science. It addresses a problem that is *longstanding* (100+ years of large-scale mining), *ubiquitous* across Arizona (thousands of sites), *growing* (hundreds of thousands of tons of new tailings generated each day), and *fraught* (the potential hazards and public perception of mine tailings is a major concern with existing and new projects). The proposed work also builds on existing Board of Regents initiatives, including the tri-university Arizona Abandoned Mine Lands project (PI: Mark Barton). Four major Arizona mining companies have existing partnerships with UA on surveying, sampling, and analyzing tailings.

The proposed work will help make Arizona the global leader in (re)processing mine tailings, building expertise, knowledge, and technology for worldwide impact. Near-term benefits to Arizona's economy, environment, and public health include:

- It will turn an economic liability into a potential asset. Nobody currently knows how much metal is locked up in Arizona's copper mine tailings. Having an assessment of the potential recoverable metal content can in effect create new mineral resources in the state out of what had been a waste product. This would attract business interest and investment in new (re)mining projects.
- It will help keep metals for Arizona's industry available. Domestic production of numerous critical minerals is negligible (USGS 2022 Critical Minerals List), leaving the US dependent on imports from China, Russia, and other variably reliable foreign sources. Being able to produce some of these metals from reprocessing copper mine tailings would enhance US minerals, supply chain, and technology independence and help prevent shortages from hobbling Arizona's (or US) industries.
- It will produce the state's first extensive assessment of the volume of copper mine tailings and what toxic/critical metals they contain. This can better inform permitting processes, environmental monitoring strategies, mining research, and policy decisions, particularly as copper mining increases to meet future demand and produces more tailings.

Scope of Work

Principal Investigator I. Barton will lead overall efforts and integration of the various individual tasks and results, with day-to-day management organized by an project coordinator. Cabrera will serve as project liaison, ensuring that input and feedback from the State Mine Inspector are addressed throughout the project. Each of the three tasks will be supervised by task team leaders responsible for communication and integration of the task team. The whole project team will meet monthly (or more often as required) for progress updates and to ensure communication and integration. Quarterly meetings will be scheduled with the Arizona State Mine Inspector to provide regular updates and to ensure that the project meets Arizona's needs.

Task 1. Characterization: Understand the critical mineral content and context in copper mine tailings

The first step is assessment. The geologic types, amounts, and even locations of copper mine tailings from Arizona's 100+ years of mining are only partially known, as is their critical metal content. To evaluate these, we will employ two tools: examination of available documentary records to assess rough amounts of tailings and ore produced and ore characteristics, coupled with state-of-the-art field characterization at multiple scales to estimate volumes, tailings and water composition, and critical mineral content.

There are no data nor adequate framework for this challenge, hence we will <u>build a database on copper mining and tailings in Arizona</u> with data compiled from many sources including USGS reports, production records, and other available documents to identify what was mined (original ore characteristics), when it was mined, and approximately how much ore and tailings were produced. For tailings currently being produced, we will work with our multiple current industry partners to assess their types, amounts, characteristics, and critical mineral recovery potential. These data on the types, volumes, and compositions of copper mine tailings around Arizona, will provide the crucial background context for, and a check on, what has to be more far more selective field and lab characterization.

Field characterization will be carried out at multiple scales and with multiple methods. At the largest scale, team members expert in remote sensing will use existing airborne and satellite multispectral and hyperspectral infrared imagery combined with historic topographic data to locate copper mine tailings facilities across the state and estimate their volumes. This will produce a hyperdimensional spatial dataset from which we can extract tailings' surface mineralogy, water content, and dissolved metal content. Linked with the production records, geologic information, and the database produced by the ongoing ABOR Abandoned Mine Lands project, this will yield a first-order estimate of the volumes, locations, and geologic types of tailings in Arizona.

Using these state-scale assessments and the tailings dataset accumulated from records, the team will focus on about a half-dozen accessible sites representing various geologic types, estimated metal contents, and periods of operation. Task Team 1 will conduct high-resolution UAV-based scans of the sites using hyperspectral infrared, magnetometric, and ground-penetrating radar. This will produce a second spatial dataset mapping out tailings mineralogy and surface water composition, with billions of hyperdimensional data points per tailings facility scanned. This will reduce the number of samples needed to adequately represent the heterogeneity of tailings, which (if drilled and sampled by usual industry procedures) would run to many millions of dollars. Consequently, we will use this high-resolution hyperspectral and geophysical imagery, along with samples from current (hopefully future) partners and from geologic proxies for the same deposits in order to characterize the diversity of minerals and related substances that are in tailings. For any realistic assessment of future recovery, it is essential to understand original geologic material, how it changed over time as a deposit is mined, and how tailings evolve post-deposition due to aging and interaction with water, air, and microbes.

Task 2. Testing: Assess recoverability of critical metals from (re)processing mine tailings

Samples taken during Task 1 will be analyzed for overall composition and mineralogy down to the nanoscale. Particular focus will be on their content of metals on the 2022 US critical minerals list that are present in copper ores (antimony, arsenic, bismuth, cobalt, gallium, germanium, indium, manganese, nickel, tellurium, zinc, platinum-group metals, rare-earth elements, and titanium). Analysis will identify their content and species in tailings waters, colloids, and solids. Using the results, we will scope out which critical metals are present in recoverable form(s) in each type of tailings in order to focus extraction testing most effectively.

Extraction testing will evaluate conventional (1-2) and novel (3-4) techniques for tailings reprocessing, chosen for potential to recover numerous critical metals from diverse tailings types at low operating cost. (1) Flotation, which uses distinctive surface properties of metallic minerals, is routinely applied to separate them from nonmetallic species. (2) Controlled gravity and magnetic fields are common means of separating metallic and related (e.g. rare earth-bearing) minerals from the rest of the rock and may work for tailings, depending on mineralogy. (3) Dissolved metals can be recovered from liquids by solvent extraction, a multi-step technique common in copper mining but untested for tailings, which contain different, less concentrated metals. (4) Direct single-step extraction from solution, without solvent cycles, is a novel technique for extracting low-concentration critical metals. Co-PI Maier has invented a method of directly extracting rare earth elements from acid mine drainage, which will be modified and applied for other critical metals from tailings. We will also test direct extraction via selective adsorption onto granular solids, a new technique under study for lithium.

Each sample will be divided into multiple subsamples so that different tests can be performed on the same material (enabling comparisons in Task 3). Team members will test each method and combinations of methods on subsamples of each material collected in Task 1. Emphasis will be on assessing how each method performs by technical criteria, i.e. what percentage of the critical metal content in the sample it can recover, how pure the product is, and what reagents and equipment cost, as inputs to Task 3.

The outputs from Task 2 will be measurements of metal recoverability for each tailings facility sampled. Combined with the Task 1 database and infrared/geophysical imaging, this will allow a first-order estimate of the potential critical metal resource that can be obtained by (re)processing Arizona's copper mine tailings.

Task 3. Find value: Analyze economic and social feasibility

Task 3 will integrate the results from Tasks 1 and 2 to identify the best method(s) for potential larger-scale deployment and economic and social constraints. The team will compare each method according to technical (amount of metal obtained, consumption of chemicals, equipment requirements), economic (value of metal, estimated cost of process scale-up, value from decreased hazard), and social (potential issues related to facility design, environmental footprint) criteria for all processes tested. Using this analysis, we will identify the most promising method(s) of economically reprocessing copper mine tailings to recover critical metals from the tailings sampled and tested. Using the estimated volumes of various tailings types (T1), and recovery results (T2), we will calculate rough order-of-magnitude estimates for the amount of *economically* recoverable critical metals in past and present Arizona copper mine tailings and outline next steps for field pilot study.

Goals and Timeline

Performance Period	Goals	Anticipated deliverables
Year 1	• Secure access/collaboration from mining companies in state (build on UA's existing partnerships) • Hire project staff • T1. Review existing data sources and reports • T1. Initial remote sensing data acquisition and flights • T1. Selection and sampling campaigns on tailings sites	• At least 2 mining companies on board • Staff hired • Dataset structured, being filled • At least 2 imaging datasets collected or obtained
Year 2	• T1. Rest of remote sensing data collection, processing • T1. Estimate tailings volumes, potential metal resource • T1. Finish beta version of T1 tailings database • T1-T2. Analyze composition of tailings samples • T2. Identify target metals for different tailings sites • T2. Extraction testing from reprocessed tailings underway	• Database and order-of-magnitude estimates for tailings volume and critical metal contents • Sample analyses complete, tailings mineralogy and critical metal content known
Year 3	• T2. Finish extraction and reprocess testing, analyze results • T3. Extrapolate scaled-up costs and obtained value for T2 test results • T3. Integration of T1 and T2 results with techno-economic assessment and identification of each method • T3. Comparison of T1 and T2 methods and identification of best performance • Engagement and dissemination of results (theses, publications, final database)	• All extractive metallurgy tests complete • Quantification, techno-economic analysis complete • Overall assessment of recovery potential • Final, tested version of tailings database
Final	Integrated dataset on Arizona copper mine tailings locations, volumes, types, and estimated content of recoverable critical metals. Full report with appendices to ABOR.	

Final project deliverables will be the dataset and a report to ABOR and the State Mine Inspector covering the results from each task and identifying promising and/or necessary areas for future work on tailings (re)processing. The team will summarize the results in a presentation to the State Mine Inspector.

Three Year Budget Overview

Salaries & Wages	**Faculty Summer Salary[1]**	**$192,513**
	Postdocs[2]	**$719,711**
	Grad Students[3]	**$460,335**
	Researchers[2]	**$210,800**
	Undergrad Students	**$29,992**
	Program Coordinator – maximum ½ time	**$165,979**
Employee Related Expenses (ERE)	ERE for all categories above	$492,244
Equipment		$78,100
In-State Travel	Excludes fieldwork (in Operations below)	$9,000
Partner awards (ASU, NAU or UA)	ASU[4]	$326,576
	NAU[5]	$494,810
Supplies & Materials	Operations and field expenses[6]	$168,133
Other Costs	Analytical expenses[7]	$284,167
Total Three Year Cost		$3,632,359

[1] Faculty will design and direct hyperspectral scanning campaigns and sampling and materials characterization (T1); assess, improve, and test novel methods of metal extraction from tailings (T2); and evaluate feasibility of alternative (conventional and novel) methods for critical metals extraction (T3).

[2] Postdocs and researchers will develop and build architecture for tailings critical metal database (T1); conduct field multi-scale state-wide and test-case specifichyperspectral imaging with UAVs (T1); use resulting spectral hypercubes in coordination with geophysical scans to map surface mineralogy (T1); interpret sample and analytical results to quantify extractability of critical metals (T1-T2); and develop and apply algorithms for quantifying scaled-up cost and life cycle impact of critical metals extraction from tailings (T3).

[3] Grad students will extract and interpret tailings-related data from from extensive literature and documentary records and enter results into database (T1); assist with hyperspectral and geophysical scanning (T1); collect and analyze tailings solid and liquid samples and other proxies when direct samples are not available (T2); perform critical metal extraction testing (T2); and analyze extraction rates (T2). Graduate student tuition remission is included under this item. Undergrad students will assist with these tasks.

[4] ASU subaward includes collaborative thermal infrared scans of tailings around the state; full support for one graduate student to collect and analyze thermal infrared results; full support for another graduate student and faculty to collect and analyze colloidal critical metals in tailings samples via single-particle mass spectrometry and test critical metal extractability by sorption; and associated analytical expenses.

[5] NAU subaward includes UAV-mounted ground-penetrating radar apparatus; full support for one graduate student and one postdoc to carry out geophysical scanning of tailings and process resulting data; and travel to and data collection at multiple tailings field sites across the state.

[6] Operations and field expenses include rental and operation for UAV-mounted high-resolution hyperspectral infrared imaging spectrometers and magnetometers; field drills and other sampling equipment; laboratory chemicals, consumables, and experimental and safety equipment; sample preparation of solids, fluids and colloids; and software and computer time for processing hypercubes resulting from hyperspectral scans.

[7] Analytical expenses cover the wide variety of necessary activities including specialized sample preparation petrographic, X-ray diffraction,, and electron microscopic, and LA-ICPMS characterization of solids (tailings, rocks, and products from extraction experiments), and multiple modes of mass spectrometric chemcial analysis of solutions, both from tailings, associated waters, and extraction experiments.