Supplemental Materials. Examples of Remining Operations, Investigations, and Companies

The examples provided in this appendix include remining projects targeting metals in tailings, coal ash and waste, secondary recovery from ore production by-products, acid mine drainage and sludges, and projects from remining companies. Nearly all the projects are in the characterization or economic evaluation phase, although several have established laboratory phases to examine the most effective processing methods. One project, owned by Rio Tinto in California, USA, has completed a pilot-scale project to produce lithium from waste rock at Rio Tinto's boron mine.

The projects in full operation are:

- Kasese Cobalt site in Uganda: recovery of cobalt from former copper mine tailings using bioleaching methods.
- Golden Sunlight Mine, Montana, USA: recovery of gold from existing gold tailings using existing facilities.
- DRDGold, South Africa: recovery of gold from former gold mine dumps and tailings.
- New Century Project, Australia: recovery of zinc from former zinc/base metals tailings.
- Pan African Resources, South Africa: recovery of gold from historic gold tailings.

The phase of development for each projects is included as the final bullet. The citations for the references in this appendix are included in the main body of the review. Additional remining projects likely exist, but the examples in this appendix provide an overview of the types of projects that currently exist around the world.

A.1 Tailings and Other Mine Wastes

- Neves Corvo tailings, Portugal [117])
    - Neves Corvo Mine and Cerro do Lobo Tailings Management Facility
    - 10 million tonnes waste rock, 18.6 million tonnes thickened tailings (2010 – 2020); whole TMF stores 48.6 million tonnes since 1989 (beginning of operations), with 30 million tonnes slurry tailings.
    - Waste rock: 0.3-0.9% Cu, 0.4-1.1% Zn; tailings: up to 0.3% Cu and 0.4% Zn; drilling into TSF – up to 3% by wt Cu and up to 2.1 wt % Zn at depths of ~16-17 m.
    - Ongoing geochemical and mineralogical characterization aimed at resource estimation and valorization and reprocessing technologies
    - In characterization and evaluation phase.
- Rammelsberg tailings pond, Germany [118,119]
    - 7 million tons flotation tailings from a high-grade massive sulfide ore deposit (Cu Zn Pb)
    - Examined recovery of Pb, Zn, Cu, Au, Ag, Co, In, Ga from reprocessing using flotation, bioleaching and chemical leaching
    - 3D model of tailings composition created – relatively homogenous throughout
    - Upstream tailings dam presents potential for failure – tailings pond used for flood control
    - Favorable public opinion: jobs, revival of old mining traditions, site remediation

    - Tailings remining could result in mobilization of toxic substances and generation of AMD (19.3% of the tailings is sulfidic)
    - In characterization and evaluation phase.
- Remining of tailings at three sites in Europe [120]
    - Developing methods for 3D modeling of tailings, recovery/removal of valuable and hazardous metals, and use of tailings in construction materials.
    - 1) Plombieres TSF, East Belgium (byproduct of pyrometallurgical processing of MVT ores). Using Mineral Liberation Analyzer, Electron Probe Micro-Analyzer, x-ray fluorescence to collect data on modal mineralogy, mineral deportment, grade to assess valorization potential of the wastes.
    - 2) Davidschacht TSF, Freiberg mining district, Germany. Polymetallic hydrothermal vein ores. Used geostatistical modeling to estimate tonnages of Zn, Pb, Cu, In and As, Cd. Results used to optimize sampling of TSF. Mineralogy assessed with MLA and modeled to evaluate potential for metal recovery and AMD production.
    - 3) Neves Corvo Mine, Portugal. Generates waste rock and tailings from active mining of high-grade Cu-(Pb)-Zn deposits in the Iberian Pyrite Belt. See Oliveira et al., 2022, above.
    - All projects in characterization and evaluation phase.
- Characterization of tailings for remining potential, Finland [36]
    - 19 historic and active mines
    - Information includes tailings pile size (Mt); content in tailings (g/t) for 21 metals, including Cd, Co, Cr, Cu, Mn, Ni, Sb, V, Zn, and infrastructure (cover, road, reservoir).
    - The mine type was not identified.
    - Processing approaches are discussed generally but not as applied to the tailings described.
    - *Challenges*: Economic feasibility due to management of high iron and/or sulfur content relative to low content of target metals; processing must be site-specific.
    - *Advantages*: Technical feasibility of processing approaches are viable because they have been used in other mining applications.
    - In characterization and evaluation phase.
- Characterization of mine waste for critical minerals, U.S. Geological Survey [30]
    - U.S. Geological Survey's Earth Mapping Resources Initiative (Earth MRI) partners with State Geological Surveys to characterize mine wastes, currently in Colorado, New Mexico, and Florida for their potential for hosting critical mineral resources.
    - Colorado: tailings, waste rock, metallurgical waste, perpetual mine-related water (ponds, discharges); includes three Superfund sites. Mg, Mn, REEs, Zn.
    - New Mexico: Targeting mine wastes in three mining districts: Copper Flat (porphyry Cu), Black Hawk (arsenides), Carlisle-Center/Steeple Rock (low sulfidation, volcanic-epithermal Au-Ag deposit). Known minerals include Te, As, Bi, Mg, Mn, Zn, Co, Ni, REEs, W, fluorite.
    - Florida: Phosphate waste streams (gypsum stacks, tailings, waste rock, phosphate slimes) Known to contain REEs.
    - https://ngmdb.usgs.gov/emri/#3/44.46/-101.07 (accessed on 31 October 2023; click on Mine Waste and zoom in on State of interest)
    - *Challenges*: will take 10 years to complete

- *Advantages*: full geochemical characterization of mine wastes and mine discharge waters.
- Projects in progress (2023; began in 2022).

- Recovery of cobalt from iron ore tailings, Australia [121]
  - Savage River iron ore mine, Western Tasmania
  - The tailings are generating AMD; 38 Mt of pyritic tailings were deposited from 1967 to 1982
  - Refractory cobalt in pyrite (up to 3 wt %)
  - Describes laboratory bench scale tests using biohydrometallurgical techniques.
  - *Challenges*: separation of cobalt from high concentrations of iron was accomplished at pH 3, but nickel and copper were still in solution; they aim to produce cobalt hydroxide, an intermediate saleable product.
  - *Advantages*: remediation of AMD site.
  - In characterization and evaluation phase.
- Recovery of cobalt from historic copper and lead mine tailings, Missouri, USA [122,123,124]
  - The Missouri Cobalt site is on the U.S. EPA's list of Superfund cleanup sites. The responsible party is in the process of completing a remedial investigation/feasibility study. A Time-Critical Removal Action to consolidate and cover surface contamination on the Missouri Mining Investments property (aka Madison Mine and Anschutz Mine) began in 2020 and is scheduled for completion in 2023. U.S. EPA (2019 and 2023c).
  - Missouri Mining, Inc. purchased the historic Madison/Anschutz Mine in southeastern Missouri, USA, and has remediated "more than 100 years of historic mining activity"; an affiliate, Missouri Cobalt, LLC, has reprocessed historic tailings to recover cobalt, nickel, and copper. Madison Mine Processing Plant (MMPP) will regrind the tailings and use froth flotation to recover the metals. Operation of a new underground mine, mill, and hydrometallurgical facility began in 2021. Missouri Cobalt (2023).
  - A presentation at the 2023 annual SME meeting described the Missouri Cobalt's Madison Mine Project—Helping to Fill the US Critical Minerals Vacuum. G. Sutton; Madison Mine, Missouri Cobalt, Fredericktown, MO. "…completed and current progress towards a fully integrated critical metals facility in southeast Missouri." (https://www.smeannualconference.com/2020SMEAnnualConference/includes/themes/ACE23/assets/SME_MXC23_Technical%20Program2_2023.pdf; accessed on 13 September 2023)
  - *Advantages*: Cleanup of historic sites may co-occur with new mining activity. Recovery of critical metal, cobalt, from historic mine tailings. Copper and nickel also in wastes.
  - Cleanup conducted from 2018 to 2021, construction for new mining began in 2021.
- Retreatment of multiple metals from tailings, Peru [125]
  - Cerro de Pasco, Peru
  - Quiulacocha tailings storage facility, ~115 hectares, deposited between 1921 and 1992
  - Original high-grade copper-silver-gold ore with up to 10% Cu, 4 g/t Au, >300 g/t Ag in underground mine; processed ~58.3 Mt of zinc-lead-silver ore from open pit and underground workings (1952-1992) with average grades of 8.6% Zn, 3.3% Pb, 98 g/t Ag.
  - Drilling and sampling/analysis program with quality assurance/quality control elements will be conducted.

    - Authorization from the Peruvian Ministry of Energy and Mines to proceed with a workshop with the local community, approved by the Rural Community of Quiulacocha.
    - Cerro de Pasco Resources will submit an Environmental Impact Statement for the project.
    - *Advantages*: reprocessing tailings and storing the residue in an approved modern facility will help remediate the greater Cerro de Pasco mining complex and help restore economic activity; the aim is to create opportunities in a circular economy.
    - In discovery phase.
- Characterization and reprocessing of remobilized tailings from the Buchans River Delta, Newfoundland and Labrador, Canada [126]
    - Buchans Mining camp in Buchans, Newfoundland and Labrador, Canada
    - Operated by ASARCO from 1928 to 1984; one of world's largest volcanogenic massive sulfide (VMS) deposits – Au, Ag, Cu, Pb, Zn
    - Produced ~16 million tonnes of ore, avg mill head grade was 14.51% Zn, 7.56% Pb, 1.33% Cu, 126 g/t Ag, 1.37 g/t Au (Thurlow, 2010); tailings were dumped into the Buchans River from 1926 to ~1965; tailings flowed into Red Indian Lake and formed a delta.
    - EnviroGold Global (NVRO) obtained rights to reprocess tailings from the delta.
    - Delta samples contain ~1.6% Pb and ~7% Zn.
    - NVRO used ground-penetrating radar to assess tailings thickness in the delta.
    - Coring for metallurgical testing and confirmation of resource ongoing.
    - *Challenges*: remobilization of Pb and other contaminants during/after excavation; weathering of submerged tailings?
    - *Advantages*: metals leaching into salmon lake and Buchans River no longer a salmon river – remining could improve situation.
    - In characterization and evaluation phase.
- Bioleaching of historic tailings, Uganda [127]
    - Historic sulfidic copper mine tailings at the Kasese Cobalt Company site in Uganda targeted for cobalt recovery
    - First experiments conducted at laboratory scale by Bureau de Recherches Géologiques et Minières (BRGM; the French geological survey) in Orleans in 1989; 1998 first inoculation of bioleach tanks on site – a world first.
    - Major decrease in acid mine drainage from site, which is on the border of a nature reserve/national park.
    - Conducted stirred tank bioleaching; ~90% of the cobalt was solubilized in 6 days at 42°C.
    - *Challenges*: Passivation of chalcopyrite, optimizing use of thermophilic organisms at industrial scale.
    - *Advantages*: Technically and economically feasible at industrial scale, low cost, addressed AMD problems, high Co recovery rates, limited environmental impacts, political motivation to remediate because at border of a nature reserve, Queen Elizabeth National Park.
    - Bioleaching of sulfidic tailings at the Kasese site in operations since 1998 (ten years after first lab tests by BRGM).
- Recovery of rare earth elements (REEs) and other metals from bauxite residue, Europe [52]

- Bauxite residue (BR), also known as red mud; focus on potential use of all waste material (circularity) but also recovery of critical minerals
- Locations: throughout Europe
- Metals: Fe, Al, REEs (mainly Ce, La, Y, Nd, scandium), Cr, Ga.
- Abundant source materials in Europe. Alumina refineries operate in Bosnia Herzegovina, France, Hungary, Germany, Greece, Ireland, Romania, Spain, and the Ukraine, while significant BR deposits from refineries that have stopped their operations (legacy sites) exist in Italy, France, Germany, Hungary, and other countries. The current BR production in the EU is 6.8 Mt/y while the cumulative stockpiled level is >250 Mt (dry).
- Could supply large percentages of world demand for gallium; extracting REEs from Greece's annual production can meet ~10% of EU REE demand.
- *Challenges*: The large quantities of BR require multiple technologies that address the waste considering the circular economy
- *Advantages*: Reprocessing BR could address the enormous amounts of land it occupies and avoid other catastrophic releases such as the 2010 Hungarian red mud spill, BR can provide an alternative raw material for cement and steel, incentives could be provided to meet EU circular economy requirements
- In initial characterization and evaluation phase.

A.2 Coal ash/waste

- Recovery of REEs from coal ash resources, Eastern United States [128]
  - The Department of Defense, the National Energy Technology Laboratory (NETL), and private partner Physical Sciences Inc. (PSI) are pursuing technology for recovering REEs and other critical minerals from coal ash.
  - Production of REE concentrates from Appalachian coal ash have already been demonstrated by NETL and PSI, including recovery of yttrium and scandium from coal-fired power plant ash, in collaboration with the University of Kentucky. A micro-pilot facility is located at PSI's Andover Massachusetts location, and a pilot facility for chemical processing is located at Winner Water Service's Sharon, Pennsylvania plant.
  - *Advantages*: remediation of coal fly ash impoundments, domestic source of critical minerals
  - In characterization and evaluation phase.
- Extraction of REEs and yttrium from coal ash, many countries [129]
  - Critical review of contents and extraction potential of REEs and yttrium (REY) from coal ash in 15 major coal producing countries
  - Characterization approaches, advantages and disadvantages and current extraction techniques are discussed.
  - History: Vanadium and silver recovered from Poland coal ash in the late 19th century. More recent focus on gold, germanium, gallium, and uranium. Coal and coal ash have been the main uranium source for nuclear applications after WWII, and extraction of germanium from coal ash in China and Russia is the main source of Ge (>50%) for world industry.

    - *Challenges*: The REE and yttrium content in coal ash and ponded ash are not known. Portable XRF instruments developed for screening coal ash in the field, but their precision and accuracy need improvement.
    - *Advantages*: can contain up to 1-3% rare earth oxides (similar to conventional economic ores), fly ash is readily available and has small particle size that avoids mining and milling costs, relatively free of radioactive substances compared to coal ores.
    - In characterization and evaluation phase.
- Extraction of REEs, lithium, and cobalt from coal ash and coal wastes, Pennsylvania USA [97]
    - Preliminary estimates: Coal refuse in Pennsylvania contains ~52,000 metric tons of cobalt and 0.5 million metric tons of manganese. Developing integration of cobalt and manganese from these secondary sources into the Li-ion battery supply chain.
    - *Challenges*: Finding high concentration REE feedstock, characterizing materials for REE extraction, developing efficient processes that minimize environmental impact, financial modeling to evaluate competitiveness in global REE market.
    - *Advantages*: Reclamation of abandoned mine lands and remediation of acid mine drainage (AMD); domestic sources of REEs; heavy to light REE ratio in AMD samples is
    - In characterization and evaluation phase.

A.3 Secondary recovery from ore production by-products

- Recovery of lithium from boron plants, California USA, Rio Tinto [130,131]
    - Produced from waste rock at Rio Tinto's boron mine in the Mojave Desert, ~195 km north of Los Angeles, California
    - Roasting and leaching waste rock to recover high grades of lithium for EV batteries
    - Found lithium in mine waste at concentrations higher than domestic projects under development.
    - Pilot plant will produce 10 tonnes/yr of lithium carbonate; if built an industrial-scale, plan will be able to produce 5,000 tonnes/yr – enough for ~15,000 Tesla Model S batteries – similar to production from Albemarle's Silver Peak Mine in Nevada (only Li-carbonate production in the US in 2021).
    - Small-scale processing trial in 2019 demonstrated roasting and leaching process; in demonstration/pilot phase in 2021.
- Recovery of tellurium from copper anode slime, Utah USA [132]
    - ~90% of the world's tellurium is contained in copper ore
    - Tellurium will be refined in North America by 5N Plus, in partnership with Rio Tinto; Te will primarily be supplied to First Solar for manufacture of solar panels.
    - ~20 tons of tellurium per year will be produced at the new circuit built at the Kennecott refinery – from by-product streams generated during the copper refining process.
    - *Advantages*: reduces amount of waste that needs treatment and is discarded as mine tailings; supports manufacturing of solar panels.
    - In evaluation phase.

A.4 Acid mine drainage and sludges

- Recovery of REEs from coal acid mine drainage, Appalachia USA and Berkeley pit lake, Montana USA [77]

- Collaborating with University of West Virginia University and West Virginia Department of Environmental Protection
- Coal AMD estimates derived from 140 samples from northern and central Appalachian coal mines; two samples were collected from the Berkeley Pit Lake in Butte, Montana USA; measured REE content.
- Focus on remining wastes from abandoned mines to extract metals and minerals for renewable energy; also studied environmental injustices and how to mitigate the injustices.
- The US has ~500,000 abandoned hardrock mines with an estimated cleanup cost of up to $54 million that is not covered by mining companies.
- Discussed environmental justice issues related to virgin extraction: marginalized communities around coal mines in Appalachia; involved local communities in the development of the remining projects to protect their interests and the environment.
- *Advantages*: Jobs to local communities, improve economic development, extract valuable resources from mine waste that is polluting rivers and groundwater, remining as a way to offset mine cleanup and land restoration costs.
- In characterization and laboratory evaluation phase.

- Extraction of REEs, cobalt, and manganese from acid mine drainage, Pennsylvania USA [97,83]
  - The preliminary estimate is that 60 metric tons of cobalt and over 5,500 metric tons of manganese are being discharged with acid mine drainage into the State's waterways every year.
  - Three AMD sites and sludge samples shown to be highly enriched in REEs.
  - Heavy to light REE ratio in AMD samples is higher than in many ores.
  - Two-stage process developed that removed 90% of aluminum and 85% of REEs at pH values below 7, which suppressed the precipitation of iron that would otherwise dilute the target metals.
  - Acid mine drainage discharged to Pennsylvania streams every year contains 60 metric tons of cobalt and >5,500 metric tons of manganese.
  - *Advantages*: reclamation of AMLs and remediation of AMD; domestic sources of REEs; heavy to light REE ratio in AMD samples is higher than in many ores; sale of cobalt and manganese recovered could help offset costs of mine reclamation and stream restoration.
  - In laboratory evaluation phase.

A.5 Remining companies

All remining companies emphasize the dual goals of supplying minerals using a circular economy framework and contributing positively to remediation of long-standing environmental impacts from mining. Some of the companies listed are also mining virgin ores. Many of the companies are targeting gold, but others focus on metals of interest for renewable energy.

- Barrick, Canada. Reprocessing tailings at the Golden Sunlight Mine in Montana, USA for gold. Tailings from other nearby operations are also accepted for reprocessing. The reprocessed tailings are planned to be disposed of in an open pit at the mine site. The tailings reprocessing operation began in February 2022. An EIS for the project was submitted to and approved by the Montana Department of Environmental Quality (MDEQ, 2021).

    - https://www.barrick.com/English/news/news-details/2022/golden-sunlights-tailings-reprocessing-project-a-model-for-sustainable-closure/default.aspx (accessed on 13 September 2023)
    - In operation.
- DRDGold, South Africa. Conducts large-scale retreatment (reprocessing) of former gold mine dumps and tailings focused on gold recovery. DRDGold currently has one facility in South Africa, Far West Gold Recoveries (FWGR), which is owned by Sibanye-Stillwater, a platinum group metal mining company. Another retreatment plant, Ergo, is in South Africa east of Johannesburg. FWGR has mineral resources of 2.46 million ounces (Moz) of gold, and ERGO has mineral reserves of 3.58 Moz of gold.
    - https://www.drdgold.com/ (accessed on 13 September 2023)
    - In operation.
- EnviroGold Global, Canada. A publicly traded company that partners with mining companies to deploy their technology at operating mines and waste stockpiles. Obtained the rights to reprocess tailings from the Buchans River Delta in Newfoundland and Labrador, Canada for lead and zinc (see Section A.1 above). Reduces the acid-generation potential of sulfidic wastes by oxidizing the sulfides in tailings resulting from operating and legacy mines. They target copper, zinc, lead, nickel, gold, and silver in wastes from polymetallic sulfide ore bodies and estimate $1.16 trillion US of unrecovered metal in these materials.
    - [126,133] and https://envirogoldglobal.com/ (accessed on 13 September 2023)
    - In permitting and start-up.
- New Century Resources, Australia. Involved in virgin extraction/mining, tailings management, and sustainably extending the life of mines by extracting value from tailings or other remnant resources at mines. They have protocols and procedures to respect and support cultural heritage and sites of significance. Century project in Queensland is the largest tailings remining and processing operation in Australia. Since 2017 the tailings have been hydraulically mined, pumped to the existing processing plant to remove remnant zinc, and then pumped into the original open pit for final storage.
    - https://newcenturyresources.com/ (accessed on 13 September 2023)
    - In operation.
- Pan African Resources, South Africa. Conducts mining and tailings retreatment for gold. Acquired Mintails, a previously mismanaged operation, to reprocess tailings for gold recovery. In 2020, the company processed 14,051,680 tons of historic gold tailings and produced 79,751 oz gold.
    - https://www.panafricanresources.com/tailings-retreatment/ (accessed on 13 September 2023)
    - In operation.
- Phoenix Tailings, United States. Focuses on creating REEs from mine tailings with no carbon emissions. Products include ferro-dysprosium alloy, neodymium, and dysprosium; products in development include other REEs, metallic iron products, iron oxide products, precious metals, battery metals, and aggregates. Collaborating with US Department of Energy (second link). Phoenix Tailings (PT) has developed novel techniques to separate rare earth oxides (REOs) without the use of hazardous chemicals and reduce them to REMs using 35-45% less energy. PT will separate REOs through selective halogenation and use mixed halide salts to reduce them.

    - https://phoenixtailings.com/products/ and https://arpa-e.energy.gov/technologies/projects/novel-technique-domestic-rare-earth-oxide-separation-and-rare-earth-metal (accessed on 13 September 2023)
    - In laboratory evaluation phase.
- Regeneration, United States. A project of *Resolve* created as a public benefit corporation (B-Corp) that aims to supply materials for the energy transition from legacy and abandoned mine sites and associated wastes. Rio Tinto provided initial investment and is a partner in Regeneration.
    - https://www.resolve.ngo/regeneration.htm (accessed on 13 September 2023)
    - In early company set-up and evaluation phase.