January 2025

TECHNICAL GUIDANCE

REUSE OF SOLID MINING WASTE

Prepared By

The Interstate Technology & Regulatory Council (ITRC)

Reuse of Solid Mining Waste Team

ABOUT ITRC

The Interstate Technology and Regulatory Council (ITRC) is a state-led coalition working to reduce barriers to the use of innovative environmental technologies and approaches so that compliance costs are reduced and cleanup efficacy is maximized. ITRC produces documents and training that broaden and deepen technical knowledge and expedite quality regulatory decision making while protecting human health and the environment. With private and public sector members from all 50 states and the District of Columbia, ITRC truly provides a national perspective. More information on ITRC is available at www.itrcweb.org.

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Reuse of Solid Mining Waste

Technical and Regulatory Guidance

January 2025

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1 INTRODUCTION

1.1 Overview

Solid mining waste represents a significant quantity of waste material in the United States and around the world. The reuse of solid mining waste can consist of reprocessing and repurposing the waste for resource recovery or a new application or product. This reuse serves as a solution to two significant needs: (1) a domestic supply of minerals and materials for sustainable development and national defense purposes and (2) the reclamation and remediation of land to reduce risks to human and environmental health. Solid mining waste has a range of physical and chemical compositions that make it both potentially valuable and potentially hazardous to human health and the environment. The different types of mining sites and potential wastes for reuse provide a significant challenge but also an opportunity for innovation.

From a commercial perspective, mining removes most of the primary minerals of interest; however, waste materials can still contain valuable minerals and other materials that can be recovered. Historic mines may contain waste rock or low-grade ores that were either too uneconomical to process or contained certain minerals that couldn't be extracted using the technologies available at the time of operation. Also, certain minerals may not have been commonly used or used at all by industry at the time of the mine's operation. Today, some materials formerly viewed as waste may now be considered a resource. Improvements in extraction and mineral processing technologies have occurred over time. Interest in trace metals and rare earth elements (REEs) has increased, especially with the drive toward renewable energy sources that is increasing demand for key minerals required for solar panels and batteries. Many metals and REEs are defined as critical minerals, a designation that changes depending on the need for the material in the United States and the risk of supply chain disruption. Increases in metals commodity prices, especially for precious metals (for example, gold, silver, platinum) and REEs, have made some mining waste materials economically viable for metal extraction, even for waste from relatively modern mines. In addition, some types of mining wastes may provide raw material inputs for construction products such as concrete, asphalt, bricks, rock, and granular materials. Through technological advancement, appropriate regulatory guidance, and market changes, solid mining waste reuse can be sustainable, environmentally sound, and economically viable.

To evaluate a potential application for solid mining waste, the material must be thoroughly characterized for physical, chemical, mineralogical, radiological, and toxicological properties. This comprehensive characterization allows the waste and reuse to be evaluated in the context of current and future environmental contamination risks. There are key human health and environmental concerns to consider based on the characterization. Existing mining waste can represent a potential environmental concern even while contained, but the method of processing that waste for reuse can increase or decrease that risk. The potential impacts of the specific mining waste on human and environmental receptors must be considered when evaluating a desired end use of the waste. The reprocessing and final application of solid mining waste must be planned carefully with a life-cycle analysis (LCA) to minimize potential risk.

Due to the variability in the types of mining waste, their potential impacts, and their potential end uses, the regulatory landscape for solid mining waste reuse is varied. Solid mining waste reuse is not a widespread activity. Regulatory practices are fragmented, and new policies are under development. There are different regulatory requirements at federal, state, and tribal levels. For example, some states such as Oklahoma have agencies and programs designed to permit beneficial reuse, while most states do not (State of Oklahoma 2024). A list of states with beneficial or special use permit programs can be found in Appendix A. Regardless of the jurisdiction over a site, stakeholder engagement in the reuse of solid mining waste is key to gaining community and regulatory acceptance of reuse projects. In addition, community needs must be factored into the potential reuse, as different local value and risk reduction may be realized through proposed beneficial reuse. Environmental justice guidelines or requirements may also be a factor in the development of a solid mining waste reuse project to ensure that disadvantaged communities are provided opportunities to participate in and benefit from the reuse and are not disproportionately affected.

Different applications may be viable for solid mining waste reuse, though not every waste can be reused. Depending on the composition of the material, specific minerals may be extracted through different processes for resource recovery; in other instances, the whole material may be used, such as for structural fill. Generally, there are applications for solid mining waste reuse in construction, industry, and environmental projects. Solid mining waste can be transformed through a variety of technological processes to produce a new product, though this depends on the existing physical and chemical composition of the waste and the desired end composition.

1.2 Solid Mining Waste

Waste can be defined in multiple ways. Mining waste is typically defined as all extracted material considered to be nonvaluable at the original time of extraction or production. For this guidance, solid mining waste is defined as any naturally occurring material that has been disturbed by mining, milling, or smelting activity and is not used or marketed by that activity, such as the following:

- waste/development rock, overburden, chat, tailings (fine and coarse), slimes or fine tailings, smelter waste, and sludges
- soils and sediments affected by mining
- solid residues derived from treatment of mining-influenced water (MIW)
- suspended or dissolved solids in MIW (sludge, filter backwash, reverse osmosis concentrate, and regeneration fluids)

1.3 Purpose

The overall purpose of this guidance is to provide an understanding of the issues and opportunities within the field of solid mining waste reuse for interested parties, their consultants, and other stakeholders, including those individuals who are looking for further guidance during the development and review of a site-specific solid mining waste reuse plan. Conceptually, solid mining waste reuse plans discuss the relevant site-specific technical and regulatory considerations associated with the intended waste reuse application. These plans will vary based on relevant jurisdiction, but should generally include waste characterization, technical feasibility, LCA and risk assessment, regulatory restrictions, and stakeholder considerations. Solid mining waste reuse plans must evaluate and mitigate potential environmental impacts on a site-specific basis to protect human health and the environment. An overview of these considerations is provided in this document, but specific plan requirements are beyond the scope of this guidance document (Figure 1-1).

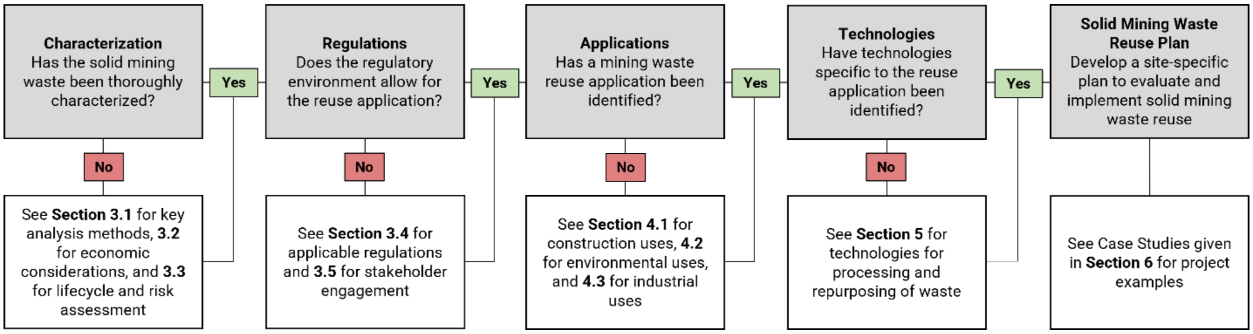


Figure 1-1. Solid mining waste reuse guidance organization.

Source: Samantha Fuchs, Geosyntec

This guidance will include general best practices for characterizing and understanding the potential applications for reuse of solid mining waste. Characterization includes physical, geochemical, mineralogical, radiological, and toxicological evaluations. These parameters inform the potential applications for reuse of the solid mining waste. Additionally, key risk considerations will be provided to avoid inappropriate reuse, such as reuse of a material in an application that could increase harm to human health and the environment. This guidance will also provide a review of suggested technology and processes to transform solid mining waste into materials with beneficial uses.

The regulatory environment for solid mining waste reuse is complex. This guidance provides an overview of current laws and regulations at federal, state, and tribal levels that may be applicable to a solid mining waste reuse project. These regulations are highly specific to the site location, waste composition, and mine status. For instance, overburden from an active mine would have very different reuse requirements for potential reuse compared to waste rock at an abandoned site under the superfund program. Links to a variety of state, federal, and tribal agencies will be given for further information, and suggested contacts will be provided to address specific questions.

1.4 Guidance Organization

The overall structure of this guidance is provided in Figure 1-1. This guidance provides detailed information on key topics relevant to the reuse of solid mining waste. The scope of mining and mining waste issues is discussed (Section 2). Characterization and evaluation practices for the purposes of understanding existing solid mining waste are described (Section 3.1), as well as economic considerations (Section 3.2), LCA and risk assessment (Section 3.3), regulatory considerations (Section 3.4), and stakeholder engagement (Section 3.5). The possibilities for reuse of solid mining waste are discussed through potential resource recovery applications, including key contexts for viability based on human health and environmental risk assessment and economic feasibility (Section 4). The current state and practice of technological processes needed to reprocess solid mining waste is discussed (Section 5). Finally, several case studies are provided to exemplify the range of types of sites and potential reuse technologies and applications (Section 6).

2 MINING AND MINING WASTE

The mining industry supplies essential material for construction, energy, and technological development around the world. The process of identifying and extracting ore for development produces billions of tons of waste. The existing and future need for resources produced from mining is projected to increase with continued development, especially in the energy sector (Section 2.1). Common mined materials include a variety of geological materials and minerals (Section 2.2). Several different types of waste are produced following extraction, with a variety of physical and chemical compositions (Section 2.3). Mining waste represents several potential physical and chemical hazards to human health and the environment. Although the mining industry is projected to continue to be the world's largest producer of waste, intentional practices can reduce the hazards of solid mining waste (Section 2.4).

2.1 Status and Future of the Global Mining Industry

Worldwide, the generation of solid mining waste from the primary production of mineral and metal commodities has been estimated at more than 100 billion tons (Tayebi-Khorami et al. 2019). As of 2023, the global mining footprint is estimated at more than 100,000 km^2, with 50% of this footprint consisting of waste storage facilities or permanent waste disposal locations (Valenta et al. 2023). These wastes are generated during different stages of the mining process, which include exploration, mine development, mineral extraction, mineral processing (in other words, mineral beneficiation), refining, reclamation, and remediation. Market projections indicate that the demand for minerals will continue to increase on a large scale (Aguilar, Betti, and Gomez 2023). One key aspect driving continued mining operations is the need for materials for carbon-neutral technology and industrial development. Decarbonization is driving the expansion of renewable power generation and the shift from combustion engines to electric vehicles. A global commitment to an energy transition has heightened the focus on materials security. In April 2023, the Group of 7 (Canada, France, Germany, Italy, Japan, the European Union, the United Kingdom, and the United States) adopted a Five-Point Plan for Critical Minerals Security, which acknowledged the increasing global demand for critical materials for the clean energy transition. The plan implements five points: forecasting long-term supply and demand, responsibly developing resources and supply chains, promoting critical minerals recycling, promoting resource-saving innovations and substitute technologies, and preparing for supply disruptions (G7 Ministers of Climate, Energy and Environment 2023).

Specific minerals are required for new technology development. The energy transition will require significant amounts of raw materials, including lithium, nickel, REEs, copper, and aluminum (Azevedo et al. 2022). For example, the global demand for refined copper is projected to increase from 25 million tons in 2021 to 53 million tons in 2050 (S&P Global 2022). Based on current supply trends, there could be up to a 20% shortfall in the copper required to meet the 2050 net-zero climate goal. Meeting this demand would require additional mines and recycling facilities (Aguilar, Betti, and Gomez 2023). Applications of critical minerals and energy transition minerals are discussed further in Section 4. Additionally, specific sectors such as road transportation and power generation are materials intensive; to build new components with reduced carbon emissions, more physical materials are needed (Azevedo et al. 2022). Even with an increased focus on sustainability and improvements in efficiency, waste will continue to be generated at an accelerated pace due to demand.

The role of the mining industry in the U.S. economy is shown in Figure 2-1. In 2023, the value of nonfuel minerals produced at mines in the United States was approximately $105 billion, with net exports of mineral raw materials estimated at $4.7 billion (USGS 2024b). Nevertheless, the United States relied on imports for more than 50% of the country's nonfuel mineral consumption. Most imports come from China and Canada (USGS 2024b).

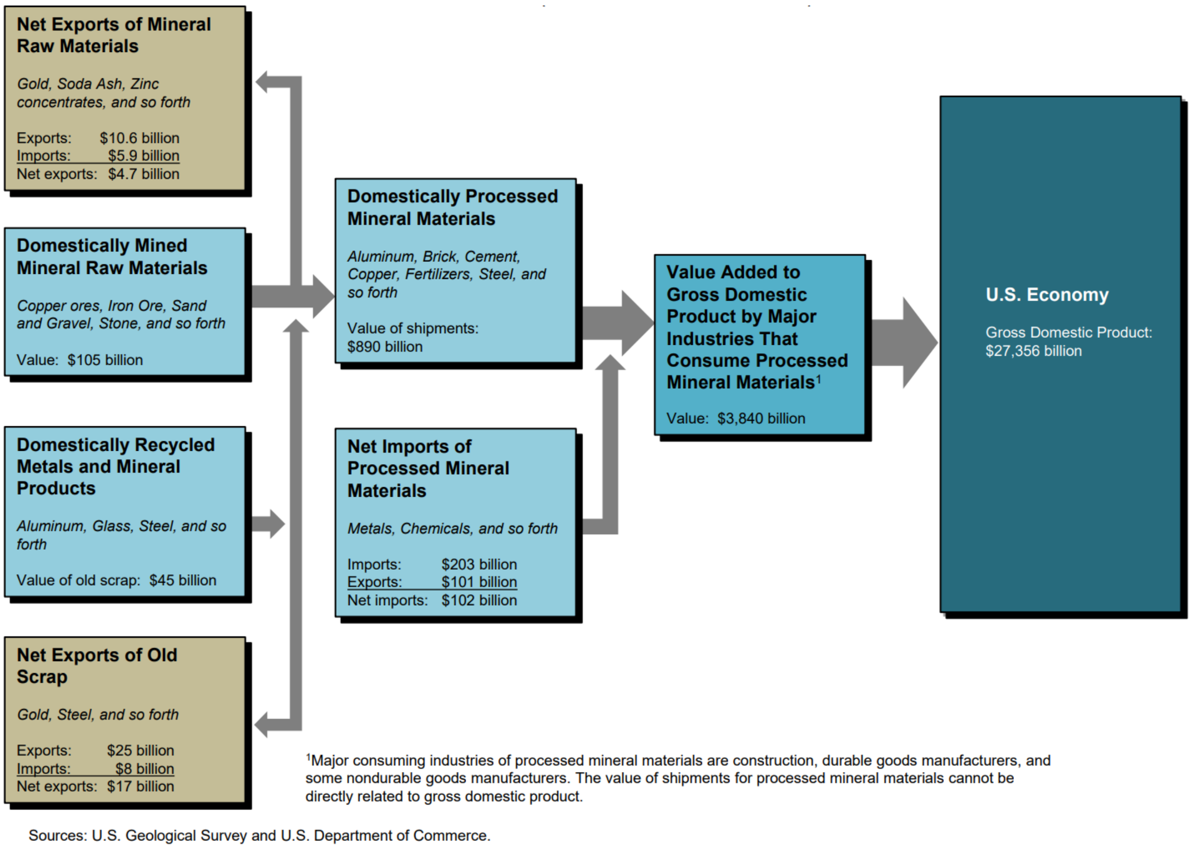


Figure 2-1. Role of nonfuel mineral materials in the U.S. economy in 2023.

Source: U.S. Geological Survey (2024b)

2.2 Common Mined Materials

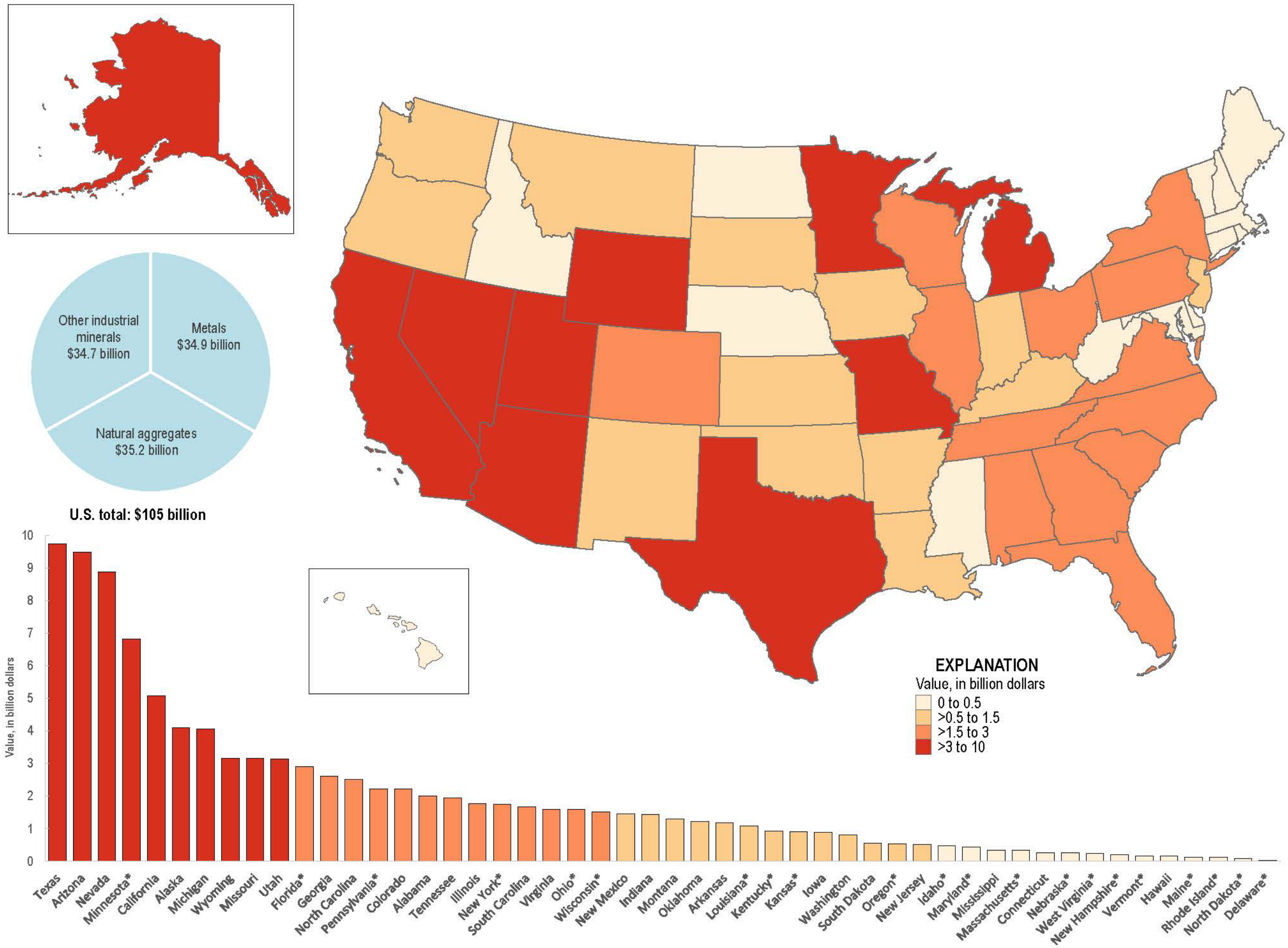
Different types of materials are mined for various purposes, from construction to energy to commodities. The type of mined materials influences the solid mining waste typically produced during mining. Mining processes vary based on the local geology and geography, type and grade of the ore deposit, age of the mine, available technology, and federal, state, and tribal regulations.

Common mined materials include the following:

- Metals
- Coal
- Oil Shale
- Limestones
- Clays
- Construction Aggregates (including sand, gravel, and crushed stone)

- Chalk
- Gemstones
- Rock Salt
- Other Nonfuel/Nonmetal Minerals

A diagram showing the value of nonfuel mineral commodities produced in the United States is shown in Figure 2-2. The state with the highest mineral commodity value is Texas, which produces construction aggregates and industrial materials like sand and gravel, crushed stone, cement, and lime (USGS 2024b). Other leading states produce metals in addition to construction aggregates and industrial minerals. For example, Arizona produces copper and molybdenum mineral concentrates, and Nevada produces copper and gold.



*Partial total; excludes values that must be withheld to avoid disclosing company proprietary data, which are included with "Undistributed" in table 3.

Figure 2-2. Value of nonfuel mineral commodities produced in 2023, by state.

Source: U.S. Geological Survey (2024b)

The major processing and recovery phases of the mining process are shown in Figure 2-3. Many of these processes and required technologies are similar for mining and the reuse of mining waste and are further described in Section 5.

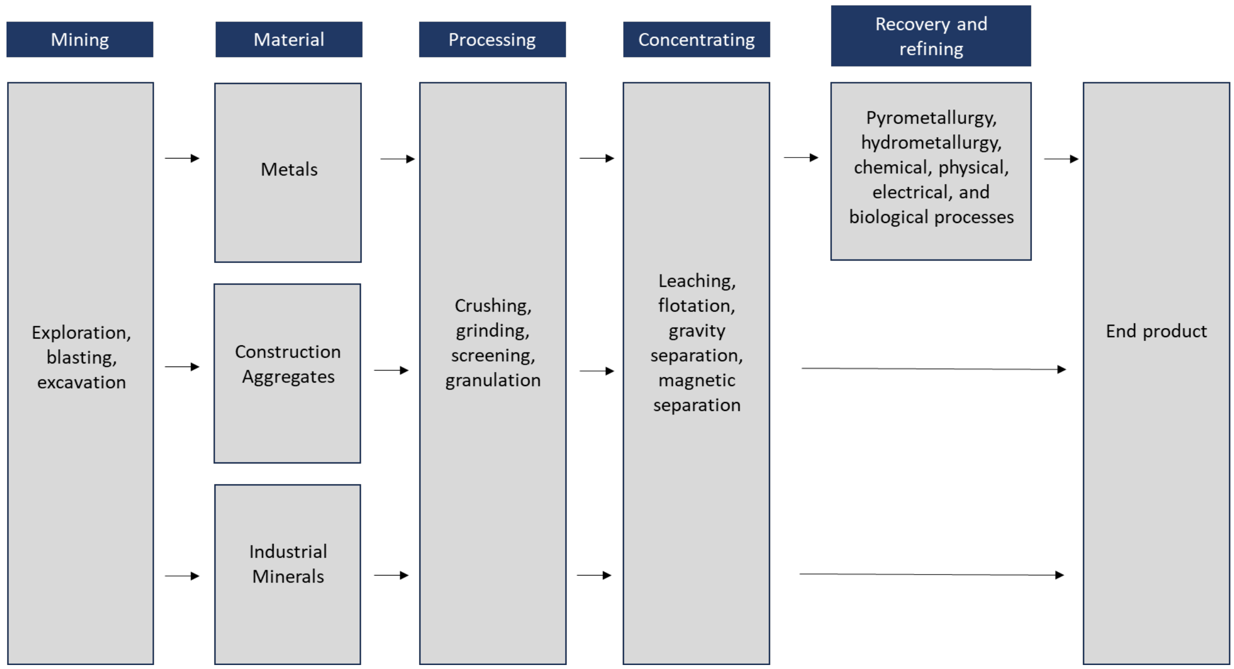


Figure 2-3. Major phases of the mining process.

Source: Stephanie Aurelius, Geosyntec

2.3 Common Types of Mining Waste

Generally, mining and metallurgical wastes are heterogeneous materials that can include ore, gangue, industrial minerals, metals, coal or mineral fuels, rock, loose sediment, mill tailings, metallurgical slag, roasted ore, flue dust, ash, and processing chemicals and fluids (Hudson-Edwards, Jamieson, and Lottermoser 2011). Although the primary commercial extraction of desired materials has already occurred, solid mining wastes can be a source of additional value. For example, slag is a by-product or waste material generated by high-temperature metallurgical processing or pyrometallurgical processing of ores or mineral concentrates; however, a properly characterized slag can be used as a concrete aggregate in construction, a source of phosphate for fertilizer, or as an acid neutralizer for acid mine drainage (AMD). For more information on the technological processes involved in mining and the production of mining waste, see Section 5.

Due to the amount and variety of solid mining waste, sustainable and environmentally responsible reuse would beneficially decrease the volume of waste and allow redevelopment or reclamation of the land (for examples see Sections 6.1.3.3 and 6.2.5). In order to evaluate the reuse of solid mining waste, the material must first be characterized to identify its physical and chemical composition. Waste characterization is key to determining a possible end use as well as current and future environmental and human health risks. Solid waste characterization is described in Section 3.1.

Multiple organizations employ variable definitions for mining wastes, but for the purposes of this guidance, common mining waste types are summarized in Table 2-1 and shown in Figure 2-4.

Table 2-1. Description of various types of mining wastes

Mining Waste Type	Description
Chat	A local name in Oklahoma, Kansas, and Missouri for coarse-sized mining waste material produced from mill discharges during mineral processing operations such as crushing, gravity separation, and concentrating processes. Typically refers to fine gravel to sand-sized particles.
Gangue*	The minerals without value in an ore; that part of an ore that is not economically desirable but cannot be avoided when mining the deposit. It is separated from the ore during beneficiation.
Leachate	A solution or suspension formed when liquid travels through a solid and removes some components of the solid. These components may be dissolved or suspended within the liquid.
Mining-Influenced Water*	Any water affected by mining, milling, or smelting activities. This includes groundwater, surface water, acid mine drainage, acid rock drainage, and mine-impacted water.
Mining-Influenced Water Residuals	Materials formed or accumulated from various physical processes, chemical reactions, or biological reactions, which includes natural oxidation and reduction reactions, settling of suspended solids, and chemical and biological treatment processes.
Overburden*	Material of any nature, consolidated or unconsolidated, that overlies a deposit of useful and minable materials or ores, especially those deposits that are mined from the surface by open cuts or pits.
Slag	By-product of ore smelting. Main types of slag include ferrous, ferroalloy, and nonferrous.
Slimes*	Material of silt or clay in size, resulting from the washing, concentration, or treatment of ground ore.
Tailings*	The solid waste product (gangue and other material) resulting from the milling and mineral recovery process (washing, concentration, or treatment) applied to the ground ore. This term is usually used for sand to clay-sized refuse that is considered too low in mineral values to be treated further, as opposed to the concentrates that contain the valuable mineral or metal.
Waste Rock	All nonvaluable rock that is excavated during mining operations. Also known as development rock, it refers to cobble to boulder-sized material, although weathering of rock material especially at older abandoned mines, results in degradation to finer particle-size fractions.

*Definitions are from ITRC (2010)

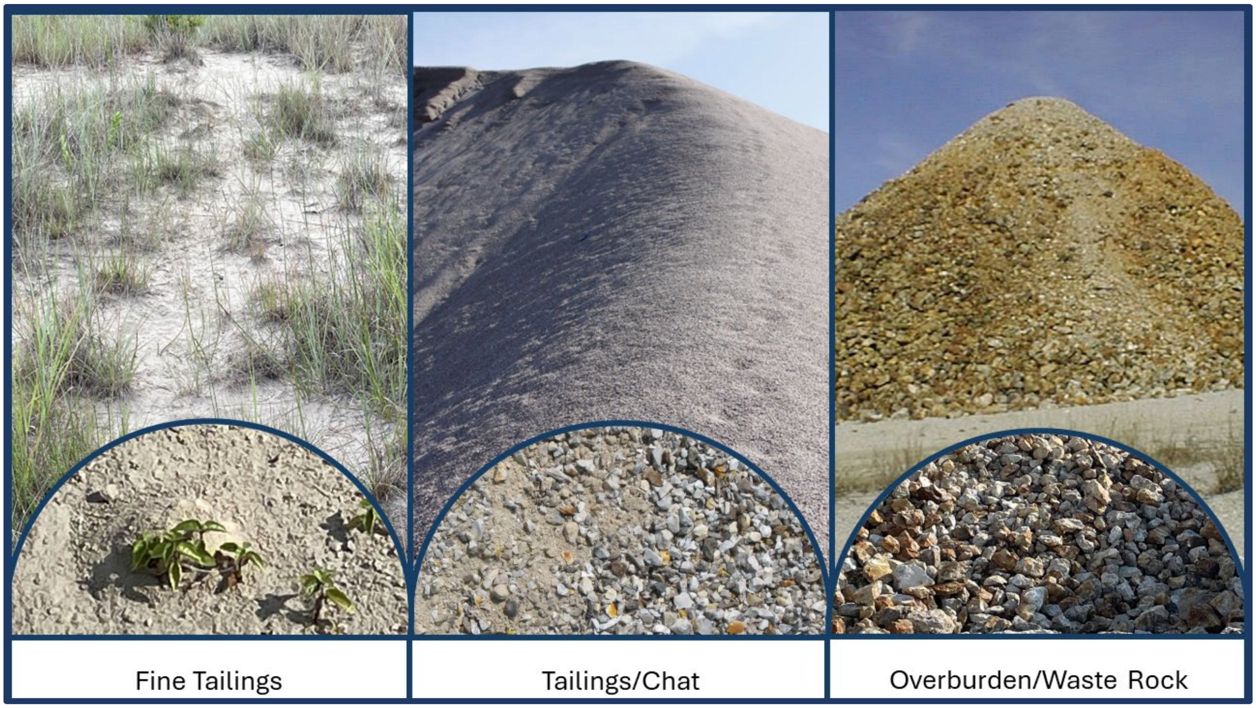


Figure 2-4. Relative grain size comparison for several types of mining waste.

Source: Interstate Technology & Regulatory Council Reuse of Solid Mining Waste Team

2.4 Mining Waste Hazard Reduction

Mining waste can pose a significant number of physical and chemical hazards to human health and the environment. Some potential hazards and impacts are listed below:

- **Waste pile hazards.** Waste rock, also known as development rock and including overburden and gangue, refers to all nonvaluable rock that is excavated during mining operations. In the past, waste rock was often dumped in large piles near the mine site. This leads to issues such as changes in drainage and erosion patterns, sediment loading to surface waters, slope failure, acid and alkaline mine drainage, and dispersal of contaminants into the environment. Contaminants include but are not limited to metals, metalloids, sulfides, and radioactive minerals. For further information on radioactivity hazards in mining waste, see Section 2.5.

- **Tailings impoundment hazards.** Tailings are the waste materials left over after the valuable minerals have been extracted from the ore and typically contain significant fluids from the ore refinement process. In traditional mining methods, tailings are often stored in large impoundments or tailings dams that pose geotechnical, geochemical, and environmental risks such as dam failures through piping or overtopping and surface and groundwater contamination. Fine-grain tailings can also pose risks due to wind-blown dusts. Tailings dam failures can cause immediate infrastructure damage, loss of life, and long-term environmental damage from the release of contaminants, such as arsenic and mercury. The Brumadinho Dam disaster in 2019 at the Córrego do Feijão iron-ore mine in Brazil resulted in the deaths of 270 people after a catastrophic tailings dam failure. The mudslide traveled 10 km, ultimately reaching the Paraopeba River and causing sediment and toxic contaminant loading (Silva Rotta et al. 2020).

- **Fluid production hazards.** Mining processes may include fluids that present hazards to human health and the environment. For instance, the most common mining process for gold uses a solution of cyanide to leach gold from crushed ore. Contaminated fluids are often stored on-site as part of a treatment process, such as in settling, precipitation, and evaporation ponds. In the event of accidents or improper construction, contaminated fluids can be released into the environment. For example, the Gold King Mine release occurred when excavation during investigation caused pressurized water to leak into the mining tunnel and into the surrounding environment (Water Resources Mission Area 2018).

Fluid leaching and drainage hazards include the following:

- **Acid mine drainage.** AMD is an environmental concern associated with mining activities. It occurs when some sulfide minerals in the waste rock or tailings come into contact with air and water, leading to the formation of sulfuric acid. This acid can then leach metals and other potentially toxic contaminants from the mining waste and discharge into nearby water bodies and groundwater aquifers, posing ecological and human health risks. Acid rock drainage results in a similar environmental concern, but the source of the rock is not necessarily affiliated with a mine. AMD typically has a pH of 2–6, but may also include circumneutral waters at pH 5–8 (USGS 2016).

- **Alkaline mine drainage**. Alkaline mine drainage typically occurs in rocks containing calcite or dolomite. The raised pH can cause leaching of metals and other contaminants, posing risks similar to AMD.

Through pollution prevention and improved management processes, the human health and environmental impact of solid mining waste can be minimized. Many of these methods are already widespread. Overall, these advancements contribute to more responsible mining practices. Several hazard mitigation strategies can be employed as exemplified below.

- **Resource recovery.** With the advancement of mining technologies, there is an increasing emphasis on resource recovery from mining waste while it is still in the processing circuit, prior to disposal. Modern mining technologies enable the extraction of additional valuable minerals from the waste stream. For example, techniques such as flotation, leaching, and bioleaching are used to recover valuable metals from tailings or low-grade ores. This not only reduces the amount of waste generated but also maximizes the use of resources and may reduce the environmental footprint of mining operations.

- **Waste pile management.** With the advancement of mining technologies, waste pile management has become more sophisticated. Techniques such as cemented backfilling, where waste rock is used to fill underground voids, and reclamation, where waste rock is capped, reshaped, and revegetated, are now commonly employed to reduce the environmental impact of waste rock disposal. Separating waste rock based on type can allow for safer management or future use, such as separation of acid-generating rock and non-acid-generating rock, or separation of radioactive materials for disposal. Finally, best management practices include liners, covers, and leachate collection and removal to prevent environmental release.

- **Tailings impoundment management.** Best practices for management of tailings impoundments are to ensure both geotechnical and geochemical stability. Different types of tailings management tailored to the specific site conditions may help to reduce environmental risk from structural failure or contaminant release. One proactive form of tailings management includes “dry stacking,” where the tailings are filtered to reduce water content (generally to less than 20% liquid by weight), which causes the material to behave more like dry soil. This allows disposal in sequential, compacted lifts through conventional trucking or conveyance methods. Another alternative method involves changing rheology characteristics and dewatering to produce “thickened” or “paste” tailings (Väätäinen, n.d.). Thickened tailings are formed by dewatering or filtering to create a slurry with higher solids content and yield stress where the solids can still eventually settle freely. Paste tailings are dewatered more than thickened tailings to create a viscous, nonsegregating mixture. Both thickened and paste tailings can be disposed of within surface containment facilities or as backfill within underground workings, depending on site conditions (Verburg 2001). In some cases, cement or other binders may be added to increase the strength of the material.

- **Acid mine drainage management and treatment.** Mining processes focus on preventing or minimizing AMD through various methods as specified by regulations. These methods can be active or passive. Treatment methods include neutralization, electrocoagulation, evaporation, bioremediation, and encapsulation of sulfide-bearing materials to prevent contact with air and water. Management methods include caps, liners, leachate collection, and overall water management systems to control the flow of water to or through the waste.

- **Speculative Accumulation**. For waste products that cannot be eliminated or processed for further recovery, it is beneficial to consider potential future uses when evaluating disposal of the waste. That is, the process by which mining waste is initially stored or accumulated greatly affects the potential future uses of that waste. Speculative accumulation of mining waste refers to the practice of stockpiling or storing mining waste materials with the expectation of future economic gain or use. Advances in technology, changes in market conditions, or new environmental regulations, policies, or incentives may make it economically viable to recycle, reprocess, or otherwise extract valuable minerals or resources from previously discarded waste material. Governments or regulatory bodies may also introduce stricter regulations on waste disposal, leading mining companies to hold onto waste materials in anticipation of future recycling or reclamation opportunities. Speculative accumulation encourages the management of mining waste with the potential for future reuse or reprocessing in mind. Nevertheless, speculatively accumulated mining waste must still be appropriately managed to minimize environmental and human health hazards until a future use or disposal method is undertaken.

2.5 Potential Radioactivity in Mining Waste

Radioactive elements (also known as radionuclides or radioisotopes) are (1) naturally occurring and have varying activity levels based on the native soil and geology type, (2) can be concentrated through human activity such as mining and mineral processing, and (3) can be present in mining waste. The U.S. Environmental Protection Agency (USEPA) memorandum entitled “Potential for Radiation Contamination Associated with Mineral and Resource Extraction Industries” (USEPA 2003, 2) expands on this point:

> Radioactive contaminants at mines or mineral processing/manufacturing facilities are often overlooked in site assessments, inspections, site investigations, environmental impact statements, or site cleanups. Such omissions may occur because the radioactivity is unexpected or because the principal mineral(s) being mined or processed were not suspected to be radioactive. However, the geological emplacement or geothermal phenomena which formed other valuable minerals may have also concentrated radioactive minerals as well, or the process of mining, beneficiation, and milling may have resulted in a concentration of the radioactive minerals in the waste. In some instances, the mineral(s) being mined may have radioactive elements included in their molecular structure which imparts radioactivity to the ore or even the finished product.

Common radioactive elements include uranium, thorium, and their decay products, radium and radon. Radon gas is a known carcinogen that can lead to lung cancer; thus, human exposure to radionuclides that produce radon gas as a decay product is often a driving concern when dealing with radioactive elements.

Naturally occurring radioactivity is commonly referred to as naturally occurring radioactive material (NORM). Human activities that have concentrated or increased exposure to NORM are commonly referred to as technology-enhanced naturally occurring radioactive material (TENORM). Both NORM and TENORM require careful management to minimize health and environmental risks associated with their presence for the following reasons:

- **Radiation Exposure Risk.** NORM and TENORM contain radioactive elements that can pose health risks if not properly managed. Assessing their presence helps in determining potential radiation exposure risks to workers and the environment.

- **Regulatory Compliance.** Presence of applicable or relevant and appropriate regulations regarding the handling of radioactive materials. By assessing NORM or TENORM in mining waste, stakeholders can ensure they comply with these regulations. Regulatory considerations are discussed in Section 3.4.

- **Environmental Impact.** Understanding the levels of NORM or TENORM in mining waste helps in the evaluation of potential environmental impacts when considering waste reuse applications.

- **Worker Safety.** Identifying the presence of radioactive materials is crucial for ensuring worker safety. Proper measures can be implemented to minimize exposure risks during the reuse of mining waste.

- **Public Health.** Assessing NORM or TENORM in mining waste reuse applications is important to safeguard public health, as any release of radioactive materials into the environment can have long-term consequences.

A project description emphasizing the need for careful management of NORM and TENORM waste is presented in Section 6.1.3.4 which discusses the Denver Radium Site and Uranium Mill Tailings Remedial Action sites in Colorado where legacy uranium and radium wastes were used in concrete aggregate due to poor planning and a lack of characterization, which led to increased public health risks.

Overall, the need for radiological surveys and/or testing may warrant further consideration to make informed decisions about the beneficial reuse of mining waste reuse. Radiological testing methods are described in Section 3.1.4.5.

Additional information can be found at the following links:

- USEPA web page on TENORM (USEPA 2014e)

- USEPA web page on Abandoned Mine Lands: Policy and Guidance (USEPA 2015a)

- USEPA 2008 Technical Report on Technologically Enhanced Naturally Occurring Radioactive Materials from Uranium Mining (USEPA 402-R-08-005)

    - Volume 1 – Mining and Reclamation Background (USEPA 2008b)

    - Volume 2—Investigation of Potential Health, Geographic, And Environmental Issues of Abandoned Uranium Mines (USEPA 2008c)

- USEPA 2003 Memorandum on Potential for Radiation Contamination Associated with Mineral and Resource Extraction Industries (USEPA 2003)

- Multi-Agency Radiation Survey and Site Investigation Manual or MARSSIM (USEPA-402-P-20-001) (USEPA 2015b)

3 SOLID MINING WASTE REUSE CONSIDERATIONS

For potential reuse of solid mining waste, a thorough evaluation of the material must be conducted, both of the material itself and the conditions surrounding its potential reuse.

A thorough physical, chemical, mineralogical, radiological, and toxicological assessment of the solid waste is necessary to understand the material (Section 3.1). This information contributes to the overall economic evaluation of a reuse project, such as for extracting additional minerals (Section 3.2). This characterization is necessary to identify contaminant limitations for the proposed application; limitations can be specific to a site, such as a numerical remediation goal, other type of cleanup criteria set for a specific site, or various applicable state, tribal, or federal regulations. A waste that may have appropriate characteristics for one application may be unsuitable for another application; depending on how and where the material is used, a chemical or physical reaction may occur that could cause a material to transition from a stable form to a mobile form, becoming a leached contaminant. An LCA and risk assessment for the current status of the waste and the proposed reuse application may be needed to evaluate existing and potential unintended risks (Section 3.3). Specific regulations exist governing the potential reuse of solid mining waste based on known human and environmental risk (Section 3.4). Additional community engagement and environmental justice needs should be considered when evaluating solid mining waste reuse options (Section 3.5).

3.1 Waste Characterization

For potential reuse of solid mining waste, a thorough evaluation of the characteristics of the material is needed to ensure the material can be reused appropriately. Integrated approaches combining multiple characterization methods are often employed to obtain a comprehensive understanding of solid mining waste. This allows for a holistic assessment of physical, geochemical, mineralogical, radiological, and toxicological properties. Testing methods will depend on the mining waste type, test objectives, and the availability, completeness, and reliability of previous test results. The data obtained from these characterization methods are used to inform waste management strategies, understand the resource recovery potential and economic value, identify potential technologies needed for reprocessing, develop reclamation or remediation plans, and mitigate the potential environmental and human health risks associated with mining waste.

3.1.1 Characterization Goals

Key goals of solid mining waste characterization include identifying possible resources for recovery, providing data for the environmental risk assessment, and ensuring compliance with applicable regulations. These goals concern the composition of the waste, the methods for evaluating the waste, the potential ways it may react in a new application, and appliable regulatory requirements. The primary goals for characterization may vary significantly among sites; for instance, an owner of an active mine may be seeking to understand whether the waste stockpile has an economically viable composition of minerals for sale, whereas the responsible party for an abandoned mine may be seeking to offset remediation costs by reusing waste material for capping while complying with cleanup regulations. Potential characterization goals are discussed below:

- **Resource recovery potential.** Solid mining waste characterization can provide insights into the potential for resource recovery from the waste material. By analyzing the waste for its mineralogical, chemical, and physical characteristics, it is possible to identify whether it has economically viable resources that can be extracted or recovered. Understanding this information about waste resources facilitates the development of a reuse plan that considers the material’s characteristics, appropriate processing methods, and requirements for additional capital investment. Additionally, this information can reduce the need for additional mines, as waste materials are treated as potential resources, reducing environmental impacts. For instance, national programs like the U.S. Geological Survey (USGS) Earth Mapping Resources Initiative provide information regarding characterization to assess potential critical mineral resources, including critical minerals from mining waste (USGS 2024a; Lederer et al. 2024).

- **Acid generation potential and leachability.** Solid mining waste characterization can help determine the potential for acid generation and metal leachability of the waste. This type of characterization assesses the stability, reactivity, and long-term behavior of mining waste. Acid generation potential and leachability in mining waste can be simultaneously beneficial and harmful, which is why this type of characterization is important to make informed waste management and reuse decisions. Some types of mining waste contain minerals that have become oxidized and reduced in particle size, making them more reactive and leachable and increasing the potential for acid generation. The presence of acid-generating materials can also increase the leachability of desirable minerals in the mining waste. This could be beneficial, if leaching can be limited to the minerals of interest, or harmful, if there is leaching of toxic contaminants instead or along with the desired minerals. For instance, the presence of acid-generating sulfide minerals in mining waste, such as pyrite, can lead to AMD, which can have environmental consequences and limit potential reuse applications; however, leachability may also be beneficial for recovery of trace gold and silver that also reside within the mining waste.

- **Environmental risk assessment.** Solid mining waste characterization allows for the assessment of potential environmental risks associated with the waste material, such as acid generation potential (above). Analyzing the waste for a range of physical and chemical parameters helps in the identification of potential contaminants, their concentrations, and their ultimate fate and transport. The exposure pathways and potential risks can differ based on the media (such as solid or liquid). This information is crucial for evaluating the potential impact of the waste on human and ecological risk receptors. It also enables the development of appropriate waste management and remediation strategies to minimize risks. Characterization allows for the risk assessment of both the current environmental risk of the material and site as well as potential future environmental risk for possible applications (see Section 3.3.1). Additionally, the treatment materials and by-products associated with transforming the waste into a new application will need to be evaluated in the environmental risk assessment.

- **Communication with stakeholders.** The results of testing may be shared publicly as part of regulatory requirements or as part of generating public interest in the project. This may help with gaining public support for a reuse project by demonstrating that chemicals of potential concern are below maximum contaminant levels, or that elevated levels causing concern are known and being contained or treated.

- **Compliance with regulations.** Solid mining waste testing helps to ensure compliance with environmental regulations and standards. Many jurisdictions have specific guidelines and limits for the management and disposal of mining waste. These regulations may vary, depending on the status of the mine as active, inactive, abandoned, or closed. The current characterization may be limited because of a focus on specific minerals, site history, regulatory orders, or abandonment prior to current regulations, requiring additional testing to be done. Additional characterization can provide more thorough information for regulatory compliance for alternate stages of waste disposal or waste reuse. By conducting comprehensive testing, responsible parties and government entities can determine whether the waste material meets the regulatory requirements for reuse in a new application and whether permits are needed. With the data for compliance, it is then possible to implement appropriate treatment, containment, and disposal or reuse. For further information about regulatory considerations, see Section 3.4.

- **Assessing the feasibility of mining waste reuse as part of remediation.** Characterization of a Comprehensive Environmental Response Compensation, and Liability Act (CERCLA)-regulated or state-regulated solid mining waste site allows for the assessment of off-site reuse alternatives and compliance with federal and state off-site rules for hazardous waste management. During the feasibility study phase of a contaminated site, cleanup alternatives are proposed and evaluated to address cleanup requirements. Adequately characterizing a site's mining waste source during the remedial investigation phase allows for the identification and evaluation of on-site and off-site cleanup alternatives that involve solid mining waste reuse as all or part of a remedy. Waste characterization results for the appropriate chemicals of concern (for example, metals associated with mining) provide a numerical comparison to regulatory cleanup action levels for those chemicals. For example, a cleanup alternative may include a repository to contain waste materials; if other available on-site mining waste is appropriately characterized and found to have acceptable parameters, it could be used as the cover material instead of using imported materials (see Sections 6.2.2 and 6.2.7).

3.1.2 Characterization Constraints

In order to characterize solid mining waste, evaluation plans need to be made specific to the material and site conditions. Several aspects that characterization plans should consider are given below:

- **Site Access.** To even begin to test waste material, the site must first be accessed. Site access depends on the legal ownership of the site and authorization to enter and collect samples. Particularly at abandoned sites, unknown hazards such as unsafe geotechnical conditions or contaminants may be present that must be evaluated before proceeding to fully characterizing the waste.

- **Sampling considerations.** The representativeness of the samples collected can influence the accuracy and reliability of test results. Solid mining waste testing is subject to sampling variability, as it is often not possible to collect samples from every part of the waste pile or deposit. The heterogeneity in composition and characteristics (including grain size) of the waste material within the deposit may not be fully captured by a limited number of samples collected, and a method, such as incremental sampling methodology, may be needed (ITRC 2020). It is important to carefully plan and execute the sampling process to minimize this limitation.

- **Cost and time constraints.** Sampling and analysis can be costly and time-consuming, especially when comprehensive testing is required. Analyzing samples for multiple parameters, conducting leachability tests, and performing detailed mineralogical analysis can involve significant expense and may require specialized laboratory facilities and expertise. Additionally, the time required to collect samples, prepare them for analysis, and obtain the test results can potentially slow down or delay decision-making processes related to waste management and remediation. Cost and time constraints also depend on the status of the site and the party evaluating potential reuse. For example, the owner of an active or inactive mine may be considering characterization costs in the context of investment for potential revenue generation or reduced liability. In contrast, a responsible party for an abandoned mine with environmental contamination may be focused on cost-effective characterization while meeting project timeframes and cleanup goals. Initial planning and defining project scope and timelines can allow for cost and time-frame constraints to be met while characterizing solid mining waste for reuse.

- **Predictive capability and application limitations.** Solid mining waste testing provides valuable information about the current composition and characteristics of the waste material; however, it has predictive capability limits regarding long-term behavior and potential environmental impacts. For example, the testing may not account for future changes in environmental conditions related to climate change or changes in land use. Test results should be interpreted with caution and supplemented with other methodologies, such as modeling and monitoring, to further understand the long-term fate and behavior of the waste material. The usefulness of the testing results may depend on the intended waste reuse application; the appropriate characteristics for one application may be inappropriate for another application.

3.1.3 Common Sampling Types

It is important to carefully select the appropriate sampling practice based on the specific objectives, known or suspected characteristics of the mining waste material, and the desired level of accuracy and representativeness. Proper sampling techniques are crucial to ensure that the collected samples accurately reflect the composition and characteristics of the mining waste, which in turn helps in making informed decisions regarding waste management and environmental impact assessment. Here are several mining waste sampling collection types that are commonly used to obtain representative samples for analysis.

- **Grab sampling.** Grab sampling involves collecting a small sample of mining waste material at a specific location and time. This method is typically quick and easy to perform, but it may not provide a representative sample of the entire waste pile or deposit. Grab sampling is often used for preliminary assessments or when time and resources are limited. Grab sampling can be used for both solids and liquids.

- **Core sampling.** Core sampling involves drilling or auguring a cylindrical core from the mining waste material. This method allows for the collection of a vertical profile of the waste pile or deposit, providing information about the lithostatic composition as it varies with depth. Core sampling is commonly used when a detailed analysis of the waste material is required.

- **Composite sampling.** Composite sampling involves collecting multiple grab samples from different locations within the waste pile or deposit and combining them to create a representative composite sample. This method helps minimize sampling and spatial variability and provides a representation of the average composition of the waste material. This type of sample collection can also be used for assay sampling where grab samples are collected from a desirable mineral or metal present in the waste material. The grab samples are then crushed, ground, and homogenized to create a representative composite sample for analysis. Assay composite sampling is typically conducted to assess the economic viability of extracting valuable metals from the waste. Regulations may require evaluating a specific area for comparison to numerical standards, in which case composite sampling may not be sufficient. Incremental sampling methodology is a structured sampling and data processing protocol to identify representative concentrations over a defined area or volume (ITRC 2020).

3.1.4 Common Testing Methods

This section describes common physical, geochemical, mineralogical, acid-base accounting (ABA), radiological, and toxicological methods used to characterize solid mining waste, both solid material and mining-impacted liquids with recoverable solids. Table 3-1 provides a summary of methods with standards. Many additional methods exist and can be found in other sources, such as the International Network of Acid Prevention's Global Acid Rock Drainage Guide (GARD Guide) (INAP 2018).

Table 3-1. Common physical, geochemical, mineralogical, acid-base accounting, radiological, and toxicological methods and standards

Media	Analysis	Publishing Organization	Standard Number	Standard Title
Physical Characterization				
Solids	Particle size	ASTM International	ASTM D6913-04	Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis (ASTM International 2017)
		ASTM International	ASTM C136-06	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (ASTM International 2015)
Solids	Density	ASTM International	ASTM D7263-21	Standard Test Methods for Laboratory Determination of Density and Unit Weight of Soil Specimens (ASTM International 2021d)
Solids	Porosity	ASTM International	ASTM D4404-18	Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry (ASTM International 2018b)
Solids	Permeability	ASTM International	ASTM D2434-22	Standard Test Methods for Measurement of Hydraulic Conductivity of Coarse-Grained Soils (ASTM International 2022b)
		ASTM International	ASTM D5084-16a	Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter (ASTM International 2016)

Media	Analysis	Publishing Organization	Standard Number	Standard Title
Solids	Compaction	ASTM International	ASTM D698-12R21	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3 (600 kN-m/m^3)) (ASTM International 2021b)
		ASTM International	ASTM D1557-12R21	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3 (2,700 kN-m/m^3)) (ASTM International 2021c)
Solids	Durability/ hardness	ASTM International	ASTM E18-22	Standard Test Methods for Rockwell Hardness of Metallic Materials (ASTM International 2022e)
		ASTM International	ASTM C1895-20	Standard Test Method for Determination of Mohs Scratch Hardness (ASTM International 2020b)
Liquids	Density	ASTM International	ASTM D7777	Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Portable Digital Density Meter (ASTM International 2018d)
		ASTM International	ASTM D4052	Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter (ASTM International 2022c)
Liquids	Turbidity	American Public Health Association (APHA)	APHA 2130 2023 Standard Methods	2130 Turbidity (APHA 2017a)

Media	Analysis	Publishing Organization	Standard Number	Standard Title
Liquids	Solids	APHA	APHA 2540 2023 Standard Methods	2540 Solids (APHA 2017b)
Geochemical Characterization				
Solids	Elemental composition	ASTM International	ASTM E1621-22	Standard Guide for Elemental Analysis by Wavelength Dispersive X-Ray Fluorescence Spectrometry (ASTM International 2022f)
		USEPA	USEPA Method 6200	SW-846 Test Method 6200: Field Portable X-Ray Fluorescence Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment (USEPA 2007a)
Solids/ Liquids	Elemental composition	USEPA	USEPA Method 6010D	SW-846 Test Method 6010D: Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) (USEPA 2018f)
Solids/ Liquids	Elemental composition	USEPA	USEPA Method 6020B	SW-846 Test Method 6020B: Inductively Coupled Plasma – Mass Spectrometry (USEPA 2014d)
Solids/ Liquids	Elemental composition	USEPA	USEPA Method 7000B	SW-846 Test Method 7000B: Flame Atomic Absorption Spectrophotometry (USEPA 2007b)
		USEPA	USEPA Method 7010	SW-846 Test Method 7010: Graphite Furnace Atomic Absorption Spectrophotometry (USEPA 1998)

Media	Analysis	Publishing Organization	Standard Number	Standard Title
Solids	Rare earth element detection	Peer-Reviewed Publication: *Talanta*, Vol. 8	Savvin, 1961	Analytical Use of Arsenazo III: Determination of Thorium, Zirconium, Uranium and Rare Earth Elements (Savvin 1961)
Solids/ Liquids	Carbonyl compounds	USEPA	USEPA Method 8315A	SW-846 Test Method 8315A: Determination of Carbonyl Compounds by High Performance Liquid Chromatography (USEPA 1996b)
Solids/ Liquids	Elemental leachability	USEPA	USEPA Method 1312	SW-846 Test Method 1312: Synthetic Precipitation Leaching Procedure (USEPA 1994c)
Solids/ Liquids	Elemental leachability	USEPA	USEPA Method 1311	SW-846 Test Method 1311. Toxicity Characteristic Leaching Procedure (USEPA 1992)
Solids	Elemental leachability (long term)	ASTM International	ASTM D5744-18	Standard Test Method for Laboratory Weathering of Solid Materials Using a Humidity Cell (ASTM International 2018c)
Liquids	Organics (natural)	ASTM International	ASTM D7573-18ae1	Standard Test Method for Total Carbon and Organic Carbon in Water by High Temperature Catalytic Combustion and Infrared Detection (ASTM International 2019)
		ASTM International	ASTM D4129-05	Standard Test Method for Total and Organic Carbon in Water by High Temperature Oxidation and by Coulometric Detection (ASTM International 2020d)

Media	Analysis	Publishing Organization	Standard Number	Standard Title
		ASTM International	ASTM D1252-06	Standard Test Methods for Chemical Oxygen Demand (Dichromate Oxygen Demand) of Water (ASTM International 2020c)
Mineralogical Characterization				
Solids	Mineralogy	Peer-reviewed Publication: *Minerals*, Vol. 12	Ali et al. 2022	X-Ray Diffraction Techniques for Mineral Characterization: A Review for Engineers of the Fundamentals, Applications, and Research Directions. (Ali, Chiang, and Santos 2022)
Solids	Mineralogy and elemental composition	Peer-reviewed Publication: *Applied Sciences*, Vol. 13	Ali et al. 2023	Mineral Characterization Using Scanning Electron Microscopy (SEM): A Review of the Fundamentals, Advancements, and Research Directions (Ali, Zhang, and Santos 2023)
Solids	Mineralogy	Peer-reviewed Publication: *Minerals and Materials Characterization & Engineering*, Vol. 2	Gu 2003	Automated Scanning Electron Microscope Based Mineral Liberation Analysis. An Introduction to JKMRC/FEI Mineral Liberation Analyser (scrip.org) (Gu 2003)
Solids	Petrography	Textbook: *Mineralogy*	Perkins 2020	Chapter 5: Optical Mineralogy (Perkins 2020)
Acid-Base Characterization				
Solids	Acid-base accounting (ABA)	Peer-reviewed Publication: *Geoderma*, Vol. 308	Skousen 2017	A Methodology for Geologic Testing for Land Disturbance: Acid-Base Accounting for Surface Mines (Skousen 2017)
		International Network for Acid Prevention	INAP	Global Acid Rock Drainage Guide (INAP 2018)

Media	Analysis	Publishing Organization	Standard Number	Standard Title
Radiological Characterization				
Solids	Gamma radiation	International Atomic Energy Agency	IAEA-TECDOC-1363	Guidelines for Radioelement Mapping Using Gamma Ray Spectrometry Data (IAEA 2003)
Solids	Alpha radiation	ISO	ISO/DIS 23548	Measurement of Radioactivity—Alpha Emitting Radionuclides—Generic Test Method Using Alpha Spectrometry (ISO 2024)
Solids	Beta radiation	UR-Energy USA	ASTM STP47436S	Chapter 18: Practices for Measurement of Radioactivity (ASTM International 1978)
Solids	Radiographic imaging	ASTM International	ASTM E1742/E1742 M-18	Standard Practice for Radiographic Examination (ASTM International 2024a)
Toxicological Characterization				
Solids/ Liquids	Metals	USEPA	USEPA Method 6010D	SW-846 Test Method 6010D: Inductively Coupled Plasma–Optical Emission Spectrometry (ICP-OES) (USEPA 2018f)
			USEPA Method 6020B	SW-846 Test Method 6020B: Inductively Coupled Plasma–Mass Spectrometry (USEPA 2014d)
			USEPA Method 7470A	SW-846 Test Method 7470A: Mercury in Liquid Waste (Manual Cold-Vapor Technique) (USEPA 1994d)

Media	Analysis	Publishing Organization	Standard Number	Standard Title
			USEPA Method 7471B	SW-846 Test Method 7471B. Mercury in Solid or Semisolid Wastes (Manual Cold-Vapor Technique) (USEPA 2007c)
Solids/ Liquids	Organics	USEPA	USEPA Method 8270E	SW-846 Test Method 8270E: Semivolatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC-MS) (USEPA 2018h)
		USEPA	USEPA Method 8260D	SW-846 Test Method 8260D: Volatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC-MS) (USEPA 2018g)
		USEPA	USEPA Method 8081B	SW-846 Test Method 8081B: Organochlorine Pesticides by Gas Chromatography (USEPA 2007e)
Solids	Organics	USEPA	USEPA Method 8151A	SW-846 Test Method 8151A: Chlorinated Herbicides by Gas Chromatography (GC) Using Methylation or Pentafluorobenzylation Derivatization (USEPA 1996a)
			USEPA Method 8015C	SW-846 Test Method 8015C: Nonhalogenated Organics by Gas Chromatography (USEPA 2007d)
Solids	Asbestos	ASTM International	ASTM D7521-22	Standard Test Method for Determination of Asbestos in Soil (ASTM International 2022d)

Media	Analysis	Publishing Organization	Standard Number	Standard Title
Solids/ Liquids	Leachability	USEPA	USEPA Method 1311	SW-846 Test Method 1311: Toxicity Characteristic Leaching Procedure (USEPA 1992)
			USEPA Method 1312	SW-846 Test Method 1312: Synthetic Precipitation Leaching Procedure (USEPA 1994c)
Solids	Flashpoint	USEPA	USEPA Method 1010B	SW-846 Test Method 1010B: Test Methods for Flash Point by Pensky-Martens Closed Cup Tester (USEPA 2018d)
			USEPA Method 1020C	SW-846 Test Method 1020C: Standard Test Methods for Flash Point by Setaflash (Small Scale) Closed-Cup Apparatus (USEPA 2018e)
Solids	Ignitability	USEPA	USEPA Method 1030	SW-846 Test Method 1030: Ignitability of Solids (USEPA 2014c)
Solids	Corrosivity	USEPA	USEPA Method 9040C	SW-846 Test Method 9040C: pH Electrometric Measurement (USEPA 2004b)
			USEPA Method 1110A	SW-846 Test Method 1110A: Corrosivity Toward Steel (USEPA 2004a)

3.1.4.1 Physical Characterization Methods

Physical characterization methods describe the physical properties of mining waste materials, which influence the stability, transportability, potential for erosion, and the geochemical characteristics of mining waste materials. These properties include particle-size distribution, density, porosity, permeability, compaction, and durability/hardness characteristics. These characteristics primarily focus on solids but can include solids recovered from liquids.

- **Particle size.** Particle-size distribution analysis is used to determine the range and distribution of particle sizes in mining waste materials. This information is important for understanding the material's physical characteristics, such as its texture, grading, and potential for compaction. The analysis is typically conducted using techniques such as sieve analysis. The waste material is passed through a series of sieves with different mesh sizes, and the amount of material retained on each sieve is measured (ASTM International 2015; 2017). The results are presented as a particle-size distribution curve, which shows the percentage of material in each size range. Figure 3-1 is an example of a particle-size distribution chart.

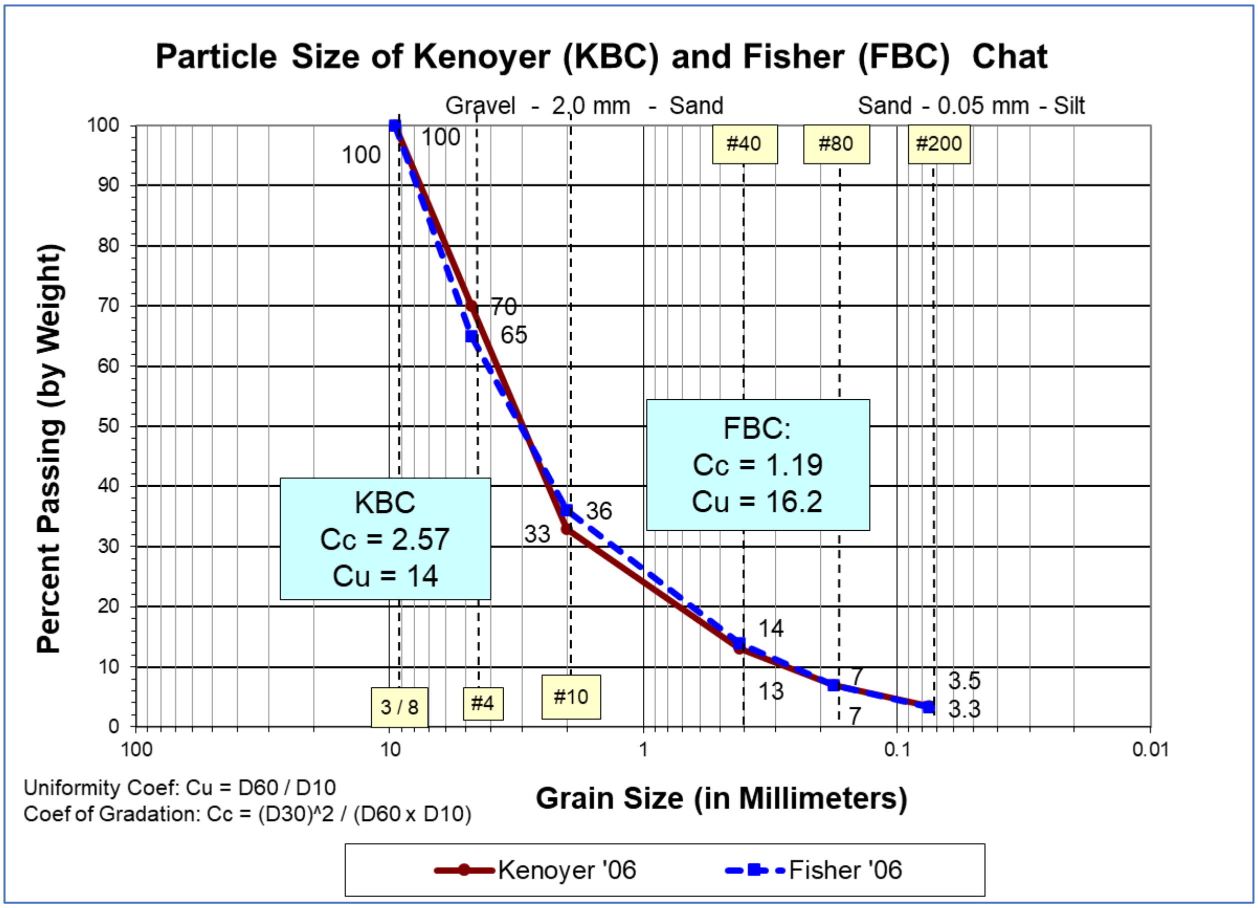


Figure 3-1. Particle-size distribution for chat samples from two chat piles at the Tar Creek Superfund Site.

Source: Oklahoma Department of Environmental Quality

- **Density.** Density measurement is used to determine the mass per unit volume of mining waste materials. It provides information about the material's compactness and can be used to estimate its weight and volume. The density of mining waste can be measured using various methods, including the water displacement method, where the material is submerged in water and the volume of water displaced is measured, or the direct measurement method, where the mass and volume of the material are measured directly (ASTM International 2021d).

- **Porosity and permeability.** Porosity and permeability assessment is used to evaluate the void spaces and the ability of fluids (such as water or air) to flow through mining waste materials. Porosity refers to the percentage of void spaces within the material, and permeability refers to the ease with which fluids can flow through the material. These properties are important for understanding the material's ability to retain or transmit water, air, or other fluids. Porosity can be determined via methods such as the water saturation method or the mercury intrusion porosimetry method. Permeability can be assessed through laboratory tests, such as constant head or falling head permeability tests (ASTM International 2016; 2018b; 2022b).

- **Compaction.** Compaction testing is used to evaluate the ability of mining waste materials to be compacted to achieve a desired density. Compaction is important for waste management and engineering purposes, as it can affect stability, settlement, and permeability. The testing involves compacting the waste material using standardized procedures, such as the Proctor compaction test or the modified Proctor compaction test. The compaction process involves applying a specified amount of energy to the material and measuring the resulting density. The test results provide information about the material's compaction characteristics, including the optimum moisture content and maximum dry density (ASTM International 2021b; 2021c).

- **Durability and hardness.** Common test methods include abrasion testing, compressive strength testing, Mohs hardness scale testing, and Rockwell hardness testing. Abrasion testing involves subjecting the waste material to abrasive forces, such as rubbing or grinding, and measuring the amount of material loss and provides an indication of the material's durability and resistance to wear. Compressive strength testing measures the ability of mining waste to withstand compressive forces by applying a gradually increasing load to a sample of the waste material and measuring the maximum load it can withstand before failure. The Mohs hardness scale is a qualitative scale that ranks minerals based on their relative hardness. Rockwell hardness is a quantitative test that measures the hardness of a material by measuring the depth of penetration of an indenter under a specific load (ASTM International 2020b; 2022e).

- **Density, turbidity, and solids content in liquids.** There are extensive methodologies for the analysis of water and wastewater (APHA, AWWA, and WRF 2023). Physical properties of interest for solids recovery of mining-impacted waters include density, turbidity, and solids that are dissolved and suspended. As with solids, density is a measurement of mass per unit volume. Turbidity, total dissolved solids, and total suspended solids provide information regarding particulates of different sizes and solubility. These solids can be removed by different physical and chemical properties for water treatment and material recovery (APHA 2017a; 2017b; ASTM International 2018d; 2022c).

3.1.4.2 Geochemical Characterization Methods

Geochemical testing methods, such as X-ray fluorescence (XRF), inductively coupled plasma (ICP), inductively coupled plasma–mass spectrometry (ICP-MS), and atomic absorption spectrometry (AAS), are commonly used to analyze the chemical composition of mining waste. These methods provide valuable information about the presence and concentration of various elements in the waste material.

- **X-ray fluorescence (XRF).** XRF is a nondestructive analytical technique that measures the elemental composition of a sample. It works by bombarding the sample with X-rays, which causes the atoms in the sample to emit characteristic fluorescent X-rays. The emitted X-rays are then detected and analyzed to determine the elemental composition of the sample. XRF is widely used in mining waste analysis to determine the concentrations of major and trace elements (ASTM International 2022f; USEPA 2007a).

- **Inductively coupled plasma (ICP).** ICP is a technique used to ionize elements in a digested or dissolved sample to measure their chemical concentrations. It involves introducing the sample into a high-temperature plasma (a gas that has been heated to a very high temperature) where the atoms are ionized. The ionized atoms are then quantified using optical emission spectrometry (OES) or MS.

    - **Inductively coupled plasma–optical emission spectrometry (ICP-OES).** ICP-OES employs ICP to produce excited atoms or ions that produce electromagnetic radiation; this radiation is specific to individual elements. The intensity of detection is correlated to concentrations of elements in the sample, which can all be measured simultaneously. ICP-OES is widely used for metals and trace element detection as well as minerals processing to provide data on the material grade. ICP-OES is also known as ICP-AES, for atomic emission spectroscopy (USEPA 2018f).

    - **Inductively coupled plasma–mass spectrometry (ICP-MS).** ICP-MS employs ICP with a mass spectrometer to atomize the sample. It allows for the simultaneous measurement of multiple elements and provides excellent sensitivity and detection limits. ICP-MS is particularly useful for the analysis of metals and nonmetals and for differentiating isotopes in liquid samples (USEPA 2014d).

- **Atomic absorption spectrometry (AAS).** AAS is a technique that measures the absorption of light by atoms in a sample digested or dissolved in an aqueous substrate. It works by passing the light of a specific wavelength through the sample and measuring the amount of light absorbed. The absorption is directly proportional to the concentration of the element being analyzed. AAS is commonly used for the analysis of specific elements, such as metals, in mining waste (USEPA 1998; 2007b).

- **High-performance liquid chromatography (HPLC).** An HPLC test involves the separation of a sample into a flowing liquid (mobile phase) and sorbents within a column (stationary phase). HPLC can identify compounds present in samples that can be dissolved in liquid to trace concentrations as low as parts per trillion (USEPA 1996a).

- **Synthetic precipitation leachate procedure (SPLP).** SPLP is a test of the mobility of both organic and inorganic analytes present in solids, wastes, and liquids. SPLP attempts to replicate the leaching of contaminants due to weathering in situ by rain or snowmelt (USEPA 1994c).

- **Toxicity characteristic leachate procedure (TCLP).** TCLP is a test of the mobility of both organic and inorganic analytes present in solids, wastes, and liquids. TCLP seeks to reproduce the leaching of contaminants in landfills due to exposure to typical landfill leachate (USEPA 1992).

- **Humidity cell testing (HCT) procedure.** HCTs are laboratory-scale leachability tests that are typically performed on drill cores, mining waste, or wall rock under oxidizing conditions. Unlike short-term tests like SPLP and TCLP, HCT is a long-term leachability test conducted over a period of weeks to estimate the leachate characteristics of analyzed material (ASTM International 2018c).

3.1.4.3 Mineralogical Characterization Methods

Mineralogical testing plays a crucial role in mining waste characterization to help understand the mineralogical composition, distribution, and potential environmental impacts of mining waste materials. Overall, mineralogical testing provides valuable data for designing effective waste management strategies and evaluating the potential for resource recovery from mining waste. Descriptions of several mineralogical testing methods is provided below:

- **X-ray diffraction (XRD).** XRD is a well-established technique that is used to determine mineralogy. XRD is based on how a beam of X-rays is diffracted by the crystalline structure of a mineral. The resulting diffraction patterns are compared to known minerals to identify the crystalline phases that are present. XRD analysis is typically done with a stationary instrument in a lab, but portable XRD devices have been developed to be used on-site. Lab-based instruments can give semiquantitative results but can be limited in their ability to quantify the percentage of a bulk sample or the composition. XRD has some limitations. It cannot identify amorphous phases, and it cannot provide the chemical composition of a mineral. Mineral chemistry can be determined using other methods such as electron microprobe (Ali, Zhang, and Santos 2023).

- **Scanning electron microscopy (SEM).** SEM is a high-resolution imaging technique that uses a focused beam of electrons to scan the surface of a sample. It provides detailed information about the morphology, texture, and elemental composition of the minerals present in the sample. SEM can be used to identify and characterize individual mineral grains, as well as to analyze the distribution and association of minerals within the mining waste materials (Ali, Zhang, and Santos 2023).

- **Mineral liberation analysis.** This is a quantitative mineralogical analysis technique that combines automated SEM with image analysis software. It provides detailed information about the liberation and association of minerals within a sample. Mineral liberation analysis can determine the mineralogy, grain-size distribution, and mineral liberation characteristics of mining waste materials. It is particularly useful for assessing the potential for mineral recovery from mining waste and optimizing mineral processing operations (Gu 2003).

- **Petrography.** Petrography yields information about relationships between ore, gangue, and secondary minerals (formed by weathering and oxidation) that may determine the suitability of a particular resource recovery technology. It can also be used to identify whether weathering has altered the outer layer of particles. Materials are assessed by chemical, physical, and mineralogical methods, including hand-sample observation and optical mineralogy of thin sections (Perkins 2020).

3.1.4.4 Acid-base Accounting (ABA) Methods

ABA is a method used in the context of mining waste characterization to assess the potential for AMD from the waste material. The ABA method involves measuring and calculating the acid-producing (AP) and acid-neutralizing potential of the mining waste material. It helps in determining whether the waste material has the potential to generate acidic drainage and the extent of acid generation (Skousen 2017).

Numerous methods exist such as the Sobek, Modified Sobek, or the Lapakko methods; they can be found in the International Network of Acid Prevention's GARD Guide, Table 5-1 (INAP 2018).

3.1.4.5 Radiological Characteristic Methods

Radiological testing methods are used to assess the presence and concentration of radioactive elements (such as uranium and thorium) in mining waste. Uranium and thorium may be present in different geologic materials such as fuel minerals, granite, monzonite, shale, and phosphates. Furthermore, certain radioactive elements (such as radium in coal) can become enriched during the processing and use of the host material (for example, coal combustion residuals). These methods help to evaluate the potential radiological hazards associated with the waste and when determining appropriate management strategies. Here are some common radiological testing methods for mining waste:

- **Gamma spectrometry.** Gamma spectrometry is a technique used to measure the gamma radiation emitted by radioactive isotopes in a sample. It involves placing the mining waste sample in a gamma spectrometer, which consists of a scintillation detector and a multichannel analyzer. The detector detects the gamma radiation emitted by the radioactive isotopes, and the multichannel analyzer measures the energy of the gamma rays. By analyzing the energy spectrum, the concentrations of specific radioactive isotopes, such as uranium, thorium, and their decay products, can be determined (IAEA 2003).

- **Alpha spectrometry.** Alpha spectrometry is a technique used to measure the alpha radiation emitted by radioactive isotopes in a sample. It involves dissolving the mining waste sample in an appropriate chemical solution and depositing the dissolved sample onto a detector surface. The detector measures the energy and number of alpha particles emitted by the radioactive isotopes. By analyzing the energy spectrum, the concentrations of specific alpha-emitting isotopes, such as radium and radon, can be determined (ISO 2024).

- **Beta counting.** Beta counting is a technique used to measure the beta radiation emitted by radioactive isotopes in a sample. It involves placing the mining waste sample in a beta counter, which consists of a gas-filled detector. The detector measures the number of beta particles emitted by the radioactive isotopes. By calibrating the detector with known standards, the concentrations of specific beta-emitting isotopes, such as strontium and cesium, can be determined (ASTM International 2024a).

- **Radiographic imaging.** Radiographic imaging, such as X-ray imaging or gamma imaging, is used to visualize the internal structure of mining waste and identify areas of potential radioactivity. It involves exposing the waste material to X-rays or gamma rays and capturing the transmitted radiation on a detector. The resulting image provides information about the distribution and concentration of radioactive isotopes within the waste (ASTM International 2024a).

3.1.4.6 Toxicological Characteristic Methods

Toxicological testing of mining waste involves assessing the potential health risks associated with exposure to metals, organics, asbestos, and emerging contaminants present in the waste material. This testing is important to evaluate the potential for contamination of soil, water, and air, and to determine appropriate measures for waste management and remediation. The following methods can provide insight into the toxicological characteristics of mining waste.

- **Metals testing.** Metals testing involves analyzing the mining waste for the presence and concentration of toxic metals such as lead, arsenic, mercury, cadmium, and chromium. This is typically done using laboratory techniques such as ICP-MS, ICP-OES, or AAS. The results of metals testing help in assessing the potential for metal toxicity and determining the appropriate remediation measures (USEPA 2014d; 2018g).

- **Organics testing.** Organics testing involves analyzing the mining waste for natural organics, such as dissolved organic carbon and chemical oxygen demand, and hazardous organic compounds, such as polycyclic aromatic hydrocarbons, volatile organic compounds, and pesticides. This is typically done using techniques such as GC-MS or HPLC. Natural organic compounds may mobilize or transform other materials under environmental conditions, such as inorganic mercury transforming to methylmercury. Organics testing helps in assessing the potential for organic compound toxicity and determining the appropriate remediation measures (USEPA 2007e; 2018g; 2018h).

- **Asbestos testing.** Asbestos testing involves analyzing the mining waste for the presence of asbestos fibers. Asbestos is a group of naturally occurring minerals that can cause serious health issues when inhaled. The testing typically involves microscopic examination of the waste material to identify and quantify asbestos fibers. Asbestos testing helps in assessing the potential for asbestos-related health risks and determining the appropriate remediation measures (ASTM International 2022d).

- **Leachability testing.** Leachability testing is conducted to assess the potential for contaminants to leach out of the mining waste material and contaminate the surrounding environment, such as soil and groundwater. This testing is important to evaluate the mobility and potential for migration of contaminants. Leachability testing involves subjecting the waste material to specific leaching conditions, simulating different environmental scenarios. The leachate is then analyzed for the presence and concentration of contaminants. Common leachability tests include TCLP and SPLP. Kinetic tests, such as HCT, are long-term dynamic leaching tests that mimic on-site variable geologic and weathering conditions of the waste rock or tailings. HCT tests reduce the uncertainty of the static leach tests (Maest and Nordstrom 2017). The results of leachability testing help in determining the appropriate waste management strategies, such as containment, treatment, or disposal. The results also aid in assessing the potential for environmental impacts and the need for remediation measures to protect human health and the environment (USEPA 1992; 1994c).

3.2 Economic and Market Considerations

The reuse of solid mining waste requires understanding the balance between what is technically achievable, economically feasible, and socially and environmentally acceptable. Project costs depend on the status of the mine and the goals of the responsible party considering solid mining waste reuse. Ideally, reuse of solid mining waste will generate income by creating a financial asset through additional resource recovery or product development and reduce potential remediation costs or long-term liability, rather than create a liability for a responsible party. However, the viability of a potential reuse project is commonly driven by economic, geopolitical, and market considerations, which can change rapidly (ITRC 2010). Therefore, it is recommended that an economic and technical feasibility evaluation be performed to assess market conditions, technology effectiveness and safety, vendor reliability, and availability.

Several components to consider when performing an economic and technical feasibility evaluation include but are not limited to the following:

- **Quantity of the mining waste material.** The amount of material that is available for potential reuse is a common limiting factor when assessing the viability of a reuse project.

- **Quality of the mining waste material.** The quality of the mining waste material is a major factor in determining its potential for resource recovery. For example, the metals concentration, or grade, within the waste material has a direct influence on whether it is technically and economically viable to extract further minerals. The higher the grade of ore, the higher the economic feasibility of the overall project.

- **Site access and rights.** Mineral and surface rights and permitting may be factors in cost evaluations for a potential site. See Section 6.2.8 for an example.

- **Location of the mining waste in relation to the processing equipment or facility.** A site may or may not have the space for necessary processing equipment. A unique waste composition may require more specialized processing, which could require a specialized facility rather than purchasing the equipment to conduct the processing on-site. Waste may have to be transported to a location for treatment and processing before reuse. See Section 6.2.7 for an example.

- **Location of the mining waste material in relation to the beneficial reuse location or facility.** A location that is remote and difficult to access can pose practical constraints on equipment and activities and increase transportation costs. For reuse of mining waste as construction materials or aggregate, the mining waste must typically be located within a reasonable proximity of urban areas or construction projects requiring the material (ITRC 2010).

- **Regulatory requirements.** The source and composition of a waste considered for reuse may or may not be restricted by federal, state, or local regulations, which can affect the cost for treatment and processing and the overall viability of a project. If the site or material is considered contaminated, treatment will be required to reduce contamination to required levels; however, resource recovery opportunities may offset the cost of treatment. See Section 3.4 for more information on regulatory considerations.

- **Processing and technology costs.** Different treatment processes will have different associated costs for solid mining waste reuse. See Section 5 for more information.

- **Buyer landscape.** The mining waste owner should survey interested buyers to identify needs for particular products that can be generated from solid mining waste. For example, REEs may need to be in specific forms for processing, and buyers may have needs and expectations when purchasing a recovered resource that affects the price.

- **Geopolitical effects on minerals and commodities.** Geopolitical risks, such as political instability and military conflicts or threats that can have regional or global impacts, can drive market demand associated with metal and mineral sales. Abundant resources (in other words, a flooded market) may limit the feasibility of a reuse project whereas a strong demand can make the reuse project economically viable.

- **Incentives for reuse of mining waste.** Grants, tax incentives, or other incentives may be available from local, state, or federal governments or from private sector and nonprofit groups to offset limitations such as cost associated with reuse of solid mining waste. The Infrastructure Investment and Jobs Act (a.k.a. Bipartisan Infrastructure Law [BIL]) enacted November 21, 2021, has provided funding for the U.S. Department of Energy (USDOE), U.S. Department of Defense (DOD), the U.S. Department of the Interior (USDOI), and the USEPA in part to address issues related to mining waste (U.S. Congress 2021). Mining activity status can determine eligibility for other incentives, such as abandoned mine programs (USEPA 2024a). Incentives may be through mining waste cleanup programs (USEPA 2024a; USDOI 2024b); critical mineral research and production, such as REEs (USDOE 2022; 2023b; USGS 2022a); or land reuse programs, such as renewable power generation (Macknick, Lee, and Melius 2013; USEPA 2011b; 2012).

3.3 Life-Cycle Analysis and Risk Assessment

Mining and metallurgical activities produce a considerable amount of waste that contains metals, metalloids, and other contaminants. As a result, mining waste facilities are associated with soil, surface water, and groundwater contamination that can pose a significant risk to both human health and the environment (Karachaliou et al. 2016). To minimize impacts, a comprehensive LCA and risk assessment and management approach allows for the selection of measures to minimize health hazards, use the site for new purposes, and secure the opportunity for resource recovery (Karachaliou et al. 2016).

Regardless of on-site or off-site reuses, it would be inappropriate to reuse mining wastes in a manner that leaves the material in a condition that may adversely affect human health or the environment. Solid mining waste includes different types of hazards, from physical hazards, such as dust, to toxicological hazards, such as metals, which can be released into the surrounding air, soil, and water without proper management (see Section 2.4). These hazards may persist or transform following the reuse of solid mining waste in another application in both short- and long-term durations. These hazards can cause harm to ecological receptors through the food chain, such as through bioaccumulation of metals (Das, Mallavarapu, and Ghosh 2023). To humans, these hazards can manifest themselves in acute or chronic manners resulting in a variety of diseases including but not limited to respiratory, cardiovascular, neurodegenerative, cancers, and chronic inflammation (da Silva-Rêgo, de Almeida, and Gasparotto 2022). Any reuse of solid mining waste must evaluate the potential environmental implications of the specific waste, processing, and reuse application to protect human health and the environment.

3.3.1 Life-Cycle Analysis

An LCA of mining waste measures the environmental impact of a material from extraction to end-of-life disposal. LCA considers all of the inputs and outputs of materials, energy, water, and emissions that occur in each stage of the life cycle and assesses their potential effects on different environmental impact categories, such as climate change, acidification, eutrophication, human toxicity, and land use. LCA is important in understanding the environmental implications of decisions and actions for mining operations. LCA can allow for comparison of various scenarios for potential use and disposal of mining waste, as well as comparison to new mining for needed resources; these scenarios can illustrate trade-offs in terms of different impact categories, such as carbon footprint, water consumption, or human or ecological toxicity (Biondini and Frangopol 2023). LCA is also used to identify possible improvements throughout the different stages of a product. For additional information on LCA, see the ISO Standard on Environmental Management—Life Cycle Assessment ISO 2020 (ISO 2020).

The development of a site-specific LCA differentiates the impacts occurring at a given location. Site-specific environmental impact assessment models increase the level of detail and accuracy of environmental assessments (Yao et al. 2021). LCAs have limited use for mining waste in part due to the difficulty of quantifying the various inputs and outputs involved (Norgate, Jahanshahi, and Rankin 2007); however, the development of a rigorous mining-specific LCA framework can support data collection that covers the temporal and spatial dimensions of mining (Awuah-Offei and Adekpedjou 2011). For instance, Yao et al. (2021) assessed the environmental impacts of a gold mine to determine the importance of off-site effects. The areas of protection were human health, ecosystem quality, and resource depletion. The results of the study confirmed the importance of considering both on-site and off-site impacts and the pertinence of including the LCA perspective in mining environmental impact assessments.

3.3.2 Ecological and Human Health Risk Assessment

The opportunities for solid mining waste reuse may be limited because of unacceptable risks to human health and the environment. Human health risks may be determined for residential, recreation, or industrial exposures. Environmental risks can be determined for broad groups of aquatic and terrestrial receptors or for specific species. Formal LCAs and risk assessments may be required under regulatory requirements, depending on the status of the site and applicable jurisdiction. To learn more about risk assessment, see USEPA's risk assessment resources (USEPA 2024f), as well as the Interstate Technology & Regulatory Council's (ITRC's) risk assessment resources (ITRC 2023).

An assessment of the potential impacts and risks associated with mining waste reuse and reprocessing alternatives should be developed and considered when selecting methods for processing and final applications. This assessment should examine potential impacts and risks over the life cycle of the reuse or reprocessing, including potential releases to the environment and exposures to workers and the public during these stages, as applicable:

1. Excavation and handling of material at its source
2. Transport to a location for reuse or reprocessing
3. Storage and handling at reuse or reprocessing location
4. By-products or waste from reprocessing (for example, residual after extraction)
5. Transport of product incorporating reused or reprocessed waste to the point of use
6. Possible exposures associated with product use (for example, using cement with waste added)
7. End-of-life of repurposed waste or product incorporating waste (for example, landfill, road foundation)

The assessment should include all contaminants and potential exposure pathways, the site condition and potential geochemistry changes that can occur following waste excavation for repurposing, and whether processing results in new or increased or decreased risks from the material or its residuals. It should also consider new human and ecological exposure pathways that may result from repurposing, reuse, or reprocessing. For example, is the material now more available for release to surface water, does the new use result in human dust exposures at new locations, or is the waste being reused in a product with reduced leaching potential, resulting in overall reduced risk and improvement of the site? In cases where reuse is a substitute for other material, for example agricultural lime, it is possible that the impacts and risks of use and beyond in the life cycle are no greater than the current practices. Consideration should be given to impacts and risks up to that point, including considering whether the source of the waste now has new potential impacts.

Although risk assessment estimates are subject to uncertainty, the risk-based approach provides a formal basis for evaluating and ranking potential hazards with respect to a branch of factors (for example, economic, social, political). Moreover, a risk assessment prioritizes local conditions and needs and directs the proposed solution toward the most suitable site- and time-specific actions so that the site is safe for its users until technological advancements and economic developments make the recovery of stored materials feasible. Beyond the mining waste, environmental risks may also be present at the site due to mining operation impacts, such as lubricant spills, PCBs (polychlorinated biphenyls), and residual dynamite from blasting, that impact the overall risk of a solid mining waste reuse project. Finally, a risk assessment assimilates different kinds of technical and nontechnical information, helps all parties involved (for example, competent authorities, site managers, and the public) understand the true dimensions of the problem, and thus minimizes any delays in the remediation actions required (Karachaliou et al. 2016). See Sections 6.1.1.1 and 6.2.1.

3.4 Regulatory Considerations

This section focuses on the environmental review, cultural resource, and regulatory considerations for mining and mining waste reuse within the United States. Mining sites and their associated wastes are located in varied environments and are subject to variable federal, state, and tribal regulations and authorities. These requirements depend on the site mining activity status (Section 3.4.1) and ownership of mineral and surface rights (Section 3.4.2), as well as environmental (Section 3.4.3) and cultural resource considerations (Section 3.4.4) that influence what regulations apply to a particular site. The site could be an active mine, an inactive mine, a closed mine, or an abandoned mine. The site could include surface or mineral rights that may be leased or owned by different parties than the operators. Additionally, the site could be environmentally benign or have contaminants hazardous to ecological receptors or human health. Navigating the pathway to reusing solid mining waste will be site specific. The following sections offer a more detailed discussion of the important characteristics to consider when evaluating the regulatory landscape of a potential reuse project. Figure 3-2 depicts federal regulatory acts related to mining waste reuse.

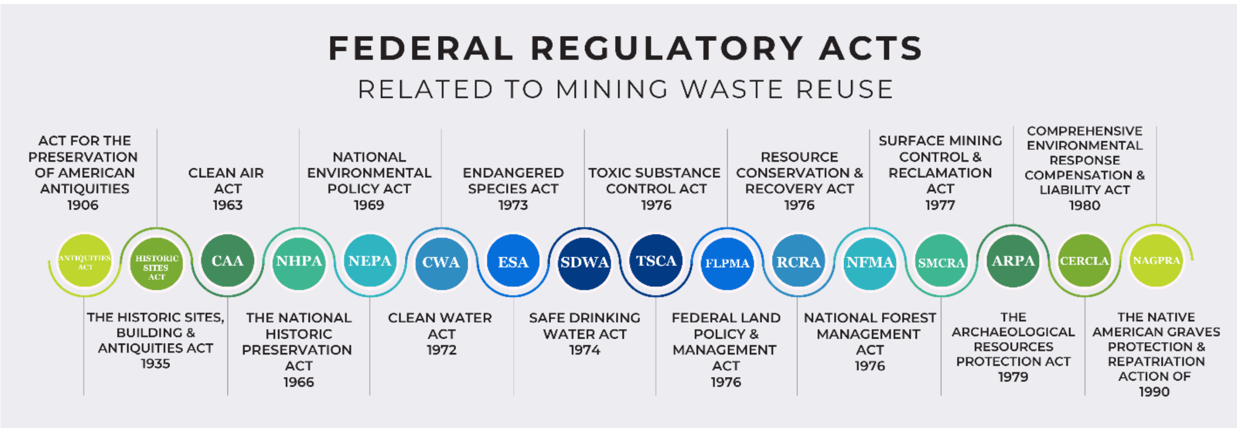


Figure 3-2. Federal regulatory acts related to mining waste reuse.

Source: Jessica Rayfield, Alabama Department of Environmental Management

Activities regarding worker health and safety, including waste characterization and processing, are governed under applicable regulations administered by the Mine Safety and Health Administration (MSHA) and the Occupational Safety and Health Agency; these regulations will not be discussed within this document.

3.4.1 Mining Activity Status

A mining site is defined by its mining activity status. The definitions of site activity may vary based on the regulatory authority or may be specific to an applicable program. This document categorizes mine sites as active mines, inactive mines, abandoned mines, or closed mines. Generally, for solid mining waste reuse, it is critical to determine whether the site is abandoned and whether a potentially responsible party (PRP) can be identified. If the site is abandoned, additional incentive programs are available that could provide funds for reclamation, which may include solid mining waste reuse as a strategy (see Section 4.3.3).

3.4.2 Ownership Rights—Mineral, Surface, and Water

The mineral and surface rights of a site may be held by no parties, one party, or multiple parties. Depending on land ownership and resource type, these rights may be owned or leased. Leased rights may have production requirements or may be limited to a set time frame. Due diligence should always be conducted to determine who owns the surface and mineral rights of a given site during the planning phase (BLM 2024). A summary of different types of rights to be considered is shown in Figure 3-3. See Section 3.4.2.2 for a detailed discussion on mineral and surface rights.

Figure 3-3. Mining mineral interest ownership.

An interactive version of Figure 3-3 is available on the web guidance version of this document at: https://mw-1.itrcweb.org/solid-mining-waste-reuse-considerations/#3.3

Source: Jessica Rayfield, Alabama Department of Environmental Management

3.4.2.1 Mineral Law

A detailed history of mineral law is beyond the scope of this document; however, a brief summary of mineral laws may be helpful in understanding the connection between mining and reusing mining waste at former and future mine sites.

The Mining Law of 1872 sets the stage for the exploration and acquisition of valuable mineral deposits in the United States. The interest in these materials led to subsequent laws, including the Mineral Leasing Act of 1920, the Materials Act of 1947, and the Mining and Mineral Policy Act of 1970. These federal laws are instrumental in promoting the development of a stable and lucrative mining sector while developing sustainable and responsible methods of mineral extraction and processing. Though the mining laws do not specifically cover reuse of mining waste, understanding mining law and subsequent mining practices may help identify opportunities for solid mining waste reuse.

A foundation for preventing needless or excessive degradation of public lands during mining and reclamation under the Mining Law is provided by the Bureau of Land Management (BLM) surface management regulations, issued under the Federal Land Policy and Management Act in 1981 and updated in 2001 (USDOI 1976). The National Historic Preservation Act (NHPA), the Endangered Species Act (USFWS 1973), the National Forest Management Act (USFS 1976), the Clean Water Act, the Clean Air Act, and other state and federal laws ensure that mining activities on public lands are conducted in environmentally responsible ways. Although the National Environmental Policy Act (NEPA) applies generally to mining on federal lands and mining of federally managed minerals, it does not apply to activities that cause little or no disturbance of public lands or resources. For mining and exploration activities, it is prudent to work with the BLM District or Field Office with jurisdiction over the land involved to ensure compliance with all federal requirements.

3.4.2.2 Mineral and Surface Rights

Understanding mineral rights is a crucial part of efficiently and effectively exploring the reuse of mining waste. Mineral rights can encompass various below-the-surface resources such as oil, natural gas, gold, silver, copper, iron, coal, uranium, and other minerals. Due to the long history and complexity of distribution of mineral rights in the United States, multiple mineral rights holders may be vested in different minerals within the same mining waste, and each rights holder could expect compensation or royalties from the extraction, use, or reuse of those minerals. Before reusing solid mining waste, any interested party should conduct a detailed search and seek legal counsel to determine the rights to all minerals known or potentially contained within the waste.

The rights to the minerals must be held to allow for the exploration of minerals found underneath the surface of a property (see Section 6.2.7). Surface rights differ from mineral rights in that surface rights allow ownership and control over only the surface of the land and do not necessarily include rights to the minerals underneath. When surface rights and mineral rights are held by different parties, this is referred to as a “split-estate.” In some states for the split-estate case, it is mandatory for mineral owners and surface owners to sign a “surface use agreement” that specifies their respective rights and obligations concerning the use of the land surface. The surface owner often has the rights to resources such as sand, gravel, and surface or groundwater when considered part of the surface estate. The distribution of surface and mineral rights varies from location to location and depends on local laws, individual property deeds, and historical land grants. When considering a mining waste reuse application, it is essential to first gain a clear understanding of the surface and mineral rights involved.

Another factor for mining waste reuse projects to consider is areas of federal and state-protected lands where mining may be strictly regulated or banned. For example, mining claims on federal lands cannot be situated in regions that have been “withdrawn” from mineral entry by a public land order, special act of Congress, or regulation. These include national parks, national monuments, tribal reservations, military reservations, areas used for scientific testing, the majority of the U.S. Bureau of Reclamation's reclamation projects, and the majority of the U.S. Fish and Wildlife Service’s wildlife protection areas. Mining claims are also forbidden on the territory that Congress has designated as a wild segment of a Wild and Scenic River or as a member of the National Wilderness Preservation System. Individual states may also designate areas where mining is not allowed, such as those designated for scientific and natural purposes, state parks, wildlife management, and recreational areas.

Each state has different protocols for approving the transfer of mining leases that encompass state-owned lands. By reviewing state rules and contacting the relevant state agency, one can acquire information about royalties payable under state mineral leases, assignment forms, and costs related to transfers of interest in state mineral leases. Minerals that are privately owned are usually leased to development companies, sometimes with an option to buy. The leases vary in length but are commonly for a finite term such as 5, 10, or 20 years. Some leases have a fixed duration that can be renewed, and others have a stated main period that can be extended by mining operations or production.

Reusing mining waste successfully, economically, and efficiently requires a thorough understanding of surface and mineral rights. Ownership by the state, federal, tribal, or private entity can dictate the process and requirements of the entire mining or mining waste reuse project. The interested party must perform a thorough search and may want to retain legal counsel to ascertain the rights to the minerals in the mining waste and ownership of the land surface before any reuse operations commence.

3.4.2.3 Water Rights

In addition to mineral rights and surface rights, any prospective project to reuse mining waste must also consider water needs. Water usage for mining is typically managed through allocation of water rights. Similar to mineral rights, allocation grants the use of water but does not denote ownership. Water rights are managed by the state and vary widely. Water rights are divided between surface water and groundwater, and most states have provisions for the inevitable overlap between the two.

The surface water management systems of today grew out of simple ideals and methods for sharing water that were developed by American settlers and early governments. Today these systems reflect the needs and uses of early America, and the variation among states is dictated primarily by the relative abundance of natural water supplies. Groundwater rights are managed in a manner similar to surface water rights, with special regulations when use of groundwater may impact existing surface water uses. Additional rules and requirements are placed on groundwater use to ensure that supplies are not diminished at rates faster than they can recover.

One large difference between groundwater rights and surface water rights is that surface water rights generally do not have to be exercised to be kept active. This policy, often termed “use it or lose it” is typically applied to groundwater and not surface water rights. This is not always the case, however, especially when interstate compacts between states are involved.

When considering water needs for a new mining waste reuse project, the most important thing to keep in mind is that water law, especially for groundwater rights, is a constantly evolving issue. A water right on paper, such as when transferring land ownership, is not necessarily a water right that can be fully exercised in the present day. Many communities are feeling the effects of decreasing water supplies, and community members may be weary of any new project that will increase industrial water uses regardless of how beneficial the project is from a mining waste reuse standpoint.

3.4.2.4 Site Access Considerations

Site access is an essential consideration for both private and public properties when developing successful reuse of solid waste mining projects. Site access is typically established in a formal document identifying liabilities that may arise directly or indirectly from a site activity. Site access documents, often called “access agreements” may cover, but are not limited to, vehicle access, sampling activities related to characterization, the extent of the site work, and the use of existing infrastructure (for example, connections to electrical power, potable water, etc.). Access agreements may also need to consider ongoing site activities such as active mining, clean up, or reclamation. Specifically, such agreements must ensure noninterference with ongoing remedial actions or remedial operations, accommodate long-term operation and maintenance requirements, and avoid spreading or exacerbating existing contamination in soil or groundwater.

It is crucial to identify and act upon site access requirements early in the project, as the process of executing the necessary agreements can be time-consuming and demanding. This is particularly true for sites that require interaction with multiple property owners who play a significant role in the site access process and therefore require additional planning time.

3.4.3 Environmental Review

The NEPA or a state NEPA-like environmental review process is an important element in the planning of a solid mining waste reuse project on public lands and, though not required, may have applicability to projects on private lands. An environmental review allows for the assessment of a proposed project prior to making decisions. This section introduces the environmental review process on a federal, state, and local level and highlights the importance of tribal input. The environmental review process could apply to proposed mining projects for new mines and the expansion of existing mines. The environmental review process equally applies to mining waste reuse projects. A cleanup managed under CERCLA would not require NEPA; however, CERCLA cannot manage mining waste reuse. That reuse would need to happen under a separate state or federal permit, and NEPA may be required as a component of that permitting process. Additionally, if a project is managed as a Resource Conservation and Recovery Act (RCRA) corrective action, an environmental review may not be necessary. Limited resources and materials on the environmental review process for mining waste reuse projects exist; therefore, this section does not go into the details of environmental review, but rather highlights the process and identifies applicable resources.

3.4.3.1 Federal Environmental Review—NEPA

NEPA came about in 1969 over concerns about the environmental impact of federal projects—specifically that projects could result in more harm than positive benefit. NEPA establishes requirements for federal agencies to assess the environmental effects (impacts) of proposed federal projects (or actions) prior to making key decisions regarding the project including whether to proceed with the project. NEPA established the Council on Environmental Quality (CEQ) as an executive office of the White House. The CEQ advises the president, establishes environmental policies, implements NEPA, and coordinates environmental reviews for infrastructure projects. The NEPA process includes evaluating whether a proposed project's environmental effects are significant. The process also includes input from state, local, and tribal governments, as well as public participation. The Surface Mining Control and Reclamation Act of 1977 created the abandoned mine land (AML) reclamation program and the Office of Surface Mining Reclamation and Enforcement (OSMRE) to specifically regulate the surface mining industry and enforce the act. OSMRE also must comply with NEPA requirements and provides the "Handbook on Procedures for Implementing the National Environmental Policy Act," which is specific to mining and includes information regarding AML sites (USDOI 2021).

The NEPA process applies to mining projects on federal lands. Resources on the environmental review process include the following:

- National Environmental Policy Act of 1969 (U.S. Congress 1969)
- The White House, Council on Environmental Quality (White House 2024)
- A Citizen's Guide to NEPA (CEQ 2021)
- USEPA, NEPA Home Page (USEPA 2024c)
- USEPA, Publication EPA/530/R-95/043; Background for NEPA Reviewers: Non-Coal Mining Operations (USEPA 1994e)
- National Environmental Policy Act / Office of Surface Mining Reclamation and Enforcement (USDOI 2024b)
- Handbook on Procedures for Implementing the National Environmental Policy Act (OSMRE 2019)

- USDOI Departmental Manual, 516 DM 13—Managing the NEPA Process—Office of Surface Mining (OSMRE 2004)

The CEQ's "A Citizen's Guide to NEPA" provides an overview of the process, as well as a description on navigating through the process. The USEPA's NEPA site offers information describing the requirements of NEPA and how they are met. The USEPA publication "Background for NEPA Reviewers: Non-Coal Mining Operations" lists mining activities and associated environmental impacts.

3.4.3.2 State and Local NEPA-like Environmental Planning Review Requirements

In addition to state input on the federal NEPA process, some states and local jurisdictions have a NEPA-like environmental review process. State NEPA-like processes vary from state to state and can apply to nonfederal projects within the specific state or local jurisdiction. The CEQ maintains a list of jurisdictions that have NEPA-like environmental planning review (Council on Environmental Quality 2024b). These state and local environmental review processes are similar to NEPA and typically identify whether a proposed project's impacts to human health and the environment are significant (Council on Environmental Quality 2024b).

3.4.3.3 Tribal Government Review

Federal and state laws, including NEPA, require tribal consultation on a government-to-government relationship. This section covers consultation requirements for government-to-government tribal participation to address traditional rights, as well as historical and cultural resources. These rights include traditional homelands where hunting, gathering, and religious activities occurred. In some treaties these traditional homelands are called "usual and accustomed" areas. The government-to-government participation includes recognizing the tribe as a sovereign nation. Many states may have similar requirements and may recognize tribes not on the federally recognized list. Many federal and state agencies have resources for assisting with tribal consultation. It is important to consult tribes before the project starts, during the course of the project, and after the project is completed (GSA 2023b).

Key tribal engagement requirements on a federal level include the following:

- 40 Code of Federal Regulations (CFR) Part 1501—NEPA and Agency Planning, see sections 1501.2 and 1501.7 Lead agencies (U.S. Congress 2020)
- Consultation and Coordination with Indian Tribal Governments, Executive Order 13175 of November 6, 2000 (U.S. President 2000)
- Tribal Consultation and Strengthening Nation-to-Nation Relationships, Memorandum of January 26, 2021 – 02075 (U.S. President 2021)
- Uniform Standards for Tribal Consultation, Memorandum of November 30, 2022 – 26555 (U.S. President 2022)

Resources on tribal engagement include the following:

- Government-to-government engagement (GSA 2023b)
- CEQ Guidance and Executive Orders Related to Native Americans (Council on Environmental Quality 2024a)
- USDOI, Bureau of Indian Affairs (BIA), Tribal Leaders Directory, provides a list of federally recognized tribes (USDOI BIA, n.d.)

- The National Conference of State Legislatures provides a list of states with dedicated committees on Indian affairs or state-tribal relations (National Council of State Legislatures 2021)

3.4.4 Cultural Resource Considerations

Consideration of cultural resources is an important part of mining waste reuse project success. Cultural resource considerations should be considered as part of the planning process and should be considered prior to making all project decisions—well before the start of a mining waste reuse project. Cultural considerations may include both non-mining-related and mining-related resources. Historical mine sites range from sites managed by the National Park Service (NPS) to historical sites managed by local government and nongovernmental organizations.

In addition to understanding cultural resources, it is critical to understand the laws that protect these resources. This section presents cultural resource regulatory requirements and other considerations related to cultural resources.

3.4.4.1 Federal and Tribal Lands Cultural Considerations

This section discusses archaeology and historic preservations laws that cover both federal public lands and tribal lands. The intent of the section is not to explain the laws in full, but rather to provide a high-level overview to help prompt the proper considerations on this subject. These laws include the following:

- **Act for the Preservation of American Antiquities (Antiquities Act).** The Antiquities Act was signed into law on June 8, 1906, and was the first federal law that protects cultural resources on federal lands. This law lays out the requirements for conducting archaeological investigations and identifies penalties for unauthorized activities (in other words, archaeological looting).

- **The Historic Sites, Building and Antiquities Act (Historic Sites Act of 1935).** This law established a national policy related to survey, research, and acquisition of historic and archaeological sites of national importance.

- **The National Historic Preservation Act (NHPA).** The NHPA of 1966 created a national program for the preservation of historic sites and a system for inventorying those sites that are significant on a national, state, and local level. Sites identified as significant typically result in a National Historic Site designation. A key section of the NHPA is Section 106, which requires federal agencies to consider the effects of projects on historic properties. The NHPA authorized the creation of the National Register of Historic Places, which is administered by the USDOI, NPS, which lists nationally important districts, sites, buildings, structures, and objects (NPS 2024b).

- **The Archaeological Resources Protection Act.** This act was signed into law on October 31, 1979. It provides for the protection of archaeological resources and sites on public and tribal lands.

- **The Native American Graves Protection and Repatriation Act of 1990.** This act identifies requirements for Native American human remains and other cultural artifacts to be planned for and safeguarded when they are transported from federal or tribal.

The two main agencies that offer extensive information on archaeological and historical cultural resources are the NPS and the Advisory Council on Historic Preservation.

The NPS provides descriptions of mining-related archaeological and cultural resource types, which helps the reader understand the wide range of cultural resources that may be encountered. This wide range of mining-related archaeological and cultural resource types includes mining and quarry operations from as far back as prehistoric times up to the modern era. These NPS mining-related archaeological and resource management categories include the following examples:

- **Archaeological resources,** such as a Native American stone quarry.
- **Cultural landscapes,** such as an abandoned mining settlement.
- **Structures and installations,** including examples like mining equipment, tailings, and adits.

Additional NPS resources that will aid individuals in identifying cultural resources at mining sites include the National Register Bulletin "Guidelines for Identifying, Evaluating, and Registering Historic Mining Properties" (Noble and Spude 1997).

In addition to the NPS, other federal land management agencies have staff and programs dedicated to cultural resources, including the BLM and the U.S. Forest Service. The Advisory Council on Historic Preservation maintains a list of Federal Preservation Officers and a list of Tribal Historic Preservation Officers.

Resources about federal law include the following:

- U.S. General Services Administration (GSA) Section 106: National Historic Preservation Act of 1966 (GSA 2023a)
- National Historic Preservation Act of 1966 (NHPA) (GSA 1966)
- NEPA and NHPA: A Handbook for Integrating NEPA and Section 106 Synopsis (Advisory Council on Historic Preservation 2024b)

Resources about Federal Historic Preservations Offices available online include the following:

- Federal Preservation Officer List (Advisory Council on Historic Preservation 2024a)
- Advisory Council on Historic Preservation (Advisory Council on Historic Preservation 2024c)

Resources from the NPS available online include the following:

- National Register of Historic Places (NPS 2024b)
- National Register of Historic Places FAQs (NPS 2024c)
- NPS, Abandoned Mineral Lands, Cultural Resources (NPS 2024a)
- NPS, National Register Bulletin 42, Guidelines for Identifying, Evaluating, and Registering Historic Mining Properties (Noble and Spude 1997)
- NPS Abandoned Mineral Lands, Servicewide AML Inventory (NPS 2023a)
- NPS Abandoned Mineral Lands, Understanding AML (NPS 2022a)
- NPS Archeology Laws, Regulations, and Guidelines (NPS 2023c)

- NPS Archeology, Antiquities Act (NPS 2023b)

Resources about Tribal Consultation and Tribal Historic Preservations Offices available online include the following:

- Consultation with Indian Tribes in the Section 106 Review Process: The Handbook, June 2021 (Advisory Council on Historic Preservation 2021)
- Role of the Tribal Historic Preservation Officer in the Section 106 Process (Advisory Council on Historic Preservation 2013)
- Native American Tribal Consultation (GSA 2023c)
- National Association of Tribal Historic Preservation Officers (National Association of Tribal Historic Preservation Officers 2024)
- National Association of Tribal Historic Preservation Officers, Tribal Historic Preservation Officer Directory (National Association of Tribal Historic Preservation Officers 2024)

3.4.4.2 State and Local Lands Cultural Considerations

The NHPA, under Section 106, requires federal agencies to identify who should participate in a Section 106 review; at a state level the consulting party typically includes the State Historic Preservation Officer (SHPO). In addition to consulting on Section 106 reviews, many states have a State Historic Preservation Office that is the primary agency within a state with duties specific to historic preservation and, commonly, cultural resources at historic sites of a state and local interest. SHPOs consult with tribal governments within a state regarding tribal cultural resources. Under the NHPA, SHPOs nominate historic properties for the National Register of Historic Places. In addition to their responsibilities at a national level, SHPOs are the contacts for a state-specific historic or heritage register for sites of state importance. The National Conference of State Historic Preservation Officers maintains a list of SHPOs.

Resources for SHPOs available online include the following:

- National Conference of State Historic Preservation Officers, SHPO Directory (National Conference of State Historic Preservation Officers 2024)

3.4.4.3 Private Lands Cultural Considerations

Archaeological and historical sites on private property may not be subjected to federal and state laws that govern archaeological resources on public lands. A private landowner can play an essential role in protecting archaeological resources for future generations. Your SHPO is an excellent resource for understanding the laws in your area and will be able to provide you with information regarding the protection of cultural resources.

3.4.4.4 Other Local and Nongovernmental Organization Considerations

Mining museums and preservation associations (societies) are a common feature of historic mining areas and districts. Though they are not regulatory in nature, they can be a source of valuable information regarding local mining history and site-specific information.

3.4.5 Potentially Applicable Regulations and Programs (Federal, State, and Tribal)

As noted throughout the various sections of this guidance, a site-specific approach is recommended. The following section will discuss and provide resources to aid in determining the applicability of certain regulatory aspects to an individual site. The discussion will focus on potential federal, state, and tribal regulations.

3.4.5.1 Federal Regulations

This section provides a brief discussion of the potentially applicable federal regulations and programs that should be considered when determining the environmental compliance of a reuse project. The list does not provide a complete representation of federal regulations but is intended to aid in the environmental review process. Additional information can be found on the USEPA "Regulatory Information by Sector" web page (USEPA 2013b). Additionally, the National Mining Association fact sheet on regulations governing mining provides a similar list of federal regulations to consider (National Mining Association, n.d.).

National Environmental Policy Act (NEPA)

As discussed in Section 3.4.3.1, NEPA establishes requirements that federal agencies assess the environmental effects (potential impacts) of proposed federal projects.

Resource Conservation and Recovery Act (RCRA)

Under RCRA, regulated materials are considered "solid wastes," including materials discarded from mining operations. The USEPA simply defines hazardous waste as "a waste with properties that make it dangerous or capable of having a harmful effect on human health or the environment" (USEPA 2023c).

When Congress amended RCRA in 1980, it temporarily excluded regulation of solid waste from extraction, beneficiation, and processing of ores and minerals. Mining operations include the extraction, beneficiation, and processing of minerals. Extraction is the initial removal of ore from the earth. Beneficiation involves separating and concentrating the extracted ore through physical technologies such as grinding or crushing. Mineral processing, often performed for metals recovery, involves processes that cause significant physical and/or chemical changes to the ore or mineral, such as smelting.

This exclusion is commonly referred to as the Bevill Amendment. After further evaluation, USEPA established regulatory boundaries for the Bevill Amendment in 1989 and 1990. Although wastes from beneficiation are exempt from RCRA under the Bevill exclusion, wastes from mineral processing are not unless they are identified as exempt under 40 CFR 261.4(b)7. Despite the exclusions, some solid mining waste may be subject to land disposal regulations under RCRA (USEPA 2015c; 2016b).

It should also be noted that RCRA-exempt radioactive waste including NORM and TENORM could be regulated under other federal regulations such as CERCLA or the Atomic Energy Act. Section 2.5 provides a more in-depth look at potential radioactivity in mining waste.

For more information, please see the following resources:

- USEPA-Enforcement Alert: Hazardous Waste Management at Mineral Processing Facilities (USEPA 2000)
- Special Wastes in Mining (USEPA 2024g)

- Legislative and Regulatory Timeline for Mining Waste (USEPA 2016b)
- 54 Federal Register 36592, Sept 1, 1989 (National Archives 1989)
- 55 Federal Register 2322, Jan 23, 1990 (National Archives 1990)

Comprehensive Environmental Response Compensation, and Liability Act (CERCLA)

CERCLA grants the U.S. federal government the authority to implement cleanup actions to address mining waste as necessary to protect public human health and the environment. A key component of ensuring this protection is that it includes the USEPA's Off-site Rule, which requires that CERCLA waste be placed in a facility regulated under RCRA or other appropriate and applicable federal or state regulations. CERCLA liability extends past time—the Act grants the U.S. federal government the ability to seek relief and response action from PRPs since the origination of the mining waste. If solid mining waste is reused in a way that creates the potential to impact human health and the environment, then the PRP could be subject to regulation under CERCLA. Therefore, CERCLA applicability should be determined when considering a reuse project on a site-specific basis (USEPA 2015a; 2016c).

Clean Water Act

The Federal Water Pollution Control Act of 1948 was amended in 1972 to create the Clean Water Act. The Clean Water Act creates a standard process for regulating the discharge of pollutants into the waters of the United States (USEPA 2013c). Additionally, it created a set of water quality standards for surface water; however, the Clean Water Act does not directly regulate contamination to groundwater systems, which are addressed under provisions of other laws such as the Safe Drinking Water Act (USEPA 2013c; 2015d), RCRA, and CERCLA. Additionally, under Section 404 of the Clean Water Act, the U.S. Army Corps of Engineers (USACE) has jurisdiction over permitting for projects that involve dredge or fill activities within waters of the United States (USEPA 2024d). Many states have received authority to implement the National Pollutant Discharge Elimination System program (USEPA 2014b). State-specific agencies are provided in Appendix A.

Clean Air Act

The Clean Air Act regulates air emissions and sets air quality standards similar to the Clean Water Act. When considering a reuse project, it is important to determine compliance with all applicable air quality standards (USEPA 2016a).

Toxic Substance Control Act (TSCA)

The Toxic Substances Control Act (TSCA) requires regulation of chemicals known to present a risk to human health and the environment under the condition of use. This act also requires manufacturers to report production and use information for quantities over certain levels. The Toxic Substance Control Act should be considered when reuse is being proposed (USEPA 2013d).

3.4.5.2 State Regulations

State-specific regulatory requirements for the reuse of solid mining waste can vary drastically by state. Some states, such as Washington, may require a state environmental protection assessment similar to the federal NEPA assessment. Other states and state agencies issue special reuse permits, for example, the Oklahoma Department of Environmental Quality (DEQ) (State of Oklahoma 2024). A site-specific assessment should include state-specific regulations. It should also be noted that regulatory authority can be divided among different state agencies and may be based on mine activity status or material mined. Appendix A provides a list of potential agencies with links to aid in contacting each state individually.

3.4.5.3 Tribal Regulations

A number of federally recognized tribes may require consultation through different procedures or processes. Additionally, some states may recognize tribes not listed on the federal list. It is important to reach out to a representative of the potentially affected tribe(s) and inquire about a consultation before, during, and after a project. See Section 3.4.4 for a full discussion of cultural resource considerations and resources for contacting tribal representatives.

3.5 Stakeholder Considerations

Stakeholders having an interest in the reuse of solid mining waste may consist of federal, state, local, and tribal governments; business and industry groups; landowners; community members and organizations; and nongovernmental organizations. Stakeholder concerns will vary widely depending on their primary interests and values. These concerns could include public health and safety, ecological health of the environment, and individual economic well-being. With reuse, the concerns might include how the land will be used, how and where the waste material might be reused, and opportunities to convert a negative waste into a positive resource. Cultural and historic values may also impact stakeholder interest and acceptance. Stakeholder engagement is an important aspect of project planning and should be considered throughout the life cycle of the project.

3.5.1 Environmental Justice

Environmental justice is one aspect of stakeholder consideration; it focuses on protecting all people from disproportionate human health and environmental effects and providing equitable access to a healthy, sustainable, and resilient environment (USEPA 2014a). Environmental justice especially focuses on providing for communities that have historically been disadvantaged due to the legacy of racism and other structural or systemic barriers. Ensuring that projects include environmental justice in project planning allows for directly impacted stakeholders to voice their concerns and goals. This encourages public acceptance and increases the benefits a project may provide that are specifically sought by impacted communities.

Environmental agencies at the federal and state levels have made significant changes in how they address environmental justice with contaminated site projects. Recognition that disinvested communities have experienced historical impacts of toxic releases more than other communities has spurred regulatory changes. These changes apply to a solid mining waste reuse project on federal lands and possibly to sites under state jurisdiction. For example, Washington state recently amended their Model Toxics Control Act to address environmental justice and address environmental health disparities by requiring the State of Washington's Department of Ecology to consider low-income populations and people of color when prioritizing sites for cleanup and selecting cleanup actions (Washington State Ecology 2024).

Considerations of environmental justice may factor into approval of the cleanup remedy, or in the case of solid mining waste reuse, the approval of a project. Environmental justice drivers for reuse could lead to grant opportunities, such as the USEPA's Community Change Grants. Such approvals and grants could make the difference that allows a project to move forward when it would otherwise be not economically feasible.

3.5.2 Community Acceptance

Community acceptance comes from engaging the community within the development area, understanding the local community's unique needs, advocating for community engagement and assessment tools, and giving special consideration to a community's physical, mental, environmental, and economic health. Effective community engagement often includes public meetings, websites, fact sheets, and press releases, as well as developing information sensitive to the various needs of the local community, such as multi-language materials. Robust stakeholder engagement planning can help create reuse sites that will be transformed from underused, contaminated properties into valuable areas that serve several community health needs. Public comments and community acceptance of permits that may be required can have a significant impact on whether projects can go forward (ATSDR 2020).

3.5.3 Stakeholder Engagement in Solid Mining Waste Reuse Projects

The benefits and opportunities from reducing mining waste can drive regulated parties and stakeholders to evaluate reuse options from both economic and community perspectives. Public attitudes to the reuse of solid mining waste will be based on stakeholder interests and site-specific concerns. Stakeholders seek to minimize risks and maximize benefits according to their valuation of a product, service, brand, or business. Globally, mining operations can be seen negatively, and the opportunities for reusing mining waste have yet to be largely implemented, which may not provide stakeholders with confidence that reusing mining waste is a safe and accepted practice. Nevertheless, some projects have been implemented and provide best practices and lessons learned for further development.

Stakeholders generally support planned activities that will limit the adverse effects of the solid mining waste and, if possible, create jobs, decrease health and safety risks, and create value for the community, such as by creating recreational opportunities. The Eagle Picher Mill Site in Arizona was a lead-zinc ore milling site from 1943 to 1959 where waste was placed in a 35-acre tailing impoundment. In 2016, the site underwent voluntary remediation. The site was assessed, contaminants were excavated, and the remaining material was safely capped and topped with clean soil, allowing the site to be transformed into a public park owned by the town. The park now includes walking trails, shade structures, and pollinator gardens (Section 6.2.1). Another example is the Old Works Golf Course, a signature Jack Nicklaus golf course, which was built at the former Anaconda Smelter Site (Section 6.2.5).

Occasionally, the planned activities may benefit one stakeholder group while inadvertently causing negative effects to another. For example, extracting critical minerals from existing mining waste may provide a valuable resource to one group, but extend the time period for final site closure, representing continued potential risks to human and environmental health. The Golden Sunlight Mine in Cardwell, Montana, is one example where remining the tailings impoundment extended the mine life for a projected 20 years (Section 6.1.7.3). This was seen as a value to the community because it created job stability, increased tax revenue, and reduced long-term environmental risk despite the extended time to closure (Miller 2004).

Conversely, at the Tar Creek Site in Northeast Oklahoma, where large-scale chat reprocessing and reuse have been approved, past improper reuse of bulk unencapsulated chat material for gravel roads, fill material in residential developments, sand for children's play areas, and base material for railroads resulted in regulator and public concerns (Section 6.2.7). Today, the reuse of chat is confined to uses in which the chat is encapsulated. Complexities associated with resource evaluation can complicate regulator and public acceptance (ITRC 2010). Resolution of these possible conflicts requires thorough characterization and open communications with all stakeholders beginning with initial planning and continuing throughout the project.

4 POTENTIAL APPLICATIONS FOR REUSE OF SOLID MINING WASTE

This section presents potential reuse applications for solid mining wastes. The applications are organized into three main categories: construction, environmental, and industrial. In general, construction uses are meant to encompass any related engineering and construction discipline involving civil, water, geotechnical, transportation, and structural components. These uses include fill or other granular materials and products such as bricks, asphalt concrete, and cement concrete. Environmental uses include applications that are related to land reuse, environmental remediation of a mine site, other remediation or treatment purposes, soil amendment and fertilizers, and carbon sequestration. Industrial uses include the wide range of metal and mineral industrial manufacturing needs, as well as critical minerals required for energy transition applications.

There is some overlap with the specific technologies and approaches for the applications in these three categories, such as structural and related environmental uses for mine site reclamation. These differences are primarily related to on-site uses for reclamation versus off-site uses in other types of construction. For example, reuse of solid mining waste as a fill or other granular material for on-site reclamation of the mine could also be applied to other civil infrastructure. In addition, some applications in construction could be defined as industrial. Regardless of the potential applications, the full life cycle of the mining waste should be considered, and a plan for safe recycling or disposal at the end-of-life for the materials should be developed (Section 3.3).

Reuse of mining waste is subject to applicable local and state laws that may allow or restrict use based on numerical standards or other metrics (Section 3.4). Site-specific numerical remediation goals may also apply, which could restrict mining waste reuse. To ensure compliance with goals and standards, prior to being put to reuse, mining waste must first be characterized (Section 3.1) to determine the applicability of any potential reuse application. After characterization, mining wastes could be classified as contaminated (exceeds the requirement) or noncontaminated (meets the requirement). In general, it is assumed that contaminated solid mining waste materials would not be suitable for various uses or would have greater restrictions in place, whereas noncontaminated mining waste materials could have more unrestricted use. For some contaminated media, there are applications that may involve methods of either encapsulation/solidification or physical capping that may influence the acceptability of reuse of the waste. For example, encapsulation/solidification methods can be effectively used to stabilize contaminants of concern (COCs), such as metals, through the blending of mining wastes with concrete or asphalt. Additionally, capping methods can be used to reduce water infiltration and air movement (oxidation), thereby greatly reducing the potential for leaching and MIW generation through the installation of concrete or asphalt covering, building structures, or low-permeability covers.

4.1 Construction Uses

Mined materials are fundamental to building civil infrastructure; however, the use of these resources has limitations, placing pressure on current and future infrastructure needs. In addition, there is increased demand for preserving existing natural resources and landscapes, reducing transportation costs, and reducing greenhouse gas emissions. The following subsections provide summaries of several common construction uses where solid mining waste may potentially be reusable as a substitute for conventional resources. This section focuses on off-site construction uses of mining wastes rather than on-site uses that may be part of a mine reclamation project. Mine reclamation applications for mining wastes are described in Section 4.2.2.

4.1.1 Fill and Gravel Materials

Fill and gravel material for construction can include any number of applications ranging from backfilling/grading commercial, residential, or industrial construction sites to construction of road and other transportation corridors (for example, railway). For civil construction projects, fill materials can come from off-site sources such as quarries or direct from the construction site as borrow material generated from subgrade excavations.

The specifications required for fill and gravel materials vary widely based on application. For example, general fill and compaction applications require well-graded aggregates, whereas filter sand and self-compacting bedding gravels typically use coarse and poorly graded materials that can be placed without need for further compaction. Foundation materials should be compactible to the specified density and at the standard Proctor moisture. Excessively clayey or sand-rich fill soils may not compact as functionally as well-graded materials and may not be acceptable under potentially applicable regulations. Poorly graded sand is another commonly used material for applications such as pipe bedding and cover and could be used as a fill material for beach and shoreline replenishment. Fine sand-like mining waste materials could be used as proppants in hydraulic fracturing for oil and gas production.

In addition to the variable applications, the type of fill specification can vary based on regional or state requirements that are in different climatic zones. For example, more northern latitudes may require fill material gradation and depth for buildings and road foundations that can withstand freeze and thaw cycles that would not be required in southern latitudes that are not subject to these climatic conditions. In other areas prone to seismic risks, applicable local and state regulations may have different specifications for fill materials depending on the application. In coastal flood or river floodplain zones, local regulations may require other specifications.

Defining the full array of fill and gravel material specifications is outside the scope of this guidance document; however, an adequate assessment of solid mining wastes from an abandoned or closed mine may confirm their suitability, geotechnically and environmentally, to be used for a beneficial purpose. The U.S. Department of Transportation (USDOT) Federal Highway Administration provides guidelines for the use of waste and byproduct materials in pavement construction. The guidelines include suggestions for sources and types of mineral processing wastes that may be suitable for asphalt paving applications, with specifications and design considerations and examples of successful reuse applications (USDOT 2016). Conversely, a lack of characterization and poor planning has resulted in unsuitable materials being used and subsequent threats to human health and the environment (Section 6.1.3.4).

Prohibited use of deleterious fill materials is often part of a general fill specification. In the case of mining wastes that may contain metals or could generate leachate or AMD, these properties are typically defined as deleterious. Wastes that can increase the load of total or suspended solids to surface water bodies or can promote eutrophication (for example, nitrogen-containing blasting residuals or phosphate minerals) are also considered deleterious. Applicable local and state regulations such as institutional controls or other laws may restrict use of certain mining wastes as fill. In contrast, fill materials that may be capped with concrete, asphalt, or other materials (for example, low-permeability covers) that restrict air and water flow may be less subject to limitations from the chemical properties of the mining waste material (for example, metals, AMD potential). As for any reuse, haul cost for large quantities of fill would likely restrict its reuse. In some cases, however, mining wastes may be present within cities or otherwise populated areas close to the mine site, and reuse of these wastes could be more cost effective.

Most states allow for beneficial reuse of recycled rock or mine tailings in road base material according to the specifications of their departments of transportation (DOTs) (for an example, see Section 6.2.7). Although most state's specifications do not specifically refer to recycled mine tailings for beneficial reuse, they do offer the opportunity to submit information and quality assurance packages to have a determination made with regard to the substitution of these materials as road base or coarse aggregates.

In most cases, municipalities within each state will use their state DOT's specifications for construction of roadways in their districts. The following are examples of some states with applicable specifications:

- Pennsylvania DOT (PennDOT) Publication 408, Section 703, and PennDOT Bulletin 14—In Pennsylvania, the reuse of mine tailings would need to follow the specifications in PennDOT Publication 408, Section 703 (PennDOT 2020). Approval of specific reuse sources would need to be approved through the process in PennDOT Bulletin 14 (PennDOT 2023).

- West Virginia DOT Standard Specifications, Section 703—West Virginia allows the reuse of slag and other materials produced from steel manufacturing. The specifications establish percentages of various materials in the coarse aggregate and base materials used for a project (West Virginia DOT 2023).

- Kentucky Transportation Cabinet Standard Specifications, Section 805—Kentucky allows the reuse of materials that are not on the approved list. "The Department will consider a source for inclusion on the Aggregate Source List when the aggregate producer complies with KM 64-608 and provides the following: 1) A Quality Control Plan. 2) A satisfactory laboratory facility with all necessary testing equipment. 3) A Qualified Aggregate Technician to perform the required testing" (Kentucky TC 2019).

- Ohio DOT Standard Specifications Section 304 (Ohio DOT 2023b) and Section 703 Aggregate (Ohio DOT 2023a).

- Illinois DOT Standard Specifications, Section 1004—Illinois allows the reuse of chats in road base coarse aggregate. "Chats shall be the tailings resulting from the separation of metals from the rocks in which they occur" (Illinois DOT 2016).

- Indiana DOT Section 904 Aggregates (Indiana DOT 2022).

- Colorado DOT Standard Specifications, Section 703 (Colorado DOT 2021).

- New Mexico DOT, Section 812 Rock Riprap (New Mexico DOT 2019).

4.1.2 Rock Riprap

Riprap is another granular structural material; its size gradation is much larger than gravel's. As with fill and gravel materials, numerous structural uses of rock riprap exist. Riprap is used to armor shorelines, streambeds, bridge abutments, foundational infrastructure supports, and other shoreline structures against erosion (for example, subaqueous capping). Riprap is also used underwater for stabilization of bridges or other types of structural pillars and foundations.

Riprap gradations can vary widely based on structural use or as specified by the required weight to withstand hydrologic forces. Riprap typically is specified by the size or weight of a percentage of the material. For example, a riprap type for a specific use may have a d50 6-inch particle size, which means that on average 50% of the material must be 6 inches in size. Uses and size ranges can vary significantly, but generally d50 for riprap ranges from 6 to 24 inches. A percentage by weight may also be specified for uses that require the stone to withstand hydrologic forces, such as flow within a stream channel or tidal activity. For example, a 100-pound d50 riprap should have at least 50% of the stone with a weight of 100 pounds. A d50 specification is just one representation of riprap size or weight, but specifications may contain multiple requirements, such as a d15, d85, and d100. Stone should also be durable, angular, and resistant to weathering. Projects commonly require a maximum length to width ratio of 3:1, which is intended to avoid the use of stones that are too long and flat in shape that can result in a lack of interlocking and stone movement under hydrologic, seismic, or other forces.

Solid mining waste that contains a higher percentage of larger-sized durable stone may be a potential product for reuse. Igneous rock, such as granite, are usually the most durable and are commonly used for riprap. Rock material derived from sedimentary deposits such as sandstone may not meet durability requirements of a state DOT or similar type of specification if the rock was weathered. Additionally, mining waste that contains acid-generating minerals may not be suitable from a durability and weathering standpoint. Not only would these rock materials potentially generate AMD, but they would also degrade more readily. For example, pyrite dissolution leaves pores in the rock matrix, which leads to further weathering from water infiltration and freezing and thawing cycles. In addition to potential AMD generation, these types of rocks likely also contain metals that may not be acceptable for various uses, especially those that interact with water. Continued weathering eventually leads to cracking and particle-size reduction, which increases reactivity with smaller particles, and leaching of metals.

Off-site use of large riprap material may be more limited compared to local sources of fill and granular materials if long transportation hauling is required. In many cases, large riprap material is better suited to on-site or local reuse.

4.1.3 Bricks

Structural bricks are used in building construction, building cladding, retaining walls, walkways, and ornamental purposes. Bricks can be fired or unfired. Fired bricks are typically made of a mixture of clay or pulverized shale with some sand or other aggregate that is molded into a shape, dried, then fired in a kiln at about 2,000°F (1,093°C). Unfired bricks are made of aggregates that are chemically set at relatively low temperatures with a binder such as Portland cement or an alkali-activated binder such as fly ash, granulated blast furnace slag, or sodium silicate.

Several ASTM International standards are relevant to bricks, including the following:

- ASTM C652-22 Standard Specification for Hollow Brick. Solid Masonry Units Made from Clay or Shale (ASTM International 2022a)
- ASTM C62-17 Standard Specification for Building Brick. Solid Masonry Units Made from Clay or Shale (ASTM International 2023b)
- ASTM C216 Specification for Facing Brick. Solid Masonry Units Made from Clay or Shale (ASTM International 2023c)
- ASTM C67 Test Methods for Sampling and Testing Brick and Structural Clay Tile (ASTM International 2018a)
- ASTM 1790-2 Standard Specification for Fly Ash Facing Brick (ASTM International 2021a)

In fired bricks, mining wastes have the potential to replace the clay and the sand or aggregate. Waste clay, generated during the processing of several industrial minerals such as kaolin, iron ore, and phosphate, is usually collected in settling ponds. The sand can be replaced with appropriately sized waste silicate aggregate. In brick making, any materials containing volatiles must be used with caution to avoid having the materials generate hazardous gas during the firing process. Sulfide-rich waste materials, for example, are undesirable because they will result in the emission of SO_x during firing.

Mining wastes can be incorporated into unfired bricks more readily because there are no high-temperature reactions that can generate regulated air pollutants. Iron-ore tailings, copper tailings, red mud from producing bauxite via the Bayer process, quartz-feldspar tailings from spodumene mining, and lead-zinc mine tailings have all been tested in unfired bricks using a variety of binders. For example, unfired bricks from iron-ore tailings can be made with fly ash, granulated blast furnace slag, or sodium silicate (Thejas and Hossiney 2022).

4.1.4 Asphalt Concrete

Asphalt concrete, also known as asphalt, black top, or pavement, is a mixture of mineral aggregate bound together with a bitumen binder. The many formulations (designs) include hot mix asphalt, warm mix asphalt, cold mix asphalt, and macadam. Hot mix asphalt concrete is the most common pavement for high-traffic courses like highways. The mix design of the various forms of asphalt concrete varies based on expected road loads and durability needed for the specific job site as well as state DOT and USDOT requirements.

Mining waste is used in asphalt concrete as the aggregate; it may be the only aggregate or blended with other aggregates. Whether a particular mining waste is acceptable for use in an asphalt concrete project depends on many geotechnical and environmental factors as defined in the project specifications and the regulatory conditions surrounding its use (for example, from a superfund site). The aggregate properties need to meet the desired asphalt design criteria, including particle-size gradation, angularity, and durability (hardness). Other important aggregate properties include mineralogy (density, porosity, and strength) and chemical/physiochemical properties (wetting, adhesion, and stripping). The waste should not create a health risk when used in asphalt (see Section 6.1.9.1). For example, mining waste from the Tar Creek Superfund Site (chat) meets some of the particle-size distribution requirements for the size ranges smaller than the #10 sieve, but it is often blended with other non-chat aggregates to meet the gradation requirements of hot mix asphalt in highway construction projects that include larger particles. Figure 4-1 is a test specimen of asphalt concrete with chat making up part of the aggregate mix (see Section 6.2.7).

Figure 4-1. Test Specimen of asphalt concrete with mining waste (chat) making up part of the aggregate mix.

Source: Oklahoma Department of Environmental Quality

Reuse of chat at the Tar Creek Superfund Site in northeast Oklahoma is a good example of the reuse of mining waste as an aggregate in asphalt concrete. It is primarily composed of well-graded chert particles with fractured faces. It meets specifications, a large volume of material is available, infrastructure for processing and transportation already exists, adequate sampling and testing for environmental and geotechnical concerns has been conducted, and it has been accepted by regulators (Section 6.2.7). The large accumulations of chat in the Tar Creek area have been reworked (re-milled) several times, so the initial larger-sized rocks have been broken up, resulting in a well-graded durable material that meets local use requirements for asphalt concrete in county roads. Figure 4-2 shows the gradation curves for the material from several chat piles and the lead concentrations of each sieve fraction used in the particle distribution tests.

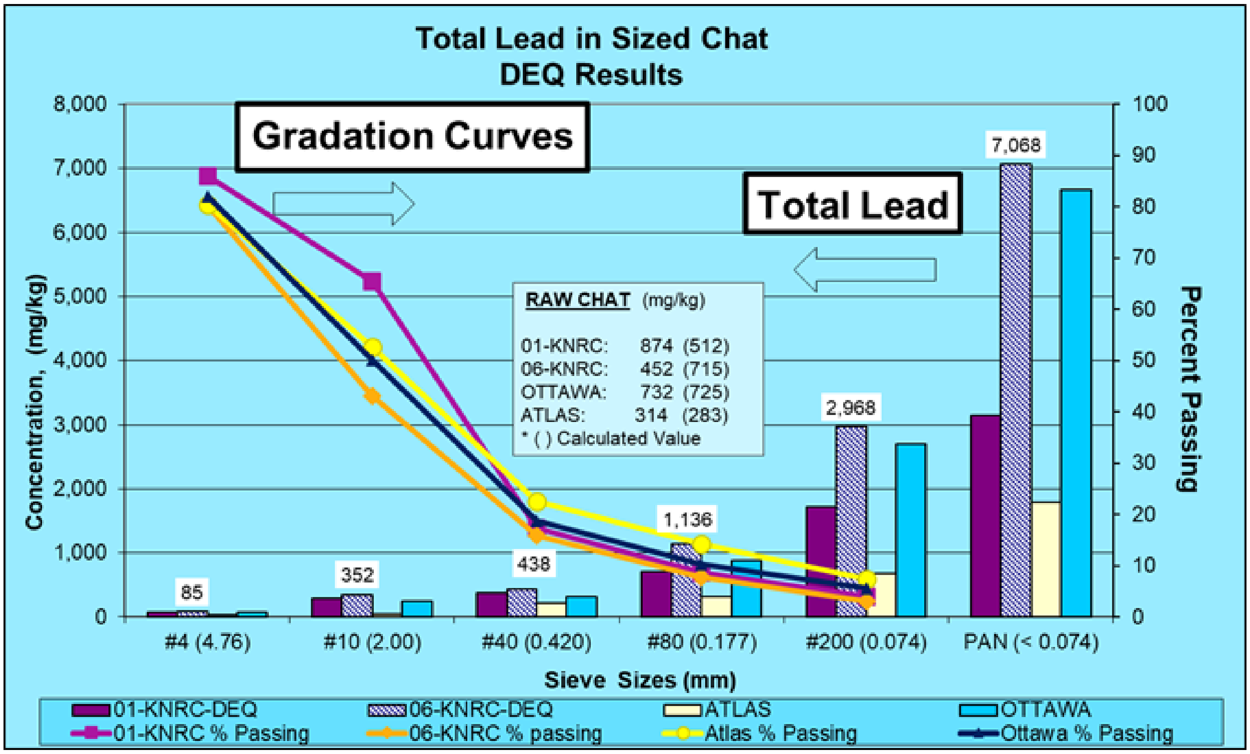


Figure 4-2. Graphs of particle-size gradation curves and corresponding lead concentrations for various raw chat samples.

Source: Oklahoma Department of Environmental Quality

Currently, chat is processed through wet screening (washing, Figure 4-3) to remove the fine-sized particles containing high metals concentrations. The larger-sized particles are transported to job sites many miles from the source to be blended with other particle sizes and binder to attain the asphalt design for each specific application. Chat meets some of the Oklahoma DOT standard specifications for highway construction for Type A, Type B, and Type C mixes, and “mine chats” are cited as appropriate materials in several sections of the specifications. Type A mixes are typically used as a base course, and Types B and Type C are typically used as a surface course (Oklahoma DOT 2019).

Another aspect of reuse of mining waste involves conducting environmental assessments or LCAs. The chat at the Tar Creek site and other nearby superfund sites contains elevated concentrations of cadmium, lead, and zinc, which are exempt from characterization as hazardous waste (Bevill Amendment, 40 CFR Part 261.4; see Section 3.4.5.1). This exemption does not apply when the waste is reprocessed or taken off site for reuse. In such instances, additional regulatory requirements, such as transportation rules and compliance with the “off-site rule”' (40 CFR 300.440), as well as additional regulatory actions or approvals come into play (ITRC 2010). USEPA conducted an LCA of the risk to human health and the environment via exposures to metals in the chat during processing, transport to and storage at the point of use, and after encapsulation in asphalt, resulting in the so called “Chat Rule” (40 CFR Part 278), which allows for reuse of chat from the superfund site if encapsulated in asphalt (see the Tar Creek Case Study, Section 6.2.7). The sale of chat has been incorporated into the record of decision for Operable Unit (OU) 4 of the Tar Creek Superfund Site where part of the remedial action includes transporting excavated chat to a processor for use in asphalt instead of disposal at the repository (USEPA 2008a).

Figure 4-3. Wet screening (washing) of chat to separate different size fractions and remove fines.

Source: Oklahoma Department of Environmental Quality

4.1.5 Cement Concrete

Concrete is widely used in the construction of buildings and infrastructure and is made of aggregates and a binding cement. Portland cement, the most common cement, is made from a high-temperature reaction of a mixture of limestone and clay/shale with later additions of gypsum. The production of cement accounts for a significant amount of anthropogenic greenhouse gas emissions from the use of fossil fuels and the release of carbon dioxide from the limestone. The use of mining waste as cement replacement materials not only reduces mining waste storage but can also reduce air emissions from cement production (Horns 2023).

Concrete aggregates are typically a mixture of smaller (sand) and larger rock pieces derived from crushed rock or quarried from unconsolidated sediments. Similar to asphalt (Section 4.1.4), mine tailings can be used as the aggregate phase in concrete if they meet specifications. For example, iron mine tailings have been used to replace the sand in concrete (Sabat et al. 2015). Tailings used as aggregates must be characterized for physical properties, such as grain size distribution, and chemical properties, such as leaching (see Section 3.1). The results will determine their suitability for use in concrete.

Several organizations have developed specifications for structural concrete. Some of the more notable organizations include the following:

- **American Concrete Institute (ACI).** ACI develops standards, technical resources, and educational programs for concrete design, construction, and materials (American Concrete Institute 2024).
- **American Society of Civil Engineers.** This is a professional organization that develops standards and specifications for various aspects of civil engineering, including structural concrete (American Society of Civil Engineers 2024).
- **ASTM International.** ASTM International develops international voluntary consensus standards. (ASTM International 2024b).
- **National Ready Mixed Concrete Association.** This is an industry advocate for the ready mixed concrete industry (National Ready Mix Concrete Association 2024).

The material specification sections for concrete aggregates provided by the ACI and ASTM International provide guidelines and standards for the selection, testing, and use of aggregates in concrete mixtures. It is important to consult with a licensed structural engineer for evaluations of substitutions for aggregates, especially with mining tailings. The material specification sections specific to concrete aggregates are as follows:

American Concrete Institute (ACI):

- **ACI 318 Building Code Requirements for Structural Concrete.** This document provides requirements for concrete materials, including aggregates, used in structural concrete (American Concrete Institute 2019).
- **ACI 211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.** This standard provides guidelines for selecting concrete proportions, including the use of aggregates (American Concrete Institute 2009).
- **ACI 211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete.** This standard provides guidelines for selecting proportions for lightweight concrete, including lightweight aggregates (American Concrete Institute 2004).

ASTM International:

- **ASTM C33/C33M Standard Specification for Concrete Aggregates.** This specification covers the requirements for concrete aggregates, including grading, durability, and quality (ASTM International 2023a).
- **ASTM C330/C330M Standard Specification for Lightweight Aggregates for Structural Concrete.** This specification covers the requirements for lightweight aggregates used in structural concrete (ASTM International 2023d).

- **ASTM C637/C637M Standard Specification for Aggregates for Radiation-Shielding Concrete.** This specification covers the requirements for aggregates used in radiation-shielding concrete (ASTM International 2020a).

Both organizations have standards for the use of aggregates in concrete, but they do not specifically address the substitution of aggregate with mining wastes. The use of mining wastes as aggregates in concrete is a topic of ongoing research and development in the concrete industry. Current recommendations include consulting with experts in the field, conducting thorough testing and analysis, and ensuring that the resulting concrete mixtures meet the required performance and durability standards (see Sections 6.1.5.1 and 6.2.3).

Using substitute aggregates from mining tailings, such as mining waste or by-products, in concrete mixtures can have advantages and disadvantages. Although beneficial reuse of materials that would otherwise require transportation and disposal offers significant cost savings as an advantage, potential adverse impacts from using substitute aggregates from mining tailings need to be evaluated (Sections 6.1.3.4 and 6.2.3).

- **Quality and Consistency.** Mining tailings may have variable properties and characteristics, which can affect the quality and consistency of the concrete mix. Inconsistent properties of the substitute aggregates can lead to variations in the strength, durability, and performance of the concrete.

- **Chemical Composition.** Mining tailings may contain harmful chemicals, metals, or contaminants that can leach into the concrete mix over time. This can impact the long-term durability and environmental impact of the concrete structures. Some minerals in mine tailings degrade when exposed to water and oxygen—this property will adversely affect concrete. Tailings with these properties should not be used in concrete. For example, sulfide minerals such as pyrrhotite will weather to produce sulfuric acid and secondary minerals. The expanded volume of these reaction products will crack and degrade concrete if present in the aggregates (Mauk et al. 2020). Additionally, lack of characterization and poor planning by using concrete aggregate with radioactive-bearing minerals at the Denver Radium Site and Uranium Mill Tailings Remedial Action sites in Colorado resulted in human health threats (Section 6.1.3.4).

- **Workability and Handling.** Substituting traditional aggregates with mining tailings may affect the workability and handling of the concrete mix. The properties of the substitute aggregates can influence the flowability, setting time, and overall performance of the concrete during placement and finishing.

- **Structural Integrity.** The use of substitute aggregates from mining tailings may pose risks to the structural integrity of the concrete structures. The properties of the substitute aggregates, such as particle shape, size distribution, and strength, can impact the overall strength and load-bearing capacity of the concrete.

Regulatory requirements and standards for the use of substitute aggregates in concrete may vary depending on the region and jurisdiction. Compliance with regulations related to material quality, safety, and environmental impact is essential when using mining tailings as substitutes in concrete mixtures. There are environmental regulatory considerations for the use of granular mining waste, such as chat, for aggregates in cement. Specific regulations are mentioned in the Tar Creek Superfund Site case study (Section 6.1.9.1 and Section 6.2.7).

In addition to replacing aggregates in cement concrete, mining wastes can potentially replace the raw materials used in Portland cement production. Some limestones can be replaced by other calciumbearing minerals, such as anorthite plagioclase, as long as the calcium-silicon and aluminum-silicon ratios of the mixture are in the correct range. Materials that are added to concrete to enhance binding are called supplementary cementitious materials (SCMs). Common SCMs include blast furnace slag, steel slag, and fly ash. Granulated mining wastes that contain calcium, silica, and alumina with certain level of pozzolanic activity (in other words, the calcium hydroxide reactive capacity) can also be used as SCMs (Simonsen et al. 2020).

4.2 Environmental Uses

Environmental uses of solid mining waste materials are those that involve land reuse, environmental remediation/reclamation of a mine site and other types of disturbed lands, use as soil amendments and fertilizers, and use for carbon sequestration.

4.2.1 Land Reuse

Mining waste disposal facilities provide a large open space that can be used for a broad range of land reuse activities; renewable energy generation and recreation are two primary examples. Renewable energy generation presents a growing and attractive option for converting old mine sites into profitable opportunities that can also help meet state and national goals for conversion to sustainable energy. Recreational uses of mine sites are much more varied and rarely present a significantly profitable opportunity. They also require additional assurance that the site is safe for use by the public. Once stabilized and deemed safe, mine sites can be reused for recreational projects that may generate profits and can be used to educate and include the public in conversations about mining and mine sites.

For a mining waste pile to be put to new land use, it must first be chemically and physically stable. Much of the same waste characterization and risk assessment as described for mining waste reprocessing must be completed (see Section 3.1 and Section 3.3). Additional regulatory considerations may apply if the site is required to be fully reclaimed prior to installation of land use infrastructure. The range of potential uses also depends on community factors such as the population density and land use of the area surrounding the mine, the level of community involvement, and the public perception of the mine site and new reuse activity.

The federal government, through the USDOE and USEPA, offers several incentive programs to promote the reuse of mining waste facilities for wind, solar, pumped hydro-storage, and geothermal energy projects, some of which include the following:

- **Energy Community Tax Credit Bonus,** also established by the Inflation Reduction Act, offers tax credits for renewable energy projects, facilities, and technologies located in energy communities (Interagency Working Group on Coal and Power Plant Communities and Economic Revitalization 2024).

- **RE-Powering America's Land** is a USEPA initiative that encourages renewable energy development on current and formerly contaminated lands, landfills, and mine sites when such development is aligned with the community's vision for the site (USEPA 2024e).

- **Clean Energy Demonstration Program on Current and Former Mine Land**, through the USDOE and funded by the BIL and Inflation Reduction Act, will fund up to five new clean energy projects to demonstrate the conversion of current and former mine lands to clean energy projects. This opportunity is no longer available for funding; the five projects selected for award negotiations were announced in 2024 (USDOE 2023b).

- **Abandoned Mine Land Economic Revitalization Program,** administered through the OSMRE, provides funds to eligible states and tribes to explore and implement strategies that return legacy coal mining sites to productive uses through economic and community development (USDOI 2024a).

Some states have adopted their own incentives for renewable power generation on stabilized mining waste facilities; however, the practice is not widespread at the time of this document. For example, the Vermont Public Utilities Commission adopted rules that incentivize the use of mineral extraction sites for installation of new renewable energy projects (Vermont Public Utility Commission 2024). Some states and municipalities offer incentives that support installing renewable energy on contaminated lands in the form of city bonds, tax incentives, or other programs (Section 3.2). The Database of State Incentives for Renewables & Efficiency provides general information on federal, state, and local incentives and policies for renewable energy (North Carolina Clean Energy Technology Center 2024).

Land reuse and renewable energy generation at closed mine sites is becoming increasingly popular, and many operators have found it a worthwhile endeavor, even without significant state or federal incentives. Case studies of sites that have successfully implemented land reuse projects on mining waste facilities offer a pathway for prospective sites. For example, in Virgina, federal funding has helped facilitate projects from reclamation and portal closure to solar installations to construction of a year-round event venue, all on abandoned coal mine lands (Virginia Department of Energy 2021).

4.2.1.1 Renewable Energy

Solar

Solar power generation requires large open areas of land. Abandoned or reclaimed mine sites offer excellent opportunities for solar installations that allow the reuse of land that may not be suited for other applications. Solar installations on abandoned land or reclaimed mine sites have been successful at locations around the world. For example, the closed Chevron Questa Molybdenum Mine in Questa New Mexico, owned by Chevron Mining Inc., includes a 21-acre pilot solar installation on a portion of their reclaimed tailing facility (Figure 4-4). The solar project has been fully operational since April 2011 and has successfully provided enough energy to power more than 150 homes annually (USEPA 2013a). The project required coordination with numerous federal, state, and local government agencies, stakeholders, the local electric cooperative, and the public. The project initially used New Mexico’s Renewable Energy Production tax credit, which expired in 2021. Today the project stands as a leading example of how renewable energy projects can be successfully implemented on former mine lands and superfund sites (Section 6.1.8.2). The success of the pilot solar installation has encouraged additional clean energy development proposals for the site, including expanding the existing solar installation and hydrogen production and storage facilities that would be powered by renewable energy (USDOE 2023a; USEPA 2013a).

Figure 4-4. Solar installation at Chevron Questa Mine.

Source: Interstate Technology & Regulatory Council Reuse of Solid Mining Waste Team

Additional solar reuse projects include, but are not limited to, the following:

- **Pennsylvania Mine in Keystone, Colorado.** This is a superfund site that uses a hybrid solar-diesel generator to recharge equipment and power remediation activities.
- **Kidston Pumped Storage Hydro Project under construction in Kidston, Far-North Queensland, Australia.** Solar and hydro-electric power will be generated at the former gold mine site.
- **Amazon's solar farm in Garrett County, Maryland.** This site is called the CPV Backbone and is being built on the site of the recently closed Arch Coal mine (Lahey 2023).
- **The Elizabeth Mine Superfund Site in Stafford, Vermont.** This is a superfund site that had a 7-megawatt solar farm installed at the site as part of the land reclamation for the remedial action (USEPA 2019b).
- **Wise County Ida Solar Project in Wise County, Virginia.** This is the first large-scale solar development in Southwest Virginia. It is on previously coal-mined land and is projected to generate more than 3 megawatts of clean energy to be used by the Mineral Gap Data Center (Wise County, Virginia 2021).

Wind

Due to the large on the ground spacing required between windmills, renewable energy generation from wind on closed mine facilities offers an opportunity to implement multiple land reuses at the same mine site, such as wind power generation and grazing. Successful examples include the Buffalo Mountain Wind Farm outside of Oliver Springs, Tennessee, which is situated atop a former strip mine for coal. At this site, the Tennessee Valley Authority manages wind turbines that supply power to local residents. Another example is the Klettwitz wind farm situated in a former lignite mining region in Brandenburg, Germany, which is the largest wind farm in Europe (USEPA 2023a).

Geothermal

Geothermal installations on abandoned or reclaimed mine sites have been successfully implemented. For example, the Underground Mine Education Center in Butte, Montana, is on 65 acres of land donated to Montana Technological University. The donated land includes the Orphan Boy mine shaft that contains geothermally heated water that stays at an average of 78°F year-round. In 2012, Montana Technological University was awarded a grant from the USDOE to install a 50-ton ground-source heat pump (GSHP), which has successfully provided heating and cooling for the 50,000 square-foot Natural Resources Building. Figure 4.5 depicts the location of the mine shafts in relation to the university. More information on this case study example can be found in Section 6.1.7.4.

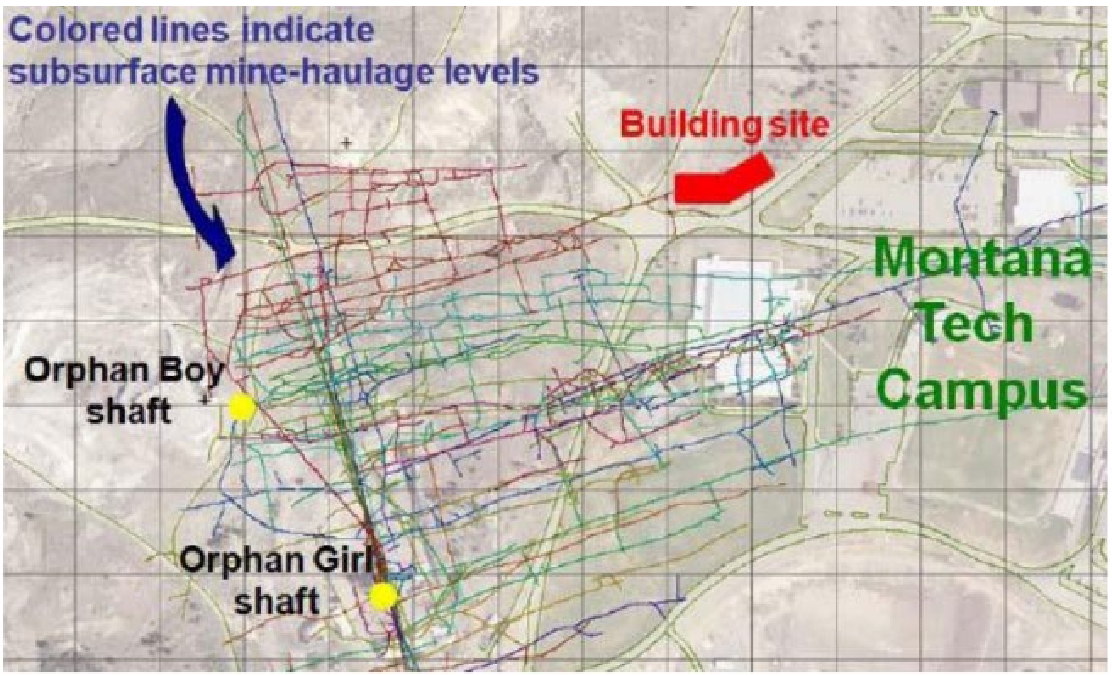


Figure 4-5. Orphan Boy and Orphan Girl mine shafts in relation to Montana Technological University.

Source: Montana Technological University

Geothermal heating harnessed from abandoned mine shafts has also been successfully completed in several other areas (Preene and Younger 2014; Watzlaf and Ackman 2006). Some examples include the following:

- **Park Hills, Missouri.** Mine waters from flooded lead mines are used to heat and cool an 8,100-square-foot municipal building.

- **Springhill, Nova Scotia.** Mine waters in abandoned coal mines are being used to heat and cool a 151,000-square-foot building.

- **Henderson, Colorado.** Mine water from an old molybdenum mine is used for direct heating of mine ventilation air to prevent icing of shafts and equipment and to control mine working temperatures.

4.2.1.2 Recreation

Recreational use of closed mining waste facilities has taken place almost as long as mining itself. Often prompted by intrepid adventurers, this type of reuse can pose serious health risks if not properly managed. From drownings and health concerns caused by unknowing citizens swimming in flooded quarries to collapses on curious cavers while exploring open mine shafts or adits, the harmful effects of unregulated recreational use of closed mine sites have a long and unfortunate history (MSHA 2007).

Because of the potential for harm, reuse of mining waste and closed mine sites for recreational opportunities must be carefully evaluated. Again, much of the waste characterization (Section 3.1) and risk assessment (Section 3.3) described for mining waste reprocessing must be completed. While not always feasible, many sites can be stabilized and safely converted into interesting and unique attractions. Examples of recreational uses of closed mine facilities are as varied as the mining operations themselves.

Sports

The Old Works Jack Nicklaus signature golf course (Figure 4-6), located in Anaconda, Montana, is situated on an 1800s copper smelter site (see Sections 6.1.7.1 and 6.2.5). After lying idle for nearly a century, the copper smelter became a superfund cleanup site in 1983. Anaconda citizens formed a group in 1989 to promote the construction of a "world-class" golf course on the smelter site. The golf course was developed as part of the superfund remedy; therefore, no formal permits were required; however, design criteria from applicable regulations were included as part of the design (USEPA 1994a). The site uses the copper slag for its signature black sand traps and was requested by Jack Nicklaus because the copper slag met all his requirements for high-performing sand traps. The design and construction of the course was completed by the Atlantic Richfield Company (Atlantic Richfield). The course was donated to the community of Anaconda, which now owns and operates the site. Protections were provided to the community via a prospective purchaser agreement with USEPA (VisitMT.com 2024). See Section 6.2.5 for more information.

Figure 4-6. Black sand traps at the Old Works Jack Nicklaus signature golf course.

Source: CDM Smith on behalf of the U.S. Environmental Protection Agency Region 8

The Copper Mountain Sports & Recreation Complex Area was built on the site of the Clark Tailings Repository and is currently used as a community sports facility in Butte, Montana. The Clark Tailings Repository was capped with a multilayer soil cover along with a monitored irrigation system to minimize the risk from over-irrigation. The Sports & Recreation Complex is operated by the county, but the underlaying repository is permitted under RCRA (Section 6.1.7.4).

Hiking and Biking

Hiking trails offer many advantages as a land reuse option for old mine sites. Hiking trails have a relatively low cost to implement and maintain and also allow completely reclaimed sites to remain undisturbed. At Treadwell Beach on the coast of Douglas Island, Alaska, the old Treadwell gold mine has been restored and converted into a recreational area attached to Sandy Beach and Savikko Park. In its heyday, from 1911 to 1917, the Treadwell mine was the largest gold mine in the world. Today the park offers walking trails and interpretive signage that conveys the history of the Treadwell Mine (Corvus Design 2018).

The fully reclaimed Flambeau mine located near Ladysmith, Wisconsin, is the only metallic mine (copper-gold) that was permitted, constructed, operated, and reclaimed under the state's existing regulatory framework. Reclamation was substantially completed in 1999; post-mining land uses for the site are light recreation and wildlife habitat. Much of the needed material for backfilling, contouring, and wetland construction was sourced from materials removed during site construction. Native grasses, shrubs, and trees were planted on the site, and a public trail system was established (Wisconsin DNR 2024).

Another example of reusing a mining site for hiking can be found in the Eagle Picher case study (Section 6.2.1).

Many mines use railway systems to connect to nationwide shipping and receiving railroad lines. After mine closure, these rail lines remain flat, open pathways, often traversing wild and rugged landscapes. Similar to the rails-to-trails model, some communities have converted old rail lines to biking and hiking paths. One example of such a project is the Mineral Belt Trail in Leadville, Colorado (Lorentzen 2018). This trail forms a loop around the city by connecting portions of old mine rail lines. The trail incorporates old mining infrastructure such as a mining tower and ore carts with interpretive signage along the way. Another example is at the Keeney's Creek Rail Trail in West Virginia, where the rail line formerly used for coal mining has been converted into a hiking and biking trail system that is part of the New River Gorge National Park and Preserve (NPS 2022b).

Skiing

Park City Mountain ski resort, located in Park City, Utah, is the largest ski resort in the United States. It also boasts an interesting history with three old mine sites completely enclosed within the ski area: the Silver King mine, the California-Comstock Mine, and the Thaynes mine. The old mine sites have been used by skiers since the mid-1970s, and many of the original buildings still stand and are in use as part of the ski resort today. Many of the mine sites and tailings dumps within the ski resort have been reclaimed. Other mine sites around the town have also been reclaimed and now host neighborhoods, business districts, and other resorts (Buck 2023).

One unique reuse of a mine site exists in Bavaria, Germany, where the by-products of an old kaolinite mine have been converted into a giant sand dune. People enjoy summertime sand skiing and sandboarding. The sand is pure quartz, and unlike most mining waste, poses little risk to human health or the environment. The park is called Monte Kaolino, with hiking trails, camping, and a ski lift. The park was used to host the Sandboarding World Championship until 2007 when the site was renovated to include more attractions (Debczak 2021).

4.2.2 Environmental Remediation/Reclamation

Remediation/reclamation of mine sites typically requires fill, gravel, and rock materials to stabilize and restore disturbed areas. Mine reclamation is a term often used in mining permitting and the mining industry to represent the post-mine condition or, in general, for the restoration of disturbed lands. Remediation is a term more related to restoration of a contaminated site. For the purposes of this section, the term remediation is used for simplification to represent any type of on-site environmental reuse. It is beneficial to source remediation materials locally from on-site or near a mine site to reduce costs. This section presents several on-site reuses of mining waste materials for the purpose of mine site remediation. These uses can be structural in nature similar to construction uses described in Sections 4.1.1 and 4.1.2 or may provide some other environmental remedial benefit such as neutralization, stabilization, infiltration reduction (capping or lining), or contaminant concentration reduction (for example, metals) through blending and dilution. Categories of environmental remediation uses of mining wastes presented include containment (for example, cover or liner systems), grading and backfill, gravel and riprap uses, and treatment materials.

As stated in Section 3.3, mine site remediation is implemented to reduce risks to human health and the environment, and any new reuse of mining wastes either on-site or off-site should not pose unacceptable risks to human or environmental receptors of concern. With this best practice in mind, reuse of mining wastes on-site during remediation are described below with respect to meeting or exceeding the applicable numerical remediation goals, or in other words, noncontaminated or contaminated, respectively. If mining waste meets the specification requirements as a suitable replacement for an off-site material and is used in a manner consistent with the remediation goals, then the mining waste may be reused for a remediation purpose. As an example, at the Kittimack Site in the Bonita Peak Mining District Superfund Site, low pH tailings were blended with high pH water treatment plant sludge to address a public health threat and mitigate these exposures. The blended mixture was stacked into an approximately 30-foot-tall revegetated berm along County Road 2 east of Silverton, Colorado (Section 6.2.2).

4.2.2.1 Containment

Containment involves physical measures applied to contaminated media to control the release and transport of contaminants and prevent direct contact or exposure to the contaminants. Mining waste remediation usually requires construction of an on-site repository as a containment method to consolidate wastes or in-place capping to prevent exposure risks and infiltration to those materials. There are numerous types of cover systems, including low-permeability, evapotranspiration (ET), and exposure barrier, and their applicability depends on site and owner requirements. In addition, the surfaces of covers may be vegetated with grasses/forbs, shrubs, trees, or covered with a rock riprap material instead of vegetation. The variety of cover system types and surfaces employed at mine sites are based on site-specific characteristics (for example, climate conditions), waste material characteristics, and legal requirements (for example, a state requirement for a low-permeability cover type). Most containment applications for site remediation would also require development of environmental covenants to document the waste materials that are contained beneath the cover and place use restrictions on the land to avoid disturbing the wastes (see Section 6.2.1).

Mining waste materials of varying characteristics may be used as a component of the cover layer or the entire cover itself. Contaminated mining wastes that exceed remediation goals should not be used on the surface of the cover where receptors of concern would be exposed to the contaminants (usually metals).

Exposure Barrier

Exposure barriers are designed primarily to limit direct exposure to contaminated media by potential receptors but may also provide some reduction in infiltration. Exposure barriers are constructed of natural materials such as soil or rock with thicknesses that vary depending on site conditions, cover objectives, and substantive requirements of any applicable permits. Site conditions include factors such as climate and the nature of material being covered. Exposure barriers provide an erosion/protective surface over the underlying material, potential reduction in net infiltration, and a stable surface for establishing vegetation. Usually, rock type covers are preferred in steeper slope scenarios for stabilization (in other words, steeper than 2:1 horizontal to vertical) or where there is an excess of this type of rock resource available on-site.

Exposure barriers mitigate the potential for risks related to incidental ingestion or inhalation; however, they do not provide a significant barrier to infiltration of water into underlying contaminated media. A rock cover could be considered rather than a revegetated cover if suitable growth media are either limited or exceedingly expensive; however, this type of exposure barrier would be even less effective at reducing infiltration. Regular maintenance may be required to maintain the integrity of the exposure barrier.

Some specific examples of reuse of mining wastes in an exposure barrier cover are as follows:

- **Using a non-acid-generating mining waste as a subsoil or topsoil for a soil exposure barrier.** This could be implemented if the mining waste is in compliance with applicable remediation goals and could be processed in a manner that would allow that material to meet the specification requirements. In a soil exposure barrier cover, a common approach is a 12- or 18-inch subsoil layer and a 12- or 6-inch topsoil layer.

    - **A topsoil** material should have appropriate nutrient and organic matter content and meet soil texture requirements for the types of proposed vegetation. Topsoil for reclamation may be generated from an on-site borrow source within an unimpacted area to reduce costs of haulage; however, there are cases where an off-site topsoil may be brought on-site. A common reclamation approach is to ensure processed on-site soil is screened to a size smaller than 2-inches to create a topsoil, followed by amendment with fertilizer, organic matter, and agricultural lime (depending on pH requirements). There may be site-specific cases where mining waste materials could be processed into topsoil material. For example, a coarse tailings material could be used that meets remediation goals for a surface application and is not reactive (for example, leachable or acid-generating).

    - **A subsoil** material can usually contain less nutrients and organic matter and may be coarser in nature. Subsoil for reclamation is also usually generated from an on-site borrow source within an unimpacted area; subsoil is usually obtained from an adjacent area within the B horizon (subsoil or overburden). A common reclamation approach is to ensure processed on-site soil is screened to a size smaller than 6-inches to create a subsoil, followed by amendment with fertilizer, organic matter, and agricultural lime (depending on pH requirements). The need for screening material should be based on the specified thickness of the subsoil layer and the nature of the borrow soil used. If only a 12-inch subsoil is specified and the borrow soil is coarse with greater than 6-inch cobbles, then screening is likely needed to ensure the subsoil layer consists of adequate soil-like material. Similar to topsoil, if a mining waste material meets the remediation goals and other specifications, it could be used as a surface or subsurface material. Mining waste that exceeds human health–related remediation goals on the surface may be suitable for reuse as subsoils as long as it does not contain metals concentrations that would impact surficial vegetation growth through wicking or penetrating root structures.

- **Using a non-acid-generating mining waste as a rock exposure barrier.** The same metrics described in Section 4.1.2 for construction uses of rock riprap apply to the use of riprap for a mining waste cover layer. This could be implemented if the mining waste contained a sufficient quantity of larger-sized durable stone and the rock was not acid-generating. Screening of the on-site rock would likely be needed to remove finer grains and meet the specified gradation for the project design. The specified use of rock riprap rather than a vegetated cover over mining waste is usually because the final grade is too steep for a stable soil slope. The use of rock provides less infiltration protection but may meet the specifications needed to stabilize an area from erosion.

Evapotranspiration (ET) Covers

ET covers, also known as alternative or store-and-release covers in certain guidance and some state solid waste regulations, are designed to limit direct exposure to contaminated media by potential receptors and provide significant reduction in infiltration—but without the use of low-permeability materials (for example, clay, geomembranes). ET cover systems use water balance components to minimize percolation. These cover systems rely on soil properties (for example, soil texture and associated soil water storage capacity) to store water until it is either transpired through vegetation or evaporated from the soil surface. The greater the storage capacity and evapotranspirative properties are, the lower the potential for percolation through the cover system. Examples of typical ET vegetation are perennial grasses and forbs that have shallower root structures that do not penetrate to deep strata the way the roots of many woody species do. ET covers are typically only applicable for use in drier environments such as the semiarid and arid desert areas of the western United States (Wang et al. 2004).

Rather than low-permeability type covers, ET covers rely on a thick layer of natural soil materials that can accept various types of vegetation, including trees. Typical synthetic low-permeability covers cannot be planted with trees because of the potential destruction of the low-permeability layer. The ET cover thickness and material properties must be sufficient to store and release precipitation under various climate scenarios and an acceptable design threshold storm event. Changes in local climate and precipitation should also be considered. The ET cover layers can also contain a capillary break layer of coarser sand or gravel placed under the finer-grained soil layer. The differences in the unsaturated hydraulic properties (in other words, soil matric potential) between the two layers minimize percolation into the coarser grained (lower) layer under unsaturated conditions.

Design of ET covers requires modeling and collection of the geotechnical properties of the proposed materials, which often come from locally obtained borrow material. For any cover system that contains soil-like layers, a borrow investigation to evaluate on-site or local soil resources is usually a required predesign activity. Because of the large quantities of cover materials needed, local borrow sources are needed for ET covers to be cost effective.

As noted above, ET covers can require several layers of differing materials and in some cases several feet of material to provide the needed infiltration protection. Mining waste could be reused/reprocessed as a component of an ET cover if the material meets the remediation goals and is not potentially toxic to vegetative growth of the surficial vegetation. One example may be the use of a coarse mine rock at the base of the ET cover with an overlying geotextile layer and then ET cover finer-grained soils above the geotextile. The coarse nature of the mine rock and finer-grained soils above the geotextile can create a capillary break effect to help maintain soil moisture within the ET cover layer. In another example that is similar to the use of mining waste as subsoils for exposure barrier covers, processing methods such as crushing and screening of mining wastes may be able to create the required soil gradations needed for the lower ET cover layers below the vegetative/topsoil layer. A detailed case study is provided for the Tar Creek Superfund Site, which includes a description of the remedial reuse of transition soils at the Tar Creek repository as part of the ET cover (Section 6.2.7).

Low-Permeability Covers and Liners

Low-permeability covers and liners can be constructed of compacted clay, bentonite-amended soil, geosynthetic clay, or geomembrane materials. Depending on the material type and construction method, the saturated hydraulic conductivities for the barrier layers are typically between 1×10^{-5} and 1×10^{-9} centimeters per second. In addition, low-permeability systems generally include shallow-rooted plants and additional layers, such as surface layers to prevent erosion, protection layers to minimize freeze/thaw damage, internal drainage layers, and gas collection layers (Rock, Myers, and Fiedler 2012). Low-permeability systems limit direct exposure to contaminated media by potential receptors and reduce infiltration as well as upward migration of groundwater into buried waste. These types of covers and liners limit AMD generation and subsequent leaching. Like ET covers, for any low-permeability cover or liner system type, local or on-site borrow soil sources are preferred to reduce implementation costs.

Bentonite-amended soil covers and liners can consist of soils amended with bentonite. These systems are generally used as one component of a low-permeability multilayer system. In these systems, the low-permeability layer (bentonite-amended material) is placed directly over or under the contaminated media. A drainage layer, a subsoil/frost protection layer, topsoil, and vegetation are also components that support these types of covers and liners. Alternatively, pure clay layers can be used as a low-permeability material. Bentonite-amended soil or pure clay layer systems may be subject to desiccation during dry periods of the year, which can adversely affect their performance. They can also be affected by freezing or by ion exchange, which can increase the permeability if sodium in the bentonite (sodium montmorillonite) mineral lattice is replaced by calcium. Regular maintenance may be required to maintain them if installed on steep slopes. Once installed, liners are very difficult or impossible to maintain without removal and reinstallation. This cover type may be more applicable to a constructed repository or regraded mining wastes in place with more moderate slopes (in other words, a ratio of 3 horizontal to 1 vertical [3H:1V]). While implementing this process option would be technically feasible, large quantities of off-site clay may need to be obtained and transported to cover or line mining waste and contaminated soils.

Geosynthetic multilayer covers or liners may consist of a low-permeability layer composed of a geosynthetic membrane geomembrane or a geosynthetic clay liner. Geosynthetic liners include products such as high-density polyethylene, linear low-density polyethylene, or polyvinyl chloride. These are flexible synthetic materials that can be installed over or under contaminated media to reduce water infiltration into the waste material or migration of contaminants out of the waste material. The liners are sensitive to sunlight, so they must be covered to protect them from degradation and must also be underlain or overlain by sand or other fine-grained bedding materials to protect the liner from damage. Commonly, these types of liners are overlain or underlain by a drain layer, erosion protection layer, topsoil, and vegetation. A rock cover over the low-permeability cover layer could also be installed if slopes are particularly steep or if a suitable growth medium is either not available or exceedingly expensive. A geosynthetic clay liner is a hybrid between a bentonite-amended soil cover and a geosynthetic liner. It consists of a thin layer of bentonite sandwiched between two layers of geosynthetics (membrane or fabric). It is installed in a manner similar to other geosynthetics and is also subject to degradation by sunlight and freezing.

Geosynthetic materials are readily available but may be higher in cost than conventional soil materials when suitable borrow materials are available nearby. The limitations of geosynthetic multilayer covers and liners are similar to those of other systems on steep slopes. Vegetation must be limited to shallow-rooting plant communities, and maintenance is required to prevent establishment of deep-rooted species. Uses of mining wastes for low-permeability covers and liners are similar to other types mentioned previously; the mining waste must meet remediation goals if used outside the protective nature of the low-permeability layer and also meet any specified gradation requirements and soil quality. Below the low-permeability layer, mining wastes can be processed to meet specifications and used as a bedding layer for the geosynthetic material if upwelling groundwater is not expected to react with the waste materials. This approach has been used at the Midnite Mine Superfund Site located outside Wellpinit, Washington. At this abandoned uranium mine, several hundred thousand cubic yards of mining waste rock were crushed and screened to create a bedding material for the low-permeability geosynthetic layer at the site repository. This approach provides a significant cost savings for the project with a beneficial reuse of the mining waste that otherwise would need to be disposed of within the repository (Section 6.1.11.1).

4.2.2.2 Grading and Backfill

Mine remediation often requires some amount of backfill, grading, and smoothing to tie into existing grades as part of the land reclamation process. For example, after mining wastes that exceed remediation goals have been removed for consolidation in a repository, other mine-related waste materials that may not exceed remediation goals could be used as backfill within the excavated area, for cover material over contaminated mining waste areas, or to feather grades to tie into existing conditions of a remediated area.

Specifications for a general fill for use during mine site remediation may be subject to similar restrictions and requirements as noted in Section 4.1.1 for off-site construction uses of fill and gravel materials. Adequate assessment is needed to confirm that mining wastes meet the remediation goals and will not lead to unacceptable risks at the surface (or subsurface) where placed. Fill or gravel mining waste materials that are acid-generating, leachable, or have the potential to react with local groundwater would typically not be acceptable for reuse and reclamation.

Another on-site reuse of fill and gravel materials is for backfill and plugging of underground mine voids, such as was done at the Tar Creek Superfund Site (Section 6.2.7). This use could involve physical haulage of more granular (cobble) or finer-grained fill materials by rail or underground mine truck. For vertical shafts, backfill typically is completed using cobble to boulder-sized material first, followed by successively finer-grained materials up to the existing grade. For mine tunnel closure, solid mining wastes are often backfilled in stages behind an engineered bulkhead structure. Other uses involve slurried injection of tailings paste that could consist of a tailings and concrete mixture or other stabilizers. Paste backfilling is a current underground mine backfill technology that facilitates the maximum use of mill tailings with enhanced stability of the underground workings and provides bulk disposal of mining solid waste. Binder type and dosage and tailings type play important roles in paste backfill performance (Behera et al. 2020). This reuse of solid mining wastes can be implemented during mining to both dispose of tailings and to provide structural support for tunnels and stopes that may be mined above or below existing voids. This type of backfill operation can reduce the potential for subsidence and rock bursts, reduces the size of aboveground tailings storage, and may reduce the potential for AMD generation within flooded workings areas.

4.2.2.3 Gravel and Riprap Material Uses

In contrast to off-site uses of riprap for off-site construction, on-site uses of gravel riprap from solid mining waste for reclamation may have greater applicability and would be more cost effective from a haulage perspective. Numerous uses of riprap can be implemented during reclamation of a mine, such as buttressing the toe of steeper graded areas or repositories, gabion rock walls, run-on and runoff channel lining, stream bank stabilization, surface cover layer for steep areas (in contrast to a vegetated cover surface), and access prevention. Mine remediation usually requires construction of repositories and associated run-on and runoff stormwater controls. With steeper sloped areas that may result in high surface-water velocities within these stormwater controls, gravel or riprap may be needed to maintain stability. In addition to stormwater control channels, larger-sized rock (riprap) is often used to armor steeper reclaimed areas and repository covers or at the toe of slopes. For stream restoration, riprap can be used for armoring embankments within areas of high velocity or erosional scouring. Sites that need to manage and treat water may contain buried pipelines. Gravel materials of a certain specified gradation may be needed as pipe bedding.

As with off-site uses, on-site use of riprap or gravel within channels or streams should not be acid-generating or leachable to avoid causing impacts to surface water quality. Less reactive rock types could be more acceptable for various on-site uses since the rock would be less prone to weathering and particle-size reduction. Where placed at the surface, any gravel or riprap use will likely need to meet the remediation goals for the site that are protective of human health and the environment.

4.2.2.4 Treatment Materials

Some types of mining waste materials may have beneficial properties that can provide treatment of other more toxic or leachable solid mining wastes and MIW. Treatment uses may include, but are not limited to, the following:

- Adsorption of metals in MIW
- MIW neutralization
- Stabilization of acid-generating mining wastes through neutralization or other chemical reactions (see Sections 6.1.3.1 and 6.2.2)

Adsorption technology involves a process where metals or other contaminants are adsorbed onto the surface of an adsorbent (Qasem, Mohammed, and Lawal 2021). Solid mining wastes have the potential to be used as cost-effective adsorbents for the treatment of wastewater contaminated by metal (for example, arsenic, cadmium, copper, lead, manganese, zinc, and others) (Nadaroglu, Kalkan, and Demir 2010; Nguyen et al. 2019; Pérez, Espina, and González 2022). Several solid mining wastes have been studied and used as effective adsorbents for wastewater, including clay-bearing mining waste, red mud, coal mine–drainage sludge, iron-ore slime, and waste mud from copper mines (Nguyen et al. 2019).

While these mining wastes have the potential to adsorb metals, it is important to assess the optimal properties for application and determine whether the specific mining waste must undergo any alteration to achieve its optimal potential. Characteristics such as a smaller particle diameter, larger surface area, increased porosity, amorphous texture, and abundant reactive sites are optimal conditions for adsorbents (Siddiqui and Chaudhry 2017). While alteration can overcome several physical limitations, it is also important to assess whether the alteration could result in the inadvertent release of other contaminants of potential concern. For example, amendments of arsenic-containing tailings with lime could lead to arsenic release under alkaline high pH condition at the sediment–water interface by means of desorption (Zeng et al. 2023). Additionally, the materials should be evaluated to assess the stability of the absorbents and their sensitivity to variable redox conditions. Evaluation of the altered material through leachability testing is the type of information that can feed into a comprehensive analysis of risk to human health and the environment over the life cycle of the project (see Section 3.3).

One application for mining waste is to beneficially use iron sludge from coal mining to remove metals from wastewater. Iron sludge can be a product of MIW or a by-product of processing and treatment of MIW. Iron sludge has a high iron-oxide content, which has an affinity for sorption of arsenic and other metals (for example, lead, cadmium, manganese, and zinc) in contaminated water. Particular care should be given to understanding the geochemical conditions and parameters when disposing of generated wastes. For example, when disposing of red mud used for the adsorptive removal of arsenic, it is important to monitor and maintain redox conditions to limit remobilization of arsenic. Other potential mining waste adsorbents and their applicability for pollutant removal during the treatment of MIW are listed in Table 4-1.

Table 4-1. Metal adsorption by different mining wastes for mining-influenced water purification

Mining Waste Sorbent	pH	Temp. (°C)	Time (h)	Adsorbent Dosage (g/L)	Adsorption Isotherms	Metal	Metal Conc. (mg/L)	Adsorbent Capacity (mg/g)	Removal (%)
Iron Slag (Feng, van Deventer, and Aldrich 2004)	4.8	18	24	2	Langmuir	Cu	200	88.5	99.41
						Pb	200	95.24	99.94
Steel Slag (Feng, van Deventer, and Aldrich 2004)	3.2	18	24	2	Langmuir	Cu	200	16.21	93.27
						Pb	200	32.26	96.23
Waste Mud from Cu/Zn Industry (Ozdes et al. 2009)	4.0	25	4	10	Langmuir Freundlich	Pb	207	24.4	99.4
Vanadium Mine Tailings (Shi et al. 2009)	5.2	25	3	20	Freundlich	Pb	200	3.816	95.3
						Cr		3.868	99.1
						Cu		3.240	91.2
						Cd		2.844	94.9
						Ni		2.207	98.0
Iron-Ore Slimes (Panda, Das, and Rao 2011)	5.1	28	5–270	10	Langmuir Freundlich	Pb	20–500		95
						Cd			80
						Cu			70
Industrial Waste Sludge (Mishra, Paul, and Bandyopadhaya 2013)	5.0	25	3	20	Langmuir Freundlich Redlich-Peterson Tempkin	Zn	5,000	7.26	88

Mining Waste Sorbent	pH	Temp. (°C)	Time (h)	Adsorbent Dosage (g/L)	Adsorption Isotherms	Metal	Metal Conc. (mg/L)	Adsorbent Capacity (mg/g)	Removal (%)
Red Mud (Laboratory experiment) (Çoruh and Ergun 2011)	6.0	20	4	10	-	Cu	100	10	99.9

Note: adapted from Iakovleva and Sillanpää (2013).

MIW residuals also typically have excess neutralization potential (NP) from overdosing or unused alkalinity (from lime or caustic neutralization). The excess alkalinity may be beneficial in some site-specific cases as a partial treatment for acidic MIW. At the Berkeley Pit in Butte, Montana, lime treatment sludge from the site water treatment plant used for mining and milling operations has been disposed of in the pit for more than 25 years. Over time, this disposal has slowly provided excess NP to the very acidic water in the pit and resulted in an increase in pH to approximately 4 (Section 6.2.6).

A stabilization/neutralization treatment use can involve mixing high NP waste material into a highly AP waste material. This may be implemented by blending the high NP material with the high AP material through placement and tillage or capping the high AP material with the high NP material. At the Captain Jack Mill Superfund Site in Boulder County, Colorado, the latter was implemented (Anton et al. 2014). At this site, a lead-containing waste rock with high NP was placed as a cap over other waste rock with high AP within the on-site repository. Since the on-site cover still allowed some water infiltration, the reuse of this high NP waste provides a buffering layer to mitigate future acid generation within the acid-generating waste rock layer (Section 6.1.3.2).

4.2.3 Soil Amendments and Fertilizer

The use of soil amendments is primarily focused on agricultural applications. Amendments can be used to improve soil texture or to improve the nutrient, mineral, or organic matter content of the soil to benefit the plants being grown. Conventional fertilizers are typically manufactured from industrial processes using mined raw materials or extracted nitrogen from the atmosphere. Organic amendments can come from a variety of sources including stripped topsoil, compost, biochar, and biosolids.

A condensed U.S. Department of Agriculture (USDA) soil definition indicates soil is a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface (NRCS 2024). The USDA and some state-level agriculture agencies refer to soil amendments as substances and materials added to soil to improve the soil's properties, to change the chemical characteristic of soil, or to change the physical characteristic of a soil (APHIS 2024; Pennsylvania Department of Agriculture 2024; State of California 2024).

This section discusses two soil-amending methods using solid mining waste. One soil-amending method is to incorporate nutrient-containing products. A second soil-amending process is adding solids that change the physical soil particle size gradation ratio. The Unified Soil Classification System and USDA soil texture classifications have some similarities in classification by soil particle size gradation ratio. For this document, soil particle size gradation ratio is a soil texture component. Particle-size gradation ratio is a quantification of particle sizes in a given soil sample. Generalizing from the USDA soil manual, soil texture is a relative proportion of sand, silt, and clay particles in soil material with particles less than 2 millimeters in diameter (Soil Science Division Staff 2017).

The Unified Soil Classification System is the primary method of categorizing particle size and soil texture used in the United States, with examples such as silty sand (SM), poorly graded sand (SP), and well-graded gravel (GW). The USDA soil texture triangle may also be visualized with sand, silt, and clay as the endpoints. Other soil classifications and nomenclature exist but are not presented herein.

Understanding soil nutrients and soil particle gradation ratios may be beneficial when evaluating whether solid mining waste is appropriate for amending soil. As with other potential reuses of solid mining waste, there are some limitations and concerns to using some mining waste material because of the inherent metal content. Depending on the source material, some mine overburden, milled material, low-grade material, and off-specification material may contain environmentally toxic or detrimental contaminants. Mining waste and tailing compositions may contain elements that pose a real or perceived hazard to the environment. Examples include, but are not limited to, metals and metalloids, like arsenic associated with some iron deposits, arsenic associated with some sulfate deposits, and radium and uranium associated with some phosphate deposits(USEPA 2018c).

As presented in Section 3.1, analytical laboratory screening to evaluate chemical components and leaching potential are recommended. The potential amendment material and target soil to be amended should also be tested for basic agronomic properties, such as nitrogen-phosphorus-potassium, organic matter, sodium adsorption ratio, and micro and macronutrients. Other gardening-specific advocates may suggest other target-specific metal analyses options (Johns Hopkins Bloomberg School for Public Health 2019; Minnesota Department of Health 2023; USEPA 2015e). To assess whether mining waste material amending soil may be detrimental, waste material chemical concentrations can be compared to USEPA regional screening levels and other applicable risk-based screening guidance (USEPA 2023d).

4.2.3.1 Mining Waste as a Nutrient Amendment

Certain solid mining waste may provide macronutrients and micronutrients beneficial to plant growth. The USDA suggests that nitrogen, phosphate, and potassium provide essential plant nutrients. Calcium, sulfur, and magnesium are also important as macronutrients. Other elements such as boron, chloride, copper, iron, manganese, molybdenum, nickel, and zinc are micronutrients, which are chemicals required for life, but in very small amounts (USDA et al. 1998; USDA 2024; USEPA 2018c). Although much mineral fertilizer is produced from commercially sourced mines, some mining waste and tailing sites have materials containing macronutrients and micronutrients that are not the targeted, commercially mined product. Soil-amendment source material may be found within overburden, mine spoils, low-grade peripheral locations, mine tailings, and nontarget aggregate products. Micronutrient metals may be found in overburden and tailings associated with mined mineral enrichment zones.

Examples of possible soil amendment material may include mining waste composed of the following:

- phosphate (as a phosphorus source)
- potash (as a potassium source)
- limestone (as a calcium source)
- sulfates, sulfides, and sulfur (as a sulfur source)
- gypsum (as calcium and sulfur sources)

4.2.3.2 Mining Waste as a Physical Gradation Amendment

Modifying the proportion of a select set of particle sizes can improve soil texture. For agricultural land use, adding organic material may be a necessary component in addition to amending the physical particle-size. Adding engineered, specific-sized aggregate may improve physical soil characteristics. Size-graded mine (mill) tailings have been milled to industry-specified particle sizes for mineral extraction. Many ores are crushed and milled to produce a preferred sand-, silt-, or clay-sized particle (USEPA 1994f).

Target areas that are deficient in a preferred particle size or have an overabundance of a particle size can be amended by supplementing the area with an engineered particle size. Sandy regions can be amended with silt- and clay-sized particles to increase moisture holding capacity. Note that adding organic material should also be a component when amending agricultural soil. Clay-rich soils especially benefit from organic amendments, and sand-sized particle amendments are also a consideration (Abdullahi et al. 2019).

Efforts to protect arable lands could benefit from certain mining waste applications. Erosion control and embankment replenishment may use engineered particle size amendments. In areas suffering particle erosion, a replenishment program using sand-sized particles deposited along embankments and waterways (sand supplementation) may be of interest (USACE n.d.). Similarly, clay-sized particles may be layered into water-retaining basins or stockpiled, shaped, and compacted into water-retaining structures (Golev et al. 2022; USEPA 1994f).

4.2.4 Carbon Sequestration

Carbon sequestration involves the removal and storage of carbon dioxide from the atmosphere through geochemical or biological processes that convert carbon dioxide to bicarbonate ions or carbonate minerals. Carbon sequestration can occur naturally and can be enhanced through geoengineering measures. This section briefly describes how mining waste can sequester carbon dioxide through geochemistry.

Any natural or artificial mineral rich in alkaline earth metals, particularly abundant elements like magnesium and calcium, can be used for carbon sequestration. While other elements may also form carbonate minerals, their abundance, stability, or toxicity limit their large-scale reactions with carbon dioxide. Between 0.1 and 1 tons of carbon dioxide can be sequestered per 1 ton of rock depending on the percentage of alkaline-rich minerals present (Renforth 2012). Success of a carbon sequestration project is measured through verification and quantification of this ratio.

The suitability of mining waste repurposed for carbon sequestration depends on the mineral composition, reactivity, and availability. Waste rock, tailings, slag, and even mine water are examples of types of mining waste that can be used for carbon sequestration. Bullock et al. (2021) estimates that between 9 and 17 gigatons of mine tailings are generated per year, which could potentially sequester between 1.1 and 4.5 gigatons of carbon dioxide per year.

Advantages of reusing mining waste for carbon sequestration include (1) the waste material can be more reactive due to increased surface area from the grinding process compared to natural rock weathering and (2) mining waste is frequently disposed of in piles or buried at shallow depths, making them more accessible and available for use.

A limitation of reusing mining waste for carbon sequestration is that mining waste materials rich in calcium and magnesium may also contain metals. Geochemical sampling to characterize the metals content in the mining waste can be a useful way to assess whether the potential application is protective of human health and the environment (Section 3.1).

Two broad carbon sequestration applications are applicable to mining sites and mining waste material:

- **Natural Sequestration.** Natural sequestration may occur at mining sites where mining waste is exposed to the surface. For mining companies with long-term goals to operate carbon neutral mines, knowledge of the passive sequestration rates could provide useful information to better understand natural sequestration processes. Furthermore, changes to best management practices could potentially improve the natural carbon sequestration rates.

- **Enhanced Sequestration.** Carbon sequestration rates can be enhanced through the intentional spreading of finely ground alkaline-rich mining waste over large land areas (to target the same geochemical processes previously described).

For further information about carbon sequestration, please see the online textbook *Carbon Dioxide Removal Prime*r (Wilcox, Kolosz, and Freeman 2021). In addition, USGS's *Carbon dioxide mineralization feasibility in the United States* is a useful resource (Blondes et al. 2019).

4.3 Industrial Uses

Industrial uses of solid mining waste materials are those that involve the removal of valuable and critical minerals for beneficial reuse. This section introduces mining waste reuse applications in general manufacturing, pigments, and critical minerals.

4.3.1 Manufacturing

Many manufacturing industries use metals and other raw materials from mining. Examples include but are not limited to aerospace, automotive, chemical, construction, defense, electric power, electronics, energy, food, industrial robot, low technology, meat, mining, petroleum, pulp and paper, steel, oil and gas production, shipbuilding, telecommunications, textiles, and water. As presented in Section 2.1, the United States relies on imports of mineral raw materials for more than 50% of its nonfuel mineral consumption (USGS 2024b), with the majority coming from China and Canada. With governmental incentives through grants and tax credits, domestic sources may be increased with new mines and through reprocessing solid mining wastes.

Many reprocessing activities are aimed at recovery of high-value minerals such as silver and gold. Additional metals such as copper, zinc, and (most recently) certain critical minerals can be recovered from mining waste alongside silver, gold, or other primary metals. These types of mines with multiple metals in an ore material or mining waste can be defined as co-occurring metals deposits. This suggests that precious metals (for example, gold, silver) may still be the main economic driver of the reprocessing operation. In one example, Golden Sunlight, a historic gold operation, has initiated reprocessing of its tailings impoundment to primarily recover sulfur, while also recovering gold and potentially other critical minerals or REEs as an additional revenue stream (Section 6.1.7.3). The sulfur is specifically targeted for its Nevada Gold Mines Goldstrike operations, which is internal customer for its reprocessing stream (Barrick Gold Corporation 2022). Rio Tinto is in the process of constructing a new tellurium plant at the Kennecott Copper mine in Utah that will produce 20 tonnes per year of tellurium extracted from waste streams as a by-product of copper smelting. Tellurium is used for production of a semiconductor, cadmium telluride, which is used to make thin film photovoltaic solar panels (Rio Tinto 2021).

Several reprocessing operations also target or plan to target the removal of deleterious elements such as arsenic and uranium, although gold and silver continue to be the main products. The recent focus on mining wastes as a potential source of critical minerals has led to newly funded research in the United States (USDOE 2024b; USGS 2023), much of which focuses on REE recovery from coal fly ash and other mining wastes. Section 4.3.3 provides expanded information on recent federal government investments. As an example, Salmon Gold (Resolve, n.d.) is a partnership currently operating in Alaska, the Yukon Territory, and British Columbia that produces gold by remining former placer mine sites while restoring habitat for salmon and other species to a level that exceeds regulatory compliance standards.

4.3.2 Mineral Pigments

Mineral pigments are powders or dyes used to add color to raw materials and finished products in industrial manufacturing. Derivation of pigments from natural mineral sources has a long history dating back to early prehistory. Synthetic dyes and powders were introduced into industry beginning around the 1850s; however, natural mineral powders are still widely used today such as ochre (ferric oxide), sienna (magnesium and iron oxide), azurite (copper hydroxycarbonate), cobalt minerals, aluminosilicates, spinel (magnesium aluminum oxides), and many other minerals. Various methods, such as precipitation, filtration, washing, and calcination, can be employed to obtain pigments.

Various industries, including paint, brick, and cement, use pigments and colorants. Starting from solid mining wastes, mineral pigments can be made by physical separation from minerals, such as magnetite, hematite, and titanite, and through chemical synthesis of compounds, such as calcite and zinc ferrite. Mine sites that may contain mining wastes with these types of mineral sources (and many others) could potentially be used as raw material sources for pigments. Inorganic pigments from mining waste, particularly from AMD treatment sludges, represent a growing industry, supplying sectors such as construction, art, and cosmetics. Iron-oxide-based pigments have diverse applications across various sectors:

- **Cement Industry.** Essential for coloring concrete elements, bricks, ceramics, stucco, asbestos sheets, and tiles, which enhances construction materials.
- **Rubber Industry.** Hematite is crucial for manufacturing rubber with exceptional stability.
- **Paper Industry.** Pigments are used to enrich the variety and aesthetics of paper products.
- **Paints, Dyes, and Coatings.** Pigments are crucial in manufacturing durable primary and anti-corrosive enamels.
- **Fashion and Textile Industry.** Used to provide shades and hues in fashion and textile products, contributing to unique designs.
- **Plastics Industry.** Used to color various plastics, creating products with lasting and appealing colors.
- **Cosmetics.** Employed in cosmetics to add color to a range of products, enhancing beauty and variety.
- **Water Treatment.** Used in metal-removal processes for water intended for human consumption and industrial waste treatment.

Treatment of AMD through lime precipitation generates a sludge with concentrated amounts of metals, including iron. This process helps reduce metal levels in water but also produces materials that can be beneficially reused as pigments. Recovered pigments can be sold to offset treatment costs.

Multiple studies have been conducted to recover different types of iron minerals for pigments. Ryan et al. (2017) discussed resource recovery during AMD treatment. The goal was to minimize waste by extracting iron contaminants in usable forms, particularly iron oxides, to serve as industrial inorganic pigments. Almeida et al. (2011) studied AMD treatment by adding alkaline reagents to raise pH and precipitate metals as oxides/hydroxides. They investigated the production of goethite and hematite from iron in AMD, with pigments characterized and tested for paint and colored concrete production. Magnetite has also been synthesized from AMD through stepwise selective precipitation of ferric and ferrous iron in a controlled environment. Akinwekomi et al. (2020) synthesized minerals like goethite, hematite, and magnetite from AMD treatment.

A successful case using AMD for pigments is True Pigments of Corning, Ohio (True Pigments 2022). True Pigments constructed a pipeline system to collect AMD from a century-old coal mine. The AMD was filtered, and the resulting sludge was washed to remove impurities. The sludge was sent to a kiln where different shades were obtained by controlling the temperature. The resulting product was shipped to Portland, Oregon, for the production of oil paints by Gamblin Artists Colors (Business Insider India 2022). A similar technique was used to successfully produce iron oxide–based pigments from sludge at an abandoned coal mine site in Lowber, Westmoreland County, Pennsylvania (Hedin 2002).

It is crucial for pigments to meet specific physicochemical properties that depend on their final application and to be evaluated for potentially toxic heavy metals. Some restrictions may exist that limit the concentrations of heavy metals, such as lead, in pigments to be sold. The presence of heavy metals may be of particular concern for products used by children.

4.3.3 Critical Minerals

Critical minerals are a fluctuating list of metals and materials that are deemed by the Secretary of Energy to serve an essential function in one or more energy technologies and have a potential supply chain disruption. This list is updated every three years. The 2023 list (USDOE 2023c) includes the following two primary groups (minerals with an asterisk are those not designated by the USDOI as critical; however, the USDOE has deemed them to be critical based on short- and medium-term supply shortages):

- **Critical materials for energy:** aluminum, cobalt, copper,* dysprosium, electrical steel* (grain-oriented electrical steel, non-grain-oriented electrical steel, and amorphous steel), fluorine, gallium, iridium, lithium, magnesium, natural graphite, neodymium, nickel, platinum, praseodymium, terbium, silicon,* and silicon carbide.*

- **Critical minerals:** The Secretary of the Interior, acting through the Director of the USGS, published a 2022 final list of critical minerals that includes the following 50 minerals: aluminum, antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, chromium, cobalt, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, germanium, graphite, hafnium, holmium, indium, iridium, lanthanum, lithium, lutetium, magnesium, manganese, neodymium, nickel, niobium, palladium, platinum, praseodymium, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thulium, tin, titanium, tungsten, vanadium, ytterbium, yttrium, zinc, and zirconium (USGS 2022b).

According to the Interagency Working Group on Mining Laws, Regulations, and Permitting (Interagency Working Group on Mining Laws, Regulations, and Permitting 2023), the announced clean energy demands will cause total mineral demand to double in less than 20 years. Certain minerals will be needed at greater levels during the same period to achieve climate goals. For example, 19, 21, and 42 times the amount of current nickel, cobalt, and lithium production will be needed, as well as a large increase in copper demand. The Biden-Harris administration has stated a need for the United States to assure that a reliable and sustainable supply of these critical elements can be responsibly developed. Estimates suggest that more than 300 new mines will be needed globally to meet the demands of the green energy agenda (Barbanell 2023). To the extent possible and feasible, recovery of these minerals from mining waste will aid in achieving this objective and should also reduce environmental liabilities at the mine facility.

The Infrastructure Investment and Jobs Act (also known as the BIL) enacted November 21, 2021, has provided funding for the DOD, USDOE, USDOI, and USEPA in part to address issues related to mining waste and critical mineral supplies (U.S. Congress 2021). A significant level of effort has been funded through the U.S. Inflation Reduction Act (U.S. Congress 2022b) to assess concentration of critical minerals and REEs at abandoned mine sites. Funds have also been appropriated by the Additional Ukraine Supplemental Appropriations Act (U.S. Congress 2022a). Investments in 2023 are extensive and wide reaching. Numerous examples of investments are provided in a summary list below (USGS 2024b).

- USDOE loans up to $700 million to a company to develop a domestic supply of lithium carbonate for electric vehicle batteries from a mining project in Esmeralda County, Nevada.
- USDOE announced $16 million in funding from the BIL to support projects in North Dakota and West Virginia for the development of REEs and other critical minerals extraction and separation refinery.
- DOD awarded $94.1 million to a company to establish a domestic rare earth permanent magnet manufacturing capability.
- DOD awarded $15 million to a company to support feasibility studies to enhance the definition and characterization of currently known cobalt resources at operations in Idaho and to assess requirements of a domestic cobalt refinery.
- USDOE announced $32 million in funding for projects to build facilities that produce REEs and other critical minerals and materials from domestic coal-based resources.
- USDOE announced $30 million in funding to help lower the costs of the onshore production of REEs and other critical minerals and materials from domestic coal-based resources.
- DOD awarded $37.5 million to a graphite mining project in Alaska.
- DOD announced a $3.2 million award to support a graphite project in Alabama to help secure a domestic supply of graphite to be used in the production of large-capacity batteries.
- DOD awarded $20.6 million to advance nickel exploration and mineral resource definition at a project in Minnesota.
- DOD awarded $90 million to support the reopening of a lithium mine in North Carolina.
- DOD awarded $12.7 million to a company to increase titanium powder production for defense supply chains at a facility in Virginia.
- Driven by tax incentives from the Inflation Reduction Act, production was restarted at a high-purity granular polysilicon facility in Washington that had been idled for four years. The material produced was to be shipped to a new fully integrated solar manufacturing facility in Georgia, scheduled to open in phases in 2024, that will produce silicon ingots, wafers, and cells for solar module production.
- DOD through the Defense Production Act awarded Stibnite Gold Project $59.4 million under a Technology Investment Agreement to develop antimony trisulfide recovery by-product from a gold mine processing operation in Idaho (See Section 6.1.4.1).
- The USGS's Earth Mapping Resources Initiative is providing funding through cooperative agreement grants to state geological surveys to coordinate mapping activities, characterizations of mining waste, and assessments of the potential for critical minerals in mining waste (USGS 2024a). In June 2024, the Oklahoma Geological Survey was awarded a grant for critical mineral and REE characterization at the Tar Creek Superfund Site in the amount of $295,238 plus up to $70,000 in analytical costs provided by the USGS.

- USDOE currently has a funding opportunity for a phytomining research grant opportunity, see USDOE – ARPA-E (USDOE 2024a).

- USEPA (Office of Mountains, Desserts, and Plains) obtained funding for the Environmental Monitoring and Remediation Technology Assessment Initiative, and a cooperative agreement grant was awarded to Battelle Memorial Institute in March 2024 to conduct engineering and technology assessments and reporting regarding the recovery of critical minerals from mining waste at legacy mining and mineral processing sites during remediation (USEPA, n.d.).

In addition to these investments, operating and closed mines are also evaluating their options for recovery of these assets. Once levels are determined, subsequent evaluations are needed to determine the economic and operational feasibility of metals recovery. If mineral processing equipment exists at the facility, this recovery process may have increased viability. For smaller volumes of materials, an evaluation would be required to determine the appropriate processing technique and location. An example of this is the Madison County Superfund Site where an interested party purchased a closed mine at a CERCLA site and worked with the Missouri Department of Natural Resources (DNR) and USEPA to develop a plan to reprocess the mine tailings for cobalt and nickel recovery, close the tailings, and reopen the mine (Sections 6.1.6.1 and 6.2.4).

Many mining wastes that contain higher grades of critical minerals or REEs have been previously processed and, in some cases, concentrated, which has resulted in the production of tailings or leach pad wastes. These materials would be further processed via leaching or other extraction processes, along with differing levels of concentration. One of the biggest obstacles to REE resource development is a lack of transparency in pricing on world markets (Leon and Daphne 2023). This is because of the influence of federal subsidies and tax incentives on market prices, international subsidies, secrecy surrounding international trade practices (to track mineral origins), and lack of domestic supply. The second most important obstacle is the lack of domestic primary processing facilities, and those facilities that do exist are designed to process REEs from heavy sands or carbonatite deposits, rather than from various types of mining wastes such as tailings. Other barriers preventing widespread implementation of reprocessing mining wastes include environmental liabilities, technical knowledge gaps, global market economics, and unpredictable community reception.

Major energy transition minerals and their applications are summarized in Table 4-2.

Table 4-2. Major energy transition minerals and their applications

Mineral	Energy Transition Element[1]	U.S. Critical Mineral[2]	Rare Earth Element[2]	Energy Transition Applications
Aluminum (Al)	X	X		Power lines
Cobalt (Co)	X	X		Rechargeable batteries
Copper (Cu)	X			Power lines
Graphite (C)	X	X		Rechargeable batteries
Lithium (Li)	X	X		Rechargeable batteries
Nickel (Ni)	X	X		Rechargeable batteries, wind turbines

Mineral	Energy Transition Element[1]	U.S. Critical Mineral[2]	Rare Earth Element[2]	Energy Transition Applications
Zinc (Zn)	X	X		Electric vehicle motors
Dysprosium (Dy)	X	X	X	Electric vehicle motors, wind turbines
Neodymium (Nd)	X	X	X	Electric vehicle motors, wind turbines
Praseodymium (Pr)	X	X	X	Rechargeable batteries, electric vehicle motors, wind turbines
Terbium (Tb)	X	X	X	Electric vehicle motors, wind turbines

[1] Barbanell (2023)
[2] USGS (2022b)

4.4 Applications Tools

This webtool allows the user to identify potentially appropriate applications and technologies based on several primary sorting criteria. Applications are described in Section 4 above, and technologies are described in Section 5. To use the tool, select at least one variable from each of the three categories listed below.

- Waste type (waste rock, overburden, chat, tailings, gangue, slag, mining-influenced water residual/slime)
- Particle size (cobble, gravel, sand, or silt/clay)
- Mineralogy (metals, sulfates & sulfides, oxides, carbonates, silicates, coal, and uranium/radionuclides)

Potential applications for the waste will appear in the first and second columns in the table below, with technologies which may be appropriately used listed in the remaining columns. The webtool will filter for appropriate and potentially appropriate (with further processing) identified.

The webtool is available in the web guidance version of this document at: https://mw-1.itrcweb.org/4-potential-applications-for-reuse-of-solid-mining-waste/#application_tool

5 TECHNOLOGY REVIEW

This section introduces common mining technologies and describes major waste reuse considerations associated with each technology based on common evaluation criteria. Information in this section is summarized from the following sources:

- *Mine Waste—Characterization, Treatment, and Impacts* (Lottermoser 2010)
- *How Mining Works* (Dunbar 2016)
- *Agromining: Farming for Metals* (van der Ent et al. 2021)
- Recycling and Reuse of Mine Tailings: A review of Advances and Their Implications (Araujo et al. 2022)
- *Mine Wastes and Water, Ecological Engineering, and Metals Extraction* (Kalin-Seidenfaden and Wheeler 2022)
- Recent Progress on Ex Situ Remediation Technology and Resource Utilization for Heavy Metal Contaminated Sediment (Xu and Wu 2023)

This section is organized as follows:

- **Evaluation Criteria.** Section 5.1 describes the criteria used to identify waste reuse considerations.
- **Mineral Beneficiation Technologies.** Section 5.2 describes bulk mechanical and physical separation and concentration processes including crushing, grinding, screening, granulation, flotation, gravity separation, and magnetic separation.
- **Mineral Processing Technologies.** Section 5.3 describes major refining and recovery processes, which vary based on the desired metal; these technologies include hydrometallurgy, pyrometallurgy, electrometallurgy, and biometallurgy.
- **Other Considerations.** Section 5.4 describes technologies such as stabilization and solidification.

For organizational purposes, mining waste reuse technologies are described separately, although treatment train approaches are frequently used to separate minerals or metals of interest from mining waste in a manner similar to traditional mining practices. For example, at the Madison County Mines (MCM) Superfund Site in Fredericktown, Missouri (Section 6.2.4), legacy tailings were reprocessed using crushing and grinding, flotation, and hydrometallurgy aqueous concentration to produce a filter cake material for electric vehicle batteries.

5.1 Evaluation Criteria

Mining waste reuse considerations are presented for each technology based on the following criteria:

- **Applicability.** This criterion describes the applicability of different mining waste media for reuse based on the reuse technology.

- **Effectiveness.** This criterion describes the effectiveness (in other words, performance track record) of each technology.
- **Implementability.** This criterion describes the maturity, operational complexity, and potential for data collection needs for each technology.
- **Health Protectiveness.** This criterion describes human and ecological health protectiveness and worker safety considerations for each technology.
- **Sustainability.** This criterion describes typical energy, water, and chemical use considerations for each technology.

Several other criteria were considered, such as relative cost, environmental resiliency, and stakeholder and community considerations, but were not retained as evaluation criteria because they are location specific and beyond the scope of this guidance. A general discussion of stakeholder community considerations is presented in Section 3.5.

5.2 Mineral Beneficiation Technologies

Beneficiation involves separating and concentrating the extracted ore through physical or mechanical processes. Initially, mechanical processes such as crushing, grinding, and screening are conducted for bulk material separation. Next, mineral concentrating involves separating valuable minerals (ore) from barren minerals to increase the grade or concentration of the mineral of interest and remove impurities or gangue minerals.

All mineral concentration technologies produce a stream of tailings that contain barren minerals as well as some valuable ones that could not be separated. Historical mining operations that may have used the same technologies for concentration described in this section are likely to have employed less efficient equipment and/or reagents and are generally found to have produced tailings that may be elevated in recoverable resources. Advances in mineral concentration equipment and chemical reagents can be successfully applied to historical tailings to further extract target elements from them.

Various methods are used for concentration, depending on the characteristics of the ore and the desired minerals. Some common concentration technologies include flotation, gravity separation, and magnetic separation.

5.2.1 Crushing and Grinding

Crushing and grinding are used to reduce the size of rocks or ores to expose and extract minerals efficiently.

Technology Description

The crushing process typically consists of several steps. The first step is primary crushing, where the raw material is initially reduced in size by blasting or using large mechanical excavators. The primary crusher, often a jaw crusher, breaks the material into manageable sizes. The crushed material is then conveyed to secondary and tertiary crushers for further reduction as required.

Grinding involves the reduction of the crushed ore or rock to a finer size using grinding mills. These mills can be ball mills, rod mills, autogenous mills, or semi-autogenous mills, depending on the type of ore and the desired particle size. In the grinding process, the ore is typically fed into the mill along with water and sometimes grinding media (such as steel balls) to aid in the grinding action.

The purpose of crushing and grinding is to liberate minerals of interest from the surrounding rock or ore matrix. By reducing the size of the ore particles, the surface area available for chemical reactions and physical separation processes increases, allowing for more efficient extraction of the desired minerals. Additionally, crushing and grinding can help expose minerals of interest that may be encapsulated within the ore, making them more accessible for subsequent processing steps, such as flotation or leaching.

Waste Reuse Considerations

Crushing and grinding can effectively reprocess mining waste by reducing the size of the waste material into smaller particles. These technologies can be applied to coarse rock waste (in other words, waste deemed to have too low a grade to be considered an ore at the time the mine was active) and stockpiled ore in preparation for further metal extraction. It can also be applied to repurpose materials within the mine site for other industrial needs. The latter may involve crushing and grinding waste rock, barren rock, or overburden material to change their grain size for the target application. An example would be using granular slag or waste rock as an aggregate for concrete, as a solid proppant in oil and gas production, or as competent rock for backfill.

Crushing and grinding are mature and effective technologies. While crushing and grinding equipment is widely available and the operational complexity is low, the implementability of these technologies depends on whether the mining waste is located on an active or closed mining site. At closed mining sites, mobilization of equipment or construction of a new grinding mill could be needed to reprocess mining waste.

These technologies generate dust and noise that pose potential human health concerns. Proper dust control and noise reduction techniques are common safety measures. In terms of sustainability, crushing and grinding do not use chemicals because these technologies use mechanical forces to break down the waste material; however, crushing and grinding are energy-intensive technologies. Water usage is typically low as water is generally only used for dust suppression.

5.2.2 Screening

Screening is a process used in the mining industry to separate particles of different sizes and classify them into various grades or fractions. These processes are essential for efficient mineral processing and are commonly employed in the initial stages of ore processing.

Technology Description

Screening involves the use of a vibrating screen or a series of screens with different-sized openings to separate particles into different grades or fractions. The material is fed onto the vibrating screen, and the screen's motion causes smaller particles to pass through the openings while larger particles are retained on the screen surface. Screening is commonly used to classify materials into different size ranges or to remove fine or oversize particles.

The screening process is crucial for efficient mineral processing as it helps to ensure that the ore is properly sized for subsequent processing steps. By separating particles into different size fractions, screening enables more effective and targeted processing, leading to improved recovery of valuable minerals and reduced waste. Additionally, screening can be used for quality control purposes to ensure that the final product meets the desired specifications.

Waste Reuse Considerations

Screening can be used effectively to reprocess mining waste by separating particles into various grades and fractions, leading to improved recovery of valuable minerals and reduction of waste. This technology sorts mined materials from large boulders to granulated/crushed ore material to fine-grained mined material to ensure that the final product reaches the market in the right size, shape, and quality. The material can be screened by size in preparation for further mineral processing, for repurposing within the mine site for other industrial needs, or for use as aggregate for concrete off-site.

Screening is a mature and effective technology. Screening is widely available and the operational complexity is low, but the implementability of this technology depends on whether the mined material is located on an active or closed mining site. At closed mining sites, mobilization of equipment or construction of screening technologies could be needed to reprocess mining waste.

This technology is often used in conjunction with crushing and grinding; therefore, this technology generates dust and noise that may cause potential human health concerns. Proper dust control and noise reduction techniques are common safety measures. Adopting efficient screening and separation solutions can increase yield and productivity while reducing environmental impact and minimizing ore processing costs. In terms of sustainability, this technology uses mechanical forces to vibrate the material forward and across screens and therefore is energy intensive. The screens work under constant vibration, so wear on the screens is natural, and they will need consistent preventive maintenance. Water usage varies; water may be used during screening, for dust suppression, or to accelerate particle sorting. See the information about chat washing in the Tar Creek Case Study (Section 6.2.7).

5.2.3 Granulation

In the mining industry, granulation refers to the process of forming granules or agglomerates from fine particles of ore or minerals.

Technology Description

Granulation is often used to improve the handling, transportation, and processing of bulk materials. Specifically, the granules formed through this process can have improved physical properties, such as increased particle size, improved flowability, reduced dust generation, and enhanced resistance to degradation.

There are two main methods of granulation: dry granulation and wet granulation.

- **Dry Granulation.** Dry granulation involves the compaction of dry powders or fine particles without the use of a liquid binder. The process typically involves feeding the dry material into a roller press or a compaction machine. The material is then compressed between two rollers that exert high pressure to form compacted sheets or flakes. These sheets are then broken down into granules of the desired size using a granulator or a milling machine. Dry granulation is commonly used when the material being processed is sensitive to moisture or when the addition of liquid binders is not desirable.

- **Wet Granulation.** Wet granulation involves the addition of a liquid binder to the fine particles to form granules. The process begins by mixing the dry material with a liquid binder, which can be water or a solution containing binders such as polymers or adhesives. The mixture is then agitated or kneaded to ensure uniform distribution of the binder. The wet mass is then passed through a granulator, which can be a high-shear mixer or a fluidized bed granulator. The granulator breaks down the wet mass into granules of the desired size. The wet granules are then dried to remove the moisture and obtain the final granulated product.

Both dry and wet granulation processes have their advantages and are chosen based on the specific requirements of the material being processed. Dry granulation is preferred when moisture sensitivity is a concern, while wet granulation allows for better control over the granule size and can enhance the flow and compressibility of the material. The choice between the two methods depends on factors such as the properties of the material, the desired granule characteristics, and the intended use of the granulated product.

Waste Reuse Considerations

Granulation can be used effectively to reprocess mining waste by forming granules or agglomerates from fine particles of ore or minerals, leading to improved physical properties, such as particle size, flowability, reduced dust generation, and resistance to degradation, which aid in the handling, transportation, and reprocessing of mined materials. This technology can be applied to dry powders or fine particles.

Granulation is a mature and effective technology. The equipment and resources to implement this technology are widely available and the operational complexity is medium. Wet granulation, the more widespread granulation technique, involves multiple unit processes such as wet massing, drying, and screening, which are complex, time-consuming, and expensive and require large spaces and multiple pieces of equipment. The implementability of this technology depends on the infrastructure that exists at the mining waste site. At sites that lack the existing infrastructure, construction of equipment for granulation for specific material end uses will be required.

These technologies can be used to decrease fines and manage dust, which improves worker and community safety. In terms of sustainability, wet granulation can require a binder/chemical to allow the aggregates to be physically and chemically durable in areas impacted by AMD. Depending on the fine's composition and the end use, the binder can be readily available. The binders used for wet granulation can pose a risk to workers if proper personal protective equipment is not maintained. Dry granulation is achieved by mechanical forces, either by roller compaction or by slugging, and is not water intensive. Depending on the composition and end use of the waste material, wet granulation could require substantial water usage.

5.2.4 Flotation

Flotation refers to a process used to separate valuable minerals found in ore (in other words, a natural mixture of valuable and gangue minerals) that has been finely ground and mixed with water to produce a slurry (see Section 6.2.4).

Technology Description

Flotation uses the differences in the surface properties of minerals to separate them. During the flotation process, finely ground material is mixed with water and chemical reagents. Air bubbles are then introduced into the slurry, causing the minerals to attach to the bubbles and rise to the surface as a froth. The froth, containing the desired minerals, is then skimmed off and further processed to obtain the desired concentrate. Flotation is commonly used in the mining industry to extract minerals such as copper, gold, lead, nickel, and zinc.

Several types of reagents are used during froth flotation to facilitate the separation of minerals. These reagents can be categorized into three main groups: collectors, frothers, and modifiers.

- **Collectors.** Collectors are chemicals that selectively bind to the surface of the desired mineral particles, making them hydrophobic (repelling water) and allowing them to attach to air bubbles. Common collectors include xanthates, dithiophosphates, and mercaptans.
- **Frothers.** Frothers are chemicals that help to create a stable froth by reducing the surface tension of the water and stabilizing the air bubbles. This allows the mineral-laden bubbles to

rise to the surface and form a froth. Common frothers include pine oil, methyl isobutyl carbinol, and polyglycol ethers.

- **Modifiers.** Modifiers are reagents used to control the pH level and other chemical conditions in the flotation process. They can help to optimize the separation of minerals by adjusting the surface properties of the particles. Common modifiers include pH regulators (such as lime or sulfuric acid), depressants (which inhibit the flotation of unwanted minerals), and activators (which enhance the flotation of specific minerals).

The specific choice and combination of reagents depends on the type of ore being processed and the desired minerals to be recovered. Different ores may require different reagents to achieve effective flotation separation. The use of flotation reagents may require careful control of process parameters, reagent usage, and containerization of all processes.

Waste Reuse Considerations

Flotation can be used effectively to reprocess mining waste by using differences in surface properties to segregate minerals of interest from other less desirable minerals. In general, flotation is most effective for silt, very fine sand, and fine sand-sized particles (in other words, particles in the range of 0.01 to 0.15 millimeters). The grain size for flotation may vary depending on the specific mineral being targeted and the flotation process being used. Therefore, it is critical to conduct laboratory testing and field studies to determine the optimal flotation size for a specific mineral or ore type before implementing flotation on a larger scale.

Flotation is considered a mature and effective technology. The equipment and resources to implement this technology are typically available, and the operational complexity is moderate and requires skilled operators and equipment maintenance. The implementability of this technology depends on the existing infrastructure at the mining waste site. At sites lacking existing infrastructure, construction of a flotation system could be needed. Flotation is also applicable to the recovery of metal-bearing sulfides (commonly found in deep sediments) that have been affected by mining waste.

This technology uses chemicals that could pose potential human health concerns if not properly handled, stored, and disposed of. Froth flotation chemicals can be harmful if ingested, inhaled, or in contact with the skin or eyes.

In addition to chemical use, flotation is a water-intensive technology, so proper water usage and waste disposal management is critical to reduce worker exposure to chemicals and minimize potential releases to the environment.

5.2.5 Gravity Separation

Gravity separation is a method to separate particles based on density differences between minerals.

Technology Description

Gravity separation relies on the principle that heavier particles will settle faster than lighter particles when subjected to a gravitational force. Gravity separation techniques include jigging, shaking tables, spiral concentrators, and centrifugal concentrators. These methods are particularly effective for separating dense minerals from lighter gangue minerals.

Waste Reuse Considerations

Gravity separation technology can effectively reprocess mining waste by using the differences in density between valuable components and waste materials. This technology can be applied to various types of mining waste, including tailings, coal gangue, and other waste materials that contain valuable minerals or elements. It is particularly effective in separating and recovering valuable metals, such as gold, silver, or copper, from tailings.

Gravity separation technology is an established and effective technology for mining waste reuse. The equipment and resources required for its implementation are widely available in the mining industry. The implementability of this technology at closed mining sites depends on the existing infrastructure. In cases where the infrastructure is lacking, additional resources and infrastructure may be needed to implement gravity separation effectively. This may include the installation of gravity separation equipment, the establishment of water management systems, and the development of appropriate waste handling and processing facilities.

This technology is generally considered safe for workers as it does not involve the use of hazardous chemicals or high temperatures. Proper safety protocols and training should still be implemented to ensure the well-being of workers during the operation and maintenance of gravity separation equipment. Ecological concerns can be addressed by implementing proper waste management practices, such as containment and treatment of any potential contaminants that may be present in the waste materials. Additionally, monitoring and regular inspections can help ensure that the gravity separation process does not have any negative impacts on the surrounding environment.

In terms of sustainability, gravity separation offers several advantages. It typically requires minimal chemical usage, as it relies primarily on the differences in density between materials. This reduces the need for potentially harmful chemicals and minimizes the environmental impact associated with their use. Gravity separation also has the potential to reduce water usage, as it can often operate with minimal water requirements. Additionally, the energy requirements for gravity separation are generally lower compared to other separation technologies, contributing to overall energy efficiency in mining operations.

Other considerations for mining waste reuse include the proper handling and disposal of any remaining waste materials that cannot be effectively separated or recovered. This may involve implementing appropriate storage and containment systems to prevent environmental contamination. It is also important to consider the economic viability of gravity separation technology for specific mining operations, as the cost of implementing and maintaining the necessary equipment and infrastructure should be carefully evaluated. Overall, by addressing these considerations, gravity separation can be a sustainable and effective technology for mining waste reuse.

5.2.6 Magnetic Separation

Magnetic separation is used to separate minerals with magnetic properties from nonmagnetic minerals.

Technology Description

Certain ferrous-bearing minerals, such as magnetite, ilmenite, and hematite, exhibit magnetic properties and can be easily separated using magnetic separators. Additionally, magnetic separation can be used to remove magnetic waste rock from target minerals with low magnetic susceptibility such as lithium. The ore is passed through a magnetic separator, which creates a magnetic field that attracts the magnetic minerals, allowing them to be collected as magnetic concentrate.

Waste Reuse Considerations

Magnetic separation technology can be applied to various types of mining waste, including tailings, coal ash, and other waste materials containing magnetic minerals or elements. It is particularly effective in separating and recovering magnetic minerals, such as iron ore, from tailings or other waste streams.

Magnetic separation technology is an established and effective technology for mining waste reuse. The equipment and resources required for its implementation are widely available in the mining industry. The implementability of this technology at closed mining sites depends on the existing infrastructure. In cases where the infrastructure is lacking, additional resources and infrastructure may be needed to implement magnetic separation effectively. This may include the installation of magnetic separators, the establishment of appropriate waste handling and processing facilities, and the development of proper waste containment and disposal systems.

This technology is generally considered safe for workers as it does not involve the use of hazardous chemicals or high temperatures. Proper safety protocols and training should still be implemented to ensure the well-being of workers during the operation and maintenance of magnetic separation equipment. Ecological concerns can be addressed by implementing proper waste management practices, such as containment and treatment of any potential contaminants that may be present in the waste materials. Additionally, monitoring and regular inspections can help ensure that the magnetic separation process does not have any negative impacts on the surrounding environment.

In terms of sustainability, magnetic separation offers several advantages. It typically requires minimal chemical usage, as it relies primarily on the magnetic properties of the materials. This reduces the need for potentially harmful chemicals and minimizes the environmental impact associated with their use. Magnetic separation also has the potential to reduce water usage, as it can often operate with minimal water requirements. Additionally, the energy requirements for magnetic separation are generally lower compared to other separation technologies, contributing to overall energy efficiency in mining operations.

Other considerations for mining waste reuse include the proper handling and disposal of any remaining waste materials that cannot be effectively separated or recovered. This may involve implementing appropriate storage and containment systems to prevent any potential environmental contamination. It is also important to consider the economic viability of magnetic separation technology for specific mining operations, as the cost of implementing and maintaining the necessary equipment and infrastructure should be carefully evaluated. Overall, by addressing these considerations, magnetic separation technology can be a sustainable and effective technology for mining waste reuse.

5.3 Mineral Processing Technologies

Major metal processing technologies for metal extraction and recovery include pyrometallurgy, hydrometallurgy, electrometallurgy, and biometallurgy.

5.3.1 Pyrometallurgy (High-Temperature Metals Recovery)

Pyrometallurgy uses heat to separate and purify metals.

Technology Description

The pyrometallurgical process in the mining industry refers to a set of techniques using high temperatures to facilitate chemical reactions that separate and purify metals from the surrounding rock or ore material.

The pyrometallurgical process typically consists of the following steps:

- **Roasting.** Roasting is the initial step in the pyrometallurgical process where the ore is heated in the presence of oxygen. This process is used to remove volatile impurities, such as sulfur, arsenic, and carbon, as well as to convert certain minerals into more desirable forms. Roasting can also help in the decomposition of complex ores and the oxidation of metal sulfides.

- **Smelting.** Smelting is the process of extracting metals from their ores by heating them with a reducing agent, such as coke or carbon, in a furnace. The high temperature in the furnace facilitates reduction of metals to their elemental and molten form so they can be isolated from the other compounds (such as oxides and silicates) present in the ore. The molten metal, known as the matte, is then tapped or poured out of the furnace and further processed.

- **Refining.** Refining is the final step in the pyrometallurgical process where the impurities in the molten metal matte are further removed to obtain a purer form of the target metal. Various refining techniques, such as electrolysis, fractional crystallization, additional smelting, or chemical precipitation, can be employed depending on the specific metal and its impurities.

Waste Reuse Considerations

The pyrometallurgical process is commonly used for the extraction and refining of metals such as copper, lead, zinc, nickel, and iron from solid waste such as low-grade waste rock and unmined or stockpiled ore. It is most effective on preprocessed concentrated ore with high metal content and relatively simple mineralogy. The exception is roasting, which can be used as an initial step to decompose sulfides. Pyrometallurgical processes can also be used to decrease the concentration of metals in a solid waste to make a final product that is attractive to buyers (for example, removal of iron and other metals from smelting waste such as slag makes it better suited for uses such as concrete aggregate, backfill, or proppant). An example of using pyrometallurgy can be found at the East Helena Superfund Site where two million tons of unfumed zinc slag will be crushed and shipped to South Korea for smelting. This action will offset remediation costs and reduce the amount of selenium-containing waste (Section 6.1.7.2).

Pyrometallurgical technologies are mature and effective. The equipment and resources required for its implementation are widely available in the mining industry. The implementability of this technology depends on the existing infrastructure at the mining waste site. At sites lacking existing infrastructure, additional resources and infrastructure may be needed to implement pyrometallurgy effectively. This may include the installation of furnaces, smelters, or other high-temperature processing equipment, as well as the establishment of appropriate waste handling and processing facilities. Alternatively, a mineral concentrate could be produced on-site, which then could be shipped to a smelter elsewhere. Regardless of the location of the smelter, these technologies require implementation by specialized, knowledgeable personnel given the high operational complexity.

This technology is generally considered safe for workers, but proper safety protocols and training should still be implemented to ensure the well-being of workers during the operation and maintenance of pyrometallurgical equipment. Ecological concerns can be addressed by implementing proper waste management practices, such as containment and treatment of any potential contaminants that may be present in the waste materials. Additionally, monitoring and regular inspections can help ensure that the pyrometallurgical process does not have any negative impacts on the surrounding environment. One possible negative impact worth mentioning is that the pyrometallurgical processes can influence the chemical solubility of metals and metalloids in certain ore types. For example, roasting arsenic-bearing sulfides converts arsenic, copper, and zinc from a relatively insoluble reduced form into a highly soluble oxidized form. In terms of sustainability, pyrometallurgy offers several advantages. It can often operate with minimal chemical usage, as the high temperatures are primarily responsible for the separation and recovery of metals or elements. This reduces the need for potentially harmful chemicals and minimizes the environmental impact associated with their use. However, flue gases and other smelter outputs require proper environmental management because elements such as arsenic, mercury, and sulfur can be present in flue gases derived from sulfide ore processing.

Pyrometallurgy can also reduce water usage, as it can often operate with minimal water requirements. Nevertheless, it is important to consider the energy requirements of pyrometallurgical processes, as they can be energy intensive. Implementing energy-efficient practices and using renewable energy sources can help mitigate this environmental impact.

Other considerations for mining waste reuse through pyrometallurgy include the proper handling and disposal of any remaining waste materials that cannot be effectively processed or reused. This may involve implementing appropriate storage and containment systems to prevent environmental contamination. It is also important to consider the economic viability of pyrometallurgy for specific mining operations, as the cost of implementing and maintaining the necessary equipment and infrastructure should be carefully evaluated. Overall, by addressing these considerations, pyrometallurgy can be a sustainable and effective solution for mining waste reuse.

5.3.2 Hydrometallurgy (Aqueous-Phase Metals Recovery)

The hydrometallurgical process in the mining industry refers to a set of techniques used to extract and recover metals from their solid ores or concentrates using aqueous solutions.

Technology Description

Hydrometallurgy involves the use of chemical reactions and solution-based processes to dissolve and separate the desired metals from the surrounding rock or ore material. Additional preprocessing steps (such as grinding, concentration, evaporation, or roasting) may be necessary to optimize the outcome of these technologies.

- **Leaching.** Leaching is a hydrometallurgical process where the ore or concentrate is treated with a leaching agent (in other words, a leachate) to selectively dissolve the target metal or metalloid into a solution (often referred to as a pregnant leach solution or pregnant liquor solution) for ease of transport and further processing. The leaching agent can be an acid, such as sulfuric acid or hydrochloric acid; a base, such as sodium hydroxide; or a combination of processes such as those used for gold or silver cyanidation. Leaching is also a natural process in which metal-bearing sulfide minerals are oxidized (biotically or abiotically) in contact with oxygen and water, producing MIW. MIW may contain sufficient concentrations of recoverable elements released by the direct oxidation of sulfide minerals to make it economical for resource recovery.

- **Solvent Extraction.** Solvent extraction is a hydrometallurgical process used to selectively separate and extract specific target metals from aqueous solutions. It involves the use of an organic solvent that can selectively form complex ions or bonds with the desired metal ions. The loaded organic molecule is then subjected to further processing to recover the metal in a purified form. Solvent extraction is widely used in the mining industry for the extraction and purification of metals such as copper, uranium, and REEs.

- **Ion Exchange.** Ion exchange is a hydrometallurgical process used for the separation and purification of metals from aqueous solutions. It involves the exchange of ions between the solution and a solid resin or exchange material. The resin contains functional groups that can selectively bind to specific metal ions, allowing for their separation. The metal ions are adsorbed onto the resin and can be recovered by treating the resin bed with specific reagents. Ion exchange is commonly used in the mining industry for the recovery and purification of metals such as gold, silver, copper, zinc, manganese, and uranium, and multiple manufacturers have produced metal-specific resin types that are commercially available. Recent developments are focusing on the use of ion exchange resins for the recovery of REEs.

- **Aqueous Concentration.** Aqueous concentration includes all physical processes that reduce the volume of pregnant liquor solution prior to additional extraction. Reverse osmosis, ultrafiltration, membrane microfiltration, filter pressing, and evaporation are used to minimize the volume of aqueous solution that needs to be handled or transported, increasing the concentration of target metals or metalloids in the resulting brine. Most filtration processes have the additional benefit of separating elements primarily present in a solid phase as a suspended solid, allowing for removal of undesirable elements or mineral phases that may cause problems in later steps.

- **Chemical Precipitation.** Chemical precipitation makes use of chemical reactants added to a pregnant liquor solution to remove target or nontarget elements from the solution and into a solid phase for ease of processing, transportation, or sale. The three most common chemical precipitation processes are pH adjustment, alkalinity adjustment, and flocculation/sorption adjustments. Cementation is a common chemical precipitation process used for copper extraction.

The process of pH adjustment uses acidic or basic reactants that adjust the pH of a pregnant liquor solution to allow selective precipitation of metals based on their different metal hydroxide pH ranges. Although metal hydroxides will form (or dissolve) over wide pH ranges, most metals and metalloids have optimal precipitation and sorption rates at defined narrow pH bands. For example, iron is most likely to precipitate as a mineral or as a colloid at pH values greater than 3 standard units (s.u.), most REEs and uranium precipitate out of solution at a pH of 5 to 6 s.u., copper precipitates most efficiently at a pH of 8.5 to 9.5 s.u., zinc precipitates most efficiently at a pH of 9 to 9.5 s.u. and nickel precipitates at a pH of 10 to 10.5 s.u.

Alkalinity adjustments make use of both pH and carbonate species adjustments to foster (or minimize) the formation of complex metal and metalloid ions. For example, the formation of carbonate-uranium ions may have a positive effect on the recovery of REEs during pH adjustment. Alkalinity adjustments are typically made by manipulating CO_2 saturation in the pregnant liquid solution or through the adjustment of hardness (in other words, adding calcium or magnesium).

Flocculation is a wastewater treatment process that is easily translatable into resource recovery. An anionic or cationic flocculant is added to an aqueous solution to promote precipitation of select metals in combination with pH adjustment. Flocculants commonly target iron and aluminum solids that are difficult to separate without more expensive methods.

Cementation makes use of aqueous cupric copper ions' ability to accept electrons from other oxidation processes and form elemental copper at very low pH. This historical process involves getting a low pH cupric copper solution to flow over an elemental iron surface (one with a very high specific surface area such as scrap iron or fine iron shavings). Oxidation of elemental iron to form ferrous and later ferric ions provide electrons that are used by the reduction of cupric ions to elemental copper. Elemental copper deposits on the solid iron surface and is able to largely replace it. The process requires continuous use of very low pH solutions (<2 s.u.) to keep ferrous and ferric ions in solution, replenishing the iron metallic surface and management of ferrous oxides (see Section 6.1.7.4).

Waste Reuse Considerations

Leaching, solvent extraction, ion exchange, chemical precipitation, and filtration are aqueous-phase metal recovery technologies that can effectively reprocess mining waste. These technologies can be applied to various types of mining waste, including tailings, mine-influenced water, and to a lesser extent, slag. Leaching and solvent extraction are particularly suitable for waste materials with high metal concentrations, while ion exchange and chemical precipitation are effective for removing metals from dilute waste solutions. Aqueous concentration is commonly used to separate solid particles from the waste solution after metal extraction.

Leaching, solvent extraction, ion exchange, chemical precipitation, and aqueous concentration are well-established technologies, and the equipment and resources required for their implementation are widely available. Recent development in the field of ion exchange resins and solvents has been targeted at recovery of less common elements such as lithium, nickel, cobalt, manganese, and REEs. The implementability of these technologies depends on the existing infrastructure at the mining waste site. In cases where there is a lack of infrastructure, the establishment of suitable facilities and systems may be necessary to enable the implementation of these technologies.

Hydrometallurgical processes offer several advantages over traditional pyrometallurgical processes, including lower energy consumption, less intensive industrial machinery, and the ability to process low-grade or complex ores. It can also be more complex and requires careful control of process parameters, reagent usage, and containerization of all processes. In the case of ion exchange, the management of reagents needed to regenerate resin beds can be intensive and generate significant waste. Hydrometallurgy processes can also be used to remove undesirable elements from the aqueous solution, concentrating the grade of the solution containing recoverable elements but creating additional waste streams.

Worker safety and ecological concerns associated with these technologies can be addressed through proper training, adherence to safety protocols, and regular monitoring of environmental impacts. Additionally, the use of nontoxic or low-toxicity chemicals in the extraction process can enhance worker safety and minimize ecological risks. Furthermore, the efficient use of water and energy resources should be prioritized to ensure the sustainability of these technologies.

Other considerations for mining waste reuse include the potential presence of hazardous substances in the waste, such as metals or radioactive elements, which may require specialized treatment or containment measures. The potential impact on local communities and ecosystems should also be carefully evaluated to ensure that the reuse of mining waste does not cause any unintended harm.

5.3.3 Electrometallurgy (Electrically Mediated Metals Recovery)

In the context of metal recovery and extraction from mining waste, electrometallurgical processes are applied to extract and refine metals from aqueous solutions or from solid phase into aqueous solutions using electrical energy. The main electrometallurgical processes are electrowinning, electrorefining, and electrocoagulation.

- **Electrowinning.** A process used to extract metals from pregnant solutions obtained through hydrometallurgical processes. In electrowinning, the pregnant solution is passed through an electrolytic cell with an anode and a cathode; a direct current is applied in the cell. Metals in the sacrificial anode are oxidized, and the released electrons are used to reduce target metals at the cathode where a solid metal deposit forms. Electrowinning is commonly used for the recovery or extraction of metals such as copper, gold, nickel, and silver.

- **Electrorefining.** A process used to purify impure metals obtained from other processes. The impure metal acts as the anode, and a thin sheet or electrode made of the target impurity metal is made to act as the cathode. Both the anode and cathode are immersed in an electrolyte solution. When a direct current is applied, impurity metals in the anode oxidize and dissolve into the electrolyte. The electrical field migrates the positively charged target ions toward the cathode where they are reduced and deposited as a pure metal layer.

- **Electrocoagulation.** A commonly used wastewater treatment technology that can be used, in the context of resource recovery from mining waste, to remove undesirable suspended solids or ions (such as aluminum species) from an aqueous solution by forcing them to coagulate into particles large enough for physical separation. Electrocoagulation is commonly used to remove metal ions such as Cu^{2+}, Ni^{2+}, Cr^{3+}, and Zn^{2+} from wastewater generated by metal plating processes and could potentially be used to create solid sludges with high concentrations of target metals.

- **Electrokinetic migration and extraction.** Makes use of electrical currents that force charged ions present in aqueous solution in water contained by saturated solid media (such as saturated soil, aquifer, or sediment) to migrate toward a collection point (in other words, a pumping well). Electrokinetics involves the use of electrodes inserted in the soil, aquifer, or sediment that needs to be treated and the application of sustained high electrical voltages. Electromigration removes targeted metal cations (positively charged) by forcing them to migrate toward the negatively charged cathode. Electrokinetic migration for metals recovery uses chemical additives that prevent the formation of immobile metal hydroxide solids. Electrokinetics also form hydroxide ions at the cathode under oxidizing and alkaline conditions.

Waste Reuse Considerations

Electrometallurgy can be used effectively to reprocess mining wastewater or aqueous solutions derived from solid mining waste to extract valuable metals, purify them, and remove contaminants. Electrowinning is particularly effective for waste media that contain high concentrations of metal ions in solution.

Electrometallurgy is a mature technology with widely available equipment and resources for implementation. The exception is electrokinetics, which is still considered an emerging technology. The operational complexity of these technologies varies depending on the specific application. The implementability of these technologies also depends on the existing infrastructure at the mining waste site. In cases where there is a lack of existing infrastructure, the implementation of electrometallurgical processes would require the establishment of a suitable power supply, water sources, and waste management systems.

These technologies generate potential health and safety concerns for workers due to the presence of hazardous materials and the use of electrical currents as well as the potential production of hazardous gases at the cathode (hydrogen gas) and anode (oxygen gas). Workers may be exposed to toxic metals, corrosive chemicals, electrical hazards, and explosive atmospheres. To address these concerns, common safety measures include the use of personal protective equipment, proper ventilation systems, and regular monitoring of air quality and worker exposure levels.

In terms of sustainability, electrometallurgy offers several advantages. It can significantly reduce the environmental impact of mining waste by recovering valuable metals and removing contaminants from liquid waste or the liquid products of other processes. This reduces the need for traditional mining activities, conserves natural resources, and minimizes the release of pollutants into the environment. Additionally, electrometallurgical processes can often be operated with minimal chemical usage, as the electrolysis itself facilitates the separation and purification of metals. Water usage can be optimized through recycling and reuse, and energy usage can be minimized through the use of efficient electrolytic cells and renewable energy sources.

5.3.4 Biometallurgy (Biologically Mediated Metals Recovery)

5.3.4.1 Biomining/Bioleaching

Technology Description

This process harnesses the power of microbes to extract valuable metals from mining waste media. Some specialized microbes, such as bacteria and some types of fungi, oxidize sulfide minerals, biomining employs molecular biological tools to characterize the microbial consortia and design amendment plans that will optimize the growth of a particular strain(s) and increase the rate of sulfide oxidation. The microbial optimization process can include the addition of liquid or solid amendments to enhance conditions for a particular species, adding or enhancing complementary species to the existing microbial consortium, using microbes to improve heat and oxygen transfer, and modifying the shape of the leach pile for optimal moisture and oxygen distribution.

Biomining involves the use of microbes to oxidize sulfide minerals by targeting areas with poor oxygenation, low moisture, or large particle size. This process is most efficient when applied in controlled environments that can be efficiently used to increase leaching productivity of historic heap leach piles and tailings that may have been suboptimally crushed (or in heap leach piles that were inadequately built and have poor oxygen penetration). Biomining includes bioleaching where metal ions are released into aqueous solutions where they can be transported for further recovery using methods, such as those described in the hydrometallurgy section (Section 5.3.2). Overall, biomining is applicable to various solid waste media types, such as low-grade ores, waste rock, and tailings, and is particularly useful for low-grade copper and gold ores and tailings that are not amenable to traditional extraction methods.

Waste Reuse Considerations

Biomining is an emerging and promising technology for reprocessing mining waste, although it has been used for many years for the extraction of copper from low-grade ore and waste rock. The equipment and resources are widely available, and the operational complexity can range from low to medium, depending on the specific application. The implementation at closed sites requires the establishment of a suitable bioreactor, nutrient supply, containerization, and waste management system. Bioreactor systems are typically built in situ directly on the waste but can also be built as a pass-through ex situ system.

This technology may pose health and safety concerns for workers due to the presence of acidic aqueous conditions. To address these concerns, common safety measures include the use of personal protective equipment.

In terms of sustainability, biologically mediated metals recovery offers several advantages. It can significantly reduce the environmental impact of mining waste by using natural processes and minimizing the need for traditional chemical extraction methods. Biomining can also be operated with minimal chemical usage, as the microorganisms themselves facilitate the solubilization and extraction of metals. Water usage can be optimized through recycling and reuse, and energy usage can be minimized by using efficient bioreactor systems and renewable energy sources. Proper management of MIW and other affected media, such as surface water, sediment, and groundwater, are important considerations to ensure protection of the environment.

5.3.4.2 Phytomining

Technology Description

This section describes a phytotechnology called phytomining, a technology that uses plants to extract valuable metals from mining waste. Another phytotechnology, phytostabilization, involves the use of plants to stabilize sediment and is discussed in Section 5.4.

These plants, called hyperaccumulators, absorb metals from the soil through their roots. Perennial plants native to the area from where the waste was extracted are typically good hyperaccumulators, since these plants are already adapted to soils with high concentrations of metals, high electrical conductivity, and poor organic matter content. Given the uniqueness of climate, geology, and soil conditions needed for a diverse vegetation cover to thrive, it is advantageous to use a survey of native plants in mineralized areas to discover the species best suited for phytomining. During phytomining, metals are stored in the plant leaves and stems, so plant selection is not as important as adequate plant growth under adverse conditions. To this effect, significant land regrading, soil amendment addition, and water management may be necessary to create a vegetation cover with well-established roots that can maximize the typical shallow depth of impact of this technology.

When the plants are fully grown, they can be harvested and processed to extract the metals. Metals extraction from plants may involve other hydrometallurgical or pyrometallurgical processes. For example, a common extraction approach involves burning the harvested plants to produce ash, which can then be recovered via hydrometallurgical and electrometallurgical reactions.

The success of phytomining depends on the concentration and bioavailability of the metals in the soil and the success in creating a diverse vegetation cover that will make plants more resilient to potentially toxic soil conditions and lack of water and organic matter. The pH, redox state, and presence of sorption surfaces in the soil can affect the bioavailability of metals. The water capacity and fertility of the soil are important for plant growth. Phytomining is limited by the root system of the target hyperaccumulating plants, which may extend up to several meters in length, as well as the permeability of the waste material. Finally, the availability of native hyperaccumulator plants or the ability to adapt nonnative plants to local conditions is crucial.

Waste Reuse Consideration

Phytomining can be used effectively to reprocess mining waste by using plants to extract valuable metals from the waste media. This technology can be applied to various waste media types, such as tailings, sludge, and soil, as well as sediment and surface water impacted by metals.

Phytomining is an emerging and promising technology for reprocessing mining waste. The implementation of phytomining would require the establishment of suitable media for planting (with enough amendments for nutrient and organic matter content); fertilizing, watering, and harvesting systems; and processing facilities for metal extraction. Phytomining may require the modification of the waste to permit plant growth; modifications might consist of hydrological improvements (such as adding sand), the addition of organic matter (which may be derived from waste such as manure and biosolids from urban wastewater treatment), and fertilizers.

Phytomining does not generate significant health and safety concerns for workers, as the process does not involve hazardous materials or complex machinery. Workers should still follow general safety guidelines, such as wearing appropriate protective clothing and equipment, to minimize any potential risks associated with working on a mining waste site. The accumulation of metals in plants can pose a potential ecological concern to wildlife, which may require land use controls such as fencing to prevent direct exposure.

In terms of sustainability, phytomining offers several advantages. It can significantly reduce the environmental impact of mining waste by using natural processes and minimizing the need for traditional extraction methods. Phytomining also has the potential to remediate and restore the mining waste site, as the plants can help stabilize the soil and improve its quality through the addition of organic matter and establishment of a soil microbial ecosystem. Additionally, phytomining can be operated with minimal chemical usage (other than fertilizer), as the plants themselves facilitate the extraction of metals. Water usage can be optimized through recycling and reuse, and energy usage is generally low compared to other reprocessing technologies.

5.4 Other Considerations

Mining wastes can impact other media, such as sediments. This section briefly describes ex situ stabilization and solidification technologies that warrant further consideration for addressing mining-impacted sediments.

5.4.1 Stabilization and Solidification

Technology Description

Stabilization and solidification technologies are used to treat sediments impacted by subaqueous deposition of mining waste. Such waste can contain enough metals and metalloids to make reuse without treatment unfeasible (extraction of metals from sediment is covered in Section 5.3: Mineral Processing.

Solidification involves the addition of various types of cement and other pozzolanic materials with binders (such as kaolinite, fly ash, or kiln dust) to physically bind sediment (and the associated metals) into a solid mass that can be reused due to its reduced capacity to release inorganic contaminants and its increased strength.

Stabilization modifies the solubility, leachability, and toxicity of metals and metalloids present in the sediment. Demonstrated ex situ technologies for the stabilization of sediments containing mining waste include sediment washing, chemical treatment (also covered in Section 5.3.2), electrokinetic stabilization, biometallurgical technologies (covered in Section 5.3.4), vitrification (covered in Section 5.3.1), and phytostabilization.

- **Sediment washing.** Sediment washing involves high-pressure washing of sediment with additives that facilitate the removal of inorganic acids, organic chelators, and surfactants. Inorganic acids affect the solubility and desorption of metals at low pH and facilitate removal as solutes. Organic chelators form effective and stable metal-organic complexes that can remain on sediment solid surfaces while being less susceptible to leaching. Organic surfactants, such as rhamnolipids, also form effective metal-organic complexes but also facilitate desorption of metals from sediment solid surfaces. Surfactants have the additional benefit of forming foams when air is introduced into the metal-bearing solution that facilitates its separation and removal.

- **Chemical treatment.** Chemical treatment aims to modify the form in which a metal or metalloid is present in sediment or its residual pore water to create a more stable, less leachable, or less bioavailable form. This includes pH modification by addition of an alkaline slurry to form stable hydroxides, use of reduced iron or manganese solids that form hydroxides upon oxidation that are capable of strongly adsorbing other metals, use of calcium and alkaline reagents for the formation of carbonates that incorporate metals into their structure, and addition of sulfidic reagents for the precipitation of stable sulfides that can be removed using flotation methods (Section 5.2.4).

- **Electrokinetic stabilization.** Makes use of electrical currents that force charged ions present in solution in saturated sediment to precipitate as hydroxides after reaction with the by-products of water electrolysis. Electrokinetic stabilization involves the use of electrodes inserted in the saturated media and the application of sustained high electrical voltages. The application of sustained voltage prompts the development of alkaline and reducing conditions at the cathode and acidic and oxidizing conditions at the anode. It differs from electrokinetic migration (Section 5.3.3) in that reactions to form metal hydroxide solid precipitates are not impeded.

- **Biometallurgical technologies.** Uses microorganisms to recover metals from minerals, ores, and waste materials. This process generates minimal waste materials and operates with reduced energy consumption, low or ambient temperatures.

- **Vitrification.** Uses high temperatures, like smelting, to separate out the economic materials. Residual products are then bound up in a non-reactive glass material that is more easily disposed of using conventional disposal techniques. The process consumes high amounts of energy and is expensive compared to other processes.

- **Phytostabilization.** In specific marine nearshore settings, phytostabilization can potentially be used as an in situ technology for geotechnical and chemical stabilization of impacted sediments as long as the metals and metalloids in the sediment and its pore water do not pose a risk to coastal biological receptors. For freshwater and cold marine settings, phytostabilization is primarily an ex situ technology that requires excavation, amendments, and soil bulking in order to transform the sediment into a medium suitable for growing plants. Depending on the nature of the waste, amendments and nutrients may be necessary to facilitate chemical stabilization of metals and metalloids into stable hydroxide or carbonate forms that will allow for phytostabilization.

Waste Reuse Considerations

Reuse goals for sediment treated with stabilization and solidification technologies include avoidance of landfill disposal and use as upland fill, geotechnical fill, capping material, or reclamation material (in lieu of borrow soil). Solidification technologies have the objective of turning metal-bearing sediment into a solid mass with a reduced capacity to release inorganic contaminants and its increased strength. Stabilization modifies the solubility, leachability, and toxicity of metals and metalloids present in the sediment (see Section 6.2.2 for an example).

Solidification of sediment is a mature and effective technology. Stabilization of sediment is still an emerging but promising technology. In both cases, the equipment and resources to implement this technology are widely available, but the operational complexity can be high depending on the volume and type of sediment to treat, which control the number of steps and reagents needed. Because mining-impacted sediments are not necessarily found close to former mine sites, it may not be possible to reuse existing mine infrastructure (even if present). In any case, work near water, complex dredging activities, and protection of the existing water resource during sediment dredging introduce additional complexities.

In terms of sustainability, solidification using cement has a high carbon footprint associated with the high energy demands and emissions associated with cement production. Electrokinetic stabilization technologies also have a high energy demand. Sediment washing and chemical technologies demand great quantities of freshwater for implementation, owing to the high volumes of reagents and sediment that need to be treated.

While the overall goal of ex situ solidification and stabilization technologies is to give the sediment enough geotechnical strength to allow for reuse, an important secondary goal is to reduce or eliminate the potential for inorganics to reach potential receptors, whether it be via groundwater, surface water, direct soil contact, or airborne particulates. For all sediment solidification and stabilization technologies, the long-term potential for release and transport of inorganic constituents (whether it is caused by leaching, advection, and/or diffusion) as influenced by climatic and other long-term factors (such as erosion, change in land uses) remain a concern when using these technologies.

For further reading, please see “Recent Progress on Ex Situ Remediation Technology and Resource Utilization for Heavy Metals Contaminated Sediment” (Xu and Wu 2023).

6 PROJECT SUMMARIES AND CASE STUDIES

This section presents several project summaries where mining waste reuse has been considered, and in some cases, successfully implemented. Table 6-1 lists the project summaries and the eight sites that have full case studies.

Table 6-1. List of mining sites with project summaries

State	Site Name	Mine Status	Target Application	Mining Waste	Mineral of Interest
AZ	Eagle Picher Mill Voluntary Remediation Program Site – Brief – Full Case Study	Closed	Remediation, land reuse	Tailings	Not applicable
CA	Empire Mine State Historical Park – Brief	Closed	Land reuse, metal recovery, road construction reuse, and potential remediation reuse	Tailings and waste rock	Gold and silver
CO	Bonita Peak Superfund Site, Kittimac Tailings – Brief – Full Case Study	Abandoned	Remediation, reclamation, two waste streams commingled for inert monofill	Water treatment sludge, tailings	Not applicable
CO	Captain Jack Mill Superfund Site – Brief	Abandoned	Remediation, use of neutralizing waste rock to stabilize/cap acid-generating waste rock	Waste rock	Not applicable
CO	Central City/Clear Creek Superfund Site – Brief	Abandoned	Metal recovery from water treatment sludge	AMD treatment sludge	REEs
CO	Denver Radium and Ultra Mill Tailings Remedial Action Sites – Brief	Abandoned	Land use management of legacy mining waste in the environment	Tailings	Not applicable
ID	Stibnite Mining District – Brief	Abandoned	Metal recovery from historical tailings	Tailings	Gold, antimony

State	Site Name	Mine Status	Target Application	Mining Waste	Mineral of Interest
MI	Copper Mine Tailings on the Keweenaw Peninsula, Torch Lake Superfund Site – Brief – Full Case Study	Abandoned	Construction uses	Tailings	Not applicable
MO	Madison Mines Superfund Site – Brief – Full Case Study	Active permit to reopen	Metal recovery from historical tailings	Tailings	Nickel, cobalt, copper
MT	Anaconda Smelter Superfund Site – Brief – Full Case Study	Closed	Remediation, land reuse	Slag	Not applicable
MT	East Helena Superfund Site – Brief	Closed	Metal recovery from slag	Slag	Zinc
MT	Golden Sunlight Mine – Brief	Closed	Metal recovery from tailings	Tailings	Gold, sulfur, REEs
MT	Silver Bow Creek/Butte Area Superfund Site – Brief – Full Case Study	Closed/ active	Remediation and economic value	AMD and AMD treatment sludge	Copper, zinc, manganese, magnesium, REEs
NM	Carlsbad Potash and Salt Mining – Brief	Active	Mine process wastewater evaporation for salt products	Wastewater	Salt
NM	Chevron Questa Mine Superfund Site – Brief	Closed	Remediation, land reuse	Tailings	Molybdenum
OK	Tar Creek Superfund Site – Brief – Full Case Study	Abandoned	Remediation, construction uses, critical minerals	Chat	Zinc, germanium
SC	Brewer Gold Superfund Site – Brief – Full Case Study	Abandoned	Remediation through reprocessing mining waste for economic value	Waste Rock	Copper, gold

State	Site Name	Mine Status	Target Application	Mining Waste	Mineral of Interest
WA	Midnite Mine Superfund Site – Brief	Closed	AMD treatment sludge, uranium extraction, on-site remediation for waste containment	Sludge, waste rock	Uranium

6.1 Project Summaries

This section provides summaries of a variety of mining waste reuse projects from several states within the United States. Project summaries are listed by state. More detailed case studies for several sites are presented in Section 6.2.

6.1.1 Arizona

6.1.1.1 Eagle Picher Mill Voluntary Remediation Program Site

The Eagle Picher Mill site was used for lead-zinc ore milling from 1943 to 1959. Mill waste was placed in a 35-acre tailing impoundment. In the late 1960s, the buildings were demolished, and the tailings impoundment was capped with a vegetated soil cover. The site entered the Arizona DEQ Voluntary Remediation Program in September 2016 to address residual impacts from these historic mining operations that posed a risk to human health and the environment (Arcadis U.S., Inc. 2022). The Volunteers, Amax Arizona Inc. (Amax), and Anaconda Arizona Inc., conducted a human health risk assessment (HHRA) for recreational use, excavated contaminated soils and placed them on the existing tailings pile, and constructed an engineered cap over the tailings, which was topped with 2 feet of clean soil. A land-use restriction was put in place to restrict the site to nonresidential uses and provide for long-term maintenance of the engineered cap. The Volunteers developed an open space landscape design to transform the site into a public park, including walking trails, shade structures, and pollinator gardens (also see Section 6.2.1).

6.1.2 California

6.1.2.1 Empire Mine State Historic Park

The Empire Mine site is an old, abandoned gold mine in the foothills of the Sierra Nevada range that operated from the 1850s through 1955 and recovered about 5.8 million ounces of gold. The land was purchased in 1975 by the California Department of Parks and Recreation (State Parks) from Newmont Exploration Limited, which retained some subsurface mineral rights (California DTSC and California CVRWQCB 2006). The site is now operated and managed by State Parks as a museum of historical mining with the mine and mill buildings preserved for tourism, along with areas for picnicking and trails for hiking, biking, jogging, and horseback riding (California DTSC 2006; ITRC 2017). It covers 852 acres in Nevada County near the City of Grass Valley, which is about 50 miles northeast of Sacramento, California. The gold mining process involved underground hard-rock stope mining with ore brought to the surface at the head works. The ore was then size reduced in a crusher and stamp mill prior to gold extraction via mercury amalgamation (until the 1920s) followed by flotation and cyanide leaching at the on-site cyanide plant. The mine has an estimated 367 miles of shafts and tunnels, most of which are abandoned and flooded, and the milling produced waste rock piles and tailings with mercury, cyanide, and arsenic concentrations above water quality standards and recreational risk-based levels in some places. The

California Department of Toxic Substances Control, along with the Central Valley Regional Water Quality Control Board, began evaluating the environmental impacts with characterization beginning around the late 1970s and early 1980s and continues to implement various remedial measures (California DTSC 1993). These measures consist of removal and remedial actions of areas with contaminated soils and sediments exceeding risk-based criteria (e.g., excavation with off-site disposal or capping with clean soil or gravel and closing certain trails to eliminate potential exposures).

The main current reuse application is as a historical park and mining museum. As early as 1947, the mined waste rock and mill sands were reused in construction of California State Route 49 of the Mother Lode Highway; this resulted in construction cost savings (Lathrop 1949). Also, waste rock and other mining wastes that meet certain requirements may potentially be used on-site as part of a remedial action, if approved. One of the main sources of contamination at the site was the cyanided sulfide tailings area from which arsenic was leaching into nearby streams and affecting fish and wildlife. In 1982, the U.S. Bureau of Mines Reno Research Center and California State Parks entered into a Memorandum of Agreement to assess the economic potential of the cyanided sulfide tailings and to determine an appropriate method for containing the arsenic effluent and/or for disposing of the tailings (Walters, Piros, and Mallory 1985). They found that the tailings pile covered about 5 acres of land and contained 43,000 tons of material composed of minus 200 mesh pyrite with minor chalcopyrite, arsenopyrite, and galena and averaged 0.25 ounces of gold per ton. At the time, the estimated economic value was between $2.5 million and $3.9 million (at $400/ounce), depending on the recovery process. The recommended means of controlling the arsenic pollution was excavation and reprocessing of the entire tailings pile (Walters, Piros, and Mallory 1985). Later, in 1985, the Empire Mine Park Association and State Parks sold and removed the majority of the cyanided sulfide tailings pile to the Homestake McLaughlin Mine for use of the sulfides in their process and recovery of the gold contained in the tailings. After removal of the tailings in 1986, sampling of surface water associated with Little Wolf Creek showed improved water quality (California DTSC 1993).

6.1.3 Colorado

6.1.3.1 Bonita Peak Mining District Superfund Site

The Bonita Peak Mining District site consists of 48 historic mines or mining-related sources where ongoing releases of metal-laden water and sediments are occurring within the Mineral Creek, Cement Creek and Upper Animas River drainages in San Juan County, Colorado. Historic mining operations have contaminated soil, groundwater, and surface water with multiple metals. USEPA and the Colorado Department of Public Health and Environment (CDPHE) have overseen investigation and reclamation of the Bonita Peak Mining District site since the early 1990s. The site was added to the National Priorities List (NPL) in 2016 (USEPA 2024b).

Since 2018, innovative methods to reduce mobilization of metals from legacy mining tailings have been used in the district. One innovative use is the reuse of sludge waste from the Gladstone Interim Water Treatment Plant (IWTP), where MIW from the Gold King Mine is treated. At this location, 14,000 cubic yards of sludge from the IWTP were mixed with 20,000 cubic yards of tailings at the Kittimac tailings area. The sludge is intended to immobilize metals found in the tailings, thereby reducing human health and environmental impacts. A berm was created with the sludge/tailings mixture to prevent trespass activities at the location. Groundwater monitoring is conducted to ensure there are no negative impacts from the interim sludge management location (USEPA 2024b). See Section 6.2.2 for more information.

6.1.3.2 Captain Jack Mill Superfund Site

At the Captain Jack Mill Superfund Site in Boulder County, Colorado, a stabilization/neutralization treatment was used where high NP waste material was used to cap a highly AP waste (Anton et al. 2014). Several individual underground mines were present at the Captain Jack site. Most of the mines contained highly pyritic deposits and resulted in high acid-generating surficial waste rock piles. Surficial waste material at one of the mines contained significant lead concentrations from galena but also had high NP from excess calcite in the deposit. The Captain Jack repository was designed to have a vegetated soil exposure barrier that would not intentionally limit infiltration into the underlying waste material. Since some infiltration and contact with high AP material was anticipated over time, once consolidated, the surface of the high AP material was blended with lime and capped with a 2-foot-thick minimum layer of the high NP-galena material. The final 2-foot-thick soil barrier cover was then placed over the high NP waste material. Together, the lime amendment and the high NP waste material were intended to react with water that may infiltrate through the soil exposure barrier cover by dissolving excess alkalinity. Should water reach the high AP material, the excess alkalinity in the infiltrating water will help to reduce the amount of AMD that may be generated. No AMD has been observed, and the cap continues to maintain a healthy stand of vegetation.

6.1.3.3 Central City–Clear Creek Superfund Site

The 400-square-mile Central City–Clear Creek Superfund Site includes several former mining towns in Colorado. For almost a century, vast deposits of gold and silver ores in the area supported a profitable mining industry. The mining industry also left behind waste rock and mine tailings that contaminated the Clear Creek watershed. USEPA added the site to the NPL in 1983. After Colorado amended its laws to allow gaming in the former mining towns, parties worked with casino developers to clean up areas in two towns to support casinos, hotels, and restaurants. As parties developed the former mining property, they led cleanup actions. The historic Argo gold mill hosts tours and serves as a tourism attraction. The mill's owners are exploring redevelopment opportunities (USEPA 2016d). Critical mineral recovery from AMD sludge research is being done on this site (Goodman, Bednar, and Ranville 2023).

6.1.3.4 Denver Radium Site and Uranium Mill Tailings Remedial Action Sites

The radium processing industry flourished in Denver, Colorado, between 1915 and 1927. Radium was first discovered in the late 1800s. It was valued for medicinal and industrial purposes such as cancer treatment, medical equipment, luminous paints, and other industrial purposes. In 1913, the U.S. Bureau of Mines entered into a cooperative agreement with a private corporation to establish the National Radium Institute, which successfully developed and operated a radium processing plant in Denver. The Colorado Plateau contained rich deposits of the radium-bearing ore, carnotite. Because of the presence of carnotite, numerous radium, vanadium, and uranium processing operations opened in Denver. The National Radium Institute used a nitric acid leaching process on carnotite ore to produce radium chloride, iron vanadate, and sodium uranate. Incidental products were sodium nitrate, barium chloride, and iron-calcium precipitate. The process was thought to recover more than 90% of radium, 85% of uranium, and about 30% of vanadium. Although much of the radium, uranium, and vanadium were recovered from ore, process residues containing uranium, radium, thorium, and other radioactive materials were discarded or left on-site when the processing facilities closed (Colorado Department of Environmental Health 2014).

In 1978, the U.S. Congress passed the Uranium Mill Tailings Radiation Control Act. This act tasked USDOE with stabilizing, disposing, and controlling uranium mill tailings and other contaminated material at 24 inactive uranium processing sites located in 10 different states where uranium was processed for sale to a federal agency. Nine of those sites are in Colorado. Although the active cleanup required by the act has been completed, residual uranium mill tailings remain in some communities. The CDPHE is authorized by Colorado Revised Statutes 25-11-301 et. seq. to assist local governments in identifying and managing the uranium mill tailings that remain in western Colorado communities. The CDPHE developed a Uranium Tailings Management Plan (CDPHE 2019) to assist utilities and private parties in the identification, proper handling, and disposal of uranium mill tailings because tailings deposits are often associated with utility rights-of-ways and private property. At the Denver Radium Superfund Site and at Uranium Mill Tailings Remedial Action sites regulated by the USDOE, some of these radioactive waste residues were used as part of street and roadway construction, fill material, or aggregate in asphalt paving surfaces, and as a free and readily available source of material for backfilling around residential structures. At the Denver Radium Superfund Site, several Denver street segments contain contaminated aggregate in asphalt. These street segments contained a 4- to 6-inch layer of radium-contaminated asphalt underlain by compacted gravel road base. Usually, these street segments were overlain by 4- to 12-inches of uncontaminated asphalt pavement. The uncontaminated asphalt did not provide sufficient shielding, and it was determined that the radium-contaminated asphalt posted a sufficient health risk to warrant taking action to protect human health. It is estimated that 38,700 cubic yards of radium-contaminated material was removed and disposed of at Denver Radium OU7 (Denver Streets).

6.1.4 Idaho

6.1.4.1 Stibnite Mining District

The Stibnite Gold Project is in Valley County, Idaho. The proposed project includes a comprehensive restoration, operation, and reclamation plan that will guide the cleanup and reprocessing of old tailings at a legacy mining site. Site reclamation is expected to reestablish habitat and water quality for an important salmon fishery that has been heavily impacted from legacy mining in the area (USFS 2022). The project should concurrently improve the local economy of Valley County and of Idaho. The proposed Stibnite Gold Project is designed to reestablish a U.S.-based source of the critical mineral antimony as a by-product of one of the highest-grade open-pit gold resources in the country. Antimony trisulfide is essential to national defense as a key component for munitions, yet no domestic mined supply currently exists. The mine was conditionally awarded up to $34.6 million in additional funding from the DOD under the existing Technology Investment Agreement through Title III of the Defense Production Act, bringing its total funding under the act to $59.4 million (Perpetua Resources 2024)

6.1.5 Michigan

6.1.5.1 Torch Lake Superfund Site

The Torch Lake Superfund Site was one of the largest copper mining regions in North America in the first half of the 1900s. Copper was extracted from the ore with stamp mills to liberate the copper metal from the host rock. Approximately 500 million tons of host rock tailings (called stamp sand) were dumped in the interior waterways of the Keweenaw Peninsula and along the shorelines of Lake Superior. The erosion of metal-containing stamp sand severely threatens the aquatic organisms living on the lake bottom and their habitats with its physical migration. The uncovered stamp sand piles are still being eroded into the water or drifting along the lakeshore. These tailings are basaltic, ready crushed, and relatively uniform. These tailings have been used as a raw material for concrete blocks, road construction, and traction on icy road surfaces. Research also demonstrated they can be used as antimicrobial roof shingle granules, sandblast sand, and aggregate in asphalt pavement (Section 6.2.3).

6.1.6 Missouri

6.1.6.1 Madison County Mines Superfund Site

An interested party purchased a closed metals mine (that was going through CERCLA to address erosional impacts from legacy mine tailings). The new property owner worked with USEPA and Missouri DNR to develop a plan to reprocess and close the mine tailings and eventually reopen the mine for critical minerals (mainly cobalt and nickel). The reuse plan involved removal of the existing vegetative cover and mine tailings followed by confirmatory soil sampling of residual metals in remaining soils and then installation of a low-permeability vegetative cover. The excavated tailings were reprocessed for metals recovery. Waste-reprocessing technologies involved crushing and grinding, flotation, and hydrometallurgy aqueous concentration to produce a filter cake material (Section 6.2.4).

6.1.7 Montana

6.1.7.1 Anaconda Smelter Superfund Site

The Anaconda Smelter Superfund Site covers more than 200 square miles of the southern end of the Deer Lodge Valley in Montana, at and near the location of the former Anaconda Copper Mining Company ore processing facilities. These facilities include the Old Works Smelter (which operated between 1884 and 1902) and the main Washoe Smelter (which operated between 1902 and 1980). From the time of the operation of the Old Works Smelter to the dismantling of the Washoe Smelter complex (which began in 1980), materials with high concentrations of arsenic, lead, copper, cadmium, and zinc were produced and released to the environment. At the Old Works Smelter site, slag covers 13 acres and has an estimated volume of 300,000 cubic yards (USEPA 1994a).

The Old Works Golf Course sits on the site of the former Old Works Smelter that underwent extensive cleanup after 1983. The Old Works Golf Course is part of the engineered cap for smelter waste that also includes chemical and hydraulic controls (USEPA 1994a). Once the cap and controls were installed, the site was redeveloped into a world-class golf course designed by Jack Nicklaus, a golfing legend and icon. The black sand bunkers throughout the course are one of the most unique features at Old Works (Golf Course Gurus, n.d.; Nicklaus Design, n.d.; USEPA 2021a). The black sand is reused smelter slag that has been processed by crushing and screening to produce a consistent texture and appearance (Section 6.2.5).

6.1.7.2 East Helena Superfund Site

In late 2020, Montana Environmental Trust Group, Trustee of the Montana Environmental Custodial Trust, announced that it had entered into an agreement with Metallica Commodities Corp., an international metals trader based in White Plains, New York. Metallica will remove and transport 2 million tons of unfumed slag that has recoverable zinc. The unfumed slag is being crushed and loaded onto trains; transported by rail to the Port of Vancouver, British Columbia; and placed on ships for delivery to one of the world's largest zinc smelting facilities, located in South Korea. The shipment of slag began in May 2021 and continues to present day. The removal of the unfumed slag material for sale will help pay for overall remedial action costs, significantly reduce the amount of selenium-containing material impacting groundwater, and reduce costs for capping the remaining slag (Montana Environmental Trust Group 2021).

6.1.7.3 Golden Sunlight Mine

The Golden Sunlight Mine produced more than 3 million ounces of gold during its nearly 40 years of operation. The mine shut down in 2019 when gold production was no longer economically viable. In March 2020, Golden Sunlight Mine submitted an application to the Montana DEQ to amend their permit to allow the mine to excavate and reprocess tailings from the previously closed unlined tailings impoundment, construct a new plant to reprocess the tailings to recover sulfur and gold, and dispose of the remaining tailings by partially backfilling a pit. The project's primary goal of recovering the sulfur and residual gold from the tailings will be realized at the processing plant at an affiliated joint venture mine in Nevada. After completing the environmental impact and public review processes, the Montana DEQ issued a Record of Decision (ROD) on September 13, 2021, that amended Golden Sunlight Mine''s operating permit. The post-closure project reuse of previously disposed tailings is expected to not only benefit the environment but also add jobs to the local economy in two states (Montana DEQ 2021).

6.1.7.4 Silver Bow Creek/Butte Area Superfund Site

West Side Soils Operable Unit. This mine-land reuse example is a site where multiple types of mine-land reuses exist simultaneously. The Orphan Boy and Orphan Girl mines were operated from about 1875 until 1956. In 1965, the Orphan Girl mine became the site of the World Museum of Mining which still operates today and is an example of recreational and educational reuse of a mine site. In 2010, Montana Technological University was gifted 65 acres of land within the West Side Soils OU of the Silver Bow Creek/Butte Area Superfund Site that included the old Orphan Boy mine. The Underground Mine Education Center was established on that site and is used today to provide hands-on education and research opportunities for students and industry professionals.

Another reuse example located at the site focuses on geothermal heating harnessed from the warm waters of the flooded underground mine shafts. In 2012, the USDOE awarded Montana Technological University a grant to install an innovative 50-ton GSHP to provide heating and cooling for the 55,000 square-foot natural resources building. The GSHP uses the flooded mine waters, which sit at 78ºF (25ºC), from the Orphan Boy workings as the heat source and heat sink to provide the energy for the closed-loop heat-pump system; it connects into the existing heating and chilling steam system in the building. Operation started in November 2013, and system performance was analyzed between January and July 2014. Results indicated the GSHP could deliver about 88% of the building's annual heating needs. Compared with a baseline natural gas/electric system, the system demonstrated at least 69% site energy savings, 38% source energy savings, 39% carbon dioxide emissions reduction, and a savings of $17,000 per year (40%) in utility costs (Hinnick 2016; Montana Technological University 2024; Rosenthal and Knudsen 2018). Also see Section 6.2.6.

Butte Mine Flooding Operable Unit. The Butte Mine Flooding OU is part of the Silver Bow Creek/Butte Area Superfund Site, located in the city of Butte, Montana. The OU consists of waters within the flooded Berkeley Pit, the flooded underground mine workings hydraulically connected to the Berkeley Pit, the associated alluvial and bedrock aquifers, and other contributing sources of inflow to the Berkeley Pit. The Berkeley Pit is the lowest point in the hydrogeological system and acts as a hydraulic sink for water with high levels of metals and arsenic released as a result of the interactions between mineralized rock and mining waste with groundwater and surface water (USEPA 1994b). The Butte Mine Flooding OU includes part of an operating mine within its boundaries that recovers copper from water pumped from the Berkeley Pit using the metallurgical process called cementation. The copper recovery system uses flumes filled with scrap iron that are inundated with acidic water from the Berkeley Pit (Gammons and Icopini 2020). At the very low pH of the water, copper in solution reacts with ferrous iron in the scrap via an oxidation-reduction chemical process involving the exchange of electrons; iron goes into solution, and elemental copper precipitates out. After sufficient contact time, the remaining iron is raised magnetically in order to dislodge any precipitate adhering to its surface; the solution containing the precipitate is then washed into settling tanks at the end of the flumes. After passing through the flumes and settling tanks, the water is pumped for secondary extraction. Approximately 80% to 95% of the copper content is recovered in the flumes (Section 6.2.6).

Butte Priority Soils Operable Unit. The Copper Mountain Sports and Recreation Complex Area was built on the site of the Clark Tailings Repository and is currently used as a community sports facility in Butte, Montana. The repository and sports facilities were designed and built by the Atlantic Richfield on the site of the historic Clark Smelter in 2001. Nearly one million cubic yards of contaminated soil were excavated from Lower Area One and placed at the Clark Tailings Repository in the late 1990s as part of the superfund remedy. A multilayer engineered cap was placed over the tailings, along with a revegetated soil cover with a monitored irrigation system to minimize the risk from over-irrigation. This remedy was installed in conjunction with the closure of the adjacent county landfill (BPSOU 2024). The Copper Mountain Sports and Recreation complex continues to be operated by the county, but the underlying repositories are managed under CERCLA and RCRA (Section 6.2.6).

6.1.8 New Mexico

6.1.8.1 Carlsbad Potash and Salt Mining

Two potash mining companies, Intrepid Potash New Mexico and Mosaic Potash, operate near Carlsbad, New Mexico. Mosaic operates a conventional underground potash mine where ore is transported to the surface and processed through flotation and gravity separation processes. The resulting waste stream contains solid salt (NaCl), clay (insoluble particles), and brine that is saturated (or nearly saturated) with salt. This mixture is discharged to a salt stack, travels through a series of settling areas, and eventually saturated brine is delivered to a natural salt playa called Laguna Grande. Here, two salt operators, New Mexico Salt and United Salt, manage the brine through a series of internal dikes to encourage evaporation. After the solid salt precipitates to a sufficient depth, the companies harvest it for use in water softeners, road salt, and swimming pools, among other products (The Center for Land Use Interpretation, n.d.-b).

Intrepid has a quite different operation but is also tied into this mining waste reuse cycle. Intrepid operates a solution and solar evaporation mine that injects brine into abandoned underground potash mine workings and extracts a pregnant brine that is rich in potash (KCl) and other minerals. Intrepid manages a series of man-made solar evaporation ponds where potash and sodium chloride precipitate for harvest and processing. The waste stream from solution mining contains solid salt and saturated brine with very little clay. The solid salt is sold to New Mexico Salt and transported to Laguna Grande for processing. Intrepid also engages in a number of other reuse applications of their mining waste, including selling excess brine to the oil and gas field for well drilling, dissolving old tailings accumulated during past conventional underground mining to create their injectate brine for solution mining, and selling their solution mine bitterns (the final brine waste from solution mining, high in $MgCl_2$) as a dust suppressant (The Center for Land Use Interpretation, n.d.-a).

6.1.8.2 Chevron Questa Mine Superfund Site

Renewable energy generation at closed mine sites is becoming increasingly popular, and many operators have found it a worthwhile endeavor, even without significant state or federal incentives. For example, at the closed Chevron Questa Molybdenum Mine in Questa, New Mexico, Chevron Mining Inc. has implemented a 21-acre pilot solar installation on a portion of their reclaimed tailing facility. The solar project was completed in late 2010 and has successfully produced an annual average of almost 2 gigawatt hours per year of electrical energy since completion. The project required coordination with numerous federal, state, and local government agencies, stakeholders, the local electric cooperative, and the public. The project initially used New Mexico's Renewable Energy Production tax credit, which expired in 2021. Today the project stands as a leading example of how renewable energy projects can be successfully implemented on former mine lands and superfund sites. The success of the pilot solar installation has also encouraged additional clean energy development proposals for the site, including hydrogen production and storage facilities that would be powered by renewable energy (USEPA 2013a).

6.1.9 Oklahoma

6.1.9.1 Tar Creek Superfund Site

The Tar Creek Superfund Site is located in Ottawa County, Oklahoma. The superfund site itself has no clearly defined boundaries but consists of areas within Ottawa County impacted by historical mining wastes. The mill tailings, accumulated in piles and bases, are locally known as chat. It consists primarily of fine gravel-sized and coarse sand–sized rock fragments of chert, dolomite, and limestone and contains elevated levels of cadmium, lead, and zinc. An estimated 40 million cubic yards (of the estimated original 165 million cubic yards) of chat remained at the mine site in 2008; most of it had been used in construction projects, including aggregate in asphalt, for more than a hundred years. Bulk unencapsulated chat was reused for gravel roads, parking lots, fill material in residential developments, sand for children's play areas, and base material for railroads.

Over time, these reuses of chat have caused widespread environmental contamination from the metals contained therein and have led to the formation of residential and nonresidential OUs. The remedy selected for the nonresidential OUs includes continued chat sales and marketing' backfilling / subaqueous disposal; excavation of chat, fine-tailings, and transition zone soils with transportation to an on-site repository; and consolidation/capping. The record of decision for the nonresidential OUs limits chat sales to only those environmentally safe uses defined in the 'Chat Rule' (40 CFR Part 278), which was the result of an LCA of chat used in asphalt, data evaluation, and the receipt and response to public comments. The environmentally safe uses for transportation applications include asphalt concrete, slurry seals, micro-surfacing or in epoxy seals, Portland cement, flowable fill, stabilized base, chip seal, or road base, with the provision that, on a case-by-case basis, the material meets the standards of either an SPLP test for lead and cadmium drinking water maximum contaminant levels and acute water quality criteria for zinc or a site-specific risk assessment. The environmentally safe uses for non-transportation applications include the following: cement and concrete used in (nonresidential) construction projects as described in the Chat Rule preamble and use in applications that encapsulate the chat as a material for manufacturing a safe product or as part of an industrial process (for example, glass, glass recycling), where all waste by-products are properly disposed of. In addition, the non-transportation cement and concrete material must pass one of the two evaluation criteria, such as a risk assessment or SPLP.

Critical minerals present in the Tar Creek mining waste are potentially economically recovery, with approximately 14 million cubic yards of fine-sized material less than the 100-mesh sieve size (<150 micrometers [µm]). An economic evaluation and LCA on the feasibility of economic recovery is needed for comparison to the costs of remediation of the mining waste and potential offset of remediation costs (Section 6.2.7).

6.1.10 South Carolina

6.1.10.1 Brewer Gold Mine Superfund Site

Brewer Gold Mine Superfund Site is located in Chesterfield County, South Carolina. Because gold mines are in the area surrounding the site and based on past knowledge of the site's geologic and mining history, mining companies approached USEPA with an interest in exploring the NPL site for additional resources. Because the site was not owned by the South Carolina Department of Health and Environmental Control (SCDHEC) or USEPA, there was no mechanism to allow for exploration. SCDHEC filed a motion for the appointment of a receiver to manage third-party access to the property and facilitate potential leasing, sale, or other use or disposition of the property, including potential renewal of mining exploration and development. Currently the site is being explored for gold and copper with hopes to sell to the company by 2030, thereby removing the $1.5 million yearly expense to the state as well as cleaning up legacy waste (Section 6.2.8).

6.1.11 Washington

6.1.11.1 Midnite Mine Superfund Site

The Midnite Mine Superfund Site is located in eastern Washington state within the boundaries of the Spokane Indian Reservation. Under leases signed by USDOI and the Dawn Mining Company, the 350-acre site operated as an open-pit uranium mine between the years 1955–1965 and again from 1968–1981. In April 2011, at the request of Dawn Mining Company, the White Mesa Mill applied for permission from the Utah Division of Waste Management and Radiation Control to process and dispose of up to 4,500 dry tons (9 million pounds) of Midnite Mine alternate feed, which are radioactive solids left over after the contaminated water is treated (this is also referred to as filter cake sludge). As a superfund site, transport of this sludge also required USEPA approval through the off-site rule process. This sludge contains metals including barium, beryllium, radium, cadmium, chromium, and lead, but it also contains economic value from its uranium content. The sludge waste is shipped in “SuperSaks”—bulk containers made of flexible, woven fabric. Once at the mill, the SuperSaks of waste are stored on-site until the waste is processed for its trace uranium content. Use of the White Mesa Mill is ongoing through the remedial action phase to manage on-site water treatment sludge, although continued acceptability reviews are required for the mill facility to receive the sludge waste.

Another reuse application for this site involves the use of waste rock materials in on-site construction of the waste containment area. Materials in a specific waste rock area of the site were crushed and sorted to generate a suitable bedding material for a low-density polyethylene geomembrane cover. Several thousand cubic yards of mining waste were processed and will be placed throughout the entire waste containment area as an 18-inch-thick layer. While this processed waste rock does not meet site cleanup criteria, it will be reused beneficially to create a compacted and smooth surface for installation of the geomembrane cover. For more information on the site, please visit USEPA’s Superfund Sites in Reuse in Washington (USEPA 2016e).

6.2 Case Studies

6.2.1 Arizona—Eagle Picher Mill Voluntary Remediation Program Site

Value Proposition Statement. This case study describes a project where property owners remediated a legacy mine site (Eagle Picher Mill) under oversight of the Arizona DEQ Voluntary Remediation Program. Using an engineering control and a land use restriction, the property owners transformed the site into a public park. Historically, the area was undeveloped; now, newly built houses, schools, churches, and government buildings surround the north and west sides of the property, making this site important to the community in terms of reuse. What was once something that could be considered an eyesore, is now a vibrant, usable space for all to enjoy.

Introduction. In September 2016, Amax, a subsidiary of Freeport Minerals Corporation, and Anaconda Arizona Inc., a subsidiary of Atlantic Richfield, entered the Arizona DEQ Voluntary Remediation Program to remediate the Eagle Picher Mill site.

The Voluntary Remediation Program encourages property owners and other interested parties to voluntarily invest resources to remediate contaminated sites as quickly as possible to healthful standards. As a result, these contaminated sites are returned to economic viability, which further benefits Arizona communities.

Site Background. The Eagle Picher Mill site consists of 230 acres on four contiguous parcels in Sahuarita, Arizona, approximately 25 miles south of Tucson. The site is bounded to the east by South Villita Road. West Twin Buttes Road and the Southern Pacific Railroad line cross the property from northeast to southwest. Interstate 19 is approximately 0.5 miles west of the western property boundary. The property is situated in the Santa Cruz Valley, a wide alluvial basin between the Santa Rita Mountains to the east and the Sierra Mountains to the west. The site elevation is approximately 2,760 feet above mean sea level, and the depth to groundwater has historically ranged from 152 to 205 feet. Groundwater monitoring wells installed at the site never identified any groundwater contamination (Arcadis U.S., Inc. 2022; Clear Creek Associates, P.L.C. 2014).

In 1943, a flotation mill was constructed on the site to process lead-zinc ore from the San Xavier Mine located approximately 8 miles to the west. Ore was transported to the site via truck or rail. After processing, tailings were deposited in a 35-acre impoundment. All mill operations ceased in 1959. In the late 1960s, buildings were demolished, and the tailings impoundment was covered with a layer of native soil and the surface was planted with native vegetation. In 1989, a geotextile material was added to the impoundment to prevent erosion; it was topped with riprap and seeded with grass. A padlocked fence was installed around the property, including no trespass signs. Periodic inspections were conducted to ensure the erosion control and safety were maintained (Clear Creek Associates, P.L.C. 2014).

The property remained fenced until remediation efforts began in 2022.

Mining Waste Reuse Summary. This section describes three main components of the mining waste reuse activities: (1) mining waste characterization methods and results, (2) regulatory considerations for mining waste reuse, and (3) the target application for the mining waste.

Characterization. The tailings consist of one main pile of noneconomic, mineralized materials and tailings milled during the processing of lead-zinc ores. Based on a conservative estimate, approximately 750,000 tons of tailings were placed in the 35-acre impoundment. Beginning in 1999, numerous sampling events were conducted to characterize the tailings pile. These sampling efforts included surface grab samples, boreholes, and test pits to characterize the thickness of the tailings. Samples were collected and analyzed using USEPA Methods 6010 and 6020 for metals. Laboratory analytical results indicated arsenic, cadmium, lead, and manganese were present at concentrations exceeding Arizona residential soil remediation levels (Clear Creek Associates, P.L.C. 2014).

Numerous sampling events were conducted to characterize the soil surrounding the tailings pile. These sampling efforts also included surface grab samples, boreholes, and test pits. Samples were collected and analyzed using USEPA Method 6010 for metals. Laboratory analytical results indicated arsenic, cadmium, manganese, and zinc were present at concentrations exceeding Arizona residential soil remediation levels in soils surrounding the tailings (Clear Creek Associates, P.L.C. 2014).

Regulatory Considerations. An HHRA was conducted using probabilistic methods to evaluate potential cancer risks and noncancer hazards to future recreators exposed to soils containing arsenic, cadmium, manganese, and zinc. Exposure estimates based on a combination of parameter distributions and point estimates were then combined with toxicity values to provide distributions of risk and hazard estimates that consider both variability and uncertainty. The resulting ninety-fifth percentile excess lifetime cancer risk estimate of 4×10^{-7} was below both the Arizona DEQ and the USEPA acceptable risk range of 1×10^{-6} to 1×10^{-4}. The resulting ninety-fifth percentile (95%) hazard index estimate of 0.17 was also below the target hazard index of 1. The HHRA also derived site-specific remediation levels (SSRLs) for recreational use for arsenic, cadmium, manganese, and zinc. The USEPA's Integrated Exposure Uptake Biokinetic (IEUBK) v2.0 model was used to evaluate the potential for adverse health effects from exposure to lead. Based on the results of the IEUBK model, exposure to lead in soil at the site is not likely to result in adverse health effects in future child recreators and, by extension, in future adult recreators. The IEUBK model was also used to derive an SSRL for lead. The results of the HHRA indicated that adverse effects to human health from exposure to arsenic, cadmium, lead, manganese, and zinc in soil are not expected if the site is developed for recreational use (Arcadis U.S., Inc. 2022).

After remediation was complete, Amax, Anaconda Arizona Inc., and Arizona DEQ signed an Engineering Control Declaration of Environmental Use Restriction (DEUR). A DEUR is a restrictive covenant that runs with and burdens a property where contamination has been left in place above residential soil remediation levels or the owner elects to use institutional or engineering controls to meet applicable soil remediation levels. The purpose of a DEUR is to ensure current and future property owners are aware of contamination on a property and take appropriate actions to prevent additional contamination. The DEUR for this site was recorded with the Pima County Recorder's Office and restricts the property to recreational use only. Pursuant to Arizona statutes, a financial assurance mechanism covering the costs of long-term maintenance and restoration is required for all engineering control DEURs, which Amax and Anaconda Arizona Inc. provided. This ensures funds are available to Arizona DEQ should the engineering control fail or fail to meet its intended purpose.

Following completion of remedial activities, Amax and Anaconda Arizona Inc. donated the property to the Town of Sahuarita (the Town). Subsequently, Arizona DEQ and the Town signed a DEUR Amendment, which identified the Town as the new property owner and documented each party's responsibilities under the DEUR. In the DEUR Amendment, Amax and Anaconda Arizona Inc. agreed to continue to provide financial assurance on behalf of the Town. The donation agreement between Amax, Anaconda Arizona Inc., and the Town contained a stipulation that if the Town is unable or unwilling to maintain the engineering control, Amax and Anaconda Arizona Inc. will take back the responsibility. Amax and Anaconda Arizona Inc. also provided funding to the Town for monitoring and maintenance costs.

Mining Reuse Application. Soils exceeding the SSRLs from two portions of the site were over-excavated at depth and consolidated onto the existing tailings pile. XRF was used as a screening tool prior to collecting post-excavation soil confirmation samples. If field screening results using XRF indicated additional removal was necessary, additional excavation was performed. In total, 67,800 cubic yards of impacted soil was consolidated onto the tailings pile. Soil confirmation samples were collected on a 100-by-100-foot grid to document post-removal conditions. Samples were analyzed for arsenic, cadmium, lead, manganese, and zinc by USEPA Method 6010C. To assess post remediation conditions, the 95%

upper confidence limits (UCL) on the mean concentrations for arsenic, cadmium, lead, manganese, and zinc were calculated using ProUCL version 5.2 (Arcadis U.S., Inc. 2022) and compared to the SSRLs. The 95% UCLs were calculated using post-excavation confirmatory samples collected as well as historic samples collected and used in the HHRA. The post-excavation confirmatory samples were collected from the bottom of the excavation, which represented the final surface soil interval. The 95% UCLs for all constituents of concern were below the SSRLs. The excavated areas were backfilled with two feet of clean fill (Arcadis U.S., Inc. 2023).

An engineered soil cap was constructed on top of the tailings pile to restrict human exposure and prevent erosion (Figure 6-1). To manage surface water, the entire site was graded to promote sloping and smooth transitions between the various excavated, backfilled, and consolidated areas. Surface water management features were constructed to promote drainage toward an infiltration basin or nearby dry wash. Once the initial grading was achieved, two feet of clean cover material was placed. For erosion protection, drainage channels were lined with riprap or articulated concrete blocks. Concrete grade control structures and cutoff walls were constructed within the drainage channels to improve the flow of water and to reduce flow velocity and scour caused by fast moving turbulent flow. Rock armoring was placed along the boundaries of the cover system (Arcadis U.S., Inc. 2023).

Figure 6-1. Articulated concrete-block–lined drainage channel installed as erosion control for the engineered cap.

Source: Arizona Department of Environmental Quality

Finally, the site was renovated into a public park. Recreational open space was designed in consultation with the Town, the Tohono O'odham Nation's San Xavier District, the Wildlife Habitat Council, Discovery Education, Bat Conservation International, the Arizona-Sonora Desert Museum, and the Watershed Management Group. Features include 1.5 miles of walking trails, 14 trailside benches, two 20-foot-by-20-foot steel ramadas, two traditional wa:ato (translated from the language of the Tohono O'odham, this means a ramada made of mesquite timbers), 2.5 acres of public gathering spaces, and parking areas. In addition, pollinator gardens were seeded, and vegetated areas were planted with native and culturally significant plants to attract bees, butterflies, and hummingbirds. Interpretive areas with informational signs and QR codes accompanied the planting areas. Bee blocks, to attract solitary bees, were also installed throughout the park. This park can serve as a STEM resource for hundreds of students at the two schools nearby. The park was formally opened to the public with a ribbon-cutting ceremony attended by Amax, Anaconda Arizona Inc., the Town, the Tohono O'odham Nation, and Arizona DEQ where the Tohono O'odham provided a blessing for the trail and park (Freeport Minerals Corporation 2022).

6.2.2 Colorado—Kittimac Tailings Site, Bonita Peak Superfund Site

Value Proposition Statement. This case study describes a site, Kittimac Tailings Site, where it was proposed that the low pH, lead-contaminated tailings be mixed with high pH water treatment plant sludge from the Gladstone IWTP. This process was expected to help manage sludge from the IWTP and immobilize metals in the tailings—a net benefit for both sites. The mixed material would be placed in an on-site repository, capped with clean fill, and revegetated.

Background and Objectives. USEPA began treating discharge water from the Gold King Mine in October 2015 at the Gladstone IWTP in Gladstone, Colorado. Water was treated using a lime pH treatment to precipitate out dissolved metals from the additional discharge. Sludge generated at the IWTP was managed on-site. By early 2018, all available on-site sludge storage capacity was filled. In an effort to relocate IWTP sludge, a stand-alone abandoned tailings site, Kittimac Tailings, was identified as a high-priority recreational area with exposure to lead contamination (Figure 6-2).

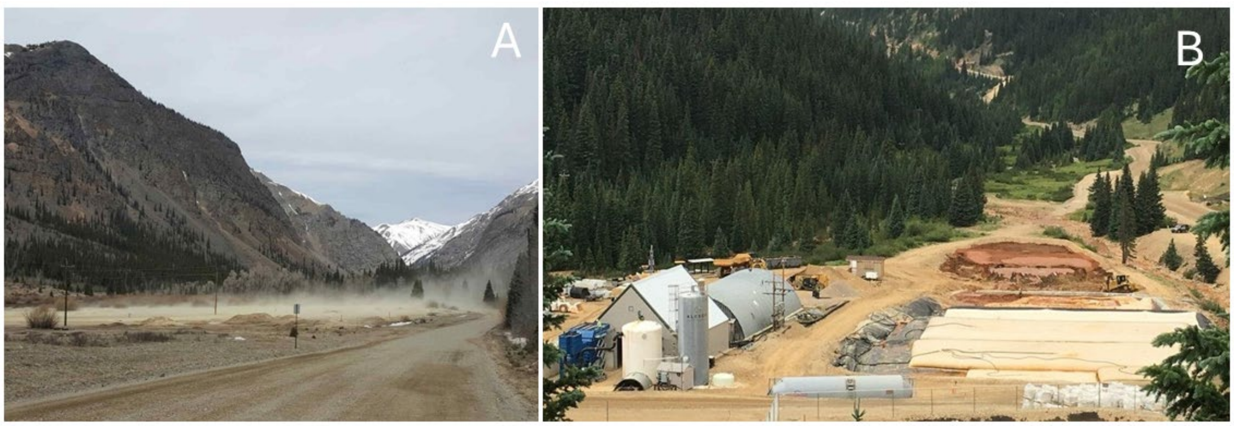


Figure 6-2. Kittimac Tailings Site pre-reclamation (A) and Gladstone Interim Water Treatment Plant and Sludge Storage (B).

Source: Colorado Division of Reclamation, Mining and Safety (A) and Colorado Department of Public Health and Environment (B)

The Gold King Mine IWTP sludge contains oxides of several metals, such as iron, zinc, and aluminum; lime, which is used to neutralize acidic mine drainage; and polymers, which are used to bind the particles together. The sludge passed the TCLP and thus is not considered a hazardous waste. Liquids associated with the sludge are also nonhazardous. Sludges and the associated water from the IWTP were managed safely on-site until storage capacity was reached.

Kittimac tailings contain metals that are a potential source of dissolved metals to the environment as found in samples taken on October 2016 and confirmed in samples taken on April 2018. In a focused treatability study, Mine Water Inc. tested the hypothesis that mixing silica-rich tailings from the Kittimac Site with metal oxides from the Gladstone IWTP would catalyze the mixture to a pH not more acidic than 11.0 s.u. (highly alkaline). This would result in beneficial pozzolanic reactions that would result in the binding and immobilization of metals. Gladstone IWTP sludge would be beneficial to the stability of metals in the resulting mixtures and result in at least incrementally lowered leachability of metals as measured by SPLP and by TCLP. A secondary objective was to determine whether freshly produced sludge was more reactive than older sludge stored at Gladstone for more than one year.

Study Method. Sludge and tailings samples were collected and mixed in various ratio mixtures for further analysis. The wash mixture was subsampled for analysis using TCLP and SPLP methods. TCLP analysis uses an organic acid mixture similar to the leachate that might be expected from a municipal solid waste (MSW) landfill. TCLP was tested for comparison if the treated mixture was disposed of into an MSW landfill. SPLP uses a pH 5.0 mixture of synthetic rainwater modified with sulfuric and nitric acids that generally correspond to rainfall that might result from poor air quality downwind of a coal-fired power plant emitting lots of sulfur oxides and nitrogen oxides. After extraction by each USEPA-approved Standard Method (1311 or 1312, as appropriate), the liquid fraction was analyzed for total metals.

Discussion of Results

Disposal of Gladstone IWTP sludge at MSW Landfill. TCLP extraction of Gladstone IWTP sludge demonstrated very high leachability for the following contaminants: aluminum, cadmium, cobalt, copper, magnesium, manganese, nickel, and zinc.

Each of these analytes were observed in the TCLP leachate at many orders of magnitude higher than observed in the predicted leachate when blended with Kittimac tailings. This indicated a beneficial effect of the blending process and a preferred type of disposal location (monofill vs. MSW landfill).

Beneficial reuse of Gladstone IWTP sludge as a treatment reagent. The aqueous stability of metals within the Kittimac tailings and stored in a monofill (no MSW leachate) was dramatically improved through addition of the Gladstone sludge to the Kittimac tailings. The Gladstone sludge was beneficial when incorporated at high pH levels into the Kittimac tailings for each metal element as measured by SPLP (Table 6-2). A few elements increased in leachable concentration, including aluminum, calcium, and potassium. These effects are not expected to be negative to the receiving environment but rather reflect the method of binding (using excess lime to dissolve the host rock and reprecipitate around the metal oxides). This reflects transitory and uncompleted reactions between the sludge and the tailings. The short duration of curing the blending mixtures is the likely cause of the uncompleted reactions, although it may take months for the full benefits of the reaction to be achieved. The soluble aluminum and calcium will tend to decrease over time (months) as the pozzolanic reactions continue to harden.

Fresh sludge proved better in binding lead and cadmium as measured under the TCLP extraction procedures. Aged sludge was better at binding lead, zinc, cadmium, and manganese as measured by SPLP leaching conditions. The differences in performance between aged sludge and fresh sludge were not significant for most metals in comparison to the huge benefits to the leachate quality of blending the sludge with the tailings (see Table 6-2).

Table 6-2. Summary of synthetic precipitation leachate procedure (SPLP) results

Metal	Kittimac Tailings	1.5:1 Fresh Sludge	1:1 Tailings Aged	1.5:1 Tailings Aged	2:1 Tailings Aged	Aged Sludge	Tailings/ Mixture
Treatment Benefit							
Lead	5,400	9.10	2.90	–	2.90	2.90	0.1%
Barium	52	31.00	18.00	47.00	12.00	2.80	23.1%
Copper	660	160.00	100.00	160.00	92.00	2.20	13.9%
Cadmium	4.4	0.16	0.16	0.16	0.16	0.16	3.6%
Iron	290	48.00	31.00	31.00	31.00	31.00	10.7%

Metal	Kittimac Tailings	1.5:1 Fresh Sludge	1:1 Tailings Aged	1.5:1 Tailings Aged	2:1 Tailings Aged	Aged Sludge	Tailings/ Mixture
Magnesium	480	78.00	93.00	49.00	69.00	11,000.00	10.2%
Manganese	40	4.10	2.70	2.70	2.70	1,100.00	6.8%
Zinc	810	7.30	5.80	5.80	5.80	5.80	0.7%
No Effect							
Antimony	3.4	3.40	3.40	3.40	3.40	3.40	100.0%
Arsenic	4.1	4.10	4.10	4.10	4.10	4.10	100.0%
Beryllium	0.33	0.33	0.33	0.33	0.33	0.33	100.0%
Chromium	2.4	4.80	4.30	3.20	4.70	1.20	133.3%
Cobalt	0.55	0.55	0.55	0.55	0.55	0.55	100.0%
Mercury	0.07	0.07	0.07	0.07	0.07	0.07	100.0%
Nickel	1.5	1.50	1.50	1.50	1.50	1.50	100.0%
Selenium	3.6	3.60	4.90	3.60	3.80	3.60	100.0%
Silver	0.85	0.85	0.85	0.85	0.85	0.85	100.0%
Thallium	2.9	2.90	2.90	2.90	2.90	2.90	100.0%
Vanadium	7.7	7.70	7.70	7.70	7.70	7.70	100.0%
Incomplete Reaction							
Aluminum	36	20,000.00	30,000.00	6,000.00	26,000.00	36.00	16,666.7%
Calcium	3,800	88,000.00	82,000.00	100,000.00	70,000.00	76,000.00	1,842.1%
Potassium	910	3,100.00	2,800.00	3,100.00	1,300.00	400.00	142.9%

Note: Concentrations in micrograms per liter (µg/L).

Study Result Recommendations. The addition of one part by volume of Gladstone sludge (either fresh or aged) to Kittimac tailings was shown to have a very beneficial effect on the stability of metals in the Kittimac tailings. It was important that the pH be uniformly elevated (above pH 11, and preferably about 11.5–12) through the addition of lime, and that the tailings be intimately mixed with the sludge through a multiple pass tilling or rototilling method. Paste pH was used as an easy and rapid field method (within a few minutes) to gauge the effectiveness of the lime amendment/catalytic process. It was found that if the lime was added to the sludge at Gladstone, it acted as a surrogate for the overall mixing process. Moreover, if the pH was found to be elevated above 11 compared to the starting pH of around 4.8 s.u. for Kittimac tailings, then mixing could be presumed to be sufficient during the placement process (Figures

6-3, 6-4, 6-5, 6-6, and 6-7). More information can be found in the Action Memorandum (USEPA 2017), Fact sheet (USEPA 2018a), and Q&As (USEPA 2018b) for the Bonita Peak site.

Figure 6-3. Kittimac tailings sludge and tailings mixing (A) and tailings berm construction (B).

Source: U.S. Environmental Protection Agency

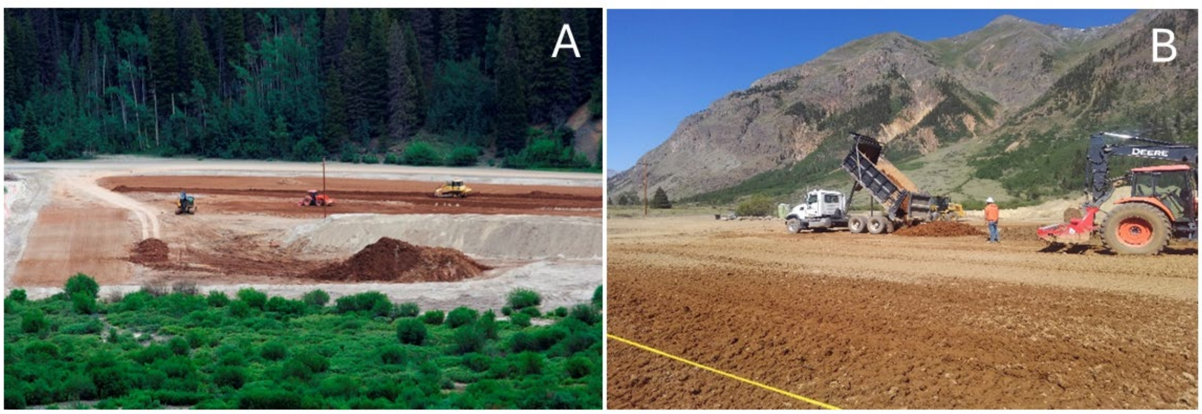


Figure 6-4. Kittimac tailings sludge and tailings stockpile (A) and sludge transportation during reclamation (B).

Source: U.S. Environmental Protection Agency

Figure 6-5. Kittimac tailings revegetation (A) and reseeded monofill (B).

Source: U.S. Environmental Protection Agency

Figure 6-6. Kittimac reclaimed and revegetated (A) and reclaimed and revegetated monofill (B).

Source: Colorado Department of Public Health and Environment

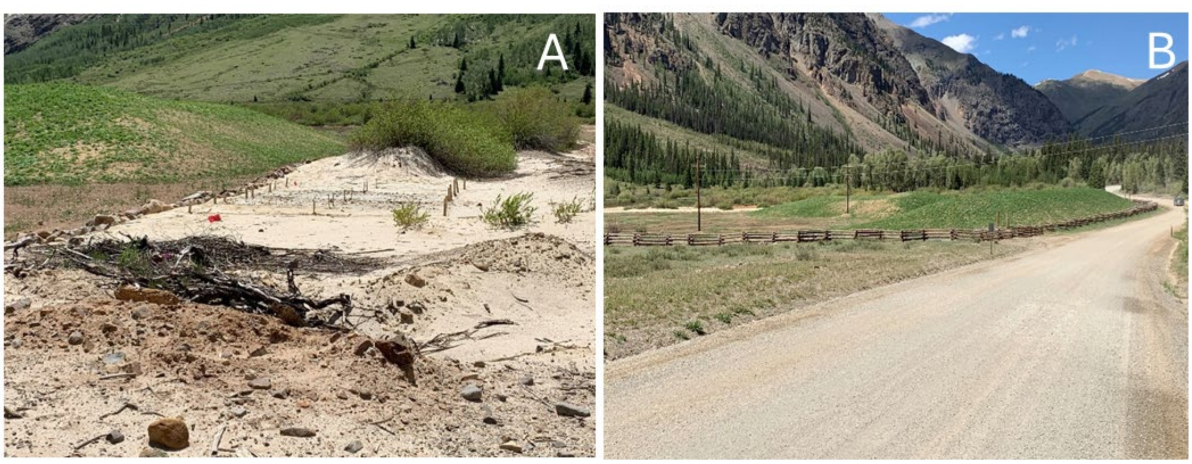


Figure 6-7. Kittimac reclaimed and revegetated berm and historic untouched narrow gauge train spur (A) and Kittimac Site reclaimed and revegetated (B).

Source: Colorado Department of Public Health and Environment

6.2.3 Michigan—Copper Mine Tailings on the Keweenaw Peninsula, Torch Lake Superfund Site

Value Proposition Statement. Historic copper mining left tons of tailings material, or stamp sands, in the Keweenaw Peninsula of Michigan. The stamp sands have elevated levels of copper and other metals. Stamp sands have been reused in a variety of construction and consumer products that capitalize on their basaltic base and residual copper concentrations.

Introduction. Starting in the 1800s, large deposits of native copper were discovered and mined in the Keweenaw Peninsula of Michigan. This area became one of the largest mining regions in North America, with operations continuing through the late 1990s. Metallic copper was extracted from the ore with the aid of steam-driven stamp mills, which crushed the rock to liberate the copper metal from the host rock. Approximately 500 million tons of host rock waste material, called stamp sands or tailings, were dumped in the interior waterways of the Keweenaw Peninsula and along the shorelines of Lake Superior. The major copper tailings dump sites include Torch Lake, Boston Pond, Freda-Redridge, Portage Lake, and Gay (Figure 6-8). These mining-related wastes occur both on the uplands and in the lakes and waterways, and mainly remain in form of stamp sands (Jeong 2003; Kerfoot and Nriagu 1999; Kerfoot et al. 2019; Michigan DNR 2017). The large quantities of copper mine tailings have had a negative environmental effect in the area. Those tailings deposited on shorelines are drifting along the lakeshore and affecting the beauty and ecological system of the otherwise pristine coastline of Lake Superior (Kerfoot, Jeong, and Robbins 2009; Kerfoot et al. 2019; Raymond 2022).

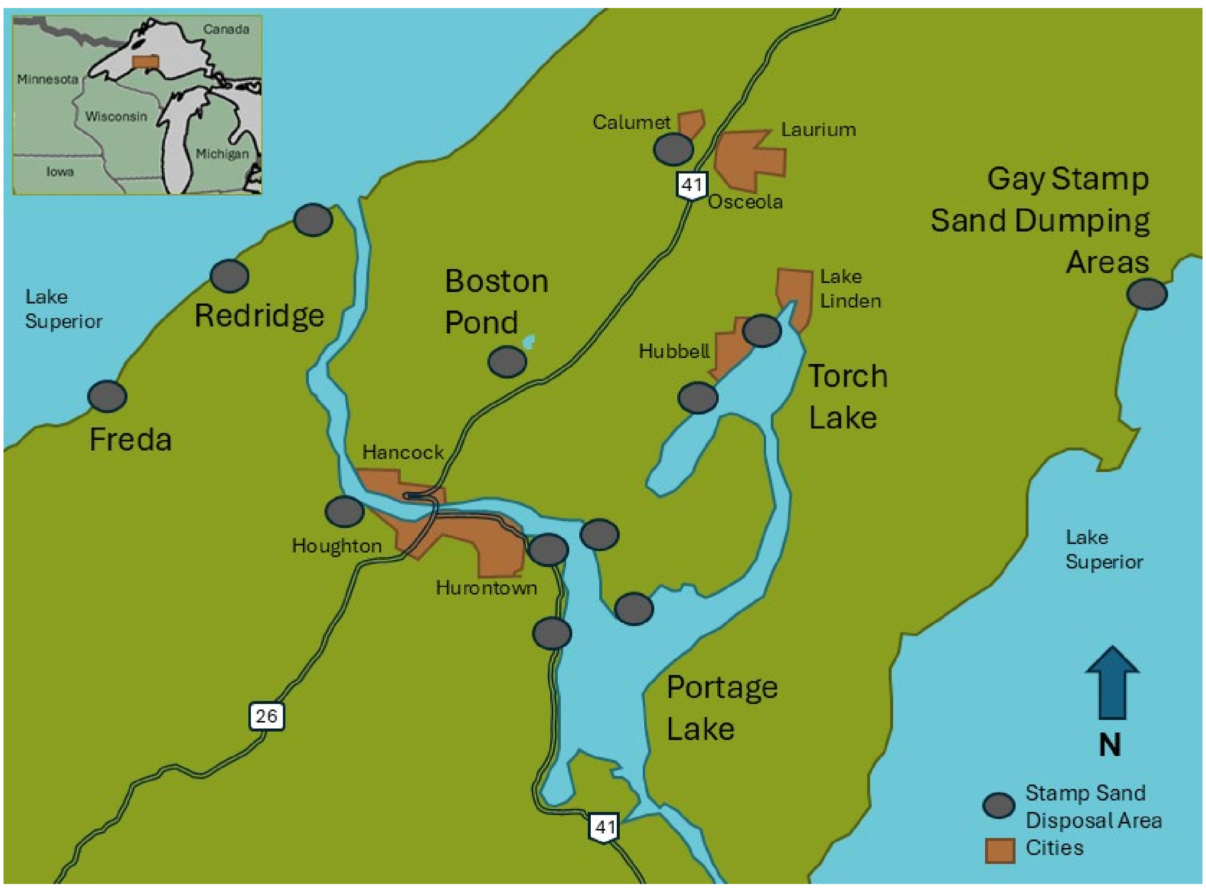


Figure 6-8. Major copper tailings dump sites in the Keweenaw Peninsula, Michigan.

Source: Interstate Technology & Regulatory Council Reuse of Solid Mining Waste Team

Copper is one of the trace elements essential to the health of plants and animals. The concentration of copper in stamp sands in Torch Lake and Gay reach 0.2%–0.6% in weight (Jeong, Urban, and Green 1999; Popko 2007). The elevated concentrations of copper are toxic to aquatic organisms such as algae, benthic invertebrates, and juvenile fish (Kerfoot et al. 2004). A major metal halo has formed around the Keweenaw Peninsula (Gewurtz et al. 2008; Kerfoot and Nriagu 1999). The erosion and physical migration of metals-containing stamp sands also severely threatens the aquatic organisms living on the lake bottom and their habitats (Chiriboga 2008).

Since the 1970s, Michigan's Water Resources Commission, the Michigan DNR, and the USEPA have undertaken several remedial activities in the Great Lakes Area of Concern (AOC). This AOC is also a superfund site. The AOC spans the lower portion of the peninsula and its western Lake Superior shoreline, a total of approximately 368 square miles in Houghton County, Michigan (USEPA 2023b). Although some sites of the contaminated stamp sands in the AOC have been covered with soils and planted with vegetation (Huang et al. 2005), the uncovered stamp sand piles, such as in Gay, are still eroding into the water. The covered stamp sands also continue loading metals into the lake and waterways via groundwater pathways (stacked stamp sands contain high penetrated porosity), threatening the ecosystem of Lake Superior (Kerfoot et al. 2004; 2019).

Among these sites, approximately 22.7 million metric tons of stamp sands have been dumped on the shoreline of the Gay site (Coastal and Marine Hazards and Resources Program 2019). Since then, the stamp sand piles have gradually eroded and migrated along the shoreline as far as 5 miles to the south. The extended concrete bank of the Big Traverse River acts as a barrier inhibiting further movement of the stamp sands. It is estimated that more than 85% of the original pile of stamp sands has been eroded (Coastal and Marine Hazards and Resources Program 2019). The tailings migration has covered the white sand beaches, decreasing the visual appeal of the area. Additionally, in Lake Superior the tailings are threatening Buffalo Reef, which is a critical lake trout and whitefish breeding ground, by filling up a trough in front of the reef and spilling over into the cobble beds around the reef (Goldstein 2023; Kerfoot et al. 2019; Yousef et al. 2013). In recent years, many efforts from the USEPA; the National Oceanic and Atmospheric Administration; Michigan DNR; USACE; the Michigan Department of Environment, Great Lakes, and Energy (MI EGLE); environmental research institutions; Indian tribes; and the local community have focused on dredging the stamp sands from the water bodies (Baxter 2022; Hayter et al. 2015; Kerfoot et al. 2016; 2023; MI EGLE 2021; Raymond 2022; Zanko, Patelke, and Mack 2013). Storing a large volume of tailings in a manner that will not adversely affect the lake or waterways is a challenge, not to mention a critical cost.

Mining Reuse Application. The giant pile of stamp sands on the shoreline at the Gay site is a related mining by-product. The stamp sands may be recycled and reused. The specific characteristics of stamp sands piled on the Keweenaw Peninsula depend on their mining origins; however, the major component of the stamp sands in this area is granular basaltic rock. The primary chemical composition of stamp sands includes SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, and Na_2O (Li et al. 2010). It contains plenty of naturally occurring metallic copper and trace elements. In addition, the particle size of the stamp sands makes it ready to be used as construction products (Li et al. 2010). These physical and chemical characteristics mean that recycled metal copper, which would be used in a wide variety of products, may potentially be produced from the stamp sands.

The stamp sand deposits in this area have been used to produce concrete blocks (by the Superior Block Company, a local construction materials company) and have been spread on the icy or snowy road surfaces in the winter season (by the Keweenaw County Road Commission). A research team from Michigan Technological University and Lesktech Ltd. investigating the stamp sands from the Gay area have demonstrated that particles sized between 8 and 50 mesh are ideal material for manufacturing roofing shingles (Li et al. 2008; 2010; Popko 2007) and also verified that the stamp sand fines in the same area have excellent antimicrobial activity (against bacteria, fungi, and molds) owing to the high copper content in the tailing matrix. This research team also found that the stamp sands in this area would be a perfect raw material to produce high-performance aggregate products for road construction with asphalt pavement (Li et al. 2013) and found potential uses as antimicrobial cement, sandblasting sand, pet mat sand, etc. The stamp sands are already crushed to the size of sand, which results in an overall energy savings of $8,000 per 1,000 tons of material used while reducing carbon dioxide emissions (Popko 2007). Further product development is ongoing.

6.2.4 Missouri—Madison County Mine Superfund Site

Value Proposition Statement. This case study describes a project where interested parties acquired a portion of a legacy mining site (the Madison County Mines [MCM] Superfund Site in Missouri) on the USEPA's NPL and then worked with USEPA Region 7 and Missouri DNR staff to develop a plan to address environmental impacts, including reprocessing of historical tailing areas for critical minerals, mainly cobalt, nickel, and copper. Other related activities included the eventual closure of the historical tailing areas and reopening the mine.

Introduction. In March 2018, Missouri Mining Investments, LLC acquired land and operational control of 1,750 acres of the former Madison Mine operation in Madison County, Missouri, from the Anschutz Mining Corporation of Denver, Colorado (USEPA 2019a). This mine is operated by Missouri Cobalt, LLC, which does business as U.S. Strategic Metals (USSM) to better represent the full suite of metals (lithium, nickel, and copper) that it plans to produce. Missouri Cobalt holds a 100-year lease on the property from Missouri Mining Investments.

The MCM Superfund Site was added to USEPA's NPL in September 2003. Missouri Cobalt, LLC and their partners/consultants, Environment Risk Transfer and Environmental Operations, worked collaboratively with USEPA Region 7 and Missouri DNR to develop a cleanup and site reuse plan for the site. In July 2019, former USEPA Administrator Andrew Wheeler made the following remarks while visiting the MCM Superfund Site to celebrate the twentieth anniversary of the Superfund Redevelopment Initiative.

> "Missouri Cobalt saw the potential of the mine and put together a plan to take it over, clean it up, and get it back into productive use. This type of environmental risk transfer is a model we hope can be adopted at other sites around the country."

Site Background. The MCM Superfund Site is in Fredericktown at the southern end of the Old Lead Belt in southeastern Missouri, approximately 90 miles south of St. Louis. The entire MCM Superfund Site encompasses approximately 520 square miles, which is approximately Madison County in its entirety, and includes the Mine La Motta Domain Tract that extends north into southern Saint Francois County.

The MCM Superfund Site is situated on the eastern edge of the Ozark Uplift within the Saint Francois Mountains. The core of the Ozark Uplift is formed by Precambrian crystalline rocks that are surrounded by Paleozoic and younger marine sedimentary strata. Topographically, the area exhibits a geologically mature landscape with rounded ridges and meandering streams that occupy comparatively wide valleys. In a few locations, rivers and streams cut across the ridges, forming steep canyons (Figure 6-9).

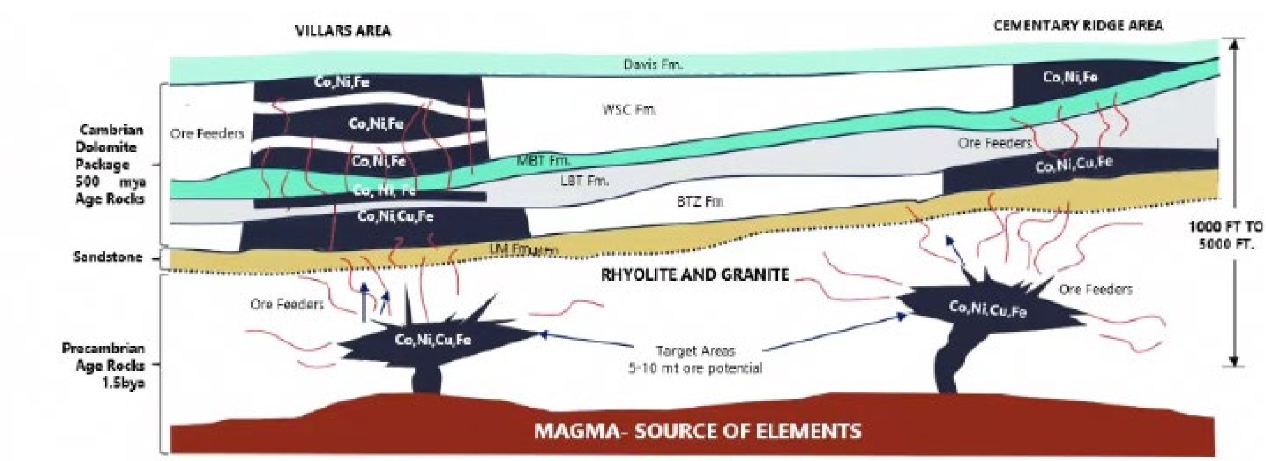


Figure 6-9. Conceptual geologic model of the Madison County Mines Superfund Site.

Source: Hall and Kennedy in Missouri Cobalt (2023)

Much of the MCM Superfund Site is underlain by Cambrian sedimentary rocks (James 1949) that rest unconformably on a Precambrian basement complex composed of metamorphosed volcanic rocks and intrusive granites that are cut by occasional diabase dikes (Tolman 1933). The sedimentary rock formations vary in thickness and locally pinch out against structural highs in the basement complex. Bedrock formations in the area include the LaMotte Sandstone, Bonneterre Dolomite, Davis Formation, and Derby-Doe Run Dolomite, all of upper Cambrian age (James 1949). Bedrock is overlain by only 50 to 150 feet of reddish clay overburden.

In the Mine LaMotte-Fredericktown subdistrict, lead-zinc-copper-cobalt mineralization occurs at about 250 to 400 feet from the surface in the lower Bonneterre Formation and the upper LaMotte Sandstone (Missouri DNR 2023). Ore bodies tend to be in arcuate shapes localized near pinch-outs of the LaMotte against buried Precambrian igneous knobs (Missouri DNR 2023). Metallic ore minerals mostly occur as deposits that have replaced dolomite crystals (Figure 6-10). These ore minerals occur as disseminated grains in horizontal sheets along bedding planes, cavity fillings, and linings on the walls of joints and fractures (USGS, Missouri Division of Geological Survey and Water Resources, and USACE 1967). Galena (PbS) is the primary ore mineral, which occurs with small amounts of sphalerite (ZnS), chalcopyrite ($CuFeS_2$), siegenite ($(Ni, Co)_3S_4$), millerite (NiS), and bravoite ($(Fe, Ni, Co)S_2$)) (Missouri DNR 2023; USGS, Missouri Division of Geological Survey and Water Resources, and USACE 1967). In the Precambrian basement complex, mineralized deposits within the intermediate igneous rocks may contain iron, cobalt, and copper-bearing minerals such as cobaltian pyrite ($(Fe, Co)S_2$)) and carrollite ($CuCo_2S_4$) (Missouri DNR 2023).

Figure 6-10. Sample of cobalt, copper, and nickel ore, Madison County.

Source: Missouri Department of Natural Resources (2023).

Based on past mining operations, at least 13 major areas of mining waste have been identified in the form of tailings and chat deposits from historical mineral processing operations and smelting activities (USEPA 2023e). Tailing deposits include silt- to sand-sized material resulting from the wet washing or flotation separation of the ore material. Chat deposits include sand- to gravel-sized material that is the result of crushing, grinding, and dry separation of the ore material. The mining waste contains elevated lead and other metals, which pose a threat to human health and the environment. These deposits have contaminated soils, sediments, surface water, and groundwater in Madison County. These materials were transported by wind and water erosion and manually relocated to other areas throughout the county. For example, mining waste and soils (contaminated from mining waste erosion) have been used on residential properties for fill material and private driveways, used as aggregate for road construction, and placed on public roads around Fredericktown to control snow and ice in the winter (USEPA 2023e).

The Madison Mine, originally discovered in the 1840s, underwent various periods of operation through 1961. The mined ore was extracted for lead, copper, cobalt, nickel, iron, zinc, and silver (USEPA 2011a).

The mine operations consisted of three distinct surface and underground workings, with shafts reaching a maximum depth of 450 feet below the surface. During its peak production in 1956 (335,000 tons), the mine had the capacity to extract 2,268 metric tons of ore per day.

The MCM Superfund Site comprises multiple OUs. The portion of interest to this case study is OU-2 (the Anschutz OU), historically referred to as the Madison Mine or Madison Cobalt Mine. It consists of all mining and mine works locations immediately southeast of Fredericktown including tailing ponds, a metallurgical pond, an old mill, a smelter and associated slag pile, abandoned shafts, a mine decline, a metals refinery complex, a remnant chat pile and mine dump, associated groundwater, surface water, sediment contamination, and an abandoned rail spur (USEPA 2023e).

Mining Waste Reuse Summary. This section describes four main components of the mining waste reuse activities: (1) mining waste characterization methods and results, (2) regulatory considerations for mining waste reuse, (3) the target application for the reprocessed mining waste, and (4) the mining technologies involved in the reprocessing of the mining waste.

Solid Waste Characterization. The OU-2 tailings consists of five main tailings piles, totaling approximately 200 acres, which have been mostly characterized as brown-orange fine tailings covered with vegetative clay covers (Anschutz Mining Corporation 2007). Several sampling events have been conducted to characterize the tailing piles since the 1990s (Environmental Operations, Inc 2018; Jacobs Engineering Group 1995; USEPA 2011c). Typically, these sampling efforts involved the use of direct-push cores to characterize the lithology and thickness of the tailings. Samples were collected for metals chemical analysis via USEPA Method 6020 or field screening with an XRF instrument. Elevated concentrations of cobalt, copper, iron, lead, manganese, and nickel exceeded USEPA screening criteria. Tailing piles were approximately 2 to 8 feet thick.

Between proven and inferred reserves, the Madison Underground Mine holds an estimated 9.3 million pounds of recoverable cobalt, likely making it the largest such reserve in North America. The site also contains an estimated 13 million pounds of nickel and 14 million pounds of copper. Existing tailings and underground deposits are expected to yield total run-rate production of at least 1.9 million pounds per year of cobalt, 2.6 million pounds per year of nickel, and 2.8 million pounds per year of copper when underground mining begins.

Regulatory Considerations. Between the mid-1980s and early 2000s, several initial environmental investigations were conducted, but negotiations between USEPA and potential responsible parties to continue those activities were unsuccessful (USEPA 2019a). In 2011, USEPA prepared draft Remedial Investigation and Feasibility Study Reports for the MCM Superfund Site (USEPA 2011a; 2011c). The reports concluded that historical mining activities have impacted soil, groundwater, surface water, and sediment. In 2014, the U.S. Fish and Wildlife Service and Missouri DNR, acting as Trustees for the site, conducted a Preassessment Screen and Determination, which concluded that the release of hazardous substances has impacted the site's natural resources and that Trustees may assert trusteeship under CERCLA and the Clean Water Act.

That step was not needed for OU-2 because in February 2019, Missouri Mining Investments, LLC voluntarily entered into an Administrative Settlement Agreement and Order of Consent with USEPA (for the 1,750-acre parcel acquired in 2018). The intent of Missouri Cobalt was to recycle existing tailings on the site into a useful product while ensuring all proper soils and hazardous waste management practices are followed, as part of their new business operations (USEPA 2019a).

In 1989, Missouri established the Metallic Minerals Waste Management Act (MMWMA), which regulates the disposal of solid waste from mining and processing of metallic minerals through permits issued by the Missouri DNR. Currently, USSM has a permit under the act for a 13-acre parcel of the site.

The general plan for reprocessing and closing the tailing piles involved the following activities, which were completed in late 2023:

- Removing the existing vegetative cover
- Removing some tailings material for reprocessing/recycling
- Confirmatory sampling to measure residual soil concentrations for chemicals of concern (including arsenic, cadmium, cobalt, copper, lead, nickel, and zinc)
- Installing a low-permeability vegetative cover (containing 18 inches of clay and 12 inches of topsoil) if residual concentrations remain above action levels
- Installing a clay cover sourced from an on-site borrow pit and sampling every 10,000 cubic yards for metals/chemicals of concern

Mining Reuse Application. OU-2 was acquired by USSM with the goal of producing large-scale quantities of battery-grade cobalt and nickel. Initially, some tailings will be reclaimed; subsequently, residuals will be capped, and additional subsurface mining will be performed.

USSM plans to build a metal crystal manufacturing plant at the site. This is an example of mining to manufacturing vertical integration to reduce costs and the carbon footprint associated with transportation.

Reprocessing Technologies. In 2019, Missouri Cobalt constructed a mine tailings processing facility to recover minerals from existing mining waste. Reprocessing the tailings produces valuable metals concentrates, including cobalt, while reducing the toxicity and volume of the mining waste (Figure 6-11).

Figure 6-11. Tailings concentrator (A) and reclaimed tailings (B) at U.S. Strategic Metals (USSM) site in Fredericktown, MO.

Source: U.S. Strategic Metals

A general description of the mining and concentrating tailings process is provided below:

- A long reach excavator removes tailings from the original deposited areas and loads a haul truck, which moves the material to the milling area stockpile.
- A loader reclaims tailings into the top of the pug mill where it is mixed with water to produce a tailings slurry. The slurry is then pumped into storage tanks before being pumped into a ball mill, where the tailings slurry is further ground to liberate valuable minerals from the host rock. The ball mill grinding process also creates fresh mineral surfaces that allow chemistry associated with the flotation stage to work better.
- The flotation process consists of eight rougher flotation cells and four cleaner flotation cells (Figure 6-12). The rougher cells receive the slurry from the ball mill circuit and produce a rough concentrate. The cleaner cells then receive the rougher concentrate that is the final product ready for drying.

Figure 6-12. Flotation process.

Source: Missouri Cobalt (2023)

- The slurry moves from the cleaner flotation cell to the concentrate thickener, where it is thickened up in preparation for concentrate filtering and drying. The thickened slurry then goes through a filter press where some water is removed to produce a concentrated filter cake containing 15% to 20% moisture. The filter cake is then discharged to a collecting conveyor and then onto a Hollo-Flyte dryer. The filter cake concentrate is then temporarily stored in the concentrate storage building prior to shipment.

*Hydrometallurgical Facility***.** In 2020, Missouri Cobalt opened a pilot hydrometallurgical facility in Earth City, Missouri (Figure 6-13). The company was successful in developing a process to recover cobalt-and nickel crystals from base metal concentrates and lithium battery scrap.

Figure 6-13. USSM staff working on cobalt and nickel crystals recovery pilot project.

Source: U.S. Strategic Metals.

A new hydrometallurgical facility is under construction at the site in Fredericktown, Missouri, to process scrap lithium battery material along with mineral concentrates from tailings, outside sources, and newly developed underground ore (Figure 6-14). Once operational, this will be the only cobalt processing facility in the U.S.

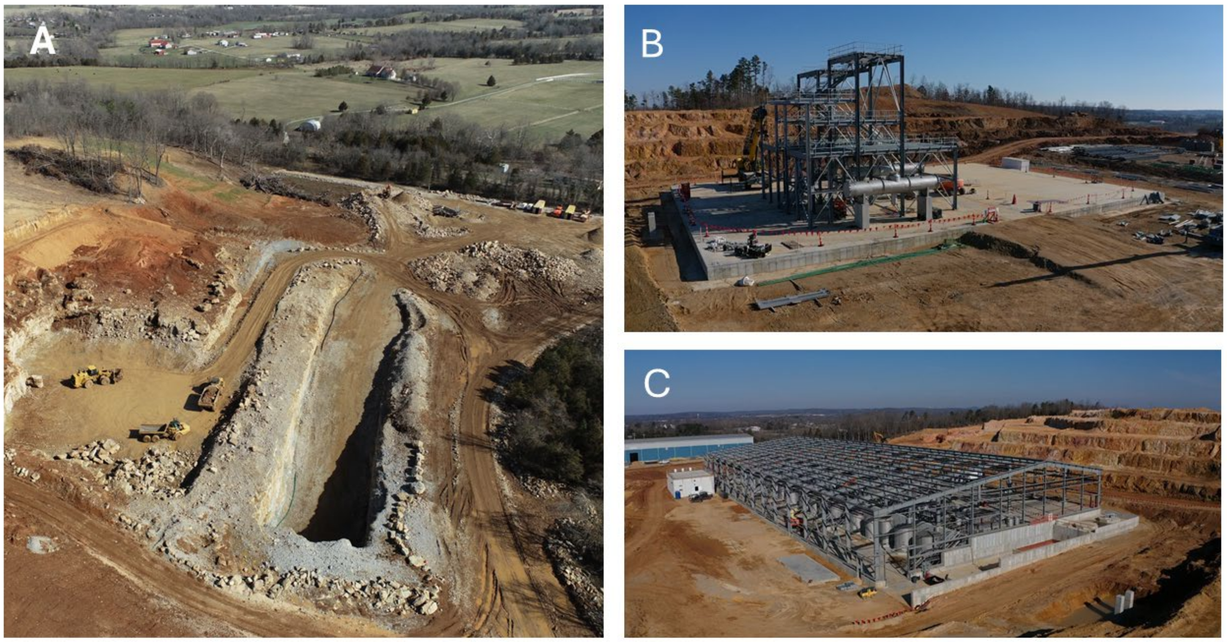


Figure 6-14. Construction of the new decline access (A), hydrometallurgical crystallizer facility (B), and Hydrometallurgical solvent extraction facility (C).

Source: U.S. Strategic Metals

6.2.5 Montana—Anaconda Smelter Superfund Site, Old Works Operable Unit

Value Proposition Statement. This case study describes a project that integrates remediation of a historic copper smelting complex, historic preservation, recreational/economic reuse of the inactive lands, and use of a copper smelter by-product [slag] as part of the redevelopment, including a world-class golf course. The Old Works site is a good example of the integration of remedy, waste reuse, historic preservation, and redevelopment.

Site and Copper Smelting History. The Old Works OU located in Anaconda, Montana, contains large volumes of milling and smelting wastes, fallout from smelter emissions, and other wastes that originated from the operation of smelters at the Upper and Lower Works from 1884 to 1902. Remnants of six brick flues and deteriorated brick foundations are the last remnants of the original Old Works facilities (USEPA 1994a).

The Upper and Lower Works were the first copper smelting facilities built to process copper ore mined in nearby Butte, Montana. The Upper Works structural area was constructed in 1883/1884, and the Lower Works smelting facilities were built in 1888. The smelters were connected to brick stacks atop adjacent hills by concrete flues. Decommissioning started in 1902 and was completed about 1906. The smelting process included the processing of lower grade ore by crushing, screening, and jigging (agitation) to concentrate the ore material. The jig tailings were discharged onto the floodplain area. Heap roast slag, composed of vitrified material, was generated by processing efforts to recover target metals from discarded tailings. During the operating time, approximately 300,000 cubic yards of slag were produced and placed within the boundaries of the Old Works OU (USEPA 1994a). Several of the structures within the Old Works area were eligible for inclusion on the National Register of Historic Places, including the remaining Old Works structural areas and the heap roast slag.

Chemical Characteristics of the Tailings Site and the Black Slag. Primary COCs at the site were arsenic, lead, cadmium, copper, and zinc. Copper smelter slag typically consists of vitrified amorphous iron, silicon, aluminum, and calcium oxides and silicates with minor concentrations of heavy metals such as copper or zinc. A summary of the analytical results from the remedial investigation from the Old Works OU ROD reveals that the maximum concentration of arsenic found at the site was 10,400 mg/kg from a sample of flue debris. The maximum concentrations of other metals were 398 mg/kg cadmium (flue debris), 59,200 mg/kg copper (heap roast slag), 2,900 mg/kg lead (floodplain wastes), and 62,100 mg/kg zinc (Upper Works demolition debris). It was also noted that no samples exceeded TCLP criteria as a characteristic hazardous waste (USEPA 1994a).

Regulatory Considerations. The Anaconda Smelter Site was listed on the NPL in 1983 under the authority of CERCLA. Atlantic Richfield, as successor to the Anaconda Minerals Company, was named a PRP.

In 1994 the USEPA selected a remedy that required the construction of engineered controls to reduce surface arsenic concentrations to below the recreational action level of 1,000 ppm in current and potential future recreational use areas and below 500 ppm in current industrial areas. The controls consisted of regrading surface materials, building borrowed-soil covers, chemical treatment, storm water controls, infiltration controls, and revegetation treatments. Building the vegetated engineered soil covers required treatment techniques such as 18-inch tilling, lime additions, and soil amendments to reduce surface arsenic concentrations below the appropriate action levels; stabilizing waste material; and promoting a permanent vegetative cover. The wastes are consolidated and graded as necessary to reduce infiltration, control runoff, and minimize erosion. Large portions of the waste are underlain by hydraulic controls that include an extensive underdrain system where excess irrigation water is collected and recycled before it comes in contact with the waste or with groundwater. Portions of the heap roast slag remain uncovered to preserve historic integrity at the site. Additionally, wastes associated with historic structures were left in place and left uncovered because of inaccessibility and limited land use. Drainage controls were used to minimize runoff from the historic structure areas (USEPA 1994a).

Beneficial Reuse of the Black Copper Slag. Redevelopment work included the construction of the Old Works Golf Course. A unique and distinguishing feature of the golf course is the use of the black sand waste. This black sand is copper slag, a by-product of the copper smelting process (Figure 6-15). When copper is extracted from ore, the impurities are separated and discarded as slag. At the Old Works, this slag is used to create the black sand bunkers that are used throughout the course.

Figure 6-15. Black slag pile in Anaconda, Montana, in 2023.

Source: Robin Bullock, Montana Technological University

The use of black sand in the bunkers at the Old Works Golf Course is not only visually appealing but also serves a practical purpose. It is highly durable and resistant to erosion, ensuring that the bunkers maintain their shape and integrity over time. Additionally, the black color absorbs and retains heat, which helps to speed up the drying process after rainfall, allowing for quicker playability.

Community Recommendation Integration with Remedy. Between 1991 and 1994, the community of Anaconda-Deer Lodge held discussions with Atlantic Richfield, USEPA, and the State of Montana concerning the community's desire to redevelop the Old Works area into a community asset. The Old Works area is in the central part of the community, only a few city blocks from the courthouse. This proximity drove a desire to work with the PRP and regulatory agencies to develop a community project that would assist in the revitalization of the community after cessation of the smelter operation. The community also noted their interest in retaining the historic smelter features and recommended construction of a golf course (Figure 6-16).

Figure 6-16. Old Works Golf Course.

Source: Robin Bullock Montana Technological University

Several notable golf course designers were interviewed by the county and the PRP prior to the selection of Jack Nicklaus. As noted on the Nicklaus Design website,

> The site became one of Jack's most challenging designs. Transforming a superfund site into a world-class golf course was something that had never been attempted and, as a result, required innovative techniques and the constant involvement of the [USEPA]. Before construction, the entire area was capped. The greens, bunkers, tree root balls and lake bottoms were specially lined to prevent any leakage upward . . .
>
> Great care was taken to keep the flavor of the days of the smelter intact. The greens and fairways lay on land that stretches in front of the ruins of the two 19th-century smelters. But the most visually unique feature of the course is the use of the remaining black slag – inert, harmless material left by the copper smelting process – in the bunkers." (Nicklaus Design, n.d.) (Figure 6-17)

Figure 6-17. Old Works Golf Course in 2023 with black slag sand traps and heap roast slag shown.

Source: Robin Bullock Montana Technological University

It was also important to have legally binding agreements that establish who would be accountable for which part of the remedy. A three-way series of documents were completed and executed simultaneously: A prospective purchaser agreement between USEPA and Anaconda-Deer Lodge County, a land transfer agreement between Atlantic Richfield and Anaconda-Deer Lodge County, and a "friendly" unilateral order from USEPA to Atlantic Richfield. Each agreement is built on the other to avoid overlapping accountabilities and to outline who would do what work and by when. As part of the unilateral order, Atlantic Richfield would complete the design and construction of the golf course. The prospective purchaser agreement outlined the protections afforded to the county and established that the county was taking on responsibility for long-term operations and maintenance of the golf course and institutional controls. The land transfer agreement provided funding for initial operations and maintenance from Atlantic Richfield to the county. The term "friendly unilateral order" was developed by USEPA to signify its desire to work expeditiously with Atlantic Richfield and Anaconda-Deer Lodge County on this project.

6.2.6 Montana—Silver Bow Creek/Butte Area Superfund Site, Butte Mine Flooding Operable Unit

Value Proposition Statement. This case study describes a project that integrates active mine operations, superfund remediation, and critical mineral recovery as an integral part of each operation. The Mine Flooding site is a good example of how to integrate a remedy with critical and potential REE recovery.

Site and Mining History. The mines in Butte, Montana, began as a series of more than 400 underground copper, zinc, silver, manganese, and molybdenum mine operations with more than 10,000 miles of tunnels under the community of Butte (Gammons and Icopini 2020). By 1955, Anaconda Arizona Inc. had elected to pursue open-pit mining in what became the Berkeley Pit. Anaconda Arizona Inc. operated the Berkeley Pit facility until 1982, when it was closed by the successor to Anaconda Arizona Inc., Atlantic Richfield. By this time, the pit was 1,780 feet deep, covered 675 acres, and had an extensive groundwater extraction system. When the mine closed, the pumps were turned off, which allowed groundwater to begin refilling the mining complex (USEPA 1994b).

The Butte Mine Flooding OU is part of the Silver Bow Creek / Butte Area site. Within the boundaries of the OU is part of an operating mine that recovers copper from water pumped from the Berkeley Pit and open-pit mining from a different deposit (the Continental Pit). The OU consists of waters within the flooded Berkeley Pit, the flooded underground mine workings hydraulically connected to the Berkeley Pit, the associated alluvial and bedrock aquifers, and other contributing sources of inflow to the Berkeley Pit. The Berkeley Pit is the lowest point in the hydrogeological system and acts as a hydraulic sink for water with high levels of metals and arsenic released as a result of the interactions between mineralized rock and mining waste with ground and surface waters (USEPA 1994b). The remedial objectives at this OU include maintaining the elevation of the water in the Berkeley Pit below a critical water level (CWL) elevation of 5,410 feet (based on a USGS datum). The PRPs are required to maintain the CWL by means of surface water controls and water treatment/discharge to protect Silver Bow Creek from receiving contaminated water from the OU (USEPA 1994b).

Chemical Characteristics of the Berkeley Pit. Water in the Berkeley Pit contains high levels of metals and arsenic as a result of water levels rising in the mine workings and from contaminated surface water inflows from the tailings impoundment (Table 6-3). The source of the contamination is AMD, which results from the oxidation of sulfide minerals in the presence of oxygen (USEPA 1994b).

Table 6-3. Average concentrations of chemicals of concern in the Berkeley Pit, 1991 and 2024

Chemicals of Concern	Average Concentrations as Noted in the USEPA Record of Decision – 1991 (ug/L)	Average Concentrations May 2024 Montana Bureau of Mines and Geology (ug/L)
Aluminum	270,000	245,143
Arsenic	710	8.17
Cadmium	1,790	2,183
Copper	167,000	58,233
Iron	897,000	1,272

Chemicals of Concern	Average Concentrations as Noted in the USEPA Record of Decision – 1991 (ug/L)	Average Concentrations May 2024 Montana Bureau of Mines and Geology (ug/L)
Magnesium	395,000	621,933
Manganese	161,000	27,516
pH (s.u.)	3.0–3.3	4.45–4.48
Sulfate	16,800,000	6,383,666
Zinc	476,000	593,800

Sources: MBMG (2024), USEPA (1994b)

Regulatory Considerations. The Butte Mine Flooding OU is part of the Silver Bow Creek / Butte Area Superfund Site and is in the city of Butte, Montana. It consists of waters within the Berkeley Pit, the underground mine workings hydraulically connected to the Berkeley Pit, the associated alluvial and bedrock aquifers, and other contributing sources of inflow to the Berkeley Pit. A major seepage area originates in the Horseshoe Bend (HSB) area and is a result of seeps from the Yankee Doodle tailings impoundment.

The remedy selected by the USEPA seeks to maintain the elevation of Berkeley Pit water below the CWL and prevent discharge of untreated water to Silver Bow Creek. The remedy includes capture and treatment of water from the HSB seeps and the Berkeley Pit using high-capacity pumps and high-density sludge (HDS) treatment technology. The HDS water treatment plant uses lime to raise the pH of the influent and promote the precipitation of metals as hydroxides that are sequestered in sludge that is discharged back to the Berkeley Pit. Thanks to cooperation between the USEPA, the Montana DEQ, and the PRPs regarding the superfund site and the mining permit requirements, the HDS treatment sludge is allowed to be reused, and the MIW water treated by the HDS plant is reused in the active mine process, thereby also reducing the flow of fresh water required for mine operations (Arcadis U.S., Inc. 2019). Similar cooperative efforts have allowed for copper recovery from the Berkeley Pit in response to several public comments (captured in the ROD; USEPA 1994e) that requested the remedy also allow for metal recovery from the treatment process. Copper recovery from Berkeley Pit water has been ongoing since the late 1990s (see Section 6.1.7.4).

Since 2019, additional treatment capacity was installed as part of a pilot study initiated by the PRPs and sanctioned by the USEPA with concurrence from the Montana DEQ. The additional treatment capacity involves treatment and discharge of water from the tailings impoundment to Silver Bow Creek while increasing the amount of Berkeley Pit water that is reused by the active mine. This cooperative effort has maintained the elevation of water in the Berkeley Pit well below the CWL, optimized the output from the HSB water treatment plant, increased the amount of water reused by the active mine, and allowed Atlantic Richfield to build an additional water treatment plant that discharges treated water to Silver Bow Creek (Saks, n.d.).

Mine Water Treatment and Sludge Reuse. Between 1994 and 2001, water from HSB was used in the mine process after some treatment. In 2001, due to the need for water to support intermittent mining operations, design and construction of the HSB water treatment plant was initiated. The HSB water treatment plant was built and operated by Atlantic Richfield and Montana Resources with a nominal treatment capacity of 7 million gallons per day and has operated continuously since 2003 (Figure 6-18).

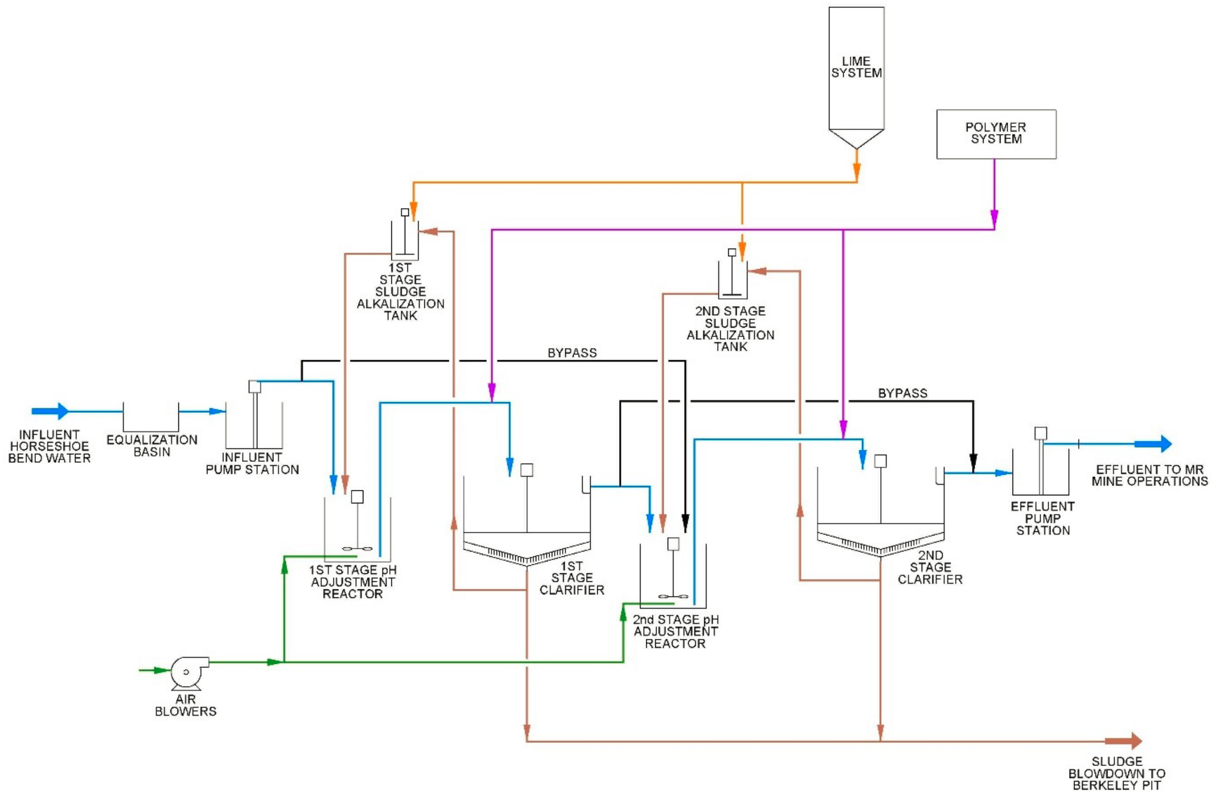


Figure 6-18. Horseshoe Bend water treatment process.

Source: Arcadis (2019)

Since the initiation of water treatment at the HSB HDS water treatment plant, sludge from the water treatment plant was disposed of by submergence within the Berkeley Pit water body. In the 1990s, pH in the Berkeley Pit was extremely acidic with an average range of 2.55 to 3.3 pH. As a result of disposal of treatment sludge with excess NP (in the form of magnesium hydroxide) into the pit for more than two decades, the average pH of the pit has continued to increase over time. As of 2024, the pH in the pit is greater than 4.0 s.u., resulting in precipitation of the majority of iron and arsenic and a decrease in metals concentrations (see Table 6-3).

Critical Mineral Recovery. In 1985 Montana Resources began mine operations in the Continental Open Pit. The Montana Resources concentrator is located near the south rim of the Berkeley Pit. Ore from the Continental Pit, located east of the Berkeley Pit, is milled and processed at the concentrator. The milling process uses water decanted from the tailings pond, imported water, water treated at the HSB water treatment system, and excess water pumped from the Continental Pit area (Figure 6-19).

Figure 6-19. Montana Resources mine water flow.

Source: Ingersoll et al. (2023)

The copper recovery system uses iron flumes filled with scrap iron and inundated with acidified water from the Berkeley Pit (Gammons and Icopini 2020). At very low pH, copper in solution exchanges for ferrous iron in the scrap; iron goes into solution, and elemental copper precipitates out. After sufficient contact time, the remaining iron is raised magnetically to dislodge the precipitate. The precipitate is then washed into the settling tanks at the end of the flumes. After flowing through the flumes, the water is pumped for secondary extraction. Approximately 80% to 95% of the copper content is recovered in the flumes (see Section 6.1.7.4).

In addition to the copper recovery process, the responsible parties continue to explore additional opportunities for mineral recovery. In 2023 Montana Technological University and West Virginia University, in cooperation with Montana Resources and Atlantic Richfield, began evaluating opportunities to recover critical elements from the Berkeley Pit and from the HDS sludge, respectively (Table 6-4).

Table 6-4. Metal concentrations in water and sludge

Sample Location	Al	As	Be	Ce	Co	Cr	La	Li	Mn	Nd	Ni	Pd	Pr	Rb	Ti	Zn
Horseshoe Bend Seep (µg/L)	90,199.9	7.7	13.0	200.0	478.9	7.4	56.2	69.7	76,663.3	122.4	310.9	9.6	25.9	31.2	60.4	145,666.7
Horseshoe Bend Post-precipitation Plant (µg/L)	114,500.0	5.4	16.5	333.0	552.3	4.3	88.7	75.6	83,433.3	173.9	370.1	10.8	38.0	27.8	71.8	166,666.7
Berkeley Pit (µg/L)	220,667.0	13.0	58.0	977.0	1,557.0	<2	269.0	252.0	255,000.0	444.0	1,167.0	31.0	101.0	57.0	87.0	596,333
Berkeley Pit Post-precipitation Plant (µg/L)	198,333.0	9.0	56.0	952.0	1,520.0	58.0	264.0	248.0	250,000.0	428.0	1,157	29.0	99.0	56.0	87.0	573,333
Stage 1 Sludge (µg/kg)	280.1	<2	<2	<2	14.0	3.8	<2	83.0	48,550.0	<2	<5	<5	<2	38.8	54.8	1,298.5

Notes: Al = aluminum, As = arsenic, Be = beryllium, Ce = cerium, Co = cobalt, Cr = chromium, La = lanthanum, Li = lithium, Mn = manganese, Nd = neodymium, Ni = nickel, Pd = palladium, Pr = praseodymium, Rb = rubidium, Ti = titanium, Zn =zinc, µg/kg = micrograms per kilogram, and µg/L = micrograms per liter.

6.2.7 Oklahoma—Tar Creek Superfund Site

Value Proposition Statement. The following case study of the Tar Creek Superfund Site in northeast Oklahoma is a good example of the reuse of mining waste in asphalt, reuse for remediation, and potential resource recovery of critical minerals. Millions of tons of mining waste are dispersed in numerous piles throughout the abandoned Tri-state Lead and Zinc Mining District of northeast Oklahoma, southeast Kansas, and southwest Missouri on what was originally flat prairie land. The chat piles in Oklahoma (Figure 6-20) were produced as a waste material from shallow underground mining of lead and zinc sulfide ores from the Mississippian-aged Boone formation.

Aerial image of the area (1.5 miles x 1.5 miles) around the towns of Cardin and Picher in Oklahoma

Figure 6-20. Aerial image of the area (1.5 miles × 1.5 miles) around the towns of Cardin and Picher in Oklahoma.

Source: Oklahoma Department of Environmental Quality

Introduction: Overview of Site and Mining History. Mining and milling in the Tri-state District began in the early 1900s and continued through the 1960s. Milling was originally completed on-site. Later, larger centralized mills were used (McKnight and Fischer 1970). The various mining and milling processes (blasting, crushing, tabling, jigging, and flotation) produced a coarse-grained “chat” waste that was conveyed into large piles (Figure 6-21) and a fine-tailings waste stream that was slurried into settling ponds.

Figure 6-21. Kenoyer chat pile.

Source: Oklahoma Department of Environmental Quality

In Oklahoma, mills were located about every 40 acres due to leasing requirements of the Native American–owned lands. This practice resulted in many large chat piles and fine-tailings ponds covering an area of approximately 40 square miles. A few chat piles were several hundred feet high and covered more than 40 acres due to centralized milling (Weidman 1932).

Regulatory Environment: Post-Mining Environmental Legacy. The Tar Creek Superfund Site (Figure 6-22) was included on the NPL in 1983, and the initial cleanup activities focused on surface water, groundwater, and mine water upwellings. In the early 1990s, the Indian Health Service in Ottawa County identified elevated blood lead concentrations in 35% of Native American children living in the area. This resulted in the formation of two other OUs focused on chat and fine-tailings accumulations in residential and nonresidential areas.

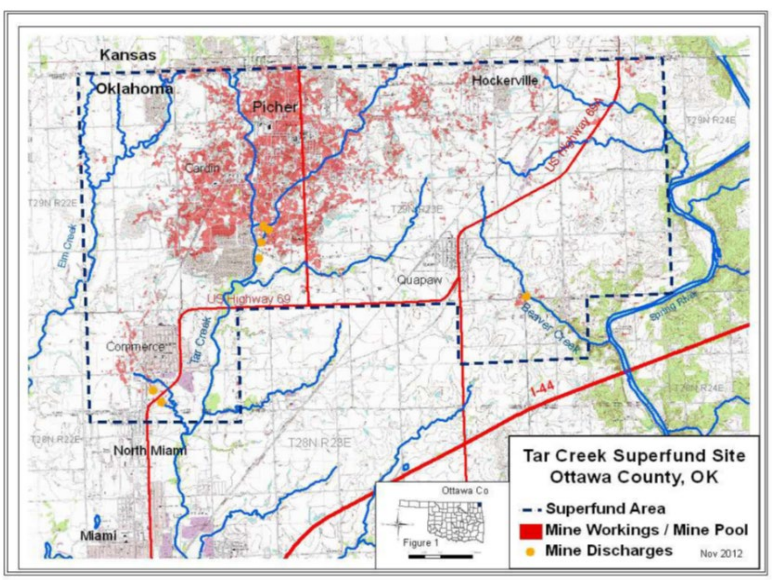


Figure 6-22. General location of the Tar Creek Superfund Site.

Source: Oklahoma Department of Environmental Quality

Much of the original chat volume, estimated at around 160 million cubic yards, is gone due to its use in construction projects over the course of more than a hundred years. An estimated 37.9 million cubic yards remained in 2008 (AATA International, Inc 2005). Reuse of bulk unencapsulated chat for gravel roads, fill in residential developments, and sand for children's play areas has caused widespread environmental contamination from metals including cadmium, lead, and zinc contained therein. Affected media include soil, sediment, surface water, and groundwater, and more importantly, demonstratable human health impacts, primarily elevated blood lead levels (USEPA 2008a). These represent negative reuse applications. The impacts and proposed remediations have been fully documented in the RODs for Tar Creek OU2, Residential (USEPA 1997) and OU4, Non-residential (USEPA 2008a).

Remediation of Chat at the Tar Creek Site. The remedy selected for chat and fine tailings in the nonresidential areas (OU4) includes continued chat sales and marketing; backfilling/subaqueous disposal' excavation of chat, fine tailings, and transition zone soils with transportation to an on-site repository; and consolidation/capping. The OU4 ROD estimated that 29,000,000 cubic yards of chat could be used for environmentally acceptable applications. The actual amount suitable for such uses may be 20% greater based on recent remedial actions (CH2MHill 2021). Chat in the perimeter areas of the site is to be excavated and hauled to a nearby chat washing facility for future processing and use in asphalt, instead of being sent to a repository for disposal. Thus, private industry, chat owners, and local residents will profit from the sale of chat for environmentally safe reuse applications as defined in the "Chat Rule" (40 CFR Part 278) and the OU4 ROD. Reuse technology through chat sales is expected to continue for 30 years. If chat is sold, it must follow the certification and record-keeping requirements described in Section 19.2.2 of the ROD. Additionally, if chat is transported off site, the receiving facility must comply with the off-site rule for fugitive dust and stormwater runoff controls (USEPA 2008a).

Mining Waste Reuse

Currently, reuse applications for chat include aggregate in asphalt for construction and filling mine shafts as remediation. Remediation reuse also includes incorporation of excavated transition zone soils in the ET cap at the repository. In addition, reuse of chat and fine tailings has been identified for potential resource recovery of critical minerals, including REEs.

Characterization is one of the first steps in deciding whether a mining waste material has any beneficial reuses. Chat and fine tailings have been subjected to many geotechnical, chemical, and mineralogical tests and studies, albeit primarily for remediation purposes and to establish the concentrations of COCs – cadmium, lead, and zinc (AATA International, Inc 2005; Andrews, Moreno, and Nairn 2013; Cates and Datin 2013; CH2MHill 2021; Datin and Cates 2002; Labar 2007; Oklahoma DEQ 2000; White et al. 2022).

The Remedial Investigation Feasibility Study for OU4 (AATA International, Inc 2005) is the most complete evaluation of bulk chat and fine tailings. The report focused on the COCs but also identified the concentrations of a target analyte list of 23 metals (Table 6-5).

Table 6-5. Summary of target analyte list metals concentrations in surface chat and surface fine tailings at the Tar Creek Site

Metal	Chat		Fine Tailings	
	Range (mg/kg)	Average (mg/kg)	Range (mg/kg)	Average (mg/kg)
Aluminum	490 – 2,930	1,270	404 – 11,500	2,654
Antimony	< 0.2 – 0.3*	0.25	0.2 – 1.0	0.38

Metal	Chat		Fine Tailings	
	Range (mg/kg)	Average (mg/kg)	Range (mg/kg)	Average (mg/kg)
Arsenic	< 3 – 9.5*	4.61	4.9 – 26.4	9.08
Barium	3 – 13	6.5	3 – 39	15.69
Beryllium	All <2	–	< 0.2 – 2*	0.57
Cadmium	40 – 133	74.57	32.2 – 170	72.44
Calcium	7,400 – 56,100	31,786	23,700 – 99,900	49,770
Chromium	8 – 30	8.29	5 – 50	16.9
Cobalt	All <10	–	< 1 – 10*	2.75
Copper	30 – 90	53.2	35 – 680	158.3
Iron	2,690 – 10,900	5,949	5,440 – 22,700	8,749
Lead	355 – 1,730	829	510 – 19,200	7,302
Magnesium	3,500 – 20,600	11,200	7,530 – 14,700	11,604
Manganese	59 – 331	163	99.7 – 310	168.9
Mercury	<0.05 – 0.19*	0.11	<0.05 – 0.83*	0.24
Nickel	< 10 – 12*	8.86	6 – 50	16.4
Potassium	<300 – 700*	410	210 – 3,340	937
Selenium	0.8 – 16	4.2	0.8 – 19	5.63
Silver	All <5	–	< 1 – 10*	2.95
Sodium	All <300	–	60 – 560	116
Thallium	0.05 – 1.04	0.44	0.16 – 30.7	4.40
Vanadium	<5 – 10*	4.0	4.5 – 40	12.54
Zinc	8,990 – 29,900	17,514	2,920 – 28,800	12,599

Note: Chat: n = 14. Fine tailings: n = 12 for cadmium, lead, and zinc; n = 9 for other metals. All values are mg/kg dry weight.
* For those below the detection limit, half of the limit value was used in the calculation of the average.

In addition to cadmium, lead, and zinc in bulk chat, the only other metals with average concentrations greater than background values in site soils were arsenic, chromium, copper, magnesium, and selenium, while average concentrations of aluminum, barium, iron, manganese, and vanadium were lower in bulk chat than in site background soils (AATA International, Inc 2005).

Chat (Figure 6-23, also see Figure 3-1) is composed of a well-graded mixture of mainly chert with minor amounts of limestone and dolomite possessing angular particle sizes ranging from less than 0.075 mm to 9.51 mm with most of the mass in the coarser sizes. The metals concentrations and leaching potential vary within and among chat piles. Sieving prior to chemical tests shows metals concentrations in chat are inversely related to particle size, with the finer-sized material containing much higher (enriched or upgraded) concentrations (see Figure 4-2). Sieved (sized chat) samples subjected to grinding to less than 0.150 mm (ground-sized chat) showed no significant increase in metals concentrations compared to the pre-ground sample, further supporting the trend of higher metals concentrations in the finer-sized chat particles and not related to surface area. TCLP leach testing data indicates the larger-sized chat particles would be nonhazardous (<5 mg/L for lead) under RCRA Subtitle C. Test results for asphalt road millings indicated that chat encapsulated in asphalt had similar or lower concentrations compared to bulk chat. The amount of carbonate minerals in bulk chat is variable, and samples yield both net alkaline and net acidic ABA values. Thus, chat piles may produce circumneutral, acidic, or basic leachate.

Figure 6-23. Chat showing surface armoring.

Source: Oklahoma Department of Environmental Quality

Life-Cycle Analysis of Chat. Because chat had been used inappropriately for many decades and those uses had caused severe environmental impacts due to the COCs contained therein, USEPA was concerned that unregulated chat sales would be a mechanism for continued spread of contamination. To incorporate chat sales into the ROD for OU4, a federal rulemaking process was implemented to justify chat reuse. USEPA conducted an LCA of chat use and developed the so called "Chat Rule," which was finalized in the Federal Register on July 18, 2007 (Federal Register 72-137) as, *"40 CFR Part 278—Criteria for the Management of Granular Mine Tailings (Chat) in Asphalt Concrete and Portland Cement Concrete in Transportation Construction Projects Funded in Whole or in Part by Federal Funds"* (U.S. Congress 2007). Chat from the Tri-state District may be reused safely in transportation projects if (a) it is used in hot, warm, or cold mix asphalt, in slurry seal, micro-surfacing, or in epoxy seal; or (b) it is used in Portland cement concrete, granular road base, flowable fill, stabilized road base, or chip seal, provided that, on a case-by-case basis, the material meets the standards of either an SPLP test for lead and cadmium drinking water maximum contaminant levels and acute water quality criteria for zinc or a site-specific risk assessment. Environmentally safe uses for non-transportation applications include cement and concrete used in (nonresidential) construction projects as described in the Chat Rule preamble and use in applications that encapsulate the chat as a material for manufacturing a safe product or as part of an industrial process (for example, glass, glass recycling), where all waste by-products are properly disposed of. In addition, the non-transportation cement and concrete material must pass one of the two evaluation criteria (SPLP or risk assessment). Other uses, including unencapsulated uses of chat, may be authorized only in state or federal remediation actions. The "Chat Rule" retains a certification requirement / notification such that states and the public know how and where chat is used in transportation projects.

Chat Use in Asphalt. Current law requires that transportation projects meet existing state DOT or Federal Highway Administration material specifications, which assure that the road surface, composed of hot, warm, or cold mix asphalt, concrete, or epoxy, is durable and will not degrade prematurely. In Oklahoma the specifications for asphalt concrete are contained in the Oklahoma DOT Standard Specifications for Highway Construction (Oklahoma DOT 2019). Note: some states have additional specification limits on metal concentrations in chat that must be met prior to its use in asphalt.

Today, outside of remediation purposes, most chat from the Tar Creek Superfund Site is being sold for reuse in environmentally safe ways as aggregate encapsulated in asphalt concrete. Chat properties that make it an ideal aggregate for asphalt include its hardness due to the large percentage of chert, its gradation, and the percentage of fractured faces due to it having been crushed during the milling process. Pile run chat (bulk chat) does not always meet Oklahoma DOT gradation specifications for base course (Type A) and surface course (Types B and C) designs; thus, mixing bulk chat with other non-chat aggregates may be necessary. Chat washing (wet screening) facilities (Figure 6-24) operate independently of the remedial action and process a large amount of chat for sale in which coarse chat particles are produced by dry or wet screening for blending with other non-chat aggregates to obtain proper gradation for reuse in asphalt. Consequently, only a fraction of a chat pile is reused. The fines from the chat washing operations are mostly deposited in settling ponds for later remediation by capping or potential reuse (i.e., resource recovery); alternatively, they may be slurried into the underground mine voids where such actions have been approved. A significant volume of sand- and silt-sized middling product of the wet screening process is generated that outpaces its demand for reuse in asphalt. Consequently, the chat at piles that have been completely reworked by washing operations (in other words, chat pile bases) contain much finer-sized poorly graded material than piles with original mill waste present, and this reduces the marketability of the chat as an aggregate for use in asphalt.

Figure 6-24. Chat washing.

Source: Oklahoma Department of Environmental Quality

The University of Oklahoma researchers conducted laboratory and field studies to determine the maximum use of pile run chat in asphalt paving (Wasiuddin et al. 2008). The laboratory studies found that 80% and 50% bulk chat from a particular pile blended with non-chat limestone from a local source would meet Oklahoma DOT gradation specifications for Superpave surface course (S5 type) and base course (S3 type), respectively (Wasiuddin, Zaman, and Nairn 2005). Following the laboratory studies, a

3,100-foot-long section of an unpaved county road was bid out and constructed with four different segments; each had different thicknesses of chat-asphalt surface and chat-asphalt base, and the subbase was chat stabilized with 10% Class C fly ash and 10% cement kiln dust. After 2.5 years of service, a distress survey of the "Test Road" was conducted. The test found that, although the road would not pass highway standards due to various issues including drainage (due to low permeability of the chat-stabilized bases) and rutting (due to air voids), it was much smoother than other asphalt roads in the county. Overall, the Test Road demonstrated that increased usage of pile run chat in asphalt that met Oklahoma DOT specifications could be accomplished.

Remediation Reuse: Remediation reuses include the following: (1) the use of bull rock / development rock and chat to fill the many mine shafts that are in various stages of collapse within remedial project areas and (2) use of transition zone soils as a component of the repository ET cap. Due to the limited volume of clean soil at the site and the large aerial extent of the repository, excavated transition soils (with low concentrations of COCs but exceeding cleanup levels) have been approved for use in the lower layers of the ET cap. These will be covered with clean topsoil to meet the ET cap specifications.

Potential Resource Recovery: Critical Minerals / Rare Earth Elements. The presence of several critical minerals has been documented in the mining waste at the site. Andrews (2013) identified zinc, aluminum, lead, and titanium as possessing potential economic recovery value based on their larger concentrations in the fine-sized material and spot price at the time. Some metals with high market prices and lower concentrations were present, such as gallium (14.35 mg/kg), germanium (8.5 mg/kg), cesium (7.7 mg/kg), and rubidium (38.7 mg/kg). These could add significant value to a metal recovery operation with price per metric ton of mining waste fines of $20.84, $36.37, $135.52, and $496.54, respectively (USGS 2024b).

At the direction of USEPA Region VI, CH2MHill (2021) investigated the economic potential recovery of zinc in the different-sized fractions of chat and fine tailings. They identified zinc in the form of sphalerite (ZnS) concentrated at an average weight percent of 2.6% in the fine-sized material due to "upgrading" as containing potential economic value based on the total mass of zinc and metal prices at that time ($1.07 per pound). Assuming 100% zinc recovery from the estimated 8 million cubic yards of fine-sized material less than 75 µm (in other words, passing the No. 200 sieve), 420 million pounds of zinc worth $440 million is available for recovery. The report provided recommendations for further studies to fully evaluate the economic viability of zinc recovery.

White et al. (2022) evaluated fine-sized particles from chat piles with microanalytical techniques, total metals analyses, and SPLPs, as well as geochemical modeling, to determine the distribution and mineral hosts of germanium. The report indicated germanium is typically associated with zinc sulfide (sphalerite – ZnS) and is recovered as a by-product of zinc smelting. Germanium concentration was found in bulk chat at just 4 to 5 mg/kg and found to be enriched in the finer-sized fractions (<37 µm) at 12 ± 3 mg/kg. They also found that 64% of the germanium (320 mg/kg) was distributed in hemimorphite ($Zn_4Si_2O_7(OH)_2H_2O$), which represents 1.4 percentage by weight (wt. %) of chat; 26% was in quartz (90 wt. % of chat); and only 10% was in sphalerite (0.3 wt. % of chat). This indicates germanium has been redistributed from sphalerite to the fine-grained weathering product hemimorphite, which impacts the potential recovery of germanium as well as its mobility and bioavailability.

Another potential source of critical minerals and REEs is in the solids of the main process units (oxidation ponds and vertical flow bioreactors) of the several passive treatment systems currently treating mine water discharges at Commerce, Oklahoma. McCann and Nairn (2022) evaluated the accumulated solids in the oxidation ponds, the first units of the Mayor Ranch and SE Commerce treatment systems to determine the metals content and potential reuse opportunities for the accumulated iron-rich sludge there. The TCLP limits for lead and cadmium indicated the sludge to be nonhazardous, but a few groundwater quality criteria were exceeded in the SPLP results; this limited the beneficial reuse options and pointed to the need for additional studies to fully evaluate options like reuse as soil amendments.

Due to the high iron (oxyhydr)oxide concentrations, a potential reuse option for the passive treatment system oxidation pond residuals is as paint pigments. Aluminum and nickel at concentrations in the hundreds of mg/kg indicate a potential for resource recovery.

Summary and Future Data Needs: Reuse of Tar Creek chat as an aggregate in asphalt will continue well into the future, but there is a need for studies to identify additional uses for this material. For example, chat in the minus 35 to plus 80 mesh fraction was evaluated for use as a proppant in the oil and gas industry but failed to meet key criteria including lack of roundness (sphericity) and crush resistance strength. Clearly, economic recovery of critical minerals is possible, with approximately 14 million cubic yards of fine-sized material less than the 100-mesh sieve size (<150 μm). Further investigations using microanalytical techniques and geochemical modeling to determine concentrations, distributions, and speciation of critical minerals and REEs within the fine-sized mining waste is needed, as well as procedures for the processing of such materials for extraction and recovery. An economic evaluation and LCA on the feasibility of economic recovery of critical minerals and REEs from the Tar Creek mining waste is needed for comparison to the costs of remediation of the mining waste and potential offset of remediation costs. Existing chat washing operations that produce aggregate from the chat piles for use in asphalt may need to be modified to collect the fine-sized (<150 μm) fraction of mining waste for future metals recovery.

6.2.8 South Carolina—Brewer Gold Mine Superfund Site, Abandoned Mine Land Regulatory Reuse

Value Proposition Statement. The following case study describes the legal process to market an abandoned superfund mine for reuse that will align with USEPA's remediation goals.

Introduction. The Brewer Site produced 178,000 ounces of oxide gold from two open pits that extended to depths of 50-meters. Brewer Gold Company (Brewer), which is owned and operated by the United Kingdom, processed more than 12 million tons of ore and waste rock mined from two open pits. After ceasing mining operations, Brewer began reclamation efforts in 1995 and continued into 1999, overseen by SCDHEC. Brewer fell short of achieving a fully reclaimed site. Brewer abandoned the site in 1999, leaving SCDHEC and the USEPA to manage the site, finalize reclamation, and treat AMD in perpetuity. SCDHEC and USEPA worked together to find an innovative solution to the $1.2 million per year (and increasing) issue in perpetuity.

Site Background

Geology. The Brewer Gold Mine occurs within the Carolina Slate Belt, a northeast-trending zone of metamorphic rocks that extends from northern Georgia to southern Virginia. The eastern limit of exposed Slate Belt rocks occurs about 1 mile east of Brewer and is defined by the onlap of Cretaceous-age and younger sediments of the Coastal Plain Province that cover the Slate Belt strata. Rocks in the area of the Brewer mine consist of deformed and regionally metamorphosed rhyolite, andesite volcanic tuffs, breccias, and flows of late Precambrian to Cambrian age that are overlain by metamorphosed sedimentary strata that include volcanic mudstones, siltstones, and sandstones (Figure 6-25). In the Brewer mine area, the regional metamorphic grade of the metavolcanic rocks has been overprinted with concentric zones of hydrothermal alteration associated with the gold mineralization. Gold was present within pyrite and copper sulfide grains and as free particles (Pardee and Park Jr. 1948; Sheetz 1991). Other metallic minerals present in the ore in minor quantities included enargite (copper arsenosulfide), covellite (copper sulfide), chalcopyrite (copper iron sulfide), tennantite-tetrahedrite (copper arsenic-antimony sulfide), sphalerite (zinc sulfide), galena (lead sulfide), cassiterite (tin oxide), bismite (bismuth oxide), native bismuth, and a variety of iron oxides and hydroxides (Graton and Lindgren 1906; Pardee and Park Jr. 1948; Sheetz 1991).

Figure 6-25. Core drilled from the Brewer Site demonstrating differences in alteration.

Source: Jen Spohn, Carolina Rush Corporation

Site History. The 1,000-acre Brewer Gold Mine Site is located on the western border of Chesterfield County, in a rural area approximately 1 mile due west of Jefferson, South Carolina, in Chesterfield County. The disturbed area that supported most mining activities covers 230 acres in the eastern portion of the larger property. The site features are summarized in Figure 6-26.

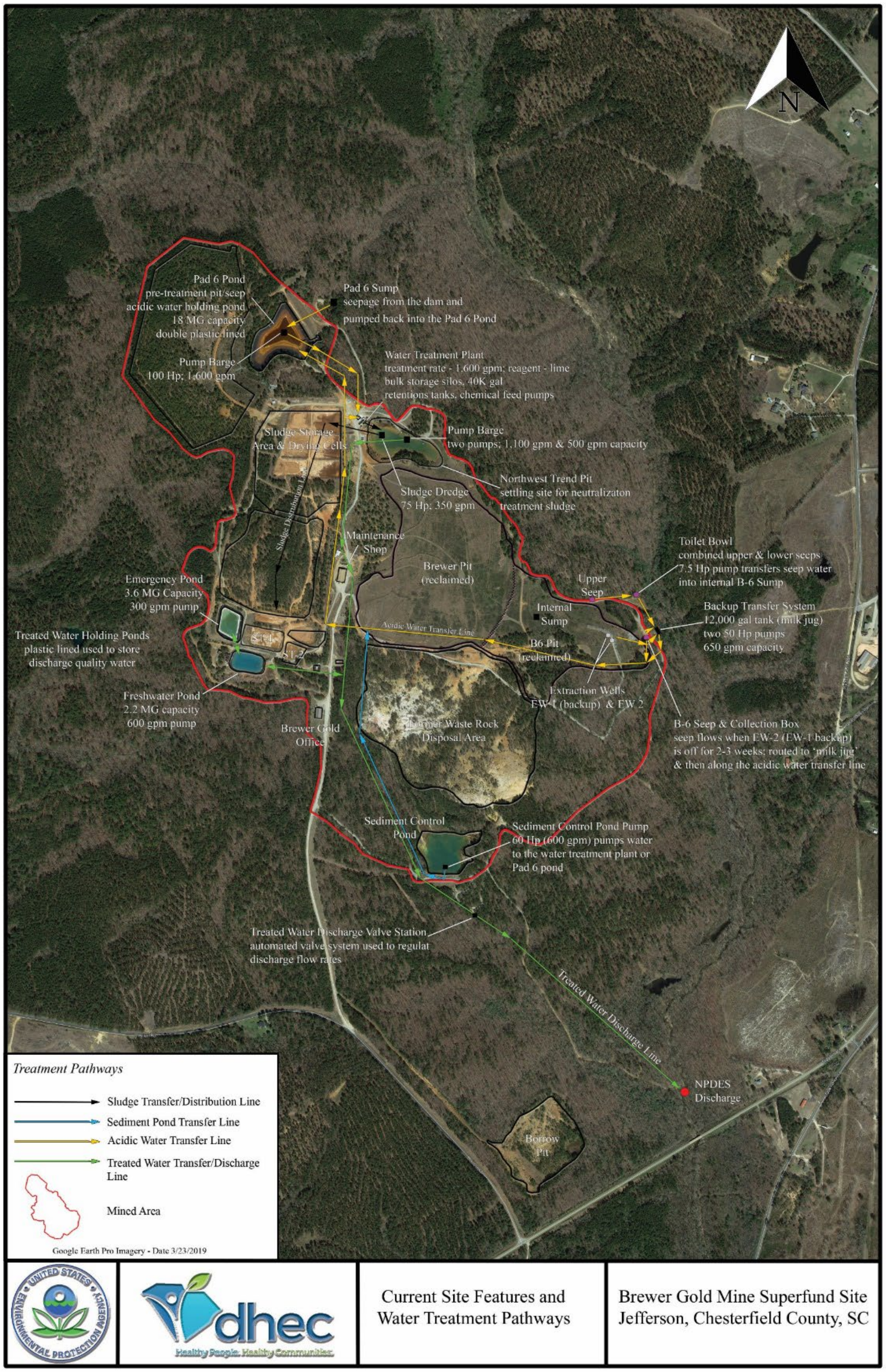


Figure 6-26. Current site operations and conditions at the Brewer Gold Mine.

Source: USEPA (2021b)

The Brewer Gold Mine was intermittently mined for gold from the 1820s through the 1990s. The most recent mining began in 1987 when Brewer used a cyanide heap leach method to produce gold up until approximately 1995. Although the pits extended below the water table, Brewer operated pumps to keep them dry for mining.

In 1990, following large rainstorms, a dam broke and allowed more than 10 million gallons of cyanide/gold solution to escape and flow into Little Fork Creek. Fish were killed in the creek and in Lynches River for nearly 50 miles downstream. USEPA and SCDHEC responded to the emergency. The dam and plastic-lined pond were repaired, and the company resumed mining in 1991.

At the end of operations in 1995, Brewer closed and reclaimed the mine following a plan outlined under an order issued by the SCDHEC. As described in the reclamation plan, a limestone-filled subdrain was keyed into the bedrock and extended eastward across waste rock fill in the B-6 Pit and westward into the Brewer Pit. The purpose of this subdrain was to raise the pH of groundwater as it traveled out of the Brewer Pit. As closure activities were completed, highly contaminated groundwater began to flow from a seep on the hillside between the backfilled pits and Little Fork Creek, 10 feet below the limestone subdrain. Due to a lower than anticipated water level within the pits, the subdrain never functioned as a passive treatment system as intended. The plan to demolish the temporary wastewater treatment plant during closure was abandoned when the plant was needed to treat the contaminated seepage (USEPA 2021b).

In 1999, following completion of the closure activities and failure of the passive treatment system, Costain Holdings (the parent company of Brewer) abandoned the site. In response to the owner's abandonment of the Brewer Gold Mine Site, SCDHEC requested emergency assistance from USEPA Region 4 to address the threat to water quality posed to Little Fork Creek by the site. USEPA initiated an emergency response on December 2, 1999, and authorized actions to continue operating the seepage collection and treatment system. As part of the USEPA removal action, an extraction well was installed in the B-6 Pit to pump contaminated water from the pit to a storage pond from which it can be taken for treatment and discharged. By USEPA’s estimates, failure to continue treatment of the contaminated waters would result in upward of 125 million gallons of untreated groundwater and runoff flowing from the site into Little Fork Creek annually, which would severely degrade the water quality of the creek.

On April 27, 2005, USEPA placed the site on the NPL. As part of the Interim Remedial Action, USEPA and SCDHEC have continued to operate the temporary wastewater treatment plant that was constructed by Costain Holdings in 1995.

Regulatory Issues. The final OU1 Surface Water Protection ROD, signed in 2014, selected the construction of a new 56 million-gallon treatment plant with passive selenium reduction and source control of sediment pond water to treat impacted water and construction of a rapid dewatering system–Joshua system to treat the sludge. The combined present worth cost (including both capital and operations and maintenance costs) as described in the final remedial design for the combined water and sludge remedies is estimated at approximately $21.25 million. The annual operation and maintenance cost was estimated to be $1.15 million.

Table 6-6 shows the operations and maintenance costs for the currently operating interim remedy. Without the current 90/10 cost-share component from USEPA, the state’s Hazardous Waste Contingency Fund would be completely bankrupted by this site alone in five years. USEPA elected to continue to implement the Interim ROD while SCDHEC pursued putting the property into a receivership to allow time for exploration activity by a potential purchaser before implementing the final ROD.

Table 6-6. Brewer Gold Mine operations and maintenance costs 2016—2023 (interim remedy for OU1)

Calendar Year	Annual Costs
2016	$1,167,000
2017	$1,185,000
2018	$1,212,000
2019	$1,171,000
2020	$1,358,000
2021	$1,314,000
2022	$1,182,000
2023	$1,361,000

Mining Waste Reuse Strategy

Receivership Process. Mining companies approached USEPA about the possibility of exploring the superfund site for additional resources; their interest was based on the site's geological and mining history and on the presence of gold mines in the surrounding area. Unfortunately, the site was not owned by SCDHEC or USEPA, and therefore there was no mechanism to allow for exploration. SCDHEC and USEPA have an interest in recovering past and future costs spent on the investigation and ongoing cleanup of the superfund site. Therefore, SCDHEC filed a motion for the appointment of a receiver to manage third-party access to the property and facilitate potential leasing, sale, or other use or disposition of the property, including the potential renewal of mining exploration and development.

Allowing a receiver to market the property serves to facilitate reimbursement of SCDHEC's and USEPA's response costs, reduction of financial and operational burdens on the state and USEPA, implementation of more cost-effective and permanent means of carrying out remedial action at the site, and facilitate potential beneficial reuse of the property.

Legal Timeline. Table 6-7 lists the documentation submitted for the receivership to be established. Brewer provided notification that it intended to close the mine in 1995. Following this notification, SCDHEC issued an Administrative Order on Consent, which required Brewer to submit a design for closure and reclamation of the site. As explained above, due to unexpectedly low water levels in the mine pits, the passive treatment system did not function as intended.

Table 6-7. Timeline used to appoint a receiver to allow exploration

Date	Document
2006	Superfund state contract
2014	First amendment superfund state contract
February 1, 2019	Summons and complaint filed in state court
February 4, 2019	Filed a motion for appointment of a receiver, which included the following: Affidavit from the Division Director describing the environmental issues at the site Affidavit from the potential receiver regarding their qualifications 2014 USEPA ROD Brewer Gold Company business entity status USEPA concurrence for SCDHEC to seek a receiver Second five-year review report
February 4, 2019	Order for the appointment of a receiver included the following: Agreement for temporary receiver Certificate of Service stating motion for appointment of a receiver was sent to all parties
February 8, 2019	Signed executed agreement for temporary receiver
February 8, 2019	Failure to serve complaint on Brewer due to the company's dissolved state
March 12, 2019	Motion for service publication and attorney affidavit
March 13, 2019	Order authorizing service by publication
Late 2019 to early 2020	Mining company presentations (technical and financial)
March 2020	First Brewer lease agreement with option to purchase
July 2022	Escrow agreement for fourth amendment to the lease
Ongoing	Receiver progress reports to the court

On November 9, 1999, Brewer notified SCDHEC of its intent to terminate corporate operations effective November 30, 1999, and exit the property at that time. SCDHEC filed suit to enjoin Brewer from ceasing operation and maintenance of the temporary wastewater treatment system and to require Brewer to ensure continued operation and maintenance of the site in compliance with applicable environmental laws until reclamation and closure were complete.

Following a hearing on November 29, 1999, the court issued an injunction pending final disposition of the merits of the case requiring Brewer to continue proper operation and maintenance of the temporary water treatment system; however, Brewer proceeded with the shutdown of all operations and abandoned the property. Brewer has not had any presence at the property and has taken no responsibility for continuing operations, maintenance, and remediation at the site since November 1999. Brewer's corporate existence was void in its state of incorporation, Delaware, on March 1, 2001, and Brewer's corporate existence ceased in South Carolina on December 31, 2007.

In February 2019, in pursuit of a receivership, SCDHEC filed a summons and complaint, which required Brewer to file an answer within 30 days. Due to the company's dissolved status, the complaint could not be served. Subsequently, the receiver was promptly appointed by the court and began looking for potential purchasers.

By October 2019, two mining companies had presented their technical interpretations of the Brewer Mine and their proposals for exploration to the receiver. Only one company can explore the site at a time. Subsequently, the receiver brought in SCDHEC and USEPA to discuss which proposal provided a greater overall benefit. By March 2020, a mining company had been selected, and the receiver and company had signed a mining lease with an option to purchase. The factors considered by the receiver, SCDHEC, and USEPA when making their selection are listed below.

1. What resource is each company searching for? What are the economics associated with that resource?
2. What is the company's background? How have they handled their other mining sites?
3. What is the scope of the resource recovery? How much does the company need to prove exists before they decide to buy the site?
4. What time frame is the company considering? How fast can they determine whether they want the site or not?
5. How much will they pay to acquire the site? How much of that money goes to the state vs. USEPA?
6. When would the company take over the operation and maintenance costs? Before buying the site? As soon as they buy the site?
7. What is the mining company's preference on whether the site remains on the NPL or not?
8. How much liability for past operations will the company be willing to take on?
9. How much of the past costs is the company willing to pay to the state and USEPA?
10. What experience do these companies have regarding a superfund/heavily regulated site?

As part of the lease agreement, the selected mining company agreed to provide the receiver with all results of their operations, including data related to or derived from drilling, testing, evaluation, and other analysis of minerals and all other data related to the company's operations. This allows the receiver to provide exploration data to another company if the lease and exploration fall through with the first company. In this event, the receiver is allowed to share the data but not the geological and technical interpretations of that data. The interpretations remain the intellectual property of the original mining company. This allows SCDHEC to entice another company to buy the site if the original exploration company chooses not to buy the site. With this stipulation, a new mining company and SCDHEC do not start at the beginning again.

Reuse Application/Current Status. As of 2024, mining exploration under the fifth lease amendment with an option to purchase is ongoing. To date, the mining company has completed two phases of drilling that included 5,400 meters of core drilling, 350 meters of sonic hole drilling, 194 meters of rotary air blast drilling (to a maximum depth of 24 meters), 2D-IP geophysics, and induced polarization survey. The company is currently working on the a third drilling program (Carolina Rush 2023).

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APPENDIX A. STATE TABLE

The agencies involved in permitting the reuse of solid mining wastes vary from state to state. This appendix provides a list of potential state agencies with regulatory authority and links to aid in contacting each state individually.

Download Appendix A – State Agencies Table (.xlsx)

APPENDIX B. GLOSSARY

A

Abandoned mine

A mine at which exploration, development, mining, reclamation, maintenance, inspection of facilities and equipment, and other operations ceased with no evidence demonstrating that the miner intends to resume mining. Typically, no potentially responsible party exists.

Active mine

The area, on and beneath land, that is currently being used for the purpose of extraction, removal, or recovery of geological material and minerals, for which a responsible entity and owner is known and where a site is operating under applicable regulatory permits.

B

Beneficiation

Any process, such as physical or chemical separation, that improves the economic value of ore by removing commercially non-valuable components.

C

Chat

A local name for coarse-sized mining waste material produced from discharges during mineral processing operations (for example, crushing, gravity separation, and concentrating processes). Typically refers to gravel- to sand-sized particles.

Closed mine

A mine that has an identifiable owner or responsible entity and has successfully undergone and completed reclamation and site closure.

Critical mineral

As used in the United States, any nonfuel mineral, element, substance, or material that the Secretary of Energy determines (i) has a high risk of supply chain disruption and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy.

E

Economic feasibility

Evaluation of financial costs, monetary or intangible values, and potential revenue for a particular project.

Environmentally sound

Describes a substance or process that results in an acceptable equivalent or reduced environmental risk and impact compared to a prior state.

F

Fine tailings

Similar to tailings, but materials are very fine to clay-sized particles, less than 0.2 mm in diameter. Typically produced from mill waste discharges as a result of the gravity separation and mineral concentration processes and accumulated into settling ponds (impoundments).

G

Gangue

The minerals without value in an ore; that part of an ore that is not economically desirable but cannot be avoided when mining the deposit. It is separated from the ore during mineral processing.

Grade

The concentration of each ore mineral in a rock, usually given as a weight percent.

I

Inactive mine

A mine is inactive if there is an identifiable owner or operator of the facility, but the facility is not currently operating.

L

Leachate

A solution or suspension formed when liquid travels through a solid and removes some components of the solid (USGS 2015).

M

Mineral

A naturally occurring inorganic element or compound having an orderly internal structure and characteristic chemical composition, crystal form, and physical properties. The term “mineral” may have different meanings depending on the context. Minerals may include metals and metal-bearing ores (gold, copper, iron, nickel, zinc, etc.), nonmetallic minerals and minable rock products (limestone, gypsum, building stone, peat, sand, salt), and fossil fuels (oil, natural gas, and coal).

Mineral rights

A right to extract a mineral from the earth or to receive payment, in the form of royalty, for the extraction of minerals.

Mining-influenced water (MIW)

Any water affected by mining, milling, or smelting activities. This includes groundwater, surface water, acid mine drainage, acid rock drainage, and mine-impacted water.

Mining-influenced water (MIW) residuals

Materials formed or accumulated from various physical processes, chemical reactions, or biological reactions, which includes natural oxidation and reduction reactions, settling of suspended solids, and chemical and biological treatment processes.

O

Ore

A mineral or minerals that can be extracted from a naturally occurring geologic formation.

Overburden

Material of any nature, consolidated or unconsolidated, that overlies a deposit of useful and minable materials or ores, especially those deposits that are mined from the surface by open cuts or pits.

P

Pozzolanic materials

Materials that will react with calcium hydroxide, in the presence of water, to form compounds with cementitious properties under ordinary temperatures and pressures. Pozzolanic materials must be in a finely divided form for the reaction to occur.

R

Rare earth elements (REEs)

The set of 15 elements from atomic number 57 (lanthanum) to 71 (lutetium). Yttrium (atomic number 39) and scandium (atomic number 21) are commonly included in the classification due to their chemical and physical similarity. These elements have diverse energy, industrial, and military technology applications. Also known as “rare earth metals,” “rare earths,” or “lanthanides.”

Remining

Further development or ore removal from a previously unmined mineral resource at a mine. Remining can include some of the technologies described herein, but activities involved with planning and operating an active mine are outside the scope of this document.

Reprocessing

Further physical or chemical alteration of solid mining waste, for example, crushing, screening, leaching, concentrating, and extracting existing mining waste or other resource recovery.

Repurposing

Adapting solid mining waste to a beneficial new purpose, which may or may not include reprocessing.

Resource recovery

The process of extracting resources of value from waste materials for repurposing. When applied to mining waste, defined resource recovery refers to the targeted and systematic extraction of valuable materials from mining waste streams.

Reuse

Using solid mining waste in a new application or product. This can include repurposing and reprocessing.

S

Slag

By-product of ore smelting. Main types of slag include ferrous, ferroalloy, and nonferrous.

Slimes

Material of silt or clay in size; results from the washing, concentrating, or treating of ground ore and is accumulated in settling ponds.

Solid mining waste

Any naturally occurring material that has been disturbed by mining, milling, or smelting activity and is not used or marketed by that activity.

Surface rights

The legal rights connected to the use, management, and ownership of the land’s surface, which usually includes the ability to occupy, develop, and use the land’s surface for various purposes. If the mineral rights are owned by another person, the mineral rights are considered severed from the surface rights.

T

Tailings

The solid waste material (gangue and other material) resulting from the milling and mineral concentration process (washing, concentrating, or treating) applied to ground ore. This term is usually used for coarse sand to clay-sized (4.75 mm to less than 0.005 mm) refuse that is considered too low in mineral values to be treated further, as opposed to the concentrates containing valuable metal(s).

APPENDIX C. LIST OF ACRONYMS

AAS	atomic absorption spectrometry
ABA	acid-base accounting
ACI	American Concrete Institute
Amax	Amax Arizona Inc.
AMD	acid mine drainage
AML	abandoned mine land
AOC	Great Lakes Area of Concern
AP	acid-producing
APHA	American Public Health Association
Atlantic Richfield	Atlantic Richfield Company
BIA	Bureau of Indian Affairs
BIL	Bipartisan Infrastructure Law
BLM	Bureau of Land Management
Brewer	Brewer Gold Company
CDPHE	Colorado Department of Public Health and Environment
CEQ	Council on Environmental Quality
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
COC	contaminants of concern
CWL	critical water level
DEQ	Department of Environmental Quality
DEUR	Declaration of Environmental Use Restriction
DNR	Department of Natural Resources
DOD	Department of Defense
DOT	Department of Transportation

ET	evapotranspiration
GARD	global acid rock drainage
GC	gas chromatography
GC-MS	gas chromatography–mass spectrometry
GSA	General Services Administration
GSHP	ground-source heat pump
HCT	humidity cell testing
HDS	high-density sludge
HHRA	Human Health Risk Assessment
HPLC	high-performance liquid chromatography
HSB	Horseshoe Bend
ICP	inductively coupled plasma
ICP-AES	inductively coupled plasma–atomic emission spectrometry
ICP-MS	inductively coupled plasma–mass spectrometry
ICP-OES	inductively coupled plasma–optical emission spectrometry
IEUBK	Integrated Exposure Uptake Biokinetic
ITRC	Interstate Technology & Regulatory Council
IWTP	interim water treatment plant
LCA	life-cycle analysis
µg/L	micrograms per liter
µm	micrometer
MCM	Madison County Mines
MI EGLE	Michigan Department of Environment, Great Lakes, and Energy
MIW	mining-influenced water
MS	mass spectrometry
MSHA	Mine Safety and Health Administration
MSW	municipal solid waste

NEPA	National Environmental Policy Act
NHPA	National Historic Preservation Act
NORM	naturally occurring radioactive material
NP	neutralization potential
NPL	National Priority List
NPS	National Park Service
OES	optical emission spectrometry
OSMRE	Office of Surface Mining Reclamation and Enforcement
OU	Operable Unit
PennDOT	Pennsylvania Department of Transportation
PRP	potentially responsible party
RCRA	Resource Conservation and Recovery Act
REE	rare earth element
ROD	Record of Decision
SCDHEC	South Carolina Department of Health and Environmental Control
SCM	supplementary cementitious materials
SEM	scanning electron microscopy
SHPO	State Historic Preservation Officer
SPLP	synthetic precipitation leachate procedure
SSRL	site-specific remediation levels
State Parks	California Department of Parks and Recreation
s.u.	standard unit
TCLP	toxicity characteristic leachate procedure
TENORM	technology-enhanced naturally occurring radioactive material
UCL	upper confidence limits
U.S.	United States
USACE	United States Army Corps of Engineers

USDA	United States Department of Agriculture
USDOE	United States Department of Energy
USDOI	United States Department of the Interior
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
wt. %	percentage by weight
XRD	X-ray diffraction
XRF	X-ray fluorescence