

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 ^[L58CCGK4] Lottermoser, Bernd. 2010. Mine Wastes. Characterization, Treatment and Environmental Impacts. Springer-Verlag. <https://doi.org/10.1007/978-3-642-12419-8>.)
- *How Mining Works* (Dunbar 2016 ^[KS8VNGXG] Dunbar, W. S. 2016. How Mining Works. Society for Mining, Metallurgy, and Exploration. Society for Mining, Metallurgy, and Exploration.)
- *Agromining: Farming for Metals* (van der Ent et al. 2021 ^[YRYIER79] Ent, Antony van der, Alan J. M. Baker, Guillaume Echevarria, Marie-Odile Simonnot, and Jean Louis Morel. 2021. Agromining: Farming for Metals. Extracting Unconventional Resources Using Plants. Second. Mineral Resource Reviews. Springer Cham. <https://doi.org/10.1007/978-3-030-58904-2>.)
- Recycling and Reuse of Mine Tailings: A review of Advances and Their Implications (Araujo et al. 2022 ^[25T8FK4F] Araujo, Francisco S. M., Isabella Taborda-Llano, Everton B. Nunes, and Rafael M. Santos. 2022. “Recycling and Reuse of Mine Tailings: A Review of Advancements and Their Implications.” *Geosciences* 12 (9). <https://doi.org/10.3390/geosciences12090319>.)
- *Mine Wastes and Water, Ecological Engineering, and Metals Extraction* (Kalin-Seidenfaden and Wheeler 2022 ^[67ZWV7WV] Kalin-Seidenfaden, Margaret, and William N. Wheeler, eds. 2022. Mine Wastes and Water, Ecological Engineering and Metals Extraction. Sustainability and Circular Economy. Springer Cham. <https://doi.org/10.1007/978-3-030-84651-0>.)
- Recent Progress on Ex Situ Remediation Technology and Resource Utilization for Heavy Metal Contaminated Sediment (Xu and Wu 2023 ^[CHG8HEWB] Xu, Qinqin, and Boran Wu. 2023. “Recent Progress on Ex Situ Remediation Technology and Resource Utilization for Heavy Metal Contaminated Sediment.” *Toxics* 11 (3). <https://doi.org/10.3390/toxics11030207>.)

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)

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 CO₂ 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.

Technology Description

- **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 Considerations

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 ^[CHG8HEWB] Xu, Qinqin, and Boran Wu. 2023. “Recent Progress on Ex Situ Remediation Technology and Resource Utilization for Heavy Metal Contaminated Sediment.” *Toxics* 11 (3). <https://doi.org/10.3390/toxics11030207>).