

Chapter 2

Overview of Mining and Mineral Processing Operations

2.1 Introduction

This chapter introduces users to the types of operations, waste streams, and waste management practices typical of historic mine sites and mineral processing facilities. Knowledge of the operating history of the site will be valuable during site scoping, site characterization, and the cleanup alternative selection process. In addition, this knowledge will assist in locating potential physical hazards, such as mine openings that may have become obscured. Knowledge of the wastes and waste management practices will provide additional insight into the potential threats to human health and the environment, as well as feasibility of response actions.

The production of minerals for economic use involves a series of physical and chemical processes. These may occur at any time from excavation of the ore that contains the metal in mineral form through production of the metal in marketable form. Users should be aware that mining terms have not been used consistently over the years. This can complicate the process of identifying site histories and operations. Some particularly noteworthy instances where this can occur are explained in the text.

The chapter is divided into sections addressing Mining (or “extraction”), Beneficiation (e. g. , milling and leaching), and Mineral Processing (e.g., smelting and refining). Each section in this chapter begins with a discussion of processes followed by a discussion of wastes generated. It is worthwhile to note that the three types of operations may or may not be co-located. For example, in many mining districts, the beneficiation plant is located at a central location to serve a number of individual mines with the concentrate being further transported to a remote smelter. In contrast, other sites, such as Bunker Hill in Northern Idaho, had the mine, concentrator, and smelter all located together. When mineral processing operations are co-located with extraction and beneficiation operations, comingling of relatively small quantities of mineral processing waste with beneficiation waste often has occurred. This is important due to the physical characteristics of the waste , as well as the applicable waste management regulations.

The definition of a mine site may be broad. EPA, in its Clean Water Act effluent limitation guidelines for discharges from mines, has defined a mine as an area of land upon or under which minerals or metal ores are extracted from natural deposits in the earth by any methods, including the total area upon which such activities occur or where such activities disturb the natural land surface. A mine, under this definition, also includes land affected by ancillary operations that disturb the natural land surface, and can include adjacent land whose use is more incidental to mining activities (e. g. , roads, workings, impoundments, dams, ventilation shafts, drainage tunnels, refuse banks, dumps, stockpiles, overburden piles, spoil banks, tailings, holes or depressions, structures, or facilities).

2.2 Mining

The initial step of the mining and mineral processing operations is the actual removal of the mineral value in ore from the host rock or matrix. Minerals may be extracted from the earth using a variety of techniques (note that the term extraction also may be used within the industry to describe pyrometallurgical and metallurgical processes--that is outside this mining definition). Most extraction processes result in the removal of ore and associated rock or matrix in bulk

form from the deposit, using blasting and various mechanical means to break the ore into pieces of manageable size or to separate the ore minerals from unwanted material.

In the interest of economic efficiency, the extraction process is designed to remove ore of a predetermined grade or higher, leaving behind as much of the lower grade ore and barren rock as possible. Because this ideal separation is not always possible in practice, some lower grade rock is mined while some higher grade ore is left behind. It is important to note that the term “ore” is an economic one. In general, ore is earthen material that contains minerals of sufficient value to be extracted economically. Because the value of a mineral can change rapidly and substantially, the distinction between “ore” and other mined materials (which generally contain mined values that cannot be economically extracted *at the time*) is also variable, both from mine to mine and, for any specific mine, over time.

2. 2. 1 Types of Mining Processes

Mining can be categorized as surface mining, underground mining, and *in situ* mining. Surface mining is used to excavate ores at or close to the earth's surface; included in surface mining are open pit mining, highwall or strip mining used to excavate coal or other deposits (abandoned coal mines are not addressed in this handbook), and dredging to excavate placer deposits. Underground and *in situ* mining both remove minerals from deeper deposits, the former by extracting under the surface and removing the ore and the latter by sinking injection, and extraction wells and leaching the ore in place.

Open Pit Mining. Surface mining with open pits has become the primary type of mining operation for most of the major metallic ores in the United States. It is the method of choice when the characteristics of the ore deposit (e. g. grade, size, location) make removing overburden (i. e. , host rock overlying the mineral laden ore) cost effective. At present, this is the most economical way of mining highly disseminated (i. e. , lower-grade) ores. Open pit mining involves excavation of an area of overburden and removal of the ore exposed in the resulting pit. Depending on the thickness of the orebody, it may be removed as a single vertical interval or in successive intervals or benches. With the larger orebodies common to metals mining, the orebody typically is mined in benches either by drilling vertical holes from the top of the bench and blasting the ore onto the adjacent lower level or, in less resistant materials, by excavating with digging/scraping machinery without the use of explosives.

Explosives typically used in open pit mining are comprised of chemicals which, when combined, contain all the requirements for complete combustion without oxygen supply. Early explosives consisted chiefly of nitroglycerine, carbonaceous material and an oxidizing agent. These mixtures were packaged into cartridges for convenience in handling and loading into drill holes. In recent years, fertilizer-grade ammonium nitrate mixed with about six percent fuel oil was recognized as an explosive capable of being detonated with a high explosive primer. This application has spread to the point where virtually all open-pit mines use this mixture (called ANFO) for primary blasting.

Dredging. Dredging is another method of surface mining that has been used to mine placer deposits, which are concentrations of heavy metallic minerals that occur in sedimentary deposits associated with current or ancient watercourses. In some mining districts, widespread stream disturbance by placer mining or dredging may be present alongside the other disturbances from underground mining, beneficiation, and/or mineral processing. Commercial dredging has not been widely practiced in the United States in the 1990's, although placer mining is still an important industry in Alaska. Some abandoned large-scale dredge operations remain in the western United States, and in some cases the dredges are still present in the dredge ponds created as part of the operation.

Underground Mining. Underground mining has been the major method for the production of certain metals but in recent years has been increasingly less common in the United States. The mid-1990's have seen a mild resurgence of underground mining as the depths of several major open pit mines have reached their economic limit. Underground mining typically has significantly less impact on the surface environment than do surface methods. This is primarily the result of reduced surface disturbance (i.e., a smaller facility "footprint") and the much lower quantities of non-ore materials that must be removed and disposed as waste. Large underground workings, when abandoned, have sometimes caused subsidence or caving at the surface, resulting in disturbance to structures, roads, and surface water drainages. In addition, drainage from underground mines may cause significant alteration to the quality of ground water and can affect surface water as well. Mine drainage water quality is highly dependent on the characteristics of host rock and can vary widely.

***In Situ* Solution Mining.** *In situ* mining is a method of extracting minerals from an orebody that is left in place rather than being broken up and removed. (*Ex situ* leaching operations, discussed as beneficiation in Section 2. 4, operate on the same principal but with excavated ore.) In general, a series of wells are drilled into the orebody and a solvent circulated through the formation by injection through certain wells and withdrawal through others. Although *in situ* solution mining is not commonly used, it has been applied to uranium and copper deposits in suitable hydrogeologic settings. Although there is little disturbance of the surface and underground at an *in situ* operation, the effect of the operation on the groundwater quality can be significant as the chemistry of the ground water must be drastically altered by the introduced solvents and the pumping operation. Furthermore, other materials in addition to the target minerals may be dissolved with the potential for affecting the local ground water, and, depending on their mobility, surrounding areas.

Surface operations include management of barren solution (i.e., leachate prior to injection) and pregnant leachate (leachate withdrawn and containing the mineral value) in surface impoundments or, more recently, tanks.

2. 2. 2 Mining Wastes and Hazardous Materials

The largest quantity of wastes generated by extraction operations are mine water and waste rock. A third waste material, overburden, is generated at surface mines. Note that the use of the terms "mining waste" and "waste management unit" in this document do not imply that all the materials in question are solid wastes as defined by the Resource Conservation and Recovery Act (RCRA). Wastes from extraction and beneficiation continue to be excluded broadly from regulation as hazardous waste, although they are regarded as solid waste; overburden, as noted below, has an additional exclusion.

Overburden. Overburden is the surface material (i.e., topsoil and rock) removed during surface mining operations to expose the ore beneath. In recent years, mine management plans required by States and by Federal land management agencies require that topsoil be salvaged and stockpiled for use in reclamation during closure or decommissioning. Overburden is specifically exempted from being regulated as a RCRA hazardous waste when it is "returned to the mine site" (40 CFR 261. 4(b)(3)).

Mine Water. Water entering a surface or underground mine is referred to as mine water. Sources of this water are groundwater seepage, surface water inflow, or direct precipitation. In the absence of a natural or manmade drainage, active mine operations below the water table must pump out mine water to access the orebody. Depending on the hydrogeology of the mine this can be accomplished as simply pumping the water from the mine to grouting the rock in the mine to prevent inflow to using a series of extraction wells around a mine to create a cone of

depression in the ground water table, thereby reducing infiltration. At some mines enormous quantities may have to be pumped continuously from the mine during operations. Active mines may use mine water for dust control and as process water in the mill circuit; otherwise they typically discharge the flow to surface water under a National Pollutant Discharge Elimination System (NPDES) permit or similar state permit. Mine water discharge from operating mines is typically regulated and often does not have the residence time in the ore or mine needed to create highly acidic waters or waters highly-loaded with dissolved metals. However, the need to treat mine water prior to discharge is highly site specific.

When a mine closes, dewatering the mine generally ceases. Underground mines often fill; mine water may be released through openings such as adits, or through fractures and fissures that reach the surface. If present, man-made gravity drains will continue to flow. Surface mines that extend below the water table will return to that level when pumping ceases, either forming a lake in the pit or inundating and saturating fill material. Recovery of ground water to or near pre-mining levels following the cessation of pumping can take substantial amounts of time, however, and the effects resulting from ground water drawdown may continue to be felt for decades.

Water from abandoned mines may contain significant concentrations of heavy metals and total dissolved solids and may have elevated temperatures and altered pH, depending on the nature of the orebody and local geochemical conditions. These waters may become acidic over time when exposed to oxygen and, if present, pyrites or other sulfide minerals. The acidic water may also solubilize metals contained in the mine and mined materials, creating high concentrations of metals in solution. These acidic metal-laden waters may contaminate down-gradient ground-water and surface water resources. Neutral and alkaline mine waters may also contain metals in excess of water quality standards and be of significant concern to human health and the environment.

Waste Rock. Waste rock consists of non-mineralized and low-grade mineralized rock removed from, around, or within the orebody during extraction activities. The cutoff grade that differentiates low-grade waste rock from useable ore is an economic distinction and may vary over time (see above). Therefore, what may have been disposed as waste rock (or stored as “sub-ore”, “proto-ore” or “low grade ore”) in the past may be ore at another time.

Waste rock includes granular, broken rock and soils ranging in size from fine sand to large boulders, with the content of fine material largely dependent on the nature of the formation and the extraction methods employed during mining. Waste rock is typically disposed in large piles or dumps adjacent to and/or down-slope of the point of extraction; waste rock frequently can be seen in close proximity to old mine shafts and openings. These sites historically were in locations of natural drainage; surface water run-on and infiltration have caused natural leaching from the waste rock piles. Waste rock has often been used on the mine site for fill, tailings dams, or other construction purposes. Current operations frequently use engineering controls to prevent run-on (e. g. , diversion systems) or run-off (drainage systems installed during construction); retrofitting waste rock sites at abandoned mines with surface water controls is often necessary for controlling waste rock impacts at abandoned mines.

Waste rock geochemistry varies widely from mine to mine and may vary significantly at individual mines over time as differing lithologic strata are exposed and geochemical processes alter characteristics of the waste. Waste rock at metal mines will contain some concentration of the target mineral along with other metals. The mobility of any particular constituent of waste rock is highly dependent on site specific conditions, such as climate, hydrology, geochemistry of the disposal unit and its foundation, mineralogy, and particle size. Waste rock from metal mines often contains sulfidic materials as components of the host rock. The concentration of

sulfide minerals and of neutralizing minerals is an important factor in the potential for waste rock to generate acid drainage.

If prone to acid generation, such uses can lead to concern about widespread contamination, acid generation, or other long-term problems. Site scoping activities often includes identifying and mapping locations where these uses occurred.

2.3 Beneficiation: Milling

Following the initial mining step, ore is reduced in size by the crushing and/or grinding circuit, and the target mineral is concentrated by various methods. These widely varying concentration processes are collectively referred to as beneficiation. Ore dressing and milling typically refer to a specific subset of operations under beneficiation and are the focus of this section. Leaching, also considered by EPA (under the RCRA program) to be beneficiation, is discussed separately in Section 2.4.

In general, the criteria established by EPA (under the RCRA program) describe beneficiation as activities that serve to separate and concentrate the mineral values from waste material, remove impurities, or prepare the ores for further refinement. Beneficiation activities generally do not change the mineral values themselves other than by reducing (e.g., crushing or grinding) or enlarging (e.g., pelletizing or briquetting) particle size to facilitate processing. Generally, no chemical changes occur in the mineral value during beneficiation. (Beneficiation operations may be referred to as “processing” in the older literature and occasionally by industry today.)

2.3.1 Types of Beneficiation (Milling) Processes

Most ores contain the valuable metals disseminated in a matrix of less valuable rock called gangue. The purpose of ore beneficiation is the separation of valuable minerals from the gangue to yield a product that has a much higher content of the valued material. Beneficiation milling operations are functionally categorized as either comminution, in which the mined ore is crushed and ground to physically liberate the target mineral, or concentration. Concentration is the separation of the mineral values liberated by comminution from the rest of the ore. These separation steps, often conducted in series, utilize the physical differences between the valuable mineral and the host rock to achieve separation and produce a concentrate containing the valuable minerals and a tailing containing the waste material and reagents. Many physical properties, including the following, are used as the basis for separating valuable minerals from gangue: specific gravity, conductivity, magnetic permeability, affinity for certain chemicals, and solubility in a leachate (leaching is discussed in Section 2.4). Types of processes that affect separation include gravity concentration, magnetic separation, electrostatic separation, and flotation.

Gravity Concentration. Gravity-concentration processes exploit differences in density to separate ore minerals from gangue. Selection of a particular gravity-based process for a given ore will be strongly influenced by the size to which the ore must be crushed or ground to separate values from gangue, as well as by the density difference and other factors. In general, the first two methods were historically used in the recovery of gold.

Coarse/Fine Concentration. Separation in this step involves particle density rather than size. Sluices are commonly used in this step, although jigs and screens may also be employed. The heavy minerals settle within the lining material of the sluice, while the lighter material is washed through. Most of the material that enters the sluice exits as

slurry waste that is discharged to a tailings pond or undergoes further concentration. After coarse concentration, most waste material has been removed, leaving a concentrate. The concentrate may then be subjected to fine concentration methods, including jigs, spiral classifiers, shaking tables, and pinched sluices. The waste at this stage is a slurry. Amalgamation sometimes followed fine concentration.

Amalgamation. Native gold or free gold can be extracted by using liquid mercury to form an amalgam. The gold is then recovered by filtering the amalgam through a canvas cone to drain off the excess mercury. Although the amalgamation process has, in the past, been used extensively for the extraction of gold from pulverized ores and placer gravels, it has largely been superseded in recent years by cyanidation processes (i.e. leaching). The current practice of amalgamation in the United States is limited to small-scale barrel amalgamation of a relatively small quantity of high-grade, gravity-concentrated gold ore. The amalgam is then retorted to separate the gold and mercury. Historically, the methods used to obtain the amalgam allowed some of the mercury/amalgam to escape the process. Several Superfund sites (notably Carson River, see Highlight 2-1) have experienced severe mercury contamination from amalgamation.

**Highlight 2-1
Carson River Mercury**

The Carson River Mercury Site consists of a 50-mile stretch of the Carson River, downstream of Carson City, Nevada. The site has been contaminated by mercury used in the amalgamation of gold and silver. In the late 1800s, large amounts of mercury were used during the milling of the Comstock Lode near Virginia City. Gold mining and processing began in the late 1880's. An estimated 7,500 tons of mercury were lost during the processing. Mercury has contaminated the hundreds of tailings piles and the Carson River sediments.

Sink/Float Separation. Sink/float separation, also known as heavy media separation, uses buoyancy forces to separate the various minerals on the basis of density. The ore is fed to a tank containing a medium whose density is higher than that of the gangue and less than that of the valuable ore minerals. As a result, the gangue floats and overflows the separation chamber, and the denser values sink and are drawn off at the bottom. Media commonly used for sink/float separation in the ore milling industry are suspensions of very fine ferrosilicon or galena (PbS) particles. The float material (waste) may be used for other applications, such as aggregate, since it is already crushed.

Magnetic Separation. Magnetic separation is applied in the ore milling industry, especially the beneficiating ores of iron, columbium and tantalum, and tungsten, both for extraction of values from ore and for separation of different valuable minerals recovered from complex ores. Separation is based on differences in magnetic permeability (which, although small, is measurable for almost all materials) and is effective in handling materials not normally considered magnetic. The basic process involves transport of ore through a region of high magnetic-field gradient where the most magnetically permeable particles are attracted to a moving surface, behind which is the pole of a large electromagnet. These particles are carried out of the main stream of ore and released into a conveyance leading to further processing. Although dry separators are used for rough separations, drum separators are most often run wet on the slurry ground in the mill.

Electrostatic Separation. Electrostatic separation is used to separate minerals on the basis of their conductivity. This process is inherently dry and uses very high voltages. In a typical application, ore is charged at 20,000 to 40,000 volts, and the charged particles are dropped onto a conductive rotating drum. The conductive particles lose their attractive charge very

rapidly and are thrown off and collected, while the non-conductive particles keep their charge and adhere by electrostatic attraction. They may then be removed from the drum separately.

Flotation. Flotation is a process by which the addition of chemicals to a crushed ore-water slurry causes particles of one mineral or group of minerals to adhere to air bubbles. When air is forced through the slurry, the rising bubbles carry with them the particles of the mineral(s) to be separated from the matrix. A foaming agent is added that prevents the bubbles from bursting when they reach the surface; a layer of mineral-laden foam is built up at the surface of the flotation cell and this is removed to recover the mineral.

Flotation concentration has become a mainstay of the metal ore milling industry because it is adaptable to very fine particle sizes. It also allows for high rates of recovery from slimes, which are generated in crushing and grinding and which are not generally amenable to physical processing. As a physical-chemical surface phenomenon, this process can often be made highly specific, thereby allowing production of high-grade concentrates from very low-grade ore (e. g. , more than 95 percent MoS_2 concentrate from 0.3 percent ore). Its specificity also allows separation of different ore minerals (e. g. , CuS , PbS , and ZnS) where desired, as well as operation with minimum reagent consumption because reagent interaction typically occurs only with the particular materials to be floated or depressed.

Details of the flotation process (e. g. , exact type and dosage of reagents, fineness of grinds, number of regrinds, cleaner-flotation steps) differ at each operation where it is practiced and may often vary with time at a given mill. A complex system of reagents is generally used, including five basic types of compounds: pH conditioners (regulators, modifiers), collectors, frothers, activators, and depressants. At large-capacity mills, the total reagent usage can be high even though only small quantities are needed per ton of ore, since tens of thousands of tons of ore per day may be beneficiated. The reagents often remain in the waste water, allowing the usage to be lowered by recycling the water. The reagents in the waste water may however impact some of the other steps in the process, prohibiting the water from being recycled.

Sulfide minerals are all readily recovered by flotation using similar reagents in small doses, although reagent requirements and ease of flotation do vary throughout the class. Sulfide flotation is most often carried out at alkaline pH. Sulfide minerals of copper, lead, zinc, molybdenum, silver, nickel, and cobalt are commonly recovered by flotation. Non-sulfidic ores also may be recovered by flotation, including oxidized ores of iron, copper, manganese, the rare earths, tungsten, titanium, and columbium and tantalum. Generally, the flotation processes for oxides are more sensitive to feed-water conditions than sulfide floats; consequently, oxidized ores can run less frequently with recycled water. Flotation of these ores involves very different reagents from sulfide flotation. The reagents used include fatty acids (such as oleic acid or soap skimmings), fuel oil, and various amines as collectors, as well as compounds (such as copper sulfate, acid dichromate, and sulfur dioxide) as conditioners.

2. 3. 2 Beneficiation (Milling) Wastes and Hazardous Materials

The wastes generated by beneficiation milling operations are collectively known as tailings. Readers should also be aware that unused or discarded chemicals associated with these beneficiation operations at historic mining sites also may remain onsite and need to be managed during remediation. These could include: mercury at sites that have used amalgamation and chemicals used in flotation such as copper sulfate, various amines, and sodium cyanide.

Tailings. Tailings are the waste portions of mined material that are separated from the target mineral(s) during beneficiation. By far the larger proportion of ore mined in most industry sectors ultimately becomes tailings that must be disposed. In the gold industry, for example, only a few hundredths of an ounce of gold may be produced for every ton of dry tailings generated. Similarly, the copper industry typically mines relatively low-grade ores that contain less than a few percent of metal values; the residue becomes tailings. Thus, tailings disposal is a significant portion of the overall waste management practice at mining and milling operations.

The physical and chemical nature of tailings is a function of the ore being milled and the milling operations used to beneficiate the ore. The method of tailings disposal is largely controlled by the water content of the tailings. Generally, three types of tailings may be identified based on their water content: wet, thickened, and dry. The type of tailing is less important from a remediation perspective than from an active management perspective, although knowledge of the type of tailings may help site managers characterize the material and better understand the potential remediation alternatives.

Although the tailings have much lower concentrations of the target mineral(s) than in the mined ore, they may be a source of contamination at the site due to the presence of sulfides such as pyrite (acid generation), metals (available for mobilization in ground or surface waters), and reagents added during beneficiation. Tailings that are fine grained and managed under drier conditions are especially prone to producing dust. Sulfide tailings oxidized by weathering are potential generators of acidic runoff.

In the past, and at present in some other countries, tailings often were disposed where convenient. The tailings were discharged into rivers if flow was sufficient, held behind dams if necessary, or placed on land. In the U.S., tailings now are managed, wet or thickened, in tailings impoundments or dry in disposal piles. In addition to placement in management units, certain tailings may be slurried as backfill into underground mines.

Tailings Impoundments. Wet tailings are slurried to tailings and settling ponds, where excess liquid is evaporated or drained and the tailings allowed to dry. These impoundments may range in size from under an acre to up to a thousand acres. While the thickness (i. e. , depth or height) of these tailings impoundments may in some extreme cases be as much as 1,000 feet, the thickness most commonly ranges from ten to fifty feet.

Four main types of slurry impoundment layouts are employed: valley impoundments, ring dikes, in-pit impoundments, and specially dug pits (See Appendix A for Glossary terms). The stability of tailing dams at abandoned mines represents a remediation concern. Historic methods of tailings management included disposal into topographically low areas, often streams and wetlands. To the extent that these areas became diked incidentally by the nature of their deposition they are considered inactive impoundments for remediation planning.

Tailings Piles. Tailings may be dewatered or dried prior to disposal, thus reducing seepage volume and the area needed for an impoundment or pile. Dry tailings piles are considerably different from tailings piles created as a result of thickened tailings disposal. Dry tailings may be disposed in a variety of pile configurations, including a valley-fill (i. e. , discharged to in-fill a valley), side hill (disposed of on a side of a hill in a series of piles), and level pile deposition in lifts that are continually added.

Mine Backfilling. Slurried tailings may be disposed in underground mines as backfill to provide ground or wall support, thereby decreasing the above-ground surface disturbance and stabilizing mined-out areas. (Waste management economics may also drive deposition in underground mines.) For stability reasons, underground backfilling generally requires tailings that have a high permeability, low compressibility, and the ability to rapidly dewater (i. e. , a large sand fraction). As a result, often only the sand fraction of tailings is used as backfill. Tailings may be cycloned to separate out the coarse sand fraction for backfilling, leaving only the slimes to be disposed of in an impoundment. To increase structural competence, cement may be added to the sand fraction before backfilling. In the proper geologic setting, this practice may have significant value to remediation teams looking to fill underground mines and fissures to stop acidic mine water release while reducing tailings volume on the surface. In other cases efforts to backfill or seal the mine could increase the risk of generating AMD.

Subaqueous Disposal. Underwater disposal in a permanent body of water, such as a lake, ocean, or an engineered structure (e. g., a pit or impoundment), has been an historical management practice and is still practiced in some other countries (e. g., Canada). The potential advantage to underwater disposal is the inhibition of oxidation of sulfide minerals in tailings, thus preventing or slowing acid generation. Substantial uncertainty exists regarding other short- and long-term effects on the water body into which the tailings may be disposed. Regulations under the Clean Water Act (e. g. , the effluent limitation guidelines for mills that beneficiate base and precious metal ores) effectively prohibit subaqueous disposal of tailings in natural water bodies (i.e., any discharge to "waters of the U. S. ").

2. 4 **Beneficiation: Leaching**

Leaching is the process of extracting a soluble metallic compound from an ore by selectively dissolving it in a suitable solvent, such as water, sulfuric acid, or sodium cyanide solution. The target metal is then removed from the "pregnant" leach solution by one of several electrochemical or chemical means. (Note that digestion, where the ore concentrate is digested completely or significantly by a strong liquor, is not considered leaching under RCRA. The significance of this difference is that wastes from digestion are not excluded from management as hazardous waste, while wastes from leaching operations are excluded.)

Specific solvents attack only one (or, at most, a few) ore constituent(s), including the target metal or mineral. (Note that *in situ* mining is fundamentally the same leaching operation except the ore is not excavated.) Ore may be crushed or finely ground to expose the desired mineral prior to leaching. The tailings from a other beneficiation process, such as flotation, may be leached to remove additional metal. Ores that are too low in grade to justify the cost of milling may be recovered by dump or heap leaching.

2. 4. 1 **Types of Processes Associated with Leaching**

The leaching process consists of preleaching activities, the actual leaching operation, and the recovery of the mineral value from the pregnant leach liquor. Each of these efforts is distinct from the others and generates different types of waste streams.

Preleaching Activities. Depending on the grade of the ore and the type of leaching operation for which the ore is intended, some preprocessing may be required. Most heap and dump leach operations use ores that are not preprocessed other than by some comminution (e. g. crushing). (Note that, under RCRA, EPA has included in the definition of beneficiation the

activities of roasting, autoclaving, agglomeration, and/or chlorinating in preparation for leaching; wastes from these activities currently are exempted from regulation as hazardous wastes.)

Roasting. The activity of roasting ores is discussed because particulate materials from roasting operations, known as fines, have been found to contribute to the environmental impacts at several mine sites being remediated under CERCLA. Certain ores are subjected to heating in roaster furnaces to alter the compound, to drive off impurities, and/or to reduce water content. For example, roasting is used to treating sulfide gold ore, to make it more amenable to leaching. The roasting, with sodium, of certain metals that form insoluble anionic species (e. g. , vanadium) convert the ore values to soluble sodium salts (e. g. , sodium vanadate), which, after cooling, may be leached with water.

Roasters do not use the intense heat of the smelters and refineries and the ores are not processed in a molten state with chemical changes occurring. Roasting may, however, drive off sulfur dioxide or other substances and emissions often have significant particulate content.

Autoclaving. Autoclaves use pressure and high temperature to prepare some ores for leaching activities. The autoclave is used to convert the ore to an oxide form which is more amenable to leaching. The ore is generally in a slurry form in the autoclave.

Leaching Operations. Leaching operations may be categorized both by the type of leachant used as well as the physical design of the operations.

Physical Design. Several types of leaching operations are used, typically dependant on the ore-grade, the leachant, and the target material.

Dump Leaching. Piles of low-grade ore are often placed directly on the ground, leachant added by a spray or drip system, and leachate containing the solubilized target metal collected from underneath the dump over a period of months or years. The dumps are dedicated, that is they are designed to leave the ore in place after leaching operations are complete. Dump leach operations designed to recover gold more often are being designed with a plastic liner prior to placing the ore in order to facilitate recovery of pregnant solution as well as to minimize release to the environment of the cyanide leachant.

Heap Leaching. In heap leach operations the ore is placed on lined pads in engineered lifts or piles. The pad may be constructed such that heavy machinery may be used to off load the leached ore for disposal prior to placing new ore on the pad but more commonly the heap remains in place when leaching ends. As with dump leaching the leachant may be applied by spray or portable drip units; recovery is from beneath the ore on the impermeable pad (typically designed with a slight grade and a collection system).

Tank Leaching. In vat or tank leaching the milled ore is placed in a container equipped for agitation, heating, aeration, pressurization, and/or other means of facilitating the leaching of the target mineral.

In all three cases a solution management system is required, either in surface impoundments or tanks. Some operations use ponds that were designed with a compacted earthen liner (e. g. , clay), but most copper and all gold operations use synthetic liners with leachate collection systems. Dumps often have a collection pond

down-gradient from the dump; heap leach units are more likely to have a system for collecting solution directly off the pad. Tank and vat leaching operations may be completely closed systems with no ponds incorporated in the design.

Leachants. Leaching also may be characterized by the type of solution being used to leach the ore and recover the target metal.

Acid Leaching. Certain target metals are particularly receptive to leaching by acidic solutions. Copper, for example, is leached by a sulfuric acid solution.

Cyanide Leaching. Sodium cyanide has been used extensively to recover gold from low-grade ores. Continued improvements in cyanidation technology have allowed increasingly lower grade gold ores to be mined economically.

Dissolution. Water is used to separate certain water-soluble compounds, such as sodium, boron, potassium, and certain salts (some that may be formed by roasting). The compounds are dissolved, purified using basic water chemistry and filtration, then recrystallized.

Recovery Processes. The values contained in the pregnant leach solution are recovered by one or more of several methods, including the following:

Precipitation. In this process, the metals dissolved in the pregnant leachate are forced into an insoluble solid form and then filtered or settled out for recovery. Methods to cause precipitates to form may be chemically treating, evaporating, and/or changing the temperature and/or pH.

Electrowinning. The pregnant leachate may be placed in an electrolytic cell and an electric charge applied. The metal plates out of the solution on the cathode. Insoluble precipitates may settle out as a material referred to as slimes.

Carbon Adsorption. Activated carbon may be used to adsorb the metal values from the solution. The carbon is then leached to recover the adsorbed metals.

Cementation. In this method, the metal is "cemented" out of solution by replacement with less active metal. For example, when a copper leachate solution (CuSO_4) is brought into contact with scrap iron plates, the copper replaces the iron on the scrap plates and the iron goes into solution (FeSO_4). The copper is then removed by washing the scrap plates.

Solvent Extraction. A chemical-specific solvent may be used to selectively extract a mineral value dissolved in the pregnant leachate. This is often used in the case of copper ore leaching; a proprietary organic chemical dispersed in a kerosene diluent is used. The copper may then be extracted from the organic base with a strong sulfuric acid which can be electrowinned.

2. 4. 2 Leaching Wastes and Hazardous Materials

Dump and Heap Leach Waste. Following leaching, the large piles of spent ore that remain are usually left in place. These leach piles vary widely in size, the largest may cover hundreds of acres, may rise to several hundred feet, and may contain tens of millions of tons of leached ore. Reusable heap leach pad operations typically have a nearby waste unit for disposal of spent ore. Alternatively, leached ore from pads may be moved to a dedicated dump for additional and long term dump leaching. Uncollected leachate from these piles is a potential source of contamination of ground water, surface water, and soil. In addition, other contaminants (notably, arsenic, mercury, and selenium, but also including many other heavy metals) that are present in the spent ore may appear in leachate over time. Acid drainage may be generated from the oxidation of sulfide ores and require control. For both dump and heap leaching, transport by wind-blown dust and/or storm-water erosion may result in physical contamination off site.

Spent Leachate. When the leach operation is decommissioned or the leachate become necessary for replacement, the spent leachate becomes a waste requiring appropriate management. Leachate in the piles may continue to be released after operations cease. For example, where gold extraction processes use cyanide to leach the metal from the host rock, the unpurged or untreated cyanide solution may be washed by rain and snowmelt into streams or ground water systems if recovery and recycling systems are not working properly.

Electrowinning Slimes and Crud. Slimes and crud result from impurities separated from the metal value in electrowinning. The slimes that settle out typically are recovered and treated to recover precious metals, such as gold and silver. Crud results from impurities that foam up in the electrolytic bath used in electrowinning; these typically are vacuumed from the cells and returned to the leach operations.

Spent Carbon. Spent carbon is the waste product remaining after the desired metals have been removed from activated carbon. The activated carbon may contain other metals and chemicals that were in the ore or used in process, including mercury or cyanide. The spent carbon is often “reactivated” in the mining process.

2. 5 Mineral Processing

Following beneficiation (i.e., leaching or milling) to concentrate the mineral value, the concentrate typically is processed to further extract and/or refine the metal, thus preparing it for its final use or for incorporation into physical or chemical manufacturing (as noted previously, mineral processing is often used within the industry to refer to any post-extraction activities, including beneficiation; EPA, at least under the RCRA program, excludes beneficiation from mineral processing). At some locations, post-mineral processing operations may occur, or have occurred, as well (note that under RCRA, EPA delineated a regulatory distinction between mineral processing and post-mineral processing, although the actual regulatory significance of this is now minimal). An example of post-mineral processing is the alloying process, in which various alloys are added to, for example, steel (i.e., a product of mineral processing) to make alloy steel (which is not a product of mineral processing). While this may not affect how a site manager approaches the remediation if the operations are co-located, it may affect the understanding of ARARS or what potential impacts from various operations may be expected.

2. 5. 1 Types of Mineral Processing Operations

There are a variety of mineral processing operations, including the following major categories: pyrometallurgical operations (e. g. , smelting, refining, roasting), hydrometallurgical operations (e. g. , digestion of phosphate in producing phosphoric acid), and electrometallurgical operations (e. g. , electrolytic refining).

Note that mineral processing may be further categorized as primary or secondary. Broadly defined, primary mineral processing is focused on processing concentrates from extraction and beneficiation of raw ores whereas secondary processing focuses on recycling metals or minerals. Primary mineral processing, such as smelting, may, and often does, incorporate into its charge mineral processing wastes (e. g. , flue dust), scrap, and/or other metals/mineral bearing materials (e. g. , sludge or residues). (Note that under RCRA, EPA requires that feedstocks be at least 50 percent extraction and beneficiation products to be considered primary; the significance focuses on certain wastes such as lead smelter slag that are exempt at primary lead smelters but regulated as potentially hazardous waste at secondary lead smelters).

Smelting. Smelting is the most common pyrometallurgical process and involves the application of heat to a charge of ore concentrate and flux in a furnace. Smelting produced separate molten streams of matte (i.e. , molten product), slag and dross, and dust, an important by-product. Historically, high-grade ore from the mine may have been smelted directly with no intermediate concentration.

Roasting. Roasting, a *relatively* low heat pyrometallurgical process, may be used to prepare ores, especially sulfide ores, for smelting (note that EPA, under the RCRA program, makes a distinction between roasting prior to leaching, which is beneficiation, and roasting prior to smelting, which is mineral processing). Roaster furnaces produce particulate matter referred to as roaster fines, as well as gaseous emissions such as sulfur dioxide. Where sulfur dioxide is generated, such as the copper smelting sector, the sulfur elements are now often captured in acid plants and saleable or useable sulfuric acid generated. In the past, sulfur dioxide emissions, as well as arsenic and other contaminants, were uncontrolled, and in some cases contaminated wide areas.

Retorting. In processing metals that are relatively volatile, retort furnaces are employed to heat the ore concentrate and vaporize the metal (e. g. , zinc, mercury, phosphorus). The vaporized metals are then condensed and recovered. The non-volatilized waste material remaining in the retort is typically referred to as slag (e. g. , zinc slag, ferrophosphorus).

Fire Refining. Fire refining is a pyrometallurgical process that typically involves heating smelted material (e. g. , blister copper) in a furnace. A flux may be added, and air then blown through the mixture to oxidize impurities. Most of the remaining sulfur and other impurities vaporize or convert to slag. Copper is fire refined with the molten copper being poured into molds to form anodes to be used in electrolytic refining if required. Refining in the lead sector, referred to as softening, generates slags with antimony, arsenic, tin, and copper oxides.

Drossing. In the lead sector, drossing follows the initial smelting. In this step, the molten lead is agitated in a drossing kettle and cooled to just above the freezing point, thereby causing metal oxides, including lead oxide and copper oxide, to solidify and float to the surface as dross. The dross, predominantly lead oxide, is treated for metals recovery. Other drossing-refining steps in the lead sector are decopperizing, where sulfur is added rather than oxygen to

remove cuprous sulfide as dross, and desilverizing, where zinc is added to alloy insolubly with precious metals that float up as dross.

Electrolytic Refining. Electrolytic refining, a electrometallurgical process typically applied in the copper and zinc industry, uses an electric current in an electrolytic bath in which the metal feed is dissolved. In the copper sector, this may occur following fire-refining by using anodes of copper that dissolve with the copper reforming on the cathode. Zinc concentrates from leaching also may be refined electrometallurgically. The leachate is placed in the electrolytic cell, a current is applied, and the metal is removed on the cathode. Within the cells, impurities will either dissolve in the electrolyte but not plate on the cathode or precipitate as a material referred to in the industry as “slimes”. Cathodes are removed and melted in a furnace and the metal cast into saleable shapes.

Digestion. Digestion is a hydrometallurgical process in which the concentrate is reacted with a strong liquor (typically hot acid) and the metal value is dissolved. This pregnant liquor is then processed to purify and precipitate the metal or mineral compound. Impurities may be left behind as digester solids or precipitated out separately from the mineral value. Primary examples of digestion operations are phosphoric acid production (i.e., in which phosphate concentrate is digested with sulfuric acid to produce phosphoric acid and calcium sulfate otherwise known as phosphogypsum) or production of titanium tetrachloride.

2. 5. 2 Types of Mineral Processing Wastes and Hazardous Materials

Each of the different types of mineral processing operations generate its own specific waste streams. Note that certain are large volume wastes, and where considered to be of low hazard, continue to be excluded from regulation as hazardous under EPA’s RCRA program. Many of the mineral processing wastes that are identified below are or were recycled back to the mineral processing facilities, since they generally contain high levels of metals. Others were disposed or dispersed at the mine site and are the focus of remedial concern at many abandoned or inactive mine sites.

Slag and Dross. Slag and dross are partially fused wastes produced when impurities in metallic ores or concentrates separate from the molten metal during smelting and fire-refining processes. Slag contains the gangue minerals, such as waste minerals and non-valuable minerals, and the flux. In some sectors, the slag is processed to recover some portion that may be of value. In these cases, the portion not recovered is disposed, typically onsite, or sold for use as fill or base material where regulations allow. Historically, several sites where slag was used as road bed material have significantly impacted local environments.

Dross is the collection of impurities, typically metal oxides, that float on the molten metal in the furnace. Often, it consists of materials that can be recovered for their mineral value. Dross often was either recycled or sent on for further processing. Both dross and slag also have historically been disposed in waste piles. Current regulation, however, calls for prescribed landfill disposal if not recycled.

Spent Furnace (Refractory) Brick. This material, as its name implies, is from the furnace or refractory liner and is generated in a relatively small quantity. Smelters within some mineral processing sectors return this material to the blast furnace to recover any accumulated mineral value; otherwise, this material is placed in disposal units. At some historical sites these brick remain, creating needs for remediation.

Potliner. Potliner is a specialized form of electrolytic cell liner used in the aluminum production process. Potliners may contain toxic levels of arsenic and selenium, as well as detectable levels of cadmium, chromium, barium, lead, mercury, silver, sulfates, and cyanide. While portions of the potliners currently are now recovered and recycled, much of the material is managed as a listed hazardous waste.

Roaster Fines. Fine particulate materials may be generated by roaster furnace operation. Currently, these materials are typically recycled to the mineral processing operation as permitted under RCRA. Historically, however, roaster fines, at least at some sites, went uncollected and were dispersed downwind; in other cases they were collected and disposed in waste piles. At least one Superfund National Priority List (NPL) site has identified roaster fine impacts on the mine site.

Stack Emissions. Emissions from the smelter and refiner furnaces are, under current regulations, treated to remove regulated materials, including particulates, lead, and sulfur dioxide. In some historic operations, these stack emissions were released unaltered, resulting in the dispersal of contaminants to a wide area, especially in the predominant downwind area. Lead contamination by smelter emission has created significant contamination at several of the NPL mine sites. Today, the dusts in these emissions are collected to meet air emission standards, and the resulting air pollution control dusts are managed appropriately.

Pollution Control Sludges. With the advent of wastewater treatment and air pollution control, sludges have been generated at most mineral processing operations. In the cases of smelter operations, these sludges are typically recycled to the smelter to recover mineral value. Where this is not feasible, the sludge is disposed onsite.

Slimes from Electrolytic Refining. Slimes result from impurities that settle out of the electrolytic bath used in electrolytic refining or electrowinning. Typically, these are recovered and treated to recover precious metals, such as gold and silver.

Spent Electrolyte. Spent electrolyte (often called bleed electrolyte when it is removed in small portions rather than at one time) typically is contaminated by a variety of metals and other compounds. Today, these electrolytes are typically purified and recycled.

Process Wastewater. Various process wastewaters are and have been generated during various pyrometallurgical operations. Historically, these have been co-managed with tailings if the smelter or refinery was co-located. In other cases, discharge to surface waters or surface impoundments was the preferred approach. Today, these wastes are managed under the Clean Water Act (i.e., under the NPDES program), RCRA (e. g, surface impoundment regulation and land application), or the Safe Drinking Water Act (e. g. , discharge into injection wells).

2. 6 *Additional Sources of Information*

For additional comprehensive references to mineral processing and associated wastes, see the following EPA documents:

USEPA, OSW. 12-95. Identification and Description of Mineral Processing Sectors and Waste Streams. WDC; and

USEPA, OSWER. 7-90. Report to Congress on Special Wastes from Mineral Processing. EPA 530-S W-90-070C. WDC.

USEPA, OSWER. 12-85. Report to Congress on Wastes from the Extraction and Beneficiation of Metallic Ores, Phosphate Rock, Asbestos, Overburden from Uranium Mining, and Oil Shale. EPA 530-SW-85-033.

USEPA, OW. 11-82. Development Document for Effluent Limitations Guidelines and Standards for the Ore Mining and Dressing Point Source Category, EPA 440/1-82/061.