Mining and its Environmental Impact: Lab and Analysis

Background Information

Metals are indispensable in our society. Copper, for example, is used for pipes, electrical wiring, and advanced electronic circuitry. Most metals are found in the rocks of Earth's crust combined with other elements. Ore is a rock that contains a large enough concentration of a mineral—often a metal—that it can be mined and processed to extract the mineral. Three basic steps are involved in modern mining: 1) extraction, which is the actually mining of the ore, 2) processing the ore to remove the valuable metal, and 3) purification/refining the metal.

Most modern industrial copper and gold mines are open pit mines; these are some of the largest mines in the world. One of the largest open-pit mines in the world is the Bingham Canyon Mine—located near Salt Lake City, Utah—it is the world's deepest man-made open pit excavation. The mine is 2.75 miles across and 0.75 miles deep. Open-pit mining is the most common type of mining. This method of extraction is used when a large ore body is relatively close to the surface but extends deep beneath the surface.

Using large excavation equipment such as hydraulic shovels and haul trucks, a large pit is dug into the Earth. Dirt, rock and ore are removed in a series of concentric circles, downward into the Earth; creating a series of giant steps called benches, usually in nine to thirty meter intervals. Haul roads are built forming ramps on which haul trucks transport ore and waste rock to the surface, where ore is processed and waste rock is dumped in waste rock piles.

After the metal is extracted from the Earth, it is processed and refined and the copper is brought to market. Metallurgy is the process whereby metal is extracted from its ore and prepared for practical use. A metallurgical process called smelting (pyrometallurgy) is used to process and refine high quality metal ore. *Smelting* involves heating the metal ore in a blast furnace to "release" the copper from the nonmetal components of the ore. Historically, copper ore had to be at least 2.5% copper by mass to yield profitable amounts of copper, by smelting. Anything below 2.5% would be considered low-grade ore and would be discarded in waste rock piles called tailings piles.

Advances in metallurgy have made it possible to remove profitable amounts of copper from lower grade ore. By the year 2000 industrial mining companies were able to profitably extract metal from ore that was 0.44% copper. On today's standards 2.5% copper is considered high-grade ore. The Asarco Mission Mine is an open-pit mine about 15 miles south of Tucson, Arizona. It is 2 miles long, 1.75 miles wide and a quarter mile deep. The copper ore extracted from the Mission Mine is 0.67% copper, which means that 13 pounds of copper are produced from every ton of ore.

Heap leach extraction is a hydrometallurgical process for extracting metals from lower-grade ore that would otherwise have been considered waste rock or tailings. In *heap leach extraction,* crushed ore and even tailings are heaped into a large pile in a lined or impermeable pond. A weak sulfuric acid solution is sprayed onto the pile of ore. Because the solubility of metals increases with a decrease in pH, the acidic solution dissolves metals from the rock as it percolates downward through the ore pile. As the crushed ore is irrigated with dilute sulfuric acid the copper (Cu^{2+}) is leached out of the ore to bond with sulfate ions (SO_4^{2-}), which yields a copper sulfate solution ($CuSO_4$). The copper sulfate collects in a liner at the bottom of the heap where it drains into a storage pond. This acidic blue, liquid is collected in tanks for refining.

In this lab you will use sulfuric acid to extract copper from copper carbonate, contained in copper ore; heap leach extraction on a very small scale. Azurite, $2CuCO_3 \cdot Cu(OH)_2$, is a form of copper ore and contains copper carbonate, $CuCO_3$. After you pulverize the copper ore, you will soak it in sulfuric acid solution, allowing it to leach copper from the azurite. The following reaction occurs:

$$CuCO_3\ (s) + H_2SO_4\ (aq) \rightarrow CuSO_4\ (aq) + H_2O\ (aq) + CO_2\ (g)$$

Several different refining techniques are used to capture the copper from the copper sulfate solution. Modern industrial metallurgy most often uses "electrowinning", where an electric current is passed through copper sulfate solution forcing the copper to plate an electrically charged flat surface called an anode. This creates copper sheets that are creates 99.9% pure copper. In this lab you will use a much easier method to capture the copper from the copper sulfate solution. One of the simplest methods is to add iron metal to the solution. The following reaction occurs:

$$CuSO_4\ (aq)\ _4 + Fe\ (s) \rightarrow FeSO_4\ (aq) + Cu\ (s)$$

This reaction occurs because the sulfate ion has a greater affinity for iron than copper. This change is observable because copper sulfate is blue while iron sulfate is colorless. Shiny copper plates the iron, while iron metal leaches into the solution. Eventually the copper builds up and the reaction stops or it may fall off the iron substrate allowing the reaction to continue. This is an example of a single replacement reaction.

Another indispensable metal in our society is gold. Gold is highly malleable and beautiful, making it excellent for jewelry. It is a good conductor of electricity and does not tarnish when exposed to air, making it an excellent material for printed circuit boards. Additionally, gold reflects various types of electromagnetic radiation, making it an outstanding reflective material for spacecraft. But most of all gold it is sought after in our civilization because, while it has been used as a base for currency, it is simply a symbol of wealth and power.

Gold is often found in the same sulfide ore deposits as copper. For this reason, many open-pit mines function as both copper and gold mines. As with copper, heap leaching can be used to extract gold from ore. However, because gold does not readily dissolve in acidic solutions, cyanide is used to leach gold from its ore.

In cyanide heap leaching, gold ore is heaped into a large pile. Cyanide solution is then sprayed on the top of the pile. As the crushed ore is irrigated with a dilute cyanide solution, the cyanide percolates downward through the ore. The gold (Au) leaches out of the ore as it bonds with cyanide (CN) and collects in a liner at the bottom of the heap where it drains into a storage pond. This gold-cyanide solution ($Au(CN)^-_2$) is known as a "pregnant solution". The following reaction occurs:

$$Au^+ (s) + 2\ CN^- (aq) \rightarrow Au(CN)^-_2 (aq)$$

One common way to recover the gold from the "pregnant solution" is to add zinc powder. This causes the precipitation of gold (Au) because zinc (Zn) reacts with cyanide to form Zinc Cyanide ($Zn(CN)^-_4$). The following reaction occurs:

$$2\ Au(CN)^-_2 (aq) + Zn (s) \rightarrow Zn(CN)^-_4 (aq) + 2\ Au (s)$$

The gold extracted may be less than 0.01% of the total ore processed. This means that for every ounce of gold recovered, 14 tons of ore is removed from the Earth. This leaves an enormous volume of waste to be dealt with. This waste is referred to as tailings, the leftover material from processing ore; it may be a finely ground solid or a liquid slurry. Tailings—for both copper and gold—are toxic waste that can generate acid mine drainage, contain toxic chemicals such as cyanide and heavy metals such as lead, zinc, arsenic, cadmium, and mercury. If not properly contained and treated these toxic wastes can enter surface and groundwater.

So far, the emphasis has been on metals mining. The next topic, acid mine drainage, is a serious pollution problem for both metals mining *and coal mining*. Acid mine drainage refers to the outflow of acidic water from a mining site. It negatively impacts stream and river ecosystems by decreasing the pH of the water and leaching toxic heavy metals out of soil and rocks.

Sulfide ore is a source for metals such as gold, copper, lead, silver, and zinc, but most importantly it contains *pyrite*. Coal too contains pyrite, in varying concentrations depending on quality. Pyrite is an iron sulfide, FeS_2, and is usually locked in rock within the Earth. However, once sulfide ore or coal is crushed, for mining and processing, the surface area available for chemical reactions greatly increases. This makes the ore or coal more "chemically available" for acid forming reactions. When exposed to the surface environment, air (oxygen) and water (H_2O) react with the Pyrite (FeS_2) to form iron hydroxide ($Fe(OH)_3$) and sulfuric acid (H_2SO_4). This occurs as rainwater or snowmelt flow through waste rock piles from metal or coal mining operations, this solution then flows into the surrounding environment as surface runoff. The following reaction occurs:

$$4\ FeS_2 + 15\ O_2 + 14\ H_2O \rightarrow 4\ Fe(OH)_3 + 8\ H_2SO_4$$

Remember from the lab that acids can leach metals from rocks because the solubility of metals increases as pH decreases. This is an important concept with respect to acid mine drainage. For example, as the acid mine drainage flows into the environment surrounding the mine it leaches metals from the rock and soil through which it flows, and these metals dissolve into the water. As metals readily dissolve into the water it becomes increasingly toxic, poisonous to macroinvertebrates and fish. Furthermore, these toxic heavy metals can bioaccumulate up through the food chain and contaminate drinking water supplies.

Some environments naturally reduce the impact of acid mine drainage. This is because they are composed of carbonate rocks like limestone ($CaCO_3$), which act as a buffer to neutralize acidic water. Other environments may not completely neutralize the acidic water but they will increase the pH and make the water less acidic. This however is not necessarily a good thing in the case of acid mine drainage, because this change in pH causes the toxic heavy metals to drop out of solution and sink to the bottom of the river or stream. In other words, when metal laden acid mine drainage becomes less acidic, the metals can no longer stay dissolved and they precipitate out of solution. One of the most distinctive examples is when previously soluble iron ions precipitate as iron hydroxide. This precipitate, known as "yellow boy" can turn streams a distinctive red/orange/yellow color and smother life in a stream bed. Additionally, bottom feeders consume the toxic heavy metals and they can bioaccumulate up through the food chain.

The presence of both toxic metals and sulfuric acid in streams and lakes is a severe environmental hazard to organisms that live there. In some regions where mining is prevalent, streams and rivers are considered dead, that is, all organisms in them have been destroyed by runoff in the form of acid mine drainage. By one estimate, 16,000 km of waterways in the Appalachian Mountains have been seriously polluted by runoff from coal mining activities.

The Iron Mountain Mine in California extracted a massive sulfide ore deposit containing: iron, silver, gold, copper, and zinc. It operated since the 1860's, closed in 1963, and was declared an EPA Superfund site in 1983. The mine is a source of extremely acidic water, pH –3.6; yes that is a negative. The acidic water leaches heavy metals such as cadmium (cadmium is toxic, significant amounts cause immediate poisoning and damage to the liver and the kidneys) from the rock and soil through which it flows. Consequently, the high levels of acidity and toxic heavy metals have effectively sterilized large portions of nearby creeks rendering them lifeless. Streams in the area experience periodic fish kills of migrating salmon, and this has been occurring since 1899. This level of water pollution necessitates expensive and perpetual water treatment to prevent contamination of nearby drinking water supplies.

To reduce acid mine drainage, modern mining operations are generally required to lay down an impervious barrier onto which waste rock and tailings will be piled. When the mine closes, the waste rock or tailings pile should be covered with an impervious layer, such as clay, that will reduce contact with precipitation and minimize surface runoff. Also, affected streams can be treated with alkaline/basic substance that buffer/neutralize the pH, substances such as calcium carbonate ($CaCO_3$), sodium hydroxide ($NaOH$), sodium bicarbonate ($NaHCO_3$), anhydrous ammonia (NH_3). This is often done by lining streams with such alkaline rocks, when they have buffered the water and become coated with "yellow boy" and other heavy metals they can be removed and replaced or simply just removed if the ecosystem has been restored.

The term hazardous waste has technically been defined by the U.S. Environmental Protection Agency to include any substance that is flammable, corrosive, reactive, or toxic. Mining waste, such as tailings, are toxic to plants, animals, and humans. For this reason, tailings must be stored, essentially forever, in tailings ponds or impoundments that are usually bound by a tailings dam, typically, an earth-fill embankment dam. Tailings impoundments can leak or fail altogether causing catastrophic and toxic floods.

As rain and snow accumulate around a closed mine site, surface water will eventually flow into the surrounding ecosystem. Mine wastewater, often referred to as *effluent,* is contaminated with heavy metals and has low pH (acidic). Therefore, mines must be prepared to treat the effluent before it flows into the surrounding environment. To this end, tailings are treated in *settling ponds* where the water is chemically treated with heavy bases (such as calcium carbonate, sodium hydroxide, etc.) to increase and buffer the pH (reduce the acidity). Additionally, bases and other chemicals are added to trigger the heavy metals to precipitate out of solution and sink to the bottom; hence the term settling ponds. Remember, a decrease in pH increases solubility of metals, so an increase in pH decreases the solubility of metals, meaning metals will precipitate out of solution and sink to the bottom. The surface water, in turn, becomes much cleaner than the water on the bottom and as allowed to flow out of the pond and into the surrounding watershed. In this way settling ponds are a method for treating and cleaning contaminated water.

Globally, there have been many partial or total tailings dam failures, resulting in environmental disasters. For example, on August 4th 2014, the tailings dam at the Mount Polley mine failed (a copper and gold mine in British Columbia, Canada), releasing its water and tailings slurry into Polley Lake. Another tailings dam—in Baia Mare, Romania—failed on January 3rd 2000 releasing cyanide-laced wastewater that was further contaminated with heavy metals. The spill discharged 100,000 m^3 of poisoned water into nearby drainage basins, eventually affecting 2,000 km of the Danube river watershed. The waste contained 50 to 100 tons of cyanide, as well as heavy metals, primarily arsenic, cadmium, copper, and lead.

In addition to these disasters, mines operating in developing countries—where environmental laws are under-enforced or nonexistent—have been charged with controversial waste disposal practices. For example, the Minahasa gold mine at Buyat Bay in north Sulawesi, Indonesia, allegedly poisoned fish, contaminated water with mercury and arsenic, and caused widespread medical problems. It was reported that, between 1996 and 2003, the mine operators purportedly ordered the daily discharge of 2,000 tons of toxic mine waste into Buyat Bay.

The Grasberg copper and gold mine in Papua New Guinea was observed to have polluted 90-square miles of wetlands by they dumping tailings and virtually burying aquatic ecosystems in mine waste, between 1997 and 2011. The Aikwa riverine system and Arafura Sea has been contaminated with levels of copper and sediment so high that almost all fish have reportedly disappeared. Nearly a third of the waste has flowed into the coastal estuary, an essential breeding ground for fish, and this is but a tidbit of information about Grasberg.

Operators of the Ok Tedi copper and gold mine, also in Papua New Guinea, successfully convinced government officials to allow them to operate without a tailings impoundment to catch and treat tailings; this, after a landslide destroyed the original tailings dam. As a result, the once-unspoiled Fly River has experienced declines in fish stocks confirmed to be between 50% and 80% lower compared to pre-mining levels. The upper stretches of the river have been described as "almost biologically dead" and species diversity in the lower stretches has been dramatically reduced.

While the United States has well-developed and better-enforced environmental regulations, it is not immune to mining's environmental impacts. Many of the copper and gold mines in the United States are in arid regions, this presents a unique set of environmental issues. Among these issues, water use and contamination are central. In an open pit-mine the ore body may extend well below the water table. To avoid flooding at the bottom of the pit, the water table must be lowered by constantly pumping out of the underground water table; a process called dewatering. This "drawdown" affects the amount of water available in underground aquifers.

Because of the dry nature of the western United States, much of the agricultural, domestic, municipal, and industrial water supplies come from groundwater that is pumped from aquifers. The water in these aquifers is recharged or replenished by annual seasonal rain and snowmelt that percolate into the groundwater and eventually into aquifers. If the drawdown, from dewatering exceeds the annual recharge, crucial water sources in this arid region can go dry.

When an open-pit mine closes and dewatering ceases the groundwater will flow into the pit creating a pit lake. The water in the pit lake will become acidic and contaminated with heavy metals. Eventually, if left untreated the contaminated water will flow back into groundwater and eventually into aquifers resulting in negative impacts on aquatic and human life. One such scenario is the Berkeley Pit in Butte, Montana, a retired gold mine. It is slowly filling with acidic water, laden with heavy metals; the water will need to be treated, essentially forever, to avoid contaminating groundwater resources.

Air pollution is another looming environmental impact that brought on by gold mining. This is because gold ores contain other metals, most notably mercury. Pure mercury is a liquid at room temperature, and is gasified easily during mining processes, sometimes reacting with other substances. Mercury is released into the air from gold mines as either mercury vapor or bounded by tiny suspended particles. Mercury is widely considered the most dangerous heavy metal because it is toxic to humans and moves freely through the environment. It is connected to various nervous system disorders and is known to impair brain development in fetuses and young children. One of the most dangerous forms of mercury, methyl mercury, can bioaccumulate in the food chain. In bodies of water downwind of gold mines in Nevada, Utah, and Idaho elevated levels of mercury have been detected, due to this, the states have posted fish consumption advisories.

Finally, in developing countries artisanal mining is common way to make a living. Artisanal mining is small-scale, subsistence mining. Artisanal miners are not officially employed by a mining company, but rather work independently, mining or panning for gold or other precious metals or minerals using their own resources. Many artisanal miners use the mercury amalgamation method. In this process, crushed gold ore is passed over surfaces coated with mercury, to which the gold binds, creating a mercury-gold amalgamation. The amalgamation is then heated, vaporizing the mercury and releasing the gold as a solid that is easily collected. This presents an obvious health risk, as the artisanal miners could easily breathe in the mercury vapor. Additionally, it is a significant source of air pollution in regions where artisanal mining is prolific.

Placer mining was widespread in the western United States during the historic gold rush of the mid-1800s. Placer mining is the process of looking for minerals, metals, and precious stones in river sediments. Miners use the water to separate heavier items, such as diamonds, tantalum, and gold, from lighter items, such as sand and mud. Once miners obtained gold ore they often used the mercury amalgamation method separate the gold from the ore. As a result, some areas of California and Nevada have been impacted by this legacy pollution; i.e. pollution that has lasting effects even though the destructive process ceased long ago. For example, in the Carson River Valley of Nevada, much of the sediment is presently contaminated with mercury due to historic gold mining.