University of Arizona
Superfund Research Program
Community Engagement Core

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TRIBAL MINING EDUCATIONAL MODULES

COPPER MINING AND PROCESSING

Tribal Mining Educational Modules

Instructor's Guide

Statement by the Authors

Suggested citation:

Stanley, J., Wilkinson, S.T., Moreno Ramírez, D., Maier R.M., & Chief, K. (2015). Tribal Mining Educational Modules: Copper Mining and Processing [PDF document]. Retrieved from http://www.superfund.pharmacy.arizona.edu/learning-modules/tribal-modules

Copper Mining and Processing

Module Summary

Copper is a chemical element that has a variety of uses based on its properties of malleability and conductivity. Copper ore deposits are found on every continent, and it has been mined around the world for more than 10,000 years. It is a necessary component for many products in the modern world. The steps involved in opening a mine and processing copper ore into a final product are very complex. This module will cover basic information about copper, copper mining in Arizona and on tribal lands, the life cycle of a mine, and the specifics of copper processing.

Learning Objectives

A. Describe basic information about copper, its occurrence, and its use
B. Articulate the history and current status of copper mining in Arizona and tribal lands
C. Detail the stages in the life cycle of a mine
D. Describe copper processing for oxide and sulfide ores

Background

I. Copper, its occurrence, and use

A. What is copper?

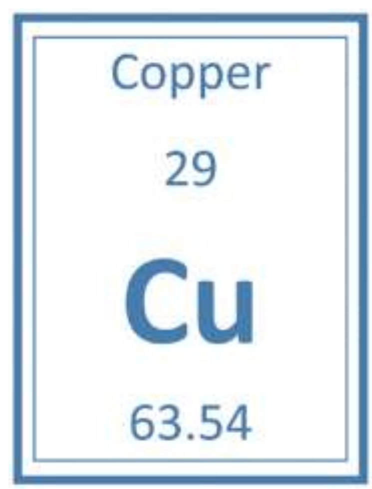

Figure 1: Copper element information.

Copper is a chemical **element** in the periodic table with the symbol Cu (from the Latin word *cuprum*, meaning 'metal of Cyprus,' where it was mined during the Roman era) (Figure 1). Copper has an atomic number of 29 and atomic weight of 63.54 grams per mole. It is an element in Group 11 of the periodic table, sharing many properties with silver and gold. In its standard state at room temperature, copper is solid. Copper is reddish-orange and has a bright metallic luster. With weathering, copper can become coated in a dull-green tarnish of copper carbonate called **verdigris**. One famous example of this is the Statue of Liberty, which is coated with 60,000 pounds of copper sheeting that has weathered to verdigris. Copper is also an essential micronutrient, meaning it is an essential dietary element in very tiny concentrations for plants and animals, including humans.

In its pure form, copper is relatively soft, and is malleable and ductile, meaning that it can be shaped or molded without breaking; for example, hammered flat into sheets or drawn out into wires. Copper is resistant to corrosion, and is a good conductor of heat and electricity (second only to silver). Because it is an element, copper can be perpetually recycled, without losing its properties. These properties can be adapted for specific uses based on whether it is used alone or alloyed (mixed with other elements). The most common copper **alloys** are **bronze** (copper and tin) and **brass** (copper and zinc), which are harder and stronger than copper.

B. Naturally Occurring Forms of Copper

Figure 2: The different forms of copper. A) Native copper; B) Azurite; C) Cuprite; D) Chalcopyrite; E) Chalcocite; and F) Malachite. Photo Credit: Arizona Geological Survey.

Copper deposits were formed by the action of hot waters, commonly associated with volcanism but also with sediments, and can be found around the world on every continent. Copper can be found in the earth's crust as pure **native copper**, but mostly occurs in combination with other elements (Figure 2). Native copper is typically found as irregular masses or veins, which fill fractures and other spaces in the earth's crust. When found in combination with other elements, copper can occur in **minerals** including copper sulfides (e.g., chalcopyrite and chalcocite), copper oxides (e.g., cuprite), copper carbonates (e.g., azurite and malachite), copper phosphates (turquoise), and additional mixed copper **ores**. Such ores can be quite complex, containing a variety of other non-metallic minerals, as well as metals and other elements (which for the purpose of copper extraction are considered wastes). Within an ore, copper concentration is commonly less than 1%. Each of the different natural forms of copper requires distinct mining and processing steps that eventually lead to 9.99% pure copper.

C. Historical and Modern Copper Use

The development of copper has a rich history. Copper has been used for thousands of years; it may have been discovered as early as 9000 BC in the Middle East. Early artifacts discovered were made of native copper and included utensils, tools, weapons, piping, ornaments, and jewelry. The largest deposit of native copper discovered to date was found in Michigan at the Keweenaw mines (Wood, 2001). Native Americans mined copper in this area between 5000 and 1200 BC, as evidenced by copper knives, arrows, spearheads, and axes. These types of artifacts have also been found throughout North and South America.

Copper **smelting**, or the use of heat and chemical reactions to extract the metal from an ore, appears to have been discovered independently in different parts of the world. A rise in the use of smelted copper defines the Chalcolithic period (from the Greek words *khalkos* and *lithos*, meaning 'copper' and 'stone,' respectively), which occurred between the end of the Stone Age and the advent of the Bronze Age (approximately 3500-2500 BC). Smelting of ores containing both copper and tin likely led to the discovery of the alloy bronze, which is easier to cast, and allowed a greater variety of materials to be made, including figurines and vessels. The addition of zinc vapor via calamine ore allowed the production of brass (often for decorative purposes), which became popular in the Roman

World during the first millennium BC. Copper's use as currency also came into prominence in the Roman World in 280 BC as brass coins and in 23 BC as copper coins.

Today, copper and its alloys have a variety of uses that impact our daily lives. To give some examples, the average U.S.-built automobile contains 50 pounds of copper, and the average U.S.-built home contains 400 pounds of copper. As seen in Table 1, the five major uses of copper are: 1) building construction, 2) electrical and electronics, 3) general consumer products, 4) industrial machinery and equipment, and 5) transportation equipment. In addition, copper is antimicrobial, and may be used in personal products such as socks, as well as handles used in hospitals, and tables used in kitchen restaurants.

Table 1: Copper consumption by major U.S. markets in 2013. Source: Copper Development Association Inc. Annual Data (2014).

Type of Market	Copper Consumption [million lbs.]	Examples
Construction	2,233	Wiring, heating/refrigeration, and plumbing
Electrical and Electronics	978	Power utilities, cell phones, computers, lighting, and anything with an on/off switch
Consumer and General Products	627	Currency, cookware, household appliances, coins, etc.
Transportation Equipment	982	Airplanes, cars, trucks, trains, etc.
Industrial Equipment	378	Manufacturing machinery, on-site equipment, off-highway vehicles, and transmission lines

Copper alloys are also used to make important and common instruments and tools. For example, bronze (copper and tin) is used to make durable tools (e.g., hammers), musical instruments (e.g., cymbals), ornaments, medals, statues, and bearings of various machines. In addition, brass (copper and zinc) is used to make musical instruments (e.g., horns) and decorative art (e.g., sculptures), and low friction (e.g., locks) and non-sparking tools (e.g., for use around explosive gases).

Worldwide consumption of copper has increased greatly over the past century as the world has developed. Currently, Asia is the leading world consumer of copper while Europe and the Americas take second and third place respectively (IWCC, 2013). Worldwide, Chile is the largest producer of copper (5.7 million tons per year), followed by China (1.7 million tons), Peru (1.3 million tons), the United States (1.2 million tons), and Australia (1 million tons) (USGS, 2014). In the United States, approximately 99% of the $9 billion dollars' worth of copper produced annually comes from five states: Arizona, Utah, New Mexico, Nevada, and Montana (USGS, 2014). Building and construction markets typically utilize a large portion of the copper around the world. Yet, individually we also contribute to the active mining of copper due to our use of consumer products. A person born today is expected to use nearly ¾ of a ton of copper in his/her lifetime (Harmon et. al., 2013). Some of this copper is newly mined, and some is from recycling of copper used before by others.

II. Copper Mining in Arizona

Figure 3: Great Seal of the State of Arizona.

The legacy of mining is etched into the landscape and history of Arizona. It is part of the culture, economy, and environment. Indeed, copper is showcased as one of the "Five Cs" upon which the Arizona economy was founded. These five industries – cattle, cotton, citrus, climate, and copper – are represented on the Great Seal of the State of Arizona (Figure 3).

Arizona produces approximately 65% of the country's copper (AZGS, 2014). In 2011, copper mining contributed $4.6 billion in direct and indirect economic benefits to the state, generating 49,800 jobs (AZ Mining Assoc., 2011). Arizona is home to the Morenci Mine, owned by Freeport-McMoRan, which is one of the largest copper mines in the world (Freeport-McMoRan, 2014).

As seen in Figure 4, there are 27 major mines in Arizona, including 10 major copper mines which produce 23 to 632 million pounds of copper per year. Of interest, only two of the 10 major copper mines are located north of Phoenix; the rest are located in the southeastern part of the state. In addition, there are two proposed major mines, which are waiting for special permitting to be approved to begin production: Rosemont Copper Mine near Tucson, AZ (on lands sacred to the Tohono O'odham and Pascua Yaqui Tribes) and Resolution Copper Mine near Superior, AZ (on lands sacred to the San Carlos Apache and related Tribes).

A. Environmental Regulation of Copper Mining in Arizona

The main environmental protection agencies which govern a mine's potential to contaminate the local environment include the Arizona Department of Environmental Quality (ADEQ) and the United States Environmental Protection Agency (US EPA). These two agencies, as well as county or other local agencies, ensure that operating mines, as well as mines which have been closed, do not release contaminated or hazardous materials outside of the mine site. Hazardous materials have the potential to leave a mine site through wind, which can carry dust; rain, which can flow in washes and streams; and in the groundwater, which can contaminate the local drinking water. If hazardous materials or contaminated water were to leave a mine site, mine owners could face very large fines on a daily basis, be rejected for future permits, and even face time in jail. Mines on reservations must meet environmental quality standards set out by the respective reservations. For instance, the Navajo Nation Environmental Protection Agency (NNEPA) has well-defined water and air quality standards, which the mines must comply with. Many of the laws in NNEPA are modeled after the US EPA; companies working in such areas often follow the governing body with the

Figure 4: Arizona Major Mines in 2014 (adapted from Arizona Geological Survey Map 38 by Nyal Niemuth).

strictest policies to ensure adequate environmental compliance. If there is no formal tribal environmental protection agency, the mines will be governed by the US EPA. Typically, mining companies will have environmental engineers on staff at the site or use environmental consulting firms to interact with the regulatory agencies.

III. Copper Mining on Tribal Lands in Arizona

Twenty-one federally-recognized tribes own lands that cover 19.7 million of Arizona's 72.9 million acres, or 27% of the state (Figure 5). Currently, there is only one active copper mine on designated tribal lands in Arizona, the Mission Mine (see Case Study #1). The Mission Mine is operating on both privately owned land as well as lands owned by the Tohono O'odham Reservation and pays royalties on the copper extracted there. In addition, the Cyprus Tohono Mine (see case study #2) may resume operations.

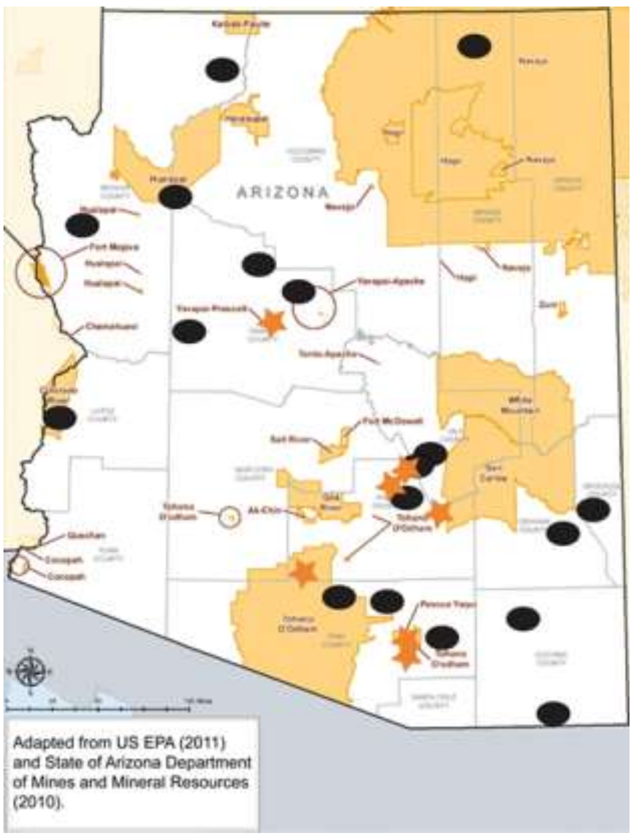

Figure 5: Major mines (black ovals), major mines on tribal land (orange stars), and tribal reservations (light orange areas) in Arizona.

A. Tohono O'odham Nation

The Tohono O'odham tribe owns 2.7 million acres, or 3.7% of the state. Metallic minerals mined on or near the Tohono O'odham reservation throughout history include copper, gold, silver, lead, zinc, iron, mercury, manganese, uranium, and tungsten. There are approximately 210 metallic mineral deposits, prospects, and quarries within the Pima County portion of the Tohono O'odham Nation. However, many of the smaller mines are the results of small-time prospectors and have since been abandoned. The two most prominent mines include the Mission Mine and the Cyprus Tohono Mine.

Case Study #1 - Mission Mine (ASARCO):

The Mission Mine is situated on 19,000 acres (29.7 square miles) of land in Sahuarita, AZ, 18 miles south of Tucson. The mining complex is comprised of the Mission, Eisenhower, Pima, Mineral Hill and South San Xavier properties and the nearby North San Xavier mine (ASARCO, 2014). While most of the mining property is owned by ASARCO, a portion of the mine complex is located on the south end of the Tohono O'odham San Xavier District and is leased to ASARCO by the Tohono O'odham Nation. The open-pit copper mine is approximately 2.5 miles long, 1.5 miles wide, and 1,200 feet deep, with 40-foot-highbenches (narrow, step-like strips cut into the side of the open pit). Early copper mining began at the site in 1900, with open pit stripping beginning in 1959. In 2012, the mine produced 134 million pounds of copper concentrate, paid $6.6 million in state royalties and $2.5 million in tribal royalties, and employed 620 people. The mine is expected to produce until 2033.

A reclamation plan for the Tohono O'odham portion of the Mission Complex details how different sections of the mine will be reclaimed both during and after active mining. For waste rock dumps and mine tailings, reclamation will include soil capping and rainwater capture to support revegetation with native plants (Gault Group, 2008). The Tohono O'odham Nation is also working with US EPA to develop renewable energy (solar panels) on a portion of the mine tailings.

Since the mine is on both private and tribal lands, ASARCO is required to file for permits with the US EPA, ADEQ, and the Pima County Dept. of Environmental Quality (PDEQ). As discharges from the mine enter unnamed tributaries and ephemeral washes of the Santa Cruz River, one of the permits is for the discharge of mine drainage and stormwater. ASARCO has been issued several notices of violation for discharges containing copper, lead, and other metals. They continue to work with the regulatory agencies to achieve compliance through construction and maintenance activities to limit additional discharges. Another permit is related to dust emissions from the mine tailings. Violations of air quality rules in 2009 and 2013 led to assessments of fines and ASARCO has taken measures to control the tailings dust and limit additional violations.

For more information about this site:

US EPA ASARCO Mission Complex Fact Sheet: http://tinyurl.com/qbacbss

US EPA Renewable Energy Development Opportunities ASARCO Mission Mine Tailings Area: http://www.epa.gov/aml/revital/asarco-solar.pdf

ADEQ Draft Fact Sheet, Pollutant Discharge Elimination System permit for ASARCO Mission Complex: https://azdeq.gov/calendar/AZ0024597fs.pdf

PDEQ ASARCO Mission Complex Mine Tailings Dust webpage: http://tinyurl.com/nrea5ye

Photo Credit: 2011-03-2897, ADMMR Photo Archive, Arizona Geological Survey.

Case Study #2 - Cyprus Tohono Mine (Cyprus Tohono Corporation, a subsidiary of Freeport-McMoRan Copper & Gold, Inc.)

The Cyprus Tohono Mine is located 32 miles south of Casa Grande, AZ, near the town of North Komelik in the Sif Oidak District. It is situated on 4,180 acres of land leased from the Bureau of Indian Affairs and the Tohono O'odham Nation. The copper mine and processing facility, formerly known as Casa Grande Mine and Lakeshore Mine, has been operated by several different companies since the 1880s. Open pit mining began in 1959 and underground mining began in 1970. Both oxide and sulfide ores were mined and processed. Open pit mining ended in 1997, and in 1999 the facility transitioned into care and maintenance mode. The Cyprus Tohono Corporation is currently considering resuming operations.

In 2009, the site was listed as a **Superfund Alternative Site** because of a groundwater plume contaminated with uranium, sulfate, and perchlorate extending one-half mile from the site. The US EPA has been investigating the site and considering options for clean-up. In response to a request from the US EPA and the Tohono O'odham Nation, the Agency for Toxic Substances and Disease Registry has completed a Health Consultation regarding human exposures and possible health impacts (ATSDR, 2014 and ATSDR, 2014).

For more information about this site:

US EPA Site Overview:
http://tinyurl.com/m5g4bl7

Photo Credit: 2011-03-6237, ADMMR Photo Archive, Arizona Geological Survey.

B. Tribal Concerns with Mining

Throughout history, tribes have faced displacement, discrimination, and marginalization due to mining on their lands (Ballard, 2003). The copper mining industry is an important source of wealth and employment in Arizona (AZ Mining Assoc., 2011). Yet, without proper planning and environmental monitoring, mining can also be a source of contamination that impacts the health of neighboring communities and the environment (US EPA, 2011). Environmental health is an important concern for communities living near mine sites, including tribes. Many times these communities are exposed to poor air quality, contaminated water, and occupational hazards (Azapagic, 2004). In general, the occupational health and safety risks are above average for the mining industries. Such risks can include chronic occupational diseases which can be a result of direct exposure to dust during metal/mineral extraction (Azapagic, 2004). These risks can be greatly reduced with the proper use of Personal Protective Equipment (PPE) which, under law, must be worn by those with a risk of exposure (Merrifield, 2013). The enforcement of such laws, and other mine safety issues, is regulated by the Mine Safety and Health Administration (MSHA), a division of the US Department of Labor.

The impacts of mining on sacred lands and artifacts are also of concern for tribal communities. Although U.S. laws for the most part protect sacred lands on and off tribal reservations, there are still potential risks for loss. For example, traditional livelihoods may be limited due to lack of access to land and/or destruction of important resources (e.g., mountains, vegetation, wildlife). Tribal communities often rely on natural resources found on sacred lands for cultural, medicinal, and spiritual purposes. For example, on the Navajo Nation in northeastern Arizona and southeastern Utah, Navajo people living in and near uranium mining areas used mill tailings, a sandy waste containing heavy metals and radium, which is radioactive, to build their traditional earthen homes (hogan), many of which remain in use today (DOE, 2013). Another example is the nearly 100 sacred and cultural sites of the Tohono O'odham Nation, which may be impacted by the proposed development of the Rosemont Copper Mine in southern Arizona (Tohono O'odham, 2009). A final example is the Oak Flat area east of Superior, AZ, lands sacred to the San Carlos Apache tribe, where Resolution Copper is proposing to mine (Allen, 2015). Innovative mining companies implementing responsible mining have recognized the need for more respectful relationships with tribal nations to ensure that when mining is undertaken, the rights and interests of the People are considered. For more details on U.S. laws protecting sacred lands, refer to the "Mining-Induced Sociocultural Impacts" module.

IV. Life Cycle of a Mine

The stages in the life cycle of a mine are: 1) Prospecting and exploration, 2) Development; 3) Extraction, and 4) Closure/Reclamation (Figure 6). Each of the stages may overlap with the next and is very lengthy and expensive.

A. Prospecting and Exploration
("Finding and Defining it")

Prospecting and exploration are precursors to mining and often occur simultaneously; together, they can take two to eight years to complete, and may cost from $500,000 to $15 million overall.

Prospecting is the process of searching the region for mineral deposits. Historically, prospectors would explore a region on foot with a pick and shovel. Modern prospecting uses a variety of geological methods. **Geology** experts use a direct method to discover surface mineral deposits by examining the area visually. **Geophysics** experts use an indirect method to identify underground mineral deposits by

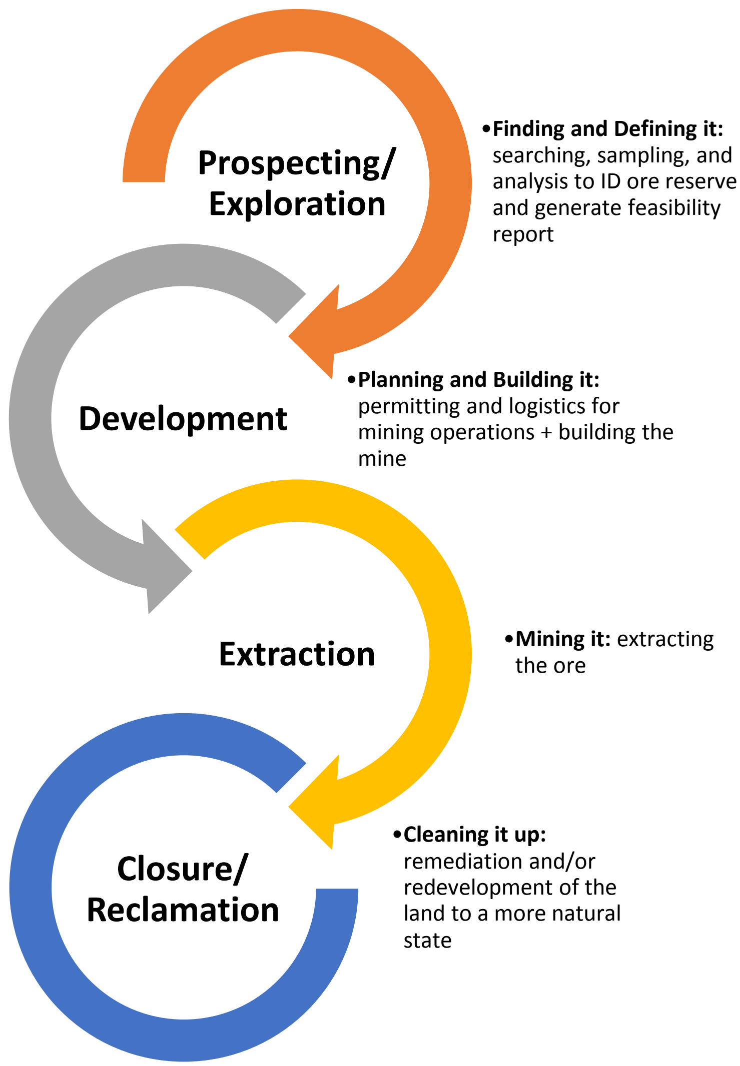

Figure 6: The Life Cycle of a Mine.

detecting rock alterations under the surface. **Geochemistry** can also be used to analyze samples of soil, rock, and water. These methods are supplemented by aerial or satellite photography, and combined with historical maps and literature to develop detailed maps of surface and underground rock formations. Drilling is used to search for mineral occurrences or the clues in the rocks that may lead to them. Information gathered in this stage may or may not lead to a discovery of valuable minerals.

In mining **exploration**, experts use additional techniques to determine the possible size and value of the mineral deposit discovered during prospecting. Depending on the ownership of the land, a Mineral Rights Lease, a contractual arrangement that allows the holder to explore/exploit an area that contains minerals, may be required. Samples that are collected by drilling undergo various analyses by geologists and **metallurgists** to determine the richness and extent of the mineral, both vertically and horizontally. Such analyses of geological confidence and technical and economic evaluation allow experts to label the deposit as a "mineral resource" and/or an "ore reserve," to better establish the economic value of the deposit and to estimate mining costs (Figure 7) (JORC, 2012).

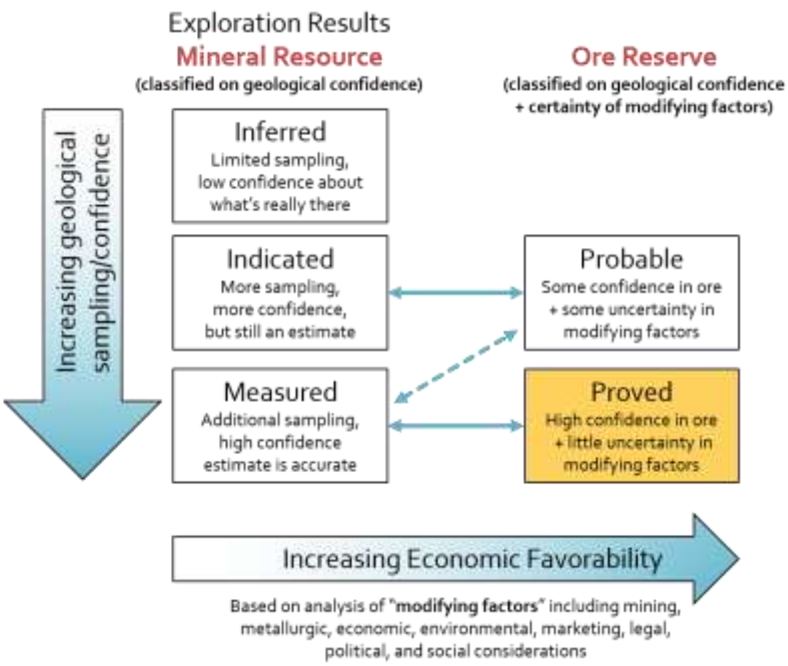

Figure 7: General relationship between Mineral Resources and Ore Reserves. Adapted from: Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC, 2012).

A **mineral resource** is a concentration of potentially valuable material that naturally occurs in the earth that can potentially be mined for economic profit. Whether it is worth extracting now or later may depend on the amount, form, location, and quality of the material, a concept called geological confidence. Experts use geological sampling and testing methods to classify a mineral resource into three different categories according to geological confidence. When the amount and quality of the mineral can be estimated with only a low level of confidence based on limited sampling, it is called an "inferred" mineral resource. Such a resource will likely not be mined at this time, but may be mined one day in the future, either because all other reserves have been exploited or because improvements in technology make it easier to extract less concentrated ores. Additional sampling may allow the amount, quality, density, shape, and physical characteristics of the mineral to be estimated with a reasonable level of confidence, and it is classified as an "indicated" mineral resource. If further sampling and reliable and detailed exploration allow the amount, quality, density, shape, and physical characteristics of the mineral to be accurately estimated with a high level of confidence, it is classified as a "measured" mineral resource.

An **ore reserve** is the part of the mineral resource that can be economically profitable to mine (i.e., there is enough valuable metal to be worth removing it and extracting it from all of the surrounding rock). After a deposit has been identified as an inferred, indicated, or measured mineral resource, it is next labeled as a "probable" or "proved" ore reserve. This classification is based on what is known about the mineral resource through sampling, combined with consideration of "modifying factors," such as mining, metallurgic, economic, environmental, marketing, legal, political, and social factors. With some information available about the concentration of the ore (i.e., indicated mineral resource), and some uncertainty in the modifying factors, the deposit can be labelled a probable ore reserve. A mine developed from a probable ore reserve has a chance of success, but is still financially risky. A measured mineral resource may also be labelled as only a possible ore reserve, if there is uncertainty in the consideration of the modifying factors; if these uncertainties can be removed, it may later be labelled a proved ore reserve. When the concentration of ore has been accurately and confidently measured to be high (i.e. measured mineral resource), and there is limited uncertainty about the modifying factors, it is classified as a proved ore reserve. This is the highest confidence category of reserve estimate, implying high geological, technical, and economic confidence that it can be mined at a profit.

Following the completion of the prospecting and exploration stages, a feasibility study is performed to formally determine whether it is economically worth developing the mineral deposit into a mine. A feasibility report is generated, in which factors such as production rate, operating costs, income tax, and the sale price of the mineral are estimated as well as put into a formula to calculate what the final rate of return will be. The mining organization can then make a decision about whether the project will be abandoned or continued at this stage.

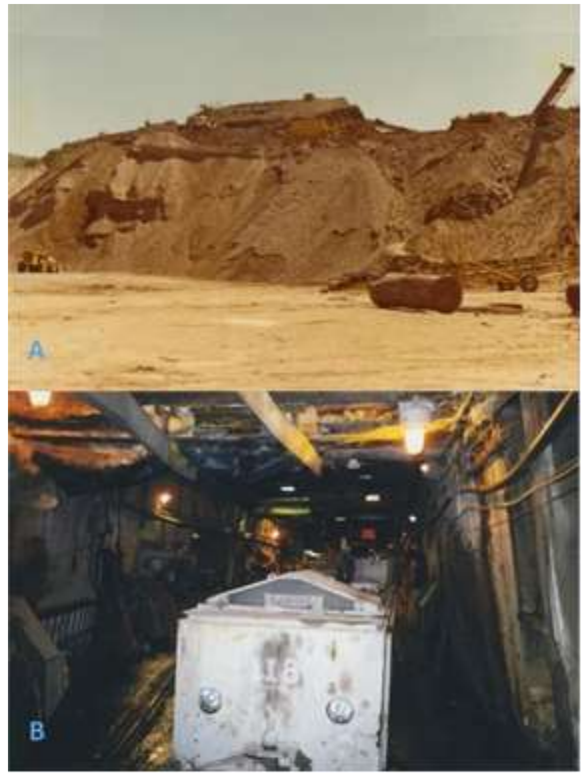

Figure 8: Surface and underground mining in Arizona. A) Floor and side of the pit at the Copper Hill surface mine. B) Mine train in the underground mine at San Manuel. (Photo credits: 2011-03-1647/2011-03-4003, ADMMR Photo Archive, Arizona Geological Survey).

B. Development ("Planning and building it")

The **development** stage usually takes 4-12 years to open an ore deposit for production, and may cost anywhere from $1 million to over $1 billion to complete depending on the type of mine. Development involves extensive pre-development planning and paperwork. Budget and financial reports are prepared and permits are requested. Reports regarding potential impacts on the environment and nearby communities are generated. Plans are assessed regarding the: 1) the mining process/technology that will be used, 2) building of access roads for transportation, 3) identification of resources such as power and water sources, and 4) construction of ore processing facilities and disposal areas for waste. At this point, tens of millions to hundreds of millions of dollars may have been invested in the project, but it may fail to open if the pre-development requirements are not met, including acceptance by the community. At this stage, just enough development of the mine site is performed to ensure that it will be able to be productive for the life of the mine, without later interruption.

Plans are made for the appropriate type of mining that will be performed. There are three major types of mining, surface mining, underground mining, and solution mining; their use depends on the type of ore and where it is located, as well as issues of safety, technology, economics, and environmental impacts (Figure 8). Surface mining, which includes strip mining, open-pit mining, and mountaintop removal, removes soil and rock from on top of the mineral deposit. It may begin as soon as the pre-development steps are complete. Underground mining uses shafts and tunnels to access deeply-buried mineral deposits, while the overlying rock is left in place. This type of mining is usually more expensive and complex, and requires a lot of additional planning for convenience and safety. Solution mining, sometimes referred to as in situ leaching, is performed by pumping a leaching solution such as an acid into the ground, where the solution then dissolves the solid minerals into a liquid. This liquid containing the minerals is then pumped out of the ground and the mineral can then be recovered by various techniques.

C. Extraction ("Mining it")

In the **extraction** stage the mineral is removed from the earth in large quantities as the mine begins producing. This stage is typically what we envision when we think of mining. Some exploration and development may continue at this stage, as well. The extraction stage can take from 5-30 years to complete, although many mines have been open for more than 100 years, and may cost anywhere from a few million dollars to hundreds of millions of dollars a year depending on the size of the mine and its location.

D. Closure/Reclamation ("Cleaning it up")

The mining organization begins planning for mine **closure** and **reclamation** early on; even before a mine is allowed to open, a reclamation plan must be set in place for its closure. In these reclamation plans the mining operator describes the processes it will use to attempt to restore or redevelop the land that has been mined to a more natural or economically usable state. This can include removing buildings and roads as well as covering up and re-vegetating rock piles. Federal and state regulations require mining companies to post funding for closure before the mining project begins. This is to ensure that reclamation is completed at the end of the mining closure (Arms, 2004). Once the mine has been depleted or is no longer economically feasible to continue mining, the mining operators must contact local and state agencies to close the mine, and must comply with their respective regulations.

The closure plan must be approved by a variety of mining stakeholders, including government and community members. Considerations when planning for closure include: protecting public health and safety, addressing environmental damage, returning the land to its original state or an acceptable new use, and sustaining social and economic benefits brought by the mine. The succeeding custodian, the party responsible for the land after the mine closes, should establish an agreement with the mining company early in the life cycle of the mine, to develop a closure plan that minimizes risks and liabilities.

The cost of closing a mine depends on the age, location, type, and size of mine, amount of waste, geological characteristics, and type of mineral being extracted. For example, a medium-sized open-pit mine that is 10-15 years old could cost a few million dollars to close, while a large open-pit mine that has been operating for more than 35 years could cost tens of millions of dollars to close (Tetra Tech, 2007). It is often less expensive for a mining company operating the mine to close a mine themselves than for the succeeding custodian to close it. For more detail on reclamation, refer to the "Mine Tailings and Waste Rock Reclamation" module.

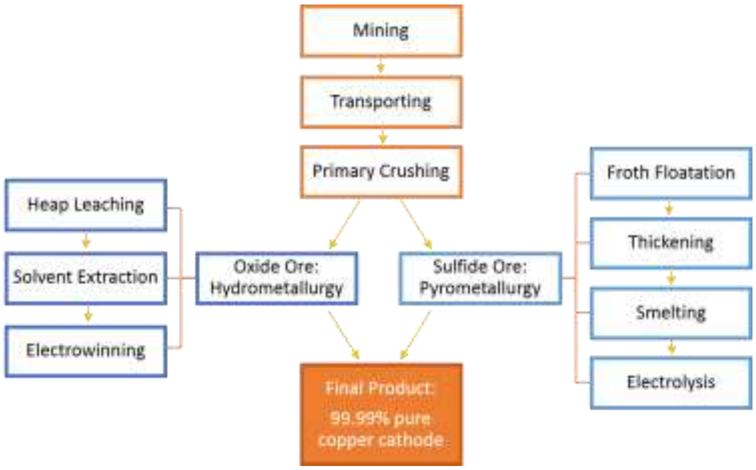

Figure 9: Oxide and sulfide ores undergo different processes to be purified into 99.99% pure copper.

V. Processing of Copper Ores

Copper processing is a complicated process that begins with mining of the ore (less than 1% copper) and ends with sheets of 99.99% pure copper called **cathodes**, which will ultimately be made into products for everyday use. The most common types of ore, **copper oxide** and **copper sulfide**, undergo two different processes, hydrometallurgy and pyrometallurgy, respectively, due to the different chemistries of the ore (Figure 9). Copper oxides are more abundant near the surface, but are considered low-grade ore, with a lower concentration of copper. Although this requires more ore to be extracted and processed, this process is less expensive, so oxides can still be mined at a profit. On the other hand, while copper sulfide ores are less abundant, they contain higher amounts of copper. Although the processing costs are higher, ultimately more copper can be extracted. Since each mine site is unique in its mineral composition, concentration, and quantities, the most economical and profitable processing of ore must be determined by the mine planners. When it is economically feasible, a mine may extract both types of copper minerals; when it is not possible, mines will only process either the copper oxides or the copper sulfides.

The first steps of copper processing are the same for both ores: mining and transporting. Copper mining is usually performed using **open-pit mining** (Figure 10), in which a series of stepped benches are dug deeper and deeper into the earth over time. To remove the ore, boring machinery is used to drill holes into the hard rock, and explosives are inserted into the drill holes to blast and break the rock. The resulting boulders are then ready for hauling; specialized haul trucks, conveyors, trains, and shuttle cars can all be used to haul the ore from the blasting site to the processing site. The size of the equipment needed to haul the tons and tons of ore is gigantic (Figure 10). Most ores are then sent through a primary crusher, which is typically located very close to or sometimes in the pit. This primary crusher reduces the size of the ore from boulder to golf ball-sized rocks.

Figure 10: A) A view of the open-pit mine in Morenci. B) A man standing next to a 170-ton haul truck at Mission mine. (Photo Credit: 2011-03-3018/2011-03-2270, ADMMR Photo Archive, Arizona Geological Survey).

A. Processing of Oxide Ore

Oxide ores are generally processed using **hydrometallurgy**. This process uses aqueous (water-based) solutions to extract and purify copper from copper oxide ores at ordinary temperatures, usually in three steps: heap leaching, solvent extraction, and electrowinning.

Heap Leaching is the process of using percolating chemical solutions to leach out metals (Figure 11). Heap leaching is very commonly used for low-grade ore, which would otherwise not be economical to send through a milling process. Following mining, transporting, and crushing to a consistent gravel or golf ball-size, the crushed ore is piled into a heap on top of an impenetrable layer, on a slight slope. The leaching reagent (dilute sulfuric acid) is sprayed through sprinklers on top of the heap pile and allowed to trickle down through the heap, where it dissolves the copper from the ore. The resulting "pregnant" leach solution of sulfuric acid and copper sulfate is collected in a small pool. The copper compound can now be seen at concentrations of between 60-70%.

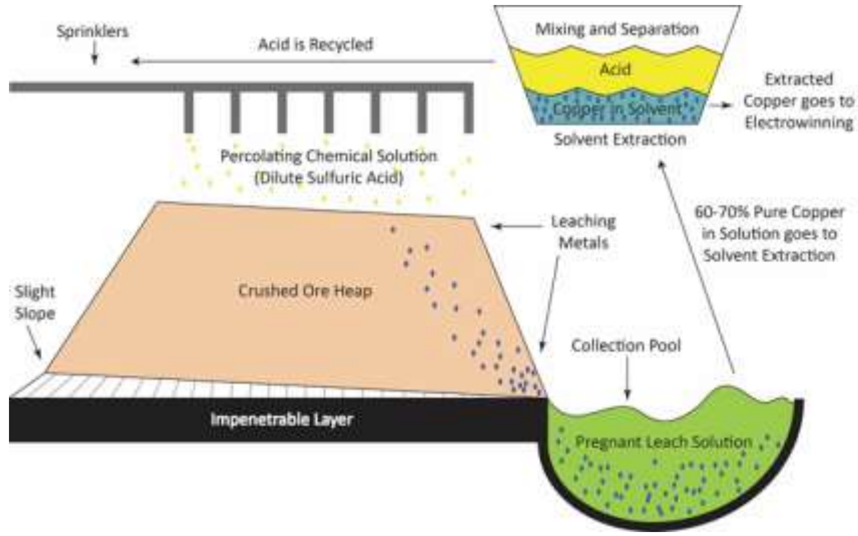

Figure 11: Heap Leaching and Solvent Extraction of Oxide Ore.

The second step is **solvent extraction**, in which two immiscible (un-mixing) liquids are stirred and allowed to separate, causing the cooper to move from one liquid to the other (Figure 11). The pregnant leach solution is mixed vigorously with a solvent. The copper migrates from the leach solution into the solvent. The two liquids are then allowed to separate based on solubility, with copper remaining in solution in the solvent, and impurities remaining in the leach solution. The leftover leach solution is then recycled, by adding additional acid and sending it back to the sprinklers in the heap leaching process.

The last step is called **electrowinning**, a type of electrolysis. An electrical current passes through an inert **anode** (positive electrode) and through the copper solution from the previous step, which acts as an **electrolyte**. Positively-charged copper ions (called cations) come out of solution and are plated onto a **cathode** (negative electrode) as 99.99% pure copper (Figure 12).

B. Processing of Sulfide Ore

Sulfide ores are generally processed using **pyrometallurgy**, the extraction and purification of metals by processes involving the application of heat. This process uses a series of physical steps and high temperatures to extract and purify copper from copper sulfide ores, in four basic steps: 1) froth flotation, 2) thickening, 3) smelting, and 4) electrolysis.

Following mining, transporting, and crushing to a consistent gravel or golf ball-size, the crushed ore is further processed

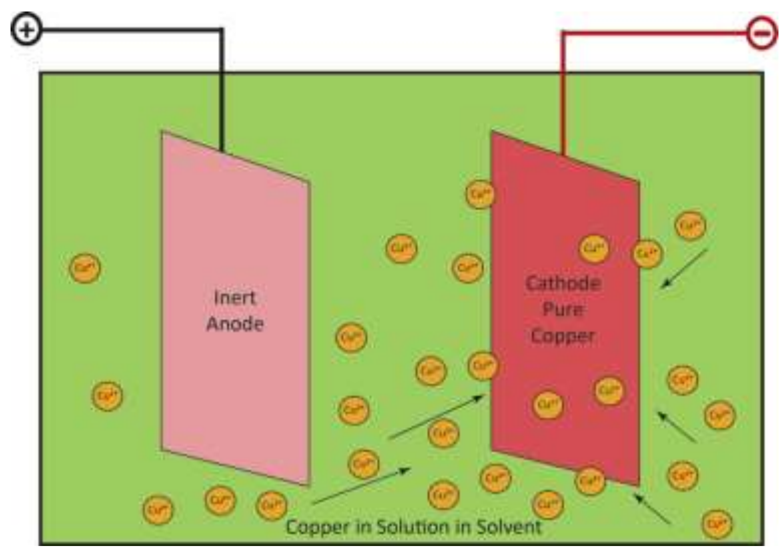

Figure 12: Electrowinning is the final step in processing oxide ore into copper cathodes.

at a mill using secondary crushers, and reduced to pebbles, and finally to fine sand. After the copper ore is crushed, liquid is added to make it a slurry. The slurry is a mix of valuable copper ore minerals and "worthless" rock, called gangue (pronounced "gang"). The slurry is placed in a tank and a process called **froth floatation** is used to separate the copper minerals from the gangue. Chemical reagents called "collectors" are added to the slurry and bind to the copper particles, making them hydrophobic, or waterproof. Pipes are used to blow air into the bottom of the tank to create bubbles, which rise to the surface, taking the waterproof copper sulfide particles along. The froth of copper-rich bubbles at the top of the tank is then skimmed off for further processing. The gangue sinks to the bottom of the tank to be removed or disposed of as **mine tailings**.

The next stage after froth flotation is the **thickening** stage. The froth is poured into large tanks called thickeners. The bubbles break and solids from the froth solution settle at the bottom of the tank. The solids are then filtered to remove excess water, which can be reused in processing additional batches of sulfide ore. The final product of the thickening stage is a combination of 30% copper and other metals; this copper concentrate is then sent to the smelter.

At the smelter, high temperatures are used to further purify the ore in a series of **smelting** steps. The copper concentrate is first sent through the smelting furnace to be heated up to 2,300 °F and converted into molten liquid. The heated liquid is poured into a slag-settling furnace. This step produces a combination of matte, a mixture of copper, sulfur and iron, and slag, a dense, glassy material made of iron, silica, and other impurities. The copper matte created by the smelting furnace contains 58-60% copper. The molten matte is then taken to another furnace called a converter to have the remaining iron and sulfur burned off; the product is referred to as blister copper, which contains 98% copper, and taken to the anode smelter. The blister copper is yellow; when the oxygen in the copper is burned off in the anode smelter, it turns a blue-green color. The resulting product, molten anode copper, is poured into molds called anode-casting wheels. The cooled **anode** slabs are 99% pure copper, are now copper-colored, have two handles molded on top, and are two inches thick, three feet wide, three-and-a-half feet high, and weigh 750 pounds (Figure 13).

Figure 13: Anodes at the Bagdad mine in Arizona. (Photo Credit: ADMMR Photo Archive, Arizona Geological Survey).

The copper anode slabs are then refined in a final step called **electrolysis** (Figure 14). The anode slabs are hung in a large tank full of an electrolyte solution made of copper sulfate and sulfuric acid. Thin sheets of pure copper, which are called cathodes and weigh about 15 pounds each, are hung in between the anodes. An electric current is applied, and positively-charged copper ions (called cations) leave the **anode** (positive electrode) and move in solution through the electrolyte solution to be plated on the cathode (negative electrode). Other

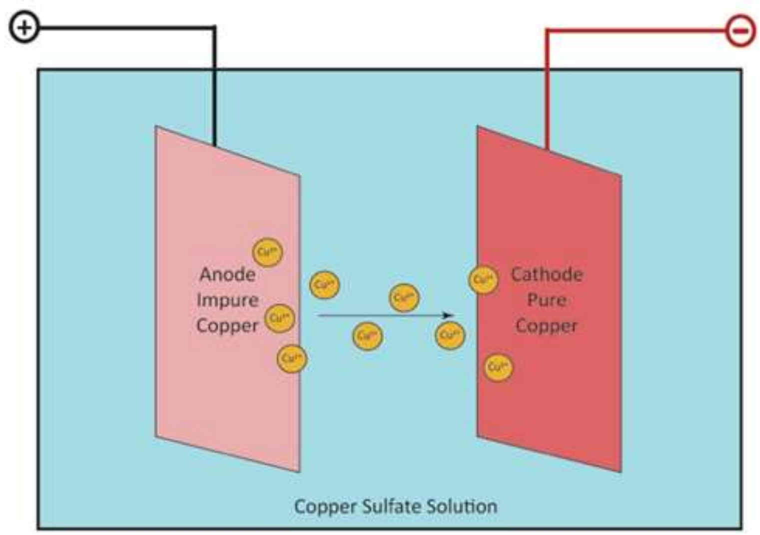

Figure 14: Electrolysis is the final process into purifying sulfide ore into copper cathodes.

metals and impurities also leave the anode to drop to the bottom of the tank or stay in the electrolytic solution. These impurities are collected and may be refined to recover other metals such as silver and gold. After 14 days of electrolysis, the anodes have gradually disappeared, and the copper cathodes now weigh 375 pounds each and contain 99.99% pure copper. The cathodes are taken out of the tank and rinsed with water to prevent further reaction. The finished copper cathodes can then be made into wires, plates, tubes, and other copper products.

C. Recycling Copper

In addition to processing copper ores, new and old copper scrap or copper alloys can be melted, re-purified, and recycled into new components. It is estimated that such recycling supplies 50% of copper used in the copper industry (Scott, 2011). In 2010, 770,000 metric tons of copper were recycled, at an estimated value of nearly six billion dollars (Papp, 2010).

Discussion Questions

- How does copper affect your everyday lifestyle – how long could you go without using copper?
- Do you think mining on tribal lands is a benefit or a misfortune – why?
- If you had $1 billion, would you invest it in a potential mine or the stock market – why?

VIDEO RESOURCES

Video Title and Author	Video Link
The Legacy of Copper Mining in Arizona (Arizona Experience)	www.youtube.com/watch?v=BucmR-kWwmo
Copper Mining Video 1 (Engr. Aquil M. Khan)	www.youtube.com/watch?v=ZjaUX4kDUSw&feature=related
Making History – Malachite and Copper (All Histories)	www.youtube.com/watch?v=_OrBw4L490Y
Ore to More – The History of Copper (Vérité, Inc.)	www.youtube.com/watch?v=RmaGh4g1JtY
Introducing Copper (University of Nottingham)	www.azomining.com/video-details.aspx?VidID=29
DIG (Joey Howell)	http://vimeo.com/14236119
Nearly One Mile Underground (Keith Yaskin)	http://vimeo.com/38616178
Copper: The Miracle Metal (Engineer Guy)	www.youtube.com/watch?v=sSVI5l-MbMQ
Copper Mining and Refining (Redox) (Bill Grosser)	www.youtube.com/watch?v=M2hjv6FS67g

Web-Based Resources

Resource Title and Author	Resource Link
Copper Education (Copper Development Association Inc.)	www.copper.org/education/
Our Mining Process (Freeport-McMoRan)	www.fcx.com/resources/fmi/index.html
Copper and Society (Copper Development Association Inc.)	www.copperalliance.org.uk/copper-and-society/environment
All About Mining (Minerals Education Coalition)	www.mineralseducationcoalition.org/all-about-mining
Copper (Minerals Education Coalition)	www.mineralseducationcoalition.org/minerals/copper
It's Not Over When It's Over: Mine Closure Around the World (World Bank and International Finance Corporation)	http://siteresources.worldbank.org/INTOGMC/Resources/notoverwhenover.pdf
Arizona Geology Magazine (Arizona Geological Survey)	http://azgeology.azgs.az.gov/article/minerals-and-mining/2011/09/2010-arizona-mining-review
Mine Closure (Infomine E-Book)	www.infomine.com/library/publications/docs/e-book%2002%20mine%20closure.pdf
Cypress Tohono Mine (US Environmental Protection Agency)	http://tinyurl.com/m5g4bl7
Society of Mining, Metallurgy, and Exploration Mining Engineering Handbook	www.smenet.org/docs/publications/MiningEngHndbk3Vol1FM.pdf
Copper Statistics and Information (US Geological Survey)	http://minerals.usgs.gov/minerals/pubs/commodity/copper/index.html

Glossary

alloy
A material made of two or more metals (such as **brass** or **bronze**), or of a metal and another material.

anode
1. An electrode through which conventional current flows into a polarized electrical device; in **electrolysis**, it is the positive terminal.
2. In copper processing, a copper anode is an intermediate product from the **smelting** furnaces which is used as a copper source from which to make copper **cathodes** during **electrolysis**.

brass
A yellowish **alloy** of two-thirds **copper** and one-third zinc, sometimes including small amounts of other metals.

bronze
A yellowish-brown **alloy** of two-thirds or more of **copper** and up to one-third of tin, sometimes including small amounts of other metals.

cathode
1. An electrode from which conventional current leaves a polarized electrical device; in **electrolysis**, it is the negative terminal.
2. In copper processing, a copper cathode is the final, 99.99% pure product of the **electrolysis** process, and is itself the primary raw material input for the production of finished copper products, such as rode, tubes, and wires.

closure
In mining, the period of time when the ore-extracting activities of a mine have ceased, and final decommissioning and mine **reclamation** are being completed. It is generally associated with reduced employment levels, which can have a significant impact on local economies.

development
In mining, the process of constructing a mining facility and the infrastructure to support it; typically occurs before **extraction** begins, but can also occur concurrently.

copper
A reddish-brown, ductile, malleable metallic element that is an excellent conductor of heat and electricity and is widely used for electrical wiring.

copper oxide ore
A **copper**-containing ore that in which some of the original minerals have been oxidized; typically processed with hydrometallurgy. Includes chrysocolla, azurite, malachite, and cuprite. Typically processed using **hydrometallurgy**.

copper sulfide ore

A **copper**-containing ore that is typically a mixture of copper carbonate, sulfate, phosphate, and oxide minerals and secondary sulfide minerals. Includes chalcocite and chalcopyrite. Typically processed using **pyrometallurgy**, although low-grade ores may sometimes use steps from the **hydrometallurgy** process.

electrolysis

Generally, a technique that uses an electric current to drive an otherwise non-spontaneous chemical reaction. Typically, an electrical potential is applied across a pair of electrodes (**anode** and **cathode**) immersed in an **electrolyte** solution, resulting in the movement of positively charged ions (cations) moving toward cathode and negatively charged ions (anions) toward the anode. For **copper sulfide ore**, electrolysis is the final stage in the process of **pyrometallurgy**, in which **anode** copper slabs are hung in a large tank full of a copper-based **electrolyte** solution and an electric current is applied, resulting in the plating of copper onto 99.9% pure copper **cathodes**.

electrolyte

A chemical compound that conducts electricity by changing into ions when melted or dissolved into a solution.

electrowinning

Generally, the electrodeposition of a metal from an ore that has been put in solution via a process commonly referred to as leaching; a form of electrolysis. For **copper oxide ore**, electrowinning is the final stage in the process of **hydrometallurgy**, in which concentrated copper solution from the **heap leaching** and **solvent extraction** processes is used as an electrolyte; an electric current is applied through an inert anode, resulting in the plating of copper onto 99.9% pure copper **cathodes**.

element

A substance that cannot be separated into simpler substances by chemical means; a pure chemical substance consisting of a single type of atom distinguished by its atomic number, which is the number of protons in its atomic nucleus. Elements are divided into metals, metalloids, and nonmetals.

exploration

In mining, the process of analyzing an area of land to find mineral deposits and acquiring the rights to explore for mineral deposits on that land.

extraction

In mining, the process of removing ore from the earth in large quantities. May also be referred to as "production" or "exploitation."

froth floatation

Generally, a process for selectively separating hydrophobic (do not mix with water) materials from hydrophilic (do mix with water) materials. For **copper sulfide ore**, froth floatation is the first stage in the process of **pyrometallurgy**, in which air bubbles are introduced into a mixture of finely crushed ore with water and a chemical that aids attachment of the bubbles to the particles of copper, which are recovered as a floating froth.

geochemistry
The science that applies chemistry to geological systems to understand the composition, structure, and processes of the earth.

geophysics
The science that applies physics to the geological systems to understand physical properties and processes of the earth and its surrounding environment.

geology
The science that deals with the dynamics and physical history of the earth, the rocks of which it is composed, and the physical, chemical, and biological changes that the earth has undergone or is undergoing.

heap leaching
Generally, an industrial mining process in which a valuable metal is extracted from a heap, or pile, of crushed ore. For **copper oxide ore**, heap leaching is the first stage in the process of **hydrometallurgy,** in which a chemical solution is applied to a heap of crushed ore, through which it percolates, dissolving the copper. The resulting pregnant leach solution is collected for further refining via **solvent extraction** and **electrowinning**.

hydrometallurgy
The process of extracting and purifying metals from ore at ordinary temperatures by leaching ore with liquid solvents. In copper processing, typically used with **copper oxide ores** and involves **heap leaching**, **solvent extraction**, and **electrowinning**.

metallurgist
Someone who specializes in metallurgy, the branch of science and technology concerned with the properties of metals and their production and purification.

mine tailings
The ore waste of mines; large piles of finely-crushed, chemically processed material (also called gangue) left over after metals of interest (such as **copper**) have been extracted from the **ore** that contained them. May contain metals or other contaminants, and may be susceptible to erosion by wind or water.

mineral
A naturally occurring, inorganic, solid substance with a definite chemical composition and an ordered atomic arrangement.

mineral resource
A concentration or deposit of minerals in the earth's crust which is potentially valuable.

native copper
An uncombined (pure) form of copper which occurs as a natural mineral. Copper is one of the few metallic elements to occur in native form, although it most commonly occurs in oxidized states and mixed with other elements.

open-pit mining

A type of surface mining in which massive, usually metallic mineral deposits are removed by cutting benches in the walls of a broad, deep funnel-shaped excavation which is open to the surface for the duration of the mine's life. This form of mining differs from underground mining that requires tunneling into the earth.

ore

A naturally occurring mineral containing valuable elements (often metals) which can be extracted from the surrounding mineral at a profit.

ore reserve

A concentration or deposit of minerals in the earth's crust which is valuable and can be mined at a profit.

prospecting

In mining, the process of physically searching a region for mineral deposits.

pyrometallurgy

The process of extracting and purifying metals from ore using high temperatures. In copper processing, is typically used with **copper sulfide ores**, and involves **froth flotation**, **thickening**, **smelting**, and **electrolysis**.

reclamation

In mining, the process of restoring land that has been mined to a more natural or economically usable state.

smelting

Generally, extraction of a metal from its ore by a process that involves heating it beyond its melting point; takes place at a smelter. For **copper sulfide ore**, smelting is a stage in the process of **pyrometallurgy**, in which a series of steps use heat and a chemical reducing agent to decompose the partially processed ore, drive off other elements as gases or slag (waste), and leave just the concentrated copper base behind. The final product is a copper **anode** slab which is then refined in a final step called **electrolysis**.

solvent extraction

Generally, a process in which two immiscible (unmixing) liquids are vigorously mixed in an attempt to disperse one in the other so that solutes can migrate from one solvent to the other. For **copper oxide ore**, solvent extraction is a stage in the process of **hydrometallurgy**, in which copper-rich pregnant leach solution from the **heap leaching** stage is mixed vigorously with a solvent, allowing the copper to migrate into the solvent and be separated out. This solution will then act as the copper source/**electrolyte** for the **electrowinning** stage.

Superfund Alternative Site

Although it is not listed on the United States Environmental Protection Agency's National Priorities List (NPL) with Superfund Sites, the Superfund Alternative approach uses the same investigation and cleanup process and standards that are used for sites listed on the NPL. The criteria that must be met for a site to be identified as Superfund Alternative are: site contaminants are significant enough that the site would be eligible for listing on the NPL; a long-term response (i.e., a remedial action) is anticipated at the site; and the site owner is willing to negotiate and sign an agreement with EPA to perform the investigation or cleanup.

thickening

For **copper sulfide ore**, a stage in the process of **pyrometallurgy**, in which the copper froth from the **froth floatation** stage is poured into large tanks called thickeners, where the copper solids settle and are filtered to remove excess water; this copper concentrate will then undergo **smelting**.

verdigris

A blue-green layer that forms on copper, brass, or bronze after atmospheric oxidation, or weathering.

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*All links were verified on July 24, 2015.