7 Gold & Silver

Gold has played a prominent role in world economic and political events. Most of the gold mined over the past 6000 years exists mainly in the form of refined gold held by governments as monetary reserve assets or by individuals in the form of jewelry, bullion coins, or small bars held as insurance against currency devaluation. In modern usage, gold is also used worldwide in numerous electronic, industrial, and dental applications, but more than three-fourths of the world's total annual demand goes toward the fabrication of jewelry and the minting of coins.

Silver has three primary applications: industrial and decorative uses, photography, and jewelry and silverware. Together, these categories represent more than 95 percent of annual silver consumption in the U.S.[1]

Forms of Gold and Silver

Gold is an isometric mineral that occurs in hydrothermal veins with quartz and various sulfides. It is disseminated in submarine massive effusives and in placers or nuggets, fines, and dusts.

Silver occurs in the metallic state, commonly associated with gold, copper, lead, and zinc. It is also found in some 60 minerals including: argentite (a sulfide), cerargyrite (a chloride), and many other sulfides and tellurides.

[1] The Silver Institute, www.silverinstitute.org

7.1 Process Overview

7.1.1 Surface Mining

Surface mining is the primary source of gold and silver. It requires extensive blasting as well as rock, soil, and vegetation removal to reach load deposits. Ore is removed from the mine and transported to milling and beneficiating plants for concentrating the ore, smelting, and/or refining.

When the gold or silver ores lie close to the surface, they often can be uncovered by stripping away a layer of dirt, sometimes only a few feet thick. The ore is mined from large sites by progressive extraction along steps or benches. The benches provide access to progressively deeper ore, as upper-level ore is depleted. After the soil and overlying rock are cleared, the ore is drilled and blasted. The portion of the ore body to be removed is first drilled in a specific pattern, the holes loaded with explosive mixtures and fragmented. Following blasting, the fractured ore is loaded by huge mechanical shovels, hydraulic excavators, or front-end loaders onto large dump trucks or railroad hopper cars.

7.1.1.1 Surface Placer Mining

Placer mining is a method of obtaining gold from sand and gravel using nearby water supplies and consists of two types: hydraulicking or dredging. The type of placer mining depends on the size of the mineral.

In hydraulic mining, or "hydraulicking," a stream of water under great pressure is directed against the base of the placer gravel bank using pipes and large nozzles called giants. The water caves the bank, disintegrates the gravel, and washes the broken material to and through sluice boxes situated in convenient positions downslope. Hydraulic mining totally disturbs large surface areas, puts much loose debris into the drainage system, and involves large surface water runoff that may cause substantial damage downstream. Many of the western states passed laws years ago to closely control "hydraulicking," and few substantial deposits of placer gravel remain that could be mined economically within the restraints of this legislation.

Another placer mining method is dredging. Large alluvial deposits are mined by floating washing plants capable of excavating the gravel, processing it, and stacking the tailings away from the dredge pond. Bucket line and dragline dredges have been used. The bucket line dredges are larger and more efficient, consisting of a continuous line of buckets that scoop the material from the gravel bank at the edge of the dredge pond, raising it to the top of the washing plant mounted in the hull. Dragline dredges are smaller and less efficient, employing a single bucket. This bucket digs the gravel and is swung over the feed hopper of a floating washing plant similar to the layout in a bucket line dredge, although usually smaller.

Dredging temporarily involves total disturbance of the ground surface, although with careful planning and engineering of the operation it is possible to plan for restoration of the surface, and perhaps even to improve some aspects of the flood plain or nearby river channel. It is not possible to restore the land to the precise original contour, for the swell factor of the gravel increases volume 20 percent or more. In many areas in the West, particularly near major construction projects or cities, clean gravel placer tailings are valuable for manufacture of aggregate or crusher run in fills of various kinds, and can be considered a resource in their own right. In a few areas, people traveling through areas of old placer tailings, expecting the area to be a wasteland, are pleased to find a great variety of fishing and water sport recreation available, and thriving wildlife in the habitat that has been created. Placer deposits can be thoroughly explored before floating the dredge. Such operations lend themselves to thorough planning, and it is possible to do a considerable amount of reclamation at only a slight increase in overall operating costs.

7.1.1.2 Underground Room-and-Pillar Mining

Underground mining occurs if the ore grade or quality is sufficient to justify more targeted mining. The room-and-pillar method involves extracting the ore by carving a series of rooms while leaving pillars of ore to support the mine roof.

7.1.2 Beneficiation

Precious metals may be recovered from the gold ore or from refining processes of base metals such as copper and lead. Because these are distinct recovery methods, they are discussed separately.

7.1.2.1 Precious Metal Recovery from Ores

In 2000, gold was produced at 641 load mines; about a dozen large placer mines; and numerous small placer mines. In addition a small amount of domestic gold was produced as a byproduct of processing base metals.[2] Silver was produced in the United States from precious-metal ores at about 30 lode mines and from base-metal ores at about 24 lode mines. Fewer placer operations recovered silver in 2000, and the quantity recovered was less than 1 percent of the total domestic production.[3]

7.1.2.2 Gravity Separation

Gravity separation relies on density differences to separate desired materials from host rock. Devices used include gold pans, sluices, shaking tables, and jigs. Gravity separation alone is used at most placer mines, and in combination with other methods and some lode miners.

7.1.2.3 Ore Preparation

Much of the extracted ore must be milled to prepare it for further recovery activities. Uniformly sized particles may be obtained by crushing, grinding, and wet or dry

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[2] US Geological Survey, *Mineral Yearbook*, 2000, Gold

[3] US Geological Survey, *Mineral Yearbook*, 2000, Silver

classification. The degree of milling performed on the ore depends on the gold and silver concentration of the ore, mineralogy and hardness of the ore, the mill's capacity, and the next planned step for recovery. Milled ore is pumped to the next operation unit in the form of a slurry. Fugitive dust generated during crushing and grinding activities is usually collected by air pollution control devices and recirculated into the beneficiation circuit. Most mills use water sprays to control dust from milling activities.

After milling, sulfide ores may be subjected to chlorination, bio-oxidation, roasting, or autoclaving. Chlorination is not commonly used to oxidize sulfide ores because of high equipment maintenance costs caused by the corrosive nature of the oxidizing agent. Bio-oxidation of sulfide ores employs bacteria to oxidize the sulfur-bearing minerals.

Roasting of sulfide ores involves heating the ores in air to convert them to oxide ores and break up their physical structure, allowing leaching solutions to penetrate and dissolve the gold. In effect, roasting oxidizes the sulfur in the ore, generating sulfur dioxide that can be captured and converted to sulfuric acid. Roasting temperatures are dependent on the mineralogy of the ore, but range as high as several hundred degrees Celsius. Roasting of carbonaceous ores oxidizes the carbon to prevent interference with leaching and reduced gold recovery efficiency.

Autoclaving (pressure oxidation) is a relatively new technique that operates at lower temperatures than roasting. Autoclaving uses pressurized steam to start the reaction and oxygen to oxidize sulfur-bearing minerals. Heat released from the oxidation of sulfur sustains the reaction.

7.1.2.4 Agglomeration

Because ores with a high proportion of small particles may retard the percolation of the lixiviant, agglomeration is used to increase particle size. This operation includes mixing the crushed ore with portland cement and/or lime, wetting the ore evenly with weak cyanide solution to start leaching before the heap is built, and mechanically tumbling the ore mixture so fine particles adhere to larger particles.

7.1.2.5 Cyanidation - Leaching

Currently, cyanide leaching is the chief method use. In this technique, sodium or potassium cyanide solution is either applied directly to ore on open heaps or is mixed with a fine ore slurry in tanks. Heap leaching is generally used to recover gold from low-grade ore, while tank leaching is used for higher grade ore.

Cyanidation is the primary means of recovery of fine gold and silver. In this process, solutions of sodium or potassium cyanide are brought into contact with an ore, which may or may not have required extensive preparation prior to leaching. Gold and silver are dissolved by cyanide in solutions of high pH in the presence of oxygen. There are three general methods of contacting ores with leach solutions: (1) heap leaching, (2) vat leaching, and (3) agitation leaching. Heap leaching and vat leaching account for most gold and silver recovery. These leaching methods are discussed in detail below.

7.1.2.6 Cyanidation - Heap Leaching

Compared to tank leaching, heap leaching has several advantages, including simplicity of design, lower capital and operating costs, and shorter start-up times. Depending on the local topography, a heap or a valley fill method is typically employed. The size of heaps and valley fills can range from a few acres to several hundred acres. Heap leaching may involve any or all of the following steps:

- Preparation of a pad with an impervious liner. Some liners may simply be compacted soils and clays, while others may be of more sophisticated design, incorporating clay liners, french drains, and multiple synthetic liners.

- Placement of historic tailings, crushed ore, or other relatively uniform and pervious material on the uppermost liner to protect it from damage by heavy equipment or other circumstances.

- Crushing and/or agglomerating the ore.

- Placing the ore on the pad(s).

- Applying cyanide solution using drip, spray, or pond irrigation systems, with application rates generally between 0.5 and 1.0 pound of sodium cyanide per ton of solution.

- Collecting the solution via piping laid on the liner, ditches on the perimeter of the heap, or pipes/wells laid through the heap into sumps at the liner surface. The recovered pregnant solution, now laden with gold (and silver), may be stored in ponds or routed directly to tanks for gold recovery, or it may be reapplied to the heap for additional leaching.

- Recovering the gold from the pregnant solution (typically containing between 1 and 3 ppm of gold). The leaching cycle can range from weeks to several months, depending on permeability, size of the pile, and ore characteristics. The average leach cycle is approximately three months.

Heap leaching is the least expensive process; therefore, low value ores are most often treated by heap leaching. In 2000, heap leaching accounted for 55 percent of gold production.[4] In many cases, heaps are constructed on lined pads with ore sent directly from the mine with little or no preparation. However, in about half of the heap leaching operations, ore is crushed, or crushed with the fines agglomerated with lime or Portland cement, prior to placement on the heap to increase permeability of the heap and maintain the high pH (optimally 10.5) needed for leaching to occur.

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[4] U.S. Geological Survey, Industry Expert

Two common types of pads used in gold and silver heap leaching include: (1) permanent heap construction on a pad from which the leached ore is not removed, and (2) on-off pads, which allow the spent ore to be removed following the leach cycle and fresh ore to be placed on the pad. Permanent heaps are typically built in lifts. Each lift is composed of a 5 to 30 foot layer of ore. On-off pads are not commonly used in the industry and are constructed to allow spent ore to be removed after the leaching cycle and re-use of the pad.

After the ore is piled on a leaching pad, the leaching solution is applied to the top of the pile by sprinklers. The solution generally has a concentration of 0.5 to 1 pound of sodium cyanide per ton of solution. The precious metals are dissolved as the solution trickles through the pile and the metal bearing solution is collected on the impervious pad and pumped to the recovery circuit. Following rejuvenation, the solution returns for reuse once the metals are removed. The leaching process will continue until no more precious metal is extracted. Typical operations will involve leaching for several months on each heap. The process is relatively inexpensive and can be operated for less than two dollars per ton of ore. However, as much as half of the gold and silver may not be extracted, either because the leach liquor never contacts the precious metal or because the metal bearing solution is trapped in blind channels. Spent ore and leaching solutions as well as residual leach liquor are generated in this process.

7.1.2.7 Cyanidation

Vat (tank) Leaching - Vat leaching is used when greater solution control than that afforded by heap leaching is necessary. In 2000, vat leaching accounted for 25 percent of gold recovery.[5] To prepare for tank leaching, ore is ground to expose the metals to the cyanide. Prepared ore is placed in a vat or tank and flooded with leach liquor. The solution is continuously cycled through, draining from the bottom of the vat, proceeding to gold recovery, rejuvenation, and returning to the top of the vat. The resulting gold-cyanide complex is then adsorbed on activated carbon. The pregnant carbon undergoes elution, followed either by electrowinning or zinc precipitation. The recovery efficiencies attained by tank leaching are significantly higher than for heap leaching. The tank leaching process may occur over a series of days, rather than the weeks or months required in heap leaching. The process is more expensive than heap leaching because the material must be removed from the vat at the end of the leaching process. While the primary advantage of vat leaching is better solution contact, channelization and stagnant pockets of solution still occur (almost as severely as in heap leaching) when solution is drained from the vat. However, some of the trapped solution is recovered when the solids are removed from the vat. Spent ore is generated in this process, and leaching solutions are recycled.

Agitation Leaching - High value ores are treated by agitation leaching to maximize the recovery of metals. The ore is crushed and ground in water to form a slurry. Cyanide is usually added at the grinding mill to begin the leaching process and more cyanide may be

[5] U.S. Geological Survey, Industry Expert

added to the leaching tanks. Ores may be leached anywhere from 24 to 72 or more hours. Silver ores tend to require longer leaching times. The method of recovering the precious metal from solution determines how the solution is separated from the solids. If the Merrill-Crowe or carbon-in-column metal recovery process is used, the leach liquor will be washed out of the solids, usually by a combination of counter-current decantation and filtration washing with water. This produces a concentrated wash solution and recovers the maximum pregnant liquor from the solids. The resultant slurry contains very little cyanide or gold and does not exhibit hazardous characteristics. If carbon-in-leach or carbon-in-pulp metal recovery is practiced, the slurry may be discarded without washing. The carbon should remove all of the precious metals, and the solution is recovered from the tailings treatment and recycled to the process.

7.1.2.8 Cyanidation - Metal Recovery

In leaching operations, after dissolving the metal, the leach solution is separated from the ore, and the gold and silver are removed from solution in one of several ways: (1) the Merrill-Crowe process, (2) activated carbon loading, and (3) activated carbon stripping. The primary difference between recovery methods is whether the metal is removed by precipitation with zinc or by absorption on activated carbon. Zinc cyanide is more soluble than gold or silver cyanide, and if pregnant liquor comes in contact with metallic zinc, the zinc will go into solution and the gold and silver will precipitate. The different recovery methods are described below.

Merrill-Crowe Process - In the Merrill-Crowe process, the pregnant leaching solution is filtered for clarity, then vacuum deaerated to remove oxygen and decrease precious metal solubility. The deaerated solution is then mixed with fine zinc powder to precipitate the precious metals. The solids, including the precious metals, are removed from the solution by filtration and the solution is sent back to the leaching circuit. The solids are melted and cast into bars. If silver and gold are present, the bars are called doré. In most cases, the metal is then sent to an off-site refinery. Most operations using zinc precipitation in the United States use some variation of the Merrill-Crowe process.

Activated Carbon Loading Process - Precious metal leach solutions can be brought into contact with activated carbon by carbon-in-column, carbon-in-pulp, and carbon-in-leach processes. Carbon-in-column systems are used at heap and vat leach operations and other situations in which the leaching solution is separated from the solids being leached prior to precious metal recovery. The leaching solution is passed through a series of columns containing beds of activated carbon. The gold and silver are adsorbed as cyanide complexes on the surfaces of the carbon. After passing through the columns, the solution is returned to the leaching circuit. When the carbon in a column is loaded with precious metals, the column is switched to a stripping circuit.

In many agitation plants, the gold is recovered from the leached material before the solution is separated from the solids. In the carbon-in-pulp system, the leached pulp passes from the last stage of the leaching circuit into another series of agitation tanks. Each tank contains activated carbon granules. The slurry flows from tank to tank in series while screens retain the carbon. When the carbon in the first tank is fully loaded with precious metals, it is removed and sent to the stripping and reactivation circuit, the carbon in the other tanks is moved ahead one stage and new carbon is added to the last stage. The carbon moves counter-current to the leached slurry and the leached slurry is finally sent to the tailings area for dewatering.

Carbon-in-leach is similar to carbon-in-pulp, except that the carbon is in the leaching tanks instead of in a separate recovery circuit. One advantage of carbon-in-leach over carbon-in-pulp is that some cyanide is released when gold adsorbs on carbon, making it available for more leaching. Another advantage is that fewer agitation tanks are necessary since the separate recovery circuit is eliminated. However, the agitation is more aggressive in the leach circuit, causing more attrition of the carbon than in the carbon-in-pulp; thus, the finely abraded carbon and its load of precious metals may be lost, reducing recovery and increasing costs due to increased carbon replacement.

Activated Carbon Stripping Process - Gold stripping from loaded activated carbon is usually done with a hot, concentrated alkaline cyanide solution, sometimes including alcohol. These conditions favor the desorbtion of the precious metals into the stripping solution. The solution then goes into an electrowinning cell, where the precious metals are plated out, generally onto a steel wool cathode. The solution is recycled to the stripping stage and the cathode is sent on to refining. Some operations refine the steel wool on site to make doré, while others ship it directly to commercial refineries. The primary waste from carbon stripping is the spent stripping solution.

7.1.2.9 Carbon Regeneration

After stripping, the carbon is reactivated on- or off-site and recirculated to the adsorption circuit. Carbon used in adsorption/desorbtion can be reactivated numerous times. The regeneration technique varies with mining operations, but generally involves an acid wash before or after extraction of the gold-cyanide complex, followed by reactivation in a kiln. The activated carbon is washed with dilute acid solution (pH of 1 or 2) to dissolve carbonate impurities and metal-cyanide complexes that adhere to the carbon along with the gold. This technique may be employed either immediately before or after the gold-cyanide complex is removed. Acid washing before the gold is removed enhances gold recovery.

The acid used for carbon washing depends on what impurities need to be removed. Usually, a hydrochloric acid solution is circulated through 3.6 metric tons of carbon for approximately 16 to 20 hours. Nitric acid is also used in these types of operations, but is thought to be less efficient than hydrochloric acid in removing impurities. The resulting spent acid wash solutions may be neutralized with a high pH tailings slurry, dilute sodium hydroxide solution, or water rinse. When the wash solution reaches a stable pH of 10, it is sent to a tailing impoundment. Metallic elements may also be precipitated with sodium sulfide.

The carbon is screened to remove fines and thermally reactivated in a rotary kiln at about 730°C for 20 minutes. The reactivate carbon is subsequently rescreened and reintroduced into the recovery system. Generally, about 10 percent of the carbon is lost during the process because of particle abrasion. Recirculating the carbon material gradually decreases performance in subsequent absorption and reactivation series. Carbon adsorption efficiency is closely monitored and fresh carbon is added to maintain efficiency at design levels.

7.1.3 Processing

Gold and silver are also recovered from the refining processes for base metals, primarily lead and copper. Smelting operations remove iron, sulfur, and other impurities from the ore and produce copper anodes for electrolytic refining. In refining operations, the anodes produced from smelting are purified electrolytically to produce copper cathodes. The refinery slimes from these operations are processed for precious metals recovery. The recovery of precious metals in lead refineries is a normal part of the operation called "desilverizing."

A major source of precious metals from the copper industry is electrolytic cell slimes. The slimes are periodically removed from the cells in the refinery for treatment. The first stage of treatment removes the copper in the slimes by acid leaching, immediately or after roasting. The decopperized slimes are then placed in a furnace and melted with a soda-silica flux. The siliceous slag formed in this melting is removed and air is blown through the molten material. Lime is added and a high lead content slag is formed which is combined with the siliceous slag and returned to the copper anode casting furnace. Next, fused soda ash is added to the furnace and air is again blown through the melt, forming a soda slag, which is removed and treated to recover selenium and tellurium. The remaining doré in the furnace is removed and sent to refining to recover the precious metals.

The desilverizing process takes advantage of the solubility of precious metals in molten zinc, which is greater than their solubility in molten lead. Lead from previous stages of refining is brought in contact with a zinc bath, either in a continuous operation or in batches. The zinc absorbs the precious metals from the lead and the lead is then passed onto a dezincing operation. The zinc bath is used until it contains 5,000 to 6,000 troy ounces of precious metal per ton of zinc. The zinc bath is then retorted to recover zinc by distillation. The zinc is returned to the desilverizing process and the "retort metal" is treated by cupellation to produce doré bullion. In the cupellation step, the base metals in the retort metal are oxidized with air and removed from the precious metals. The oxides are all treated for the recovery of their various precious metals. The doré is then sent to refining.

7.1.4 Precious Metal Refining

Typical Production Processes

The refining process used for gold and silver depends on the composition of the material in the feed. The most basic operation is "parting" which is the separation of gold and silver. Parting can be done electrolytically or by acid leaching. In either case, the silver is removed from the gold. Further treatments may be necessary to remove other impurities.

Following the "parting" process, the gold cyanide solution is electrowon onto steel wool cathodes after carbon stripping. The barren cyanide solution is returned to the leach circuit for gold and silver recovery. Sludge from the bottom of the electrowinning cell is filtered and sent to the retort for mercury recovery. The gold/steel wool cathode is placed in a vat containing a sulfuric acid solution. The solution dissolves the steel wool from the gold and silver, leaving a solid gold residue. The waste sulfuric acid and steel wool solution is discharged to the tailings slurry. The gold solids are filtered under vacuum through diatomaceous earth. The gold filter cake is then sent to the retort furnace where it is subjected to 1,200^{o}F for 14 hours. After retorting, a flux of silica and borax is added and the gold is smelted in an induction furnace. It is from this induction furnace that gold doré bars are poured. The slag generated from this retorting is sent to a ball mill for crushing, grinding, and gold recovery. Some of the slag is immediately recycled back to the smelting process to recover its gold content. The gold slag may have between three and four ounces per ton of recoverable gold.

Silver Chloride Reduction

Silver metal is produced from silver chloride by a dissolution and cementation process. The silver chloride is dissolved in a dilute solution of ammonium hydroxide and recovered by cementation. The silver is replaced in solution, causing the silver ions to be reduced and precipitated from solution as silver metal.

Mercury Recovery

Many gold-bearing ores from the western United States contain small quantities of mercury. The presence of mercury decreases the gold-loading capacity of the activated carbon. During cyanidation of mercury-bearing gold-silver ores, significant amounts of mercury are extracted. The addition of calcium sulfide to the cyanide leach slurry precipitates the solubilized mercury and also some silver. Primary mercury is also produced from gold-bearing ores by roasting or calcining. The mercury produced is of commercial grade and is ultimately sold.

7.2 Inputs/Outputs

The following lists the inputs and outputs for gold and silver mining and processing.

Inputs	**Outputs**
Fuels	Doré
Electricity	Spent Ore
Cyanide	Tailings
Carbon	Zinc Cyanide Solution
	Slag
	Base Metal Product

Figures 7-1 and 7-2 illustrate gold and silver mining and processing with major inputs and outputs.

Figure 7-1. Gold and Silver Mining Flow Diagram

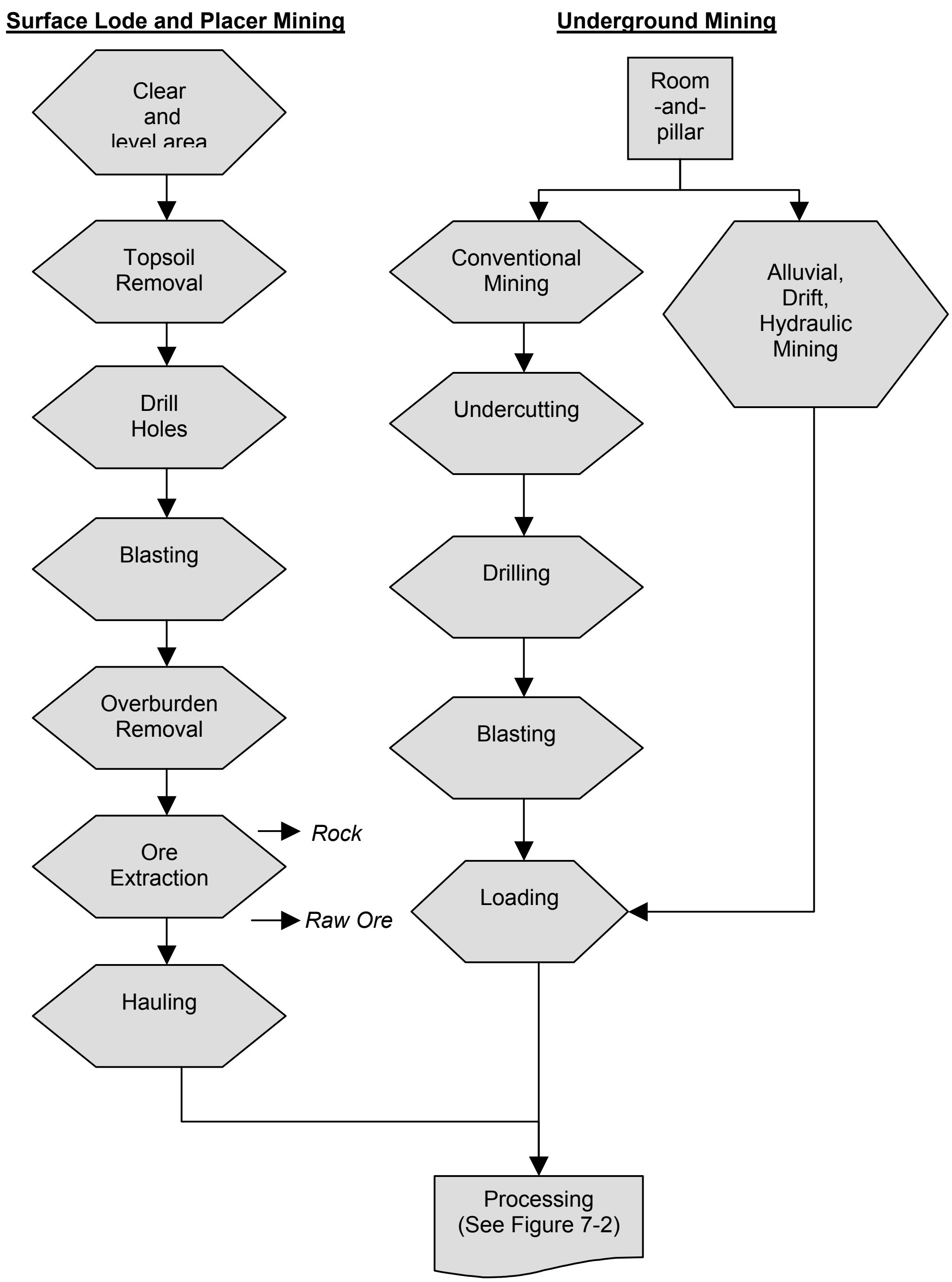
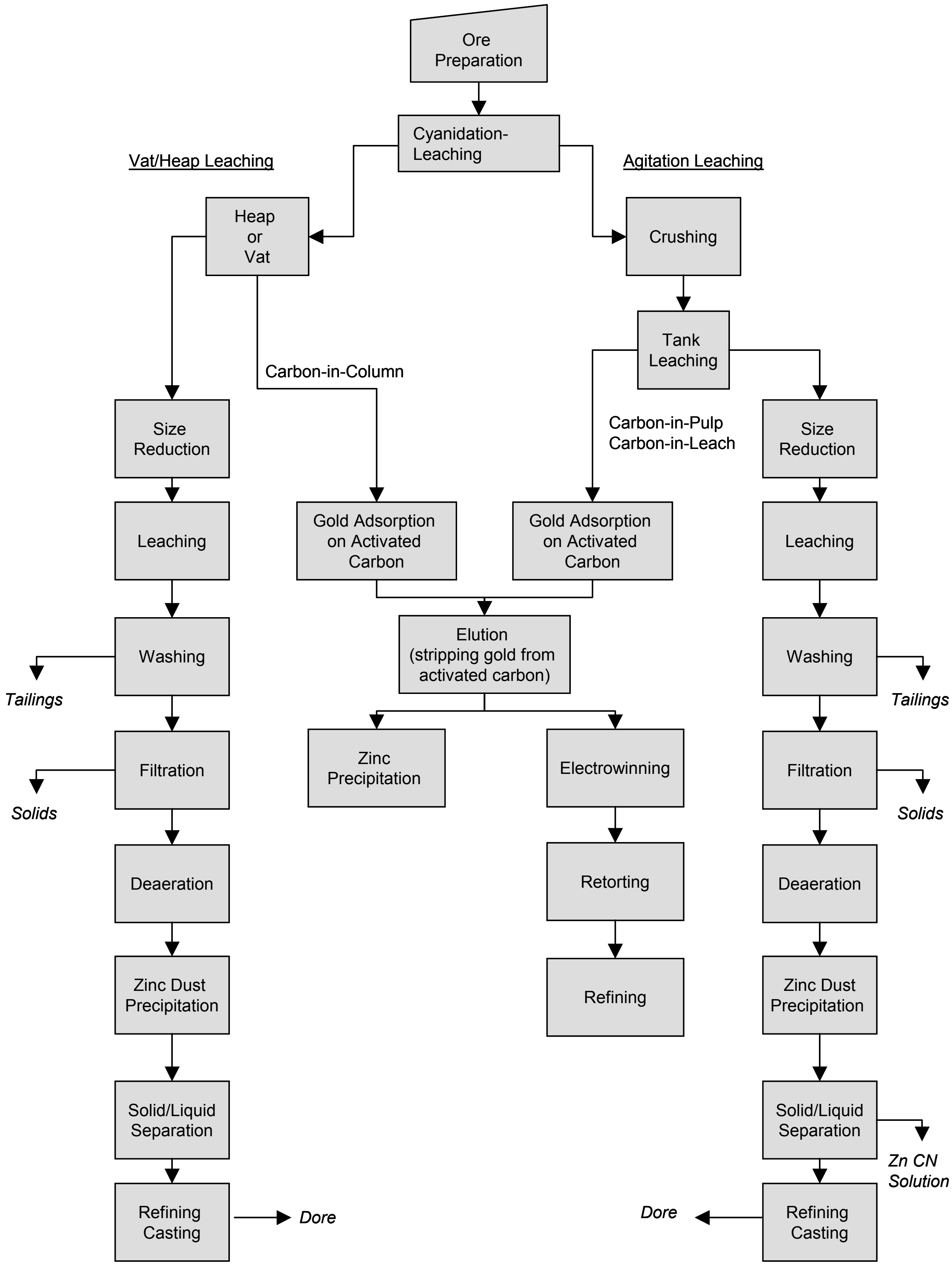


Figure 7-2. Gold and Silver Beneficiation and Process Flow Diagram

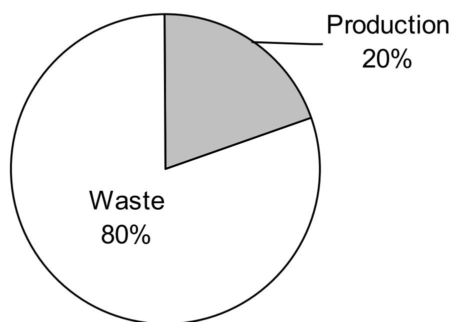


7.3 Energy Requirements

7.3.1 Materials Handled

Materials handled refers to the amount of ore and waste materials that must be handled in mining. Figure7-3 shows the amount of gold and silver mined in relation to the amount of waste material produced in gold and silver mining. When looking at energy requirements in mining and processing the tonnage of materials which must be handled drives energy consumption in mining operations. For example in 1998 the amount of gold and silver crude ore produce was 254 million tons with 1,065 million tons of waste produced. From 1994 to 1998 the average crude ore ratio was 21 percent. This means for every 100 tons of material mined there is 21 percent ore and 79 percent waste.

Figure 7-3. Materials Handled for Gold & Silver Mining



Source: U.S. Department of the Interior, U.S. Geological Survey, *Mining Yearbook*, Statistical Summary 1996, 1998
U.S. Department of the Interior, U.S. Geological Survey, *Mining and Quarrying Trends*, 1994, 1995, 1996, 1997, 1998

Major energy sources include fuel oil and purchased electricity. In 1992 gold and silver mining consumed 34.8 trillion Btu.[6] Table 7-1 shows the type and quantity of fuels consumed during gold and silver mining.

[6] U.S. Department of Commerce, Bureau of Census, Census of Mineral Industries, Subject Series, *Fuels and Electricity Consumed*, 1992

Table 7-1. Gold and Silver Production and Energy Consumed by Type [a]

	Units	1987	1992	1997
Gold and Silver Production	Thousand tons	-	0.364	0.397
Energy Consumption				
Coal	Thousand tons	Withheld	Withheld	Withheld
Fuel oil [b]	Million bbl.	1.0	2.6	3.7
Gas	Billion Cubic Feet	0.4	Withheld	Withheld
Gasoline	Million Gallons	0.2	5.4	13.2
Electricity Purchased	Million kWh	1,600.0	3,300.0	4,600.0
Electricity Generated Less Sold	Million kWh	Withheld	110.9	Withheld

[a] Gold and Silver are SIC Codes 1041 and 1044 (1997 NAICS Codes 212221 and 212222)
[b] Summation of distillate and residual fuel oil
Sources: U.S. Department of Commerce, Economics and Statistics Administration, Bureau of the Census, Census of Mineral Industries, *Industry Series*,, Gold Ores and Silver Ores.
US Department of the Interior, US Geological Survey, *Minerals Year Book*, Statistical Summary, 1997 & 1994

7.3.2 Energy Requirements

A 1976 study by the Bureau of Mines on energy use patterns showed that the amount of energy required to recover one ton of metallic gold from an underground mining operation was nearly twice that required to recover an equivalent amount of gold from an open pit operation. For purposes of comparisons only, the amount of energy required to produce one net ton of gold from all primary sources was about 59,000 million Btu, compared with about 1,500 million Btu for one net ton of silver recovered from all primary sources.[7] It estimated that 2,600 million Btu of energy were required to produce one net ton of silver from a silver ore.[8]

Due to a lack of current information on the energy requirements of mining and processing the *SHERPA Mine Cost Estimating Model* along with the *Mine and Mill Equipment Cost, An Estimators Guide* from Western Mine Engineering, Inc. was used to calculate the energy requirements of mining and processing gold and silver.

Table 7-2 shows the estimated energy requirements for a surface gold mine in the U.S. This gold mine operates over a 20-year lifetime with a 647-ton output at the end of its life. The mine runs 365 days per year with two shifts per day of 12.00 hours, which gives it a daily production of 15,000 tons of ore per day. The mine also has a daily waste

[7] U.S. Department of Interior, Bureau of Mines, *Mineral Facts and Problems*, p. 729-739, 1985
[8] Ibid.

production of 144,832 tons per day. Both the ore and waste material must be hauled 1,600 feet out of the mine at a gradient of seven percent.

Table 7-2. Energy Requirements for a 15,000 ton/day Surface Gold Mine

Equipment (number of Units)	Daily hours/ unit	Energy Consumption			
		Single Unit (Btu/ton)	All Units (Btu/hour)	All Units (Btu/day)	All Units (Btu/ton)
Rear-Dump Truck [a] (38)	24.00	8,390	199,000,000	4,780,000,000	319,000
Bulldozer [a] (56)	24.00	503	17,600,000	423,000,000	28,200
Front-End Loader [a] (28)	24.00	711	12,400,000	298,000,000	19,900
Service Truck [a] (25)	24.00	543	8,480,000	204,000,000	13,600
Hydraulic Shovel [a] (6)	24.00	2,050	7,700,000	185,000,000	12,300
Pick-up Trucks [a] (22)	24.00	543	7,470,000	179,000,000	11,900
Lighting Plant [a] (34)	24.00	136	2,880,000	69,200,000	4,620
Rotary Drill [b] (2)	24.00	1,810	2,260,000	54,200,000	3,620
Pumps [b] (2)	24.00	1,060	1,320,000	31,800,000	2,120
Water Tanker [a] (1)	12.00	2,000	2,500,000	30,000,000	2,000
Bulk Truck [a] (2)	24.00	543	679,000	16,300,000	1,090
Grader [a] (1)	4.00	165	619,000	2,480,000	165
Total			**263,000,000**	**6,280,000,000**	**418,000**

a Calculated at $0.535 per gallon of diesel fuel: average prices for sales to end-users in U.S. Petroleum Administration for Defense District No. IV, 1999

b Calculated at $0.049 per kWH: average for Rocky Mountain Region, 1999

Note: Mine operates over a 20-year lifetime with a 647-ton output at the end of its life. Mine runs 365 days per year with two shifts per day of 12.00 hours, which gives it a daily production of 15,000 tons of ore per day. Assume a daily waste production of 144,832 tons per day. Assumes ore and waste material must be hauled 1,600 feet out of the mine at a gradient of 7 percent.

Sources: BCS, Incorporated estimates (September 2002) using the Western Mining Engineering, Inc. *SHERPA Mine Cost Software* and *Mine and Mill Cost, An Estimators Guide*
Conversations with Industry Contacts

The rear-dump trucks require the most energy in the mine and are the most energy intensive pieces of equipment. Rear-dump trucks account for 76 percent of the total energy required per ton. Combined with other vehicles such as front-end loaders, bulldozers, water trucks, service trucks, bulk trucks, and pick-up trucks these vehicles account for 94 percent of the total energy consumed per ton. All of these vehicles operate on diesel fuel.

Table 7-3 shows the energy requirements of processing gold ore. The SAG mills require the most energy and are the most energy intensive equipment in processing. It operates on electric energy. The SAG mills alone account for 52 percent of the total energy required per ton in processing. The ball mills are another grinding tool and, together with the SAG mills, account for 84 percent of the total energy required per ton. The ball mill also operates on electric energy. Washing, smelting, and refining accounts for 16 percent of the total energy required per ton of processing.

The total energy required to mine and process gold is 472,400 Btu per ton. Mining requires 88 percent of the total energy consumed per ton while processing uses the remaining 12 percent.

Table 7-3. Energy Requirements for Beneficiation and Processing of Gold

Equipment (number of Units)	Daily hours/ unit	Energy Consumption			
		Single Unit (Btu/ton)	All Units (Btu/hour)	All Units (Btu/day)	All Units (Btu/ton)
SAG Mill [a] (2)	24.00	14,100	17,700,000	424,000,000	28,200
Ball Mill [a] (2)	24.00	8,800	11,000,000	264,000,000	17,600
Smelting (1)	24.00	3,260	2,040,000	48,900,000	3,260
Refining (1)	24.00	3,260	2,040,000	48,900,000	3,260
Washing [b] (1)	24.00	1,990	1,240,000	29,800,000	1,990
Electrowinnig [a] (2)	24.00	27	33,400	802,000	53
Total			**34,000,000**	**815,000,000**	**54,400**

a Calculated at $0.049 per kWH: average for Rocky Mountain Region, 1999

b Calculated at $0.535 per gallon of diesel fuel: average prices for sales to end-users in U.S. Petroleum Administration for Defense District No. IV, 1999

Note: Mine operates over a 20-year lifetime with a 647-ton output at the end of its life. Mine runs 365 days per year with two shifts per day of 12.00 hours, which gives it a daily production of 15,000 tons of ore per day. Assume a daily waste production of 144,832 tons per day. Assumes ore and waste material must be hauled 1,600 feet out of the mine at a gradient of 7 percent.

Sources: BCS, Incorporated estimates (September 2002) using the Western Mining Engineering, Inc. S*HERPA Mine Cost Software* and *Mine and Mill Cost, An Estimators Guide*
Conversations with Industry Contacts

7.4 Emissions

Sulfur dioxide can occur during ore preparation, depending on ore type. It may be routed to an acid plant and converted to sulfuric acid. This may be sold to other mines or used on-site for carbon washing and regeneration.

7.5 Effluents

Mine water is a waste stream generated from gold and silver production. This waste consists of all water that collects in mine workings, both surface and underground, as a result of inflow from rain or surface water, and ground water seepage. If necessary, the water is pumped to allow access to the ore body or to keep the mine dry. This water may be pumped from sumps within the mine pit or from interceptor wells. Mine water may be used and recycled to the beneficiation circuit, pumped to tailings ponds, or discharged to surface water. Any discharged water is subject to the National Pollutant Discharge Elimination System (NPEDES) and is exempt from RCRA. The quantity and chemical composition of mine water varies from site to site.

Spent leaching solution is generated during the leaching operations, most of the barren cyanide solution is recycled to leaching activities; however, the build-up of metal impurities may interfere with the dissolution and precipitation of gold and, therefore, require a portion of the solution volume to be bled off and disposed. These solutions may contain metallo-cyanide complexes of copper, iron, nickel, and zinc, as well as other impurities, such as arsenic and antimony, mobilized during the leaching. Management practices for these solutions are in accordance with state and federal environmental and land management requirements. Specifically, spent leaching solution from zinc precipitation is often returned to leaching process.

Other effluents from gold and silver processing are waste sulfuric acid and waste steel wool.

7.6 By-products and solid waste

Waste rock is generally disposed of in piles or dumps. An estimated 25 million metric tons of waste rock was generated in 1980 and 39 million metric tons in 1982. At surface mines, 71 percent of all material handled is discarded as waste. At underground mines, 20 percent is discarded as waste. The rest is considered crude ore. The quantity and composition of the waste rock varies by site. Depending on the composition of the ore body, this waste may contain sulfides or oxides.[9]

Spent ore, a result of cyanidation, is the ore from leaching that may contain residual cyanide. The ore in continuous or valley fill heaps is stacked in lifts and left in place for subsequent leaching, detoxification, and closure. Ore placed on on-off heap pads is

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[9] U.S. Environmental Protection Agency, Office of Solid Waste, *Identification and Description of Mineral Processing Sectors and Waste Streams*, p. 331-352, April 1998

periodically removed for ultimate disposal at an alternative site, such as waste rock or spent ore disposal sites. Typically, detoxification of the spent ore involves rinsing with water until the cyanide concentration in the effluent is below a specific standard set by the state regulatory agency. The heap may then be reclaimed with wastes in place. Spent ore from vat leaching exists in the form of a slurry composed of gangue and process water bearing cyanide and cyanide-metal complexes. The spent ore may be treated to recover cyanide if possible or neutralize it prior to disposal. The slurry is typically disposed of in a tailings impoundment with some of the liquid component being recirculated to the tank leach as make-up water.

Table 7-4. By-products from Gold and Silver Ores

By-products	Quantities
Slag	500 metric tons per year
WWTP Sludge	1,080,100 metric tons per year

Source: U.S. Environmental Protection Agency, Office of Solid Waste, *Identification and Description of Mineral Processing Sectors and Waste Streams*, April 1998.

Filter cake resulting from zinc precipitation consists primarily of fine gangue material and may contain gold-cyanide complex, zinc, free cyanide, and lime. The filter may be washed with water, which can be disposed of or reused in milling and other operations.

Tailings in slurry form, composed of gangue (including sulfide materials and dissolved base metals) and process water bearing cyanide and cyanide-metal complexes, are generated from carbon-in-pulp and carbon-in-leach processes. The characteristics of this waste vary depending on the ore, cyanide concentration, and water source (fresh or recycled). The characteristics of the gangue are dependent on the ore source. The slurry is typically disposed of in a tailings impoundment with some of the liquid component being recirculated to the tank leach or other water consumptive system.

Slag is typically generated at gold pyrometallugical processes operations. The metal-bearing slag is broken off the molten doré and then placed into barrels inside the refinery building. The slag is ground and then leached in tanks with sodium cyanide. The gold-rich slurry that results is then conveyed, by pipe, to the primary gold-bearing slurries in the mill for mixing. Slag could contain between 100 and 700 ounces of gold per ton, therefore taking weeks to accumulate enough slag to constitute a large enough batch for cost effective metals recovery. The total industry generation rate for slag is estimated at less than 500 metric tons per year. Slag is recycled and is classified as a by-product.[10]

Wastewater treatment plant sludge may be recycled. Estimates of low, medium, and high annual waste generation rate of 100 metric tons/yr, 360,000 metric tons/yr, and 720,000 metric tons/yr, respectively.[11]

[10] U.S. Environmental Protection Agency, Office of Solid Waste, Identification and Description of Mineral Processing Sectors and Waste Streams, p. 331-352, April 1998

[11] Environmental Protection Agency, Technical Background Document, "Identification and Description of Mineral Processing Sectors and Waste Streams,"

7.7 Hazardous Waste

The commodities gold and silver ore have been evaluated from extraction to the first saleable product. There are no RCRA-listed (Resource Conservation and Recovery Act) hazardous wastes associated with copper ore mining, beneficiation, and processing. The material generated from gold and silver ore mining, beneficiation, and processing is managed through recycling.