Chapter 6

Copper Production Technology

CONTENTS

Boxes

Figures

Tables

Chapter 6

Copper Production Technology

The last boom in technological innovation for the copper industry occurred in the first two decades of this century, when open pit mining, flotation concentration, and the reverberatory smelter were adapted to porphyry copper ores. With the exception of leaching-solvent extraction-electrowinning, the basic methods of copper production have remained unchanged for 65 years. Moreover, six of the mines opened between 1900 and 1920 are still among the major copper producers in the United States today.

Instead of great leaps forward, technological innovation in the copper industry in the last 65 years has consisted largely of incremental changes that allowed companies to exploit lower grade ores and continually reduce the costs of production. Economies of scale have been realized in all phases of copper production. Both machine and human productivity have increased dramatically.

This chapter briefly describes the technology for producing copper, from exploration, through mining and milling, to smelting and refining or solvent extraction and electrowinning. The chapter begins with an overview of the history of copper technology development. Then, for each stage in copper production, it reviews the current state-of-the-art, identifies recent technological advances, reviews probable future advances and research and development needs, and discusses the importance of further advances to the competitiveness of the U.S. industry. Figure 6-1 shows flow-sheets for pyrometallurgical[1] and hydrometallurgical[2] copper production. Tables 6-1 and 6-2 provide capsule summaries of these processes.

---

[1] Pyrometallurgy Is the extractIon of metal from ores anD concentrates using chemical reactions at high temperatures.

[2] Hydrometallurgy is the recovery of metals from ores using water-based solutions.

HISTORY

As early as 6000 B. C., native copper–the pure metal—was found as reddish stones in the Mediterranean area and hammered into utensils, weapons, and tools. Around 5000 B. C., artisans discovered that heat made copper more malleable. Casting and smelting of copper began around 4000-3500 B.C. (see figure 6-2). About 2500 B. C., copper was combined with tin to make bronze—an alloy that allowed stronger weapons and tools. Brass, an alloy of copper and zinc, probably was not developed until 300 A.D.

Copper was first mined (as opposed to found on the ground) in the Timna Valley in Israel—a desolate area believed to be the site of King Solomon's Mines (see figure 6-3). The Phoenicians and Remans, who worked the great mines on Cyprus and in the Rio Tinto area of southern Spain, made the early advances in copper exploration and mining methods. For example, the Romans found nearly 100 lens-shaped ore bodies in the Rio Tinto copper district. Modern geologists have found only a few additional deposits, and almost all of Rio Tinto's modern production has been from ore first discovered by the Remans.[3]

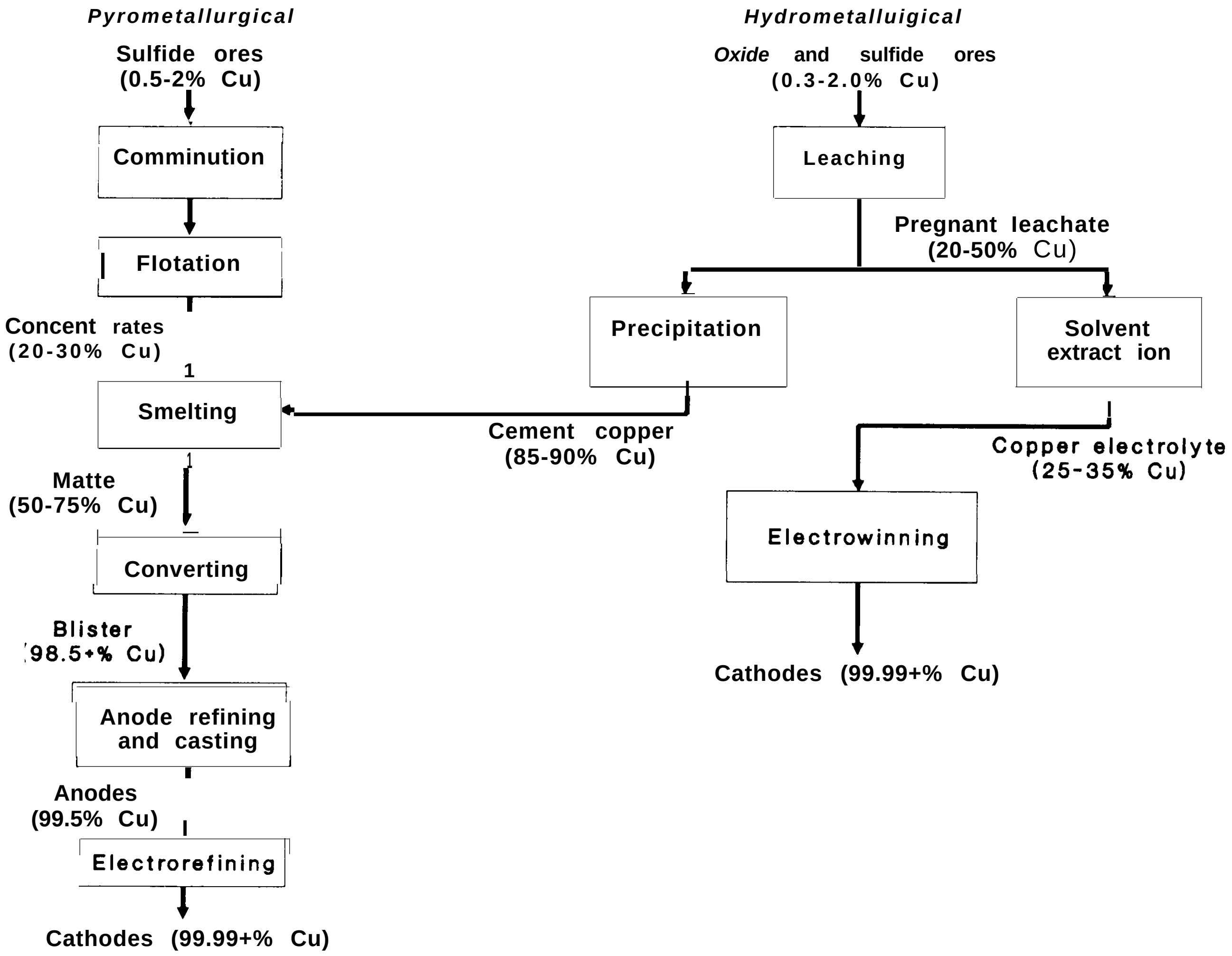
At Rio Tinto, the Remans mined the upper, oxidized, part of the ore and collected the copper-laden solutions produced by water slowly seeping down through the sulfide ore bodies. When the Moors conquered this part of Spain during the Middle Ages, the oxide ores had largely been exhausted. Learning from the Roman experience with seepage, the Moors developed open pit mining, heap leaching, and iron precipitation techniques that continued to be used at Rio Tinto into the 20th century.

In Britain, copper and tin were worked in Cornwall and traded with the Phoenicians as early as 1500 B.C. The Remans brought improved metallurgical techniques to Britain, and spurred devel-

---

[3] ira B. joralemon, *Copper; The Encompassing Story of MankInd's First MetaL* (Berkeley, CA: Howell-North Books, 1973).

Figure 6-1.-Flow Sheets for Copper Production



SOURCE: Office of Technology Assessment.

opment of the mines of Cumberland and North Wales. When the Remans left Britain early in the 5th century, however, economic development stagnated and it was a thousand years or more before Britain's metal industry was reestablished.[4] In the interim, Germany became the center of the European copper industry, bringing a number of improvements in copper mining, metallurgy, and fabricating.[5]

King Henry **VIII reopened the mines** in Cumberland and **elsewhere, and Britain** became famed for bronze casting and the manufacture of armaments. By the end of the 16th century, Britain was producing 75 percent of the world's copper. British advances in metallurgy helped to establish a world monopoly in smelting that continued until around 1900, when foreign producers built large mills and smelters that took advantage of such British inventions as the reverberatory furnace and froth flotation. b Moreover, the miners

---

[4] Sir Ronald L. Prain, *Copper: The Anatomy of an Industry* (London: Mining journal Books Ltd., 1975).

'Raymond F. Mikesell, *The World Copper Industry: Structure and Economic Analysis* (Baltimore, MD: The Johns Hopkins Press, 1979).

[6] Prain, supra note 4.

Table 6-1.—Summary of Pyrometallurgical Processes

Activity	Product	Constituents	Percent copper	Purpose or result
Big Bang	Universe		0.0058	Formation of the earth
Hydrothermal alteration	Porphyry rocks	Pyrite, chalcopyrite, etc.	0.2-6.0	Concentration of copper in earth's crust
Exploration and development	Deposit	Copper ore, other minerals, waste rock (gangue)	0.2-6.0	Location of economic resource
Mining	Ore	Copper minerals, iron and other metallic pyrites, byproducts, and gangue	0.5-6.0	Remove ore from ground and surrounding rock or overburden
Comminution.	Pulverized ore	Same as mining but in the form of fine particles	0.5-6.0	Creation of large surface area as preparation for flotation
Beneficiation (flotation)	Concentrate	Copper minerals, iron pyrites, miscellaneous minerals (including valuable byproducts), and water (8-10%)	***20-300/o*** dry	Removal of most gangue and collection of some byproduct minerals (e.g., Mo, Ni, Pb, Zn) to avoid further expense in materials handling, transportation, and smelting
Smelting.	Matte	Copper sulfide (CU$_2$S), iron sulfide (FeS), byproducts, tramp elements, and up to 3°/0 dissolved oxygen	30-40°/0 reverb, 50-75°/0 flash	Heat-induced separation of complex sulfides into copper sulfides, iron sulfides, and sulfur; removal of sulfur as off gas (SO$_2$) and removal of gangue via slag; in oxygen-charged systems, partial (50-90°/0) oxidation of iron to produce iron oxide removed in the slag and to produce heat
Converting	Blister	Copper with 0.5-2.0% dissolved oxygen and 0.05-0.2% sulfur, plus byproducts and some tramp elements	**98-99**	Oxidation and removal of most of the remaining iron and sulfur; oxidation of copper sulfide (CU$_2$S) to elemental copper and S0$_2$
Fire refining.	Anode	Copper with 0.05-0.2% dissolved oxygen and 0.001-0.003% sulfur, plus byproducts and tramp elements	**98-99**	Further removal of oxygen via introduction of carbon or removal of sulfur via injected air to produce sheets strong enough and even enough for electrorefining (i.e., devoid of blisters)
Electrorefining	Cathode	Copper with less than 0.004% metallic impurities. includina sulfur	99.99	Collect byproducts (Ag, Au, PGMs) and remove tramp elements (Bi, As, Fe, Sn, Se, Te)

SOURCE: Office of Technology Assessment, 1988

Table 6-2.—Summary of Hydrometallurgical Processes

Activity	Product	Constituents	Percent copper	Purpose or result
Big Bang	**Universe**		0.0058	Formation of the earth
Hydrothermal alteration and oxidation	**Porphyry rocks**	Copper ores	0.2-6.0	Concentration of copper in earth's crust
Exploration and development	**Deposit**	Copper ore, other minerals, waste rock (gangue)	0.2-6.0	Location of economic resource
Mining[a].	**Ore**	Copper minerals,[b] iron and other metallic pyrites, byproducts, and gangue	0.5-6.0	Remove ore from ground and surrounding rock or overburden
Leaching	**Pregnant leachate**	Solution of copper and leaching agent (water or H_2SO_4)	20-50	Dissolution of copper from ore in sulfuric acid solvent, collection of solvent for cementation or solvent extraction
Cementation (precipitation)	**Cement copper**[c]	Copper, iron (0.2-2.00/0), trace amounts of silica and aluminum oxides, and oxygen	85-90	**Remove copper from pregnant leachate and remove some impurities**
Solvent extraction	**Copper electrolyte**	Organic solvent and pregnant leachate; then organic copper mixture plus H_2SO_4	25-35	Remove copper from pregnant leachate and produce an electrolyte with sufficient copper content for electrowinning
Electrowinning	**Electrowon cathodes**	Copper with less than 0.004% metallic impurities	99.99	Recover copper from the loaded electrolyte solution, recover valuable byproduct metals (Au, Ag, PGMs), eliminate tramp metals

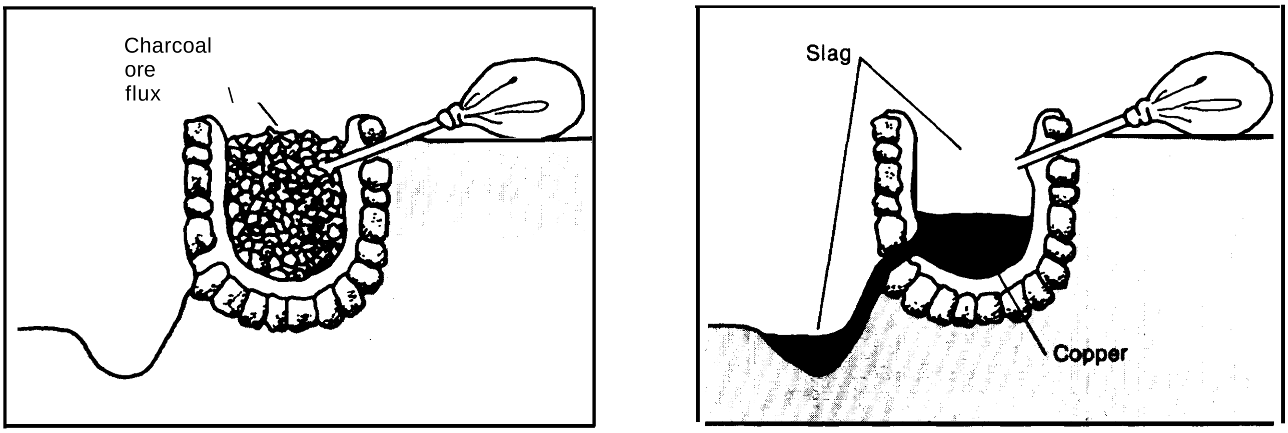
[a] Mining is essentially a comminution process (see table 6-l); dump leaching uses materials that have already been mined and broken UP with explosives

[b] Primarily low-grade oxidized minerals (e.g., malachite, azurite, chrysocolla, cuprite, tenorite) but also sulfide minerals in waste dumps.

[c] Cement copper usually is smelted, converted, and electrorefined (see table 6-l).

SOURCE: Office of Technology Assessment, 1966.

Figure 6-2.—Early Smelting Technology



The Egyptian copper smelting furnace was filled with a mixture of copper ore, charcoal and iron ore to act as a flux. It was blown for several hours by foot or hand bellows.

By the end of the smelt the copper had separated from the slag, which was tapped off.

SOURCE Robert Raymond, *Out of the Fiery Furnace* (University Park, PA: The Pennsylvania State University Press, 1986)

and metallurgists of Cornwall, Devon, and Wales provided much of the expertise for the early days of the American copper industry.[7]

Native Americans used native copper from the Keeweenaw Peninsula of Upper Michigan and from Isle Royale in Lake Superior as far back as 5000 B.C. (figure 6-4). The American colonies produced copper beginning in 1709 in Simsbury, Connecticut. By the 1830s, U.S. production in Connecticut, New Jersey, and other States was sufficient to supply the fabricators in Boston and New York, but the demand for finished copper and brass products was much greater than the Supply.[8]

Thus, the discovery of copper (and other mineral) deposits became an important part of westward expansion in North America. Each ore body is unique, however, and finding the ore often was easier than devising methods of economical copper production and transportation. Table 6-3 provides a chronology of the major copper mines in the United States, and the technological advances they contributed.

Organized copper mine development began late in 1844 at Copper Harbor on the tip of the Keeweenaw Peninsula–the first regular mine shafts in the United States. The Cliff Mine, the first great copper mine in the Western Hemisphere, opened in 1845; it contributed advanced engines for hauling ore and miners out of the shafts, and for dewatering the mine.[9]

As the population moved West, the discovery of copper deposits often succeeded disappointing gold and silver claims. For example, mining in Butte, Montana (figure 6-5) began in the early 1860s with gold, and then moved to a body of silver and copper ore. The stamp mills (crushers) and smelting furnaces in Butte could not separate the silver economically, however, and the cost of transporting the ore 400 miles to the railroad was prohibitive. Butte was about to become another Western ghost town, when adaptation of smelting furnaces led to a silver boom. Then, in 1881, a huge seam of rich "copper glance" (chalcocite) that ran 30 percent copper turned Butte into "the richest hill on earth." Railroads were opened to Butte by the end of 1881, and it was soon a city of 40,000 with four copper

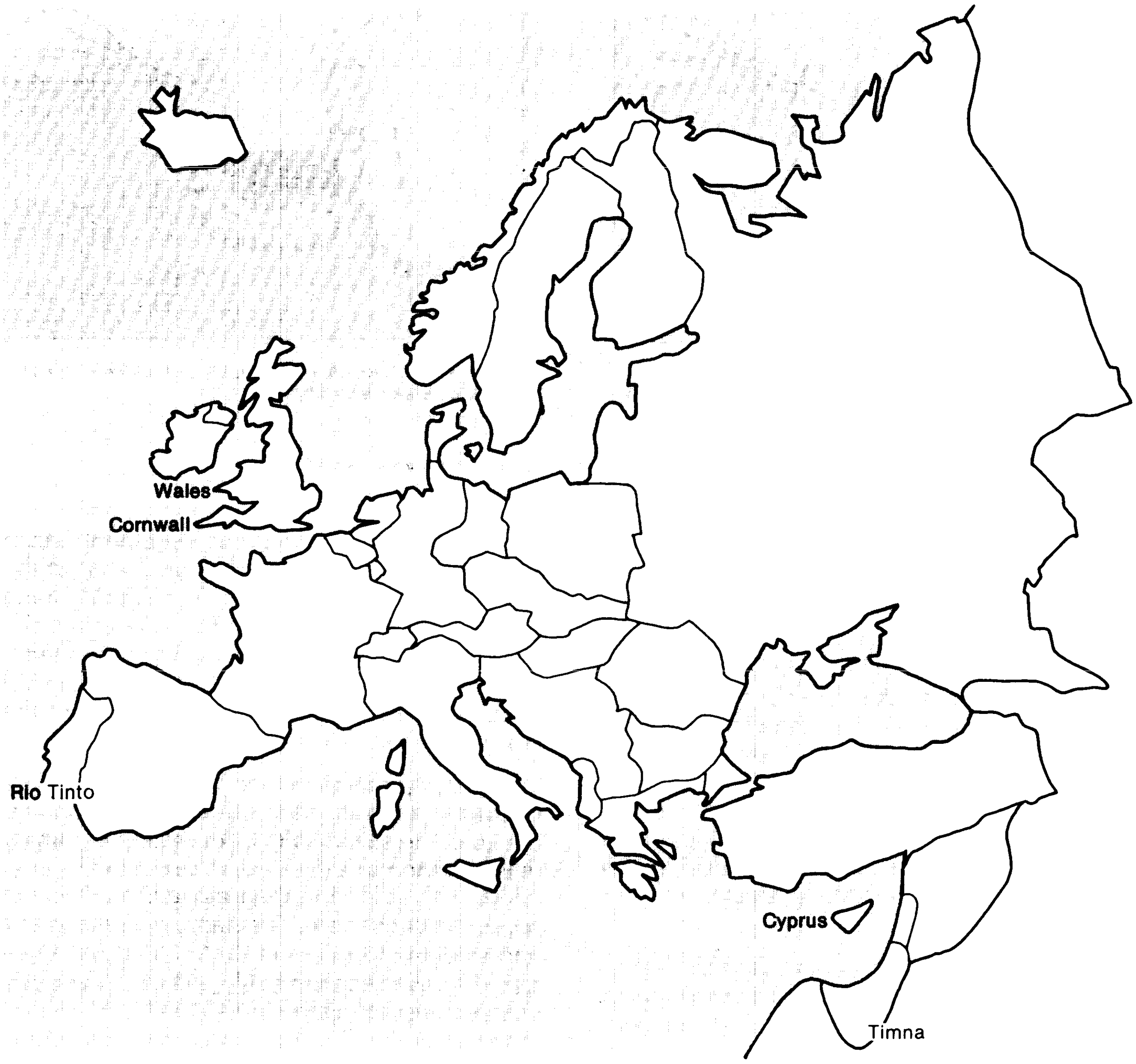
---

[7] Donald Chaput, *The Cliff: America's First Great Copper Mine* (Kalamazoo, MI: Sequoia Press, 1971).

[8] Ibid.

[9] Ibid.

Figure 6-3.—Early Copper-Producing Areas of Europe and the Middle East



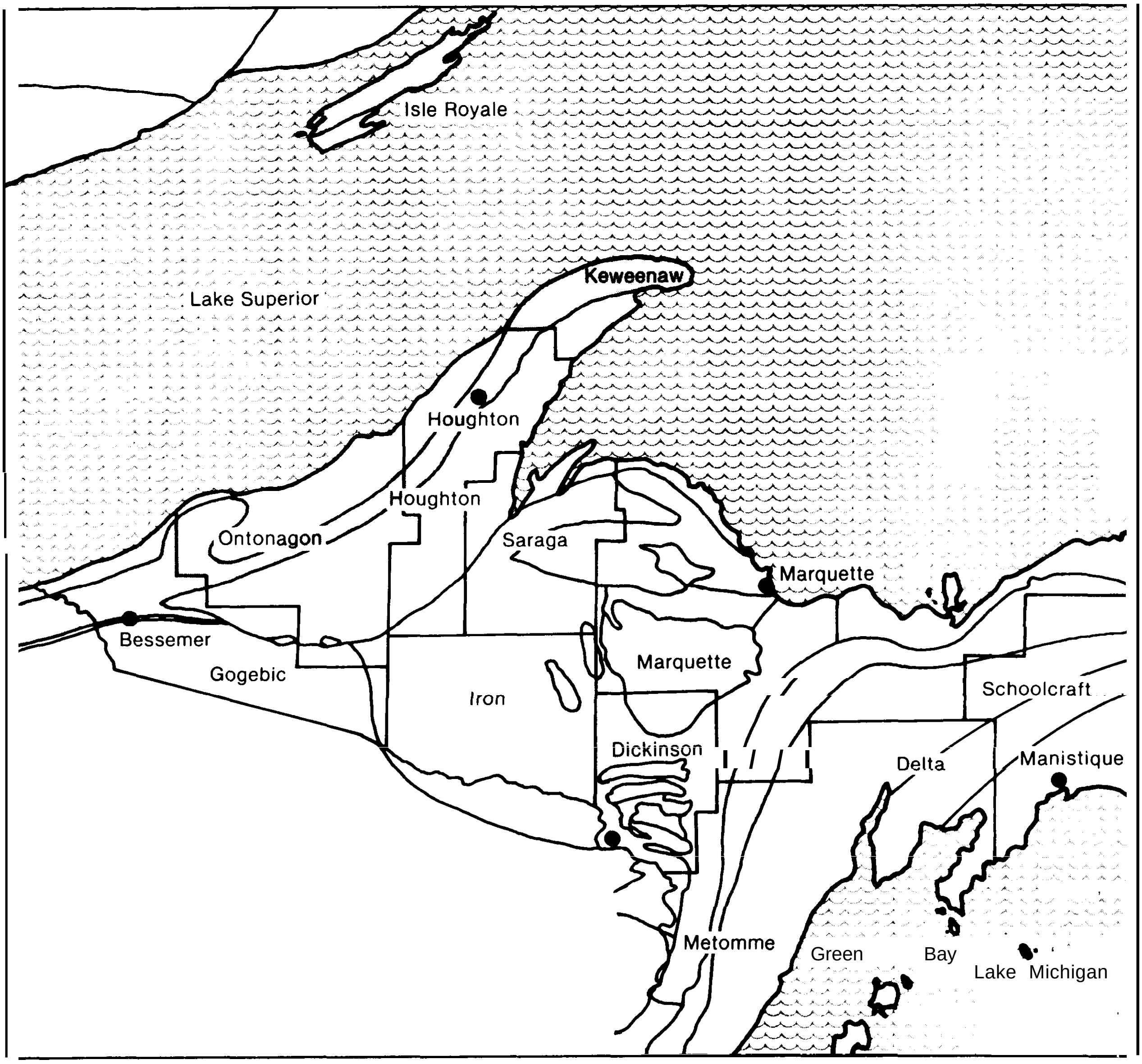
smelters. By 1887, Butte had passed the Lake Superior Copper Country in production.[10]

As in Montana, gold and silver mining in the Southwest paled into insignificance with the discovery and development of rich copper deposits. Also similar to Butte, profitable development of the southwestern deposits depended on construction of railways to transport the copper to fabricators, and on processing and smelting techniques that could economically handle the various grades and types of ore found, which included carbonates, oxides, sulfides, and silicates. A third factor was the amount of capital needed

---

[10] Joralemon, supra note 3.

Figure 6-4.—Copper Deposits of Northern Michigan



The thin band of the Keweenaw copper range shoots UP through the peninsula, then goes beneath Lake Superior. Isle Royale is in the same geological formation.

SOURCE: Donald Chaput, *The Cliff: America's First Great Copper Mine* (Kalamazoo, MI: Sequoia Press, 1971).

to develop an ore body into a producing mine and provide the necessary infrastructure to exploit it.

The Southern Pacific Railroad was completed across Arizona in 1882, and lines eventually were extended to the various mining districts (see figure 6-6). Processing and smelting methods usually had to be tailored to each ore body or district. For example, in the early 1880s the mass-produced Rankin & Brayton water-jacket furnace revolutionized the smelting of oxide ores from the Bisbee district of Arizona. This furnace could be shipped as a complete unit, requiring

Table 6-3.—Major U.S. Copper Mines

Year opened	Year closed	Name	Location	Owner	Ore grade and type	Mine type	Technological advances[a]
1844	1845	Copper Harbor	Keeweenaw Peninsula, Michigan	Pittsburgh & Boston Mining Co.	silicate, black oxide of copper	UG	First regular mine shaft in U.S.
1845	1870[b]	The Cliff	Keeweenaw Peninsula, Michigan	Pittsburgh & Boston Mining Co.	native copper	UG	First ore mass of native copper found in U.S.; development of mining and milling techniques used for at least two decades, including first Man Engine (hoist) in U.S.
1872	NA	Longfellow (and other shafts)	Clifton, Arizona	Arizona Copper Co.; then Phelps Dodge	20% then 4-5%	UG	First smelter in Arizona (1872); first railroad in Arizona; first concentrator (1886); first precipitation plant (1894); first successful mining of copper by block-caving (1910)
1875	NA	Morenci	Morenci, Arizona	Detroit Copper Co.; then Phelps Dodge	20%, then 4-5%	UG	
1880	1975	Copper Queen[c]	Bisbee, Arizona	Copper Queen Mining Co., then Phelps Dodge	23%—malachite, azurite	UG	Demonstration of large, mass-produced water-jacket furnace for smelting carbonate and oxide ores
1881	962	Anaconda (and many other shafts, later consolidated with Anaconda for open pit mining)	Butte, Montana	Anaconda Silver Mining Co. (later Amalgamated Copper), and Boston & Montana Co.; then Anaconda Minerals	30%—copper glance (chalcocite)	UG (open pit since early 1960s)	Furnace that would smelt copper and silver (1873); compressed air drills; first use of flotation (zinc—1912)
1881	NA	Old Dominion	Globe, Arizona	?, then Lewisohn Bros., then Phelps Dodge		UG	
1889	NA	United Verde	Jerome, Arizona	Senator Clark, then Phelps Dodge		UG	
1899	1917	Irish Mag	Bisbee, Arizona	Calumet & Arizona Mining Co.	30% oxides 15% sulfides	UG	
1907	active	Bingham	Bingham Canyon, Utah	Utah Copper Co, then Kennecott Copper Co., then BP Minerals America	2%—sulfides	OP	Economies of scale for milling (1907); first open-pit mining with steam shovels (1907); first porphyry mill (1904)
1908	1978	Ely	Ely, Nevada	Nevada Consolidated Mining Co. then Utah Copper/Kennecott		OP & UG	
1910	1982	Superior	Superior, Arizona	Magma Copper Co.	4-6%—sulfides	UG	
1911	NA	Miami	Miami, Arizona	Lewisohn Bros.	2.5%	UG	First pebble mill (1911)
1911	active	Ray	Hayden, Arizona	Utah Copper/Kennecott, then Asarco		UG then OP	First large-scale caving mine; first organized churn drill prospecting of copper (1908)
91	active	Chino	Hurley, New Mexico	Utah Copper/Kennecott, then Phelps Dodge		OP	
915	active	Inspiration	Claypool, Arizona	Anaconda Minerals, then Inspiration Consolidated Copper Co., then Cyprus Mines	initially 2.5%, now 0.6% sulfides and oxides	UG then OP	First flotation plant for copper (1915); first electric rail haulage of copper underground (1926)
1916	NA	United Verde Extension	Jerome, Arizona				
1917	1984	New Cornelia	Ajo, Arizona	Calumet & Arizona Mining Co., then Phelps Dodge	0.6%—sulfides	OP	First sulfuric acid leaching (1917)
1921	1931	Sacramento Hill	Bisbee, Arizona	Phelps Dodge		OP	
1929	NA	Campbell	Bisbee, Arizona	Calumet & Arizona Mining Co., then Phelps Dodge	40% copper glance	UG	

Table 6-3.—Major U.S. Copper Mines—Continued

Year opened	Year closed	Name	Location	Owner	Ore grade and type	Mine type	Technological advances[a]
1940 . .	active	**Bagdad**	**Bagdad,** Arizona	Cyprus Mines	0.5% —sulfides	OP	
1942 .	active	**Clay/Morenci**	**Morenci,** Arizona	**Phelps** Dodge	0.70/0—sulfides	OP	
1950	active	**San** Manuel	San Manuel, Arizona	Magma Copper Co.	0.6-0.70/. —sulfides	UG	
1954	7984	Silver Bell	Silver Bell, Arizona	**Asarco**	4-6% —sulfides	OP	
1955 ...,	1974	Lavender Pit	**Bisbee,** Arizona	**Phelps** Dodge		OP	
955	active	White Pine	White Pine, Michigan	Copper Range Co.	1% —sulfides	UG	
957	active	Pima	**Sahuarita,** Arizona	Cyprus Mines	0.50/O—sulfides	OP	
959	1985	Twin Buttes	**Sahuarita,** Arizona	Anaconda, then **Anamax,**	0.920/0—sulfides	OP	First solvent extraction
988	active			then Cyprus	0.730/0—oxides		**electrowinning** plant (1976)
962	active	Mission	**Sahuarita,** Arizona	**Asarco**	sulfides	OP	
963	1983	Butte	Butte, Montana	Anaconda Minerals,		OP	
986	active			then Montana Resources			
964	NA	Ithaca Peak	Mineral Park, Arizona	**Duval**		OP	
1969	active	**Tyrone**	**Tyrone,** New Mexico	**Phelps** Dodge	0.70/o—sulfides	OP	
1970	active	**Sierrita**	**Sahuarita.** Arizona	**Duval**, then Cyprus	0.3%-sulfides	OP	First in-pit crushing and conveying system
1972	1984	**Sacaton**	**Casa Grande,** Arizona	**Asarco**	sulfides	OP & UG	
1973	active	San Xavier	**Sahuarita,** Arizona	**Asarco**	sulfides	OP	
1974	active	Metcalf	**Morenci,** Arizona	**Phelps** Dodge	0.80A—sulfides	OP	
1974	leaching	Lake Shore	**Casa Grande,** Arizona	**Hecla,** then Noranda, then Cyprus	10\O —oxides	UG	
1974	active	Pinto Valley	Miami, Arizona	Cities Service, then Magma	0.460/0—sulfides	OP	
1975	1986	Johnson	Benson, Arizona	Cyprus	0.40/0	OP	
1978 . . .	active	Eisenhower	**Sahuarita,** Arizona	**Anamax,** then **Asarco**	sulfides	OP	
1986	active	San Manuel	San Manuel, Arizona	Magma	oxides	OP	

NA indicates the actual date of closing or incorporation into open pit mining is unknown.

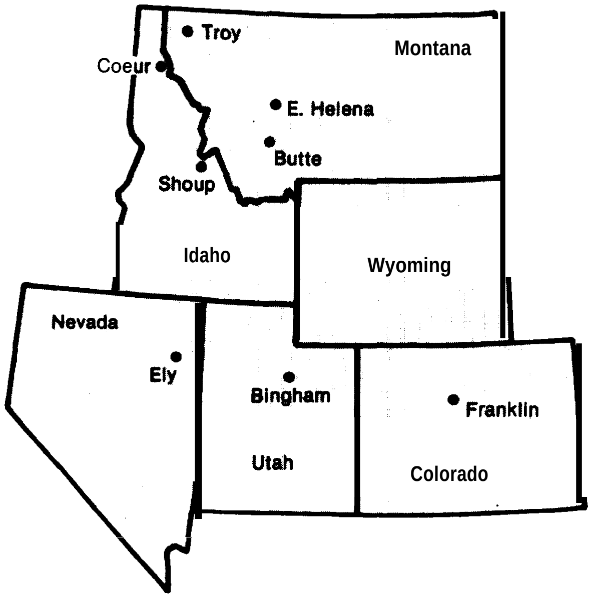
[a] Dates indicate first use in the U.S. unless otherwise indicated.

[b] Minor amounts of production continued under various owners until around 1903.

[c] Numerous other shafts were opened in Bisbee between 1877 and 1900, most of which were subsequently purchased by Phelps Dodge and managed Jointly with the Copper Queen.

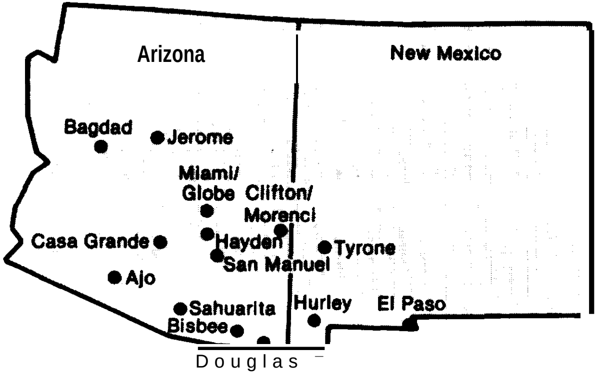
SOURCE: Office of Technology Assessment, 1988

Figure 6-5.—Copper Production Areas of the Northern and Central Rocky Mountains



SOURCE: Office of Technology Assessment, 1988.

Figure 6.6.—Copper Production Areas of the Southwest



SOURCE. Office of Technology Assessment, 1988.

few onsite engineering skills; it had improved fuel economy, important in the lightly forested mountains of southeastern Arizona; and it required no fire brick in its construction, which saved on shipping costs.[11]

Further developments in mining and processing technology followed the gradual decline in ore grades.[12] By the late 1800s, the **copper ore** grade in the Clifton-Morenci District of Arizona had declined to only 4 to 5 percent copper–too lean to be smelted directly at a profit. James Colquhoun devised a means of concentrating the ore based on techniques used to process Colorado gold ores. For some leaner oxide ores that could not be processed this way, Colquhoun worked out a process for dissolving the copper in sulfuric acid and precipitating it on iron. This first U.S. leaching plant was built in 1892.[13]

The adaptation of Colquhoun's techniques to deposits of low-grade porphyry ores was pioneered at Bingham Canyon in Utah, where gold and silver miners had found an unusually large mass of copper porphyry ore. But the ore grade, then estimated to average 2.22 percent copper, was too low to be exploited economically with traditional mining and smelting methods.[14] The Utah Copper Company's engineer, Daniel Jackling, determined that economies of scale were the key to making Colquhoun's concentration techniques economical with such low-grade ore. The Utah Copper Company's 5000-ton-per-day mill at Bingham Canyon began commercial production in 1907. Utah Copper made it even more profitable by introducing open-pit mining with steam shovels.[15]

Economies of scale in smelting also were realized in the early 1900s. Phelps Dodge had been having problems with the Copper Queen smelter in Bisbee as the mine went deeper and the copper carbonate and oxide graded into sulfide ore. An entirely new smelter was built 25 miles south of Bisbee, at a site named after James Douglas, head of Phelps Dodge's Bisbee operations. The most modern smelter of its time, it had five furnaces with a capacity of 5000 tons/day.[16] Phelps Dodge closed the Douglas smelter in 1987 because bringing it into compliance with air quality regulations would have been too costly.

As soon as Jackling showed that the low-grade porphyrins could be mined profitably, they became the focus of exploration and development.

---

[11] Lynn R. Bailey, *Bisbee: Queen of the Copper Camps* (Tucson, AZ: Westernlore Press, 1983).

[12] The importance of ore grades for mine economics and competitiveness is discussed in ch. 5.

[13] Joralemon, supra note 3.

[14] The changes in ore grade over time, and their effects on the estimated resources in an ore body, are discussed in ch. 5, box 5-A.

[15] Joralemon, supra note 3.

[16] Bailey, supra note 11.

The Nevada Consolidated Company began production in Ely, Nevada in 1908. The Lewisohn Brothers partnership, which owned the Old Dominion Mine at Globe, Arizona, opened a porphyry mine at nearby Miami, Arizona in 1911. The Utah Copper Company opened Ray Mines in Arizona and Chino Mines in New Mexico in 1911. Phelps Dodge acquired claims and started development work at Tyrone, New Mexico, during the same period.[17] Most of these porphyrins are still among the major producing ore bodies in the United States today.

Not all of the porphyry ores were amenable to Jackling's methods, **however.** For instance, available milling techniques could not recover enough of the 2.5 percent ore at the Inspiration Company's claims near Miami, Arizona. When Anaconda purchased these claims, their consulting engineer, L.D. Ricketts, expanded on Colquhoun's and Jackling's work **plus developments** in Britain, and built the first flotation plant for copper in the United States.[18] Similarly, profitable development of the 30 million tons of 1.5 percent carbonate ore at Ajo, Arizona was questionable until Ricketts developed a process of leaching with sulfuric acid that would produce copper from Ajo ore for 8.5 cents/lb (the current selling price was 14 cents/lb) .19

Phelps Dodge further refined these techniques during the 1930s. Under 1935 conditions, with the price of copper at 10 cents/lb, they proved that a profit could be made with ore that was only around 0.75 percent copper. However, demand was too low to open new low-grade mines until the wave of industrial development following World War **II. The accompanying technological advances that permitted economic exploitation of low-grade ore bodies included large-scale min**ing equipment that facilitated open-pit operations, and further improvements in crushing and flotation. More recent improvements, such as new smelting furnaces and hydrometallurgical processing methods, are described in the remainder of this chapter.

---

[17] Prain, supra note 4.

[18] A zinc flotation plant had been built in Butte in 1912.

[19] Joralemon, supra note 3.

EXPLORATION

Exploration includes *all* activities in the search for and discovery of new mineral deposits, plus the evaluations necessary to make a decision about the size, initial operating characteristics, and annual output of a potential mine. Exploration expenditures are highly sensitive to metal markets, as evidenced by the trends during the 1980s, when gold exploration has boomed while base metal exploration reached new lows. **U.S.** companies have drastically cut their base metal exploration staffs, land holdings, and most forms of prospecting.[20] Companies will continue exploration on a worldwide basis for a number of reasons, however. Their reserve base may be in mines at which production is not economic at current prices with existing technology, or they may have only a few years of production remaining at existing mines. Other countries may wish to increase mineral production to promote employment, enhance foreign exchange, and finance **economic development.** Even after discovery of a deposit and the start of mining, exploration continues in an effort to find additional ore that will keep the mine going for a longer time.

Modern exploration incorporates both direct and indirect techniques. Direct methods include geologic and photogeologic[21] mapping (figure 6-7); the study of rock types, geologic structures, and other indicators of an ore body (figure 6-8); and drilling and sampling. Indirect methods include geochemica1[22] and geophysical[23] investi-

---

[20] "MIneral Exploration, " *Engineering and Mining Journal,* July *1987.*

[21] Photogeology is the geologic interpretation of aerial photographs.

[22] Geochemistry is the study of the distribution and *amounts of* chemical elements in the Earth. Geochemical exploration uses the systematic measurement of one or more chemical properties of naturally occurring materials (e. g., rocks, glacial debris, soils, stream sediments, water, vegetation, and air) to identify chemical patterns that may be related to mineral deposits.

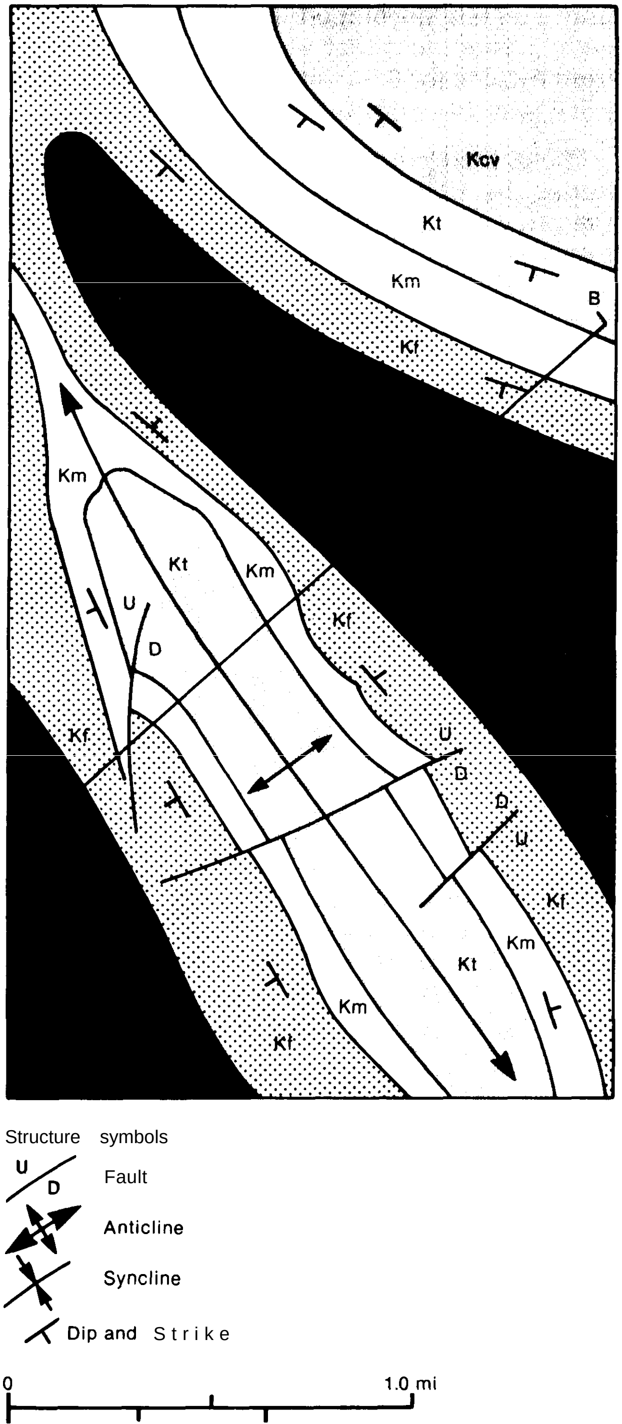
[23] Geophysics is the study of the earth by quantitative physical methods. Exploration geophysics applies the principles of physics

gations. Both direct and indirect methods are followed by Laboratory. analyses of ore samples, including ore treatment, concentration, and recovery tests; and evaluation of labor, transportation, water, energy, and environmental requirements. All of these studies must show favorable economic and technical results before a copper deposit can be considered a candidate for development. The cost of a total exploration program—from initial literature search through feasibility study—for a large porphyry copper deposit today ranges from 5 million to tens of millions of dollars.

Exploration programs are divided into two main phases: reconnaissance and target investigation (see figure 6-9). Reconnaissance determines whether the probability of finding ore in an area is favorable enough to warrant more extensive—and more expensive—investigation. When a potentially favorable target area is found, the company must acquire the right to develop it. Land can be acquired by leasing or purchasing mineral rights owned by private parties, by staking claims on Federal lands, or by leasing Federal or State land, Some lands are unavailable for exploration and development due to withdrawal for other uses (e.g., wilderness, military reservations, water projects, or urban development).

Following acquisition, the exploration team investigates the target in detail, first on the surface, and then, if warranted, by drilling. The vertical samples of ore and surrounding material taken from drill holes are assayed to show the depth at which the ore or other rock was found, the type and thickness of the material, and other data. Then, metallurgical tests are run to determine amenability of the ore to flotation or other techniques for separating the minerals from the host rock.

Figure 6-7.—Sample Geologic Map (Bighorn Basin, Wyoming)

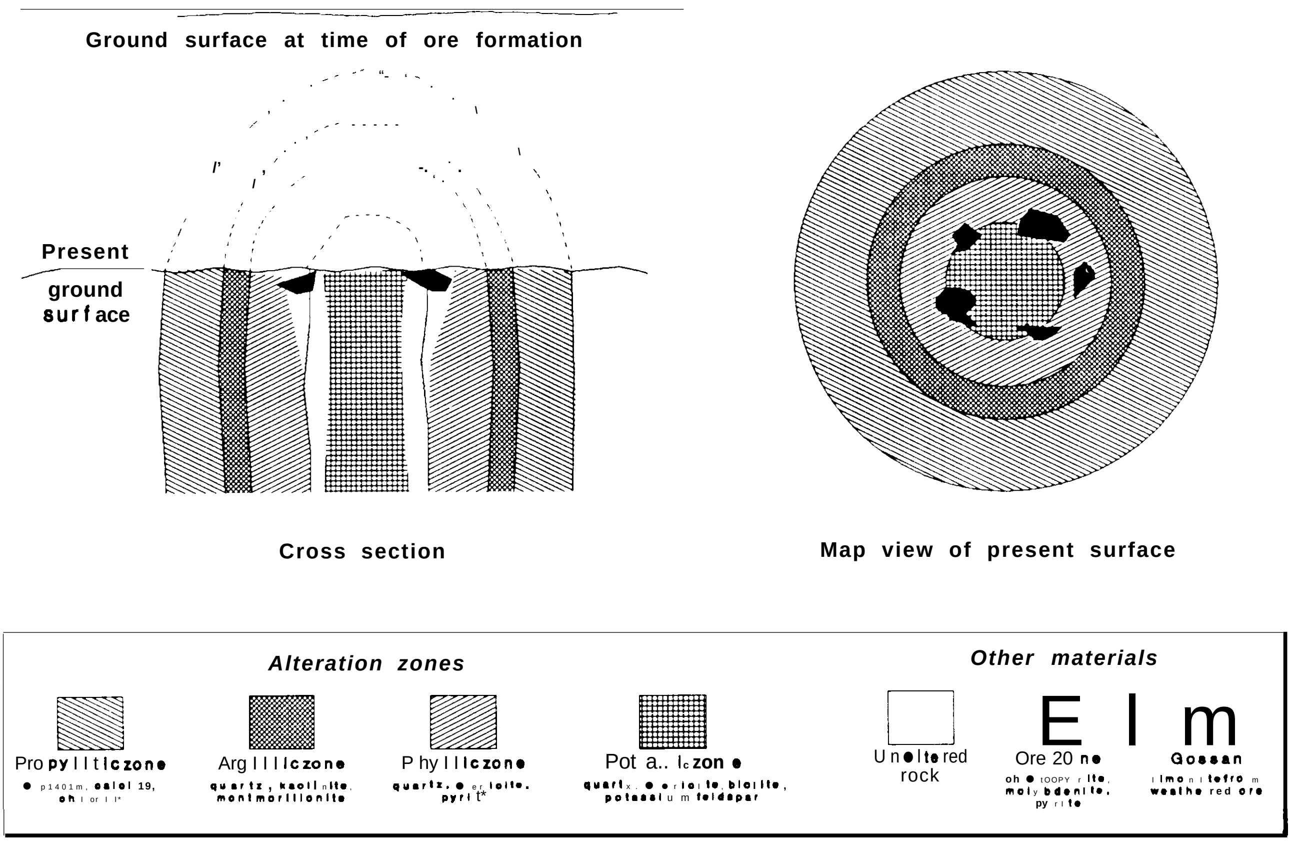


SOURGE: Floyd F. Sabins, Remote *Sensing: Principles and Interpretation* (New York, NY: W.H. Freeman & Co., 1987).

---

to the search for mineral deposits. The geophysical properties and effects of subsurface rocks and minerals that can be measured at a distance with sophisticated electronic equipment include density, electrical conductivity, thermal conductivity, magnetism, radioactivity, elasticity, specific gravity, and seismic velocity. The techniques commonly used, either singly, or in combination in exploring for metallic minerals are magnetic, electrical, and electromagnetic, because these minerals usually have magnetic and electrical properties that contrast with those of the surrounding rocks.

Figure 6-8.-Model of Hydrothermal Alteration Zones Associated With Porphyry Copper Deposits



Cross section

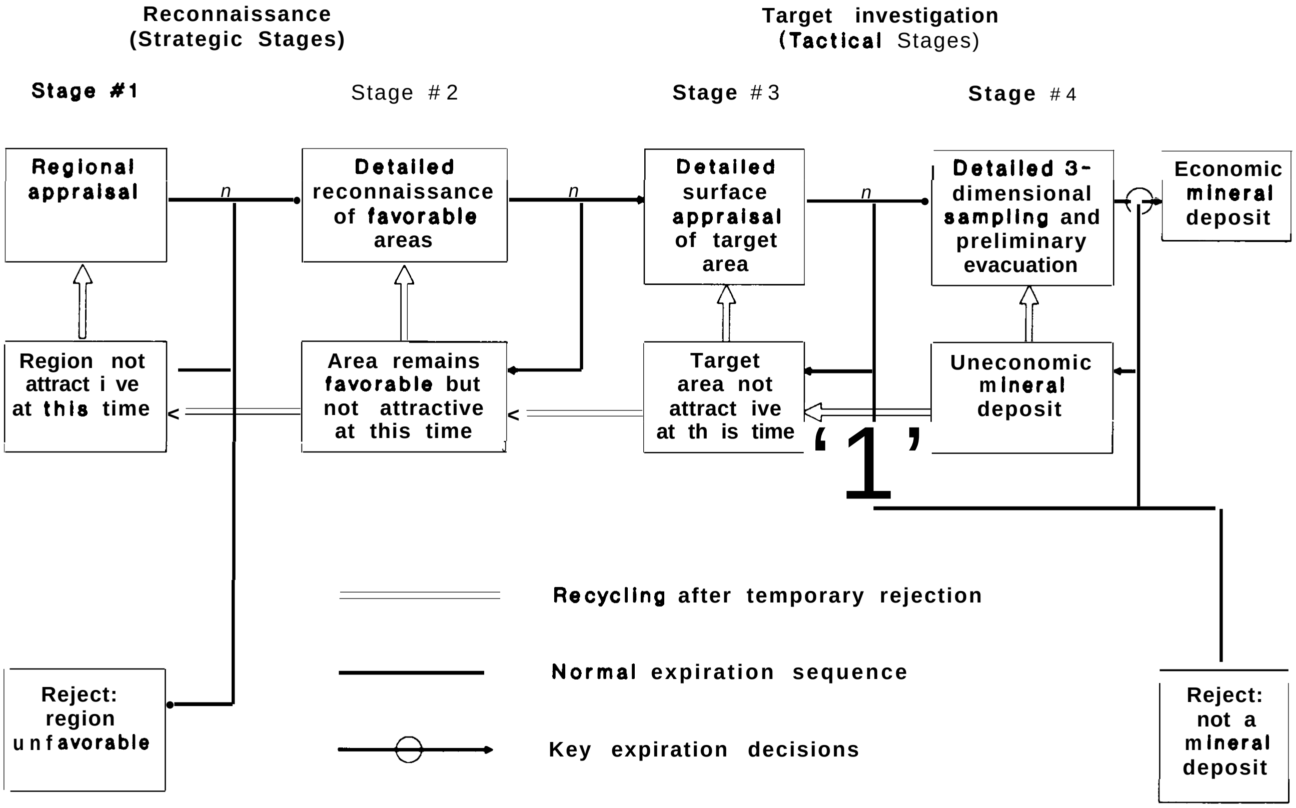
Map view of present surface

SOURCE Floyd F Sabins *Remote* Sensing *Principles and Interpretation (New* York NY W H Freeman and Co 1987)

Recent advances in exploration methods include computer and statistical techniques for analyzing and integrating data, and remote sensing technologies (see table 6-4). In addition, the industry has benefited from refined geologic models of the formation of copper ore bodies, improved and cheaper drilling techniques, and deeper penetration of electrical geophysical methods.

In the near term, it is unlikely that exploration will reveal large new U.S copper deposits that are minable with available technology, although smaller high-grade deposits probably will be found (e.g., a 3 percent copper deposit reported in Montana in 1987). More likely are technological advances that would allow known lower-grade ores to be mined economically. Such advances would stimulate exploration for deposits to which the new technology would apply. Thus, the advent of **solvent extraction and** electrowin**ning methods for recovering copper stimu**lated **exploration** for oxide deposits.

Figure 6-9.-Stages of Mineral Exploration



SOURCE: Mineral Systems Inc , *Technological Innovation in the Copper Industry* (Washington, DC: U S. Department of the Interior, Bureau of Mines, March 1983).

MINING

Mining is the extraction of minerals from ore deposits. The term “mining” encompasses traditional methods such as underground, open pit, and placer mining, as well as more exotic techniques such as in situ solution mining.[24] Table 6-5 summarizes the considerations in choosing a mining method for a particular ore body. Conventional open pit mining currently accounts for around 75 percent of domestic copper production (86 percent if dump and heap leaching are included).

In general, solution mining has lower capital and operating costs than other methods, but open pit mining offers the highest production rates and leaves the least ore behind. However, underground mining can reach greater depths. Open pit and solution mining have safety advantages over underground mining, but open pit methods have higher environmental costs than the other two. Theoretically, in situ solution mining may be more efficient than open pit mining, but its costs and production rates are unproven on a commercial scale.

Mining (and milling) represent around three-quarters of the gross operating cost of producing a pound of copper.[25] U.S. operations are at

---

[24] Solution mining is the leaching of ore with water-based chemical solutions. In situ solution mining treats the ore in place; i.e., without mining it first.

[25] This includes all aspects of mining and milling, from drilling and blasting of the overburden and ore, to transportation of concentrates to the smelter but excluding byproduct credits and working capital interest; see ch. 9.

Table 6-4.—Remote Sensing Systems and Image Types for Mineral Exploration

Image type	Wavelength region detected	Imaging system	Properties detected	Geology applications
Ultraviolet wavelength images	0.3-0.4 μm	Aerial cameras and scanners	Reflectance and fluorescence from solar radiation	Not useful
Visible and reflected IR wavelength photographs	0.4-0.9 μm	Aerial cameras, hand-held satellite cameras, Space Shuttle large-format camera	Spectral reflectance of solar energy in the visible and short wavelength IR regions; restricted to spectral sensitivity range of film	Identify visible topographic features, geologic structures (e.g. lineaments), and soil types for geologic mapping
Visible and multispectral reflected IR images	0.4-3.0 μm	Landsat Multispectral Scanner, Landsat Thematic Mapper, aerial scanners, Airborne Imaging Spectrometer, SPOT, Advanced Very High Resolution Radiometer	Spectral reflectance of solar energy in the visible and reflected IR regions	Geologic mapping, vegetative anomalies, rock types, hydrothermal alteration zones
Thermal IR images	3.0-14.0 μm	Aerial scanners, Heat Capacity Mapping Mission, Landsat Thematic Mapper band 6, and Thermal IR Multispectral Scanner	Radiant temperature, which is determined by kinetic temperature, emissivity, and thermal inertia	Rock types, surface moisture, geologic structures
Radar	1.0-30.0 cm	Aerial systems, Seasat, Shuttle Imaging Radar	Surface roughness and dielectric properties	Enhancement of geologic features, especially through dense vegetation or cloud cover, imaging of buried bedrock surfaces

SOURCE: Floyd F. Sabins, *Remote Sensing: Principles and Interpretation* (New York, NY: W. H. Freeman & Co., 1987).

Table 6.5.—Considerations in Choice of Mining Method

Physical:	
Geometry	Size, shape, continuity, and depth of the orebody or group of orebodies to be mined together Range and pattern of ore grade
Geology	Physical characteristics of ore, rock, and soil Structural conditions Geothermal conditions Hydrologic conditions
Geography	Topography Climate
Technological:	
Safety	Identification of hazards
Human resources	Availability of skilled labor
Flexibility	Selectivity in product and tonnage
Experimental aspects	Existing or new technology
Time aspects	Requirements for keeping various workings open during mining
Energy	Availability of power
Water requirements	Amount and availability
Surface requirements	Area needed
Environment	Means of protecting the surface, water resources, and other mineral resources
Economic:	
Cost limits	
Optimum life of mine	
Length of tenure	Prospects of long-term rights to mine

SOURCE William C. Peters, *Exploration and Mining Geology (New* York, NY: John Wiley & Sons, 1978)

a competitive disadvantage in mining because of relatively low average ore grades, only moderate byproduct credits, and high labor and environmental costs. Little can be done about the first two, and labor costs were lowered substantially in 1986. Therefore, further decreases in mining costs must come from improvements in mine technology and productivity. For instance, the Bureau of Mines estimates that in situ solution mining could make a domestic low-grade deposit competitive with foreign production from higher grade ores using conventional mining methods.[26] Conversely, any significant increase in mining cost could devastate the domestic industry.

Underground mining methods usually are used for deep ore bodies where an open pit would be impractical because of excessive waste removal. Figure 6-10 illustrates the basic terms applicable in underground mining; figure 6-11 shows two types of underground copper mines, Underground development and maintenance, including tunneling, rock support, ventilation, electrical systems, water control, and transportation of people and materials, add significantly to mining costs.

Open pit mining is used to extract massive deposits that are relatively near the surface. An open pit bench mine has the appearance of a bowl, with sides formed by a series of benches or terraces arranged in a spiral, or in levels with connecting ramps (figure 6-1 **2).** After removal of the overlying waste (overburden), the ore is blasted loose. Large electric or diesel shovels (or front-end loaders in smaller operations) load the ore onto trucks or conveyor belts for transport to the crusher. Open pit mining has lower development and maintenance costs than underground mining because it requires fewer specialized systems. However, the land disturbance is much greater and environmental costs can be high (see ch. 8).

In solution mining, or leaching, water or an aqueous chemical solution percolates through the ore and dissolves the minerals. The resulting mineral-laden solution, known as pregnant leachate, is collected and treated to recover the valuable minerals. Table 6-6 summarizes the four types of solution mining.

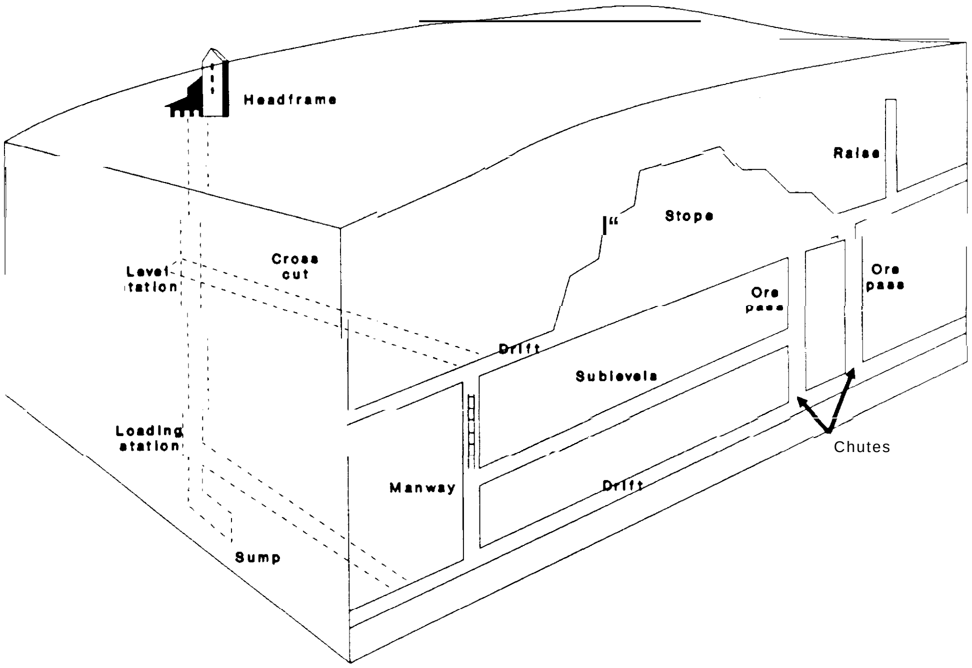
Vat, heap, and dump leaching are methods of hydrometallurgical processing of mined ore (see figure 6-13). Thus they are complements, not alternatives, to underground or open pit mining. In situ leaching is a stand-alone mining method (see figure 6-14). The leach solution percolates through the ore to be collected in wells or underground mine workings. Natural fractures or the effects of earlier mining can supply channels for the leach solution, or the ore can be blasted or fractured hydraulically.[27] U.S. companies have

---

[26] Mineral Systems Inc., *Technological Innovation in the Copper Industry* (Washington, DC: U.S. Department of the Interior, Bureau of Mines, March 1983).

[27] Jon K. Ahlness and Michael G. Pojar, *In Situ Copper Leaching in the United States: Case Histories of Operations* (Washington DC: U.S. Department of the Interior, Bureau of Mines, Circular No. 8961, 1983).

Figure 6-10.-Underground Mining Terms



SOURCE William C Peters, *Exploration and Mining Geology (New* York, NY: John Wiley & Sons, 1978)

mined copper in situ at 24 known sites (see table 6-7 and box 6-A).

Solution mining enjoys certain intrinsic advantages over conventional mining and milling, including lower combined capital and operating costs, faster start-up times, and fewer adverse environmental impacts. Furthermore, solution mining is an expedient method of extracting metals from small, shallow deposits and is particularly suited to low-grade resources. Leaching old mines (where the ore that can be mined economically has been removed) and leaching waste dumps both use an in-place resource for which the mining cost is already "off the books. "[28] As a result of these advantages, solution mining has gradually taken over an increasing percentage of domestic mine production (see ch. 4).

There have been no truly radical technological advances in mining technology for at least the last several decades. Witness a 1983 U.S. Bureau of Mines report on ***Technological Innovation in the Copper industry*** that had to stretch its time frame to the last 30 to 50 years to develop a list of innovations.[29] **Instead,** incremental improvements in existing methods, and adaptations of other types of technology to mining (e.g., computers, conveyor systems) have gradually reduced costs and increased productivity. These include improved drilling and blasting equipment and practices; larger and more efficient trucks and shovels; more efficient underground equipment such as hoists and ventilation fans; computerized truck dispatching for open pit mines; computerized and remote control systems for underground mine pumps and trains; in-pit ore crushing and conveying; and improved slope stability analyses that allow steeper pit walls.

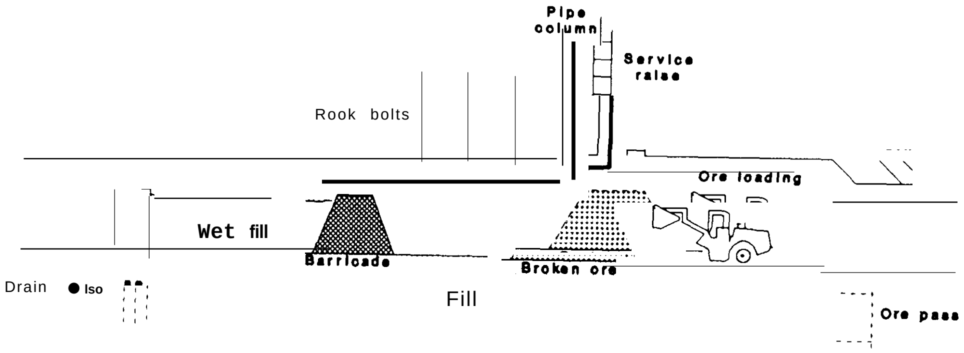
Possible future technological advances that could provide important productivity gains **in copper mining include further demonstration and development of in-pit crushing/conveying; an underground continuous mining machine adaptable to various ore and mine types; and in situ solution mining of virgin ore bodies.**

---

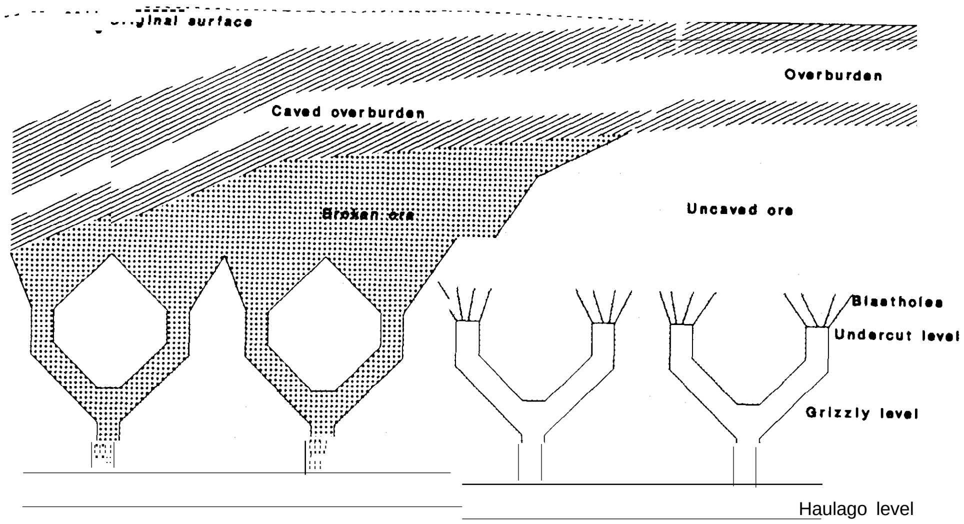
[28] Ibid.

[29] Mineral Systems **Inc.,** supra note 26

Figure 6-11.-Two Underground Mining Methods



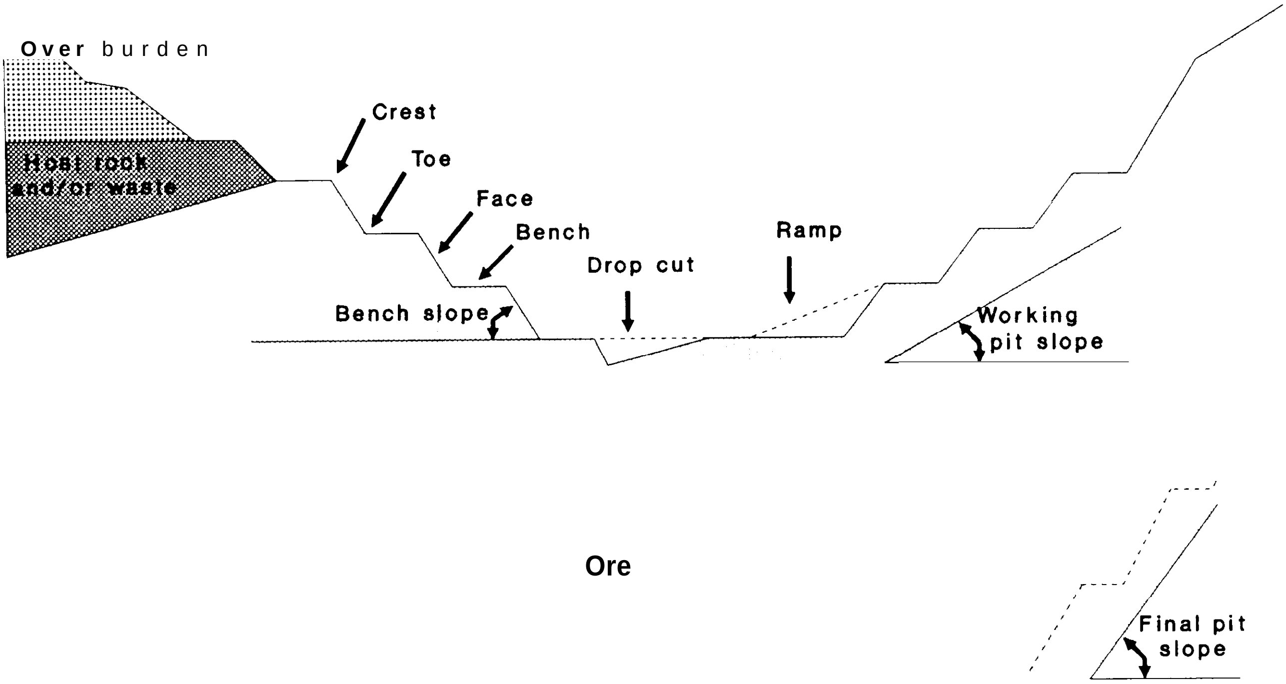
Cut-and-fill stoping



Block caving

SOURCE: William C Peters, *Exploration and Mining Geology (New* York, NY John Wiley & Sons, 1978)

Figure 6-12.-Open Pit Mining Terms



SOURCE William C Peters. *Exploration and Mining Geology (New* York, NY: John Wiley & Sons, 1978)

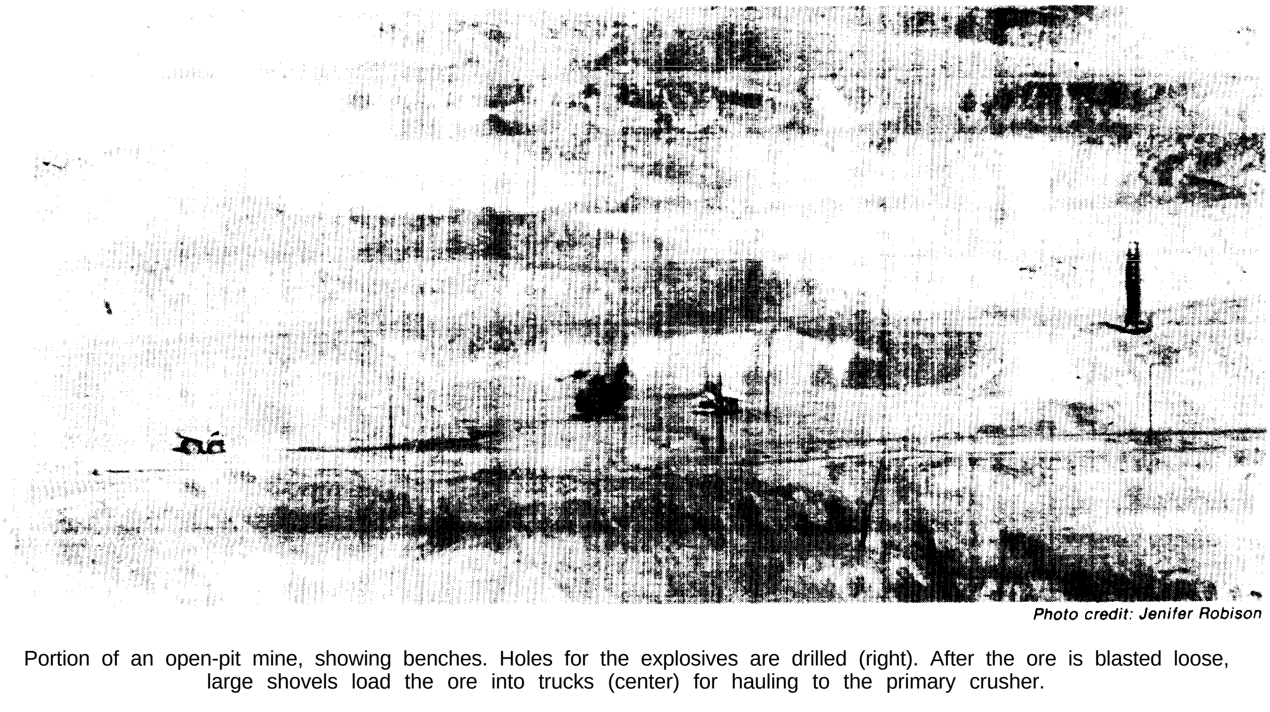


Photo credit: Jenifer Robison

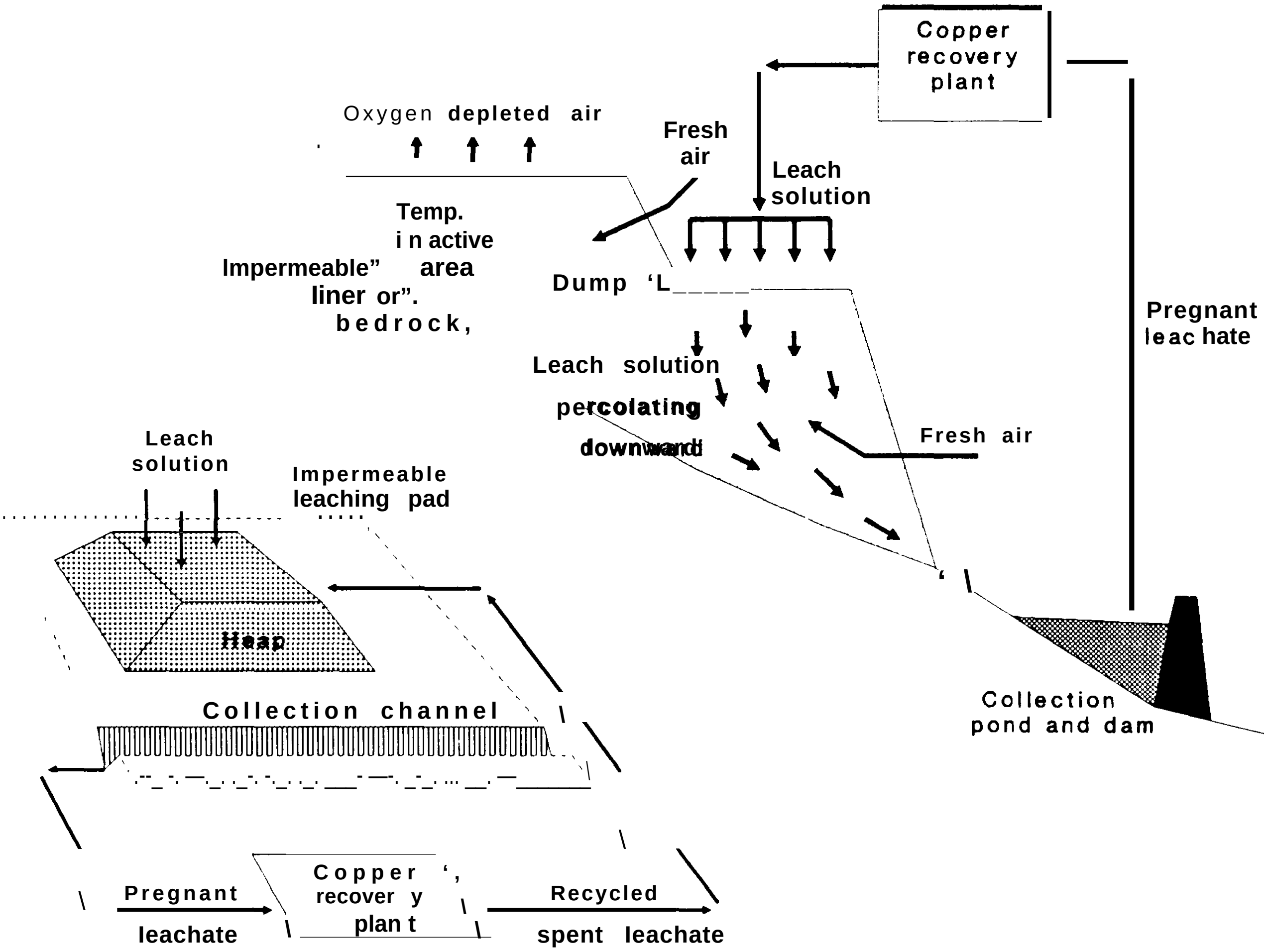
Portion of an open-pit mine, showing benches. Holes for the explosives are drilled (right). After the ore is blasted loose, large shovels load the ore into trucks (center) for hauling to the primary crusher.

Table 6-6.—Characteristics of Solution Mining Techniques

	Vat leaching	Heap leaching	Dump leaching	In situ leaching
Ore grade	Moderate to high	Moderate to high	Low	Low
Type of ore	Oxides, silicates, some sulfides	Oxides, silicates, some sulfides	Sulfides	oxides, silicates, some sulfides
Ore preparation	May be crushed to optimize copper recovery	May be crushed to optimize copper recovery	None: waste rock used	None, block caving, blasting
Container or pad	Large impervious vat	Specially built impervious drainage pad	None for existing dumps; new dumps intended to be leached would be graded, and covered with an impermeable polyethylene membrane protected by a layer of select fill	None
Solution	Sulfuric acid for oxides; acid cure and acid-ferric cure provide oxidant needed for mixed oxide/sulfide ores	Sulfuric acid for oxides; acid cure and acid-ferric cure provide oxidant needed for mixed oxide/sulfide ores	Acid ferric-sulfate solutions with good air circulation and bacterial activity for sulfides	Sulfuric acid, acid cure, acid-ferric cure, or acid ferric-sulfate, depending on ore type
Length of leach cycle	Days to months	Days to months	Months to years	Months
Solution application method	Spraying	Spraying or sprinkling	Ponding/flooding, spraying, sprinkling, trickle systems	Injection holes, spraying, sprinkling, trickle systems
Metal recovery method	Solvent extraction for oxides; iron precipitation for mixed ores	Solvent extraction for oxides; iron precipitation for mixed ores	Solvent extraction for oxides; iron precipitation for mixed ores	Solvent extraction for oxides; iron precipitation for mixed ores

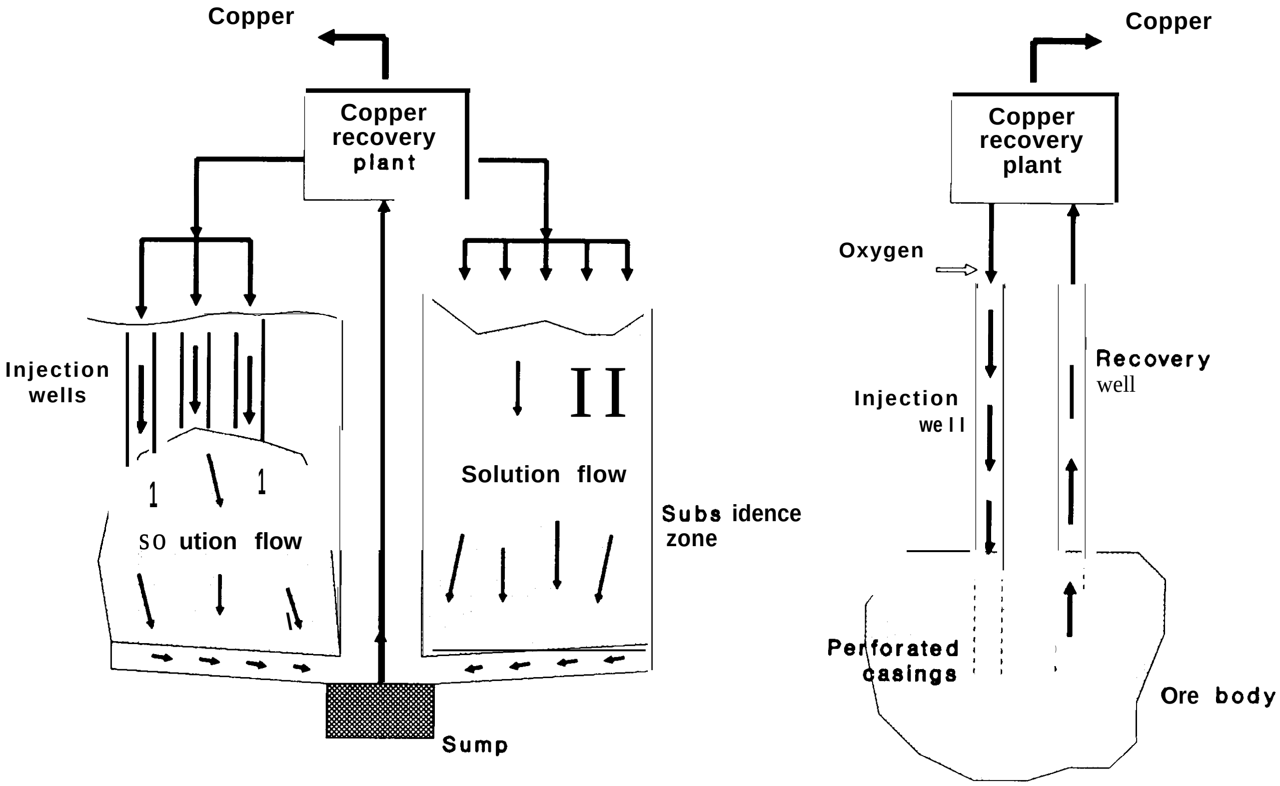
SOURCE Office of Technology Assessment,1988; based on J. Brent Hiskey, "The Renaissance of Copper Solution Mining, " Arizona Bureau of Geology, *Fieldnotes,* fall 1986,

Figure 6-13.-Heap and Dump Leaching



SOURCE J Brent Hiskey, “The Renaissance of Copper Solution Mining, ” *Fieldnotes* Fall 1986

Figure 6-14.-Types of In Situ Leaching Systems



SOURCE: J. Brent Hiskey, "The Renaissance of Copper Solution Mining, " Fieldnotes, Fall 1986

Table 6-7.—Summary of in Situ Copper Mining Activities

Mine	Cu produced (lb/day)	Average ore grade (%)	Principal Cu minerals	Ore preparation	Solution/ application	Solution recovery	Cu in solution (gpl)	Cu recovery method	Active dates
Big Mike (NV)	**5,000**[a]	1.18	Cuprite, tenorite, chalcopyrite	Blasted pit walls, terraced	Dilute H_2SO_4: sprinklers	Recovery well	2.0, then O 8	Precipitation on scrap iron	1973-74. 1978-79
Bingham (UT)	**20,000**[b]	**0.3**	Chalcocite	None, leached block-caved area	Water, launder	Tunnel	2.02	Precipitation on scrap Iron	1922-? (now part of open pit)
Burro Mt. (NM)	NA	NA	Chalcocite	None, leached block-caved area	Water	Underground workings	NA	Precipitation on scrap iron	1941-49
Butte (MT)	**33,000**[b]	0.8	Chalcopyrite, chalcocite	None, leached backfilled slopes	Very dilute H_2SO_4: rejection	Tunnel	0.5-0.75	Precipitation on scrap iron	1930s-1964
Consolidated (NV)	NA	0.3	Sulfides	None, leached block-caved area	Water	Underground workings	1.0	Precipitation on scrap iron	1925-?
Copper Queen (AZ)	5,800[a]	0.29	Chalcocite	None, leached pit and underground workings	Water; sprinklers	Underground workings	0.6	Precipitation on scrap iron	1975-present
Emerald Isle (AZ)	250 then 750[b]	**1.0**	Chrysocolla	Blasted pit bottom	Dilute H_2S0_4, perforated pipe	Recovery wells	0.59, then 0.65	Precipitation on scrap iron	**3/74-6/74,** then 12/74-6/75
Inspiration (AZ)	5,200[b]	**0.5**	Azurite, malachite, chrysocolla	None, leached block-caved area	Dilute H_2SO_4; injection holes	Underground workings	1.8, then 0.7	Precipitation on scrap iron	1967-74
Kimbley (NV)	NA	**0.32**	Chalcocite	None	Dilute H_2SO_4; injection	Recovery well	0.15b	NA	1970-71
Medler (AZ)	**NA**	**0.38**	Sulfides	None	Water; flooded drifts	Drifts	0.2-0.6	Precipitation on scrap iron	1906-09
Miami (AZ)	**30,000-35,000** [b]	**0.88**[c]	Chalcocite	Glory hole over block-caved area	Dilute H_2SO_4; pipe spray and injection holes	Drifts	0.835	Precipitation on scrap iron, then SX-EW	1942-present
Mountain City (NV)	4,800[b]	0.93-1.1	Chalcocite	Block caving	Dilute H_2SO_4; injection wells	Driff	0.5-0.6	Precipitation on scrap iron	1974
Ray (AZ)	**20,000**[b]	1.0	Chalcocite	None, leached block-caved area	Water, sprinklers	Drifts	9.23	Precipitation on scrap iron	1941-49
San Manuel (AZ)	NA	0.47-0.72	Chrysocolla, cuprite	None, leached block-caved area	Dilute H_2SO_4	Underground workings	NA	SX-EW	1986-present
Van Dyke (AZ)	NA	0.5	Chrysocolla	Wells *drilled* and hydrofraced	Dilute H_2SO_4, rejection well	Recovery well	NA	SX-EW	1976-80
Zonia (AZ)	5,000[a]	0.2	Chrysocolla	Blasted pit walls and bottom	Dilute H_2SO_4, sprinklers	Recovery well in pit bottom	2.0, then 0.8	Precipitation on scrap iron	1973-75

NA = not available.

[a] Maximum.

[b] Design capacity.

[c] Original ore body; caved stopes unknown.

SOURCE: Jon K. Ahlness and Michael G. Pojar, In *Situ Copper Leaching in the United* States: Case *Histories of Operations* (Washington, DC: U.S. Department of the Interior, Bureau of Mines Circular IC 8981).

Box 6-A.—The Lakeshore Mine In Situ Project

The Lakeshore Mine, near Casa Grande, Arizona, originally was a combination underground/leaching operation. Beginning in the mid-1970s, Hecla Mining Co. developed an underground operation in which sulfide ore was mined, crushed, and concentrated; copper sulfates were vat leached and electrowon; and oxide ores were vat leached and precipitated. Underground mining was very expensive because the surrounding rock was weak and the tunnels needed extraordinary support. Therefore, the mine shut down after around two years of operation.

Noranda purchased the property in 1979. Because of the problems with the ground, they focused on the larger oxide ore body, using block caving techniques. As the price of copper dropped, however, development of the deeper portions of the ore body became prohibitively expensive, and they began leaching the block caved areas, Noranda drilled injection holes through the caved areas, ran the solution into blocked off underground haulage drifts, and then pumped it to the surface.

As the remaining ore in these areas became depleted, Noranda developed a plan for in situ leaching of the deeper, virgin ore bodies. This plan involved injecting leach solution into the “solid” ore under. pressure, with the assumption that the solution would rise to the zone of least pressure–the dammed drifts-through the recovery wells. With an oxide ore body averaging **1..5 to 3** percent copper, this scheme, if it worked, would provide **30** years of leach production. ’ The U.S. Bureau of Mines awarded a contract for study of in situ techniques at Lakeshore (as well as at a less developed property nearby) in 1986.

Cyprus Minerals purchased the property in mid-1987, changing the name to Cyprus Casa Grande. Cyprus hopes technologies for in situ leaching will enable it to exploit 50 million tons of oxide ore containing slightly less than 1 percent copper, or around 10 million lb/yr copper leach production from the rubblized ore.[2]

---

[1] Paul Musgrove, General Manager, Noranda Lakeshore Mine, personal communication to **OTA,** April 1986,

"'Cyprus Expands Operations via Lakeshore Acquisition, " *Engineering & Mining Journal,* September 1987, at p. 19,

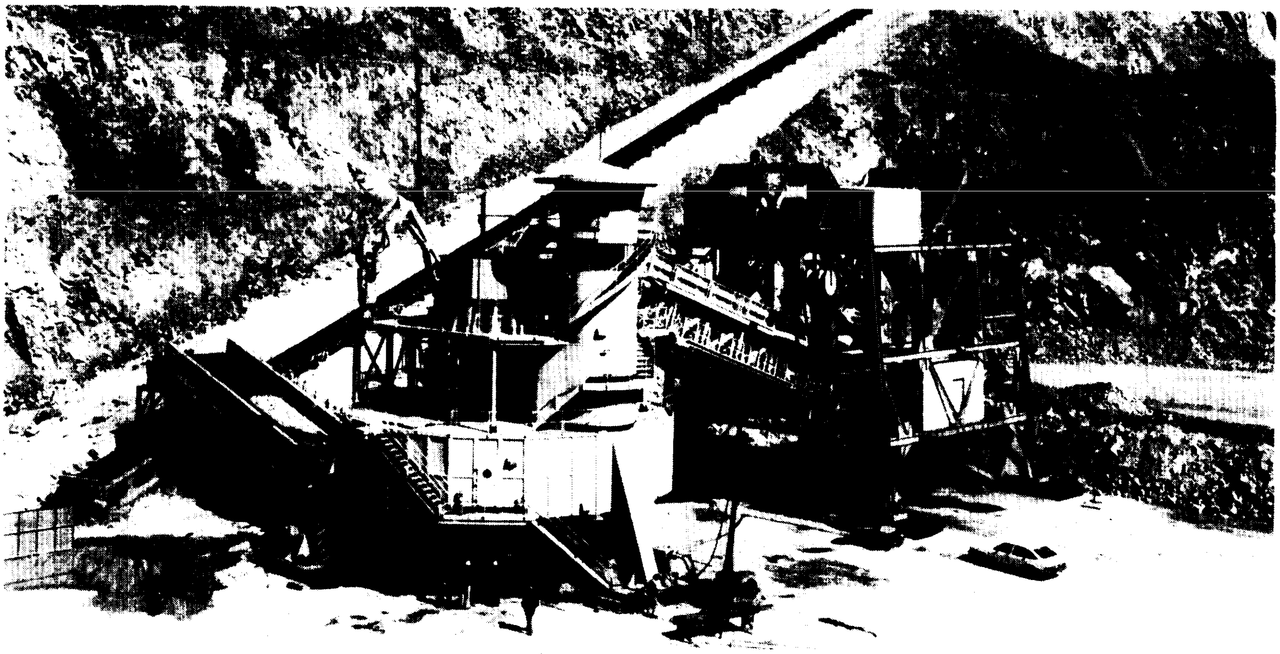


Photo credit: Manley-Prim Photography, Tucson, AZ

Crushing the ore in the pit and using conveyor belts to haul the crushed ore to the mill greatly reduces haulage costs.

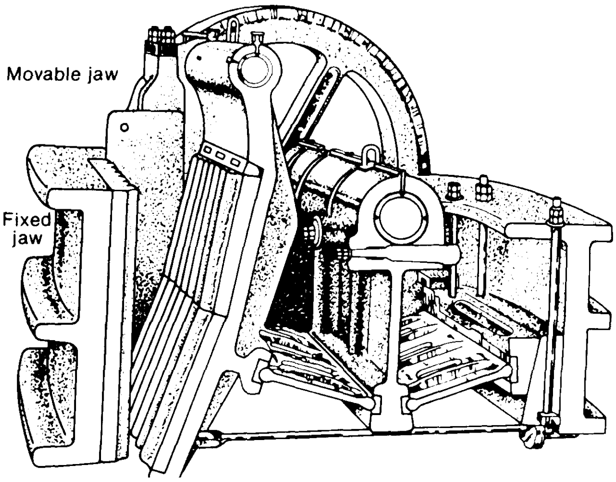
COMMINUTION AND SEPARATION[30]

The first step in separating copper from other minerals in ore mined by underground or open pit methods is comminution (pulverization) of the ore chunks—essentially from boulders to grains of sand. (Mining is actually the first stage of size reduction, accomplished with explosives.) Primary, secondary, and tertiary crushing reduce the ore to about 25 mm, and grinding accomplishes finer reductions. Separators (e.g., screens, cyclones[31]) are used between stages to control the size of particles going on to the next stage. Together, comminution / separation and flotation/dewatering (beneficiation; see below), are known as milling.

In terms of time, energy, and materials used per tonne of copper produced, comminution is expensive because the ore is still very low in grade. Crushing and grinding consume around 33 to 40 percent of the total energy required to produce refined copper (see ch. 7).[32] There also are significant materials costs and downtime for maintenance. Dust control in mill buildings is another cost factor. **Therefore, improvements in the energy, materials, or operating efficiency of crushing could make a significant difference in production costs.** For example, autogenous[33] grinding, if technically feasible, could save around 10 to 20 cents per ton of ore milled.[34]

Crushing often is accomplished in jaw, gyratory, and cone crushers, which fracture rocks by compression (see figure 6-1 5). Jaw or gyratory crushers are usually used for the first stage (primary crushing), and cone crushers for secondary and tertiary crushing. The choice is determined by feed size (jaw crushers handle larger pieces) and capacity (gyratory crushers handle 3 to 4 times more rocks of a given feed size). A pneumatic or hydraulic impact breaker (similar to a jackhammer) is used to break up rocks too large for the primary crusher.

Figure 6-15.—Jaw Crusher



SOURCE: Gordon L Zucker and Hassan E El-Shall, A *Guide to Mineral Processing,* Montana College of Mineral Science and Technology, Special Publication 85, 1982

The crushed ore is transported, usually on conveyer belts, to the grinding mills. Grinding mills can be operated wet or dry. In general, when subsequent processing is to be carried out wet (e.g., flotation), wet grinding is the logical choice. Wet grinding requires less power per tonne of ore, less space, and does not need dust control equipment. However, it uses more steel grinding media and mill lining material due to corrosion, and may be limited by the availability of water. If wet grinding is used, the crushed ore is mixed with water to form a slurry of around 40 percent solids.

Grinding mills work by tumbling the ore with **steel** rods or balls, or particles of the ore itself (autogenous and semi-autogenous grinding). Because the grinding media eventually wear down, new media must be added regularly. Mill liners, which cushion the mill shell, also wear away and must be replaced periodically. For liner replacement, the individual mill has to be taken out of

---

[30] Unless otherwise noted, the material in this section is from Errol G. Kelly and David J. Spottiswood, *Introduction to Mineral Processing* (New York, NY: John Wiley & Sons, 1982).

[31] A cyclone is a centrifugal device for separating materials according to weight or size.

[32] Charles H. Pitt and Milton E. Wadsworth, *An Assessment of Energy Requirements in Proven and New Copper Processes,* report prepared for the U.S. Department of Energy, contract No. EM-78-S-07-1743, Dec. 31, 1980.

[33] Autogenous or ''self'' grinding uses only pieces of ore as the grinding media. Semi-autogenous grinding uses a few large steel balls to break the ore down into intermediate size particles.

[34] A.K. Biswas and W.G. Davenport, *Extractive Metallurgy of Copper* (New York, NY: Pergamon Press, 1980).

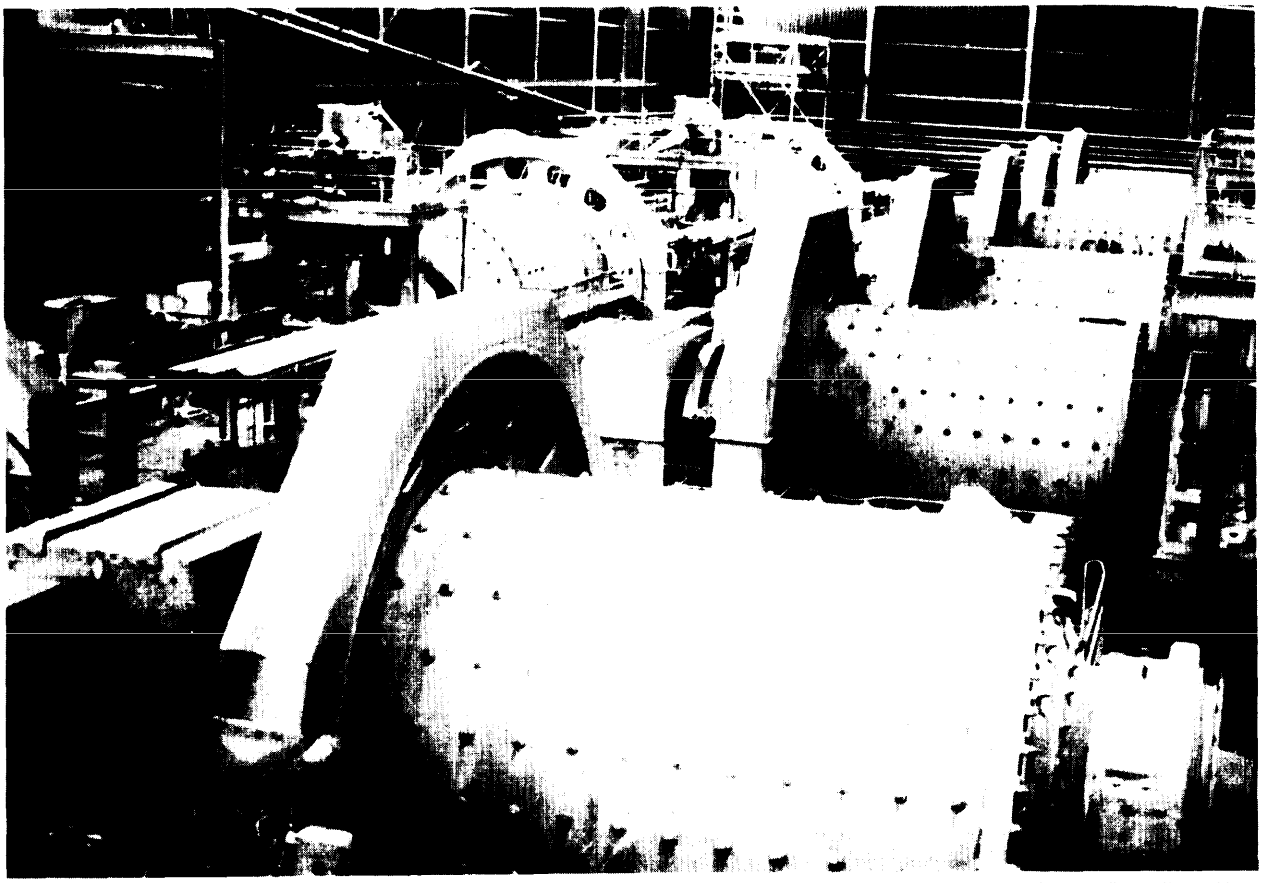


Photo credit: Jenifer Robison

Ore is tumbled in large cylindrical mills with steel balls or rods, or chunks of hard ore (autogenous grinding), until it is pulverized.

production. Even so, mills usually can achieve 99 percent operating time.

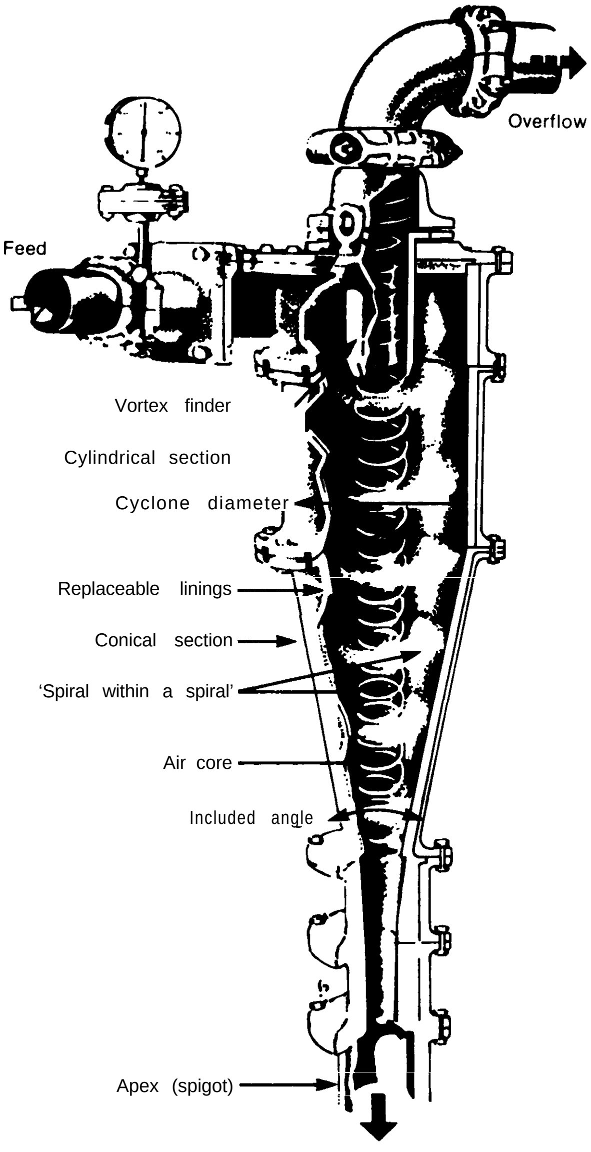
Size separators control both the size of material fed to crushers or grinders and the size of the final product. Thus they control both under- and overgrinding.[35] There are two types of separators: screens for coarse materials, and classifiers for fines. Screens separate ore sizes mechanically using a slotted or mesh surface that acts as a "go/no go" gauge. Classifiers are based on particles' settling rate in a fluid (usually water). The hydrocyclone (figure 6-16) is the industry standard for classifying because of its mechanical simplicity, low capital cost, and small space requirements. Often the hydrocyclone gives relatively inefficient separations, however, resulting in recycling of some concentrates for regrinding and final concentration.

Recent technological advances in comminution have increased the size and efficiency of both crushing and grinding equipment. instrumentation and controls have improved throughput rates and the consistency of particle size in

---

[35] There is an Optimum mix between crushing and grinding. Any breakage produces a range of product sizes, and when the reduction ratio (feed size/product size, or amount of reduction achieved) is comparatively low, some of the feed is already as fine as the product of that or the next phase (e.g., fines that sift out of a primary crusher). By screening this material out and bypassing the next reduction stage, the size of the machine can be reduced because throughput is lower. Also, removal of finer particles will make the equipment more efficient by reducing cushioning effects inside the mill. Overgrinding also can be avoided by operating the final stages in closed circuit with high circulating loads, so that material is sized frequently and thus has little chance of being ground unnecessarily before it is removed from the circuit.

Figure 6-16.—Hydrocyclone



SOURCE: Errol G. Kelly and David J. Spottiswood, *Introduction to MIneral Processing (New* York, NY: John Wiley & Sons, 1982).

crushing and grinding mills.[36] Size separation, in contrast, has seen few significant innovations since the basic screen was invented.

Research has improved the capacity, energy utilization, and availability of cone crushers, which make finer feed for ball mills. This has reduced the amount of grinding media consumed, and in some cases eliminated the need to use both rod and ball mills.[37] Autogenous and semiautogenous grinding can eliminate the need for secondary and tertiary crushing, allow larger mill diameters, and reduce the amount of grinding media consumed. Autogenous mills already have lower maintenance and capital costs than conventional mills. However, they only operate efficiently within narrow ranges of ore grade and hardness of feed material. Before autogenous grinding can be used more widely, additional work is needed to develop an improved understanding of ore properties such as hardness, moisture content, and shattering characteristics; and to develop more durable mechanical/electrical components .38

Areas that could especially benefit from R&D include: 1) better classification in closed circuit grinding, to avoid over- and undergrinding; 2) the use of pebble milling instead of autogenous or steel grinding media; 3) evaluation of optimal energy consumption in size reduction by tradeoffs among blasting, crushing, grinding, and regrinding; 4) evaluation of alternative grinding devices (such as attrition mills and the Schenert roller) that might have higher grinding efficiencies; and 5) stabilizing control strategies in grinding and classification .39 Solution mining (discussed previously) bypasses grinding, and often crushing, entirely; improvements in this area therefore would eliminate these costs.

---

[36] Biswas and Davenport, Supra note 34.

[37] C.A. Rowland, "Innovations in Crushing and Grinding Technology, " paper presented at the 1986 American Mining Congress International Mining Show, Las Vegas, NV, Oct. 5-9, 1986.

[38] Mineral Systems Inc., supra note 26.

[39] Ibid.

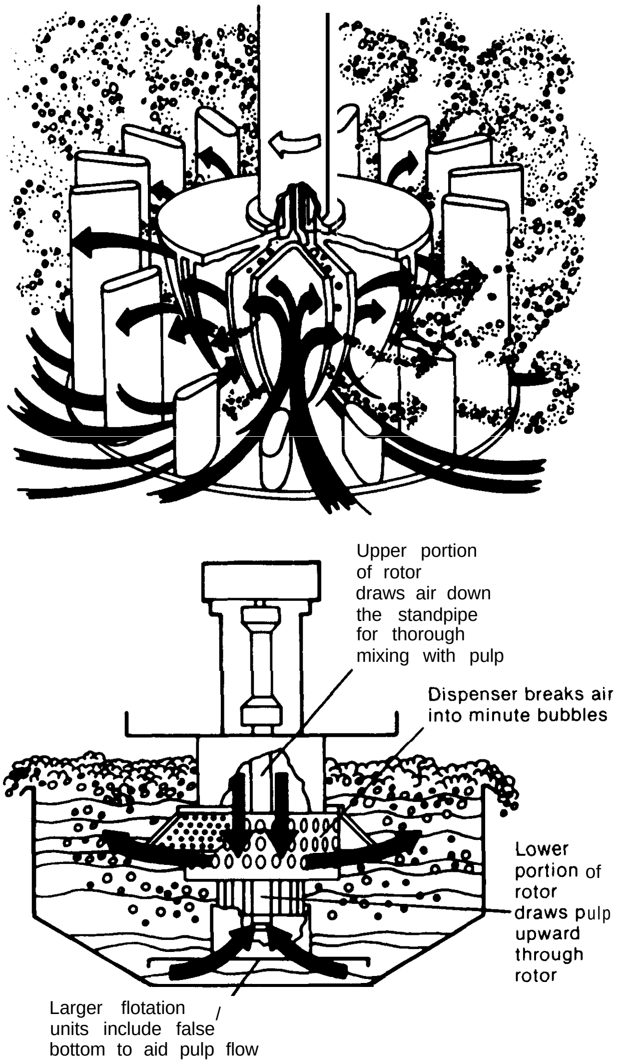
BENEFICIATION

The second step in separating copper from other minerals in mined ore is beneficiation, or concentration. The purpose of concentration is to eliminate as much of the valueless material as possible to avoid further expense in materials handling, transportation, and smelting. Froth flotation is the prevalent concentration method in the copper industry; it separates the pulverized ore (containing around 0.6 to 2.0 percent copper) into concentrates (with 20 to 30 percent copper) plus tailings (wastes of 0.05 to 0.1 percent copper).[40]

A flotation cell resembles a large washing machine (see figure 6-1 7) that keeps all particles in suspension through agitation. The ore is first conditioned with chemicals that make the copper minerals water repellent (hydrophobic) without affecting the other minerals.[41] Then air is bubbled up through the pulp; with agitation, the hydrophobic copper minerals collide with and attach to the air bubbles and float to the top of the cell. As they reach the surface, the bubbles form a froth that overflows into a trough for collection. The other minerals sink to the bottom of the cell for removal.[42]

The simplest froth flotation operation is the separation of sulfide minerals from waste oxide minerals (e. g., limestone, quartz). The separation of different sulfide minerals (e. g., chalcopyrite from pyrite) is more complex, because the surfaces of the minerals have to be modified so that the reagent attaches specifically to the mineral to be floated.[43]

Figure 6-17.—Flotation Cells



SOURCE: Errol G. Kelly and David J Spottiswood, Introduction to *Mineral Processing (New* York, NY: John Wiley & Sons, 1982),

in practice, each ore is unique. Therefore there are no standard concentration procedures. A thorough knowledge of the mineralogy of the ore is essential for the design of a plant. Once a mill is in operation, continued appraisal of the mineralogy is critical to fine tuning to maintain efficiency. This arises because ore bodies are not homogeneous; variations in feed mineralogy are normal and may occur to such an extent that major circuit modifications are required.[44]

Conventional flotation is carried out in stages, the purpose of each depending on the types of

---

[40] Biswas and Davenport, supra note 34.

[41] The principal chemical reagent used is the collector, which attaches (adsorbs) preferentially to the mineral to be recovered. To Improve the degree of selective adsorption, other chemicals may be added to the slurry, Including activators, which modify the surface properties of a mineral so that it becomes more amenable to flotation; depressants, which reduce the floatability of one or more mineral constituents; dispersion agents to help the selective reaction of other reagents; and pH regulators.

[42] Biswas and Davenport, supra note 34.

[43] Ibid.

[44] Kelly and Spottiswood, supra note 30.

Photo credit: US. Bureau of Mines

In flotation, the copper attaches to bubbles and floats to the top, where it forms a froth that overflows into a trough for collection,

minerals in the ore (see figure 6-18). Selective flotation for copper sulfide-iron sulfide ores uses three groups of flotation cells (figure **6-1 8a):**

- **roughers use a moderate separating force to float the incoming ore to produce a high copper recovery with a concentrate grade of 15 to 20 percent;**
- **cleaners use a low separating** force to upgrade the rougher concentrate by removing misplaced waste material, resulting in a final high-grade copper concentrate of 20 to 30 percent and;
- scavengers provide a final strong flotation treatment for the rougher tailings (with a large concentration of reagent and vigorous flotation) to recover as much copper as possible.

As shown in figure 6-1 8a, the tailings from the cleaner flotation and the "float" from the scavenger flotation (middlings) are returned to the start of the circuit. A regrind often is necessary for this to be effective. Alternatively, there may be a regrind between rougher and cleaner flotation,[45]

For more complex ores, the first stage often is a bulk float, similar to the rougher, in which much of the waste and some of the byproduct metals are eliminated (figure 6- 18b). The bulk concentrate then goes to roughers, which float the copper and eliminate the remaining metals, and then to cleaners. Again, there may be a regrind and second rougher cycle.[46]

The product of froth flotation contains 60 to 80 percent water, most of which must be removed before the concentrate can be transported or smelted, Dewatering is accomplished first by settling in large vats, known as thickeners. The solids settle by gravity to the bottom of the vat, where they are scraped to a discharge outlet by a slowly rotating rake.[47] Filters are used for final dewatering.

Over the last 10 to 20 **years, advances have been made in flotation chemicals, flotation cell design, and automated circuits.** Automated flotation monitoring and control systems improve metal recovery and reduce reagent consumption. Most U.S. operations have now installed these systems. Continued improvements in sensitivity would enhance the potential savings, however.

In flotation chemistry, a major development was the recognition that adsorption of sulfide minerals on air bubbles is an electrochemical process. Changing the electrochemical potential (by varying the chemical reagents) activates or depresses the various minerals, making them float or not float, and thus improves flotation efficiency. This offers significant savings—perhaps $1 million annually—in reagent costs. Other potential benefits of electrochemical control include higher recoveries and lower operating costs, Even

---

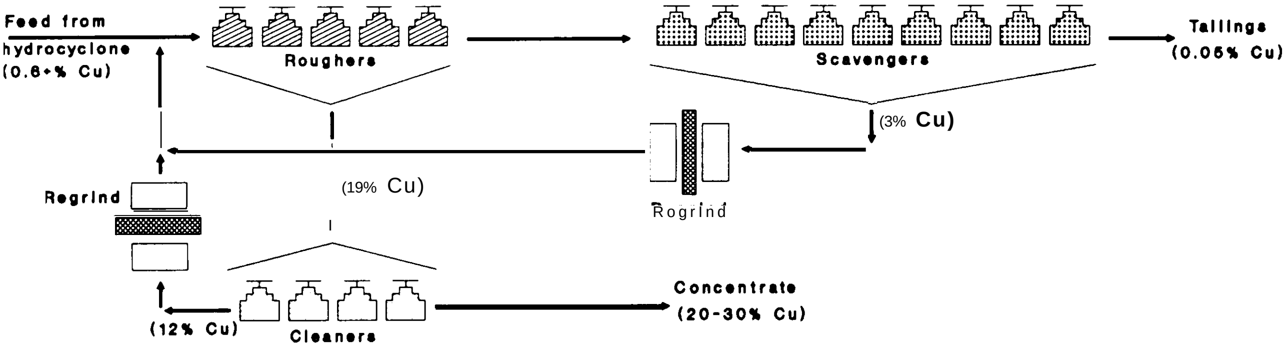
[45] Biswas and Davenport, supra note 34.

[46] Ibid.

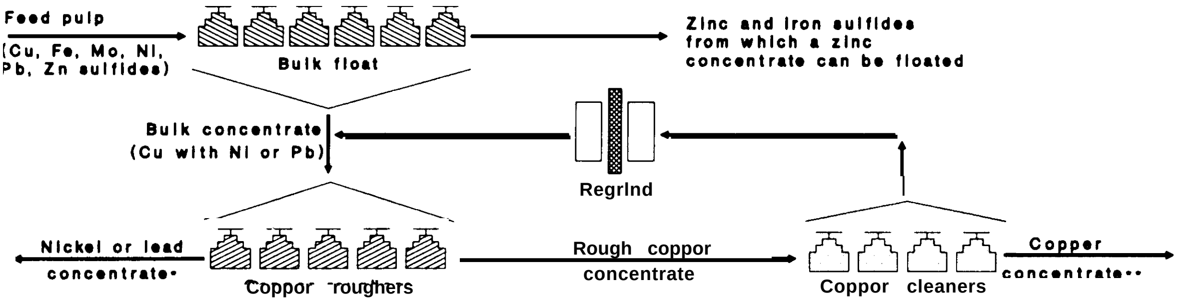
[47] The liquid from the thickeners usually is recycled to the grinding and flotation circuits. This prevents adverse environmental impacts from the trace metals in the liquid (e.g., copper, arsenic, cadmium, lead, and zinc; see ch. 8). Water recycle systems also reduce water use, an important consideration in the arid regions where much of the world's copper is produced.

Figure 6-18.-Flowsheets for Copper Flotation

6-18a.--Representative flowsheet for flotation of copper sulfides from iron sulfides



6-18 b---Summary flowsheet for production of copper, lead. nickel, molybdenum, and zinc concentrates from a hypothetical complex ore



* PbS may also be floated from copper sulfides
** MoS2 is floated off at this point.

SOURCE A K. Biswas and W.G Davenport, *Extractive Metallurgy ot Copper* (New York, NY: Pergamon Press, 1980),

a 1 percent improvement in copper recovery (with no decrease in grade) could represent from $1 million to $5 million of additional income annually.[48]

An important trend in cell design is the tendency toward larger cells. In the 1960s, newly installed cells had a volume of 3 or 4 cubic meters; today, flotation cells may have a volume of 85 cubic meters.[49] Experiments also are proceeding with the use of column cells, which use pneumatic agitation (see figure 6-1 9). Therefore they can be more energy efficient and less costly to maintain than mechanical agitators, Other potential advantages of column cells include better recovery of fine particles (and thus fewer cleaning circuits), simpler control of electrochemical potential, and simpler automated process controls. Moreover, one column cell will replace several banks of mechanical flotation cells. Although these benefits have not been quantified, the improved recovery and capital and operating cost savings could add up to several millions of dollars annually.[50]

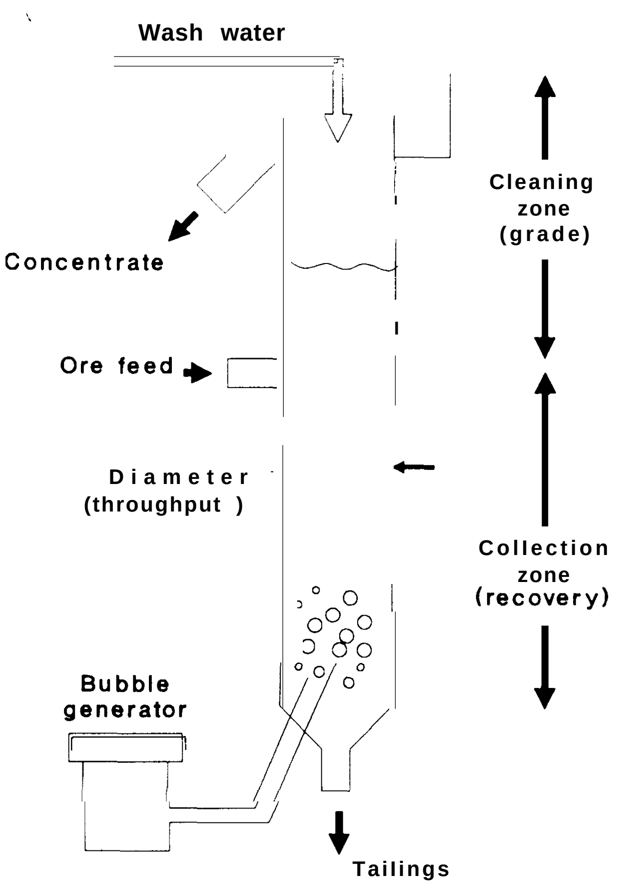
---

[48] Garret R, Hyde and Alexander Stojsic, "Advances in Froth Flotation, " paper presented at the 1986 American Mining Congress International Mining Show, Las Vegas, NV, Oct. 5-9, 1986.

[49] Biswas and Davenport, supra note 34.

[50] Ibid.

Figure 6-19.-Column Cell



SOURCE J D McKay et al "Column Flotation, " U.S. Bureau of Mines pamphlet, undated

Column **cells already are used** for molybdenum concentration, and are being tested in copper milling. Experience with a column cell at San Manuel, Arizona showed a concentrate grade of 29.83 **percent copper with a sulfide copper recovery of 90.36 percent, compared to the conventional San Manuel flotation circuit with 29.99 percent copper in the concentrate and a recovery of 90.12 percent**.[51]

PYROMETALLURGY

Pyrometallurgical processes employ high-temperature chemical reactions to extract copper from its ores and concentrates.[52] These processes generally are used with copper sulfides and, in some cases, high-grade oxides. The use of high temperatures for metallurgical processing has several **advantages: chemical reaction rates are rapid, some reactions that are impossible at low** temperature become spontaneous at higher tem**perature, and heating the mineral to a liquid** facilitates separation of the metal from the residue. Depending on the copper minerals and the type of equipment, pyrometallurgical recovery may take as many as four steps: roasting, smelting, converting, and fire refining.

Smelting is a relatively small component in the total cost of copper production—about 17 percent of gross U.S. production costs. In relative terms, however, the United States is least competitive in smelting.. This is primarily attributable to high U.S. labor and energy costs. Thus, improvements in smelter labor productivity and energy efficiency would enhance domestic industry competitiveness, Domestic smelters also are at a disadvantage compared to some other coun-

---

[51] 13. V. Clingan and D. R. McGregor, "Column Flotation Experience at Magma Copper Company," *Minerals and Metallurgical Processing, vol.* 4, No. 3, August 1987, p. 121.

[52] Pyrometallurgical processes typtcally operate at temperatures ranging from 500° C to 1250° C.

tries due to the high level of environmental control required in the United States (ch. 10).

Roasting prepares ores and concentrates for either pyrometallurgical or hydrometallurgical processing. For the former, it dries, heats, and partially removes the sulfur and volatile contaminants (e. g., arsenic) from the concentrate to produce a calcine suitable for smelting. In hydrometallurgical processing, roasting converts sulfide minerals to more easily leachable oxides and sulfates .[53]

In smelting, concentrates or calcines are processed at high temperatures to produce a liquid copper-rich matte for converting, plus slag and sulfur dioxide (SO_2). The heat required to melt the concentrate is generated from three sources: 1) retained heat from roasting, 2) external energy sources such as fossil fuels and electricity, and 3) the heat produced by the chemical combination of iron sulfides with oxygen, The slag is discarded, either directly or after further copper recovery in an electric furnace or flotation cell. The SO_2 is captured for pollution control (see ch. 8).

Figure 6-20 shows changes in smelting technology along with the increase in copper produc-

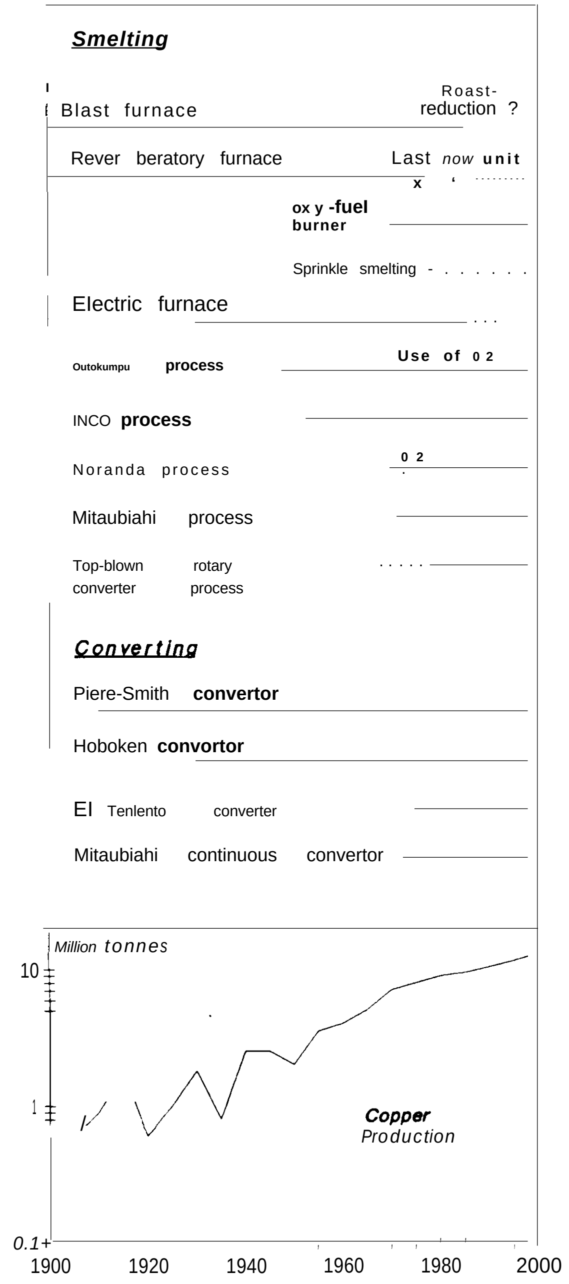
Photo credit: Manley-Prim Photography, Tucson, AZ

Tapping the smelter.

---

[53] Biswas and Davenport, supra note 34.

Figure 6-20.-Development of Smelting Technology Compared with World Copper Production



SOURCE United Nat Ions Industrial Development Organization

tion. The earliest large-scale method of producing copper matte was in blast furnaces, which could handle ores containing 5 to 20 percent copper. With the decline in ore grades, direct smelting became too expensive, and the industry shifted to concentration followed by hearth or reverberatory smelting (see box 6-B). Flash furnaces, which combine roasting and hearth smelting and are more efficient than reverberatories, were introduced in the 1940s.

In recent years, concerns about the air quality impacts of reverberatory furnaces have led to the widespread adoption of electric and flash furnaces in the United States. As table 6-8 shows, almost all of the domestic smelters that are still operating upgraded their furnaces from reverberatories to more modern technology within the last 15 years. Most furnaces that were not upgraded were closed permanently (e.g., Phelps Dodge's Douglas, Morenci, and Ajo smelters; Kennecott's Ely and Ray smelters; Anaconda's Butte smelter; Asarco's Tacoma plant) .[54]

Copper matte converting is the final stage in smelting; it usually is carried out in a Pierce-Smith converter (figure 6-25), which separates the matte into blister[55] copper (at least 98.5 percent copper) and slag. After the molten matte is poured into the converter, air is blown into the matte through nozzles (called "tuyeres"). First, the iron sulfide in the matte oxidizes into iron oxide and SO_2; silica is added and the iron oxide forms an iron silicate slag, which is poured off after each blow. This leaves molten copper sulfide (white metal or chalcocite, Cu_2S). The remaining sulfur in the white metal is then oxidized to SO_2, leaving blister copper. Converter slags contain from 2 to 15 percent copper, and generally are recycled to the smelting furnaces, where their high iron content often serves as a smelting flux.[56]

Continuous production of blister copper has long been a goal of copper producers. Continuous reactors combine roasting, smelting, and converting in one operation that produces blister copper directly from concentrates, while taking advantage of the heat generated by the oxidation of sulfides. The benefits of continuous

---

[54] The decline in domestic smelter capacity is discussed in ch. four.

[55] The term "blister" refers to the bumps on the surface of the copper created when the oxygen and sulfur that remain dissolved at high temperatures form gases when the copper is solidified.

[56] A flux is a substance that facilitates the separation of the smelter charge into matte and slag.

Box 6-B.—Smelting Furnaces

The reverberatory furnace (figure 6-21) consists of a large, refractory-lined[1] chamber. Fuel-fired burners melt the concentrates, forming an upper layer of slag (composed of iron silicate with less than 0.5 percent copper) and a lower layer of matte (30 to 45 percent copper). The reverberatory furnace was widely favored by the copper industry over the last 50 to 60 years because of its versatility; all types of material, lumpy or fine, wet or dry, could be smelted. However, the reverberatory furnace has relatively high fuel requirements, and its sulfur dioxide gas is too dilute for economic conversion into sulfuric acid or treatment with other pollution control methods (see ch. 8).

The electric furnace is an electrically heated hearth furnace (figure 6-22) that is similar in operation to the reverberatory furnace, but with more advantageous environmental control conditions for the effluent gases. The heat for smelting is generated by the flow of electric current between electrodes submerged in a slag layer. Although electric furnaces use electrical energy efficiently because of low heat loss, heat generation from sulfide oxidation is limited. The heavy reliance on external energy and the high price of electricity can result in relatively high energy costs,

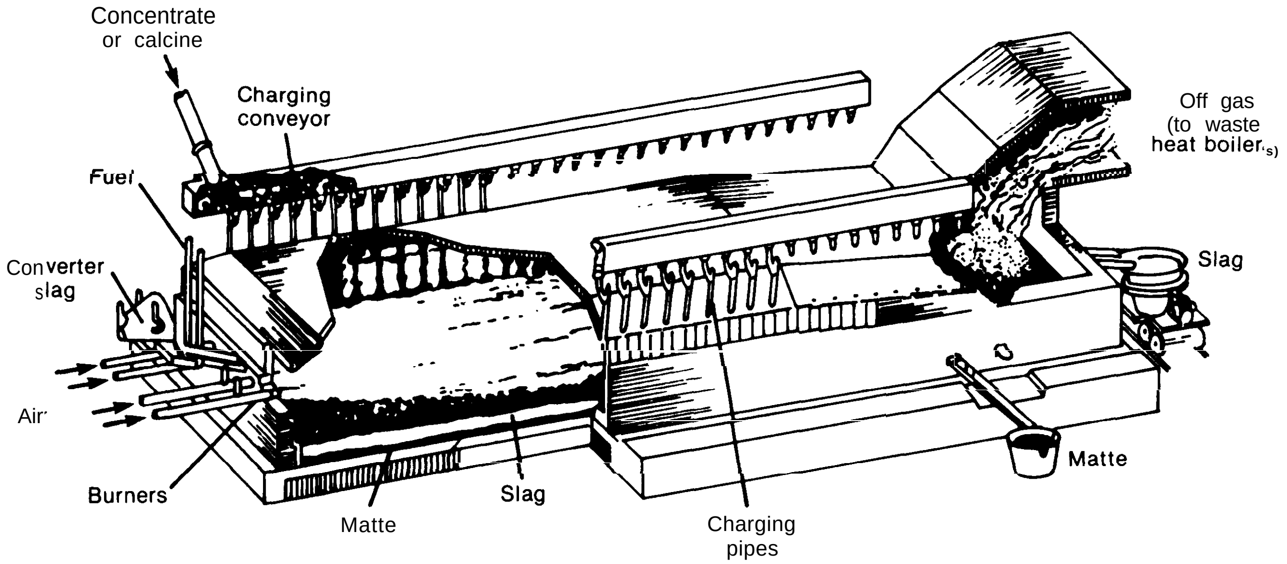
In flash furnaces, concentrates are blown, together with oxygen or an air/oxygen mixture, into a hot furnace. The sulfide particles in the concentrates react quickly with the oxygen and combustion is extremely rapid. This produces enough heat to provide a large proportion of the thermal energy needed for smelting. As a result, flash furnaces have relatively low fuel costs. Their production rates also are high due to the rapid rate at which the mineral particles are heated, and the matte is relatively rich (50 to 75 percent copper). Further, their waste gases are rich in SO_2, permitting economic pollution control. The principal disadvantage of flash furnaces is the high copper content of the slag (around 0.7 to 1.0 percent copper). This means that the furnaces cannot be used efficiently to recover copper from converter slags, and in some cases, the smelter slag must be recycled through the comminution and beneficiation plants.

There are two basic types of flash furnaces: 1) the INCO process (figure 6-23) uses commercial oxygen and requires no external energy (i.e., is autogenous); 2) the Outokumpu process (figure 6-24) uses preheated air or oxygen-enriched air. The Outokumpu flash furnace can be autogenous if the air is enriched ***to*** about 40 percent oxygen; otherwise it requires external fuel.

---

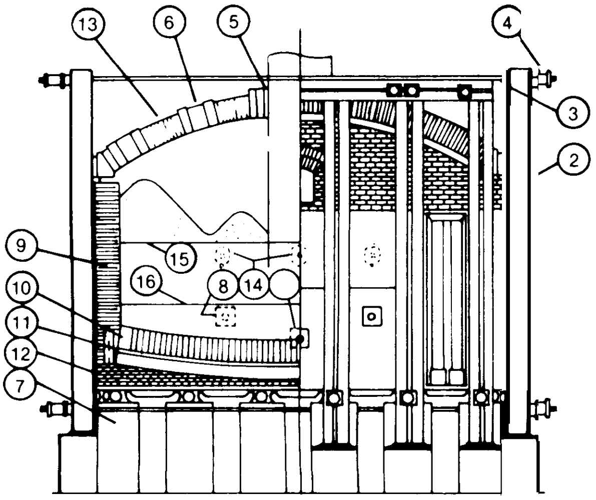
[1] Refractories are heat-resistant materials, usually made of ceramic.

Figure 6-21 .—Reverberatory Furnace



SOURCE: McGraw Hill Encyclopedia of Science and Technology.

Figure 6-22.— Electric Furnace



Legend

1. Drain out taphole
2 Buckstay
3. Tie-rod
4. Tie-rod spring
5. Electrode openings
6. Furnace Inspection ports
7. Furnace support pillars
8. Matte tapping blocks
9. Magnesite refractory bricks
10 Magnesite hearth and sub-hearth
11 Magnesite castable
12 Fire-clay bricks
13 Firebrick roof
14 Slag tapholes
15 Average slag level
16 Average matte level

SOURCE A K Biswas and W G. Davenport, *Extractive Metallurgy of Copper* (New York, NY Pergamon Press, 1980)

blister copper production include lower capital cost, reduced materials handling, low heat losses, very low energy requirements, **economical** SO_2 gas recovery, and the ability to apply online computer controls to the entire copper-making process.

Two types of continuous reactors are in limited use: the Noranda process and the Mitsubishi process. The Noranda reactor (see figure 6-26) is a single-step process that always contains three liquid phases–slag, matte, and blister copper. The Mitsubishi reactor (figure 6-27) has three interconnected furnaces through which matte and slag flow continuously by gravity.

Neither of these processes has yet proven to be truly continuous. First, the slag contains as much as 10 percent copper. Slag from the Noranda reactor is recycled through comminution and beneficiation. Mitsubishi slag is reprocessed in the intermediate electric settling furnace. Second, the blister copper from the Noranda reactor contains more impurity metals (e. g., antimony, arsenic, bismuth) than blister produced by conventional smelting/converting. This requires either more expensive electrorefining or the restriction of single-step continuous smelting to rather pure concentrates. Third, while the Noranda reactor operates more efficiently with oxygen-enriched air, oxygen levels above about 30 percent greatly increase equipment wear. As a result, the Noranda reactor typically is used to produce a very high-grade matte (70 to 75 percent copper), which is then treated in a converter.

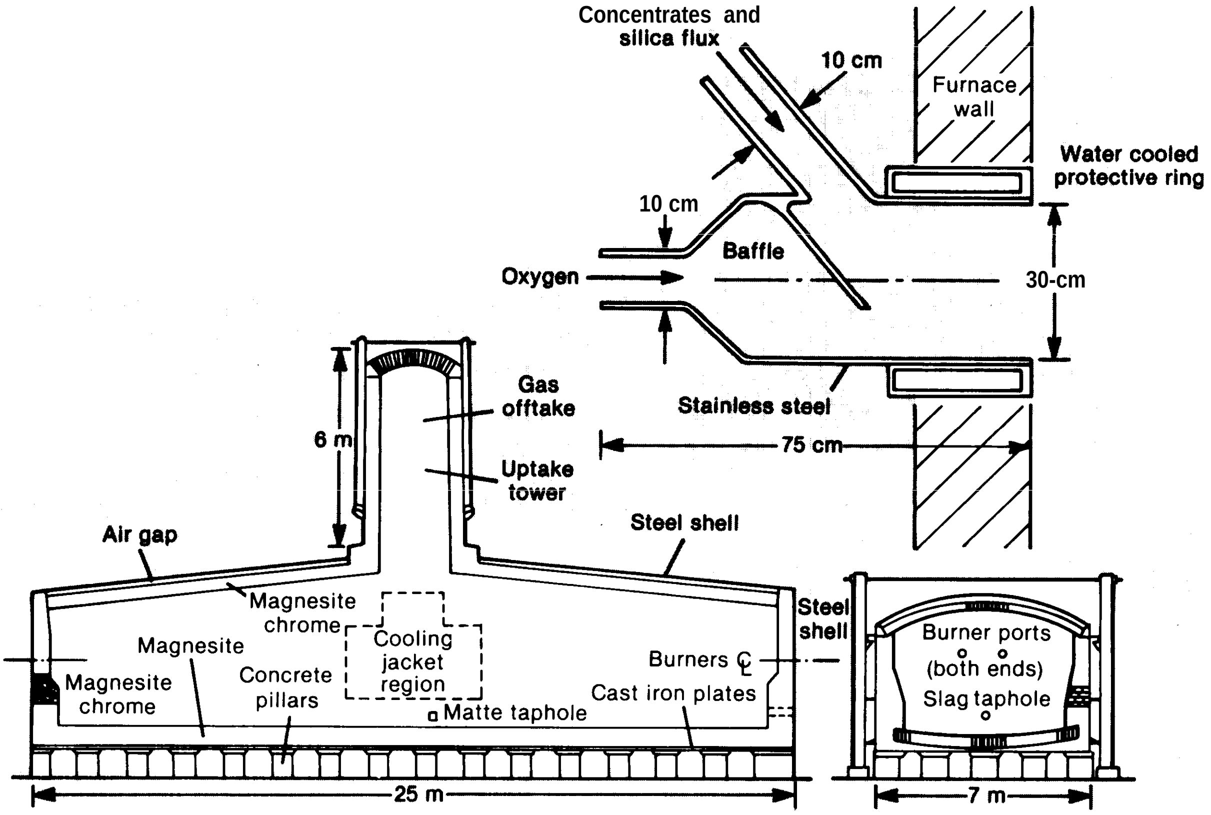
Fire refining further purifies blister copper to produce anodes pure enough for electrorefining. The residual sulfur is removed by blowing air through the molten blister (in a furnace similar to a Pierce-Smith converter) to form SO_2, until the sulfur content has been lowered to 0.001 to 0.003 percent. The oxygen is then removed by blowing natural gas or propane through the tuyere until oxygen concentrations have dropped to 0.05 to 0.2 percent.

The molten copper is then poured into an anode casting wheel—a circular arrangement that is rotated to bring the molds under the furnace mouth. The anodes are cooled with water sprays as the wheel rotates. The critical parameters in anode casting are smoothness, straightness, and uniform thickness to ensure efficient electrorefining.

Recent improvements in pyrometallurgical processing of copper concentrates have focused on reducing energy requirements (see ch. 7) and on producing fewer gaseous emission streams with higher SO_2 concentrations for more cost-effective air pollution control (ch. 8). Better quality control of the product to reduce materials rehandling also has been a factor. Most domestic smelters now have on-line computer controls for greater throughput with better matte quality and almost automatic operation.

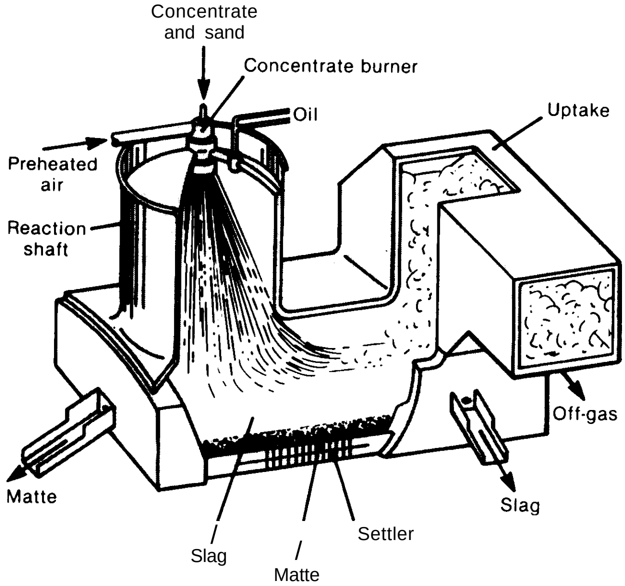
One area in which further improvements would greatly assist the United States is continuous smelting, because it would decrease materials handling and therefore increase labor productivity, would decrease energy use, and

Figure 6-23.—INCO Flash Furnace



SOURCE: A.K. Blswas and W.G. Davenport, ***Extractive Mefallurgy of Copper (New*** York, NY: Pergamon Press, 1980).

Figure 6.24.—Outokumpu Flash Furnace



SOURCE: McGraw Hill Encyclopedia of Science and Technology.

Table 6.8.-Smelter Technology in the United States

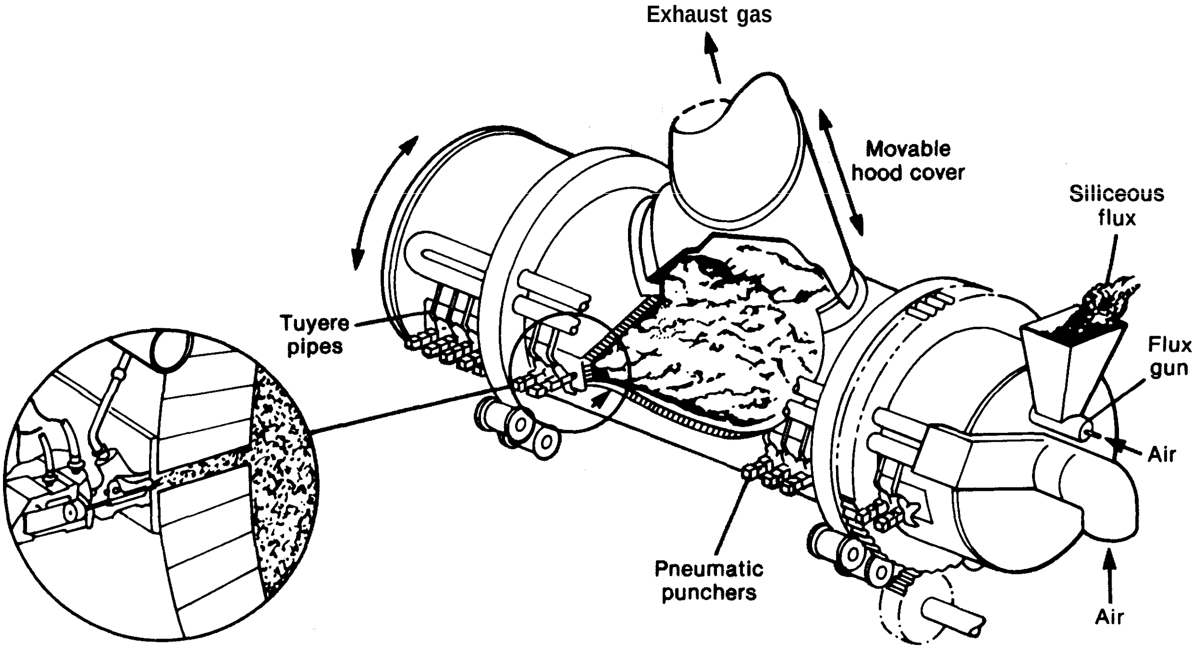
Smelter	Type
Hayden (Arizona)	INCO flash furnace
Inspiration (Arizona)	Electric furnace
Morenci (Arizona)*	Reverberatory furnace
San Manuel (Arizona)	Outokumpu flash furnace
White Pine (Michigan)	Reverberatory furnace
Hidalgo (New Mexico)	**INCO flash furnace**
Hurley (New Mexico)	**INCO flash furnace**
Great Falls (Montana)*	**Electric furnace**
Copperhill (Tennessee)*	**Electric furnace**
El Paso (Texas)	**Reverberatory furnace**
Garfield (Utah)	**Noranda reactor**

‘Not operating,

SOURCE Office of Technology Assessment, 1988,

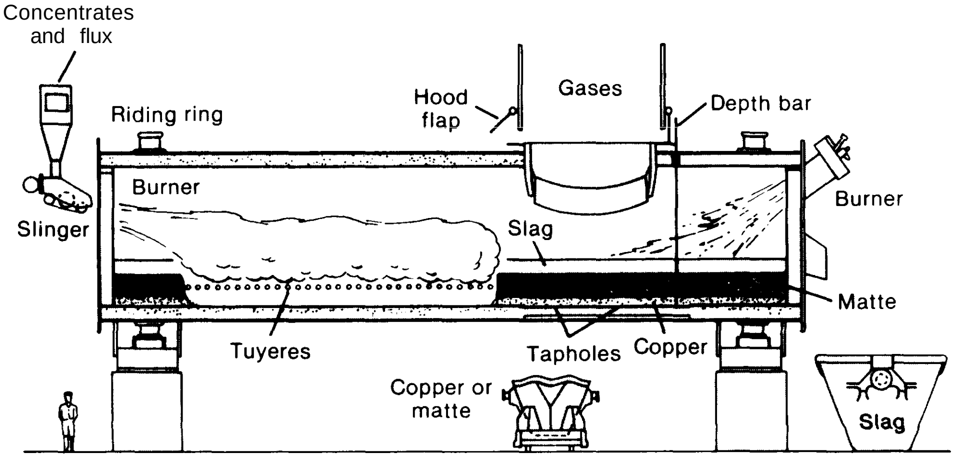
would make environmental control more cost-effective. However, installation of an entirely new smelting system has a high capital cost. Because most U.S. smelters already installed new furnaces within the last 15 years, it is unlikely that they would undertake another such investment without a clear demonstration of substantial cost advantages, and without a very favorable business climate. Instead, U.S. companies will increase the proportion of copper they produce with hydrometallurgical methods

Figure 6-25.—Pierce Smith Converter



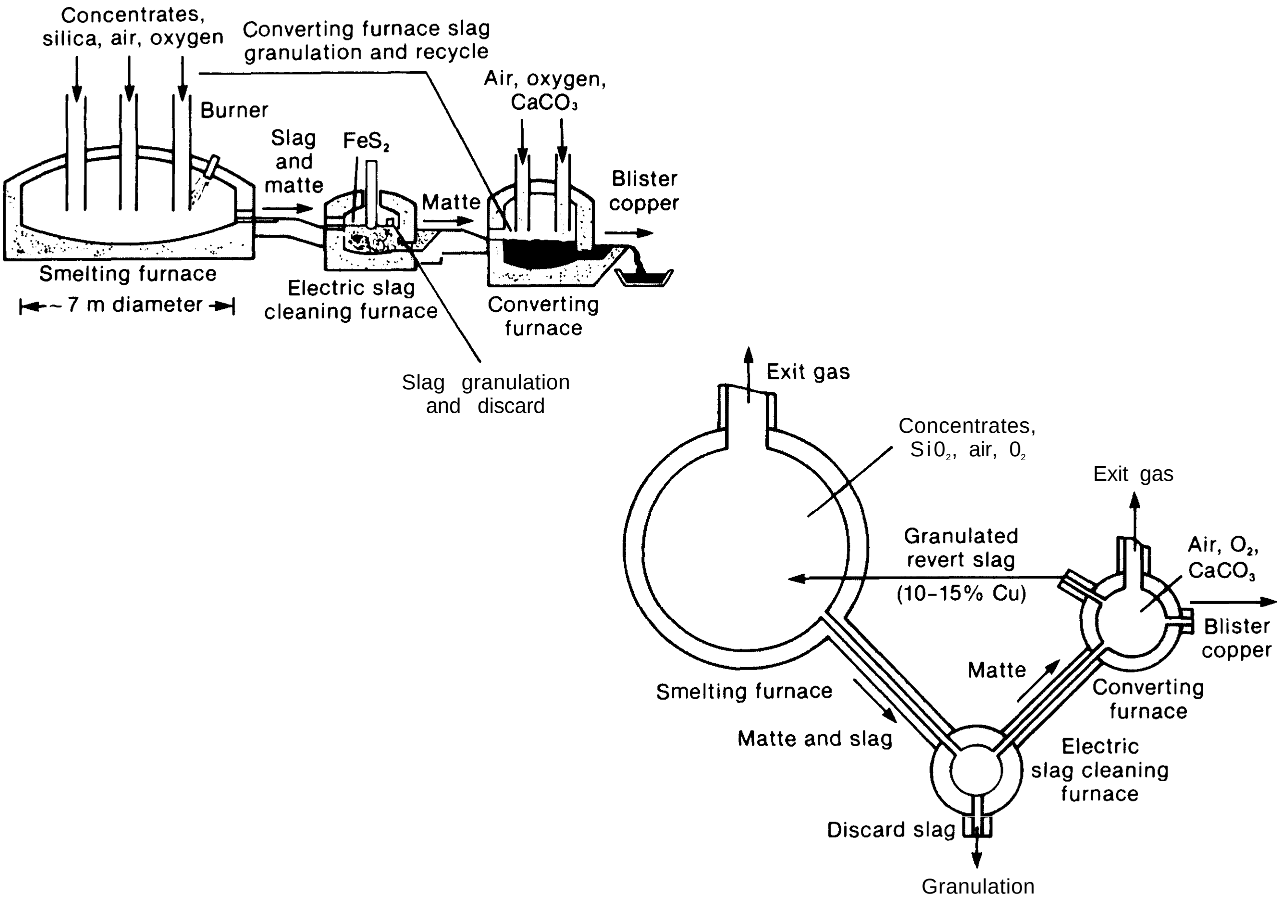
SOURCE: McGraw Hill Encyclopedia of Science and Technology

Figure 6.26.— Noranda Reactor



SOURCE. McGraw Hill Encyclopedia of Science and Technology

Figure 6-27.—Mitsubishi Continuous Smelting System



SOURCE: McGraw Hill Encyclopedia of Science and Technology.

HYDROMETALLURGY

Hydrometallurgical copper recovery is the extraction and recovery of copper from ores using aqueous (water-based) solutions. Hydrometallurgical processes are applied mainly to oxide ores, and to low-grade oxide and sulfide mine wastes. ST As discussed in the section on mining, above, and in chapter 4, about 25 percent of domestic copper production is now through the use of solution mining techniques. Once the ore has been leached, the copper is recovered from the pregnant leachate through precipitation or solvent extraction.

These processes have several advantages over pyrometallurgical copper recovery methods, including the ability to treat lower grade ores (even waste dumps) economically, flexibility in scale of operations, simplified materials handling, and good operational and environmental control. Copper can be produced from dump leaching plus solvent extraction and electrowinning for around 30 cents per pound .[58] This is a clear cost advantage over pyrometallurgical production.

Solvent extraction is still largely confined to copper oxides. Hydrometallurgical techniques for

---

[57] Chemical solutions also can be used to process copper concentrates. While several of these solutions are commercially avail. able, their materials and energy costs are higher than for conventional smelting or leaching (see ch. 7).

[58] Edward E. Malouf, "New Developments in Hydrometallurgy, " paper presented at the American Mining Congress Mining Convention, San Francisco, CA, Sept. 22-25, 1985.

sulfides and complex ores are being developed. These will greatly aid the United States in overcoming its low ore grade disadvantage. It should be made clear, however, that dump leaching–exploitation of low-grade mine wastes—is primarily a means of lowering average production costs. It is not a substitute for conventional copper production by pyrometallurgical or other leaching methods.

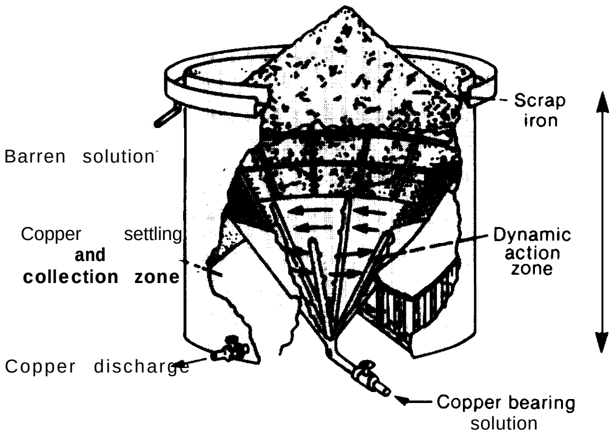
In **iron precipitation,** or cementation, the pregnant leach solution flows through a pile of scrap iron/steel, and the copper precipitates onto the steel surfaces. Precipitation works through an electrochemical reaction: there is a transfer of electrons between the iron, which dissolves into the solution, and the copper, which precipitates out of the solution. Cement copper detaches from the steel surfaces as flakes or powder under the force of the flowing solution. There are numerous precipitator designs and configurations (see, for example, the Kennecott cone precipitator shown in figure 6-28).

The principal advantage of precipitation is that virtually all of the copper is recovered from the leachate. Cement copper is still relatively impure, however, and subsequent treatment is required, usually through normal smelting/refining. Typically, cement copper contains around 85 to 90 percent copper, 0.2 to 2 percent iron, plus trace amounts of silica and aluminum oxides, and oxygen.

Photo **credit Manley-Prim** *Photography, Tucson, AZ*

A solvent extraction-electrowinning plant. The pregnant leachate flows to the collection ponds upper left). The solvent extraction tanks are shown at center, and the electrowinning plant at lower right.

Figure 6-28.–Kennecott Cone Precipitator



SOURCE: A K. Blswas and W.G. Davenport, *Extractive Metallurgy of Copper* (*New* York, NY: Pergamon Press, 1980).

In **solvent extraction, an organic chemical that dissolves copper but not impurity metals is mixed with the pregnant leachate from solution mining.** The copper-laden organic solution is separated from the leachate in a settling tank. Sulfuric acid (H_2SO_4) is then added to the pregnant organic mixture, which strips the copper into an electrolytic solution for electrowinning (see below).

Solvent extraction is advantageous in that the electrolyte has almost no impurities and few environmental problems. Solvent extraction also makes relatively efficient use of the various solutions used: the spent leachate is returned to the leaching operation, the barren solvent is recycled to the pregnant leachate, and the spent electrolyte to the loaded solvent (see figure 6-29).[59]

New **developments in hydrometallurgy have resulted primarily from a better understanding of the chemical and biological** processes that occur in leaching; from improved heap and dump construction methods that speed up the leaching process; from automated controls and improved solvent recycling rates in solvent extraction; and from advancements in electrowinning (see below).

---

[59] Biswas and Davenport, supra note 34.

ELECTROMETALLURGY[60]

Electrometallurgy deals with the use of electricity to refine metals. Virtually all primary copper receives electrolytic treatment, either through electrorefining of copper anodes or electrowinning of solvent extraction solutions. **In essence, an electric current is** used to bring about chemical changes that extract (electrowin) or purify (electrorefine) the copper.

Refining is the stage of copper production in which the United States is most cost competitive. . This is due in part to low delivery costs and in part to major improvements in refinery labor productivity. More widespread use of automated controls and materials handling systems should enhance our refining cost position further. Because refining is only around 8 percent of the total cost of copper production, however, it provides little leverage in overall competitiveness.

Electrorefining virtually eliminates the oxygen, sulfur, and base metals that are harmful to copper's properties (e.g., reduce its electrical conductivity) and decrease its value. At the same time, electrorefining allows the recovery of valuable impurities such as gold and silver. The end product, cathode copper, is 99.99+ percent pure, with less than 0.004 percent metallic and other impurities (including sulfur).

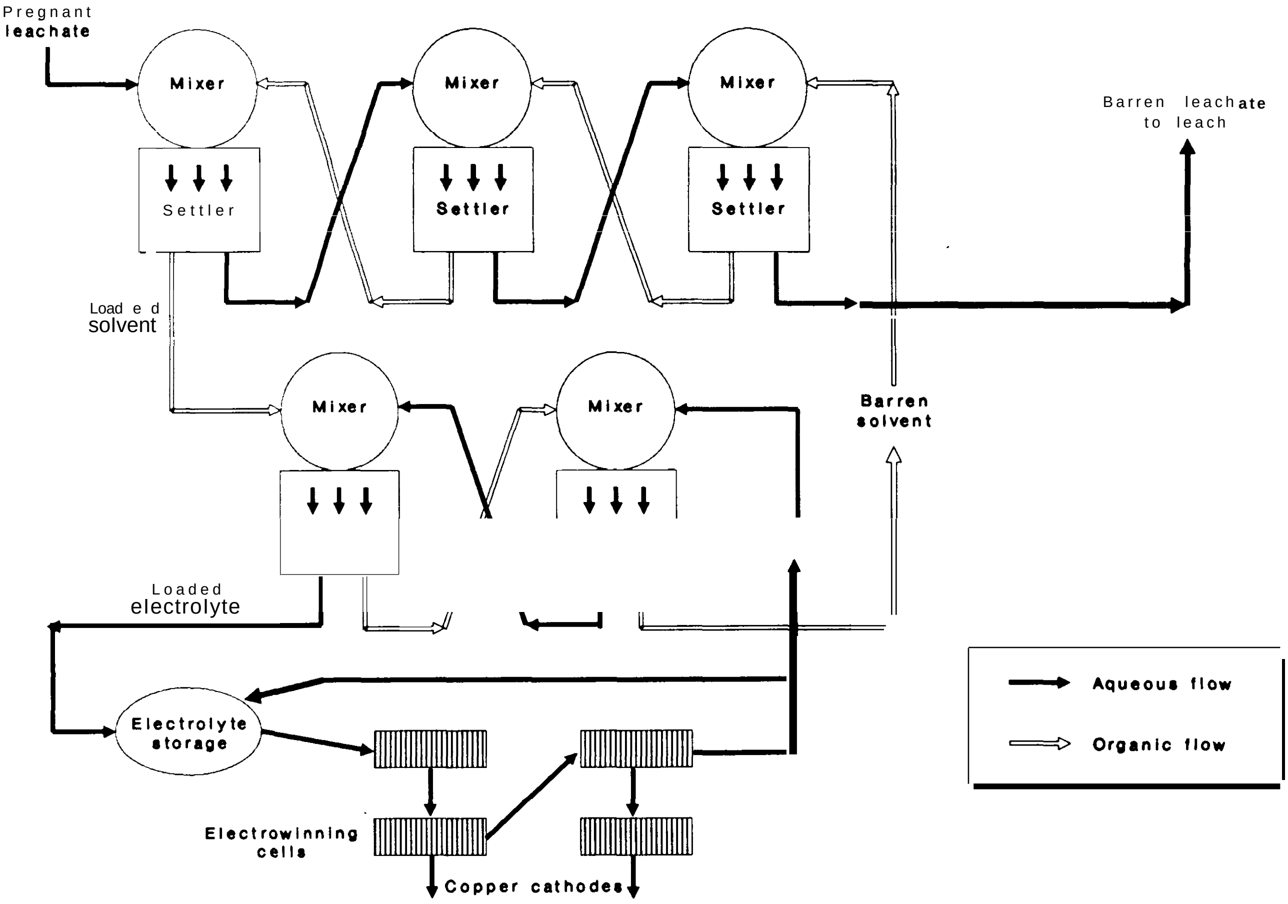
In electrorefining, the fire-refined copper anodes are hung vertically in between cathode starter sheets in long tanks, or cells, filled with an acidic copper sulfate solution. Usually the cathode starter sheets are themselves thin pieces of copper, which become incorporated into the cathode. An electric current is run through the solution and the copper gradually corrodes from the anode and plates onto the cathode. The cathode copper is shipped to the rod mill or fabricator for melting and casting.

Electrowinning is the recovery of copper from the loaded electrolyte solution produced by sol-

---

[60] The material in this Section is from Biswas and Davenport, Supra note 34, unless otherwise noted.

Figure 6-29.-Flowsheet for Solvent Extraction



SOURCE: A. K. Blswas and W.G. Davenport, *Extractive Metallurgy of Copper (New* York, NY: Pergamon Press, 1980).

vent extraction. The basic difference between electrowinning and electrorefining is that in the former, the copper is already in the electrolyte. Therefore, electrowinning uses inert (non-dissolving) anodes, typically made of lead alloyed with calcium and tin, or of stainless steel. These react electrochemically to produce oxygen gas and sulfuric acid, The cathode copper is stripped from the starter sheets (which are reused), and then shipped to the rod mill or fabricator. The acid is recycled to the leaching operation. The cells and electrical circuitry are otherwise similar to those used in electrorefining, although voltages are higher.

Recent innovations in electrorefining and electrowinning have focused on increased productivity through automation and periodic current reversal. Automation of electrometallurgy operations includes computer monitoring of cell voltages, infrared scanning of cells to locate and correct short-circuits, robotic cathode stripping, programmable robotic cranes for automated anode and cathode handling, and machine straightening of cathode starter sheets.[61] Periodically reversing the direction of the direct current for a brief period can increase refinery capacity by as much as 15 percent.[62]

---

[61] Mineral Systems Inc., supra note 26.

[62] Biswas and Davenport, Supra note 34.

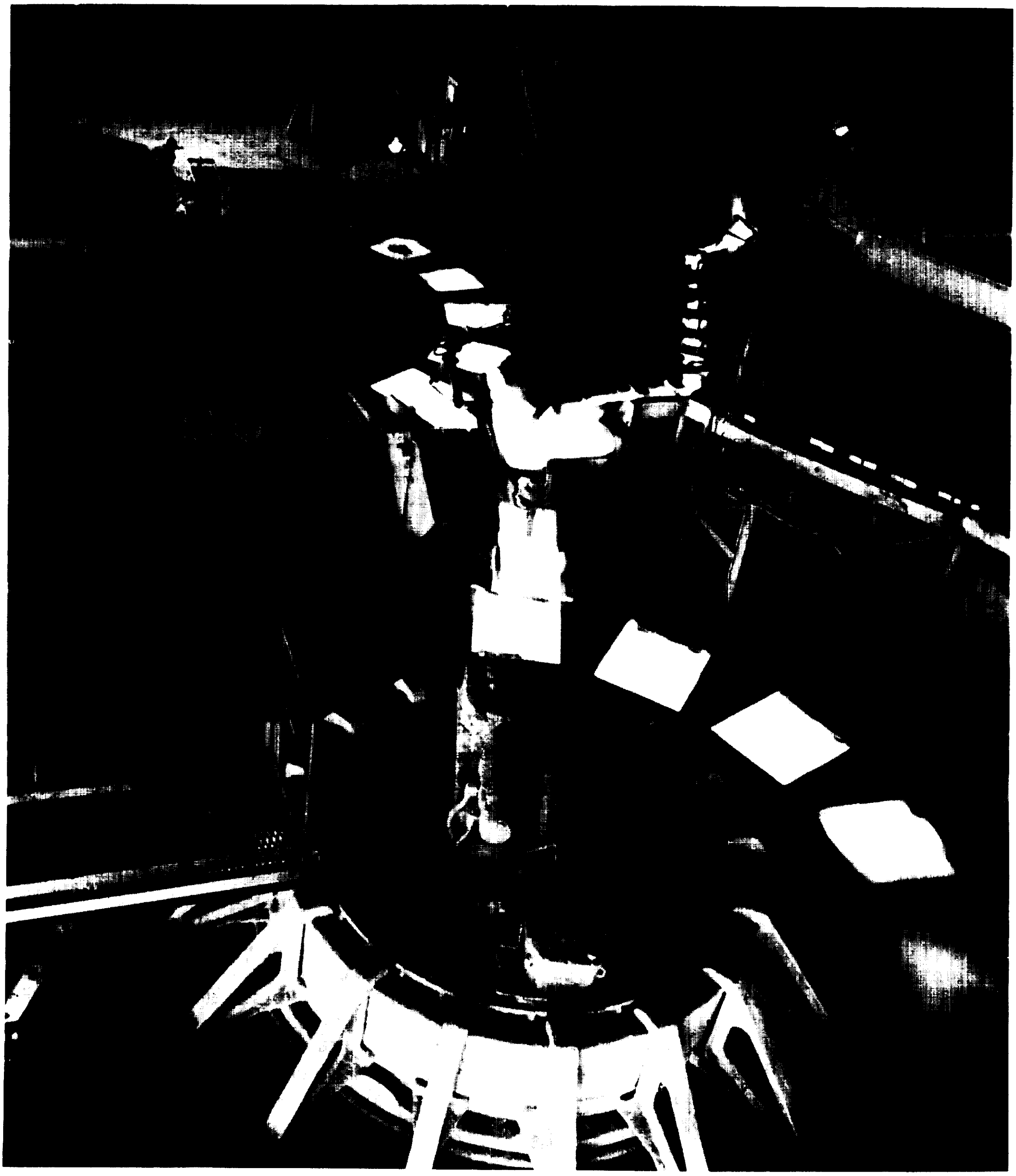


Photo credit: Manley-Prim Photography, Tucson, AZ

Anode casting wheels.

MELTING AND CASTING

Cathode copper is melted and cast into continuous rod or wirebars for wire manufacture, into slabs or billets for mechanical use, or ingots for alloying. The three major forms of copper are:

- **electrolytic tough pitch copper** (less than 0.001 percent sulfur, 0.0015 to 0.03 percent oxygen) for wire and other electrical uses;
- **phosphorus deoxidized copper** (begins with a 90 percent copper and 10 percent phosphorus alloy, removes the oxygen as P_20_5, leaving 99.95 to 99.99 percent copper and 0.01 to 0.05 percent phosphorus) for plumbing, radiators, and other uses requiring welding; and
- **oxygen-free copper,** which combines the high electrical conductivity of electrolytic tough pitch copper and the weldability of phosphorus deoxidized copper, for finely-drawn wire and electronic components.

The cathodes typically are melted in a shaft furnace. They are placed in an opening near the top of the furnace and melt as they descend the shaft. The liquid copper flows immediately into a separate gas-fired or induction-heated holding furnace, and then to casting.

Most mills making electrolytic copper now use continuous casting machines that integrate the

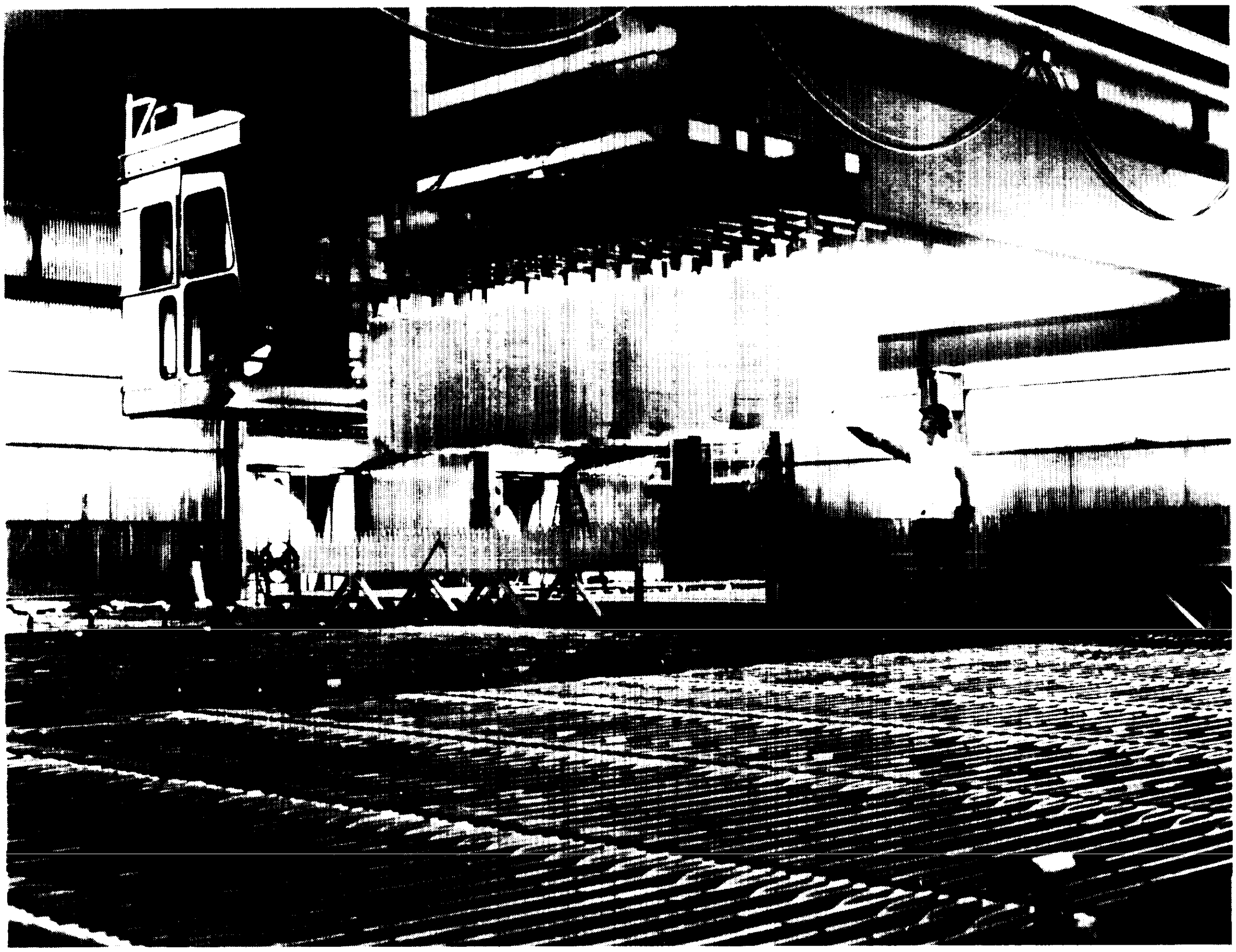


Photo credit Manley Prim Photography, Tucson, AZ

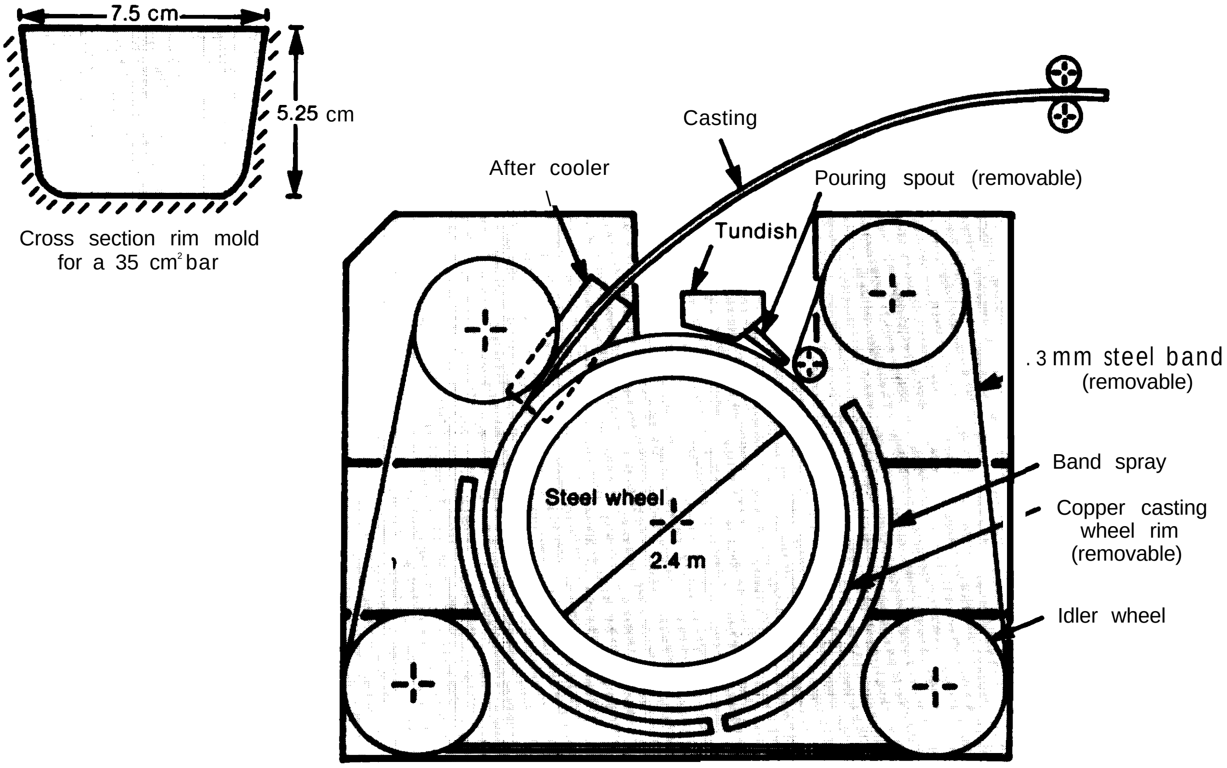
Cathode starter sheets above the electrorefining cells.

casting and subsequent fabrication of 5/16-inch rod in one continuous operation. In the continuous casting wheel patented by Southwire Corp., the liquid copper is poured onto a wheel with a bar-shaped well in the rim (figure 6-30). As the wheel turns, a belt covers the copper and it is partially cooled with a water spray. It exits the other end of the wheel as a red-hot but solidified continuous bar that then enters a single-pass rod-rolling mill (see figure 6-31). In the mill, the bar is extruded in several stages until it is the required thickness. When nearly cool, it is coiled automatically.

Before shipping to customers, the rod is tested in a metallurgy lab for surface quality, electrical conductivity, chemical composition, and physical properties such as hardness, tensile strength, and elongation failure. Any batch that does not meet standards is remelted and recycled through the rod mill.

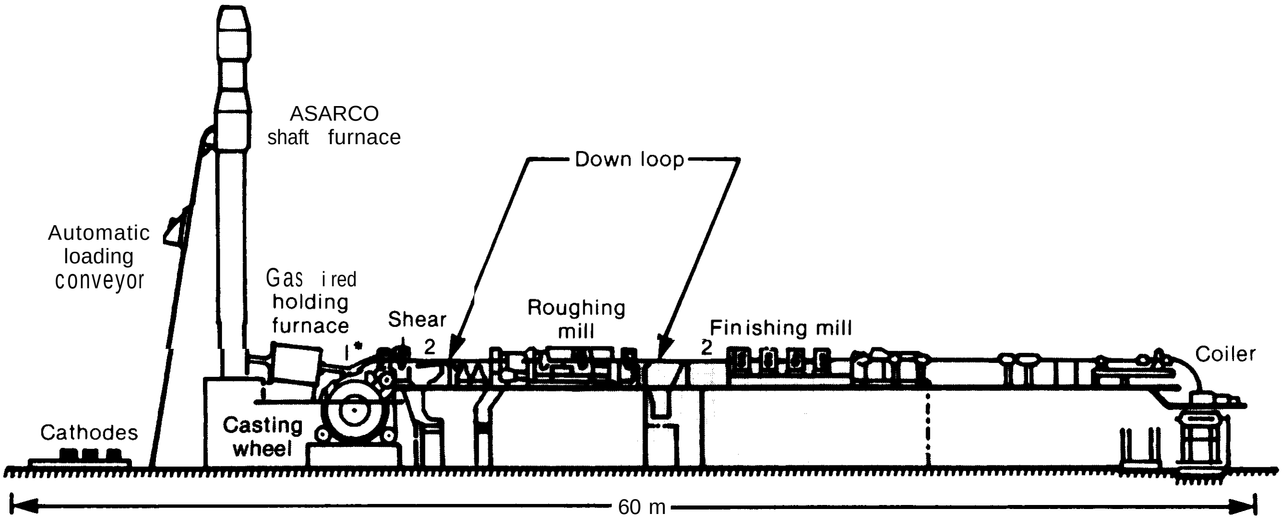
Continuous cast rod–now the industry standard—brought substantial improvements in productivity in melting and casting, through both automation and significant increases in the quality of the final product and thus fewer batches that have to be reprocessed.

Figure 6-30.—Continuous Casting Wheel



SOURCE: A.K. Biswas and W.G. Davenport, *Extractive Metallurgy of Copper* (New York, NY: Pergamon Press, 1980).

Figure 6-31.—Continuous Rod Rolling Mill



*NOTE The numbers refer to sensor positions for automatic control

SOURCE A K Biswas and W G Davenport, *Extractive Metallurgy of Copper (New* York, NY: Pergamon Press, 1980)