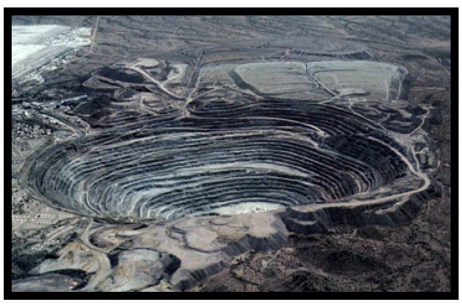
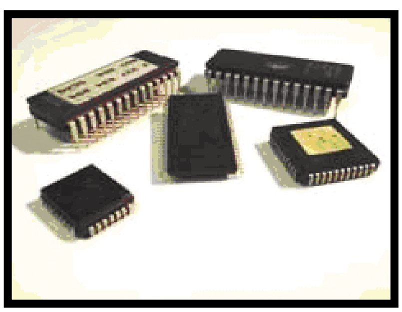
Technological Advancement–A Factor in Increasing Resource Use

By David R. Wilburn, Thomas G. Goonan, and Donald I. Bleiwas





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On the cover:
Top left: Photograph of an open-pit mine in the Sonoran Desert near Ajo, Ariz. (Walker, 1997).
Top right: Photograph of Amarillo copper refinery (courtesy of ASARCO, Inc., 1999).
Bottom left: Photograph of computer chips (courtesy of Connecticut Metal Industries, 2003).
Bottom right: Photograph of scrap metal to be sorted and recycled (courtesy of Racelogic, Limited, 2003).

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
barrel (bbl) (petroleum, 1 barrel=42 gal)	0.1590	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per minute (ft/min)	0.3048	meter per minute (m/min)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)
	Energy	
kilowatthour (kWh)	3,600,000	joule (J)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

Technological Advancement—A Factor in Increasing Resource Use

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Abstract

The possibility of mineral resource depletion has been repeatedly raised as a concern because ever-growing populations will place ever-growing claims against finite resource endowments. This report addresses this perception and analyzes how technology has helped to ease resource constraints for many mineral commodities. Case studies on aluminum, copper, potash, and sulfur are provided to identify the effects of technology on resource supply.

In spite of losses of resources accessibility resulting from environmental policy and expanding urbanization, mineral producers historically have been able to expand production and lower production costs. Between 1900 and 1998, production increased by 6,000 percent for sulfur, 3,770 percent for potash, 3,250 percent for aluminum, and 2,470 percent for copper. For the same period, constant-dollar (1998) prices decreased by 94 percent for potash, 90 percent for aluminum, 89 percent for sulfur, and 75 percent for copper.

The application of technology has made mineral deposits available that were overlooked or considered to be nonviable. As technology changes, producers can meet the demands for higher quality, more energy efficient, and more environmentally safe products with less physical material. Also, technological changes have increased the amount of materials recycled and remanufactured. Technological advances can occur as breakthroughs, but it most often advances incrementally and is driven by the profit motive.

Introduction

The Earth is made up of chemical elements that exist in fixed amounts. Except for a few metals (eg. gold and silver), it is not the elements themselves that are the objects of human affection, but rather the properties that these elements possess alone or in partnership with other elements. In this context, resources are these useful properties. To this point, humanity has not yet exhausted mineral resources, yet many fear the prospect of running out.

Technology represents ways that humans apply experience, ingenuity, and knowledge to organize capital, energy, and materials to get what they want and need. Application and organization of technology are the means to make things useful, to acquire things that are already useful, or to transform things that are not useful into things that are. Human actions with respect to nonfuel mineral resources are characterized by changing the form of resources through rearrangement and separation to maximize their utility. The total available resource consists of in situ (not yet extracted) materials, in-use materials, and the byproducts of production and use (wastes). Future material requirements can likely be met by continually rearranging resources in these forms as long as they are not inaccessible or permanently destroyed.

In a market system, higher prices reflect demand and supply and provide incentives to suppliers and consumers. In short, the very mechanism (higher prices) that signals a resource constraint stimulates efforts to develop technologies to meet the challenge. Gold, because of its rarity and high price (a measure of desire or usefulness), has been recycled throughout the ages. A modern article of jewelry that contains recycled gold could conceivably contain gold from an earring worn by Helen of Troy (Amey, 2000).

Rising prices for natural resources, expressed in constant dollars, would provide one kind of evidence that technological advances have been ineffective in keeping up with changes in demand. Constant prices would demonstrate that technological advances have kept pace with the changes. Decreasing prices would indicate that technology has been more than sufficient to overcome obstacles to supply.

Figure 1 shows the increase in U.S. apparent consumption during the 20th century for 86 significant minerals. Figure 2 shows slightly declining U.S. mine production composite price index, comprising data for five metal commodities (copper, gold, iron ore, lead, and zinc) and seven industrial mineral commodities (cement, clay, crushed stone, lime, phosphate rock, salt, and sand and gravel). The advancement of technology resulting in greater productivity is a major contributing factor that the price index has a downward trend.

> Technology builds upon accumulated knowledge to organize capital, energy, information, and material resources in response to human needs.

This study examines the history of technology as it pertains to the availability and pricing of mineral resources in general. Appendices 2 through 5 provide detailed examples of selected commodities to demonstrate how technology has historically been able to respond to human needs.

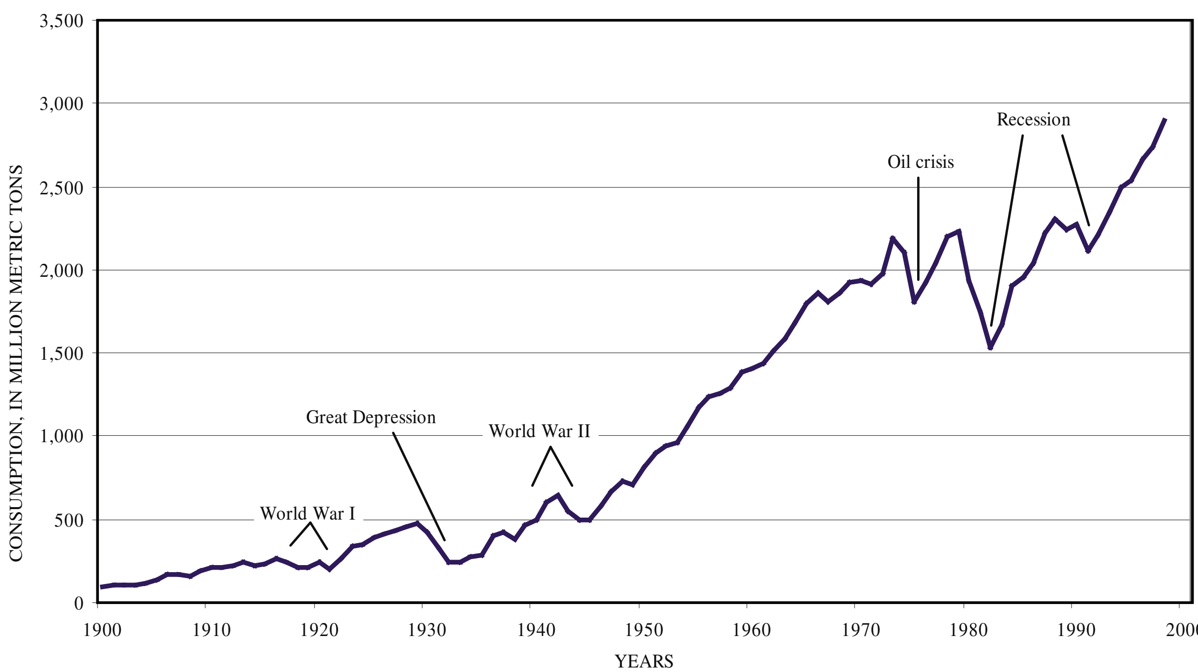

Figure 1. U.S. apparent consumption of minerals, 1900 to 1998. Adapted from Sullivan and others, 2000).

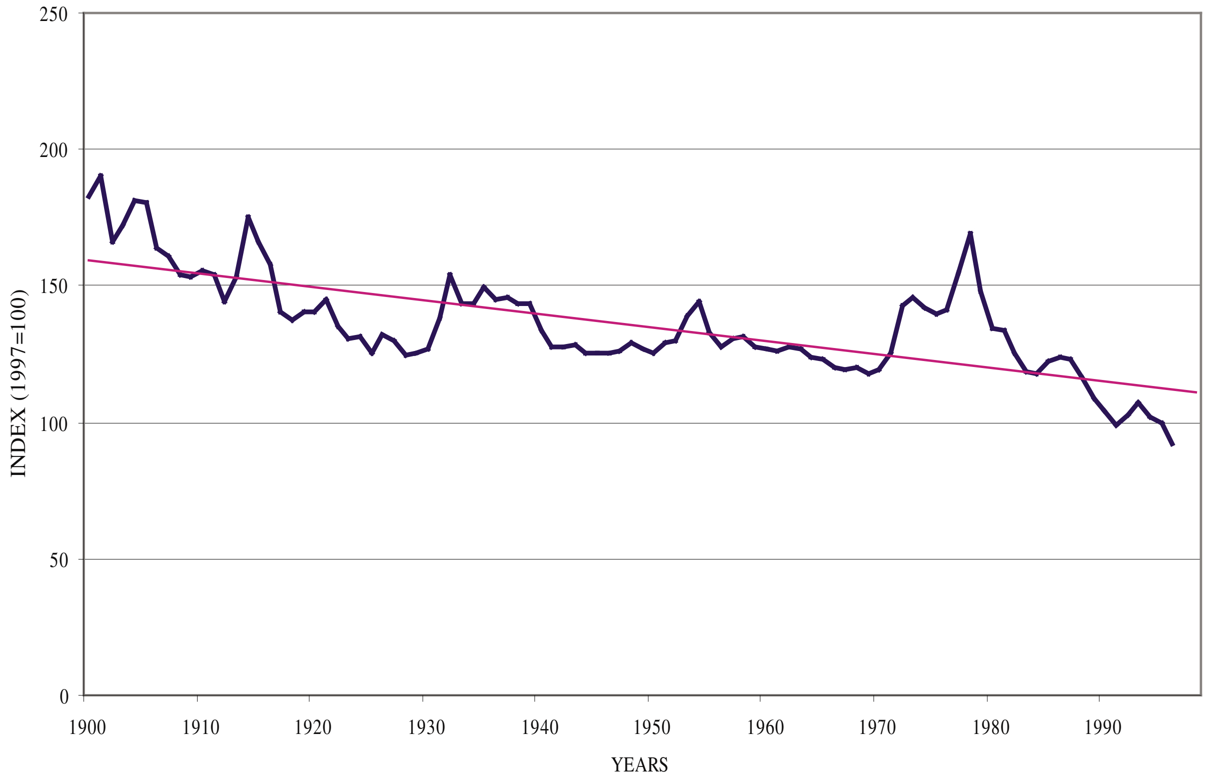

Figure 2. Composite mineral price index for 12 selected minerals, 1900 to 1998, in constant 1997 dollars (Sullivan and others, 2000). The metallic mineral commodities are copper, gold, iron ore, lead, and zinc, and the industrial mineral commodities are cement, clay, crushed stone, lime, phosphate rock, salt, and sand and gravel.

Relationship Between Technology and Mineral Supply

Technology is the application of knowledge to practical purpose. Through an ongoing process of discovery and knowledge building, humans apply technological knowledge to meet the needs of individuals, industries, and society. Technology changes in response to increased knowledge and the shifting priorities among economic, political, or societal factors. Technology is built upon accumulated knowledge about how best to organize capital, energy, information, labor, and material resources.

Several common themes emerge from the history of technological changes in mineral-commodity industries. Despite their long histories, natural resource industries have managed to maintain a high level of technological sophistication through continual incremental innovation and restructuring. These industries have made use of technological innovations from within and outside their industry. Innovations generally are not generally revolutionary, rather they are evolutionary.

Greater understanding of geologic mineral-deposit models has aided the discovery of numerous resource types. Technology has been developed to extract and process many of these diverse resources, and mineral supply has expanded as a result.

Most natural-resource producers have accommodated increased concerns for environmental protection and worker health and safety and yet remain competitive. Data collected by the USGS suggests that during the past 100 years, world production of nonfuel minerals has managed to meet increased demand at lower real prices. Figure 3 and table 1 show production/price (expressed in 1998 dollars) relationships during the 20th century for the four commodities discussed as case studies in Appendices 2 through 5.

Between 1900 and 1998, world primary plus secondary aluminum metal production increased by about 31,000 percent, but the aluminum metal price decreased in constant dollar terms by 84 percent. For the same period, world copper metal production increased by about 800 percent, but its price decreased by 75 percent. A similar trend is apparent for industrial minerals. Since 1900, world potash production increased by 148,000 percent, but its price decreased by 87 percent. Also, world sulfur production increased by 13,000 percent, but its price decreased by 85 percent (Buckingham and Ober, 2002; Buckingham and Plunkert, 2002; Buckingham and Searls, 2002; Porter and Edelstein, 2002). Advances in technology played a significant part in these trends.

Table 1. World production and real value relationships, in percent, for aluminum, copper, potash, and sulfur, 1900 to 1998

[Buckingham and Ober, 2002; Buckingham and Plunkert, 2002; Buckingham and Searls, 2002; Porter and Edelstein, 2002]

Commodity	Percentage increase in production	Percentage decrease (in 1998 dollar unit value)[1]
Aluminum	31,000	84
Copper	800	75
Potash	148,000	87
Sulfur	13,000	85

[1]The real value (1998 dollars per metric ton) is defined as 1 metric ton of apparent consumption as reported by the U.S. Geological Survey (1999) divided by the Consumer Price Index with a base year of 1998.

Although circumstances or social pressures, such as environmental regulation or localized resource shortages, may initiate technological change, innovations tend to generate additional

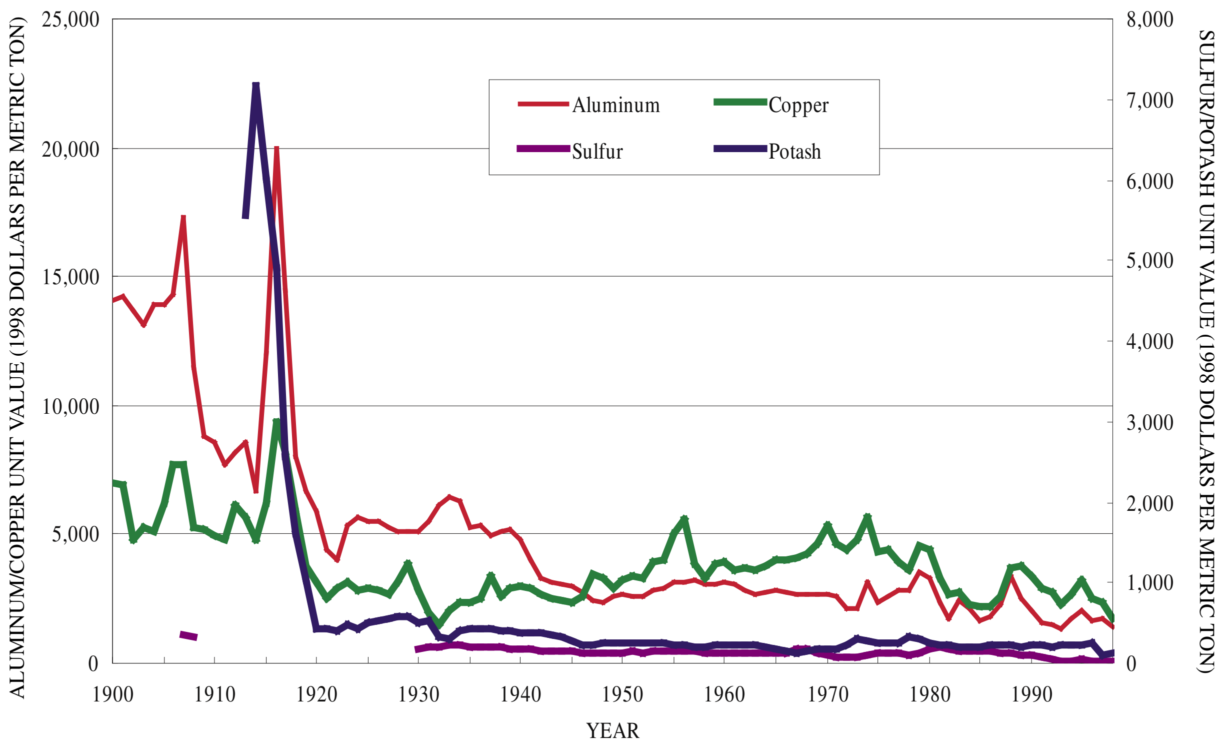

Figure 3. Unit values for selected minerals, 1900 to 1998 (Buckingham and Ober, 2002; Buckingham and Plunkert, 2002; Buckingham and Searls, 2002; Porter and Edelstein, 2002). The unit value (1998 dollars per metric ton) is defined as 1 metric ton of apparent consumption estimated from the "Annual Average Primary Price" in U.S. dollars as reported by the U.S. Geological Survey (1999), divided by the Consumer Price Index with a base year of 1998.

change most often on an incremental level (Simpson, 1999, p. 18). When an industry is capital intensive (that is, has invested large amounts of money on facilities or equipment), its owners have an incentive to perpetuate the industry. They can do so by investing in technologies to reduce production costs (Appendix 3).

Technological innovations and their applications are difficult to predict. During the past 50 years, advances that used such materials as silicon in computer chips, gallium in semiconductors, and nickel, cadmium, and lithium in batteries and printed circuits have had enormous impact on the electronics industry (figure 4). In 1949, Popular Science wrote that the Electronic Numerical Integrator and Calculator, which was the most sophisticated computer of the day, required 18,000 vacuum tubes and weighed 30 metric tons (t). The magazine predicted that computers in the future might require only 1,000 tubes and weigh only 1.5 t (Los Alamos National Laboratory, 2001). The computer power that was in those 30 t can now fit in a modern pocket calculator that can be widely purchased at a low price. These advances have resulted in the use of diverse materials, lower weight, improved durability, decreased energy consumption, and increased performance at markedly lower costs.

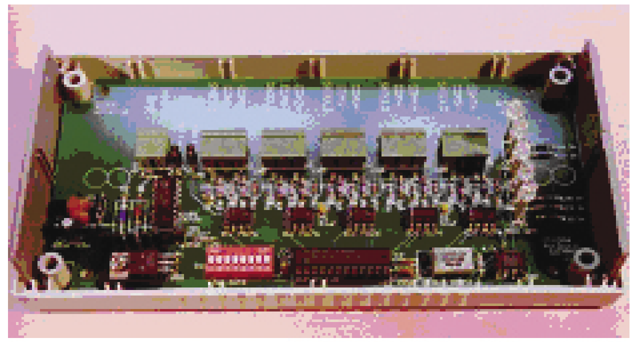

Figure 4. Computer circuit board. Courtesy of Airborn Electronics Company, 2001.

President Truman created the President's Materials Policy (Paley) Commission in 1951 for the purpose of addressing concerns about domestic shortages of copper and other strategic materials during the Korean conflict and suggesting long-term solutions. The Commission issued the five-volume "Resources for Freedom" report in June 1952. The second volume, "The Outlook for Key Commodities," included an analysis of copper supply. The findings were pessimistic about the Nation's future copper supply from domestic. The Commission reported that U. S. reserves of copper ore, which contained at least 1 percent copper, were fixed in size and not likely to include lower grade ores. The copper industry, however, performed much better than expected. The average ore grade of copper extracted from U.S. mines in the early 1970s approached 0.6 percent (Hyde, 1998, p. 182). The average U.S. copper ore grade in 2000 approached 0.5 percent (Daniel Edelstein, Copper Commodity Specialist, U.S. Geological Survey, oral commun., 2000). The ability to mine these low-grade ores at a profit was generally achieved through technological improvements.

Productivity can serve, in part, as a measure of the impact of technology. Productivity is used as a measure of the efficiency of the production process. Implementation of the solvent extraction-electrowinning process (SX-EW), which requires a small workforce to recover large quantities of low-cost copper resources, is one major innovation that has helped sustain the copper industry since 1985. Other factors, such as increased capital investment, industry consolidation, and labor contract changes, contributed to improved productivity after 1985. (Labor contract changes are considered to be an administrative technology when included under the definition of technology given on page 1.)

Application of Technology to the Materials Cycle

Technology improves the efficiency of the flow of minerals and materials to meet the needs of the consumer (figure 5). Technological improvements focus on developing methods to facilitate or improve the efficiency of exploration and development; extraction, processing, and fabrication; and product use and disposal. The technological methods used in each sector of these "nodes" of the materials cycle depend upon economics, environmental consequences, the relative political power of competing interests, and societal effects.

Humans separate materials from existing combinations and recombine them into forms that have more use.

Minerals exploration requires the ability to use techniques to locate economically recoverable resources. Mining technology allows the valuable resources to be extracted from the Earth. Processing technology provides a means of preferentially separating useful mineral constituents from undesirable minerals and materials by biological, chemical, and physical methods. The breaking of chemical and physical bonds (mineral processing) to extract useful substances often requires high-energy requirements that technological advances strive to minimize. Manufacturing

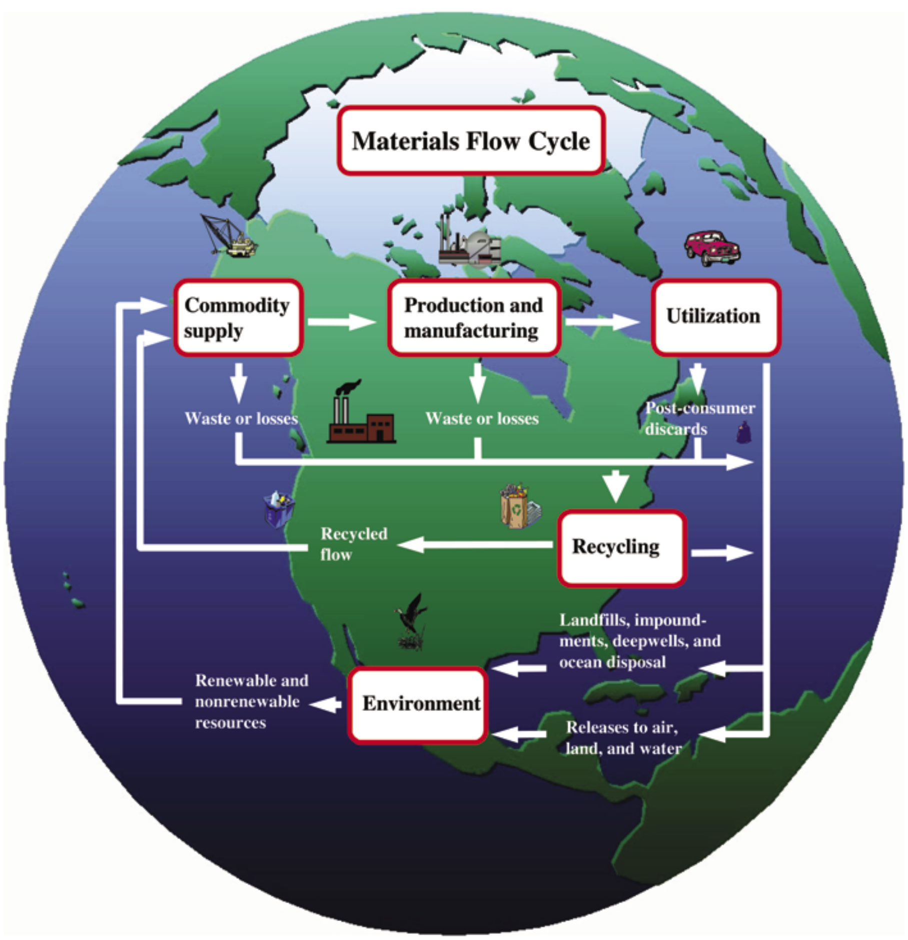

Figure 5. The materials flow cycle. Adapted from U.S. Geological Survey, 1998.

technology creates combinations of materials to form desired products. Consumer products are then distributed to locations where their useful properties are needed; this process requires transportation technology. Some materials are lost to the environment during processing or transportation; technological advances can minimize these losses and their effects on the environment. As products become obsolete, they are recycled or disposed of in landfills where they are potential resources for future recovery (figure 6).

The following sections discuss the role of technology as it applies to the materials flow cycle for minerals. The cycle includes mineral exploration and extraction; processing and fabrication; use; and recycling, which includes remanufacturing and reuse. Figure 5 is a generalized flow diagram of the materials flow cycle.

Figure 6. Wastes deposited in landfills may become significant sources of materials in the future. Photograph courtesy of A. MacIntire, DB Enterprises Inc., August 22, 2000.

Exploration—"Finding the needle in the haystack"

The history of mineral exploration shows the incremental and mutually reinforcing nature of technology. Throughout human history, technology has influenced where and how prospectors look for minerals by drawing upon mineral-deposit models that were developed from previous exploration experiences and mining activities, available technological tools, current knowledge of the earth sciences, and mining and processing capabilities. As knowledge grew and technology progressed, mineral-deposit models were gradually refined, new search areas were identified, and prospecting methods and equipment became more sophisticated. (Additional information can be found in Appendix 1.)

The increasing sophistication of mineral-deposit models allowed reevaluation of known resource areas or application to other areas with similar geologic characteristics. The exploration histories of the Carlin Trend gold deposits in Nevada and the Olympic Dam copper/uranium deposits in Australia, which are discussed in Appendix 1, are two examples that show how technological development in ore processing and geologic modeling led to the discovery of additional resources. Fine-grained gold from the Carlin Trend became an economically viable resource only after such technologies as cyanide leaching were developed to extract it.

Exploration technology builds upon evolving mineral deposit models, incremental advances, and occasional breakthroughs that expand search areas.

Technological advances in processing ores encourage exploration for a greater variety of resource types. Lower grade porphyry copper ore bodies became more attractive for exploration with the advent of froth flotation to separate valuable minerals from waste material, large-scale open pit mining, Pierce-Smith converting, and a large-scale copper-refining process that uses oxygen as the reacting agent. Waste dumps used by U.S. copper producers became exploitable following the development of the SX-EW process, which allowed waste material from previous mining to be reprocessed for copper. Application of the Olympic Dam copper/uranium model to Europe and the United States has lead to the expansion of mineral supply by identifying unknown deposits (Pratt and Sims, 1990). New deposit information, redefined deposit models, and (or) technological breakthroughs may make it possible for economic recovery of material that was considered to be noneconomic.

Major innovations that transformed exploration technology can borrow from breakthroughs made in other sciences and industries. Geologists applied or adapted some of the technological advances in geochemistry, geophysics, and oil and gas drilling to aid in mineral exploration. Computer and laboratory facilities provided the means to measure newly discovered resources with increasing accuracy. Long-range exploration and characterization efforts reduced environmental disturbance. By the end of the 20th century, exploration and mining used sophisticated models, such as those developed by the USGS and based on integrated science (Cox and Singer, 1987; Bliss, 1992). The newer models rely heavily on computer modeling of grade and tonnage. Tools have been developed to detect mineral deposits under water and at great depths below the Earth's surface. Remote sensing methods, such as satellite imagery, can provide a means of identifying areas with mineral-deposit potential without the need to visit remote sites or to disturb environmentally sensitive areas.

During the past 50 years, mineral exploration has located significant nonfuel mineral resources of economic interest several kilometers below the oceans' surface. Extensive but thin deposits of manganese nodules and crusts that contain important amounts of cobalt, copper, and nickel have been located on the floor of most of the oceans of the world by using geochemical, geophysical, and remote sampling techniques. First discovered in the 1870s, manganese nodules were considered to be geologic curiosities. The potential of these deposits as sources of cobalt, copper, manganese, and nickel was not appreciated until the 1950s. Between 1958 and 1968, numerous companies began serious prospecting of the nodule fields to estimate their economic potential. By 1974, 100 years after the first samples were taken, exploration documented that the Clarion-Clipperton zone, which is one broad belt of seafloor between Hawaii and, was literally paved with nodules over an area of more than 3.5 million square kilometers. The area has been estimated to contain 7.5 billion metric tons of manganese, 340 million metric tons (Mt) of nickel, 265 Mt of copper, and 78 Mt of cobalt (Morgan, 1999).

The application of geophysical methods to minerals exploration after World War II led to the discovery of many deposits and the extension of known ones. Airborne electromagnetic surveying (AEM) was developed in the late 1940s to differentiate highly conductive ore bodies from low-conductivity host rocks (figure 7). During the next 25 years, AEM was useful in the discovery of diamondiferous kimberlite pipes on the Canadian Shield, uranium deposits, and volcanogenic massive sulfides, as shown in figure 8. The frequency of discovery of these types of deposits increased

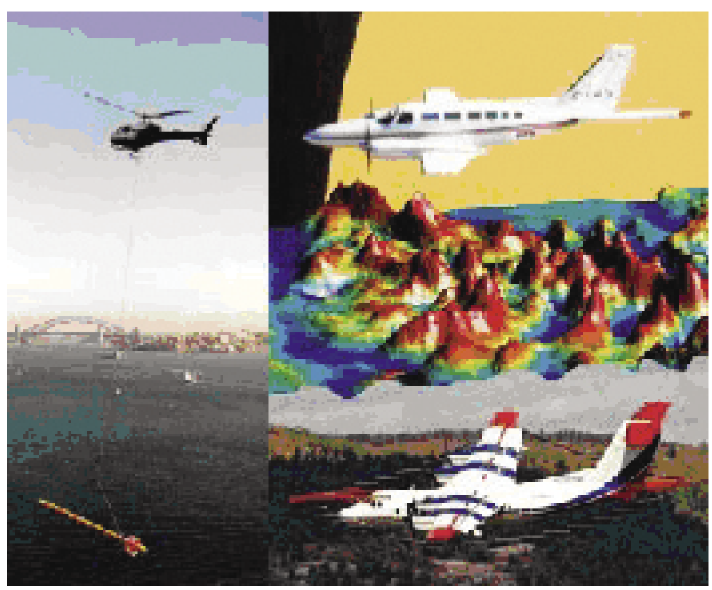

Figure 7. Airborne geophysical methods. Photograph courtesy of R. Petersen, Fugro Airbourne Surveys, Ottawa, Ontario, Canada, September 20, 2000.

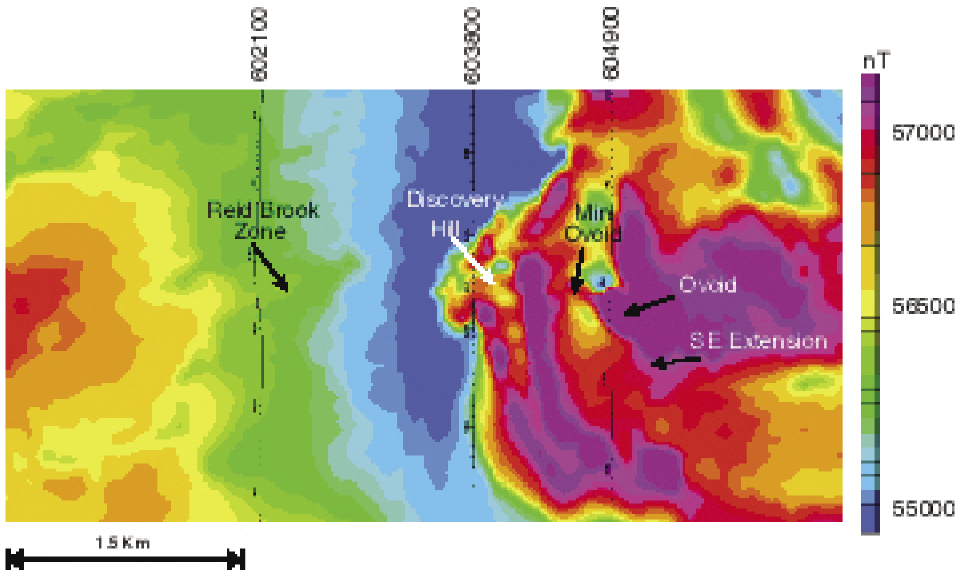

Figure 8. Magnetic maps such as this aided the discovery of the Voisey's Bay nickel-copper deposit, Newfoundland, Canada. Photograph courtesy of Steve Balch, Inco Technical Services, Ltd., reprinted with permission of Inco Limited and Voisey's Bay Nickel Company Limited, October 27, 2000.

significantly as exploration took place in a wide variety of geologic environments (Ascough, 1999, p. 60).

Gravity methods have been used since the 1950s to detect density contrasts between the dense mineral deposits and the less dense host rock. Although gravity anomalies often are difficult to discern and interpret, gravity methods have been used to investigate the exploration targets detected by AEM, geochemical, or magnetic surveys and can serve as a screening device that provides additional evidence to support continued exploration (Thomas, 1999, p. 101). Gravity methods have been successful in exploring for many types of deposits, which include natural gas, petroleum, porphyry coppers, and sulfur.

Mineral exploration with magnetic methods, which detect contrasts between host rocks and magnetic mineralized zones, are most useful with iron ore deposit models, but they also aid in exploration for other deposits and can be used in advanced stages of exploration to define target ore zones better (Lowe, 1999, p. 131-132). The use of these geophysical tools as well as aerial photography and computer modeling has dramatically altered the scope of mineral exploration.

Extraction—"Separating the needle from the haystack"

Once a deposit has been located, technologies are required to determine if it is economically and technically viable to develop. Advances in blasting, such as the development of ammonium-nitrate fuel oil (ANFO) blasting agent, drilling, and equipment design and capacity have reduced costs and improved mining efficiency. The use of larger capacity equipment and increased mechanization has also improved productivity and reduced mining costs (figure 9). Mine planning and ore extraction have become more efficient and less costly because of computer technologies that enable realtime deposit modeling, sampling, and analysis of ores. The case studies in Appendices 2 through 5 describe how technology has been used

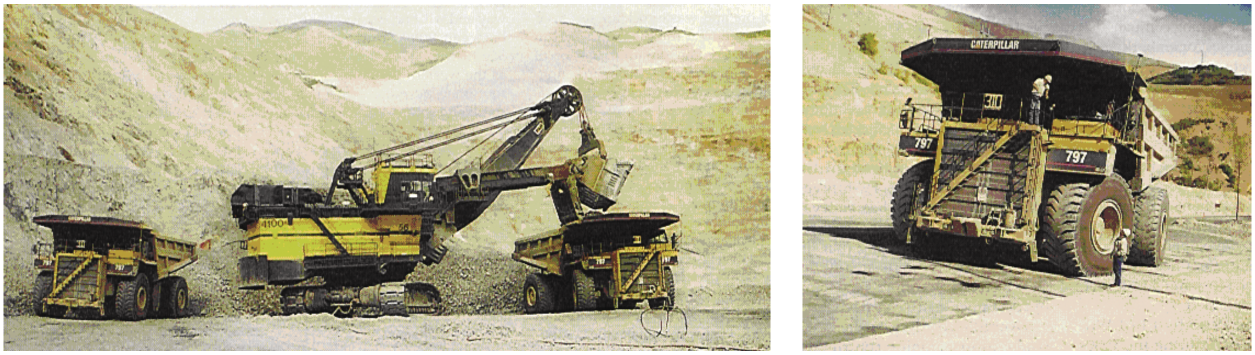

Figure 9. Loading and hauling equipment at Bingham Canyon copper mine, Utah. Photographs reprinted with permission of Rocky Mountain Construction, 2000.

to improve extraction and separation capabilities of aluminum, copper, potash, and sulfur ores, thereby expanding mineral supply.

As with many natural resource industries, technological advances in the copper industry consist of occasional major changes combined with continuous incremental improvements. Large-scale copper reduction became possible between 1905 and 1930 with the implementation of large-scale open pit mining, Pierce-Smith copper converters, and sulfide flotation. Pierce-Smith technology, which was developed in 1910, allowed copper to be enriched to between 95 and 97 percent at lower costs while consuming less energy than previous methods. The advent of flotation technology in Australia in the 1920s enabled the separation of copper from the unwanted material in copper-rich sulfides and separated different metal sulfides from each other, thus making copper available from polymetallic sulfide ore bodies. This technology led to byproduct recovery of what had been considered to be waste. Many ores in Mexico, for example, could now be extracted economically. The development of porphyry copper deposits in the Southwestern United States was made possible through these technological developments and improvements in open pit mining and materials-handling equipment. In the 10 years that followed the development of the first large porphyry copper mine (1906), output from mining these low-grade ore bodies amounted to 35 percent of U.S. copper production (Hyde, 1998).

The history of the U.S. copper industry illustrates how technology contributed to the recovery of a declining industry confronted with trends of decreasing ore grades, expanding overseas competition and environmental regulation, and increasing ore complexity. Legislation that mandated higher ambient-air-quality standards with respect to sulfur dioxide (SO_2) emissions led to the oxygen-flash-smelting process, which decreased energy requirements for copper smelting by 10 to 30 percent and, like other smelting processes, also produced SO_2 that could be recovered and converted into sulfuric acid thereby lowering atmospheric emissions. This byproduct is used as the leaching agent in the SX-EW process, which allowed producers to recover copper from waste dumps, thus effectively extending mine life and rejuvenating the domestic copper mining industry. This process is widely used throughout Chile and the Southwestern United States and has been extended and combined with subsequent innovations so that even very low grade oxide ores now are economically recoverable.

Copper production predates aluminum production because of the absence of technology to separate aluminum from abundant aluminum-bearing clays or rocks. In the 1880s, development of the Bayer process to produce alumina from bauxite and the Hall-Héroult process to refine alumina into aluminum metal effectively allowed aluminum to be converted from a rare metal to a marketable commodity. The estimated (for indicative purposes only) 1887 unit value, in 1998 dollars, was about $300,000 per ton. In 1900, the estimated price was about $14,000 per ton, and by 1998 the price was about $1,400 per ton (Buckingham and Plunkert, 2002). Although the basic process has changed little since its inception, individual cell production capacity has increased to about 820 metric tons per year (t/yr) in 1995 from 15 to 20 t/yr in 1900. As a result of continuous improvements in cell design and process efficiency, cell efficiency increased to 92 to 95 percent in 1995 from 70 to 80 percent in 1900, and energy consumption decreased to about 13 kilowatt hours per kilogram (kWh/kg) of aluminum in 1995 from about 35 kWh/kg of aluminum in 1900 (Peterson and Miller, 1986, p. 113; Ǿye and Huglen, 1990, p 24; Grjotheim and others, 1995, p. 32).

The Hall-Héroult and SX-EW processes have revitalized resource industries because they often allow recovery from more diverse sources of supply.

Because aluminum production consumes large amounts of energy, early plants were located close to energy sources, which were mainly in Europe (coal) and the United States (hydropower). As energy efficiencies were achieved after World War II and transportation costs increased, transportation factors also became important considerations in site selection. Integrated mining and processing facilities were developed in Saudi Arabia, South America, and Western Australia to take advantage of abundant bauxite resources and cheap local energy.

The United States, which has limited bauxite resources, relies on foreign sources of bauxite to supply the integrated domestic aluminum smelting and refining industry. Efficient materials handling and long-distance transportation systems have been developed to move large quantities of alumina and bauxite more cost effectively.

Technological developments in one industry can advance other industries.

The potash case study shows how technology developed for one industry can be adapted to fit the needs of another (Appendix 4). Much of the world's potash comes from salt deposits formed by the evaporation of ancient lakes, oceans, and seas. Deposits in Canada, Europe, and the United States were discovered in the first half of the 20th century during the search for petroleum. Within the past 100 years, diverse and very large potash resources have been discovered by using new technologies. These resources should be sufficient to supply the world's potash needs well into the future. The deep deposits discovered in Canada were accessed by newly developed technologies that permitted shafts to penetrate rocks that contained water under high pressure. Continuous miners, which are highly mechanized pieces of equipment that are capable of producing up to 900 metric tons per hour from underground mines, were developed in the coal industry to improve productivity and safety and were adapted for use in potash mining (figure 10). Technology that is used to recover potash and sulfur through deep wells (solution mining) was adapted from the petroleum industry and is similar

Figure 10. Continuous miner at the Rocanville potash mine, Saskatchewan, Canada. Photograph courtesy of Net Resources International Limited, 2001.

in principle to the solution mining techniques that were used by Chinese miners about 1,500 years ago. Solar evaporation mining is used to recover potash from brines in the Middle East, the high deserts of Chile, and the Great Salt Lake in Utah. Flotation methods, which were originally developed by the copper industry, were adapted for use at potash operations in New Mexico during the 1930s and were quickly adopted worldwide.

The history of sulfur extraction and production technology also reflects continuous improvement of processes developed from other industries to meet changing materials use requirements and societal needs. The Frasch process, which produces elemental sulfur from underground deposits of native sulfur, was the first in situ mining technology used for sulfur production. This method, which has been used continuously since 1904, recovers sulfur from deposits that are located deep underground or underwater with little disturbance to the host rocks. The Claus process was first used in the 1950s to recover sulfur from the hydrogen sulfide produced during oil refining (figure 11). Sulfur in the form of hydrogen sulfide was found to be detrimental in the oil refining process because it is highly corrosive.

Figure 11. Technology for sulfur recovery was adapted from the oil-refining industry. Photograph courtesy of Phillips Petroleum Company, 2001.

As energy demand grew between 1950 and 1975, sulfur production as a byproduct of oil refining also grew. The Clean Air Act of 1970 set standards for coal combustion for electricity generation, pyrometallurgical processing of sulfide ores, and sulfur recovery from oil refining, which stimulated the development of sulfur-removal technologies to comply with the new standards. Sulfur dioxide gas generated from oil refining and sulfide ore smelting is well-suited for the production of sulfuric acid. The petroleum and copper industries can use sulfuric acid effectively in other on-site processes. Since 1975, sulfur and sulfuric acid production from oil refining and sulfuric acid production during pyrometallurgical processing have come to dominate U.S. sulfur production. This is an example of achieving benefits from the conversion of a waste to a useful product.

Sulfur technologies were developed to meet industry challenges. Sulfur recovery technology has increased production and the number of production sources to the level that sulfur

> Technology adapts to meet changing priorities or use patterns. It also can influence societal choices.

for the world economy is more than sufficient in the foreseeable future. At the same time, these technologies have allowed U.S. industries to comply with environmental regulations and provided other countries with technological models for environmental sustainability and industrial cooperation.

Development of the portland cement process revolutionized the cement industry during the 19th century. The portland process, in which a proportioned mixture of finely ground raw materials is converted to “clinker” by heating these materials until partial fusion takes place, allows a wider variety of natural raw materials to produce hydraulic cement with uniform strength and setting time; natural hydraulic cements, which set and harden underwater, are limited in nature and vary widely in quality and processing characteristics. Use of the rotary kiln, which was first introduced to process portland cement, led to development of alternative fuel sources, such as natural gas, petroleum, and powdered coal; increased cement production;

and reduced labor costs. U.S. industry consumption of cement increased to 110 Mt in 2000 from 3.1 Mt in 1900 (van Oss and Kelly, 2002). The U.S. construction industry uses this material in most commercial, public, and residential construction projects.

Current materials research on nickel illustrates how technology continues to be developed, even in times of abundant supply. Commercial application of several processes that use bacteria to concentrate metals contained in nickel ore (including cobalt, copper, and nickel) is very close to commercial implementation. By the year 2010, a process could come on-stream that will rely on a strain of bacteria that is usually associated with volcanic hot springs and is similar to those responsible for the formation of deep-sea metal deposits. The bacteria convert the sulfides to sulfates, which are a more easily treatable form. If proven successful, more nickel, as well as cobalt, copper, and other associated metals, could be recovered than with conventional processing methods because lower grade ores, previously mined materials, and more efficient extraction of nickel from traditional ores may be accomplished. This bacterial process also may have environmental advantages over established technologies because conventional smelting of nickel concentrate produces undesirable sulfur dioxide and dusts. Leach residue from this new method conforms to the U.S. Environmental Protection Agency's (EPA) standards for stability. Moreover, capital costs are expected to be considerably lower than for conventional operations, and because the energy-intensive requirements and environmental costs associated with conventional smelting are substantially reduced, operating costs are said to be about 85 percent lower. This process and others that use bacteria have the potential to increase the availability of nickel and its related byproducts by enabling the mining of lower grade deposits and being "friendlier" to the environment (Mining Journal, 2000b).

Minerals have been explored for and recovered from ocean water for centuries. Offshore minerals, however, have been recovered from the ocean floor by using mechanized means for just more than a century (figure 12). For example, dredging for tin and titanium minerals, and, more recently, diamond has proven to be economically successful and allows recovery of these minerals from offshore sources. Although diamond recovery off the coast of Namibia has been occurring for some time; in 1996 mining in waters that approached 100 meters (m) in depth was initiated with the use of remote-controlled vehicles; the value of the diamond was approximately $2 million (JDR Cable Systems, 2000). Aggregate and sand for construction also have been mined offshore for many years.

Figure 12. Recovery of diamond from waters off the coast of Namibia by a remote-controlled vehicle that travels along the ocean bed. Photograph courtesy of JDR Cable Systems, 2000.

Successful recovery of precious metals and artifacts from great depths and successful near-shore mining ventures have encouraged incremental technological advancements to recover materials from progressively deeper waters. Associated technological and environmental challenges include developing efficient mining techniques that are capable of raising material from great depths, processing it on ships, and disposing of waste in a manner that limits ecological damage.

The amount of infrastructure required to develop seabed resources is less than that for many land-based resources. Another economic advantage over most large-scale land mining is that most startup costs are much less; when mining is completed at one site, the operation can be moved easily to mine resources at another location. At least one study indicated that after a recovery period of as little as 6 months, mined offshore areas are biologically indistinguishable from unmined areas (Tarras-Wahlberg and O'Toole, 2000). As land-based sources become exhausted or unavailable, mining of urban coastal areas may increase.

Research in 2000 focused on the potential feasibility of recovering metals, primarily copper, lead, zinc, gold, and silver, deposited in ocean sediments near undersea hydrothermal vents. As many as 200 sites of inactive or previously active vents that deposited metals from underwater hot springs have been located; more discoveries undoubtedly will add to this number. Although few of these deposits have been closely examined and none has been fully evaluated for economic feasibility, grade, and size, some appear to have higher grades and tonnages than many of the onshore deposits currently being mined. Like manganese nodules and crusts, these undersea deposits are potentially huge resources. Many of the deposits have much higher grades and occur in shallower water than manganese nodules (2,000 m vs. 5,000 m), thereby presenting fewer economic and technological challenges.

Extraction of undersea resources from great depths requires technologies that can operate successfully in the harsh environments that are produced by darkness, extremely high pressures, and low temperatures. Space technologies, which include advanced materials, advanced power systems, intelligent sensors, multiband communications, remote sensing, and robotics, have potential applications in these environments. Numerous mining systems, such as suction and continuous bucket dredging and remote-controlled vehicles that collect and crush material before returning it to the surface for processing, are being tested.

Although mining mineral resources at great depths undersea is technologically possible, the high costs associated with mining and treating these ores, difficult environmental issues, and political and international legalities regarding ownership of minerals in international waters still are considered to be major obstacles that impede their development. Locating large high-grade deposits and granting exploration and mining permits within a country's Exclusive Economic Zone (EEZ) may avoid some of the legal and political challenges. In 1997, an exploration license was granted for exploration and evaluation of a large high-grade deposit located within Papua New Guinea's EEZ. Papua New Guinea recently granted mining licenses for tracts of seabed to a company that hoped to exploit underwater volcanic vents (Hussein, 2000). On the basis of exploration results and the level of research on ocean mining technology, this resource has the potential to be developed in the next decade.

New technologies, however, are not always better. In some cases, newly developed technologies prove inferior to those that they were designed to replace or led to unintended consequences. For example, the U.S. Department of Energy conducted research into using thermonuclear devices as explosives for large-scale construction projects from the late 1950s to the early 1970s. Ideas proposed for testing included building sea-level canals [the Aleutians, Malaysia (Kra Isthmus), and Panama], building dams, dredging harbors on continental coasts, recovering gas and oil from selected rocks, such as oil shale, and redirecting rivers (Teller, 1963).

BIGGER NOT ALWAYS BETTER

Research into using thermonuclear devices as explosives for gas and mineral extraction, and large-scale construction projects proved to have unintended consequences. Although this technology held the promise of being able to fracture or remove massive amounts of material with low production costs, testing resulted in the concerns for radioactive contamination.

In 1967, the U.S. Atomic Energy Commission exploded a 29-kiloton nuclear bomb underground in New Mexico. Project Gasbuggy, as it was designated, produced natural gas, which was radioactive and unusable. Project Rulison, which was another nuclear test conducted in 1969 in western Colorado, produced some gas and shock waves, which damaged building foundations, irrigation lines, local mines, and other structures, and resulted in concern by environmental groups and citizen backlash (Sternglass, 1982). Similar tests in the Soviet Union conducted between 1967 and 1978 left major areas contaminated with radionuclides and killed forests (United Nations Environment Programme, 1991). Although this technology held the promise of being able to move massive amounts of material with minimal cost, it came with the unintended consequences of regional contamination and ecological alteration. Perhaps these problems could have been solved, but the projects were halted when nuclear test ban treaties were initiated during the 1980s.

Fabrication—"Threading the needle"

Once ore is extracted and processed into a basic marketable commodity, such as aluminum or copper ingot, iron ore pellets, or potash crystals, it may need to be converted to a form that makes it readily usable by a manufacturer. Metals often are shaped into bars, rolls, or sheets. Industrial minerals frequently are formed into pastes, pellets, or powders. Blending materials, such as alloying metals, can change material characteristics and provide greater longevity, strength, and (or) versatility. As the needs of society change, technology develops new forms or redesigns existing ones to meet those needs.

The aluminum case study provides one example of how technological developments in fabrication significantly contributed to the growth of a mineral-resource industry (Appendix 2). Aluminum markets remained specialized until World War II when the low-weight, high-strength properties of aluminum made it the metal of choice for the structural components of aircraft. The technological improvements in casting and rolling that produced the large quantities of aluminum sheet necessary for the war effort and increased the adaptability and versatility of aluminum led

A BETTER IDEA

In the early 1970s, the aluminum can was being blamed for an environmental crisis. Billions of removable tab-tops (those small, sharp-ringed pieces of aluminum) were being discarded along beaches, parks, and roadsides and were becoming dreaded hazards to the barefoot vacationer or curious toddler. In 1976, Daniel F. Cudzik, who was an employee of the Reynolds Metals Company, saved the aluminum can. His invention of the pop-top gave consumers an easy-to-open aluminum can with a tab that stayed attached. Cudzik's invention had other unanticipated benefits. That extra little piece of aluminum that was once usually thrown away now accompanies every can that gets recycled. Since 1980, Cudzik's simple design change has enabled the additional recycling of about 200,000 metric tons of aluminum, which equates to about 3 billion kilowatthours of saved electricity. A reduction in electrical demand of this size at a typical coal-fired powerplant would prevent the release of more than 2.7 billion kilograms of carbon dioxide, 19 million kilograms of sulfur dioxide, 9 million kilograms of nitrogen oxides, 400,000 kilograms of carbon monoxide, and 400,000 kilograms of fine particulate matter (U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999).

to diversified and expanded postwar markets (U.S. Department of Commerce, 1956, p. II-13). Improvements in fabrication technology gradually allowed thinner sheets of aluminum to be produced and complex shapes to be formed and stamped. Aluminum was introduced into the beverage can manufacturing process in the 1960s, and aluminum can sales grew to account for almost all of the beverage can market and almost 90 percent of the soft drink market in 1999 from 2 percent in 1964 (U.S. Bureau of Mines, 1991 p. 4.4; Aluminum Association, Inc., 1999). This growth can be attributed to ongoing incremental refinements in aluminum can manufacturing and fabrication that facilitated recycling, reduced aluminum consumption per can, and required less energy to produce.

Continued technological refinements in beverage can design have allowed increasingly thinner cans to be manufactured. In 1972, 22 cans could be made from 0.454 kilogram (1 pound) of aluminum; by 1999, 33 cans could be made from the same amount (Aluminum Association, Inc., 1999). Design of the aluminum can pop-top is another example in which technological innovation saves materials and energy.

Because there is no shortage of ingenuity in the creation of alloy partnerships, they form powerful forces that work to overcome any short-term scarcity of materials.

Alloying is the process of adding one or more different elements to a metal for the purpose of enhancing the metal's properties for a particular application and often results in the use of less material in a particular application. Alloys are often developed to improve performance, to increase efficiency, and (or) to reduce the cost of a product in response to industry or societal needs. Alloys can overcome short-term scarcity of a material by supplying a substitute combination of materials with similar properties and (or) performance characteristics.

Alloyed materials with different properties have been combined to make composites with even more useful properties. Even the orientation or shape of the alloy within the composite has been engineered to change or improve desired physical characteristics. Examples of composites include carbon or glass fibers within plastics. Until 1997, much of the research on composites focused on the needs of the aerospace industry for high-performance lightweight materials. Aluminum/silicon alloys, which deliver such properties either alone or in a matrix, are finding expanded use not only in the aerospace industry, but also in the transportation industry (Ejiofor and Reddy, 1997).

With coatings technology, a small amount of a material can be put at a strategic location on another material, which minimizes material use and combines the desirable properties of both materials.

The development of coatings technology brings desirable properties to a material while using less of it. In the computer industry, coatings have been important for placing desired electrical properties on the surface of chips and connectors. Many of the rarer elements, such as europium, lanthanum, lithium, strontium, tantalum, and yttrium, have been incorporated into coatings that have been applied to substrates with other desirable properties.

Figure 13. Diamond coatings on ball bearings improve wear characteristics. Photograph courtesy of Refmet Ceramics Limited, 2001.

Coatings also are applied to improve surface hardness. Diamond-coated ball bearings have increased wear resistance (figure 13). Silica-based coatings are placed on lightweight plastics to improve abrasion characteristics. Carbon nitride is used to replace diamond as a coating for high-temperature applications. Heat treating stainless steels in nitrogen-rich environments (nitriding) improves the wear resistance (life) of pumps, tools, and valves (National Aeronautics and Space Administration, 2000).

Technological innovations have provided the means for developing manufactured substitutes for minerals and their products, thereby reducing the need for some materials and minerals and conserving resources. The development of synthetic diamond is one prime example of manufactured mineral products.

Diamond has many useful properties. It is the hardest known material, has the highest known thermal conductivity at room temperature, and is transparent over a very wide range of wavelengths. Diamond is also the stiffest and least compressible known material and is inert to most chemical reagents.

Synthetic diamond can be produced by subjecting graphite to very intense pressure (approaching 100 megabars) and high temperatures (in excess of 2000 Kelvin). This is similar to nature's method of producing diamond but under controlled conditions that eliminate natural impurities and other imperfections. In 1958, a technology of building diamond structures by adding atoms one at a time to an initial template (a diamond "seed") was developed. This method proved less costly and energy intensive than pressure-intensive methods. Diamonds produced early in this commercial endeavor had many impurities, but incremental technological improvements over time have resulted in diamond products suitable for many applications.

U.S. apparent consumption of industrial diamond, 90 percent of which is synthetically manufactured, has grown to an estimated 278 million carats in 1999 from 231 million carats in 1995, based on a compound annual growth rate of nearly 5 percent. Constant-dollar prices declined to $4.94 per carat in 1999 from $6.62 per carat in 1995; this indicates the ability of technology to provide industrial diamond at decreasing costs (Olson, 2000).

Another advance in the use of synthetic diamond technology has been the development of diamond films and coatings that have found application as components of cutting tools, electronic devices, optics, and other applications. Coatings and films add diamond's unique properties to other materials. The use of synthetic diamond as coatings and films has increased the service life (efficiency) of the resulting composite materials and has also reduced the United States' reliance on naturally occurring diamond.

Use—"Sewing with the needle"

Human beings use their expanding technological knowledge to make improved or new materials. Societies traditionally have depended upon these new materials to improve their products and standard of living (U.S. Bureau of Mines, 1990, p. 1.1). New materials have led to advances in agriculture, communications, computer systems, industrial processing, and medical technology (figure 14). Spin-offs from such advanced technologies used for space flight have led to the creation of new materials for consumer

Figure 14. Changing technology. Advances in materials technology have improved telecommunications and use less material. Old phone photograph courtesy of U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999; modern phone photograph courtesy of GadgetCentral, Inc., 2001.

products. Technology is often required to design resource-efficient methods to produce these or substitutable materials.

The copper case study describes how market demand, materials, and technology interrelate (Appendix 3). The discovery of electricity and its use in communication systems, lighting, and motors generated the demand for materials that could transmit electricity efficiently over long distances. The properties of copper, which include its corrosion resistance, high electrical conductivity, and the introduction of wire-forming technology that allowed copper to be formed into long strands made it the material of choice during the early 20th century for high-capacity transmission lines and household wiring systems.

FROM WIRES TO WIRELESS

More than 65 million metric tons of copper wire comprises the telephone system of the United States. The minimum replacement cost of these wires, which have been installed within the past 50 years, was $300 billion (Gilder, 1995).

The transition from wire technology to wave technology (that is, "going cellular") for telephones may render this installed copper investment obsolete in time and provide a high-grade copper "ore" that can be "mined" at lower costs than mining "new" copper.

Countries that have not invested heavily in copper infrastructure for telecommunications may not need to develop such capability because they may be able to go directly to newer technologies. One should not assume that technological development in currently underdeveloped countries places the same demand on resources that was needed to get more-developed countries to where they are today; in other words, past developmental histories should not be extrapolated to estimate future resource demand.

Other materials, however, can be substituted for copper in wiring. Aluminum is used for high-capacity transmission lines. Silicon is used to make fiber-optic cables for telecommunications. New technologies have improved transmission efficiencies for aluminum and fiber-optic cables and have made these commodities competitive.

If the price of a material increases as a result of such factors as increased demand or limited production capacity, then substitution may take place. Examples of substitution include the beverage industry's use of aluminum for steel cans and plastic for glass bottles. The automotive industry has substituted aluminum for steel body parts, copper for aluminum in radiators, and plastic for chrome bumpers. In each case of substitution, technology has succeeded in developing an alternate form with decreased cost and (or) increased performance benefits.

The search for substitutes can have unintended consequences, however. When the EPA announced in the 1970s its intention to ban the use of asbestos, friction product and high-temperature gasket manufacturers began searching for a substitute that would have the required properties such as a small cross section and high-temperature compressive creep strength and resistance. The industry selected glass fibers as a substitute. Evidence suggests, however, that glass fibers are more costly and less efficient. Glass fibers also have raised environmental concerns that equal or exceed those for asbestos (Asbestos Institute, 1995).

Substitution may benefit the consumer while increasing effective resource supply.

The EPA ban on asbestos was partially overturned in 1991 by a ruling of the Fifth Circuit Court of Appeals. Many asbestos products were exempted from the ban; these included but

WHERE DOES COPPER TECHNOLOGY GO FROM HERE?

Technological innovations often lead to new markets for a material. A look at 1998 copper patents provides an indication of future directions for copper (Greetham, 2000).

Application	Physical attributes	Technological direction
Automotive radiators	Alloying characteristics, conductivity, corrosion, heat, and resistance	When alloyed with nickel, phosphorous, and tin, copper is easily rolled into very thin sheets, which allows its use in radiators.
Computers	Conductivity, drawability, and strength	Drawing technology allows nano-sized (smaller than the human hair) films, thin sheets, or wires to be created, which can be used to make faster, smaller computers.
Superconductors	High-temperature superconductivity	Copper is a superconductor at much higher temperatures than many other metals. Superconductors are directed toward increasing the efficiency of electrical transmission.

Technological research of the 1990s was focused on reducing the amount of a material that was needed (material supply reduction) or enhancing the delivery characteristics of that material (increasing efficiency). Both had the effect of reducing overall product costs, the benefits of which eventually were passed along to the consumer as time or cost savings.

were not limited to asbestos cement pipe, asbestos clothing, disk brake pads, friction materials, gaskets, and vinyl-asbestos tiles (Asbestos Institute, 1995).

Recycling

Products that are perceived to have lost their value may be disposed of, recycled to serve as raw materials for manufacturing, remanufactured, or reused. Recycled materials must conform to the same quality and safety standards as manufactured or natural products. As landfills become full and new sites become more difficult to locate, permit, and operate, disposal costs increase. Research is focusing increasingly on developing ways to reuse materials that traditionally have been considered to be waste. The concepts of recycling, redesigning, and remanufacturing, involve turning waste materials into useful products with minimal environmental impact. Although not new, these concepts are becoming more and more important in today's society. Each of these approaches has the potential of conserving such natural resources as energy and come with significant economic savings and environmental benefits (U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999, p. 16).

Recyclable materials include such items as aluminum cans, automotive parts, construction asphalt and concrete, and copper wire (figure 15). Approximately 120 million metric tons per year (Mt/yr) of materials are recycled in the United States through auto recycling, construction and demolition recycling, and municipal programs, thus saving the equivalent of about 4 months of the Country's electricity demand (U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999, p. 16). Although recycling can include old scrap (derived from discarded products) and new scrap (purchased from the manufacturing process), only old scrap is included in apparent consumption statistics. Recycling of old and new scrap was estimated to account for approximately 63 percent of the apparent supply of lead, 55 percent of steel, 50 percent of titanium; and between 25 and 40 percent aluminum, copper, magnesium, nickel, tin, and zinc in 1998 (U.S. Geological Survey, 2000a, p. 62.1, 62.3, 62.7-62.8, 62.10-62.12). The aluminum and the copper case studies show how technology has influenced the growth of recycling and increased the availability of resources from more-diverse source (Appendices 2, 3).

Figure 15. Scrapped automobiles are a source for recycling, remanufacturing, and reuse. Photograph reprinted by permission of Centre de Recyclers Universel, March 23, 2001.

Recycling conserves embodied energy and reduces waste. This is also the goal of mandated recycling. Technology, however, can often address obstacles to recycling. For example, direct-reduced iron (DRI) technology was developed by the U.S. steel industry in the 1970s to alleviate the problems that resulted from the use of 100-percent scrap iron in electric furnace steel production. When scrap is fed to electric furnaces to make steel, it contains residual, often inseparable elements other than iron. As recycling continues, the weight percentage of these alloying elements tends to accumulate above steel specification limits. When mixed with scrap, the relatively pure DRI dilutes the undesirable content of the resulting mixture, which keeps the steel within specifications. The elements that accumulate in electric furnace steelmaking are, in fact, conserved through the use of DRI because they are removed and placed back into useful applications more quickly. DRI sustains the demand for alloy scrap.

The DRI process uses natural gas to reduce iron oxides in pellets to elemental iron. In 1999, the feed to U.S. electric furnaces was about 70 percent scrap and 30 percent DRI. DRI is a complement for scrap, and the dynamics of scrap prices affects the profitability of DRI operations. Most of the DRI production facilities are in developing countries because of the high cost of its alternative, steel scrap (Industry Canada, 1998).

Recycling technology has responded to environmental regulations by reducing the discharge of toxic

WHAT DROVE DIRECT-REDUCED IRON DEVELOPMENT?

Prior to the 1980s, the bulk of alloy steels were made in the basic oxygen vessel. The charge to the vessel included iron-rich hot metal and scrap. Scrap additions in this process did not lead to residual element buildup because iron from the blast furnaces was available to dilute the contribution from scrap.

In the 1980s, many of these vessels lost market share to electric furnaces. Consequently, blast furnace iron was not available for the dilution process. As a result, virtually all the smaller U.S. blast furnaces were shut down and permanently dismantled during this period. Direct-reduced iron became the technological substitute for hot metal and the answer to the residuals-in-scrap problem.

materials, such as arsenic, cadmium, lead, and mercury, into the environment and reduced their use in manufacturing processes and products. For example, legislation has mandated the recovery of lead from lead-acid storage automotive batteries since 1996. Technology was developed so that about 76 percent of refined lead produced in the United States in 1998 was recovered from recycled scrap, a major source of which was spent lead-acid storage batteries (U.S. Geological Survey, 2000a).

Recycling of cadmium from spent nickel-cadmium storage batteries also has grown during the 1990s. Research during this time has allowed scientists to document the toxicity of arsenic and mercury in the environment and on human health, and regulations have been implemented to limit their effects. Technology has been developed to recover and extract mercury more efficiently from its products which include control instruments, dental amalgams, electrolytic refining laboratory wastes, fluorescent and vapor lamps, measuring devices, spent batteries, and switches.

One of the characteristics of aluminum is that it is easily recyclable. The aluminum recycling (secondary) industry has processed scrap from the primary aluminum industry since about 1904. The amount of energy required to produce 1 t of recycled aluminum is about 5 percent of the energy required to produce 1 t of primary aluminum from bauxite (Wilburn and Wagner, 1993, p. 93). Before World War II, little primary aluminum was produced. Recovery of aluminum scrap was insignificant because the supply of scrap was limited. As the aluminum industry expanded during the War and entered new markets, recycled aluminum production also increased because of favorable economics, increased supply of aluminum scrap, and proven product performance. Some technical advances in alloying and die casting during the Second World War were developed specifically for the secondary aluminum industry (Aluminum Association, Inc., 1985). Technology developed during the 1950s allowed improved material separation of aluminum scrap from junked automobiles. Recycling of aluminum products increased dramatically in the 1970s when the aluminum beverage can began to be widely used. In 1999, the United States produced about 3.8 Mt of primary aluminum metal and recovered about 3.5 Mt from purchased scrap (Plunkert, 2000).

Recovery of obsolete materials from the burgeoning electronics industry continues to grow (figure 16). Table 2 lists materials recovered from U.S. electronics recyclers. The amount of recycling of obsolete electronic products to recover reusable components, such as glass, metals, and plastics, is increasing. The reuse of components and refurbishment of computers lengthens their life spans. As electronic products advance technologically, however, the amount of precious metals used in their components decreases, and as the rate of advance accelerates, old computer parts are worth less. Scrap that has lower value coupled with increasing labor, plant, and regulatory costs could result in decreased recycling. Nevertheless, recycling may continue to increase as manufacturers use, for example, management and organizational technologies to develop better ways to identify types of plastics, to design for greater ease in dismantling, and to develop leasing programs that include the return of electronic products to the manufacturer or retail distributor. Recycling also can increase through more effective collection

Figure 16. Obsolete electronics can be recycled or reused. Photograph courtesy of Monmouth Wire and Computer Recycling, Incorporated, 2001.

Table 2. Reported materials recovered from U.S. electronics recyclers

[In metric tons. Adapted from National Safety Council, 1999, p. 36; Sean Magaan, Noranda Inc., Micro Metallics Corp., oral commun., 1999]

Type of material	1997	1998
Glass	11,600	13,200
Plastic	3,700	6,500
Metals:		
Aluminum	3,900	4,500
Steel	14,500	19,900
Copper	4,300	4,600
Combined precious metals (gold, palladium, platinum, silver)	1	1
Other	3,100	3,600
Total	41,100	52,300

methods and legislation that mandates refundable deposits at the time of purchase and through take-back programs or bans on landfill disposal.

Technologies are being developed to recover materials from such nontraditional sources as mine tailings. Magnesium, which is the lightest of all structural metals and a critical constituent in some aluminum-base alloys and castings, is an important metal in the aerospace and automotive industries. Most of the world's magnesium originates from brines (including seawater), dolomites, and salt deposits (Kramer, 2000). A new low-cost extractive technology to recover magnesium from serpentinite tailings, which is a waste material generated from the mining for asbestos, is being evaluated in Australia, Canada, Russia, and the United States (Golden Triangle Resources NL, 1999). Extraction of magnesium by recycling tailings through the process offers the advantage of recovering a metal from materials that, until recently, were considered to be waste and economic and environmental liabilities. Recovery of such material reduces production from other ore sources and effectively extends the life of natural resources from which magnesium is recovered.

In Canada, the first commercial venture to recover magnesium from wastes generated from more than 100 years of asbestos mining began production in late 2000 (Deborah Kramer, Magnesium Commodity Specialist, U.S. Geological Survey, oral commun., 2000). When fully operative, the Magnola facility will be the world's leading source of magnesium and the first to use an innovative but still commercially unproven technology. Development of the extractive process took more than 10 years and millions of dollars to develop (McLean, 1999). The resource is derived from more than 250 Mt of former waste material—a legacy of more than 100 years of asbestos mining. Resources at the $500 million facility will be sufficient to produce 63,000 t/yr of magnesium metal for about 300 years (Mining Journal, 2000a).

Innovations in recycling have reduced the amount of industrial and municipal waste, thereby supplementing the supply of "new" materials and reducing the amount of material that occupies landfills. For example, Chaparral Steel Company of Midlothian, Texas, is taking automobile recycling one step farther by using an innovative flotation technology to separate the various materials in automobile shredder residue (ASR). ASR is material that is leftover following the processing of scrap automobiles and typically includes aluminum, glass, magnesium, other nonferrous metals, polyvinyl chloride (PVC) and other plastics, and rubber, all of which are potentially recyclable. This technology is based on that used in the mining industry to recover the valuable components of mineral ores (U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999, p. 23). Historically, the material was dumped in landfills because of the high costs associated with separating the mixture of material into its individual components. In the United states an estimated 3 to 5 Mt/yr of ASR is generated (Argonne National Labs). Nonchlorinated plastics may be used as a highly efficient and clean fuel source rather than being placed in landfills. Chaparral Steel anticipates that the glass can be remelted or used as roadbed material or as an abrasive for sanding devices (Chaparral Steel Company, 2000). Potentially, this new technology could be used for mining municipal landfills.

Remanufacturing

Remanufacturing is the process of disassembling a product and then cleaning, repairing, replacing, and reassembling it such that only a small part of the original product is not returned to service. Reuse of materials reduces reliance on primary mineral resources. The origins of remanufacturing can be traced to the 1920s and 1930s with the emergence of mass production and standardization of such products as the automobile and the refrigerator. Economic and resource constraints brought about by the Depression and World War II resulted in a major period of growth for remanufacturing during a time when a scarcity of such raw materials as steel drove the need to reuse durable goods (Automotive Parts Rebuilders Association, 2000a). Although estimates vary on the size and scope of the remanufacturing industry, an analysis by Boston University in 2000 found 73,000 remanufacturing firms operating in the United States. These firms represent $53 billion in annual sales and employ 480,000 people (Automotive Parts Rebuilders Association, 2000a).

Extending product life through remanufacturing is an increasingly important component of conserving the Earth's natural resources. Remanufacturing offers greater advantages than recycling. For example, if an automobile's engine is recycled, then the steel is saved from the landfill space and could be used to produce another item requiring steel. Remanufacturing, however, offers another alternative. This process retains most of the value added to the product, which includes the cost of energy, labor, and raw materials, when it was first manufactured. Rebuilt engines, for instance, require only 50 percent of the energy and 67 percent of the labor needed to produce a new engine (Automotive Parts Rebuilders Association, 2000a).

A scientist at the Energy Systems Division of Argonne National Laboratory estimated that remanufactured products conserve the equivalent of 68 million barrels per year of oil worldwide, which is equivalent to the energy content of gasoline to operate about 6 million passenger vehicles for 1 year (Automotive Parts Rebuilders Association, 2000b). In addition to saving energy and other raw materials, remanufacturing reduces the potential for the release of toxic materials, which include gases, some of which contribute to the load of greenhouse gases in the atmosphere and is thought to extend the life of landfills.

Remanufacturing also results in significant economic benefits. Purchasing a remanufactured product can cost consumers from 50 to 75 percent less than a new product. Technological advancements in product composition and design have lengthened the life of products and improved the ability to refurbish them. As part of their business plans, many companies also are designing products that can be more easily remanufactured. Signature-analysis technology may be used throughout the automotive industry by 2003. This type of analysis is a procedure that predicts the remaining life of major product subcomponents to maximize their use. Improved cleaning methods and equipment that reduce disposal rates and environmental impact by using less solvent may be developed by 2005. Additional technology goals could be established that set targets for improved auto-salvage techniques, processing methods, testing, and after-market engineering with the goal of approaching zero waste by 2020 (Automotive Parts Rebuilders Association, 2000b).

Other industries also have a history of remanufacturing. Xerox Corporation, of Stamford, Connecticut, for example, has been reclaiming metals from its product components since 1967 and “unofficially” has been accepting trade-in machines from customers for almost as many years. In 1990, the company initiated its Environmental Leadership Program with the goal of producing waste-free products. Remanufactured machines are a significant and profitable part of the company’s product line. New products are designed to be remanufactured, reused, and (or) recycled. In 1997, Xerox remanufactured equipment from more than 30,000 t of returned machines, and customers returned 65 percent of all empty copy and print cartridges to the company for recycling (Gibney, 2000).

Reuse

One of the most dramatic reductions in waste and conservation of resources can be made by product reuse, in which the form of the product is retained and the product is reused for the same purpose as during its life cycle. Examples include refillable drink bottles, refurbished computers, and used automobile fenders and bumpers. Reuse also includes finding new uses for “used-up” products, such as automotive tires, which can be used as mooring cushions on harbor docks. Reuse has the added benefits of conserving landfill space, reducing waste generation, and saving the energy and additional material that would be needed to form these materials into new shapes. Every time a product is reused, most of the energy used and the emissions produced in its original manufacturing and processing are, in a sense, retained. Moreover, technological advances in product design and collection and increases in productivity through automation have improved the efficiencies in product reuse.

> Humans use technology to separate things from less useful configurations and recombine them into more-useful configurations.

Conclusions

Predictions of resource scarcity occur periodically. This study shows how the implementation of technology, which is the organization of energy, knowledge, labor, and materials, has historically addressed scarcity concerns. Although we know intuitively that resources are finite, the historical evidence suggests that resource availability has grown consistently and that real prices (by some measures) for materials during the past 100 years have trended downward or remained relatively steady. This has taken place in the face of declining ore grades, increasing demands by a population that is growing and has increasing lifestyle expectations, and mining resources that are increasingly difficult to access because of their depth, geologic complexity, remoteness, and (or) susceptibility to adverse political and social actions. Productivity improvements and an expanding diversity of resources from which materials can be profitably extracted and manufactured have come about through advances in technology. Technological developments are driven by the desire to supply material at the highest possible profit.

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Appendix 1. History of Exploration Technology

Throughout human history, technological advances have influenced where and how prospectors look for minerals. Mineral exploration draws upon models developed from available technological tools, current knowledge of geology, mining and processing capabilities, and previous exploration. As technology progresses, these models are refined reflect knowledge of mineral deposits and inclusion of new discoveries. The evolution of exploration technology has contributed to mineral supply and the ability to meet the growing demand for minerals.

Minerals have been important since the dawn of man. Early hunters used stones, such as flint, as tips for weapons and in food preparation. Clay minerals have long been used in pottery and earthenware. People have been aware of and used metals, such as copper and gold, for at least 6,000 years. Visual observation was the first "tool" used to locate mineral resources and to develop exploration models. The earliest recorded discovery of metal resources dates from the fifth millennium B.C., when free gold was discovered in shallow Egyptian riverbeds (Smith, 1965). These early explorers would follow the "trail" of gold and in so doing developed early geologic models for successful mineral exploration. Visual properties, such as color, were used in detection.

The earliest period of mineral exploration history can be characterized as the "personal use" period. Users first identified what they needed visually and then extracted only what they needed for personal use within their local community (figure 17). Demand for minerals was local or regional, generally in areas where mineral supply was plentiful. Depletion of known deposits resulted in a shortage that continued until a new deposit was discovered, often by chance.

Figure 17. Early prospecting methods. Source: Peters, W.C., Exploration and Mining Geology, copyright 1978, by John Wiley & Sons, Inc. This material is used by permission of John Wiley & Sons, Inc. and may not be further reproduced without permission from the publisher.

Mineral exploration beyond visual observation required development of a deposit model, which necessitated a more sophisticated knowledge base that included an understanding of geologic structure, mineralogy, and the processes of ore deposition and formation. Although philosophical writings provided the principal basis for these models until the 16th century, Aristotle (384-322 B.C.) was one of the first to develop and record a geophysical model. Technologies to test such early deposit models were developed as early as A.D. 132 when Chang Heng used an early seismoscope in China to study earthquake motions. This technique has been perfected by using seismographs that interpret reflect energy waves to detect certain geologic structures and map selected geologic environments (Bates, Gaskell, and Rice, 1982, p. 2).

Georgius Agricola used observable evidence to present the first comprehensive theory of the origin of ore deposits. His book, published in 1556, described deposits formed by the replacement of preexisting material with ore (Peters, 1978, p. 1). European scientist-philosophers followed Agricola's models until 18th century mining academies refined them.

The rise of colonialism during the 16th and 17th centuries opened new territories for mineral exploration, provided opportunities for the application of existing geologic models to new areas, and led to the creation of new models. Significant exploration activity took place in Africa, the Americas, and Asia during this period. With the rise of markets for mineral products and depletion of known resources, the need for mineral exploration grew. Early entrepreneurs accepted the challenges posed by exploration, but lack of equipment, infrastructure, and knowledge generally restricted the search to regions of discovered deposits and to surface expressions of ore. Underground exploration was mainly random and rarely yielded positive results. The development of mineral occurrences into mines was limited to higher-grade, easily-separable ores, such as native copper, gold, and tin.

As mineral exploration and mapping grew in the middle 1700s, mining academies were founded to support education in such areas as geology, mineralogy, mining law, and mining science. At the close of the 18th century, the Industrial Revolution sparked the demand for minerals and led to intense scientific debate over the origin of ore deposits, which increased the understanding of ore processes. In spite of this increased demand, only rudimentary methods (for example, chemical assaying, hand drilling, and mineral spectroscopy) could provide indications of whether unexposed mineral occurrences were ore deposits.

Scientific evidence collected by the end of the 18th century proved that geologic structure, mineral deposit location, and stratigraphic sequence were linked. This provided a further refinement of deposit models. The mining and exploration community generally recognized that increasing the knowledge of known mineral occurrences could aid the search for new deposits. The need for mineral resources during the 19th century, specifically coal as fuel for electricity and transportation and copper and iron for infrastructure development, led many Governments to fund or sponsor organized geologic mapping programs. By the mid-19th century, geological surveys had been established in nearly all industrialized countries; attention was given to documenting the major mining areas and to speculation on concealed resources. The "Canadian formula" used cooperative efforts between Government scientists and private prospectors and served as a model for geological surveys throughout the world. The U.S. Geological Survey (USGS), which was founded in 1879, did not act as a consultant to prospectors in the Canadian way, but provided direct and indirect services to a growing number of people who were searching for minerals. Some of the documents prepared by U.S. and Canadian Government organizations are still considered to be reference standards for modern exploration and deposit description (Peters, 1978, p. 7).

Science in the 19th century provided a guide for expanding earlier discoveries and locating new ore fields. Self-schooled prospectors rather than scientists or "company geologists" still made most mineral discoveries in the late 19th century (Peters, 1978, p. 7). Scientific interest, however, stimulated the development of exploration and geophysical tools after 1850. Such tools as the Cornish water pump and the power hoist allowed for deeper mining and consequently contributed to the further development of geologic models that could predict mineral deposits at depth. Information on mineral zoning and structural control of ore bodies below 1,000 meters (m) could now be documented. Diamond drilling and magnetic prospecting, which were initially tested in the Lake Superior iron ranges during the late 19th century, allowed for easier and cheaper exploration at depth.

Prior to the 20th century, self-schooled prospectors made the most important mineral discoveries.

Scientific interest in the 19th century led to the development of more-sophisticated geologic models and exploration tools.

As a result, additional resources were discovered. The Comstock Lode in Nevada was mapped by self-potential (electrical) geophysical methods in 1880. Geochemical sampling techniques similar to those used today to locate subsurface mineral targets with abundant resources were developed in the early 1870s by Thomas Sterry Hunt (Peters, 1978, p. 9).

As knowledge about known mining districts increased and development of ore deposit models continued by use of analogy, the number of new discoveries multiplied and the accuracy of exploration improved. Processing still required relatively high grade ore capable of being separated easily from gangue. Technological advances in ore treatment resulted in an increase in the diversity of treatable ore types and thus expanded the geological environment for exploration. For example, sedimentary iron formations in the Lake Superior area became a potential source of iron ore as a result of advances in iron-ore-processing technology and provided the incentive for further exploration in the region.

The 20th century marked the beginning of site exploration at depth by large vertically integrated mining companies.

The turn of the 20th century marked the emergence of direct mineral exploration by mining companies. The professional mining geologist and exploration company assumed prominence four and one-half centuries after the science of mining geology began in central Europe. In 1900, the Anaconda Copper Mining Company of Butte, Montana, established the first geological exploration department at a large mining camp in Montana. Since that time, most mining companies have devoted a portion of their budget to exploration. Exploration was still primarily "prospect focused" until mid-century when the emphasis began to shift toward regional exploration.

Aerial photography, computer modeling, and geophysics enabled regional exploration for remote or hidden deposits.

Mineral exploration "exploded" during the 20th century. Knowledge of ore processes helped explorers select likely targets. Emerging technology, such as diamond drilling and early geophysical techniques, allowed them to explore potential targets at depth. Large mining companies began to fund extensive exploration programs, and investors supported such programs as successes became more frequent. Improved processing technology and separation techniques made mineral separation easier and more efficient and allowed economic recovery of lower grade materials. The exploration history of the Carlin Trend in Nevada illustrates how changing knowledge and technology has expanded mineral exploration (inset, p. 33).

Exploration geophysics (excluding magnetic methods) did not gain wide acceptance in mining until the 1940s, which was several decades after it had attained common use in the petroleum industry. By the end of World War II, geophysical theory, interpretation, and tools had proven themselves. Airborne geophysical, drill-hole, and surface exploration methods were used more frequently. Airborne geophysical methods, such as that illustrated in figure 18 proved to be the most useful in advancing mineral exploration into new and more-remote areas.

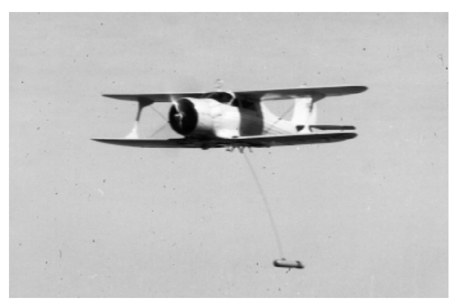

Figure 18. Beach Staggerwing aircraft conducting early geophysical survey, circa 1949. Photograph courtesy of Victor Labson, Associate Chief Scientist, Mineral Resources Program, U.S. Geological Survey, September 20, 2000.

DISCOVERY AND REDISCOVERY OF THE CARLIN TREND

The discovery of the Carlin gold deposit in Nevada is one of the most significant events in mining, but the deposit likely would not have been discovered without technological developments in mining and exploration. Because of the extremely fine grain size of the gold in this region, early prospectors overlooked Carlin (Coope, 1991, p. 2). Although a few nearby placer gold deposits were found in the late 1800s and early 1900s, their significance was not recognized until the Carlin discovery in 1961. This discovery was preceded by geological work by the U.S. Bureau of Mines, which concluded "gold is present in such a state that it is impossible to obtain by panning" (Vanderburg, 1939, p. 79). The U.S. Geological Survey conducted extensive mapping in the region during the 1940s and the 1950s. This work and the development of cyanide leaching techniques capable of recovering low-grade gold led Newmont Exploration Limited to re-explore the area. Exploration using modern drilling and assaying techniques resulted in the Carlin discovery. Placer gold recovered from the area in the late 1800s totaled less than 10,000 ounces; the 2000 annual reports for Barrick Gold Corporation and Newmont Mining Corporation list 1999 resources for the Carlin Trend at 60 million ounces (Barrick Gold Corporation, 2001; Newmont Mining Corporation, 2001). Discoveries continue.

The magnetic properties of certain rocks have been known for centuries; magnetic exploration methods detect contrasts between magnetic mineralized zones and nonmagnetic host rocks. Magnetic methods commonly are used during the reconnaissance stage. Although direct mineral exploration with magnetic methods is essentially limited to iron ore deposit models, they are important as an aid in indirect exploration for many other models, such as ultramafic-hosted asbestos deposits, kimberlite diamond deposits, and massive sulfides associated with magnetite or pyrrhotite. Magnetic methods also are used in advanced stages of exploration to define target ore zones better (Lowe, 1999, p. 131-132).

Airborne electromagnetic surveying (AEM) has become a successful tool in mineral exploration and has been adapted to search for a variety of ore types defined by deposit models in various geographic settings (figure 19). The technique was developed in the late 1940s to differentiate highly conductive ore bodies from their less conductive host rocks. This method began to flourish after World War II because of the availability of pilots and aircraft, the increase in global demand for minerals, and the rise of integrated mining and exploration companies, which could afford to fund these relatively high-cost exploration methods. During the next 25 years, AEM contributed to the discovery of diamondiferous kimberlite pipes, uranium deposits, and volcanogenic massive sulfides (Ascough, 1999, p. 60).

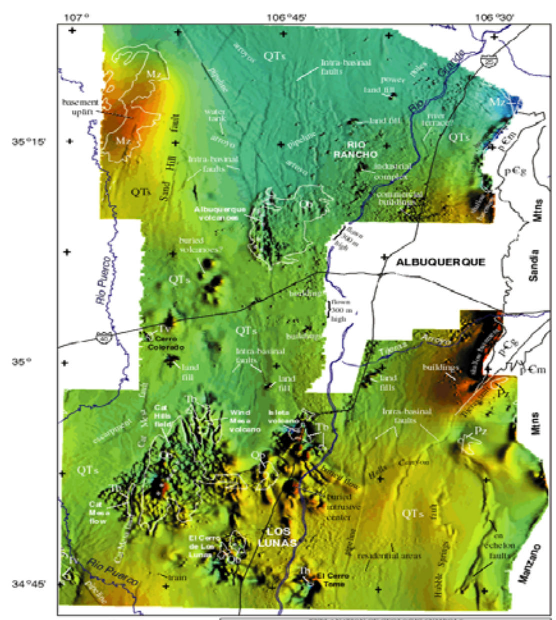

Figure 19. Airborne geophysical map of the Middle Rio Grande Basin. Photograph courtesy of Victor Labson, Associate Chief Scientist, Mineral Resources Program, U.S. Geological Survey, September 20, 2000.

High-resolution methods, such as helicopter electromagnetic-magnetic and horizontal-loop electromagnetic surveys, are used for detection of conducting minerals that occur less than 100 m below the surface. Deeper penetrating methods, such as fixed-wing AEM (to 400 m depth), time-domain electromagnetics (to 800 m depth), and magnetotellurics (to 1,500 m depth), offer superior depth of exploration but with a corresponding drop in target resolution and conductance estimates (Balch, 1999, p. 21).

Gravity methods have been used since the 1950s to detect the presence of density contrasts between the host material and the mineralized deposits. Deposit models that produce positive density contrasts include chromite and nickel sulfides, iron formations, and volcanogenic massive sulfides. Minerals that produce negative contrasts include gypsum, potash, and salt. Because gravity methods are commonly ground-based techniques, they often are used to investigate exploration targets previously detected by AEM, geochemical, or magnetic surveys. Gravity methods serve as a screening device by providing additional evidence that supports either continued exploration or termination (Thomas, 1999, p. 101).

Aerial photography began to play a part in mineral exploration in the 1920s, but did not come into prominence until after World War II. The greater flexibility offered by helicopters and the use of spacecraft-mounted cameras permitted exploration programs to operate in remote regions on large scales (of national and even subcontinent size). Equipment used to conduct modern geophysical surveys is shown in figure 20. Space-based camera systems can scan more extensively than ground stations, can supply data much faster than conventional aircraft, and data are more accessible than in previous decades. The rise of aerial photography, computer modeling, and geophysics dramatically increased the size of the area covered by mineral exploration surveys in the late 20th century.

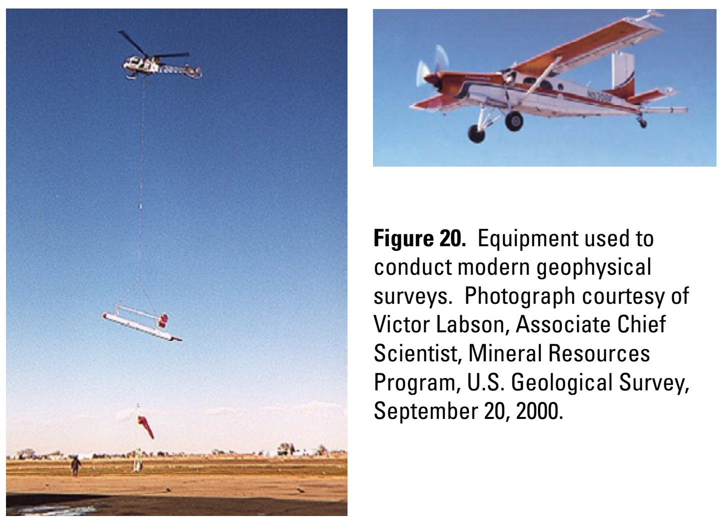

Figure 20. Equipment used to conduct modern geophysical surveys. Photograph courtesy of Victor Labson, Associate Chief Scientist, Mineral Resources Program, U.S. Geological Survey, September 20, 2000.

For the most part, mineral exploration programs became team efforts rather than individual tasks. Geochemistry, geology, geophysics, and drilling technology provided teams with the tools of discovery. Computers and laboratory facilities provided the tools of measurement. Exploration companies now had the tools not only to discover a mineral deposit with significant potential, but also to measure its potential with increasing accuracy and reduced physical disturbance. For example, the Voisey's Bay nickel-copper deposit was discovered by geophysical mapping; Voisey's Bay exploration maps are shown in figure 21.

Increased use of minerals in the late 20th century was depleting the resources of established mining districts at an increasing rate. As production from established mineral-producing districts in Europe, North America, and parts of South America began to decline, exploration companies began to expand their search for minerals into more remote and/or environmentally sensitive areas; these included those areas in which deposits are covered by surface materials, such as alluvium, unmineralized rock, or water.

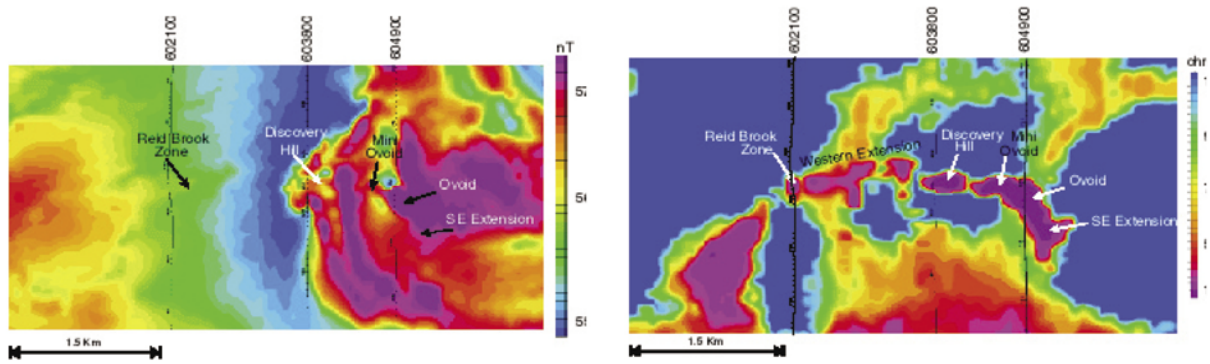

Figure 21. Magnetic and resistivity maps such as these assisted in the discovery of the Voisey's Bay nickel-copper deposit, Newfoundland, Canada. Maps courtesy of Rolf Petersen, Fugro Airbourne Surveys, Ottawa, Canada, September 20, 2000, and Steve Balch, Inco Technical Services, Ltd., with permission of Inco Limited and Voisey's Bay Nickel Company Limited, September 20, 2000.

With the computer age came the ability to predict ore-body structures and to quantify deposit potential by means of systematic modeling. Computers and advanced communication systems allow field teams to transmit data instantaneously back to the company and to speed up compilation and analysis of large volumes of data. On the basis of these analyses, a company can perform a feasibility study to determine if the deposit has sufficient potential for further capital expenditure or development.

Today, the quantity and sophistication of mineral deposit models require multiple stages of mineral exploration. A series of favorable exploration "targets" are identified during

EVOLVING GEOLOGIC MODELS DRIVE EXPLORATION AT OLYMPIC DAM

In 1997-98, the Olympic Dam deposit in Australia was the world's sixth largest copper resource and the world's largest uranium deposit (Hodgkison, 1998). Western Mining Corporation Ltd. discovered it during an exploration program in 1975 by using a geologic model for sediment-hosted copper deposits. The model postulated that oxidation of basaltic rocks could release significant amounts of copper into ground water. Under favorable conditions, this ground water would flow upward along permeable zones to precipitate the copper in the overlying sediments (Western Mining Corporation Ltd., 1993). Reconnaissance aerial geophysical surveys detected minerals-related anomalies where there was no surface expression of mineralization. Interpretation of regional geology suggested the presence of basalts at depth together with deep crustal structures that could channel fluid migration. Subsequent drilling outlined a large ore body; production began in 1988.

Geologic interpretation of the deposit has evolved since its discovery. Geologic observations from the drill core and underground exposures have added to this knowledge and resulted in the creation of revised geologic models. As a result of this new information, exploration strategies at this and other similar sites have improved.

Because the Olympic Dam deposit is considered to be a "type locality" for iron-rich copper-gold-uranium-rare earth ores, this shift also has redirected exploration efforts in other localities with similar geologic characteristics, such as the Bayan Obo district (Mongolia), the Kiruna district (Sweden), and the Pea Ridge district (United States) (Pratt and Sims, 1990).

reconnaissance exploration often by using airborne exploration techniques. Target areas are then investigated in detail by using surface methods in several stages of complexity and sophistication. The extent of exploration at each stage is subject to previous results and company policy. Areas and targets rejected at one point may be reconsidered later because of changes in technology, reinterpretation of data, and/or revised geologic models.

The application of computers, computer-aided drafting (CAD), digital mapping, global positioning systems (GPS), and satellites permit companies and national and international science

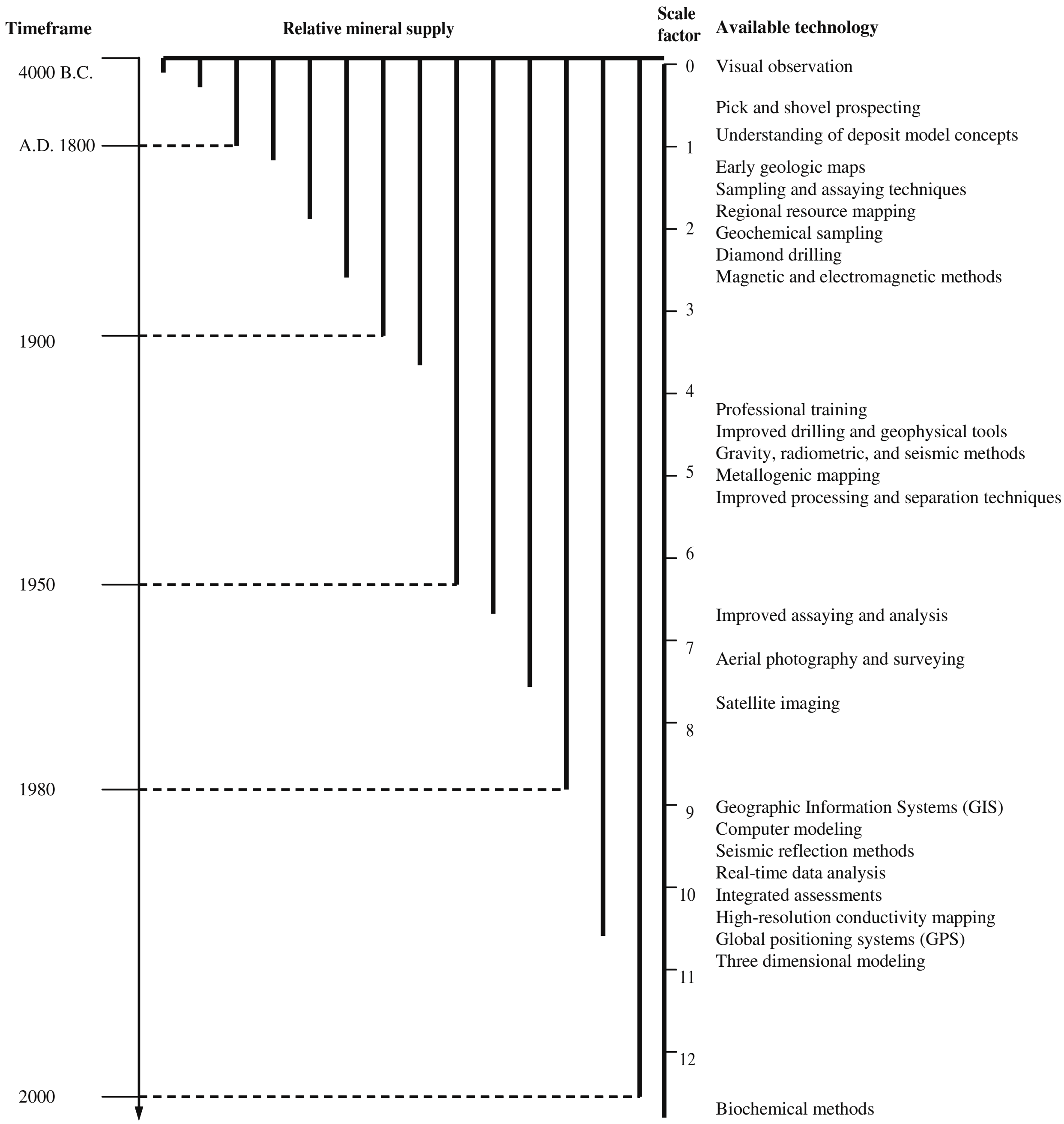

Figure 22. Comparative timeline of available exploration technology and relative mineral supply (relative scale). The length of the relative mineral supply line reflects the estimate of the relative mineral supply available at the time of technological development. Source: Peters, 1978.

agencies to collect, analyze, and store massive amounts of data on the Earth and its resources. The USGS holds one of the world's largest international collections of land-surface image maps. This collection is held in the Distributed Active Archive Center (DAAC) [formerly known as the Earth Resources Observation System (EROS Data Center)]. The Canadian Space Agency (CSA) collects environmental change and natural resource data by means of its Radarsat satellite program. The U.S. National Aeronautics and Space Administration (NASA) Earth Science Enterprise Program collects data on global change through the development and distribution of satellites that supply data to the international research community. The first step in this program is to develop an inventory map of the Earth's natural resources to provide a baseline for rational development decisions (Shuey, 2000).

The historical impact of exploration technology on mineral supply is shown schematically in figure 22. This diagram shows between 1800 and 1900, approximately twice as much was discovered as was discovered in the preceding 5,800 years of mineral discovery because geologic understanding improved and exploration methods and better mineral deposit models had been developed. In each succeeding 50-year period, significantly greater amounts of resources were identified. World mineral production followed the same general trend. For example, more copper was produced to satisfy human needs in the past 40 years than in the preceding 60 centuries (Themelis, 1994).

Advances in technology associated with mineral exploration and processing contribute to the continued and growing discovery of mineral resources. As the Carlin Trend example demonstrates, were it not for changing extraction technology, many sources of minerals would not have been discovered or fully exploited. The Olympic Dam example highlights how evolving deposit models can influence mineral exploration activities and expand mineral supply. Discoveries that are currently not economically recoverable may be so in the future because of technological processing or ore-separation improvements. If history is any indication, then future refinement of geologic models should aid in the discovery of additional mineral resources within the Earth.

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Appendix 2. Aluminum Case Study

Background

Although aluminum ore, which is primarily derived from bauxite, is relatively abundant and easy to mine, the process to extract the aluminum from bauxite is complex and energy intensive. Aluminum recovery is essentially a two-stage process—the bauxite is converted to alumina by a chemical refining process, and then, the alumina is reduced to metallic aluminum by means of an electrolytic smelting process. Technological advances in both stages of production have reduced the cost and thereby increased the supply of aluminum. World production and prices and major technological developments in the aluminum industry are shown in figure 23.

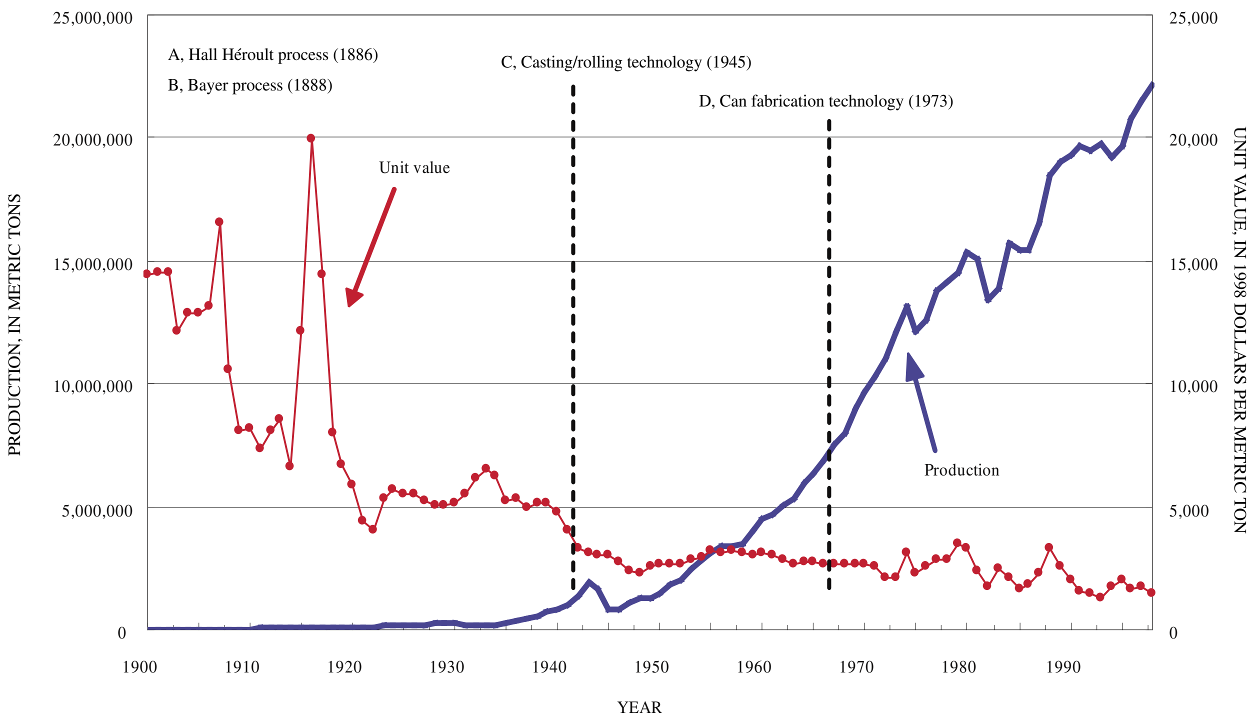

Figure 23. World aluminum production and unit value, 1900 to 1998 (Buckingham and Plunkert, 2002). The unit value (1998 dollars per metric ton) is defined as 1 metric ton of aluminum apparent consumption estimated from the “Annual Average Primary Aluminum Price" in U.S. dollars, as reported by Plunkert (1999), divided by the Consumer Price Index with a base year of 1998. The unit value trend line was fitted as a sixth-order polynomial. Letters A through D indicate major events in the history of aluminum production—A, Hall-Héroult electrolytic process was discovered in 1886; B, Bayer chemical process was discovered in 1888; C, war-initiated casting and rolling technology began major expansion in 1945; D, fabrication technology improvements stimulated aluminum can production in 1973.

Although aluminum was discovered in 1808, aluminum metal was a rare curiosity until the end of the 19th century. Aluminum is the second-most abundant element in the Earth’s crust after silicon but exists only in combination with other elements and is difficult to separate (U.S. Bureau of Mines, 1987). The first commercial aluminum (a few grams) was produced in France in 1854 by using a sodium reduction process patented by Henri Deville. In 1852, aluminum was

Primary Aluminum Industry

- Principal resources:
  — Bauxite
  — Alunite
  — Clays
  — Nepheline
  — Other sources
- Mine
- Alumina refinery
- Aluminum smelter
- Fabrication industry

Aluminum Recycling Industry

- Principal resources:
  — Old scrap (used cans, automobile parts, and so forth)
  — New scrap (production and fabrication waste)
- Scrap industry:
  — Used beverage can industry
  — Manufacturing industries
- Secondary smelter
- Fabrication industry

Figure 24. Components of the aluminum industry.

priced about $1,200/kilogram (Jefferson Lab, 2005) while gold was priced at $665/kilogram (finfacts, 2005). By 1860, the aluminum price had been reduced by one-half, but the only economic uses for aluminum were for chalices for church liturgies, jewelry, snuff boxes, and spectacle frames (Ravier and Laparra, 1986, p. 16).

In 1886, Charles Martin Hall (United States) and Paul Louis Toussaint Héroult (France) simultaneously developed a revolutionary fused-salt electrolytic process to produce aluminum from alumina. This process has been called the Hall-Héroult process (figure 23, A). The chemical process that would allow the commercial production of alumina from bauxite, the Bayer process, was patented by Karl Bayer of Germany in 1888 (figure 23, B). The effect of these two technological innovations was to reduce the price of aluminum by a factor of 20 between 1887 and 1900. These two processes provided the means for the commercial recovery of aluminum from bauxite. The first aluminum companies were founded in France, Switzerland, and the United States in 1888. A century later, these techniques are still used extensively by the aluminum industry.

The modern aluminum industry comprises two principal producing segments—the primary industry and the recycling industry (figure 24). The primary aluminum industry consists of mining, refining to produce alumina, and smelting to produce aluminum metal. The aluminum recycling industry consists of the scrap industry and secondary smelters and fabricators.

Aluminum did not become a major commodity until World War II. Prior to the beginning of the 20th century, annual world aluminum production was less than 7,000 t. By 1939, world production had increased a hundredfold to a little more than 700,000 t (Buckingham and Plunkert, 2002).

Between 1940 and 2002, world production of aluminum experienced its greatest growth (780,000 t to 26,000,000 t), on average about 6.6 percent per year[1]. World production of aluminum grew from 800,000 t in 1940 to more than 22,000,000 t in 1998. Aluminum demand for this period during this period grew at an average (simple) annual rate of just under 2 percent

[1]Calculated from the simple average of each year's growth rate during the period.

(Buckingham and Plunkert, 2002). Concomitantly, aluminum prices reported in 1998 constant dollars actually declined by two-thirds (Plunkert, 1999).

Aluminum Resources and Extraction Technology

Deposits of aluminum-bearing minerals are widely distributed and abundant in many parts of the world. Bauxite is the principal source of aluminum and large deposits occur in Australia, Brazil, Guinea, and Jamaica. Bauxite has been the principal source for metallurgical-grade alumina for the 110-year history of the aluminum industry. Bauxite price and production history since 1900 is shown in figure 25. Nonbauxitic sources that have the best potential for aluminum recovery are aluminous igneous rocks; alunite; and high-alumina clays, such as nepheline syenite; other potential sources include aluminous metamorphic rocks, aluminous phosphate rocks, aluminous shale, coal ash, coal waste, dawsonite-bearing rocks, and saprolite (Hosterman and others, 1990). Commercial extraction of aluminum from any of these resources would not have been commercially feasible without the development of the Bayer and the Hall-Héroult processes.

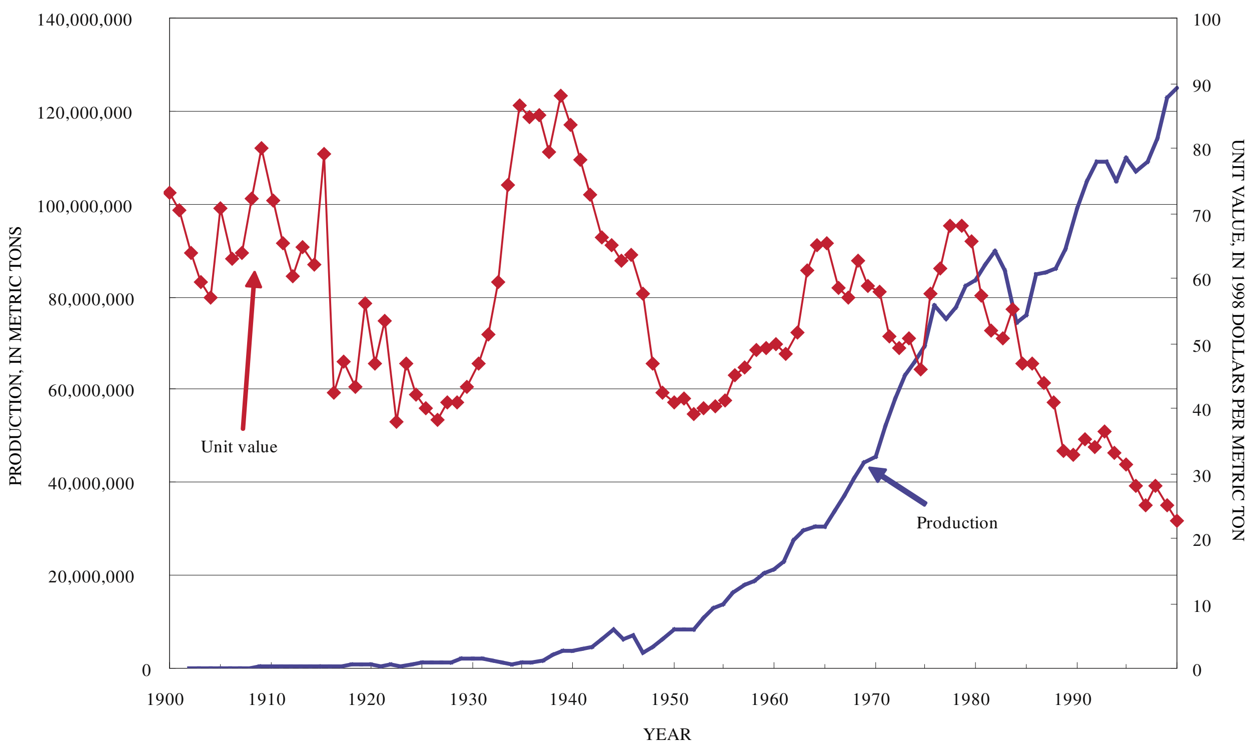

Figure 25. World bauxite production and unit value, 1900 to 1998 (Buckingham and Plunkert, 2002). The unit value (1998 dollars per metric ton) is defined as 1 metric ton of bauxite apparent consumption estimated from the “Annual Average Primary Aluminum Price” in U.S. dollars, as reported by Plunkert (1999), divided by the consumer price index with a base year of 1998.

Nonbauxite aluminum resources have been produced regionally or for nonmetallurgical applications where available bauxite resources are of poor quality or not readily available. Many countries that have limited high-grade bauxite resources have conducted research to develop more-cost-effective processes to recover nonbauxite aluminum resources. Importing bauxite, however, has been cheaper than processing domestic nonbauxite resources. The only region that produces aluminum from nonbauxite resources is Russia, where aluminum is produced from alunite and nepheline to supplement locally available bauxite. Specialized variations of the Bayer process were developed for the processing of these materials. The alumina industry of the Soviet Union, prior to its 1991 collapse, illustrates the diversity of source materials that can be used when national self-sufficiency is more highly valued than low cost production. Of the 10 refineries that operated in the Soviet Union in 1991, 4 used the conventional Bayer process to recover bauxite, 2 used the Bayer-Sinter process to recover bauxite with high silica content, 3 processed nepheline syenite ore, and 1 processed alunite ore. Economic and political changes forced the closure of several of these plants so that by 1999, only a small quantity of alumina from nonbauxite sources was still being produced.

Aluminum resources, whether from bauxite or nonbauxitic sources, are mined from near-surface deposits that can most often be recovered by conventional open-pit mining techniques. The biggest advances in mining technology to positively affect bauxite mining involve such technological improvements as larger sized equipment that increases efficiency and productivity. Costs of mining are small relative to the costs of alumina refining or aluminum smelting, the latter having expensive, high-energy requirements. Technological advances in shipping allow bauxite to be transported long distances for processing.

About 90 percent of the known production occurs in about a dozen countries. The magnitude of these resources (55 billion to 75 billion metric tons), however, is sufficient to meet the projected needs for the 21st century (Plunkert, 2000b).

Alumina Production Technology

The 110-year-old Bayer process is the most widely used method of converting metallurgical-grade bauxite to alumina (U.S. Bureau of Mines, 1987, p. 18). In this chemical process, which is shown in figure 26, bauxite is washed, ground, and dissolved in caustic soda

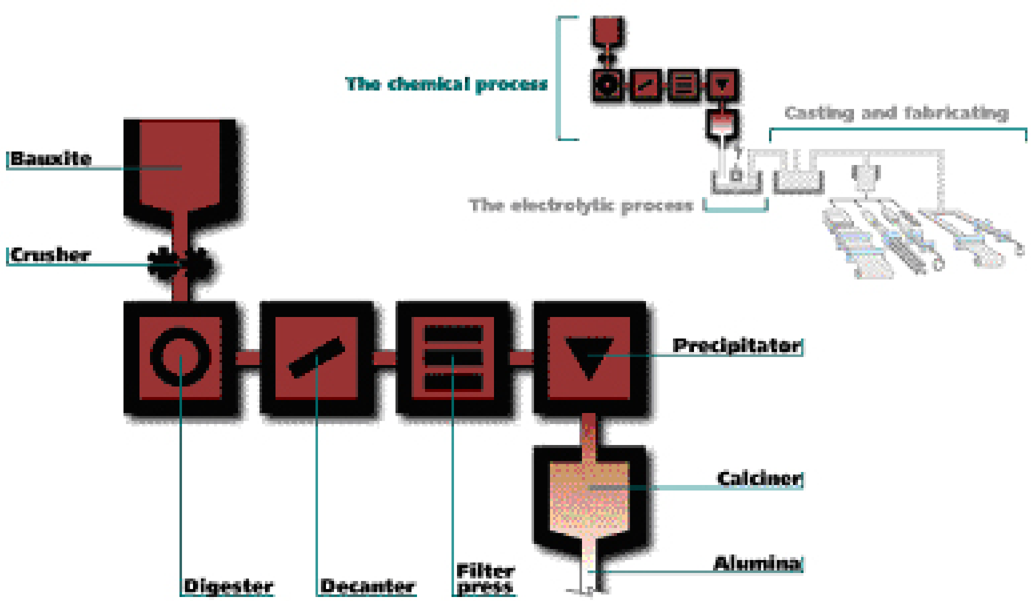

Figure 26. The Bayer process. Courtesy of Alcan Aluminium Limited, 1997.

(sodium hydroxide) at high pressure and temperature. The red mud residue is removed by decantation and filtration, and alumina hydrate is crystallized and then dried under very high temperature to form the white powder known as alumina. Variations on this process have been developed to treat various types of bauxite. Because European and northern Asian bauxites contain the minerals boehmite or diaspore, they are processed by using the European Bayer process. Most bauxite from other regions contains the mineral gibbsite and is processed by using either the American Bayer process or the modified Bayer process.

The conversion of bauxite to alumina is energy intensive. For this reason, early alumina plants were located near sources of low-cost energy. Technological advances in alumina processing followed the same pattern as aluminum processing—the progress was characterized by a series of gradual improvements accelerated by World War II. In 1915, the Martinswerk plant in Germany required 3 t of bauxite and 7 t of coal to produce 1 t of alumina. By the time the Gove plant in Australia was constructed in 1972, technologic improvements in the alumina production process were such that plants required only about 2 t of bauxite and 0.3 t of coal to produce 1 t of alumina (Peterson, 1986, p. 147).

As international competition increased after World War II, energy availability and transportation costs became prime factors for aluminum plant site selection (Peterson, 1986, p. 147). Because transportation costs for moving low-valued bauxite were so high, new plants were often located near resources or markets and local energy sources were developed to provide power. This led to the development of plants in such areas as South America and Western Australia at the expense of the higher cost plants in Europe and the United States. Although it became harder for plants with longer transportation distances to remain competitive, improved transportation technology has extended the life of these plants.

Technological advances in processing and competition led to the gradual phasing out or conversion of plants that could produce only "floury" alumina. The high energy costs associated with such plants made them less competitive (Peterson, 1986, p. 144). Newer technology that was more environmentally friendly was installed at many smelters in the 1970s, but these smelters could process only alumina with high adsorptive capacities of the "sandy" type. By the mid-1980s, most of the older floury-type plants had been forced to close or convert to the newer technology. Several new sandy-type plants came online during this period.

Aluminum Production Technology

In the Hall-Héroult process, alumina is dissolved by passing an electric current through a molten electrolyte contained within an electrolytic cell or "pot" (figure 27). At least 13 kilowatt hours of electricity per kilogram of aluminum is required to break the aluminum-oxygen chemical bond (International Primary Aluminium Institute, 2000). This amount of energy is roughly equivalent to lighting 200 60-watt light bulbs for one hour. The desire to keep energy costs as low as possible motivates the aluminum industry to continue to develop and improve technology. Most of the early plants were located near hydroelectric energy sources, which were the cheapest sources of energy during the 1880s. The Pechiney Company of France purchased land occupied by waterfalls throughout France and Switzerland just to gain access to inexpensive power (Ravier and Laperra, 1986, p. 17). In the United States, the Pittsburgh Reduction Company and the Aluminum Company of America (its successor) began to acquire

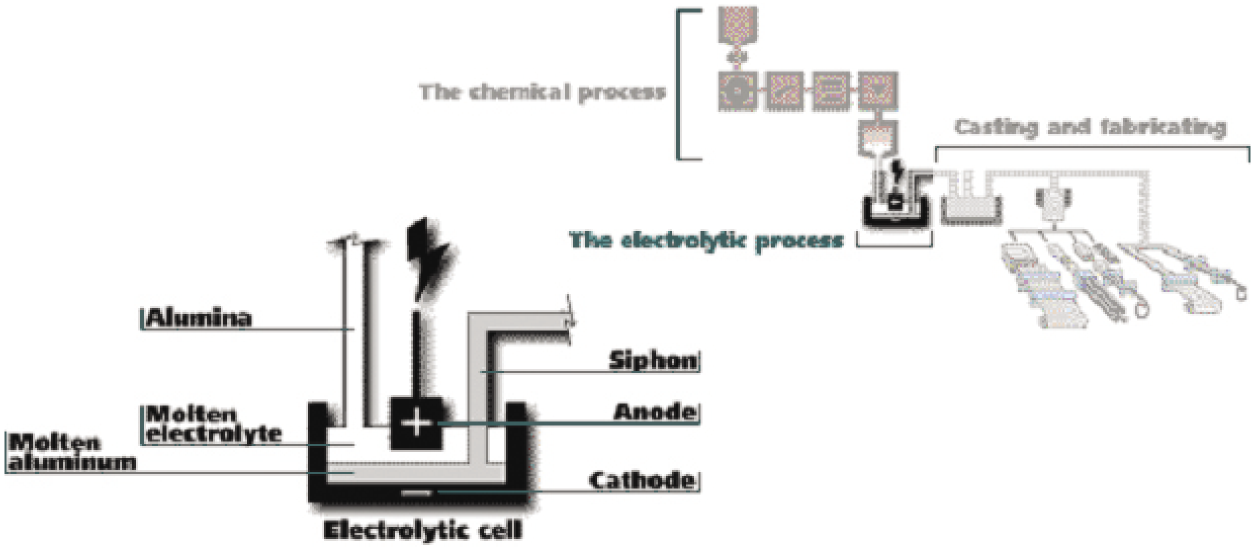

Figure 27. The Hall-Héroult electrolytic cell. Diagram courtesy of Alcan Aluminium Limited, 1997.

bauxite fields, construct fabricating facilities, and develop hydroelectric projects in the United States and Canada to support their aluminum production facilities during the late 19th and early 20th centuries. Most operating U.S. aluminum smelters are located in close proximity to low-cost hydroelectric energy sources, such as in the Pacific Northwest and the Tennessee Valley region and along the St. Lawrence River. In fact, several hydroelectric projects were designed specifically to provide electricity to aluminum smelters. Federally sponsored dam construction projects in the mid-20th century fostered smelter construction. As a result, the aluminum industry expanded rapidly in the 1960s and 1970s.

The price of aluminum started to drop after 1900 as processing and energy efficiencies began to be achieved (figure 23). Although the basic production process has changed little since its inception, progress has been made in increasing cell size while reducing cell energy consumption. Scale effects have mitigated aluminum price drops after 1945. Table 3 compares key cell performance results for selected years.

Table 3. Representative changes in aluminum cell technology, selected years

[NA, not available; kA, 1,000 amperes; V, volts; kWh/kg Al, kilowatthours per kilogram of aluminum produced; t/yr, metric tons per year. Sources: Grjothem and others, 1995; Øye and Huglen, 1990; Peterson, 1986, p. 113]

Cell parameter	1900	1945	**1995**
Cell amperage (kA)	5-15	25-50	175-300
Cell voltage (V)	NA	5	4.1
Current efficiency (%)	70-80	80-85	92-95
Energy consumption (kWh/kg Al)	35	20-25	13
Cell production capacity (t/yr)	15-20	55	820

The need to reduce the costs associated with energy consumption has motivated the industry to conduct extensive research in electrolytic cell design and technology. Improved cell design has led to improved energy efficiencies, increased production rates, and reduced labor costs per unit of production. Between 1900 and 1945, the average worldwide cell amperage and capacity increased by about 300 percent, and energy consumption decreased by about 64 percent (Peterson, 1986, p. 113; Ǿye and Huglen, 1990). Since 1945, the average worldwide cell amperage has increased by about 600 percent, production capacity has increased by about 1,500 percent, and energy consumption has decreased by 58 percent (Grjotheim and others, 1995). Worldwide labor productivity has increased from about 7 metric tons per worker to about 200 tons per worker in the past 50 years (Grjotheim and others, 1995). The unit price for aluminum in 1998 dollars has decreased to about $1,400 per ton in 1998 from about $5,000 per ton in 1925 (figure 23).

Fabrication Technology

Aluminum markets remained limited until World War II when the high-strength, low-weight properties of aluminum made it the metal of choice for the structural components of aircraft. Technological improvements, such as the development of die-casting methods, mercury-arc rectifiers for electrical conversion, new high-strength alloys, and Soderberg reduction technology, made it possible to produce the large quantities of aluminum sheet necessary for the war effort (figure 23, C). Technological developments in all phases of production during World War II increased the versatility of aluminum, which led to diversified and expanding postwar markets (U.S. Department of Commerce, 1956, p. 13). Aluminum began to be used extensively in commercial aircraft and automobiles, containers and packaging, and wiring and machinery. Since World War II, demand for the metal has continued to grow, and its use has broadened to make aluminum one of the most widely used mineral commodities in the world.

Improvements in fabrication technology, such as development of minimills and thin-sheet technology, gradually allowed thinner sheets of aluminum to be produced and complex shapes to be stamped and formed (figure 23, D), which strengthened the aluminum can manufacturing industry. The aluminum fabrication process is shown in figure 28. Aluminum was first introduced into the can manufacturing process in the 1960s, and aluminum can sales grew to approximately 100 percent of the beverage can market in 1999 from 2 percent in 1964 (Munts, 1991, p. 4-4; Aluminum Association, Inc., 1985).

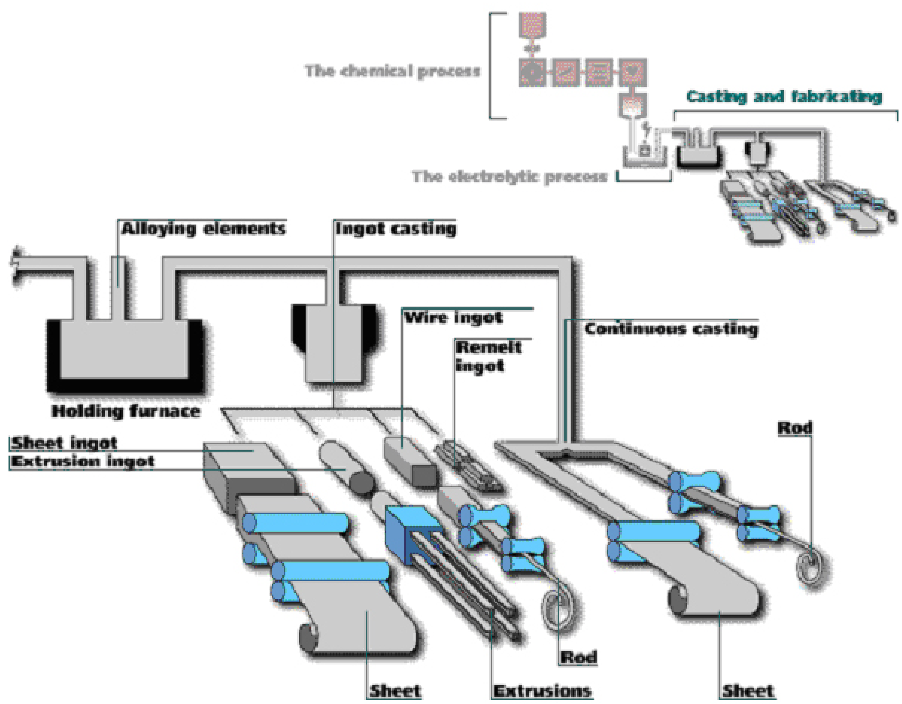

Figure 28. Aluminum casting and fabrication process. Diagram courtesy of Alcan Aluminium Limited, 1997.

Recycling Technology

One of the advantages of aluminum is that it is easily recyclable. The aluminum recycling industry, which is also called the secondary aluminum industry, began to process scrap from the primary aluminum industry in the early 1900s. The amount of energy required to produce recycled aluminum is about 5 percent of the energy required to produce primary aluminum from bauxite (Wilburn and Wagner, 1993, p. 93). In the beginning, reclamation of aluminum scrap was insignificant because the supply of scrap was limited. As the domestic aluminum industry expanded during World War II and entered new markets, recycled aluminum production also increased because of increased supply of aluminum scrap, proven product performance, and profitability. Figure 29 shows aluminum production for the U.S. primary and secondary aluminum industries.

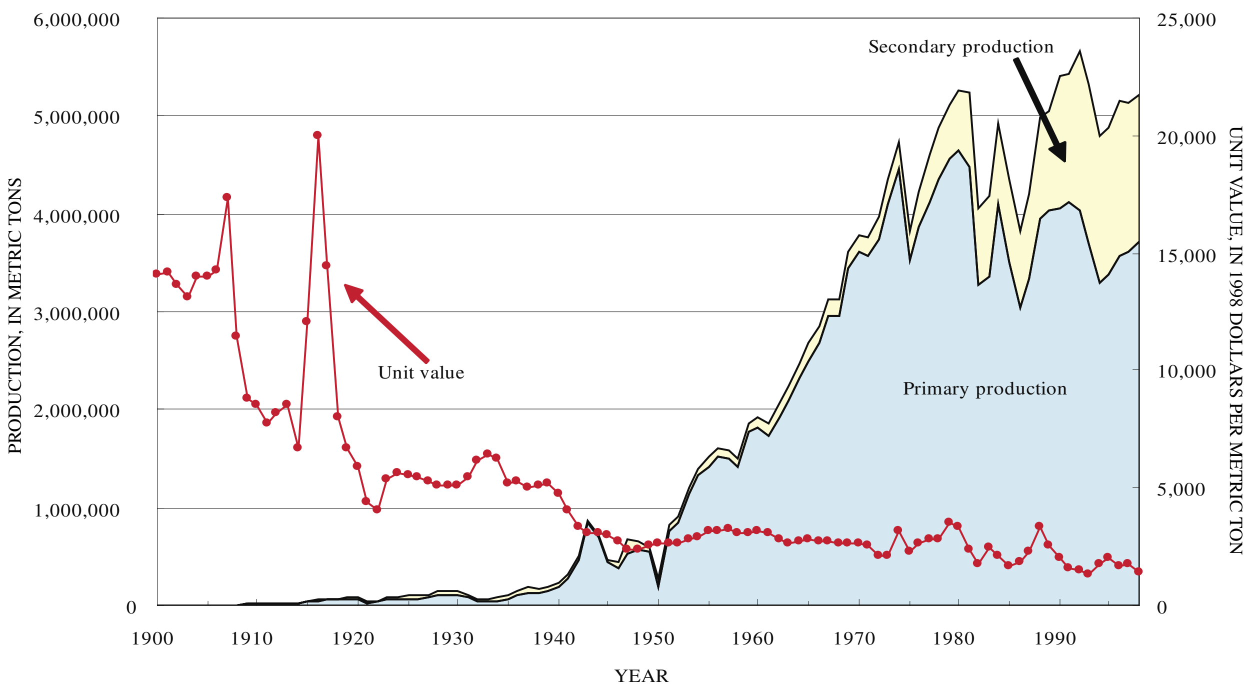

Figure 29. U.S. primary and secondary aluminum production and primary aluminum unit value, 1900 to 1998 (Buckingham and Plunkert, 2002). The unit value (1998 dollars per metric ton) is defined as 1 metric ton of aluminum apparent consumption, estimated from the "Annual Average Primary Aluminum Price" or secondary aluminum price in U.S. dollars, as reported by Plunkert (1999), divided by the consumer price index for that commodity with a base year of 1998. Area charts for primary and secondary production are cumulative.

Some technical advances in alloying and die casting during World War II were developed specifically for the aluminum recycling industry (Aluminum Association, 1985). Technology also was developed during the 1950s that allowed improved separation of aluminum from scrapped automobiles. Recycling of aluminum products increased dramatically in the 1970s when the recyclable aluminum beverage can began to be widely used. Increased public concern for the environment, beverage container deposit legislation at the State level, and resulting consumer aluminum recycling programs in the 1980s contributed to increases in aluminum recycling. Between 1950 and 1974, aluminum recovered from old (postconsumer) scrap accounted for approximately 5 percent of the total domestic demand for aluminum (Plunkert, 1990). By 1997, aluminum production from old scrap had increased to 30 percent of the total domestic demand for aluminum metal (U.S. Geological Survey, 1999). As shown in figure 29, U.S. primary aluminum production has generally declined during the past 20 years; production of secondary aluminum, however, has generally increased, thus allowing the industry as a whole to grow.

Future Directions

The driving force for developing new processes for smelting aluminum usually centers around one of three factors—capital cost reduction, energy cost reduction, or environmental considerations. Recent emphasis has been a shift to high-amperage technologies that are slightly less energy efficient but more cost efficient. New technologies that generate electric current efficiencies in excess of 96 percent or retrofitting a plant to increase capture rates for pollutants above 95 percent are possible, but the incremental improvement in efficiency that is generated is generally not worth the cost of implementing the technology. Research is now focused on developing plant designs that have a low capital cost per unit production while complying with environmental requirements.

Since 1980, five alternative aluminum-processing methods have been under study, and each faces challenges similar to those of the existing technology. Drained-cell technology features the coating of aluminum cell cathodes with titanium dibromide and eliminating the metal pad, which reduces the distance between anode and cathode thereby lowering the required cell voltage and reducing heat loss. Oxygen-evolution technology involves eliminating the consumable carbon anode by developing an electrode material that evolves oxygen. In the chloride process, aluminous material is converted to anhydrous aluminum chloride. In the sulfide process, aluminous material is converted to aluminum sulfide. Carbothermal reduction is the only nonelectrochemical process being considered and is based on an aluminum reduction process analogous to a blast furnace for iron ore. Research suggests that economic gains from any of these proposed processes would not be dramatic, and development costs would be considerable (Welch, 1999).

Summary

The aluminum industry grew as a result of initial technological breakthroughs followed by a series of cumulative improvements. The aluminum industry initially was stimulated by the development of the Bayer and the Hall-Héroult processing technologies at the end of the 19th century. Since then, gradual improvements on basic technology have allowed the U.S. industry to grow and remain competitive. Technological developments during World War II that increased the adaptability and versatility of aluminum have led to diverse and expanded postwar markets. Advances in alloying and die casting stimulated the growth of the aluminum recycling industry in the 1970s. As the result of successive technical improvements, the recycling sector grew to provide 30 percent of aluminum metal demand by 1997. The use of recycled aluminum has reduced dependence on foreign aluminum supplies, reduced energy consumption, and lessened the amount of aluminum disposed of as solid waste.

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Appendix 3. Copper Case Study

Copper Production History

Humankind has used copper metal for 6,000 years. At first, copper was used for ornaments, simple weapons, and tools. Copper is a critical metal in electrical transmission, electronic equipment, pipes for fluid transport, and many other products.

Figure 30 shows, by decade, the growth in the per capita consumption of copper during the 1990 through 1999 period. Per capita consumption is defined here as copper contained in ores produced from global copper mining operations for a given year divided by world population for the same year. One might think that the combination of increasing population and increasing amount of copper use per person over time would be unsustainable and lead to scarcity of copper. This appendix explains how copper production has managed to keep pace with copper demand.

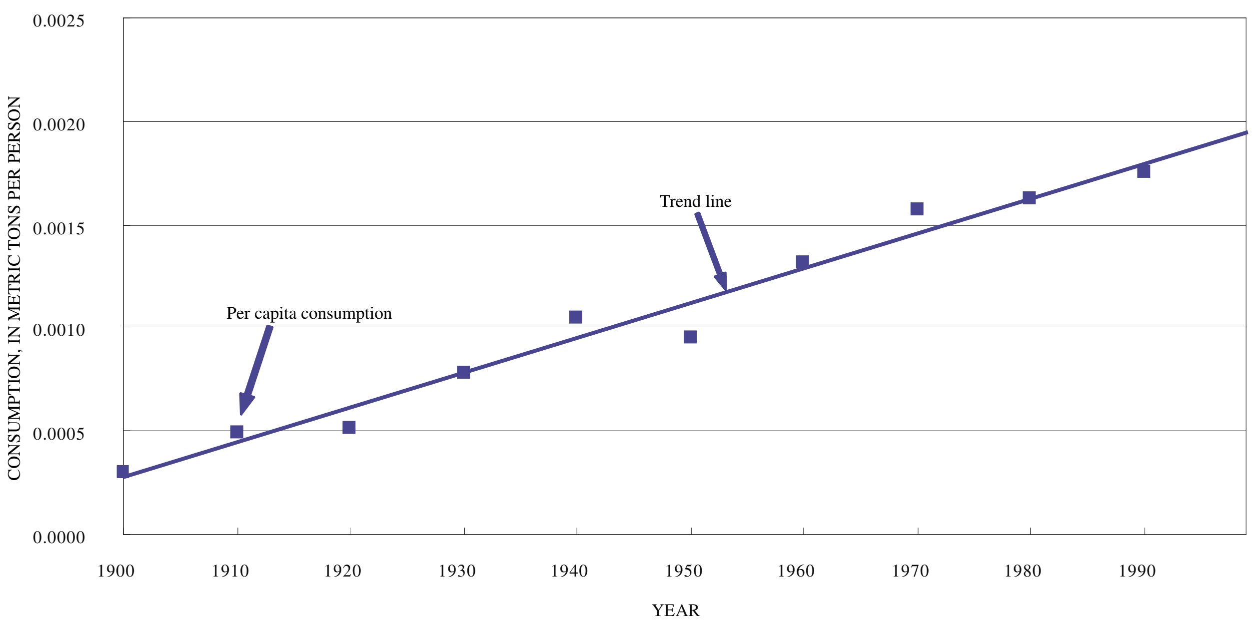

Figure 30. World copper per capita consumption, 1900 to 1990 (Porter and Edelstein, 2002; U.S. Census Bureau, 2000). Per capita consumption is defined here as world copper produced from mines for a given year divided by the world population for that year.

Throughout the 20th century, copper resources and metal production have expanded to meet an ever-growing demand for copper. Technological advances[2] have facilitated copper production from progressively more chemically diverse and lower grade ores to meet growing demand and, in recent years, to address growing concerns for the environment. Interestingly, several porphyry copper deposits were discovered by the oil industry in their search for oil (Hyde, 1998, p. 194).

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[2]Technology as defined here includes new tools and processes, revised methods of organizing resources, and changes to legal and administrative structures.

Figure 31 shows world copper production for the 20th century. In 1900, world copper mine production was about 500,000 metric tons (t) of contained copper, and it came mainly from high-grade (around 2.5 percent copper) veins and contact zones found in or near deposits that contained large quantities of much lower grade copper ore. By 1930, world mine production had quadrupled to approximately 2 million metric tons (Mt) of contained copper, and a significant proportion of this production had shifted to porphyry-copper sulfide ores supplied from extensive open pits. Worldwide mine production of copper increased to 12 Mt in 1998 from 2 Mt in 1950.

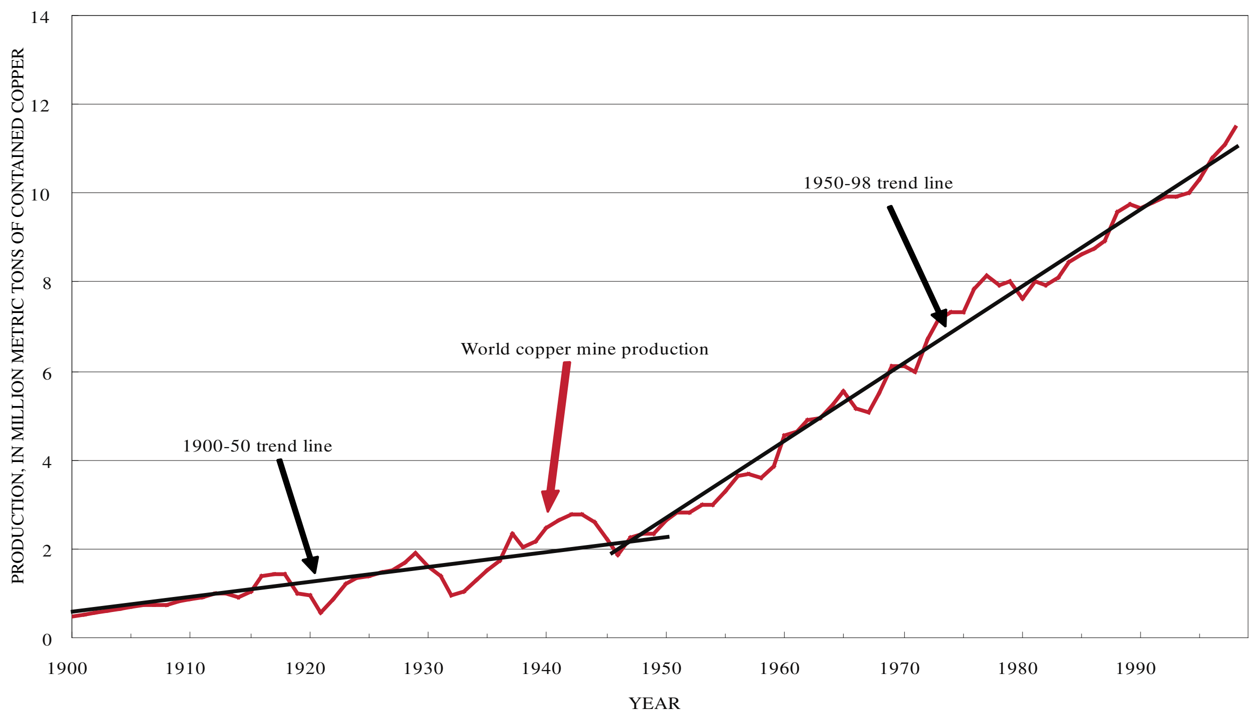

Figure 31. World copper mine production, 1900 to 1998 (Porter and Edelstein, 2002). Linear trend lines were plotted.

Figure 32 shows the growth of U.S. copper production from 1900 to 1998, and the change in constant dollar (1998) copper prices during the period. The linear trend lines for production and price show that supply has increased while prices have fallen.

In figure 32, constant dollar (1998) prices between 1900 and 1999 for copper might be characterized as being volatile as indicated by the variance from the trend lines. From 1900 to 1932, constant dollar copper prices trended downwards by decreasing at the rate of about 3 percent per year.[3] Between 1933 and 1974, constant dollar copper prices showed an upward trend, increasing at an average rate of about 2 percent per year.[2] Between 1975 and 1998, constant dollar copper prices again trended downwards by a rate of about 4 percent per year.[2] Between 1900 and 1998, constant dollar copper prices showed a generally downward trend by decreasing at the rate of about 1 percent per year.[2] For each period, whether copper production increased or decreased, short-term prices were volatile.

U.S. mine production of copper was 275,000 t in 1900, or 56 percent of world mine production, and more than 1.6 Mt in 1999, or 13 percent of world mine production (Porter and

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[3]The rate calculated is a simple average for the periods cited.

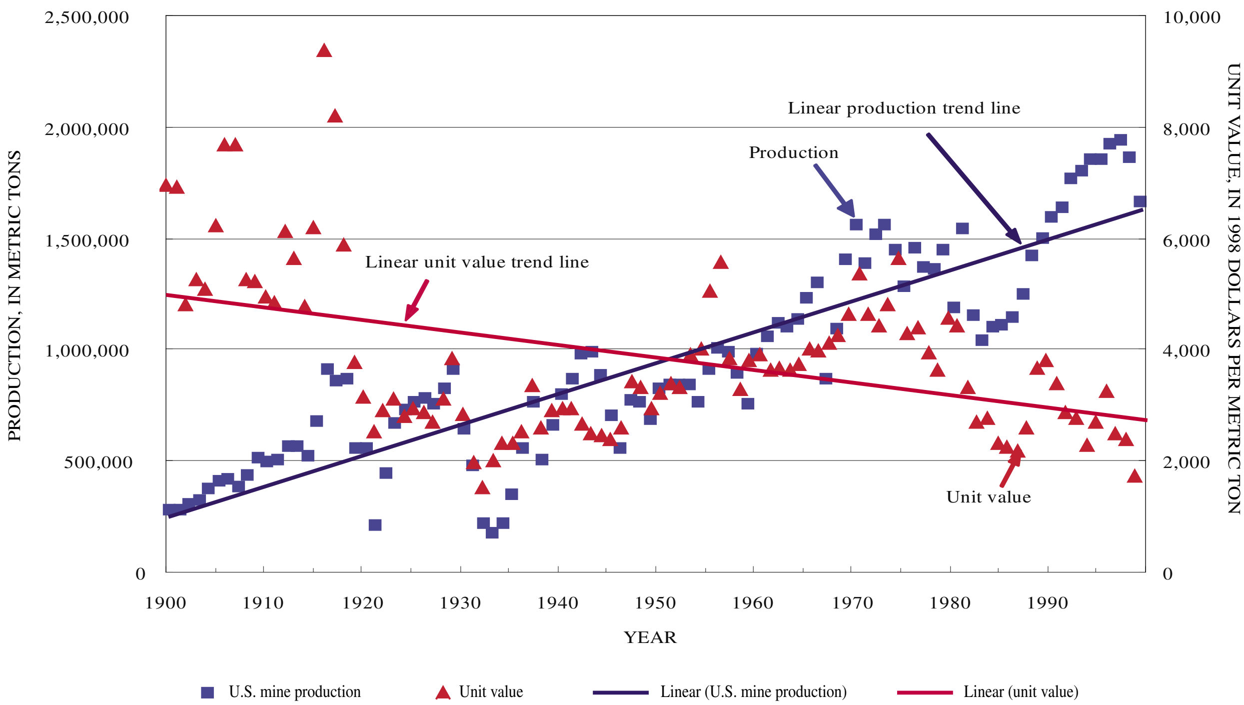

Figure 32. U.S. copper mine production and unit value, 1900 to 1998 (Porter and Edelstein, 2002). The unit value (1998 dollars per metric ton) is defined as 1 metric ton of copper apparent consumption estimated from the "Annual Average U.S. Producer Copper Price" in U.S. dollars, as reported by Edelstein (1999), divided by the Consumer Price Index with a base year of 1998.

Edelstein, 2002). Even while copper production was increasing, the reduction in U.S. market share can be attributed to the increase of global mining investment and advancing technology throughout the world, especially in Latin America. Until about 1932, more than one-half of world mine production was from the United States; since 1932, however, world mine production has grown about 4 percent annually. World mine production growth has outpaced the growth in U.S. production, which grew by about 2.4 percent annually.

Figure 33 shows U.S. production by process and material type. U.S. refined copper production grew to about 2.5 Mt in 1998 from 300,000 t in 1900, an annual growth rate of 2.2 percent.

In general, prices reflect the relationship of supply to demand. If supplies were restricted, then increasing demand would lead to an upward price trend. The general trend for metals demand has been upwards, and U.S. copper production has followed that trend (figures 32-33). Because prices for most metals have been trending downwards (figure 2) as quantities have increased, one can conclude that some phenomenon on the supply side of the relationship has worked to keep prices falling. For copper, the periods of falling prices (1900-32, 1975-98) correspond to the periods of investment in technology that allowed the processing of increasingly lower grade copper ores.

The introduction of new technology is generally aimed at improving overall productivity and reducing costs. A persistent decrease in the price of any good indicates that the substance is being supplied at a faster rate than it is being demanded or, in other words, is becoming increasingly more available. When the difference between market price and production cost narrows, one possible response is technological cost reduction.

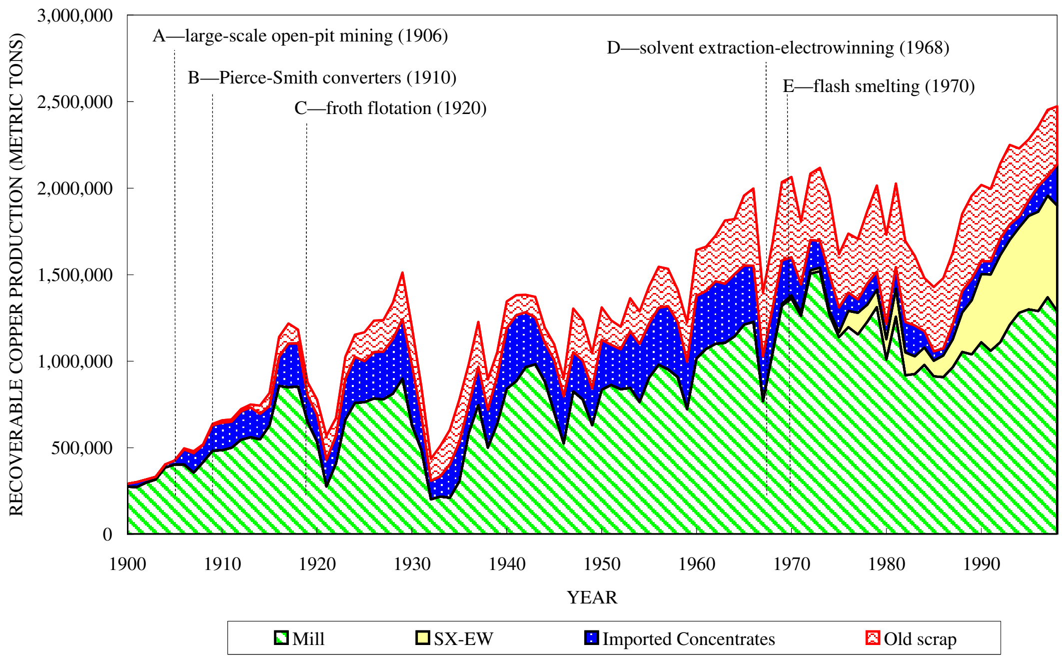

Figure 33. U.S. copper production, by component, 1900 to 1998 (Porter and Edelstein, 2002). Letters A through E indicate major turning points in the history of copper production—A, large-scale open-pit mining techniques were first demonstrated in Utah in 1906; B, Pierce-Smith copper converters were placed in service in large numbers beginning in 1910; C, froth flotation was used widely throughout the world by 1920; D, solvent extraction–electrowinning (SX-EW) was first introduced on a large scale in 1968; E, oxygen "flash" smelting began production in 1970.

Technology and Management Overview

Technical advance is usually put into practice by means of capital investment, but its effect is time-lagged. The capital intensity of the copper industry makes it hard to adopt new processes on an industry-wide basis in a short time frame. The rate at which capital stock is added or replaced may be constrained by lead-time for approvals, permits, and construction. For these reasons, technology management within the minerals industry is often a process of "adaption" rather than outright "adoption" (Groeneveld, 1998, p. 3).

Although technological improvement is mainly incremental, the copper industry has seen some major breakthroughs. Between 1905 and 1930, the following major technological advances were implemented: large-scale open-pit mining, Pierce-Smith converters, and sulfide flotation (figure 33, A-C).

The large-scale open-pit mining techniques that were first demonstrated at Bingham Canyon, Utah, in 1906 have come to dominate world copper mining (Utah History Encyclopedia, 2000). This mining method is discussed in greater detail in the "Recycling" section.

For many years, only the high-grade veins and igneous contact zones in porphyry deposits were mined. The use of large-scale open pit mining allowed the efficient economical recovery of millions of metric tons of additional lower grade copper-sulfide material from porphyry deposits. Pierce-Smith copper converters permitted large-scale copper production and were placed in service in large numbers beginning in 1910. Froth flotation of low-grade sulfide ores came into its own after a two-decade-long patent dispute; by 1920, the process had spread throughout the world. Taken together, these extractive and process advances are responsible for the growth in worldwide porphyry copper reserves.

According to Hyde (1998, p. 148), investment in materials processing equipment for U.S. copper production between 1920 and 1970 was included such advances as block caving for underground mining, diesel-electric motors for haul trucks, and larger shovels. As a result, productivity improvement was also incremental. The largest capital outlays during this period were for foreign properties that had higher ore grades. The period also included innovation in the area of organizational and administrative technology, which began with an attempt to form a domestic copper production cartel during the 1920s and, later, an international copper cartel to restrict production. During the 1950s, efforts were made to get the U.S. Government to stockpile copper.

Estimated world copper reserves

[In million metric tons of contained metal. Source: Daniel Edelstein, Copper Specialist, U.S. Geological Survey, oral commun., 2000]

1930	1950	1960	1970	1982	1998
80	91	154	280	350	330

Since 1970, oxygen flash smelting has reduced energy input at copper smelters and improved air quality by lowering smelter emissions (figure 33, E). The term “flash smelting” is applied to modern copper, lead, and zinc smelters that introduce finely divided ore and pure oxygen simultaneously into the smelting furnace as a combustible mixture. The implementation of Federal and State air pollution regulations to control sulfur dioxide emissions drove domestic investment in oxygen flash smelting. Installation of flash smelting processes also led to operating cost savings and sometimes to production capacity increases. The combined operating-cost savings and capacity increases, however, were insufficient to recover the capital investment (Engineering and Mining Journal, 1990).

Solvent extraction-electrowinning (SX-EW), which was first introduced on a large scale in the extractive copper industry in 1968, was greatly expanded beginning in the mid-1980s. The share of total copper production represented by SX-EW copper has been growing ever since (figure 33, D). In 1999, domestic SX-EW production was about 30 percent of total U.S. copper production (Porter, 2002). By 2002, domestic SX-EW production had increased to about 53 percent of total U.S. copper production (Edelstein, 2005).

Technological advances have permitted the economic recovery of copper from progressively lower grade, more chemically diverse ores. Figure 34 shows the apparent decline in world copper ore grades since 1750. At the time of the American Revolution (1775-83), the average grade of copper ore processed was about 13 percent. During the War of 1812 (1812-15), the average grade had dropped to about 9 percent, and by the time of the Mexican War (1846-48), the average grade had decreased to about 5 percent. During the Civil War (1861-65), grades continued to decrease to about 4 percent. By the Spanish-American War (1898), economically viable copper ore grades were about 3.5 percent (Groeneveld, 1998). Currently, some sulfide ores that contain less than 0.5 percent copper and some oxide ores that contain less than 0.2 percent copper are being mined by the SX-EW process.

Figure 35 shows the overall trend of decreasing copper mill yields for the 20th century. Yield (in copper mill lexicon) equals all the copper coming out of the mill in a given year as a percentage of total ore input to the mill. The calculations for 1960 through 1998 were adjusted to exclude leach ores because of data reporting anomalies. Although yield is not equivalent to ore grade, it can be used as an indicator of grade. The figure shows the same trend as figure 34;

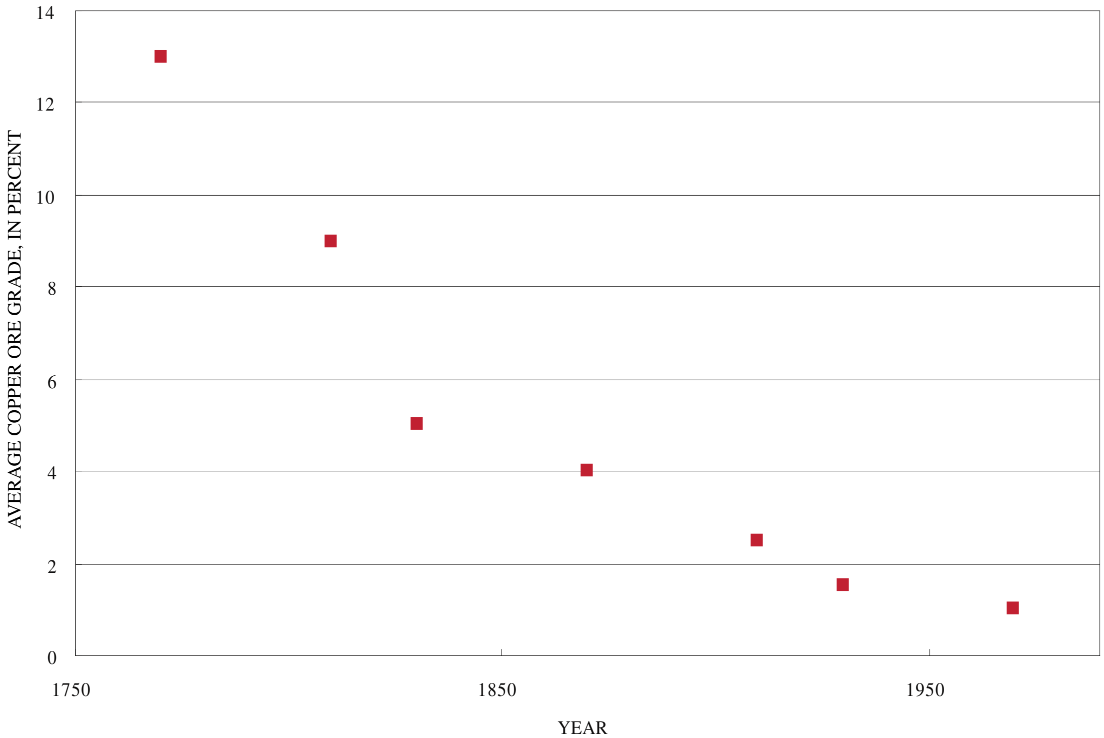

Figure 34. Historical copper industry ore grades. Data adapted from Groeneveld, 1998.

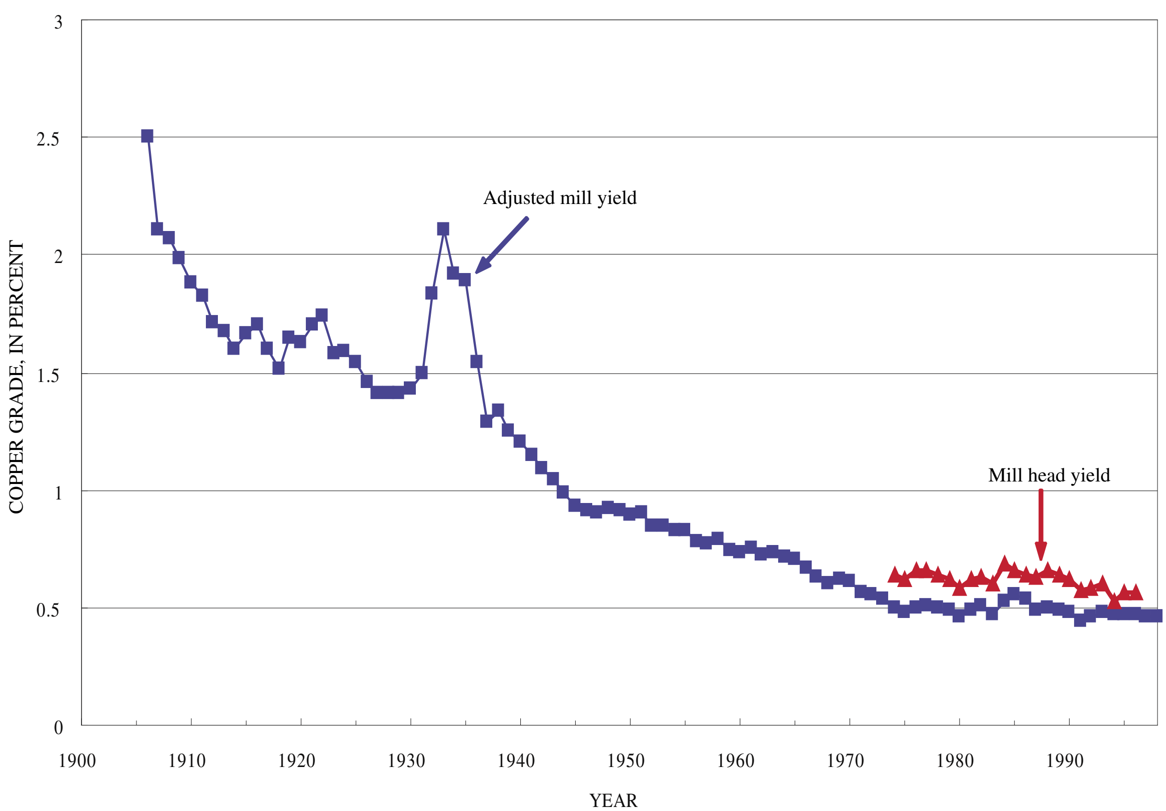

Figure 35. U.S. adjusted mill copper yields, 1906 to 1998, and head grades, 1974 to 1996. Squares represent mill yield, triangles represent mill head grade. Adapted from U.S. Bureau of Mines, 1927-34, 1933-96; U.S. Geological Survey, 1901-27, 1997-2000.

that is, downward trends in copper ore grades over time. The large peak associated with the Great Depression (1932-33) resulted from mining companies taking steps to improve short-term yield. Such steps included closing marginal facilities, high grading ores, or leaching waste dumps.

As discussed, copper prices are determined by many factors, one of which is the need for producers to recover costs. Decreasing ore grades could be expected to lead to increased production costs because lower grades require the processing of larger quantities of material to obtain the same amount of copper. Application of new technology designed to improve the economics of copper recovery from lower grade ores is a way to maintain or lower production costs. The trend line, reflecting copper prices in constant dollar terms, gradually declined through the 20th century (figure 32). Declining copper prices and/or increasing production costs narrow profitability and tend to stimulate copper companies to invest in productivity-increasing technologies. There are basically two types: management technologies are directed toward administration and reorganization; and improved process equipment technologies work directly on production methods to decrease inputs of materials and energy, materials handling costs, and/or to improve yield.

Copper Production Technologies

The important technological changes in the copper industry shown in figure 33 are explained below. In all cases, the technology was implemented over a long period of time. Although the history of technological advance has its breakthroughs, most advances come about through incremental improvement. Breakthroughs and incremental advancements have contributed substantially to making more resources available for economic production.

Open-Pit Mining

Incremental improvements in equipment that handles bulk materials helped make high-tonnage open-pit mining more cost effective. The development of large porphyry copper deposits through open-pit mining in the American Southwest is an example. Steam shovel open-pit mining operations for the Bingham Canyon, Utah, porphyry copper mineral deposit began in 1906, and electric shovel operations started in 1923.

In 1955, 42 percent of world copper production came from open-pit mines, such as the one illustrated in figure 36. By 1985, open-pit production had reached 60 percent of world copper production. Most of the mines that were closed during the 1980s and 1990s were higher cost underground mines, and most of the new mine expansions have been open pit. In 2002, more than 80 percent of the world's copper came from open-pit mines.

Figure 36. Morenci open pit, Arizona. Photograph courtesy of Bruce Richardson, Phelps Dodge Corporation, July 14, 2000.

Accompanying the growth of open-pit mining were increases in equipment efficiency and size. Trucks, which have payloads in excess of 300 t, move material from deep open pits to processing facilities at the surface. As the

OPEN-PIT MINE STARTUPS	
Bingham Canyon, Utah	1906
Ely, Nevada	1908
Cananea, Mexico	1910
Chuquicamata, Chile	1910
Miami, Arizona	1910
Morenci, Arizona	1910

pits became deeper and deeper in the mid-1980s, in-pit crushing and conveyor transportation of crushed ore became prominent, often replacing trains and trucks. Investments in computerization helped improve the dispatch of equipment, mine development, and recovery-circuit yields. Such improvements are mainly incrementally generated by the continuing desire to increase productivity and to decrease the cost of production. Copper companies increased the level of investment in process equipment technology in 1985 in response to steadily falling copper prices through the early 1980s.

Pierce-Smith Converting

Pierce-Smith copper converting was a technological breakthrough in copper smelting (figure 37). In 1910, it was implemented to treat copper mattes (metal mixtures) which contain as much as 45 percent copper and are typically produced from blast furnaces and reverberatory furnaces. Prior to Pierce-Smith converting, refining such mattes to high purity required more process steps and much more energy.

Figure 37. Pierce-Smith converter, Chino operation, New Mexico. Photograph courtesy of Bruce Richardson, Phelps Dodge Corporation, July 14, 2000.

The Pierce-Smith converter receives the molten matte from the reverberatory furnace. In the process, air (oxygen being the reactive agent) is forced through tuyeres, which are pipes that extend through the vessel's refractory lining. Oxygen reacts with the iron in the matte to form iron oxide, which, in turn, reacts with silica in the slag to form iron silicate. Like oil on water, the less dense slag floats on top of the metal, effectively separating the iron. Sulfur leaves the system as sulfur dioxide, which is collected and converted into sulfuric acid. Additionally, some sulfur also partitions into the slag and is removed. The resulting high-purity copper is called blister and contains from 95 to 98 percent copper.

With the ability to produce from 95 to 98 percent copper at lower cost than in the past and with electrorefining that results in a 99.999-percent copper product, copper became available for applications that required higher purity. Technology, therefore, was instrumental in creating the expanding demand for the high-purity copper required for electronics and electrical transmission wire.

Flotation Separation of Sulfide Ores

The increasing demand for copper throughout the 20th century stimulated research into the recovery of copper from huge low-grade porphyry copper deposits. These deposits are characterized by enormous size and a relatively uniform distribution of small amounts of copper minerals (U.S. Bureau of Mines, 1968, p. 848).

Sulfide flotation, as applied to copper ore from porphyry deposits, separates the metallic sulfide minerals from the nonmetallic host-rock minerals and then further separates the copper

COPPER TECHNOLOGY ON THE DEMAND SIDE

Although the bulk of this case study focuses on the relationship of technology to increased supply while maintaining or even lowering production costs, technology developments on the demand side (for example, the electric light and motor-driven appliances) have significantly increased the demand for copper, which has spurred the search for ways to increase its production.

The great century-long demand for general electrification and expanded and improved communications also has increased production through technological improvement of production methods. As the United States became electrified, fabrication technology to draw copper wires also was developed, and copper played a leading role in helping to shape the electrical distribution system, which features the central steam-generated powerplant, electric sockets on every wall, and electric wires in every structure.

More recently, the evolution of copper wire drawing has been toward smaller diameter wires. Nano-sized wires are smaller in diameter than a human hair and find application in the evolutionary development of faster, smaller, and more-powerful computers.

Fiber optics use silica to carry digital information on photon packages rather than on electron packages carried along copper wires. This new technology is reducing the use of copper in computers and other telecommunications equipment. Nonetheless, as long as an electrical services market survives, copper technologists will search for ways to use copper more effectively and to expand copper demand.

sulfides from the other metallic sulfides (figure 38). By using sulfide flotation, copper can be concentrated from less than 1 percent to more than 25 percent, thus making it economical to smelt. Sulfide flotation also stimulated research into bulk crushing, grinding, and materials handling equipment. Chemical research into the surface forces that exist among dissimilar materials in close proximity led to new methods, such as fine grinding to increase the surface area of the reacting materials, and to the development of chemical agents (surfactants) to promote bonding of selected minerals to flotation froth bubbles (Mouat, 2000).

The first patent that addressed the special affinity of oils and fatty substances to aid in the flotation segregation of materials was issued on August 29, 1885 (Mouat, 2000). From 1885 through the first two decades of the 20th century, legal disputes over patent rights restricted the growth of this technology. When the patent problems were overcome in the early 1920s, sulfide flotation technology expanded throughout the world. The first large-scale application of a process similar to present flotation practice in the United States began in 1912 in Montana (Chapman, 1936).

The ability of sulfide flotation to separate one type of sulfide from another is responsible for the commercial development of

Figure 38. Flotation cells, Chino operation, New Mexico. Photograph courtesy of Bruce Richardson, Phelps Dodge Corporation, July 14, 2000.

polymetallic ore bodies that otherwise would have been too complex to process. At the San Martin deposit in Zacatecas, Mexico, for example, flotation is used to recover metals from ores that contain 4 percent zinc, 1 percent copper, and 0.5 percent lead together with byproduct cadmium, gold, silver, and tungsten (Megaw and Imdex, 1999). Prior to sulfide flotation, the Bingham Canyon copper mine in Utah was a gold, lead, and zinc property with some minable copper veins. With the advent of sulfide flotation and open-pit mining techniques, the porphyry copper deposit that underlies the area became the dominant target of mining; the site is one of the world's largest copper mines (Mikesell, 1979, p. 6). By making these complex types of deposits attractive for exploration, world copper resources were expanded.

The ability to separate different metal sulfides from each other made possible the installation of byproduct circuits for the recovery of what might otherwise have been waste. Many copper mines in the American Southwest have enhanced their revenue streams with a molybdenum recovery circuit. Byproduct molybdenum from copper mines accounts for about 70 percent of the world's molybdenum supply and has negatively affected extraction from primary molybdenum resources, and increased molybdenum supply from multiple sources (Mitchell, 2000). Sulfide flotation has been similarly important for other metals produced primarily from sulfide ores, such as lead, nickel, and zinc.

Oxygen and Flash Smelting

Before oxygen flash smelting was developed, the standard copper smelting technology produced stack gases that contained low levels of unrecovered sulfur dioxide. This dilute sulfur dioxide gas was toxic in confined areas. Consequently, tall stacks, which became the signature of metal smelters, disbursed polluting gases over wide areas. Thus, the most important factor that drove the rapid implementation of oxygen smelting was environmental protection legislation that mandated ambient air-quality standards which required the capture of sulfur dioxide. After the switch to flash smelting, these tall stacks are being removed or are becoming historic relics.

> Oxygen, substituting for air in copper smelting, reduced energy requirements and permitted the making of a waste into a byproduct.

High-temperature oxygen-metal reactions essential for efficient melting were first demonstrated by using Pierce-Smith converters. The 78 percent nitrogen in natural air, which was used in the Pierce-Smith converters, however, reduced its oxidizing affects. This inert element required energy to move and heat, but contributed nothing to the smelting process.

Cryogenic (extremely low temperature) technology was developed during World War II, and became the foundation of the industrial gas industry. With this technique, oxygen could be separated from air in large quantities for pyrometallurgical use. No longer impeded by nitrogen dilution, this element could react more efficiently with the iron and sulfur available in the copper mattes and thereby generate sufficient heat to power the smelting process. Thus, iron and sulfur replaced coal as the primary fuel for copper smelting.

Several proprietary smelting processes, which are based on the principle that mixtures of gases and fine particles react together more efficiently, have been implemented worldwide since the 1950s (Themelis, 1994). "Flash" smelting has become the common name for such processes used in copper, lead, and zinc smelting. Sulfur recovery during this process has reached 95 percent, and sulfuric acid plants have become an integral part of copper, lead, and zinc smelting.

Smelting that uses pure oxygen produces a more concentrated sulfur dioxide off-gas; 25 percent sulfur dioxide compared with the 6 percent that had been produced. This off-gas can be processed more economically in an acid plant to produce the useful byproduct sulfuric acid. The sulfuric acid can be sold commercially or used on-site for the leaching of oxide ores and waste dumps to recover low-grade copper.

U.S. Copper Smelter Capacity
[NA, not available. Source: U.S. Bureau of Mines, 1989, p. 299]

Pyrometallurgical process	Smelter capacity (metric tons of copper blister) 1975	1987
Outokumpu flash	NA	160,000
Inco flash	NA	288,000
Noranda modified	NA	210,000
Electric	336,000	112,000
Reverberatory		
Primary	1,444,500	386,000
Secondary	208,400	281,000
Total	1,988,900	1,437,600

Solvent Extraction-Electrowinning

Leaching of copper from waste dumps and low-grade ores has a long history that reaches back prior to the industrial revolution (Arbiter and Fletcher, 1994). Copper dissolves in weak acid solutions. For the first one-half of the 20th century, the common technique was to precipitate the copper from the leach solution by passing it over iron (usually scrap). The resulting impure copper precipitate, or cement, was then placed directly into the smelting furnaces; this was similar to the addition of scrap.

Ion-exchange research directed mainly toward recovery of uranium during World War II found an industrial application in the recovery of copper and other commodities from solution. In 1968, the first commercial application to recover copper from solutions by using SX-EW was implemented. Solvent extraction uses specially designed organic chemicals called extractants to concentrate the copper in the leach solutions. The result is a solution that can be directly placed into an electrowinning process, thereby completely bypassing pyrometallurgical processing. Copper from SX-EW operations has the same commercial purity as electrorefined copper. Figure 39 shows one portion of the process. SX-EW hydrometallurgical methods to produce copper have been implemented throughout the Southwestern United States where arid conditions (rainfall dilutes leaching solutions), oxide ores, and sulfuric acid from pyrometallurgical smelters are available. Chile and the southwest United States are the leaders in the use of this application.

Figure 39. Electrowinning tankhouse. Photograph courtesy of Bruce Richardson, Phelps Dodge Corporation, July 14, 2000.

The benefits of SX-EW include the potential for economic recovery of copper from low-grade oxide ores, thereby expanding the reserve base; reevaluation of mine plans and redirection of ores that had been processed through flotation concentrators to leaching, which raises mill-head grades and improved overall economics (Phelps Dodge’s Chino Mine in New Mexico is an example); new reserves in wastes, such as low-grade copper-oxide stocks and caved areas; and reduction of the overall cost of copper production, particularly when used in conjunction with conventional processing of sulfide ores.

Figure 40 shows the development of SX-EW copper production in the United States from 1968 through 1998. The increase of U.S. copper reserves to 42 Mt in 1993 from 36 Mt in 1989 was a benefit from commercial application of the technology (U.S. Bureau of Mines, 1933-96).

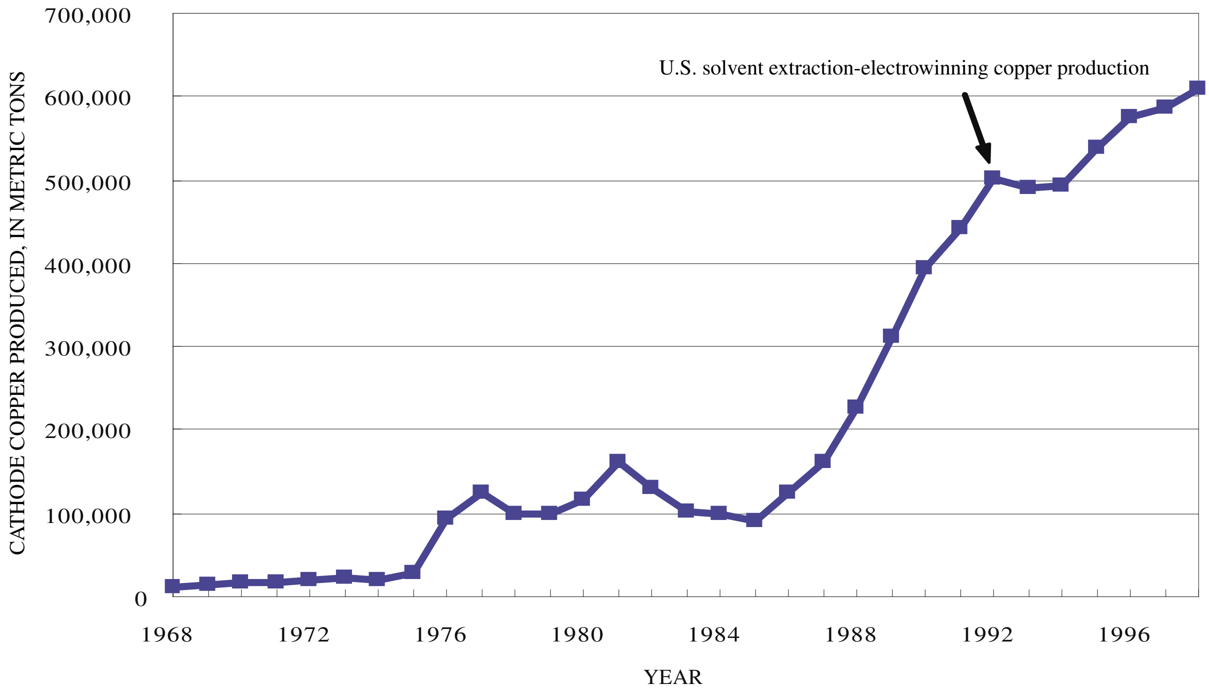

Figure 40. U.S. solvent extraction-electrowinning (SX-EW) copper production and copper industry labor productivity, 1968 to 1998. Sources: U.S. Bureau of Labor Statistics, 2000; U.S. Bureau of Mines, 1927-34, 1933-96; U.S. Geological Survey, 1901-27, 1997-2000.

Also shown in figure 40 is copper industry labor productivity for the same period. Note the trend with growth in SX-EW production for the periods from 1968 through 1982 and 1986 through 1998; this signifies incremental improvement, which was probably related to incremental improvements to the physical plant. The intervening years (1983-85) were very tumultuous with respect to industry-labor relations. The early 1980s have been characterized as follows: "real hourly wages in the mining and milling sectors, after rising persistently for more than three decades, plummeted by more than 25 percent between 1984 and 1989. This sharp reversal in the long-run upward trend in real wages was not easily achieved. Phelps Dodge confronted organized labor directly and suffered a long and bitter strike during 1983. It continued to produce during the strike, and ultimately union members who resisted [contract changes] were replaced. Kennecott shut down the Bingham Canyon mine in early 1985 after five years of consecutive losses and started a $400 million modernization program. The union agreed to a new contract in 1986 that gave the company much greater flexibility in work rules and staffing assignments as well as an average 25 percent cut in salary and benefits" (Simpson, 1999, p. 119-120).

In the early 1980s, labor productivity improvement appeared to have been more sensitive to management and labor negotiations than to the technology of new equipment, although the trend in productivity growth attributable to new equipment began increasing again after its implementation.

Research

The ultimate target of process research often is cost reduction even when other goals, such as environmental improvement, are involved. Cost reduction may be accomplished through achievement of higher metal quality (purity), improved efficiencies in separation of high-value from low-value materials, and reductions of inputs of energy, labor, and materials. One of the tools of research is model building. Improvements in computer power and calculation speed have been valuable for interpreting experimental data and in developing mathematical models capable of simulating metallurgical processes with useful accuracy (Themelis, 1994).

Important research is underway on the bioleaching of refractory sulfide ores. Such ores are resistant to leaching by regular inorganic chemical techniques, but certain bacteria tend to overcome this resistance. New developments in gene design could provide a new generation of highly efficient "bacterial miners." Other leaching agents, such as ammonia and chloride, have been used with only limited success.

In-situ leaching occurs when leaching solutions are pumped into a deposit in place to dissolve copper for later recovery by solvent extraction. A consortium of Government agencies and mining companies tested this technology. To date, it has not been used commercially. This technique, however, has future potential for low-cost copper recovery. In this process, copper-bearing solutions are recovered after leaching and pumped to a solvent extraction facility for processing. The technology avoids the high cost of mining, crushing, grinding, and pit reclamation. A major challenge has been to overcome solution loss and to protect ground water. The Pinto Valley Division of Broken Hill Proprietary Company Limited is recovering copper from in-situ leaching of the block-cave area of the old Miami Mine. This area contains 172 Mt of ore at a grade of 0.40 percent copper (Arizona Department of Mines and Mineral Resources, 2000, p. 3). In-situ leaching has the potential to improve resource recovery and expand reserves, but this potential is still unrealized.

Recycling

Scrap recycling, which includes the scrap industry organization, supporting infrastructure, and equipment selection and use, is considered to be a technology that decreases commodity scarcity by extracting and reusing commodities contained with obsolete products. For that reason, a brief description of old copper scrap recycling is included in this study. Old copper scrap is post-consumer scrap that comprises obsolete or discarded products. Figure 41 shows the history of old copper scrap use as a percentage of total U.S. apparent consumption of copper. Apparent consumption is defined as follows:

Apparent consumption = primary production + secondary production (recycling) + net imports + stock changes

As shown in figure 41, the level of recycling of old copper scrap grew to 30 percent of total U.S. copper apparent consumption in 1920 from 1 percent in 1906. Except for the period from 1929 to 1938 and post 1990, old copper scrap recycling has ranged mainly between 20 and 30 percent and has averaged about 23 percent of total U.S. apparent copper consumption. The market share of total U.S. copper consumption taken by recycled material has been slowly trending downwards since World War II. Since 1991, use of old copper scrap, as a percentage of apparent consumption, has decreased. Although this may be attributed to increasing copper consumption and longer lasting products, the principal reasons for this decrease are that domestic processing capacity has been eroding and that scrap exports have been increasing. Depressed copper scrap prices during the 1990s discouraged the collection and processing of scrap.

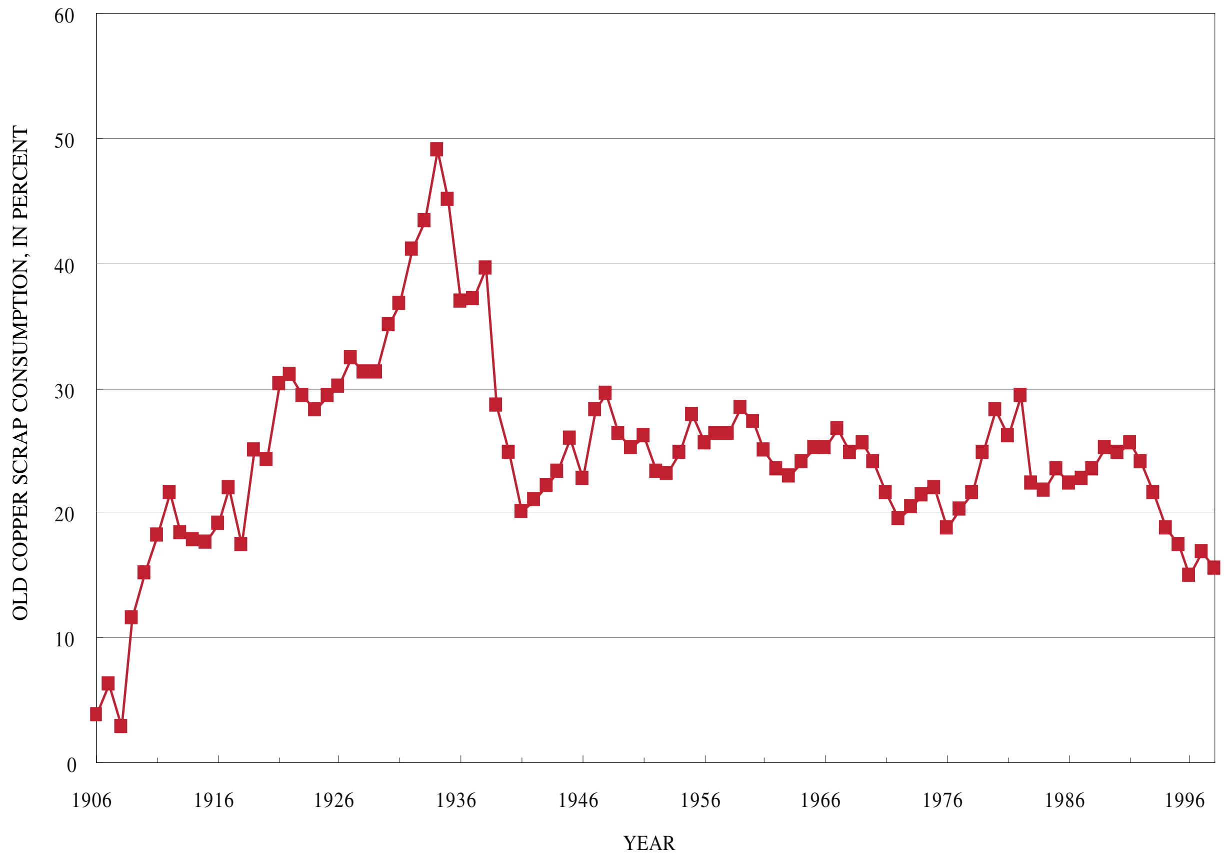

Figure 41. U.S. consumption of old scrap as a percentage of U.S. apparent consumption of copper, 1906 to 1998. Squares represent data for a specific year. Adapted from U.S. Bureau of Mines, 1927-34, 1933-96; U.S. Geological Survey, 1901-27, 1997-2000.

Summary

Experience indicates that human creativity, as applied to minerals, has had remarkable success in overcoming challenges to meet society's growing demands for more minerals at lower cost and with greater utility while reducing the environmental affects of mining and processing. In the case of copper, demand has increased dramatically. Supply has kept pace through technological changes and innovations that have increased efficiency, production, and the availability of economic resources.

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Appendix 4. Potash Case Study

Technology

Potash is one of the most essential nonmetallic minerals. "Potash ore" is a generic term that refers to a group of naturally occurring minerals that contain between 7 and 25 percent potassium, which is one of the three essential nutrients for plant growth; the others are nitrogen and phosphorous. These three elements are the chief components of agricultural fertilizers. Fertilization replaces soil nutrients that are taken up by plants. Although potassium has many industrial uses, more than 90 percent is used in agricultural fertilizers (Searls, 2000).

Early uses for potash were mostly for dyeing fabric and making baking soda, glass, saltpeter for gunpowder, and soap (Williams-Stroud and others, 1994, p. 783). Prior to the discovery of potash ore in the mid-1800s, manufacturers produced potash by burning hardwood trees and then gathering the ash and leaching out the salts contained in the ash. By evaporating the leachate in a pot, the water-soluble part of the ash that contained the potash was recovered in the bottom of the pot; hence the term "potash." Kelp (seaweed) also was an important source of potash. The first U.S. patent was issued by President George Washington in 1790, as head of the U.S. Patent Office, for an improvement in producing potash (Paynter, 1990). The process required 3 to 5 acres of timber to produce about 1 t of potash from wood ashes (IMC Global Incorporated, 1978).

Potash was America's first industrial chemical, and up until the 1860s, the United States was one of the leading producers in the world. Kelp and wood continued as part of the domestic supply chain of potassium into the 20th century. Demand surged in the 1840s when a German scientist discovered that potash was a vital soil nutrient for plant growth and could significantly increase crop yields By the end of the 19th century, saltpeter, which is a product that contains potassium, was used in explosives, fertilizers, fireworks, gunpowder, matches, and as a food preservative.

Today, most of the world's potash is recovered from salt deposits that formed from the natural evaporation of ancient lakes, oceans, and seas. The deposits are usually bedded and can be very extensive; in some cases, deposits several meters thick extend over hundreds of square kilometers. The geology of the deposits can be complicated because of folding and faulting. Understanding these geologic structures can be a major advantage in developing a mine. Technological challenges for mining these deposits can be significant when the deposits occur at great depths or are structurally complex. Potash also is extracted from salt brines in lakes and seas, sometimes in inhospitable environments like the Dead Sea, and in the harsh climate of the high deserts of Chile.

Potash ore was first discovered in Germany in 1857 while a shaft was being dug to mine salt beds. Initially, the potash beds were considered to be worthless and an obstruction to extracting edible rock salt (U.S. Bureau of Mines, 1927). After learning that potash could increase crop yields, additional shafts developed with potash as the primary target. Deposits in France were discovered in the early 1900s while drilling for coal and oil. These two countries supplied nearly the entire world's demand for potash; Germany met virtually all American needs until the beginning of World War

I when shipments stopped. At this time, potash attained its highest price because of severe supply shortages and high demand to support the manufacture of war material and increased war-related agricultural requirements. To meet high U.S. demand during World War I, potash was recovered from the evaporation of lake water in Nebraska and brines in California, supplemented by processing kelp harvested from beds on the Pacific Coast and high potassium feldspars in Utah (Gerard, 1917; Nebraska State Historical Society, 1999), and by its earliest industrial source, wood ash. Costs of production, of course, were much higher. The price of potash increased from about $1,700 per ton just prior to World War I to more than $10,000 per ton (1998 dollars) during the War. Potash resources available during this period expanded because of the high price and newly developed technologies that permitted potash to be recovered from diverse sources. In 1920, after the War ended, Germany once more was selling potash to the United States for about one-half the price of domestic product, and by the end of the year, all the Nebraska potash plants were closed (Nebraska State Historical Society, 1999). Many other domestic operations also closed at this time. During World War II, the price of potash did not react dramatically because of federally mandated price caps.

World potash production was approximately 100,000 t in 1920 and 25 Mt in 1998 (figure 42). The 250-fold increase in production resulted from technological improvements of bulk

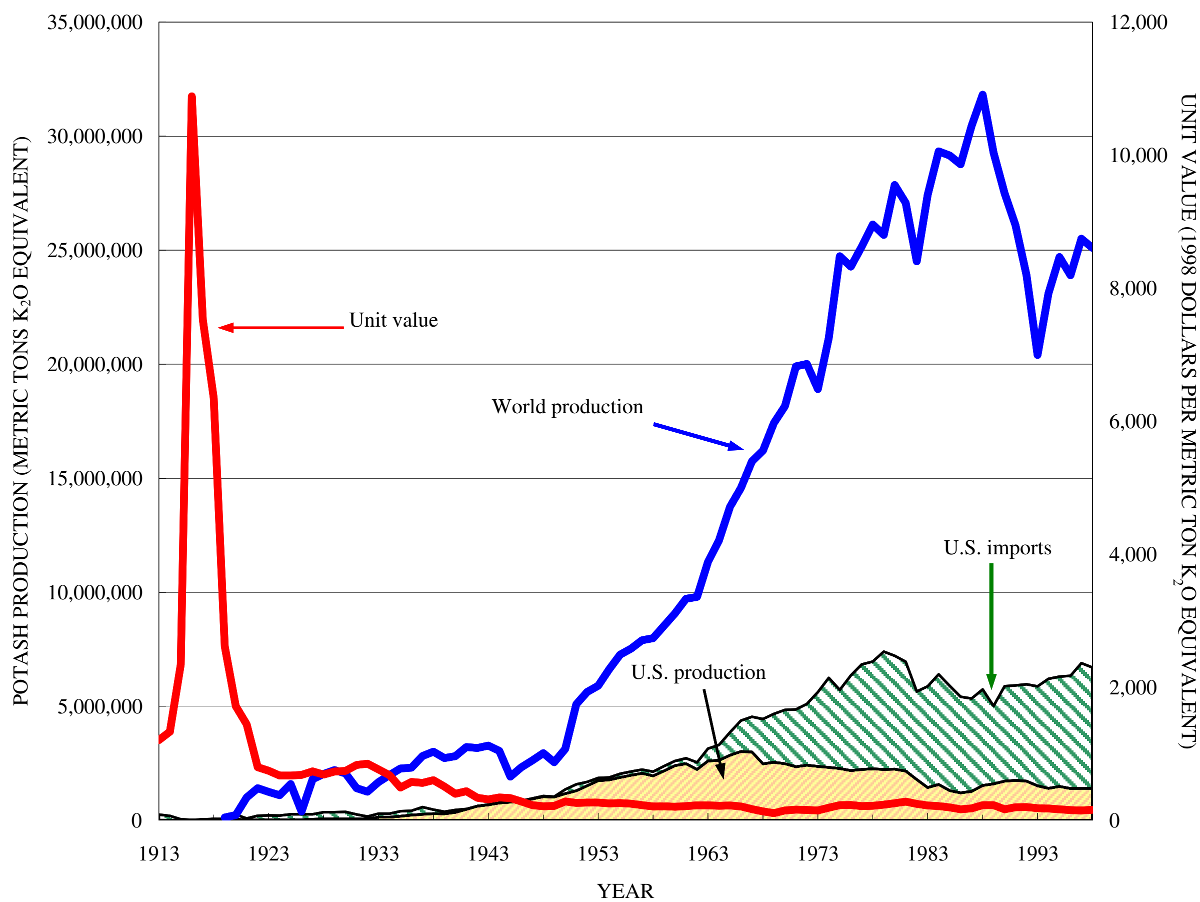

Figure 42. Potash production and unit value, 1913 to 1998 (Buckingham and Searls, 2002). The unit value (1998 dollars per metric ton) is defined as 1 metric ton of potash apparent consumption expressed in terms of potassium oxide (K_2O) equivalent. The consumer price index, with 1998 as the base year, is used to adjust unit value in current U.S. dollars to the unit value in constant 1998 U.S. dollars.

mining and research increasing potash's effectiveness at increasing crop yields at relatively low cost.

Because bedded potash salts occur in geologic environments that also commonly contain oil, the vast majority of the world's potash resources were discovered during petroleum exploration and development. In the late 1920s, oil exploration drilling in the Carlsbad area of New Mexico intersected large resources of high-grade bedded potash. In the early 1940s, one of the largest known potash deposits in the world (more than 5 billion metric tons) was encountered while drilling for oil at depths of between 1 and 2 km in Saskatchewan, Canada; this deposit was found to extend south into Montana and North Dakota (Natural Resources Canada, 1999).

Canadian and U.S. potash ores have considerably higher and more-consistent grades, expressed in terms of potassium oxide equivalent, than those found in Europe. Furthermore, the mineralogy and geologic structure are less complex than deposits in Europe. Canadian deposits are located in one of the largest agricultural areas in the world and are accessible by railroad networks that connect with the Great Lakes, the St. Lawrence Seaway, and Pacific Coast ports in Canada and the United States. Development of the Canadian potash mines in the early 1960s had a quick and profound impact on U.S. potash imports. In 1960, less than 1 percent of potash imported to the United States was from Canada, whereas about 40 percent was from France, and 30 percent, East and West Germany (Lewis and Tucker, 1961). By 1964, imports from Canada had increased to nearly 70 percent, and in the late-1990s, it approached 95 percent (Lewis, 1965; Searls, 2000).

During the past half-century, billions of metric tons of underground resources of potash have been discovered through the use of sophisticated geochemical, geological, and geophysical techniques. These deposits in Brazil, Canada, and Russia, as well as those discovered prior to this period, are large enough to supply the world's potash requirements for hundreds of years (Searls, 2000).

Between 1905 and 2002, apparent consumption of potash in the United States, which is expressed in metric tons of K_2O, increased from 117,000 t to more than 5 Mt. This increase reflects the material's use as a fertilizer in agriculture. In constant dollars, the unit value of potash in 2002 was less than 15 percent of the unit value in the early part of the 20th century. The unit value of the material trends generally downward as a result of the abundant reserves of potash; increased economies of scale in production, which are attributable to technological advances in mining and recovery methods; and efficient transportation of bulk materials (Buckingham and Searls, 2002).

Mining

Conventional Mining

Early potash mining activities in France and Germany depended on labor-intensive use of conventional pick and shovel methods in underground mines. The miners loaded the ore into trams, which were small rail-mounted wagons pushed by miners or pulled by draft animals. Ore was lifted to the surface by pulley systems operated manually or by steam engines. Open-pit potash mines are very rare because near-surface potash ores often have been dissolved by surface or ground water.

Over time, increasingly diverse and more highly mechanized mining and beneficiation methods to recover potash have resulted in very high productivity gains. An underground potash mine uses methods similar to those used in mining other bulk commodities, such as coal and salt. High productivity is necessary for profitability when a commodity such as potash has a low value-to-weight ratio. As in most mining operations, the mining methods used to recover potash are determined by sophisticated engineering studies. Selection of a method depends on depth; geologic complexities, such as faulting and folding, grade and type of ore, and thickness and type of the associated rocks; and thickness of the ore. Technologies in shaft sinking advanced with the invention of steam engines, allowing ore to be lifted to the surface by machine.

High productivity is necessary for profitability when a commodity has a low value-to-weight ratio.

Figure 43. Lanigan potash mine, Saskatchewan, Canada. Photograph courtesy of Potash Corporation of Saskatchewan Incorporated, 2000a.

The Lanigan Mine is more than 1,000 m below the Saskatchewan prairie (figure 43). It produces nearly 4 Mt/yr of potash (Potash Corporation of Saskatchewan Incorporated, 2000a). Development of the mine in the early 1950s presented major engineering challenges. Accessing the ore in Saskatchewan was delayed by nearly 10 years because the engineering technology was not available to develop shafts through water-saturated unconsolidated material under high pressure over a thousand meters below the surface without flooding the shaft or the developing mine. The first shaft, which was not built until 1962, was constructed by first freezing water in the saturated zones by drilling from the surface and circulating refrigerants. The frozen ground could then be bored. Once past these problem areas, cast iron, concrete, and other materials were placed in these zones to serve as barriers to prevent the incursion of water into the shafts (Schultz, 1973).

The mining method typically used in underground potash mines is called room and pillar. Large "rooms" are excavated and are supported by massive unmined areas called pillars. A room may be 18 to 23 m wide and as much as 1,000 m long. Potash beds require a large amount of support because of the structural incompetence of the rock and its tendency to undergo "plastic flow" under pressure. Generally, deeper mines have greater overlying pressures. When mining at great depths, the constant threats of flooding and roof collapse are carefully monitored. Mining potash beds results in an overall ore extraction rate of 90 percent if the mine is allowed to collapse under controlled conditions. Without use of complex engineering methods, extraction would be limited to perhaps 60 percent of the ore. Most underground potash mines are highly mechanized. Machines called continuous miners are capable of cutting a path into solid potash ore that measures up to 2.74 by 8.23 m, advancing at a rate of 30 centimeters per hour, and producing nearly 900 metric tons per hour of potash ore (figures 44-45).

Advances in technology always strive to conserve resources by maximizing efficiencies.

Continuous miners were initially used in U.S. coal mines in the late 1940s to increase productivity and mine safety but were quickly adapted for use in potash mining. Continuous miners can be designed to perform "realtime" sampling and measuring of ore grades to ensure

Figure 44. Continuous miner. This machine rotor cuts a circular profile to produce a width of 20 meters. Photograph courtesy of Mining Technology, Incorporated, 2000.

Figure 45. Continuous miner in action. Photograph courtesy of Cleveland Potash Ltd., 2000.

that the highest grade material is mined. This equipment also is designed to be operated by remote control for higher productivity and safety of miners. Ore is loaded onto conveyor belts attached to the back of each mining machine and is connected to a larger integrated conveyor belt system. This system transports ore to underground crushers and storage bins capable of holding tens of thousands of metric tons of ore. Ore is then supplied from the bins to the shaft where it is hoisted to the surface through the mineshaft at speeds of more than 1,100 meters per minute. Some potash mines in Canada have more than 57 km of conveyors and 4,000 km of tunnels (IMC Global Incorporated, 2000). In some mines, ore is brought to the surface by high-speed conveyor belts through inclined shafts.

Solution Mining

The technology that is being used to recover potash from brines by injecting water-based solutions through deep wells was adapted from the petroleum industry. The recovery of soluble materials from wells is not, however, a new mining method. As shown in figure 46, the Chinese performed solution mining for salt about 1,600 years ago. They drilled wells to depths that exceeded 100 m (National Geographic Magazine, 1944, p. 329; Adshead, 1991, p. 39). Chinese technology included drilling at least two holes—one to feed and flood freshwater from a nearby source into salt deposits and the other to allow the water to “well” up after dissolving the salt. Pumps that had leather flap valves and pipes made from bamboo were used to draw out the brine, which was placed in ponds where it could be concentrated by solar evaporation or in iron pans that were heated to concentrate the salts also by evaporation.

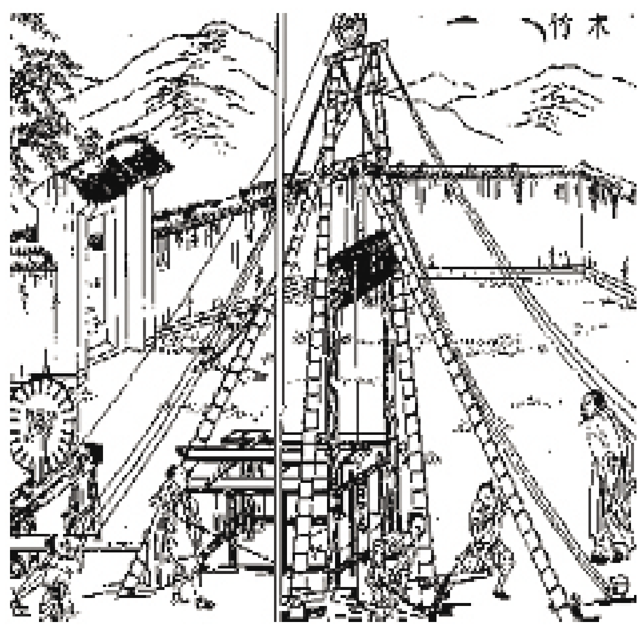

Figure 46. Salt drilling circa A.D. 400. Diagram courtesy of Salt Institute, 2000.

POTASH FROM SOLUTION MINING

The Patience Lake mine in Saskatchewan, Canada, has the capacity to produce more than 1 Mt/yr of potash from brines. The mine was converted from a conventional mine to a solution mine following accidental flooding by subsurface waters. Potash is dissolved by circulating heated brines throughout the flooded mine working at depths that exceed 1,000 m. The mine workings extend up to 18 km from the shaft (Potash Corporation of Saskatchewan Incorporated, 2000b).

Solution mining for potash is used when deposits are geologically too complex to mine profitably by using conventional underground mining techniques. This process also is used to recover the potash pillars at the end of a mine's life or when a mine is unintentionally flooded with water from underlying or overlying rock strata and conventional mining is no longer feasible. In solution mining of flooded mines, heated brines are injected by means of wells of up to several thousands of meters deep. The brines circulate throughout the flooded mine workings and dissolve the potash ore. The potassium-rich brine is pumped to the surface and placed in evaporation or crystallization ponds. As the liquid evaporates and cools, potash, sylvite, and other salt crystals form and settle to the bottom of the pond. The cooled brine is then reheated and reinjected into the mine to repeat the process. The potash crystals in the pond are pumped to a plant for further processing, sometimes by using a floating dredge (figure 47).

Figure 47. Floating dredge that recovers potash crystals from the bottom of a 53-hectare cooling pond at the Belle Plaine solution mine, Saskatchewan, Canada. Photograph courtesy of IMC Global Incorporated, 2000.

Solar Evaporation Mining

Potash and other salts have been recovered from saltwater since ancient times. Salt mining probably started when ponds of seawater evaporated naturally and left behind salts that could then be collected. Emulating this natural process, people built shallow ponds to collect seawater or lake water that contained a very high salt content and allowed it to evaporate. The first major potash recovery plant in which solar evaporation was used was initiated on the Dead Sea in Palestine in 1934. Current operations in which solar evaporation is used to recover potash are located in numerous locations, including Israel and Jordan on the Dead Sea, the high deserts in Chile, the Great Salt Lake in Utah.

At the Great Salt Lake, solar evaporation is used to concentrate the natural lake brine by pumping it through a series of shallow ponds that cover 86,000 hectares. Figure 48 shows a solar pond system at Ogden, Utah. As the water begins to evaporate, elements in the brine solution concentrate until minerals begin to form and settle out of the solution. During the summer, approximately 1.5 million liters per minute of water evaporates from the pond system. To achieve the same results by using coal as the heat source, roughly 6 Mt/yr of coal would be required.

Figure 48. Solar evaporation pond at Ogden, Utah. Photograph courtesy of IMC Global Incorporated, 2000.

The Dead Sea Works in Israel also uses solar energy to concentrate brines through evaporation and yields nearly 4 Mt/yr. The solar energy used at this operation is equivalent to about 10 Mt/yr of coal or 7 Mt/yr (54 million barrels) of oil (Bodenheimer and Zisner, 1998; Dead Sea Works Ltd., 2000). Following the precipitation of undesirable sodium chloride, or common salt, the solutions are pumped to other ponds where evaporation continues and further precipitation of salt takes place, primarily as carnallite, which is a mineral from which potash also is recovered. These salts are allowed to dry and are then harvested by using front-end loaders; trucks transport the salt to the processing plant. The process from this point is similar to that used in other potash mines. If the potassium content of the salts is above 10 percent, then they are transported directly to the plant where they are washed and sized, dried, and shipped. If the potassium content is below 10 percent, then the salt must first be processed through a flotation plant to separate the impurities that passed through the dissolution-recrystallization process. Some brine operations recover more than 3 Mt/yr of potash. Brine operations generally produce other products in addition to potash; for example bromine, chlorine, magnesium chloride, magnesium metal, sodium chloride, and sodium sulfate.

Processing

When the potash mining industry was in its infancy, in the mid-19th century, the ore was hand-sorted, crushed and ground, and sacked for shipment. In the 1920s, sacked potash ore was sent to chemical plants for further treatment to produce higher purity products, such as potassium chloride and potash fertilizer, by using methods similar to but less sophisticated than those used today. The German potash industry mined complex ores, which were difficult to process by using the relatively simple technologies of the 1920s. The French ores were simpler to treat and relied on a dissolution-recrystallization process, which is described later in this section.

Flotation of potash ore, which was a major technological advance that resulted in higher quality products and greater efficiency, was first used at the Carlsbad, New Mexico, potash operation in the early 1930s and gradually spread worldwide (Williams-Stroud and others, 1994, p. 796). The process, which was adapted from the copper industry, makes use of potash's chemical and physical properties to separate the desirable potash ore from undesirable materials, such as clays and other salts. Flotation of potash ores is described in more detail later in the "Flotation" section. This technology forms the foundation for the most commonly used treatment of potash ore.

In the 21st century, technologies previously unavailable are being used to ensure that potash specifications are constantly met at the lowest cost. Computers monitor all steps in the processing of potash ore. Ore is processed at the mine site with the goal of producing numerous high-grade potassium products, some of them through patented processes. A flow diagram of the entire processing sequence is shown in figure 49.

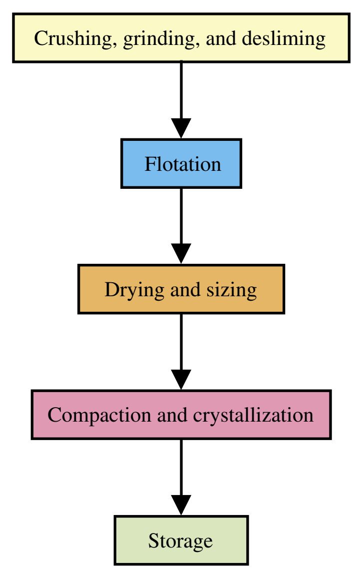

Figure 49. Typical potash mill process. Flow diagram courtesy of Potash Corporation of Saskatchewan Incorporated, 2000a.

The typical potash processing plant starts by crushing the ore and splitting it into individual particles of potash and salt each less than 0.95 centimeter (3/8 inch) in diameter. The crushed ore then is mixed with brine and pumped through 10-mesh screens, which are about the size of household window screens. Larger particles diverted by the screen go to the heavy-media separation stage. Smaller particles drop through the screens and are passed on to the flotation cells

Heavy Media

Some mining operations use a treatment process in which a mixture of larger particles of potash and salt derived from the crusher are mixed with brine and other materials. The specific gravity of this heavy-media solution allows potash to float to the surface and the salts and impurities to sink to the bottom. The high salt concentration of the brine also prevents potash and the other salts from dissolving. The coarse-sized particles of floating potash are then washed, debrined, dried, and prepared for storage and shipment. Because some particles, which are called middlings, are not separated in the heavy-media process, they are recrushed, screened, and directed to flotation. A detailed description of ore treatment is shown in figure 50.

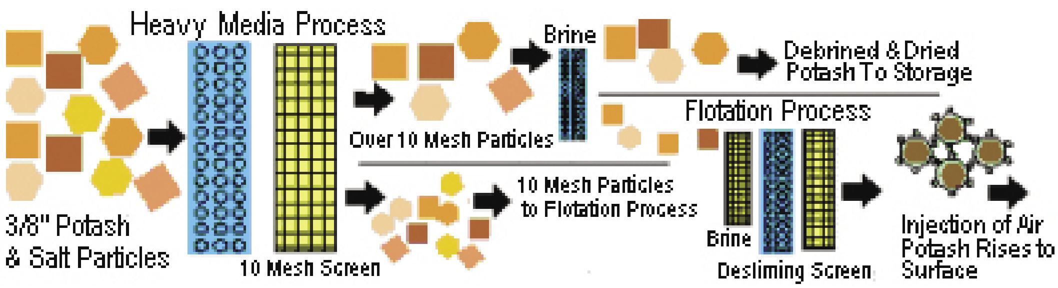

Figure 50. Potash processing sequence. Diagram courtesy of IMC Global Incorporated, 1978.

Flotation

Flotation is a process that separates materials based upon whether they are heavier or lighter than water. Insoluble materials and brine are first removed from the small particles of ore in a process called desliming. The ore is then conditioned with chemical reagents that are added to a brine solution to coat the potash particles. This slurry is pumped into flotation tanks, and air is injected into the mixture. The coated particles of potash cling to air bubbles and rise to the surface. The potash is skimmed off, debrined, and dried. The unaffected salts sink to the bottom. The potash recovered from flotation is the operation’s most important product and is called standard potash.

Crystallization

Potash dust, which is called fines, is recovered in dust collectors and treated as a separate product in the flotation process. The fines are dissolved in heated brine and recrystallized by cooling in three stages, which produces larger purer crystals of potash called white muriate. Next, the white muriate is debrined and dried and can be refined through recrystallization to a 99.9-percent-pure potassium chloride called potassium muriate, which is used in the fertilizer and chemical industry.

Dissolution-recrystallization was a major technological advancement in the recovery of potash and is used in numerous potash operations, which include underground, solution, and solar evaporation mines. Developed by the French in the early 1910s, the process treated potash ores that contained more impurities than the ores being processed by the German potash industry.

Compacting

Granular-grade potash is made by the high-pressure compaction of dry potash recovered from flotation into potash flakes. Flakes are then crushed and screened to the desired size.

Storage and Shipping

Some of the Canadian mines have large warehouses that can provide storage for approximately 1 Mt of potash products. This much potash would fill 12,000 rail cars extending 190 km. Most potash products undergo a special treatment to protect them during shipping. If a product is too dry, then it will tend to get dusty. If it is too damp, then it will tend to cake. To prevent dusting or caking, the product is sprayed with a mixture of amine and oil before loading. White muriate is treated only with amine; refined potassium chloride does not need treatment.

Recycling

Unlike most metals and many other materials, potash is not directly recycled except as animal waste used as a natural fertilizer. As a fertilizer and as a salt, potash is either absorbed by plants or dissipated into the environment. Dissipated potash is not commercially recoverable when used in these applications. An exception occurs when salts, including potash, are dissolved into solution and enter water systems that drain into bodies of water where mining operations recover salts through evaporation methods, such as at the Great Salt Lake in Utah.

Conclusions

Between 1905 and 1998, apparent consumption of potash in the United States, which is expressed in metric tons of K_2O, increased to more than 6.2 Mt from 117,100 t. This increase reflects the growing use of potash as a fertilizer. In constant dollars, the price of potash in the 1990s was less than 25 percent of the price in the 1930s. The price decreased as a result of the abundant supply of potash, which is attributable to the discovery and mining of huge, diverse potash deposits in numerous areas of the globe, technological advances in mining and recovery methods, and efficiencies gained over the years in transportation of bulk materials, especially by rail. Barring unforeseen events, abundant potash at low prices should continue for the foreseeable future.

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Appendix 5. Sulfur Case Study

Production History

Sulfur, which also is known as brimstone ("the stone that burns"), has been used in small quantities for thousands of years. Early humans used sulfur as a colorant for cave drawings, as a fumigant, in medicine, and as incense. By 2000 B.C., the Egyptians began using sulfur in the bleaching of linen textiles. Homer referred to its use as a fumigant in *The Odyssey*. In the 5th century B.C. during the Peloponnesian War, the Greeks used burning sulfur and pitch to produce suffocating gases. The Romans combined brimstone with pitch, tar, and other combustible materials to produce the first incendiary weapons. Through the use of alchemy during the Golden Age of Arabic Science about A.D. 700, Arabs were probably the first to produce sulfuric acid. Sulfur is a necessary ingredient in gunpowder, which was developed in China in the 10th century. Gunpowder's introduction into Europe led to its use in warfare in the 14th century and that made sulfur an important mineral commodity for the first time (U.S. Bureau of Mines, 1985, p. 783).

However, not until the birth of the science of chemistry in the 1700s and the growth of chemical industries in the 1800s did sulfur become of major significance to the world. Early chemists soon recognized the importance of sulfuric acid as the cheapest and most versatile of mineral acids, and it rapidly became one of the most common acids in the chemical industry (U.S. Bureau of Mines, 1985, p. 783).

World sulfur production in 1930 was about 6.4 Mt (figure 51). By 1963, world

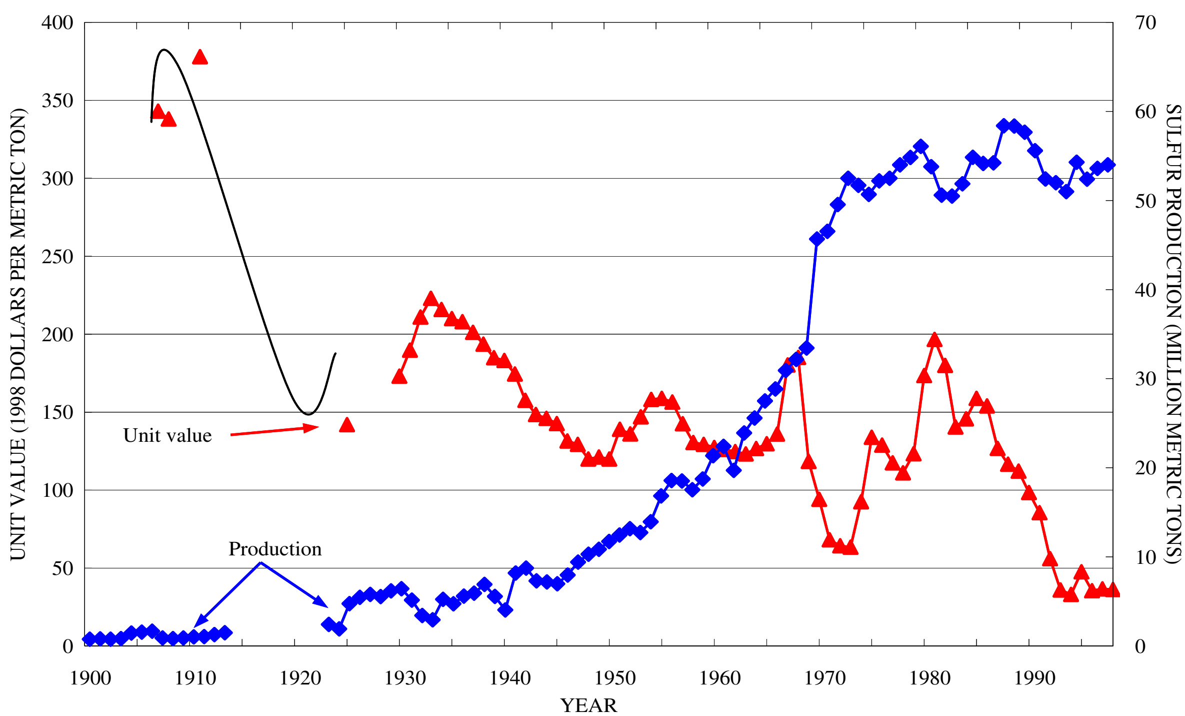

Figure 51. World sulfur production and unit values, 1900 to 1998 (Buckingham and Ober, 2002). Unit value is defined as the value (1998 dollars per metric ton) of 1 metric ton of sulfur apparent consumption. Data for 1900 to 1908 are estimated using the sulfur production unit value. Data from 1909 to 2000 are estimated using the sulfur shipments unit value. The Consumper Price Index, with 1998 as the base year, is used to adjust unit value in current U.S. dollars to the unit value in constant 1998 U.S. dollars.

production of sulfur had quadrupled. The greatest production growth was between 1963 (24.9 Mt) and 1973 (52.5 Mt). This growth resulted from accelerated demand and production of phosphate fertilizers, which used about 60 percent of the sulfur production, and large quantities of sulfur produced as a byproduct from newly discovered Canadian natural gas.

Since 1977, however, world sulfur production has averaged about 54.0 Mt (Buckingham and Ober, 2002). Between 1984 and 1996, sulfur production in some countries shifted from discretionary to nondiscretionary (mandated) sources, and world production outpaced increasing demand. Overall, between 1920 and 1998, the constant-dollar (1998) unit value for sulfur was decreasing. Government price controls for sulfur existed during World War II and the Korean conflict. The main uses for sulfur in 1999 were phosphate fertilizer production, 69 percent; petroleum alkylation (the conversion of one kind of hydrocarbon into another); catalysis, 16 percent; metals industry processes (leaching and pickling), 7 percent; chemicals, 4 percent; and other uses, 4 percent (Ober, 2000).

Sulfur is produced under market conditions and because of regulatory mandates.

Technology

Figure 52 shows the components of U.S. sulfur production from 1904 to 1998. The Frasch process was developed to take advantage of a very special set of geological circumstances that pertained to deposits in the Gulf of Mexico. This process, the use of which grew steadily from 1904 to 1975, was the principal source of U.S. sulfur until 1982 when processes that rely on recovery of sulfur from oil and gas processing started to take substantial market shares.

Around 1950, the Claus process was first used to recover sulfur from oil and gas. This

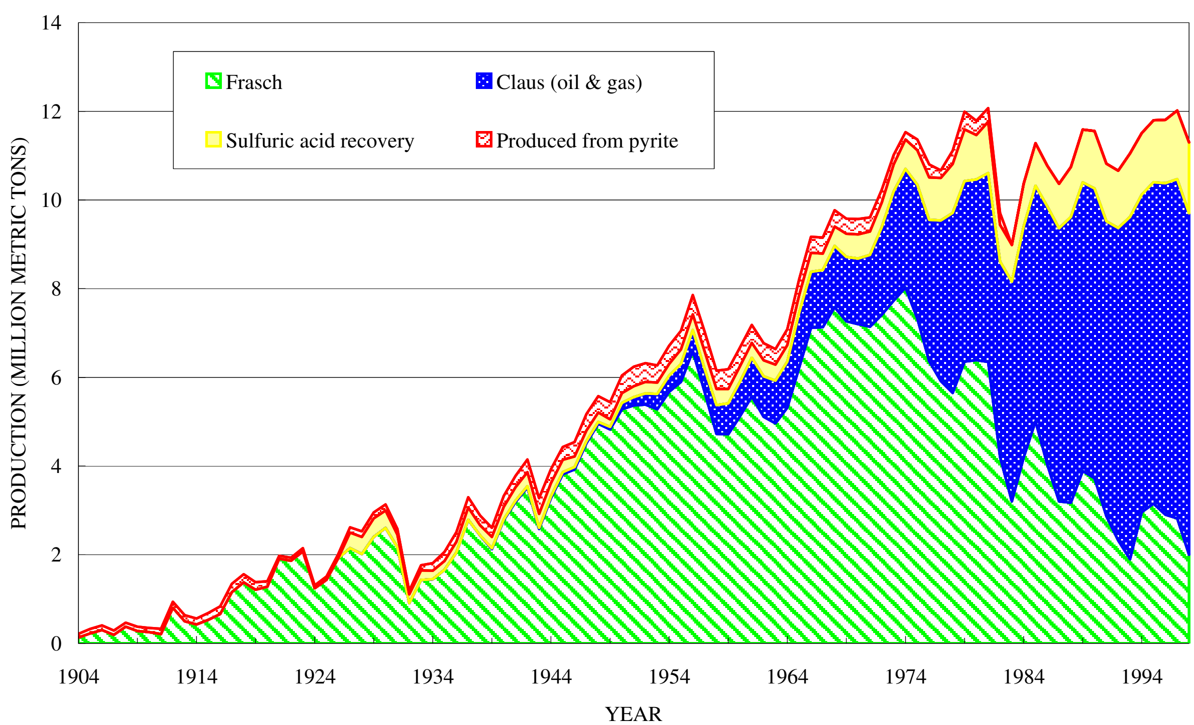

Figure 52. U.S. sulfur production by source, 1904 to 1998. Data adapted from U.S. Bureau of Mines, 1927-34, 1933-96; U.S. Geological Survey, 1901-27, 1997-2000.

process, which produces elemental sulfur from hydrogen sulfide, was added to the oil refinery infrastructure to recover sulfur from hydrogen sulfide separated during the refining process. This process became attractive for several reasons—hydrogen sulfide is an odorous toxic substance with which incidental human contact should be limited; if left in the refining operation, hydrogen sulfide causes corrosion and caking and produces foul-smelling products; increasing fuel consumption increased the need for lower sulfur levels in the final product; and the alkylation process, which is used to refine high-octane, clean-burning fuel additives, required the use of sulfuric acid as a catalyst.

From 1950 to 1975, the amount of sulfur recovered from oil refining grew steadily. Since 1975, higher growth rates for sulfur recovery from petroleum refining can be attributed to two factors. First, sulfur dioxide emissions limits specified in the Clean Air Act of 1970 drove producers to strip the sulfur from fuel before combustion. In 1997, sulfur from nondiscretionary sources represented more than 80 percent of the sulfur produced in all forms worldwide (Ober, 1998). This was a less costly approach than collecting sulfur combustion products after the fuel was burned. Second, the United States became more dependent on oil imported from abroad and from Alaska. These new sources of oil had higher concentrations of sulfur than oil recovered from wells in the contiguous 48 States. Sulfur recovered from metallurgical processes, natural gas production, and oil refining has come to dominate U.S. sulfur production.

Figure 53 shows how world sulfur recovery from industrial processes has grown through the 1990s, and how the sources of recovery sulfur have contributed relative to each other. Natural gas is the dominant source of recovered sulfur worldwide. The expansion of the "undifferentiated" portion of the area chart for 1994 and 1995 is an artifact of data reporting

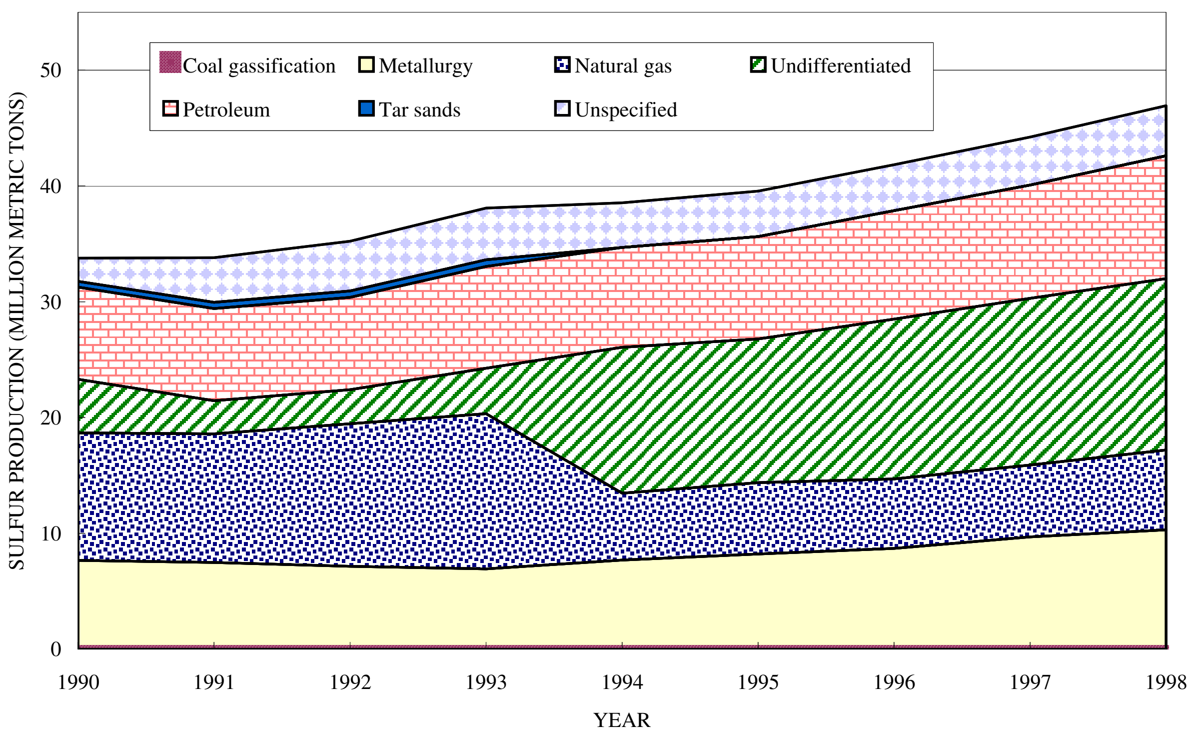

Figure 53. World sulfur production recovered from industrial processes, 1990 to 1998 (U.S. Bureau of Mines, 1933-96; U.S. Geological Survey, 1997-2000). Sulfur production from coal gasification during this period amounted to just 2,000 metric tons, which is too small a quantity to show up on this figure.

for that period. The most likely assumption is that sulfur generated from natural gas grew at a constant rate through that period.

Recovery of sulfur and some byproduct iron from the mineral pyrite, which has always been small, ended in the 1980s because of the depletion of economically minable pyrite deposits.

Production Technologies

Except for the Frasch process, which is unique to sulfur recovery, the technologies for production of discretionary sulfur from native sulfur and sulfide mineral deposits are common mining practices. The technologies for sulfur recovery, which include those for nondiscretionary recovery of sulfur during processing of other materials, are explained below. Each technology has a history of its own. Although this story of technological advance shows some breakthroughs, the pattern of technological development is more about continuous incremental improvement.

Frasch Technology

Frasch mining, which was developed by Herman Frasch in 1894, is an in-situ melting process for extracting sulfur from native sulfur-bearing limestone that caps salt domes found under the waters of the Gulf of Mexico (figure 54). The Frasch process produces elemental sulfur from these deposits by using superheated water to melt the solid sulfur. Once melted, the molten sulfur is driven to the surface with compressed air. Air and water are pumped into the borehole through a system of concentric pipes. The molten sulfur is heavier than the water and accumulates in a pool at the bottom of each well. The compressed air that is then injected into each well forms sulfur foam, which is propelled under pressure to the surface. At the surface, the sulfur foam is de-aerated and treated with a mixture of sulfuric acid and diatomaceous earth, which comprises the siliceous shells of algae; the diatomaceous earth removes organic impurities (Buckingham, 1991, p. 11). The molten sulfur is then delivered to vats to solidify. In this way, blocks of pure sulfur, which can weigh more than 1 t, are obtained (Sander and others, 1984. p. 173).

Figure 54. Main Pass Mine. It is the largest Frasch sulfur mine in the world and the largest structure in the Gulf of Mexico. Photograph courtesy of Freeport-McMoRan Sulphur Incorporated, August 17, 2000.

Native Sulfur and Pyrite Recovery Technologies

Elemental sulfur deposits not amenable to the Frasch process [and pyrite deposits] use open pit and underground mining methods. High- to medium-grade ore from these deposits can be roasted directly and the resulting sulfur dioxide gas is converted to sulfuric acid. Low-grade ores are treated by a variety of processes, which include agglomeration, direct melting, distillation, flotation, and solvent extraction to produce elemental sulfur (Buckingham, 1991,

p. 11). These methods generally are more costly than the Frasch process, they have difficulty competing with nondiscretionary production.

Technology for Recovering Sulfur From Hydrogen Sulfide

Average crude oil contains about 84 percent carbon, 14 percent hydrogen, 1 to 3 percent sulfur, and less than 1 percent each of metals, nitrogen, oxygen, and salts. Crude oils that contain appreciable quantities of hydrogen sulfide or other reactive sulfur compounds are called sour. Those with less sulfur are called sweet (Occupational Safety and Health Administration, 2000). Hydrogen sulfide is a highly toxic gas that is also a primary contributor to corrosion in refinery processing units (Occupational Safety and Health Administration, 2000).

The process of hydrodesulfurization in petroleum refineries uses a fixed-bed catalytic reactor to convert the nitrogen and sulfur compounds in the crude oil to ammonia and hydrogen sulfide (figure 55; Occupational Safety and Health Administration, 2000). The hydrogen sulfide is then recovered by converting it to elemental sulfur. The most widely used recovery system is the Claus process, which uses catalytic-conversion and thermal reactions. Typically, the process produces elemental sulfur by burning hydrogen sulfide in the presence of a catalyst and recovering the sulfur from the resulting vapor as a condensate (Occupational Safety and Health Administration, 2000).

Figure 55. Hydrogen sulfide stripping plant. Photograph used with permission of Gas Technology Institute.

Hydrodesulfurization was introduced to petroleum refining in 1954 (Occupational Safety and Health Administration, 2000). In 1970, with a push from environmental legislation and consequent regulations, this sulfur source came to dominate sulfur production, mostly at the expense of Frasch production of native sulfur and pyrite processing of sulfide ores.

Technology for Recovering Sulfur From Sulfur Dioxide Gas

The technology of choice for capturing sulfur dioxide depends upon the concentration of sulfur dioxide in the gas stream. When the concentration is low, as it is in the gas streams from electric utilities that burn sulfur-bearing coal to produce steam to generate electricity, the technology of choice is the wet scrubber. The scrubber product is a solid compound of calcium from added lime or limestone with sulfur and oxygen. With additional processing, some of this material can be made suitable as a substitute for natural gypsum.

The treatment of hydrogen sulfide and pyrometallurgical processing of metal sulfide ores generate highly concentrated sulfur dioxide gas. These sulfur resources are ideal for production of sulfuric acid, which is often used in other processes in the same plant that made the acid. For example, copper producers use sulfuric acid as a leachate in the solvent extraction process that recovers copper from very low-grade ores, and petroleum refiners use the acid for their alkylation processes. These uses are examples of sustainable industrial metabolism. In other words, wastes are consumed within the system in which they are generated. New research into biodesulfurization, which uses bacteria to reduce sulfates to sulfur, holds the promise of reducing costs of sulfur recovery processes (Monticello, 1998).

Summary

Experience indicates that human ingenuity as applied to minerals has had remarkable success in extracting elements from the Earth. In the case of sulfur, demand has increased steadily, but the price trend has been relatively flat since 1970. Technological change increased production and the number of production sources. Consequently, there is no foreseeable shortage of sulfur for the world economy. Sulfur supplies probably will continue to increase as the worldwide effort to control sulfur emissions continues to expand.

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