U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Technological Advancement – A Factor in Increasing Resource Use

Open File Report 01-197

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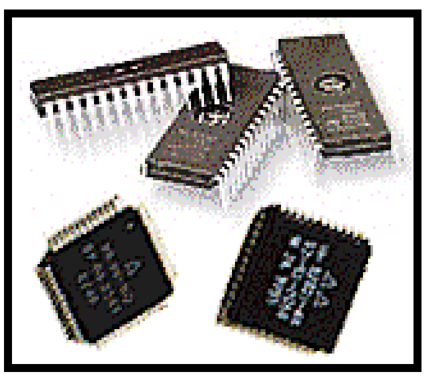

Part of a U.S. Geological Survey Circular titled "The Meaning of Scarcity in the 21st Century"

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On the cover:

Photograph of an open-pit mine in the Sonoran Desert near Ajo, Arizona.

(Courtesy of ASARCO, Inc.)

Photograph of Amarillo copper refinery. (Courtesy of ASARCO, Inc.)

Photograph of computer chips. (Courtesy of Tech-Recycling)

Photograph of scrap metal to be sorted and recycled. (Courtesy of TVI Metal Recycling)

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ABSTRACT

The specter of mineral resource scarcity has been repeatedly raised as a concern because ever-growing populations with seemingly insatiable appetites for minerals place claims against a finite resource endowment. This report analyzes how technology has helped to ease resource constraints, and uses case studies of aluminum, copper, potash, and sulfur minerals to identify the effects of technology on resource supply.

In spite of heightened demand for and increased loss of resources to environmental policy and urbanization, mineral producers historically have been able to continually expand production and lower costs. Specific production increases for the years 1900–98 were: aluminum (3,250 percent), copper (2,465 percent), potash (3,770 percent), and sulfur (6,000 percent). For the same period, constant-dollar (1998) prices decreased: aluminum (90 percent), copper (75 percent), potash (94 percent), and sulfur (89 percent).

The application of technology has made available mineral deposits that were previously overlooked or considered non-viable. Using technology, producers can meet the demand for stronger, energy-efficient, more environmentally safe products with less physical material. Technologies have been developed to increase the amount of materials recycled and remanufactured. Technology development can occur in breakthroughs, but most often advances incrementally. Technological development is driven by the profit motive.

3.1 INTRODUCTION TO THE SERIES

The potential for future mineral scarcity is an important concern of environmental activists, those desiring to limit population growth, and those concerned with wealth distribution between industrialized and developing countries. Through the years, observers from Thomas Malthus (1798) to the 1972 Club of Rome report, (Meadows and others, 1972), for example**,** predicted exhaustion of resources at various dates, most of which have come and gone without the dire consequences of societal collapse they envisioned.

Their predictions, however, continue to resonate with many who believe that mineral production cannot meet the material aspirations of a rapidly growing world population if consumption continues to increase. The perception of future scarcity, for example, motivated the Factor Ten Club, a group of resource economists, to issue the Carnoules Declarations (1994). The Declarations called for a swift 10-fold increase in material efficiency among industrialized countries to free materials for people in developing countries.

The concerns of future scarcity may in part be caused by misinterpretation and (or) the misuse of published mineral reserve estimates for nonfuel mineral commodities. A reserve is that part of an in-place demonstrated resource that can be economically extracted or produced at the time of estimation (U.S. Geological Survey, 2000, p. 196). Some misinterpret the term “reserve” as an estimate of all-that-is-left.

Mineral supply is not just a matter of physical existence of materials. It is also a function of demand generated by the price people are willing to pay, investment in exploration, mining-related facilities and infrastructure, technological innovations, employment practices, government policies, environmental conditions, and societal interests.

In fact, many of the minerals that the Earth's population demands exist in nearly inexhaustible amounts. Additionally, there is an enormous stock of resources in materials in-use (machinery, buildings, and roads) and in unutilized waste (landfills). There is, however, a growing understanding that physical scarcity is not the only, or even the most, important issue. Our industrial activities extract and transform resources into products people use. In many cases, these activities come with direct or accumulative environmental consequences that can pose serious threats to ecosystems and human health. Thus, the important issue of scarcity may be the capacity of Earth's geologic, hydrologic, and atmospheric systems to assimilate the wastes (Tilton, 1996).

This series, "Scarcity in the 21st Century", addresses resource constraints and opportunities, and the effects of their interactions on resource supply. Assessing potential supply requires a whole systems approach, both in physical terms by looking at the flows of materials through the economy, and in human terms by integrating the interactive domains of economics, environment, policy, technology, and societal values.

In 1929, D.F. Hewett, of the United States Geological Survey (USGS), reflecting on the effects of war on metal production, identified four factors he deemed most important in influencing metal production (Hewett, 1929).

1. Geology

> "First, there are the geological factors, which are concerned with the minerals present; their number and kind, which determine whether the problem of recovery is simple or complex; the degree of their concentration or dissemination; their border relations; the shape and extent of the recognizable masses."

2. Technology

> "Second, there are the technical factors of mining, treatment and refining. A review of these leaves a vivid impression of the labor involved in their improvement but they necessarily yield cumulative benefits."

3. Economics

> "The third group of factors that affects rates of production are economic, and among these factors cost and selling price are outstanding... Since 1800 the trend of prices for the common metals, measured not only by monetary units but by the cost in human effort, has been almost steadily downward…"

4. Politics

> "The fourth group of factors that affect metal-production curves are political or lie between politics and economics."

The four factors do not operate separately, but rather as parts of an integrated system, which also includes social constraints and drivers such as environmental issues and the structure of the mining industry.

"Scarcity in the 21st Century" is composed of six chapters to be published in a series of USGS Open File Reports and then compiled as a USGS Circular.

Chapter 1: "The Supply of Materials" examines the physical supply of minerals on the planet, in the ground and products-in-use, waste streams, and waste deposits (landfills). Current and future potential for recycling of products-in-use and landfill materials are examined.

Chapter 2: "Economic Drivers of Mineral Supply" explores price, investment, costs, and productivity, and their relevance to supply.

Chapter 3: "Technological Advancements – A Factor in Increasing Resource Use" investigates the impact of technological change on mineral extraction, processing, use and substitution.

Chapter 4: "Social Constraints and Encouragement to Mineral Supply" addresses social realities that affect mineral supply, nationally and globally, and the socio-cultural trends that promise to have an impact on future supplies.

Chapter 5: "Policy Drivers of Mineral Supply" examines the effect of government policies including regulations, rents and royalties, subsidies, and taxes. This volume also discusses the affects of corporate policies on mineral supply.

Chapter 6: “Overview of Minerals Supply” presents an overall view of these parameters of supply to show their synergy in supply and ultimately production.

Each chapter contains case studies on four mineral commodities (aluminum, copper, potash, and sulfur) to illustrate the concepts. In addition, the series includes an electronic database developed for this series and containing information on the major mineral commodities.

3.2 INTRODUCTION TO THIS VOLUME

Necessity (human needs and wants) is the mother of invention (technology). The Earth is made up of chemical elements, all of which exist in fixed amounts. However, it is not the elements themselves that are the object of human affection, but rather it is the properties that these elements possess (either alone or in partnership with other elements) that humans seek. In this context, resources are anything that provide these useful properties. To this point, humanity has not yet exhausted any of these resources, yet concerns have been voiced about the prospect of running out of such resources.

> **"Necessity is the mother of invention, it is true – but its father is creativity, and knowledge is the midwife"**
> **Jonathan Schattke – an American inventor**

(Cyber Nation International Inc., 2001)

Technology represents ways that humans apply human ingenuity, knowledge, and experience to organize capital, energy, and materials to get what they want and need. It is 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. If human action with respect to nonfuel mineral resources is characterized by simply changing the form of resources through separation and re-arrangement to maximize their utility, then it should be clear that the total available resource should consist of both in-situ (not yet extracted) materials and of in-use materials (manufactured stocks-in-use, emissions, or disposable wastes). It is likely that future needs can be met by continually rearranging resources in all these forms, such that resources are not permanently destroyed.

Human material needs and wants → Technology

In a market system, higher prices, or expectations of higher prices attributable to factors such as relative scarcity, increasing production costs, or increasing demand, provide an incentive for humans to find ways to offset the higher prices by relieving the underlying causes. In short, the very mechanism (higher prices) that signals a resource challenge helps to stimulate efforts to develop technologies to meet the challenge. Because of its high value (a measure of usefulness or desire), gold 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. Likewise, constant prices would demonstrate that technological advance has kept pace with the challenges, and decreasing prices would indicate that technology has been more than sufficient to overcome obstacles to supply.

Figure 1 shows the increase in apparent U.S. consumption during the 20th century for 86 significant minerals. Figure 2 shows the U.S. mine production composite price index using 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, sand and gravel). During 1997, these commodities accounted for 89 percent of metal mine production and 86 percent of industrial mineral mine production. The advancement of technology is a principal reason that these trends are not contradictory.

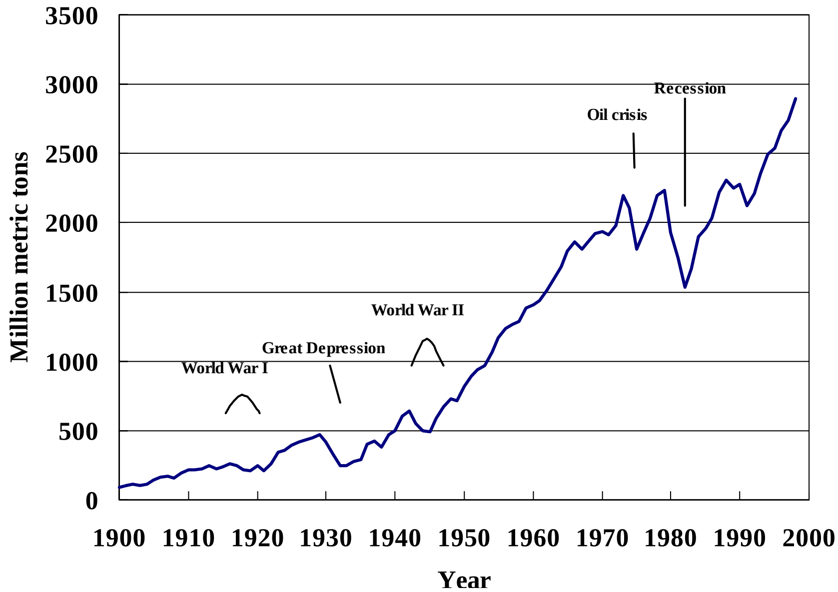

Figure 1. U.S. apparent consumption of minerals, 1900 to 1998.
Source: Sullivan and others, 2000

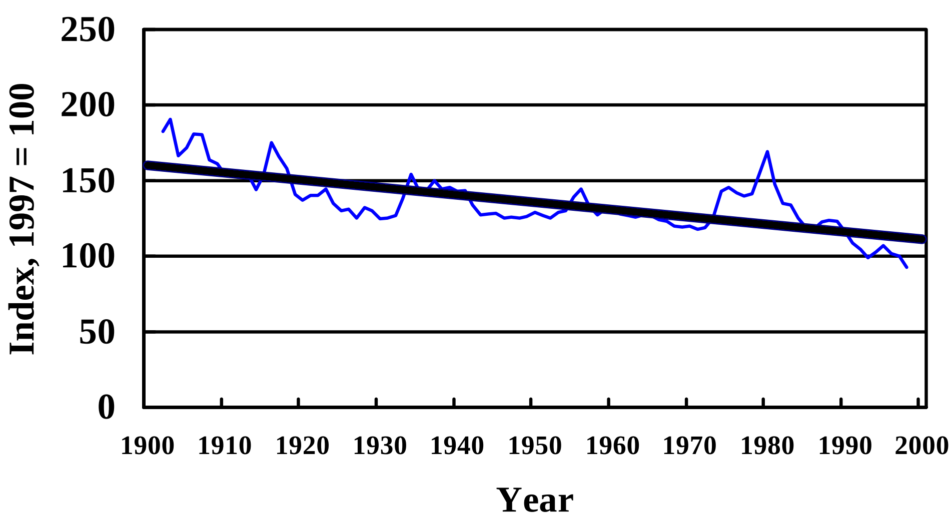

Figure 2. Composite mineral price index for 12 selected minerals, 1900 to 1998, in constant 1997 dollars. Selected mineral commodities include 5 metals (copper, gold, iron ore, lead, and zinc) and 7 industrial mineral commodities (cement, clay, crushed stone, lime, phosphate rock, salt, and sand and gravel). Source: Sullivan and others, 2000.

This study examines the history of technology as it pertains to the availability and pricing of mineral resources in general, and specifically reviews the histories of four commodities, aluminum, copper, potash, and sulfur in Appendices 2-5, respectively, to provide detailed examples of how technology has historically been able to respond to industry needs.

3.3 RELATION BETWEEN TECHNOLOGY AND MINERAL SUPPLY

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

Technology is the science of applying knowledge to practical purpose. Through an ongoing process of discovery and knowledge-building, humanity applies technological knowledge to best meet the needs of individuals, industries, or society, whether to fulfill a human desire, provide financial profit to an industry, or improve societal conditions. Technology changes as human needs and wants change in response to increased knowledge and the shifting priorities from political, social, or economic conditions. It is built upon accumulated knowledge about how best to organize capital, labor, energy, material, and information resources.

Several common themes emerge from the four appended mineral commodity case studies. Natural resource industries, despite their long histories, have managed to maintain a high level of technological sophistication through continued, incremental innovation and restructuring. These industries have made use of technological innovations from both within and outside their industry. Innovations generally do not occur in isolation, they build upon one another.

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.

Successful natural resource producers have accommodated increased concerns for worker health and safety and environmental protection and yet remain cost competitive. Statistical data collected by the U.S. Geological Survey suggests that over the past 100 years, world production of nonfuel minerals has managed to meet increased demand at lower 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 B - E and illustrate this point.

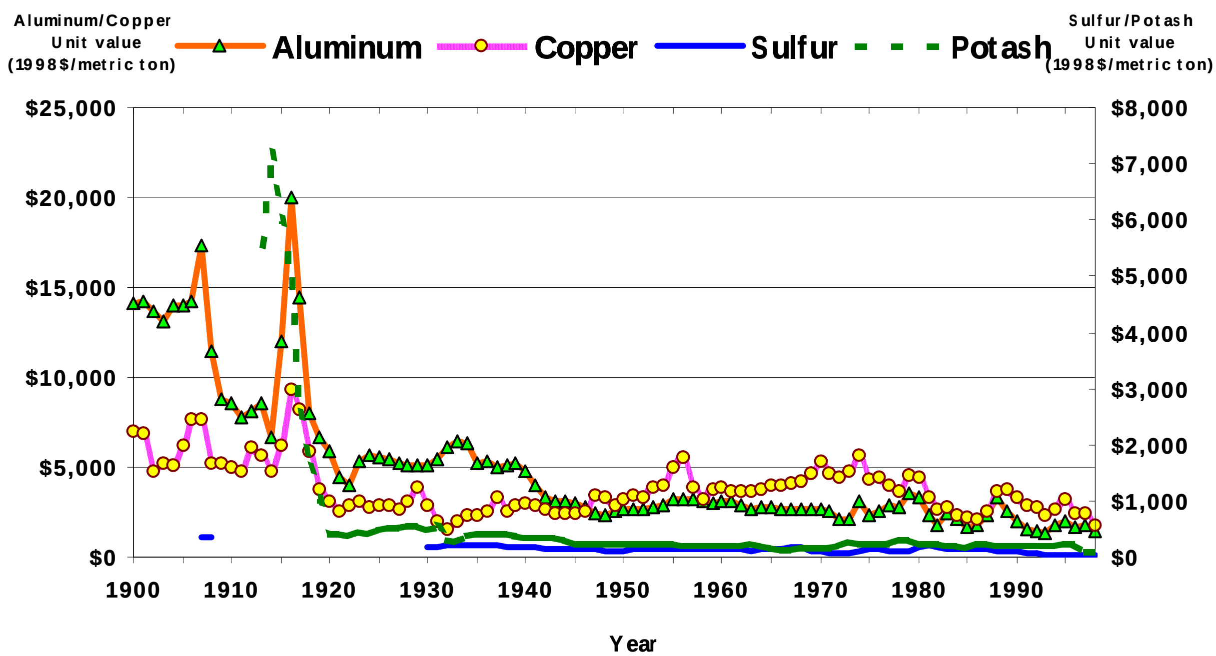

Figure 3. Prices for selected minerals, 1900 to 1998. Data from U.S. Geological Survey, 1999a.

Commodity	Period	Increase in production (percent)	Decrease in constant dollar price (percent)
Aluminum	1900 - 98	3,250	89.7
Copper	1900 - 98	2,465	75.0
Potash	1919 - 98	3,770	93.9
Sulfur	1907 - 98	6,000	89.4

Table 1. Twentieth century world production and price relationships for aluminum, copper, potash, and sulfur.

Sources: U.S. Bureau of Mines, 1927-34, Mineral Resources of the United States, 1924-31; U.S. Bureau of Mines, 1933-96, Minerals Yearbook, 1932-94; U.S. Geological Survey, 1901-27, Mineral Resources of the United States, 1900-23; U.S. Geological Survey, 1997-2000, Minerals Yearbook, v. 1, 1995-1998; U.S. Geological Survey, 1999a, selected pages.

Since 1900, world copper metal production has increased by 2,465 percent, but the copper price has decreased in constant dollar terms by 75.0 percent. World aluminum production increased by 3,250 percent while its price has decreased 89.7 percent. A similar trend is apparent for industrial minerals. For example, sulfur production since 1907 has increased 6,000 percent while sulfur price has decreased 89.4 percent. Potash production since 1919 has increased 3,770 percent, but potash price has decreased 93.9 percent (U.S. Bureau of Mines, 1927-34, Mineral Resources of the United States, 1924-31; U.S. Bureau of Mines, 1933-96, Minerals Yearbook, 1932-94; U.S. Geological Survey, 1901-27, Mineral Resources of the United States, 1900-23; U.S. Geological Survey, 1997-2000, Minerals Yearbook, v. 1, 1995-1998). Advances in technology played a significant part in these trends.

While social pressures or circumstances, such as environmental regulation or localized resource shortages, may initiate technological change, innovations tend to generate additional 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, it’s owners have an incentive to perpetuate the industry. They do so by investing in technology to either assure or expand their product markets to enhance revenue or by investing in technologies to reduce production costs. For example, international competition drove the U.S. copper industry to adopt cost reducing strategies, many of which were related to technology. This is discussed in detail in Appendix 3.

Technological innovations and their applications are difficult to predict. Advances over the last 50 years using materials such 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 magazine wrote that the Electronic Numerical Integrator and Calculator (ENIAC), the most sophisticated computer of the day, required 18,000 vacuum tubes and weighed 30 tons. The magazine predicted that computers in the future might require only 1,000 tubes and weigh only one and a half tons (Los Alamos National Laboratory, 2001). The computer power that was in those 30 tons can now fit in the modern pocket calculator that can be widely purchased at a low price. These advances have resulted in the use of exponentially less materials, including energy, while delivering superior performance and durability at markedly lower costs.

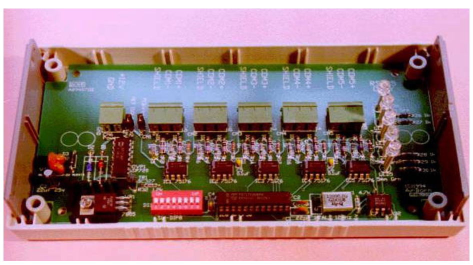

Figure 4. Computer circuit board. (Airborn Electronics Company web site at http://airborn.com.au/ab192.html. (Accessed March 22, 2001.)

The President's Materials Policy (Paley) Commission was created in 1951 by President Truman 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 a five-volume report titled *Resources for Freedom* in June 1952. The second volume, *The*

Outlook for Key Commodities, included copper. The findings of the report were pessimistic about the Nation's future domestic copper supply. The Commission reported that the United States' reserves of copper ore, containing at least 1 percent copper, were fixed in size and were not likely to include lower grade ores (Hyde, 1998, p. 182). However, the copper industry performed much better than expected. The average ore grade of copper extracted from U.S. mines in the early 1970's approached 0.6 percent (Hyde, 1998, p. 182). Ore grades currently are approaching 0.5 percent (Edelstein, D., U.S. Geological Survey copper commodity specialist, oral commun., 2000). The ability to mine these low-grade ores at a profit was achieved, for the most part, through technological improvements.

Productivity can serve, in part, as a measure of the impact of technology. Productivity is used as a measure of the effort required to extract, manufacture, or transform goods (Simpson, 1999, p. 8). Labor productivity is most affected by mining and process technology and measures the amount of labor required to produce a certain amount of output. Figure 5 shows labor productivity data for the copper industry. In addition to labor, other factors such as energy, capital, and intermediate goods are used to calculate overall productivity (Simpson, 1999, p. 192, 194). Intermediate goods are materials that are used in the production of other materials that, in turn, are sold to the public.

Gradual overall increases in copper labor productivity, shown in figure 5 between 1955 and 1982 and 1985 and 1995, probably result from both incremental technological improvements and major technical innovations. The rapid increase in labor productivity between 1980 and 1985 is attributable to innovations that came about as a result of the increased flexibility of work rules and job assignments made possible by agreements with labor during this period (Simpson, 1999, p.

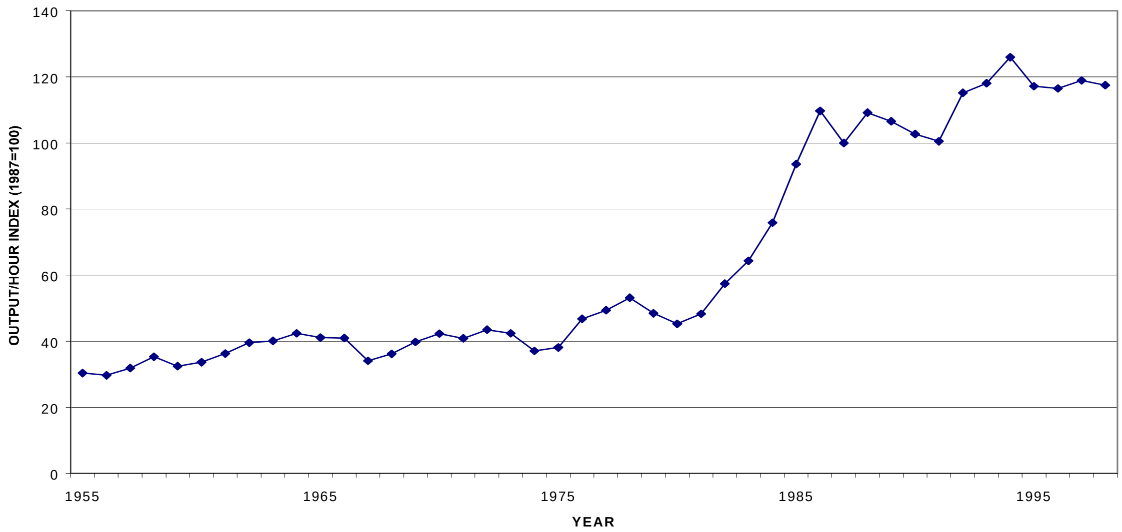

Figure 5. Labor productivity index for the U.S. copper industry (1987 = 100).
Source: Bureau of Labor Statistics, 2000, Data from Industry Productivity Database: Bureau of Labor Statistics web site at ftp://ftp.bls.gov/pub/special.requests/opt/dipts/oaehhiinin.txt and ftp://ftp.bls.gov/pub/special.requests/opt/dipts/oaehaiin. (Accessed November 30, 2000.)

126). The implementation of the solvent extraction-electrowinning process (SX-EW), which requires very little labor 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 labor and overall productivity after 1985. Labor contract changes are considered administrative and organizational technology when included under the definition of technology given on page 11.

3.4 THE APPLICATION OF TECHNOLOGY TO THE MATERIALS CYCLE

Technology is one method for improving the flow of minerals and materials (figure 6) to meet the current needs of the consumer. Technological improvements often focus on developing methods to facilitate or improve the efficiency of exploration and development; extraction, processing, and fabrication; and product use and disposal. Which methods are utilized in each sector of the materials cycle is dependent upon economics, environmental consequences, societal effects, and the relative political power of competing interests.

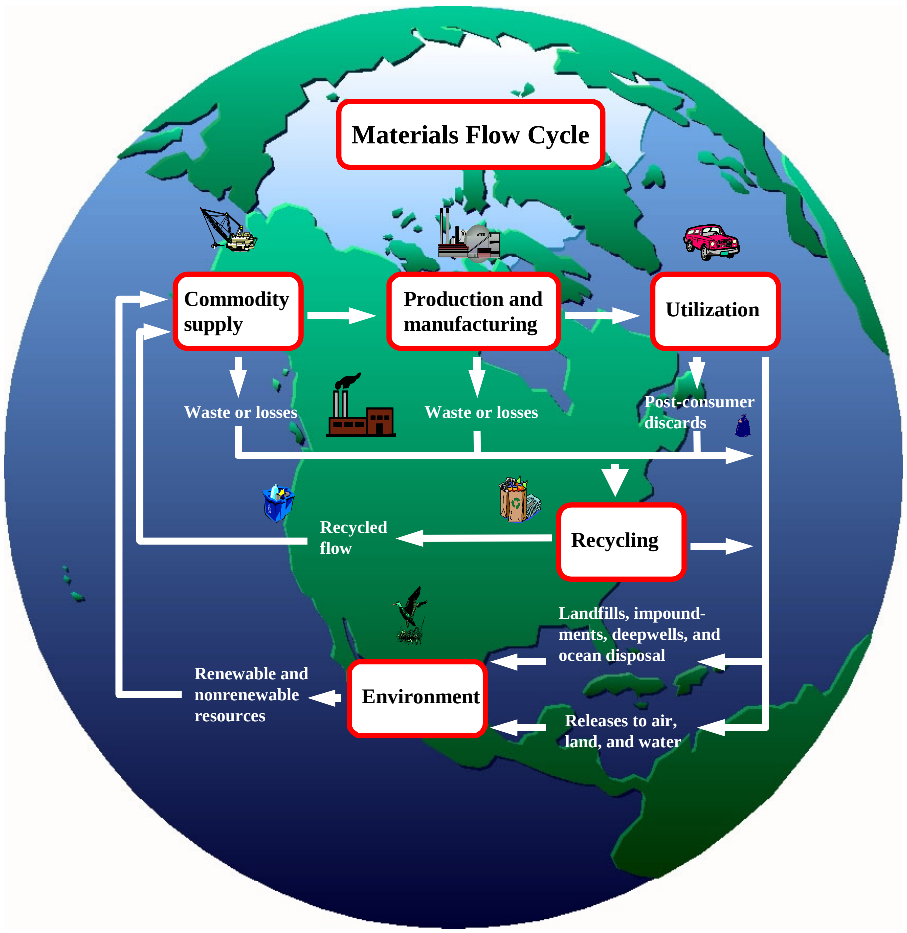

Figure 6. The materials flow cycle. (Adapted from U.S. Geological Survey Fact Sheet FS-068-98, June 1998.)

Minerals exploration requires the ability to develop 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 physical, chemical, and biological methods. The breaking of physical and chemical bonds to extract useful

> Humans separate materials from existing combinations and recombine them into forms having more use.

substances requires processing, often with high-energy requirements that technological advances strive to minimize. Manufacturing technology recombines materials in new combinations to form desired products. Consumer products are then distributed to locations where their useful properties are needed, a process requiring 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 resources for potential future recovery (figure 7).

Figure 7. Wastes deposited in landfills may become significant sources of materials in the future. (Courtesy of A. MacIntire, DB Enterprises Inc.: DB Enterprised web site at http://www.valinet.com/~nanc/dbl/pictures.html. (Accessed August 22, 2000.)

The following sections discuss the role of technology as it applies to the materials flow cycle for minerals (figure 6). The cycle includes mineral exploration and extraction (commodity supply in figure 6), processing and fabrication (production and manufacturing), utilization, recycling (including remanufacturing and reuse), and the environment.

3.4.1 EXPLORATION – *"Finding the needle in the haystack."*

The history of mineral exploration illustrates the incremental and mutually reinforcing nature of technology. Throughout human history, technology has influenced where and how prospectors look for minerals, drawing upon mineral deposit models developed from previous exploration experiences and mining activities, available technological tools, current knowledge of the earth sciences, and mining and processing capabilities. As

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

knowledge grew and technology progressed, mineral deposit models were gradually refined, new search areas were identified, and prospecting methods and equipment became more sophisticated. (refer to Appendix 1, "History of Exploration Technology").

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

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 large-scale open-pit mining, Pierce-Smith converting, froth flotation to separate valuable minerals from waste material, and a large-scale copper refining process using oxygen as the reacting agent. Waste dumps of U.S. copper producers became exploitable following the development of the SX-EW process, which allowed waste material from previous mining to be re-processed for copper. Application of the Olympic Dam copper-uranium model to the United States and Europe may lead to expansion of mineral supply by identifying previously unknown deposits (Pratt and Sims, 1990, p. 1). New deposit information, redefined deposit models, or technological breakthroughs may make it possible for economic recovery of material that previously was considered non-economic.

Major innovations can either be developed internally or adapted from other industries.

Major innovations that transformed exploration technology can borrow from breakthroughs first made in other sciences and industries. The geologist applied or adapted some of the technologic advances in geophysics, geochemistry, and oil and gas drilling to aid in mineral exploration. Laboratory and computer facilities provided the means to "measure" newly discovered resources with increasing accuracy while long-range exploration and characterization efforts reduced environmental disturbance. By the end of the 20^{th} century, exploration and mining used sophisticated models such as those developed by the U.S. Geological Survey (Cox and Singer, 1987; Bliss, 1992) based on integrated science. Newer models relied heavily on computer modeling of grade and tonnage. Tools have been developed to detect mineral deposits under water and at great depth 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 disturb environmentally sensitive areas.

Over the last fifty years, mineral exploration has located significant nonfuel mineral resources of economic interest in deep waters several kilometers below the ocean surface. Extensive but thin deposits of manganese nodules and crusts containing important amounts of nickel, cobalt, and copper have been located on the floor of most of the oceans of the world using geophysical, geochemical, and remote sampling techniques. First discovered in the 1870's, manganese nodules were considered geologic curiosities. The potential of these deposits as sources of nickel, copper, cobalt and manganese wasn't appreciated until the 1950's. 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 one broad belt of sea floor between Mexico and Hawaii, and a few degrees north of the equator (the Clarion-Clipperton zone), was literally paved with nodules over an area of more than 1.35 million square miles. The area has been estimated to contain 7.5 billion tons of manganese, 340 million tons of nickel, 265 million tons of copper, and 78 million tons 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 1940's to differentiate highly conductive ore bodies from low-conductivity host rocks (figure 8). Over the next 25 years, AEM was useful in the

Figure 8. Airborne geophysical methods. (Courtesy of R. Petersen, Fugro Airbourne Surveys, Ottawa, Canada.)

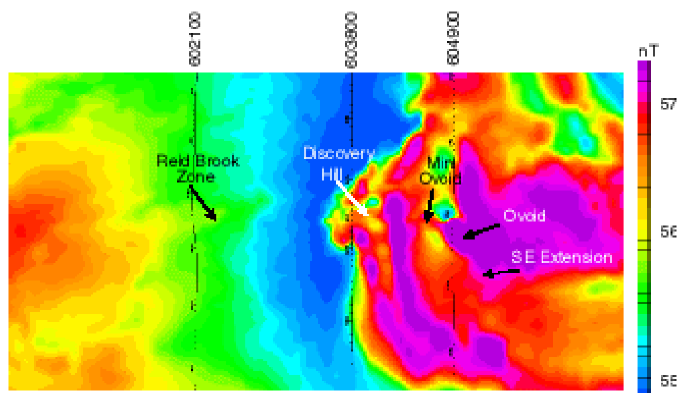

Figure 9. Magnetic maps such as this aided the discovery of the Voisey's Bay Ni-Cu deposit, Canada. (Courtesy of S. Balch, Inco Technical Services, Ltd., with permission of Inco Limited and Voisey's Bay Nickel Company Limited.)

discovery of volcanogenic massive sulfides (figure 9), uranium deposits, and diamondiferous kimberlite pipes on the Canadian Shield, to the point that the frequency of discovery of these types of deposits increased significantly in a wide variety of geologic environments (Ascough, 1999, p. 60). Gravity methods have been used since the 1950's to detect the presence of density contrasts between the dense mineral deposits and less-dense host rock. Although gravity anomalies often are difficult to discern and interpret, gravity methods have been used to investigate exploration targets previously detected by magnetic, AEM, or geochemical surveys, and can serve as a screening device that provides additional evidence that could support continued exploration (Thomas, 1999, p. 101). Gravity methods have been successful in exploring for many types of deposits, including petroleum, natural gas, sulfur, and porphyry coppers. Mineral exploration with magnetic methods, which detect contrasts between magnetic mineralized zones and host rocks, are most useful with iron-ore deposit models, but they also are important as an aid in exploration for other deposits or can be used in advanced stages of exploration to better define target ore zones (Lowe, 1999, p. 131-132). The use of these geophysical tools, along with aerial photography and computer modeling, has dramatically altered the scope of mineral exploration.

3.4.2 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 drilling and blasting, such as the development of ammonium-nitrate fuel oil (ANFO) blasting agent, and in equipment design and capacity, have reduced costs and improved mining efficiency. The use of larger capacity equipment and increased mechanization (figure 10) has also improved productivity and reduced costs of mining. Mine

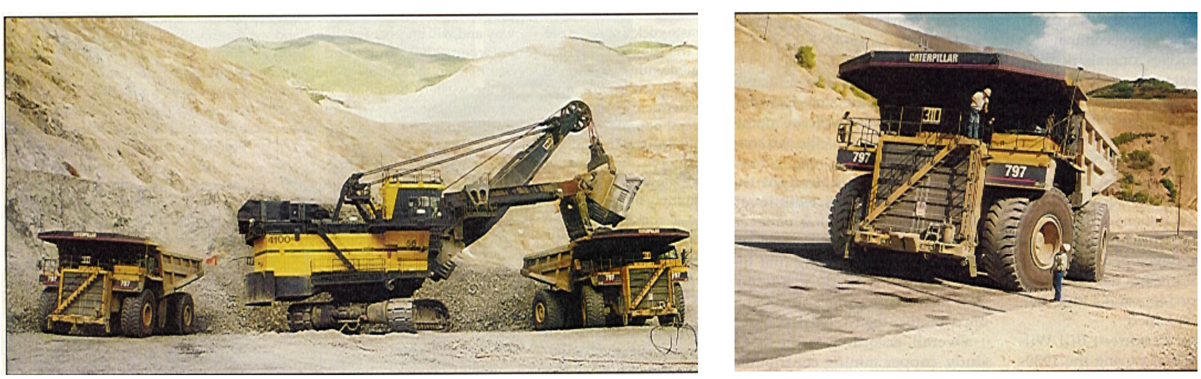

Figure 10. Shovel loading 360-ton trucks at Bingham Canyon copper mine, Utah. (Rocky Mountain Construction, August 14, 2000, p. 9.)

planning and ore extraction have become more efficient and less costly because of computer technologies that enable real time deposit modeling, sampling, and analysis of ores. Specific case studies presented in Appendices B - E describe how technology has been used to improve extraction and separation capabilities of four diverse mineral commodities, thereby expanding mineral supply.

Like 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 Pierce-Smith copper converters, sulfide flotation, and large-scale open pit mining. Pierce-Smith technology, developed in 1910, allowed copper to be enriched to 95-97 percent purity at lower costs while consuming less energy than previous methods. The advent of flotation technology in Australia in the 1920's enabled the removal of unwanted material from the desired copper-rich sulfides and separated different metal sulfides from each other, making copper available from poly-metallic sulfide ore bodies. This technology led to byproduct recovery of what previously had been considered 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 as well as improvements in open-pit mining and materials-handling equipment. The rapid emergence of porphyry ore bodies as major low-cost producers was quite remarkable. In the ten years following 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 technological 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, increasing ore complexity, expanding overseas competition, and expanding environmental regulation. Legislation that mandated lower ambient air quality standards with respect to 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. This byproduct is used as the leaching agent in the new SX-EW process, which allowed producers to recover copper from waste dumps, effectively extending mine life and rejuvenating the domestic copper mining industry. SX-EW is now widely used throughout the southwestern United States and Chile and has been extended and combined with subsequent innovations so that even very low-grade oxide ores now are economically recoverable.

Advancements such as SX-EW or Hall-Héroult revitalize resource industries as they often allow recovery from more diverse sources of supply.

Copper production predates aluminum production by almost 6,000 years, primarily because of the absence of technology to separate aluminum from abundant aluminum-bearing clays or rocks. Development of the Bayer process to produce alumina from bauxite, and the Hall-Héroult process to refine alumina into aluminum metal in the 1880's, effectively converted aluminum from a rare metal to a marketable commodity. The 1887 price in 1998 dollars was about $300,000/ton[1]. The 1900 price in 1998 dollars was about $14,000/ton, and the 1998 price was about $1,400/ton (T.D. Kelly, U.S. Geological Survey, unpub. data, 2000). Although the basic process has changed little since its inception, individual cell production capacity has increased from 15-20 tons/year in 1900 to about 820 tons/year in 1995. Cell efficiency increased from 70-80 percent in 1900 to 92-95 percent in 1995, while energy consumption decreased from about 35 kilowatt-hours/kilogram of aluminum in 1900 to about 13 kilowatt-hours/kilogram of aluminum in 1995 as a result of continuous improvements in cell design and process efficiency (Grjotheim and others, 1995, p. 32; Ǿye and Huglen, 1990, p. 24; and Peterson and Miller, 1986, p. 113).

[1] Tons, when used throughout this report, refer to metric tons.

Because aluminum production consumed large amounts of energy, early plants were located close to energy sources, mainly in Europe (coal) and the United States (hydro power). 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 Western Australia, South America, and Saudi Arabia 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. Thus, efficient materials handling and long distance transportation systems were developed to move large quantities of bauxite and alumina more cost effectively. Oil from the Arabian Peninsula, coal from the Powder River Basin of Wyoming, copper from Chile, and molten sulfur from Canada are additional examples of other mineral resources that benefited from advanced transportation technology.

Technological developments in one industry can advance other industries.

The potash case study illustrates how technology developed for one industry can be adapted to fit the needs of another industry. Much of the world's potash comes from salt deposits formed by the evaporation of ancient oceans, seas, and lakes. Deposits in Canada, Europe, and the United States were discovered during the first half of the 20th century during the search for petroleum. Over the last 100 years, diverse and very large potash resources, sufficient to supply the world's potash needs well into the future, have been discovered using new technologies. The deep deposits discovered in Canada were reached using newly developed technologies that permitted shafts to penetrate rocks containing water under high pressure. Continuous miners, highly mechanized equipment capable of producing up to 900 tons per hour from underground mines, were developed by the coal industry to improve productivity and safety, and were quickly adapted for use in potash mining (figure 11).

Figure 11. Continuous miner at Rocanville potash mine, Saskatchewan. (Net Resources International Limited)

Technology used to recover potash and sulfur through deep wells (solution mining) has been adapted from the petroleum industry, similar in principle to solution mining techniques used by Chinese miners about 1500 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, originally developed by the copper industry, were adapted for use at potash operations in New Mexico during the 1930's and were quickly adopted worldwide.

The history of sulfur extraction and production technology also reflects continuous improvement upon 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 (in place) mining technology used for sulfur production. This in-situ mining method has been continuously used since 1904. It recovers sulfur from deposits that are located deep underground or underwater, with little disturbance to the host rocks. The Claus process was adapted for use in the 1950's to recover sulfur from hydrogen sulfide (H_2S) produced during oil refining (figure 12). Sulfur, in the form of H_2S, was found to be a detriment in the oil refining process because it is

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

Figure 12. Technology for sulfur recovery was adapted from the oil refining industry. (Photo courtesy of Phillips Petroleum Company, from their web site at http://www.phillips66.com/photolibrary. (Accessed March 23, 2001.)

highly corrosive and has a strong odor.

As energy demand grew during the period 1950 to 1975, sulfur production as a byproduct of oil refining also grew. The Clean Air Act of 1970 set standards for sulfur recovery from oil refining, pyrometallurgical processing of sulfide ores, and coal combustion for electricity generation, which stimulated the development of sulfur-removal technologies in order to comply with the new standards. Sulfur dioxide (SO_2) gas generated from oil refining and sulfide ore smelting are highly suited for the production of sulfuric acid. Both the petroleum industry and copper industry can use sulfuric acid effectively in other on-site processes. Since 1975, sulfur and sulfuric acid production from oil refining and from 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 such that there is no foreseeable shortage of sulfur for the world economy. At the same time, this technology has allowed U.S. industries to comply with mandated environmental regulations and provided other countries with technological models for industrial cooperation and environmental sustainability.

Development of the "portland" cement process revolutionized the cement industry during the nineteenth century. Natural hydraulic cements, those that set and harden under water, are limited in nature and vary widely in quality and processing characteristics. The portland process, in which a properly proportioned mixture of finely ground raw materials is converted to "clinker" by heating these materials until partial fusion occurs, allowed a wider variety of natural raw materials to produce hydraulic cement with uniform strength and setting time. Use of the rotary kiln, first introduced to process portland cement, led to increased cement production, reduced labor costs, and development of alternative fuel sources such as powdered coal, petroleum, and natural gas. U.S. industry consumption increased from 3.3 million tons of cement in 1900 to 103 million tons in 1998 (T.D. Kelly, U.S. Geological Survey, unpub. data, 2000). Today, the U.S. construction industry uses this material in most residential, commercial, and public construction projects.

Current materials research on nickel illustrates how technology continues to be developed, even in times of abundant supply. Important technological innovations are underway in the processing of nickel ore. Commercial application of several processes that use bacteria to concentrate nickel, as well as copper, cobalt and other metals contained in nickel ore, are very close to commercial implementation. Within the next few years, a process could be implemented that relies on a strain of bacteria usually associated with volcanic hot springs similar to those responsible for the formation of deep sea metal deposits. The bacteria convert the metals in nickel ore to a more easily treatable form, from sulfides to sulfates. If proven successful, much more nickel, cobalt, copper, and other associated metals could be recovered than with conventional processing methods. 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 utilize bacteria, have the potential to increase the availability of nickel and its related byproducts by enabling mining of lower grade deposits while being "friendlier" to the environment (Mining Journal, 2000b, p. 371).

Exploration for and recovery of minerals from ocean water has been practiced for centuries while recovery of offshore minerals from the ocean floor using mechanized means has been practiced for just over 100 years. For example, dredging for tin and titanium minerals, and more recently diamond dredging, have proven to be economically successful and significant as additional sources of minerals. As figure 13 shows, diamonds valued at approximately 1 billion dollars were recovered off the coast of Namibia in 1996 from waters approaching 100 meters in depth using remote controlled vehicles (JDR Cable Systems, 2000).

Figure 13. Diamonds are recovered from waters off the coast of Namibia by a remote controlled vehicle traveling along the ocean bed. (Photo from JDR Cable Systems, Communication Lines: JDE Cable Systems web site at http://www.jdrcables.com/news/online9.asp. (Accessed September 11, 2000.)

Studies indicate that after a recovery period of as little as six months (Tarras-Wahlberg and O'Toole, 2000, p. 12), mined areas are biologically indistinguishable from unmined areas. Offshore mining of sands and aggregates for construction also has occurred for many years and may increase in urban coastal areas as local land-based sources become exhausted or unavailable. Successful recovery of precious metals and artifacts from great depths, together with 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 capable of raising material from great depths, processing it on ships, and disposing of waste in such 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 start-up costs occur one time; when mining is completed at one site the operation can be moved easily to mine resources at another location.

Current research has focused on the potential feasibility of recovering metals, primarily copper, lead, zinc, gold, and silver, deposited in ocean sediments near undersea hydrothermal vents. Up to 200 sites of inactive or previously active vents that deposited metals from underwater hot springs have been located and more discoveries undoubtedly will add to this number. Although few of these deposits have been closely examined, and none have been fully evaluated for size, grade, and economic feasibility, some appear to have higher grades and tonnages than many onshore deposits currently being mined. Like manganese nodules and crusts, these undersea deposits potentially are 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 require technologies that can operate successfully in harsh environments produced by extremely high pressures, low temperatures, and darkness. Space technologies including robotics, advanced materials, multi-band communications, intelligent sensors, remote sensing, and advanced power systems have potential applications in these environments. Numerous mining systems have been tested. They include suction and continuous bucket dredging and remote-controlled vehicles that collect and crush material before returning it to the surface for processing.

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 major obstacles impeding their development. Locating large high-grade deposits and granting exploration and mining permits within a country's exclusive economic zone 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 (PNG) Exclusive Economic Zone. PNG recently granted mining licenses for tracts of seabed to a company hoping to exploit underwater volcanic vents (Hussein, 2000). Based on 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 are not always better. In some cases, newly developed technologies proved inferior to technologies they were designed to replace, or led to unintended consequences. For example, the Department of Energy conducted research into using thermo-nuclear devices as explosives for large-scale construction projects from the late 1950's to the early 1970's. Ideas proposed for testing included: making harbors on continental coasts, building sea-level canals (Panama, Malaysia [Kra Isthmus], and the Aleutians), building dams, redirecting rivers, and recovering gas and oil from selected rocks such as oil shale (Teller, 1963).

In 1967, the Atomic Energy Commission exploded a 29-kiloton nuclear bomb underground in New Mexico. Project Gasbuggy, as it was designated, produced a good deal of natural gas, all radioactive and unusable. Project Rulison, another nuclear

BIGGER NOT ALWAYS BETTER

Research into using thermo-nuclear devices as explosives for large-scale construction projects proved to have untended consequences. 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.

test conducted in 1969 in western Colorado, produced some gas, but the shock waves damaged building foundations, irrigation lines, local mines, and other structures, arousing considerable environmental concerns 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, 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.

3.4.3. FABRICATION – "Threading the needle."

Once ore is extracted and processed into a basic marketable commodity (for example, iron ore pellets, copper or aluminum ingot, or potash crystals), these commodities may need to be converted to a form that makes them readily usable by a manufacturer. Metals often are shaped into rolls, bars, or sheets. Industrial minerals frequently are formed into powders, pellets, or pastes. Blending materials, for example, alloying metals, can change material characteristics and provide greater strength,

TECHNOLOGY BREEDS TECHNOLOGY

Technological advancements in product manufacturing have provided incentives for improving mining technology, resulting in increased material supplies. In the early 20th Century, when Henry Ford demonstrated the power of mass production, costs for manufacturing the Model T dropped from $600 in 1912 to $265 in 1923. The opportunity for car ownership thereby was extended to many more consumers. Ford's total output increased from 4 million cars in 1920 to 12 million cars in 1925, causing an increase in demand for materials (Gardner and Sampat, 1998, p. 11).

In response, mining companies opened new mines, reduced costs, and continually found ways to produce material from lower grade, more chemically complex, and difficult-to-process ores.

longevity, or versatility. As the needs of society change, technology develops new forms or redesigns existing ones to meet those needs.

A BETTER IDEA

In the early 1970's 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 roadsides, parks, and beaches, becoming dreaded hazards to the barefoot vacationer or curious toddler. In 1976, Daniel F. Cudzik, 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. Cudzik's simple design change enabled the additional recycling of about 200,000 metric tons of aluminum since 1980, which equates to about 3 billion kilowatt-hours of saved electricity. A reduction in electrical demand of this size at a typical coal-fired power plant would prevent the release of 400,000 kilograms of carbon monoxide, 400,000 kilograms of fine particulate matter, 9 million kilograms of nitrogen oxides, 19 million kilograms of sulfur dioxide, and over 2.7 billion kilograms of carbon dioxide. (U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999)

The aluminum case study (Appendix 2) provides one example where technological developments in fabrication significantly contributed to the growth of a mineral resource industry. Aluminum markets remained specialized 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 in casting and rolling, to produce the large quantities of aluminum sheet necessary for the war effort, increased the adaptability and versatility of aluminum, leading to diversified and expanding 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 stamped and formed. Aluminum was introduced into the beverage can manufacturing process in the 1960's, and aluminum can sales grew from 2 percent in 1964 to almost 90 percent of the soft drink and approximately 100 percent of the beverage can market in 1999 (U.S. Bureau of Mines, 1991; Aluminum Association, 1999). This unprecedented growth can be attributed to ongoing incremental refinements in aluminum can manufacturing and fabrication that reduced aluminum consumption per can, required less energy to operate, and facilitated recycling.

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

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, often resulting in the use of less material. Alloys are often developed in response to industry or societal needs, to improve performance, increase efficiency, or reduce cost of a product. Alloys can overcome short-term scarcity of a material by supplying a substitute combination of materials with similar properties or performance characteristics.

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

One can think of alloys as partnerships of elements, the purpose of which is to supply special properties to the marketplace. For example, iron can be used to form a myriad of alloys with varying amounts of boron, carbon, chromium, copper, manganese, molybdenum, nickel, niobium, silicon, titanium, tungsten, and vanadium, depending upon the properties desired. Metal demand and concern regarding scarcity of minerals during World War II generated much research into new alloy combinations.

Copper alloys include various combinations with aluminum, beryllium, cadmium, chromium, manganese, nickel, phosphorous, silicon, tin, zinc, and zirconium. Copper alloys were designed to improve metal performance related to electrical properties, ductility (ease in forming), impact resistance, hardness, and strength over various temperature ranges, as well as color for aesthetic acceptance.

More recently, a variety of alloys have been used as additives to materials with entirely different properties to make composites with even more useful properties. Even the shape or orientation 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. To date, much of the research on composites has 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 aerospace but also in the transportation industry (Ejiofor and Reddy, 1997).

The development of coatings technology brings desirable properties to a material while using less. 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 applied to substrates that have other desirable properties.

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

Coatings also are applied to improve surface hardness. For example, diamond-coated ball bearings have increased wear resistance (figure 14). Silica-based coatings are placed on lightweight plastics to improve abrasion characteristics. Carbon nitride (C_3N_4) 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, valves, and tools (National Aeronautics and Space Administration, 2000).

Figure 14. Diamond coatings on ball bearings improve wear characteristics. (Photo from Refmet Ceramics Limited, Advanced Surface Technologies: Refmet Ceramics Limited web site at http://www.diamond-like-carbon.com/wear.htm. (Accessed March 23, 2001.)

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

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

Artificial diamonds can be produced by subjecting graphite to a pressure of tens of thousands of kilograms per square centimeter (atmospheres) at temperatures in excess of 2,000 degrees Kelvin (3,140 °F). This is similar to nature’s method for 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 to be less costly and energy intensive than pressure intensive methods of producing diamond. Diamonds produced in this fashion had many impurities, but over the years incremental technological improvements have resulted in very pure diamond products.

U.S. apparent consumption of industrial diamonds, 90 percent of which are synthetically manufactured, has grown from 231 million carats in 1995 to an estimated 278 million carats in 1999, reflecting a compound annual growth rate of nearly 5 percent. Concomitantly, constant dollar prices declined from 6.62 dollars per carat in 1995 to 4.94 dollars per carat in 1999, indicating the ability of technology to make industrial diamonds more available at decreasing cost (U.S. Geological Survey, 2000, p. 58).

A more recent advancement in the use of synthetic diamond technology was the development of diamond films and coatings that have found application as components of cutting tools, optics, electronic devices, and other applications. Films and coatings add diamond's unique properties to other materials. The use of man-made diamonds as coatings and films has increased the service life (efficiency) of the resulting composite materials. Synthetic diamond manufacturing technology has reduced our reliance on naturally occurring diamonds, nearly all of which are imported from other countries. Current synthetic diamond production research is devoted to improving quality, improving coating-substrate bonding, and reducing costs. Development of additional applications is ongoing (May, 1995).

3.4.4. UTILIZATION – *"Sewing with the needle."*

Human beings have always used their expanding technological knowledge to make 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). Aluminum, bronze, iron, and some plastics all were new materials at one time. New materials have led to advances in agriculture, communications (figure 15), computer systems, industrial processing, and medical technology. Spin-offs from advanced technologies, such as space flight, have led to the creation of new materials for consumer products. Technology is often required to design resource-efficient methods to produce these or substitutable materials.

Figure 15. Advances in materials technology have improved telecommunications using less material. (Modern phone from GadgetCentral, Inc., at their web site http://www.gadgetcentral.com/sch3500_intro.htm. (Accessed March 23, 2001.) Old phone from the Working Group on Industrial Ecology, Material and Energy Flows, 1999, Materials: Washington, D.C., November 1999, p. 5, from their web site at http://www.oit.doe.gov/mining/materials/phone.gif. (Accessed March 23, 2001.)

The copper case study (Appendix 3) describes how materials, technology, and market demand interrelate. The discovery of electricity and its use in communication systems, lighting, and motors, generated the demand for materials that could efficiently transmit electricity over long

FROM WIRES TO WIRELESS

There is over 65 million tons of copper wires that comprise the telephone system of the United States. The minimum replacement cost of these wires, which have been installed over the last 50 years, is $300 billion (Gilder, 1995).

The transition from wire technology to wave technology for telephones, that is, "going cellular", may render this installed copper investment obsolete over time, and provide a high-grade copper "ore" that can be "mined", at lower costs than mining "new" copper, and used for other purposes, perhaps in the manufacture of technologies for solar energy.

distances. The properties of copper, including its high electrical conductivity, corrosion resistance, and low energy requirements, and the introduction of wire-forming technology that allowed copper to be formed into long strands, made copper the material of choice during the early 20th century for high transmission lines and household wiring systems. This is true at least in part because the large costs previously incurred in developing copper production infrastructure stimulate the copper industry to pursue technological research in order to retain market share.

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. Past developmental histories should not be extrapolated to estimate future resource demand.

Other materials have substituted for copper in wiring, however. Aluminum is used for household wiring and 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 cost competitive.

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.
(Source: Greetham, 2000)

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

Current technological research is focusing on reducing the amount of a material that is needed (material supply reduction) or enhancing the delivery characteristics of that material (increasing efficiency). Both have the effect of reducing overall product costs, which eventually are passed along to the consumer as time or cost savings.

Technological developments in all phases of aluminum production during World War II increased the adaptability and versatility of this metal, leading to diversified and expanding postwar markets (U.S. Department of Commerce, 1956, p. II-13). Aluminum began to be used extensively in commercial aircraft and automobiles, wiring and machinery, and in the container and packaging sector. Since the war, demand for the metal consistently has grown, and its use has broadened to make aluminum one of the most important mineral commodities in the world. Technology has been developed to meet this increased demand for new aluminum products.

Substitution may benefit the consumer while increasing effective resource supply.

If the price of a material increases as a result of factors such as increased demand or limited production capacity, substitution may occur. One material may replace another by providing similar performance. Examples of substitution in the beverage industry include aluminum for steel cans and plastic for glass bottles. Substitution in the automotive industry includes plastic for chrome bumpers, aluminum for steel body parts, or copper for aluminum in radiators. In the electrical industry, aluminum and copper compete in wiring; and silicon fiber optic cables, in some applications, have replaced copper. In each case of substitution, technology has succeeded in developing an alternate form with decreased cost and/or increased performance.

The search for substitutes can have unintended consequences, however. When the U.S. Environmental Protection Agency (EPA) announced in the 1970's its intention to ban the use of asbestos, friction product and high-temperature gasket manufacturers began searching for a substitute for asbestos that would also have the properties deemed necessary for that application. Such properties included a small cross-section, high-temperature resistance, and high-temperature compressive creep strength. The industry selected glass fibers as a substitute. There is evidence to suggest, however, that glass fibers are more costly and less efficient or useful. Glass fibers also have raised environmental concerns equal to, or exceeding, those concerning asbestos (Asbestos Institute, 1995).

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

3.4.4.1. 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 natural or manufactured products. As landfills become full and new sites become more difficult to locate, permit, and operate, disposal costs become more expensive. Research increasingly is focusing on developing ways to reuse materials that traditionally have been considered waste. The concepts of recycling, remanufacturing, and redesigning all involve turning waste materials into useful products with minimal environmental impact. While not new, these concepts are becoming increasingly important in today's society. Each of these approaches has the potential of conserving natural resources, including energy, and come with significant environmental benefits and economic savings (U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999, p. 16).

Recyclable materials include such items as aluminum cans, copper wire, automotive parts (figure 16), and construction asphalt and concrete. Approximately 120 million tons of materials currently are recycled in the United States every year through municipal programs, auto recycling, and construction and demolition recycling, saving the equivalent of about 4 months of electricity demand (U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flows, 1999, p. 16). Although recycling can include both old scrap (derived from discarded products) and new scrap (purchased from the

Figure 16. Scrap automobiles are a source for recycling, remanufacturing, and reuse. (Photo courtesy of Centre de Recyclers Universel, Val-d'Or, Quebec, Canada.)

manufacturing process), only old scrap is included in apparent consumption statistics. The U.S. Geological Survey estimates that recycling from both old and new scrap accounted for approximately 63 percent of the apparent supply of lead, 55 percent of steel, 50 percent of titanium, and between 25-40 percent of aluminum, copper, magnesium, nickel, tin, and zinc in 1998 (U.S. Geological Survey, 1999b). The aluminum (Appendix 2) and copper (Appendix 3) case studies in this report illustrate how technology has influenced the growth of recycling and increased the availability of resources from more diverse sources.

Market-driven recycling reduces waste and conserves embodied energy. There often are obstacles to recycling, however, that technology can address. For example, direct-reduced iron (DRI) technology was developed by the U.S. steel industry in the 1970's to alleviate problems resulting 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. The relatively pure DRI, when mixed with scrap, dilutes the undesirable content of the resulting mixture, keeping the steel within specifications. The elements that accumulate in electric furnace steelmaking practice 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. Without

WHAT DROVE DIRECT REDUCED IRON DEVELOPMENT?

Prior to the 1980's, the bulk of alloy steels were made in mills processing iron ore in blast furnaces and making steel from iron in basic oxygen vessels. There was no residual element buildup from scrap reuse because the relatively pure iron from the blast furnaces was available to dilute the contribution from scrap.

In the 1980s, many of these mills lost market share to electric furnace shops. Consequently, there was no blast furnace iron available for the dilution process. As a result, virtually all of the smaller US blast furnaces were shut down and permanently dismantled during this period. DRI became the technological substitute for hot metal, and the answer to the residuals-in-scrap problem.

DRI, scrap containing residual elements would have less value and would most likely be stored for prolonged periods, perhaps for so long that some would dispose of it as waste.

The DRI process uses natural gas to reduce iron oxides in pellets to elemental iron. In 1999, the feed to American electric furnaces was about 30 percent DRI and 70 percent scrap. 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 availability of cheap energy and the fact that steel scrap is relatively expensive (Industry Canada, 1998).

Recycling technology has responded to environmental regulations that have limited the discharge of toxic materials such as arsenic, cadmium, lead, and mercury into the environment and reduced their use in manufacturing processes and products. For example, recent legislation has mandated recovery of lead from lead-acid automotive batteries. Technology was developed so that about 76 percent of refined lead produced in the United States in 1998 was recovered from recycled scrap, of which a major source was spent lead-acid storage batteries (U.S. Geological Survey, 1999b).

Recycling of cadmium from spent nickel-cadmium batteries also has grown during the last decade. 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 more efficiently recover and extract mercury from its products and sources, including dental amalgams, spent batteries, control instruments, mercury vapor and fluorescent lamps, measuring devices, switches, and laboratory and electrolytic refining wastes.

Recycling can conserve natural resource supply, cut energy use, and often saves money.

One of the characteristics of aluminum is that it is easily recyclable. The aluminum recycling (secondary) industry, began about 1904 to process scrap from the primary aluminum industry. The amount of energy required to produce one ton of recycled aluminum is about 5 percent of the energy required to produce one ton of primary aluminum from bauxite (Wilburn and Wagner, 1993, p. 93). Prior to aluminum becoming a commodity during the World War II era, 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 increased supply of aluminum scrap, proven product performance, and favorable economics. Some technical advances in alloying and die casting during WWII were developed specifically for the secondary aluminum industry (Aluminum Association, 1985, p. 8). Technology also was developed during the 1950's that allowed improved material separation of aluminum scrap from junked automobiles. Recycling of aluminum products increased dramatically in the 1970's when the aluminum beverage can began to be widely used. In 1999, the United States produced about 3.8 million tons of primary aluminum metal, but it also recovered about 3.5 million tons from purchased scrap (U.S. Geological Survey, 2000, p. 22).

Figure 17. Obsolete electronics can be recycled or reused. (Monmouth Wire and Computer Recycling, Inc, 2001, from their web site at http://www.computerreclamation.com/gifs/photo1.jpg. (Accessed March 23, 2001.)

Recovery of obsolete materials from the burgeoning electronics industry is growing (figure 17). Table 2 reports materials recovered from U.S. electronics recyclers.

Types of Material	1997 metric tons	1998 metric tons
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, and silver)	1	1
Other	3,100	3,600
Total	**41,100**	**52,300**

Table 2. Reported materials recovered from U.S. electronics recyclers (Adapted from National Safety Council, 1999, p. 36, and Sean Magaan, Noranda Inc., Micro Metallics Corp., oral commun., 1999).

The recycling of obsolete electronic products to recover re-usable components such as metals, glass, and plastics is an economically viable growth industry. 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 has decreased, 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. Nonetheless, recycling may continue to increase as manufacturers use technologies, including organizational and management technologies, to develop better ways to identify types of plastics, design for greater ease in dismantling, and develop leasing programs that include the return of electronic products to the manufacturer or retail distributor. Recycling also can increase through more effective collection methods and legislation mandating 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 non-traditional sources such as mine tailings. Magnesium, the lightest of all structural metals and a critical constituent in some aluminum based alloys and castings, is an important metal in the aerospace and automotive industries. Most of the world's magnesium originates from salt deposits, brines (including seawater), and dolomites for which resources are considered "enormous" (U.S. Geological Survey, 2000, p. 105). A new low-cost extractive technology to recover magnesium from serpentinite tailings, a waste material generated from the mining for asbestos, is being evaluated in Australia, North America, and the former Soviet Union (Golden Triangle Resources NL, 1999). Extraction of magnesium from tailings offers the advantage of recovering a metal from materials that, until recently, were considered a waste and an environmental liability. Recovery of such material reduces production from other ore sources, so it 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 over 100 years of asbestos mining is set to begin production in early 2001 (D. Kramer, U.S. Geological Survey, magnesium commodity specialist, oral commun., 2000). When fully operative, the Magnola facility will be the world's largest source of magnesium and the first to use an innovative, but still commercially unproven, technology. Development of the extractive process took over ten years and millions of dollars to develop (McLean, 1999). All resource material recovered will be from the over 250 million tons of waste from the area's legacy of over 100 years of asbestos mining. There are sufficient resources at the $500 million dollar facility to produce 63,000 tons per year of magnesium metal for about 300 years (Mining Journal Ltd., 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 occupying landfills. For example, the Chaparral Steel Company is taking automobile recycling one step further by using an innovative flotation technology to separate the various materials in automobile shredder residue (ASR). This technology is based on that used in the mining industry to recover the valuable components of mineral ores. ASR is material that is leftover following the processing of scrap automobiles and typically includes aluminum, magnesium, other nonferrous metals, glass, polyvinyl chloride (PVC) and other plastics, and rubber, all of which are potentially recyclable (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. It has been estimated that about 2.5 million tons of ASR are generated annually (Altschuller, 1997). Nonchlorinated plastics, rather than being placed in landfills, may be used as a highly efficient and clean fuel source. The Chaparral Steel Company anticipates that the glass can be re-melted, used as roadbed material, or used as an abrasive for sanding devices (Chaparral Steel Company, 2000). Potentially, this new technology could be used for mining municipal landfills.

3.4.4.2. 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. The origins of remanufacturing can be traced to the 1920s and 1930s with the emergence of mass production and standardization of products such 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 raw materials, such as steel, drove the need to reuse durable goods (Automotive Parts Rebuilders Association, 2000a). Although estimates vary on the size and scope of the current remanufacturing industry, a recent analysis performed at Boston University found 73,000 remanufacturing firms operating in the United States. Together, these firms are a major force in the economy, representing $53 billion in annual sales and employing 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, the steel is saved from the landfill space and could be used to produce another item requiring steel. However, remanufacturing offers another alternative. Remanufacturing retains most of value added to the product (including the cost of raw materials, labor, and energy) 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 of oil per year worldwide, which is equivalent to the energy content of gasoline to operate about 6 million passenger vehicles for a year. (Automotive Parts Rebuilders Association, 2000b). In addition to saving energy and other raw materials, remanufacturing extends the life of landfills and reduces the potential for toxic materials release, including gases, some of which contribute to the load of greenhouse gases in the atmosphere. Remanufacturing also results in significant economic benefits. Purchasing a remanufactured product can cost consumers 50 to 75 percent less than a new product. Technological advancements in product composition and design have lengthened the life of products and improved on the ability to refurbish them. Companies, as part of their business plan, also are designing products that can be more easily remanufactured. Signature-analysis technology may start to 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 utilization. By 2005, there may be improved cleaning methods and equipment that reduce environmental impact, require less solvent, and reduce disposal rates. Additional technology goals should 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 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. The company initiated its Environmental Leadership program in 1990, 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 so they can be remanufactured, reused, and recycled. In 1997, Xerox remanufactured equipment from more than 30,000 tons of returned machines and customers returned 65 percent of all empty print and copy cartridges to Xerox for recycling. (Gibney, 2000).

3.4.4.3. 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, used automobile fenders and bumpers, and refurbished computers. Reuse also includes finding new uses for "used up" products such as automotive tires that can be used as mooring cushions in a harbor. With respect to recycling, reuse has the added benefits of not only reducing waste generation and conserving landfill space, but it also saves 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 conserved. Moreover, technological advances in product design and collection, and increases in productivity through automation, have improved the efficiencies in product reuse.

3.5 CONCLUSIONS

Predictions of resource scarcity re-occur periodically. This study shows how the implementation of technology, the organization of energy, knowledge, labor, and materials, has historically addressed scarcity concerns. Intuitively we know resources are finite. However, the historical evidence suggests that resource availability has grown consistently and prices for materials in real terms have continually decreased or remained relatively steady. This has occurred in the face of increasing demands by a population that is growing and has increasing lifestyle expectations, declining ore grades, mineral deposits that are increasingly difficult to access because of their depth, geologic complexity, remoteness, and susceptibility to adverse social and political 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.

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

Can the historical evidence of technology's success be extrapolated into a future when resources are infinite and free? Of course not! Nevertheless, it is expected that technology will continue to advance; supplying us with our mineral resources into the foreseeable future, unless economic incentives are constrained by non-technical social and political actions.

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APPENDICES

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 previous exploration experiences, available technological tools, current knowledge of geology, and mining and processing capabilities. As technology progresses, it gradually has refined such models to allow for the discovery of previously undetected resources, both in quantity and type of mineral as well as deposit. The evolution of exploration technology has contributed to an expanding 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 made use of metals, such as copper and gold, for at least 6,000 years. Visual observation was the first "tool" used to locate mineral resources and develop exploration models. The earliest recorded discovery of metal resources dates from the Fifth Millennium B.C., when free gold found in shallow Egyptian riverbeds was beaten into thin plates and pins (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 identified what they needed visually, then extracted only what they needed for personal use within their local community (figure 18). 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.

Mineral exploration beyond visual observation required development of a deposit model, requiring a sophisticated knowledge base including an understanding of mineralogy, geologic structure, 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 (Bates, Gaskell, and Rice, 1982, p. 2). Technologies to test such early deposit models were developed as early as A.D. 132, when Chang Heng used a "seismoscope" in China to study earthquake motions (Bates, Gaskell, and Rice, 1982, p. 2), a technique that since has been perfected using "seismographs" that interpret reflect energy waves to "detect" certain geologic structures and "map" selected geologic environments.

Figure 18. – Early prospecting methods.
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In 1556, Agricola used observable evidence to present the first published comprehensive theory of the origin of ore deposits formed by the replacement of pre-existing material with ore (Peters, 1978, p. 1). European scientist-philosophers followed Agricola's models until eighteenth-century mining academies refined them.

The rise of colonialism during the sixteenth and seventeenth-centuries opened new territories for mineral exploration and provided opportunities for the application of geologic models to new areas and led to the creation of new models. Significant exploration activity occurred in Africa, Asia, and the Americas 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 knowledge, infrastructure, and adequate equipment generally restricted the search to regions containing previously discovered deposits and to surface expressions of ore. Underground exploration was mainly random, and rarely yielded positive results. Processing techniques during this period required higher grade, easily separable ores such as native copper, tin, and gold nuggets.

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

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

Scientific evidence collected by the end of the eighteenth-century proved that stratigraphic sequence, geologic structure, and mineral deposit location were linked, providing a further refinement of deposit models. It was generally recognized by the mining and exploration community that increasing the knowledge of known mineral occurrences could aid the search for new deposits. The need for mineral resources during the nineteenth century, specifically coal as fuel for electricity and transportation, and iron and copper for infrastructure development, led many governments to fund or sponsor organized geologic mapping programs. By the mid-nineteenth-century, geologic 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, founded in 1879, did not act as a consultant to prospectors in the Canadian way, but provided services--direct and indirect--to a growing number of people searching for minerals. Some of the documents prepared by U.S. and Canadian Government organizations are still considered reference standards for modern exploration and deposit description (Peters, 1978, p. 7).

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

Nineteenth-century science provided a guide both to locating new ore fields and expanding earlier discoveries. Self-schooled prospectors rather than scientists or "company geologists" still made most mineral discoveries in the latter nineteenth century. Scientific interest, however, stimulated the development of exploration and geophysical tools after 1850. Tools such as the power hoist and the Cornish water pump 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 could now be documented. Diamond drilling and magnetic prospecting both were initially tested in the Lake Superior iron ranges during the latter 19th century, allowing for easier and cheaper exploration at depth. Additional resources were thus discovered. The Comstock Lode in Nevada was mapped by self-potential (electrical) geophysical methods in 1880, and again more resources were discovered. Sterry Hunt (1873) developed geochemical sampling techniques similar to those used today to locate subsurface mineral targets with abundant resources (Peters, 1978, p. 9).

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

As knowledge about known mining districts and development of ore deposit models grew, the number of new discoveries and the accuracy of exploration improved, by use of analogies. Processing still required relatively high-grade ore capable of being separated easily from gangue minerals. 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. This provided the incentive for further exploration in the region.

The turn of the twentieth century marked the emergence of direct mineral exploration by mining companies. The professional mining geologist and exploration company assumed prominence four and a half centuries after the science of mining geology began in central Europe. In 1900, the Anaconda Copper Mining Company established the first geological exploration department at a large mining camp in Montana. Since that time, 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.

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.

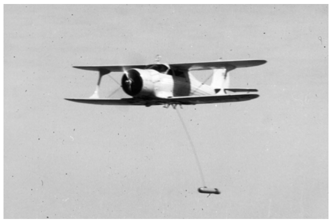


Figure 19. Beach Staggerwing aircraft conducting early geophysical survey, circa 1949. (Photo courtesy of V. Labson, USGS.)

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 its discovery would likely not have occurred without technological developments in mining and exploration (Coope, 1991). Because of the extremely fine grain size of the gold in this region, early prospectors overlooked Carlin. Although a few nearby placer gold deposits were found in the late 1800's and early 1900's, 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). The U.S. Geological Survey conducted extensive mapping in the region during the 1940's and the 1950's. 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 1800's totaled less than 10,000 ounces; Annual reports for Barrick and Newmont list 1999 resources for the Carlin Trend at 60 million ounces. Discoveries are continuing.

Exploration geophysics, excluding magnetic methods, did not gain wide acceptance in mining until the 1940's, several decades after it attained common use in the petroleum industry. By the end of World War II, geophysical theory, interpretation, and tools had proven themselves. Surface, drill-hole, and airborne geophysical methods were used more frequently. The latter proved to be the most useful in advancing mineral exploration into new and more remote areas.

Airborne electromagnetic surveying (AEM) has become a successful tool in mineral exploration (figure 20), and has been adapted to search for a variety of ore types defined by deposit models in various geographic settings. The technique was developed in the late 1940's to differentiate highly conductive orebodies from their less conductive host rocks. This method began to flourish after WWII because of availability of pilots and aircraft, increasing global demand for minerals, and the rise of the integrated mining and exploration company, which could afford to fund such expensive methods. Over the next 25 years, AEM was useful in the discovery of volcanogenic massive sulfides, uranium deposits, and diamondiferous kimberlite pipes, to the point that the frequency of discovery of these types of deposits increased significantly in a wide variety of geologic environments (Ascough, 1999, p. 60). High resolution methods such as helicopter electromagnetic-magnetic and horizontal-loop electromagnetic surveys are used for detection of conducting minerals occurring less than 100 meters below the surface. Deeper penetrating methods like fixed-wing AEM (to 400m depth), time-domain electromagnetic (to 800m depth), and magnetotellurics (to 1500m depth) offer superior depth of exploration, but with a corresponding drop in target resolution and conductance estimates (Balch, 1999, p. 21).

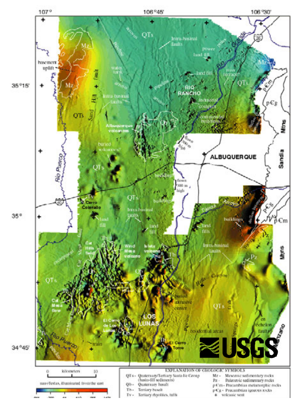


Figure 20. Airborne geophysical map of the Middle Rio Grande Basin. (Photo courtesy of V. Grauch, USGS.)

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

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 better define target ore zones (Lowe, 1999, p. 131-132).

Geophysics, computer modeling, and aerial photography enabled regional exploration for remote or hidden deposits.

Aerial photography began to play a part in mineral exploration in the 1920's, but didn't come into prominence until after World War II. The greater flexibility of helicopters and use of spacecraft-mounted cameras permitted exploration programs to operate in remote regions of nationwide and even subcontinent size (figure 21). The rise of geophysics, computer modeling, and

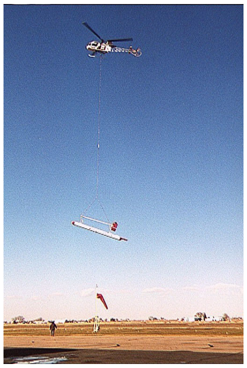


Figure 21. Equipment used to conduct modern geophysical surveys. (Photos courtesy of V. Labson, USGS.)

aerial photography dramatically altered the scope of mineral exploration; the emphasis in the latter half of the twentieth-century changed to district-wide and regional surveys. Space-based cameras can scan more extensively than ground stations, can supply data much faster, and are now more accessible than in previous decades.

For the most part, mineral exploration programs had become team rather than individual efforts. Geology, geophysics, geochemistry, and drilling technology provided the team with tools of discovery. Laboratory and computer facilities provided the tools of measurement. Exploration companies now had the tools to not only "discover" a mineral deposit with significant potential, but also "measure" its potential with increasing accuracy and reduced environmental disturbance. For example, the Voisey's Bay nickel-copper deposit was discovered by geophysical mapping; Voisey's Bay exploration maps are shown in figure 22.

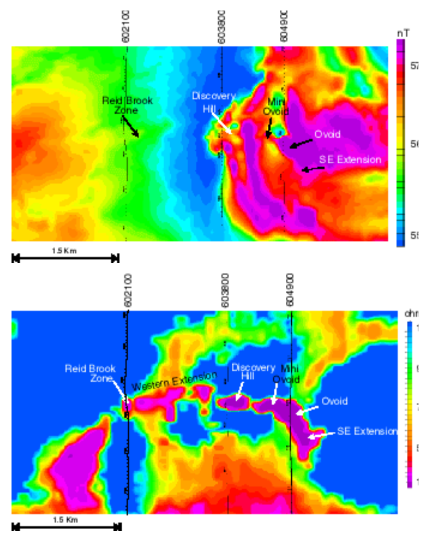


Figure 22. Magnetic and resistivity maps such as these assisted in the discovery of the Voisey's Bay Ni-Cu deposit, Canada. (Courtesy of R. Petersen, Fugro Airbourne Surveys, Ottawa, Canada and S. Balch, Inco Technical Services, Ltd., with permission of Inco Limited and Voisey's Bay Nickel Company Limited.)

Increased demand for minerals in the latter half of the 20th century was depleting established mining districts at an accelerated rate and the availability of land for new exploration was declining. 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 or environmentally sensitive areas, including those in which deposits are covered by surface materials such as alluvium, unmineralized rock, or water. Indirect prospecting methods capable of detecting hidden mineralized areas from a distance are now being used. Consequently, remote areas with harsher climates began to receive more attention.

Evolving geologic models drive exploration at Olympic Dam

The Olympic Dam deposit is currently the world's sixth largest copper resource and the world's largest uranium deposit (Hodgkison, 1998). Western Mining Corporation Ltd. discovered it in 1975 during an exploration program based on a geologic model for sediment-hosted copper deposits. The model postulated that oxidation of basaltic rocks could release significant amounts of copper into groundwater. Under favorable conditions, this groundwater 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.

Geological interpretation of the deposit has evolved since its discovery. Geological 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, future exploration strategies at this and other similar sites have improved.

Because the Olympic Dam deposit is considered 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 Kiruna district (Sweden), Bayan Obo (Mongolia), and Pea Ridge (United States) (Pratt and Sims, 1990, p. 1).

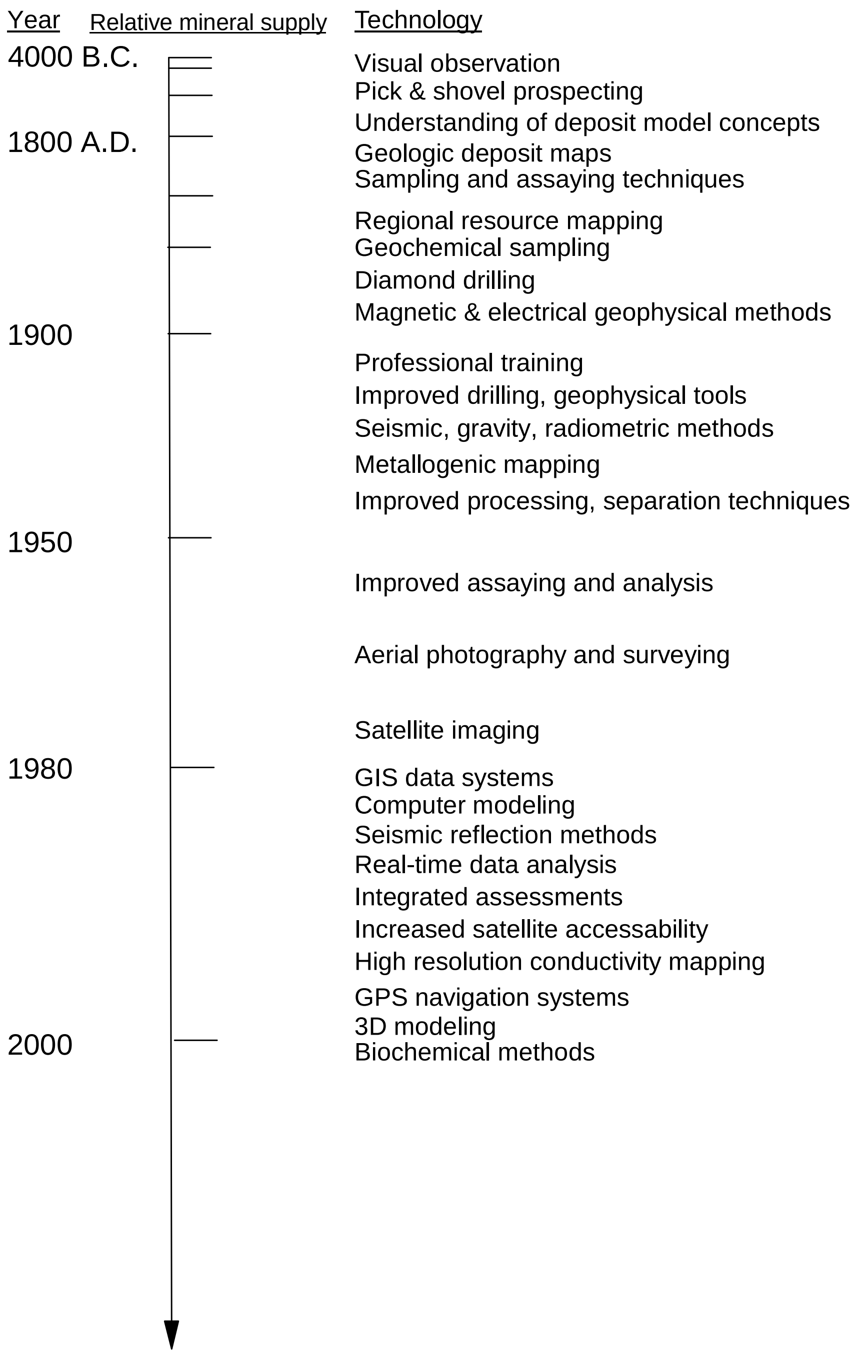
With the computer age came the ability to predict ore body structures and quantify deposit potential by means of systematic modeling. Computers now allow field teams to transmit data instantaneously back to the company, and speed up compilation and analysis of large volumes of data. Based upon these analyses, company economic guidelines, and current supply-demand conditions, a company can now evaluate a site (perform a feasibility study) to determine if the deposit has sufficient potential for further capital expenditure or development.

By the end of the 20th century, mineral exploration used sophisticated models based on integrated science, relying heavily on computer-based modeling. High resolution spectral photography and geophysics provided a means to begin identifying areas with mineral potential without the need to visit some remote sites and disturb environmentally sensitive areas. The quantity and sophistication of mineral deposit models now require multiple stages of mineral exploration. A series of favorable exploration "targets" are identified during reconnaissance exploration, often using airborne exploration techniques. Target areas are then investigated in detail 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 revised models, reinterpretation of data, or changes in technology.

The advent of digital mapping, global positioning (GPS) and computer-aided drafting (CAD) systems, satellites, and computers has allowed companies and national and international science agencies to collect, analyze, and store massive amounts of data on the Earth and its resources. The U.S. Geological Survey holds one of the world's largest international collections of land-surface image maps collected from aircraft data blanketing the United States and from satellite data. This collection is held in the Distributed Active Archive Center (DAAC) formerly knows 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 has begun to collect data on global change through the development and distribution of satellites that will 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 23. This diagram shows that only a very small fraction of the total available supply of minerals had been discovered by 1800 using technology available to that point. More mineral resources were discovered between 1800 and 1900 than had been discovered in the preceding 4,000 years as geologic understanding improved and basic exploration methods and better mineral-deposit models were developed. In each succeeding time block, a significantly greater amount of resource was identified in progressively shorter periods of time. World mineral production followed the same general trend. Data for individual types of mineral resources also follow this trend. For example, more copper was produced to satisfy human needs in the past 40 years than in the preceding 60 centuries (Themelis, 1994).

Figure 23. Comparative timeline of exploration technology and resource supply[1].



[1] Not drawn to scale.

Advances in technology associated with mineral exploration and processing both 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, future refinement of geologic models should continue to increase the discovery of additional mineral resources within the Earth.

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APPENDIX 2 – ALUMINUM CASE STUDY

INTRODUCTION

Although aluminum ore, which is primarily bauxite, is abundant and relatively easy to mine, the process to extract the aluminum from bauxite is complex and energy-intensive. Aluminum recovery is essentially a 2-stage process. First, bauxite is converted to alumina (Al_2O_3) by a chemical refining process. Then, the alumina is reduced to metallic aluminum by means of an electrolytic smelting process. Technological advances in both stages of production have subsequently reduced the cost and thereby increased demand for aluminum. World production and prices are shown in Figure 24, where major technological developments in the aluminum industry also are indicated.

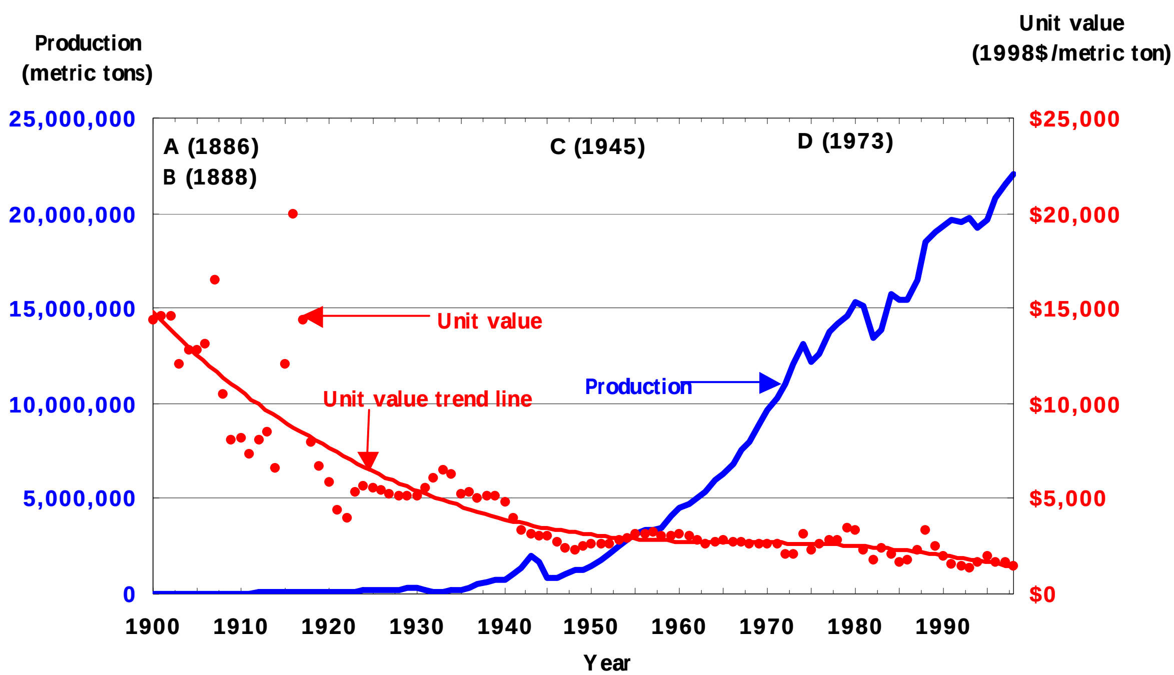

Figure 24. World aluminum production and unit value, 1900 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001). The unit value (1998$/metric ton) is defined as one metric ton of aluminum apparent consumption, estimated from the "Annual Average Primary Aluminum Price" in U.S. dollars, as reported by U.S. Geological Survey, 1999a, p. 3., divided by the Consumer Price Index with a base year of 1998. The unit value trend line was fitted as sixth-order polynomial. Letters A-D indicate major turning points 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 nineteenth-century. Aluminum is the second most abundant element in the Earth's crust after silicon (U.S. Bureau of Mines, 1987) but exists only in combination with other elements and is difficult to separate. The first commercial aluminum, a few grams, was produced in France in 1854 using a sodium reduction process patented by Deville. This first aluminum was valued at about $600,000 per metric ton (ton[1]) 1986 dollars, making it more expensive than gold or platinum. By 1860, the price had been cut in half, but the only uses for aluminum were for jewelry, snuff boxes, spectacle frames, and chalices for church liturgies (Ravier and Laparra, 1986).

In 1886, Charles Martin Hall (U.S.) 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 (A, figure 24). A chemical process to commercially produce alumina from bauxite, the Bayer process was patented by Karl Bayer, of Germany, in 1888 (B, figure 24). The effect of these two technological innovations was to reduce the price of aluminum, in 1998 dollars, from $320,000 per metric ton in 1887 to about $14,000 per metric ton in 1900. The first aluminum companies were founded in France, Switzerland, and the United States in 1888. One hundred years later, both of these techniques still are used extensively by the aluminum industry.

The modern aluminum industry is composed of two principal producing segments, the primary industry and the recycling industry (Figure 25). 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.

[1] Tons, when used throughout this report, refer to metric tons.

Fabrication of aluminum metal into marketable products is essential to both sectors of the industry. Technological events significant to the development of aluminum resources are the subjects of this report.

Figure 25. Components of the aluminum industry

<u>Primary aluminum industry</u>

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

<u>Aluminum recycling industry</u>

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

Figure 25. Components of the aluminum industry.

Aluminum did not become a major commodity until World War II. Prior to the beginning of the twentieth century, annual world aluminum production was less than 7,000 tons. By 1939 (see Figure 24), world production had increased a hundred-fold to a little over 700,000 tons (U.S. Bureau of Mines, 1933-96, Minerals Yearbook, 1932-94, chapter on aluminum). The greatest production growth occurred between 1940 (800,000 tons) and 1998 (22,000,000 tons). Aluminum demand for this period grew at a compounded annual rate of just under 6 percent (U.S. Bureau of Mines, 1933-96, Minerals Yearbook, 1932-94, chapter on aluminum; U.S. Geological Survey, 1997-2000, Minerals Yearbook, v. 1, 1995-98, chapter on aluminum). Concomitantly, aluminum prices reported in 1998 constant dollars actually declined by two-thirds (Plunkert, 2000a).

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 entire 110-year history of the aluminum industry. Bauxite production and price history since 1900 is shown in figure 26. Nonbauxitic sources having the best potential for aluminum recovery are alunite, high-alumina clays, and aluminous igneous rocks such as nepheline syenite; other potential sources include dawsonite-bearing rocks, aluminous phosphate rocks, saprolite, aluminous metamorphic rocks, aluminous shale, coal waste, and coal ash. Commercial extraction of aluminum from any of these resources was not feasible until the development of the Bayer and Hall-Héroult processes, which first provided the means for commercial recovery of aluminum from bauxite.

Nonbauxite aluminum resources have been produced regionally or for nonmetallurgical applications where available bauxite resources are of poor quality or not readily available. Countries such as the United States, which has limited high-grade bauxite resources, have conducted research to develop more cost-effective processes to recover nonbauxite aluminum resources. To date, however, it has been cheaper to import foreign bauxite than to process domestic nonbauxite resources. While some nonbauxite resources were mined in Europe in the past, the only region producing aluminum from nonbauxite resources is the former Soviet Union (FSU) where aluminum is produced from nepheline and alunite 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

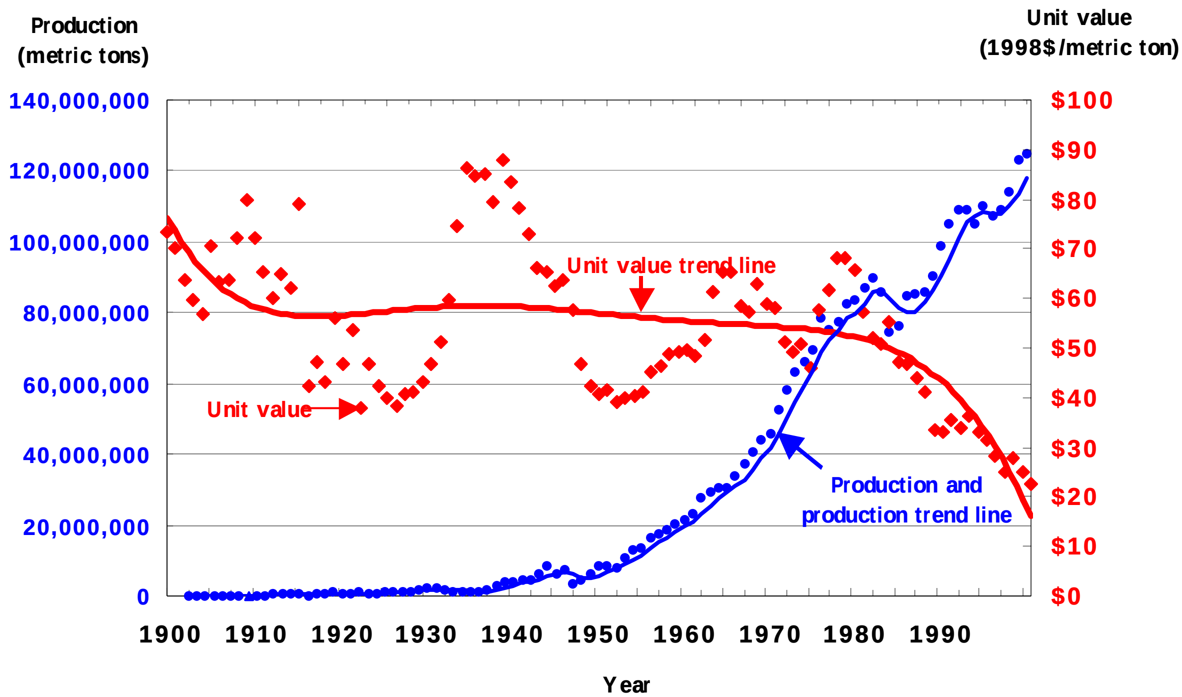

Figure 26. World bauxite production and unit value, 1900 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001). The unit value (1998$/metric ton) is defined as one metric ton of bauxite apparent consumption, estimated from the annual average bauxite price in U.S. dollars, divided by the Consumer Price Index with a base year of 1998. The unit value trend line was fitted as sixth-order polynomial, the production trend line reflects a four-year moving average.

materials that can be used when national self-sufficiency is more highly valued than cost. Of the 10 refineries operating in the Soviet Union in 1991, four used the conventional Bayer process to recover bauxite, two used the Bayer-Sinter process to recover bauxite with high silica content, three refineries processed nepheline syenite ore, and one processed alunite ore. Recent 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 bauxite mining technology involve technological improvements such as larger size equipment, which increase productivity and efficiency. 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.

In spite of growing demand for aluminum, large resources exist globally. Although bauxite resources are unevenly distributed throughout the world, with about 90 percent of the known reserves in about a dozen countries, the sheer magnitude of these resources (55 - 75 billion tons) is sufficient to meet projected needs for the 21st century (Plunkert, 2000b).

ALUMINA PRODUCTION TECHNOLOGY

The 110-year old Bayer process (figure 27) is still the most widely used method of converting metallurgical-grade bauxite to alumina (U.S. Bureau of Mines, 1987). In this chemical process, bauxite is washed, ground, and dissolved in caustic soda (sodium hydroxide) at high pressure and temperature. Red mud residue is removed by decantation and filtration, and alumina hydrate is crystallized then dried under very high temperature to form the white powder known as alumina. Variations on this process

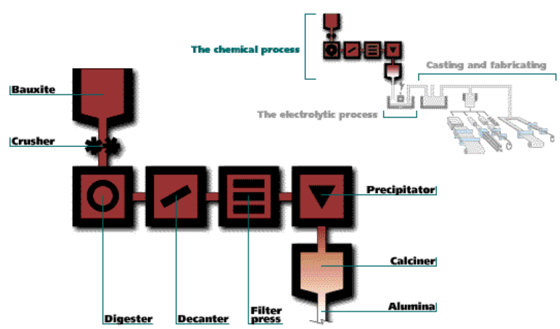

Figure 27. The Bayer process. (Photo from Alcan Aluminium Limited, from their web site at http://www.alcan.com/markets.nsf/Topics-E/Making. (Accessed October 27, 2000.)

uxite. Most European and north Asian bauxites processed using the European Bayer process; most bauxite from other regions contain the mineral gibbsite and are processed using 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 preferentially near sources of low-cost energy. Technological advances in alumina processing followed the same pattern as aluminum processing, progress was characterized by a series of gradual improvements accelerated by WWII. In 1915, the Martinswerk plant in Germany required 3 tons of bauxite and 7 tons of coal to produce one ton of alumina . By the time the Gove plant in Australia was constructed in the 1980's, technologic improvements had modified the alumina production process such that the new plant only required about 2 tons of bauxite and only 0.3 tons of coal to produce one ton of alumina (Peterson, 1986, p. 147)

As energy efficiencies were achieved after World War II, and transportation costs and international competition increased, energy availability and transportation costs became prime factors for site selection (Peterson, 1986, p. 147). Newer plants often were located near resources or markets; local energy sources were then developed to provide power. This led to the development of plants in areas such as Western Australia and South America at the expense of the higher cost plants in Europe and the United States. While 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 economic 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, more environmentally friendly technology was implemented at many smelters in the 1970's, but these smelters could only process alumina with high adsorptive capacities of the "sandy" type. By the mid 1980's, most of the older "floury" plants had been forced to close or convert to the newer technology. Several new "sandy"-type plants can on line during this period.

ALUMINUM PRODUCTION TECHNOLOGY

The Hall-Héroult process (figure 28) is a reduction process where alumina is dissolved by passing an electric current through a molten electrolyte contained within an electrolytic cell or "pot," which requires large amounts of electricity, at least 13 kilowatt-hours per kilogram of aluminum, to break the aluminum-oxygen chemical bond (International Primary Aluminium Institute, 2000). The desire to keep energy costs as low as possible motivated the developing aluminum industry to continue to improve technology. Most of the early plants were located near cheaper, hydroelectric energy sources. The Pechiney Company, in France, purchased numerous waterfalls throughout France and Switzerland just to gain access to inexpensive power (Ravier, 1986, p. 17). In the United States, the Pittsburgh Reduction Company and its successor, the Aluminum Company of America, began during the late nineteenth century and early twentieth

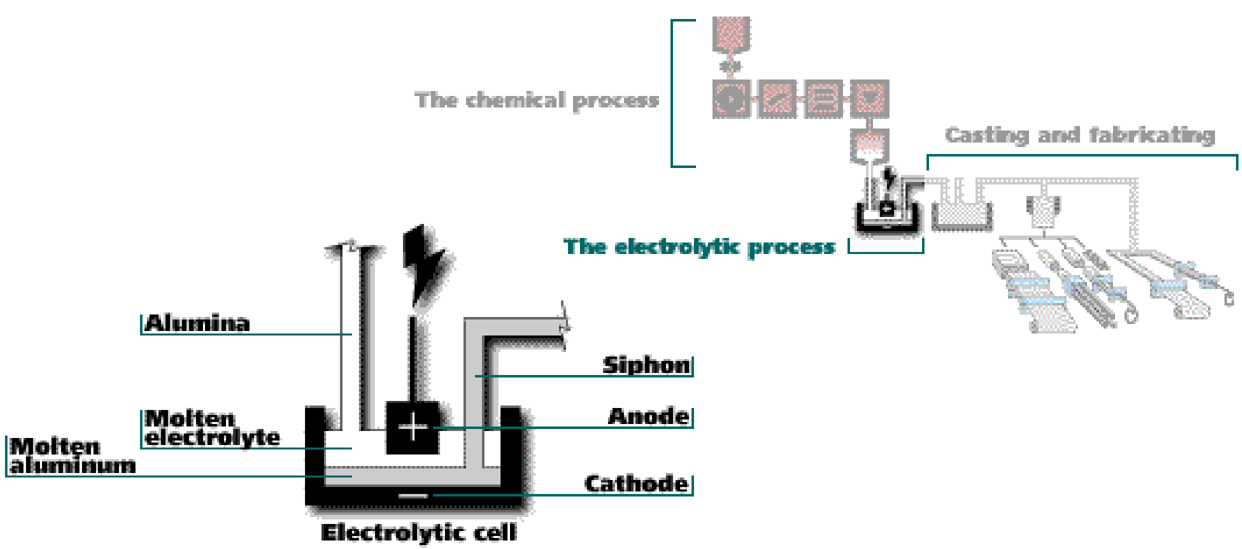

Figure 28. The Hall- Héroult electrolytic cell. (Photo from Alcan Aluminium Limited, from their web site at http://www.alcan.com/markets.nsf/Topics-E/Making. (Accessed October 27, 2000.)

century to acquire bauxite fields, develop hydroelectric projects, and construct fabricating facilities in the United States and Canada to support their aluminum production facilities. Most U.S. aluminum smelters are located in close proximity to low-cost hydroelectric energy sources, such as in the Pacific Northwest, 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 middle twentieth century fostered smelter construction. As a result, the aluminum industry expanded rapidly in the 1960's and 1970's.

The price of aluminum started to drop after 1900 (See Figure 24) as processing and energy efficiencies began to be achieved. Although the basic production process has changed little since its inception, progress has been made in increasing cell size while reducing cell energy consumption, with attendant increased efficiencies in labor and productivity. Table 3 compares key cell performance results for selected years.

Cell parameter	**1900**	**1945**	**1995**
Cell amperage (kA)	5-15	25-50	175-300
Cell voltage (V)	NA	5.0	4.1
Current efficiency (%)	70-80	80-85	92-95
Energy consumption (kWh/kg Al)	35	20-25	13
Cell production capacity (t/year)	15-20	55	820

NA: Not available; kA: 1000 amps; V: volts; kWh/kg Al- kilowatt/hours per kilogram of aluminum produced; t/year: tons per year.
Sources: (Grjotheim and others, 1995; Ǿye and Huglen, 1990; and Peterson, 1986)

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

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. Between 1900 and 1945, the average worldwide cell amperage and capacity increased about 300 percent and energy consumption decreased by about 64 percent (Peterson, 1986, p. 113; Ǿye and Huglen, 1990, p. 24). Since 1945, however, the average worldwide cell amperage has increased about 600 percent, production capacity increased about 1500 percent, and energy consumption decreased a further 58 percent (Grjotheim and others, 1995). Worldwide labor productivity has increased from about 7 tons per worker to about 200 tons per worker in the last 50 years (Grjotheim and others, 1995).

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 Soderberg reduction technology, mercury-arc rectifiers for electrical conversion, new high-strength alloys, and die-casting methods made it possible to produce the large quantities of aluminum sheet necessary for the war effort (C, figure 24). Technological developments in all phases of production during the war period increased the versatility of aluminum, leading to diversified and expanding postwar markets (U.S. Department of Commerce, 1956). Aluminum began to be used extensively in commercial aircraft and automobiles, wiring and machinery, and in containers and packaging. 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. The unit price for aluminum in 1998 dollars (see figure 24) has decreased from about $5,000 per ton in 1925 to about $1,400 per ton in 1998.

Improvements in fabrication technology, such as development of mini-mills and thin-sheet technology, gradually allowed thinner sheets of aluminum to be produced and complex shapes to be stamped and formed (Point D, figure 24). The fabrication process is illustrated in figure 29. Aluminum was first introduced into the can manufacturing process in the 1960's, and aluminum can sales grew from 2 percent in 1964 to approximately 100 percent of the beverage can market in 1999 (U.S. Bureau of Mines, 1991; Aluminum Association, 2000).

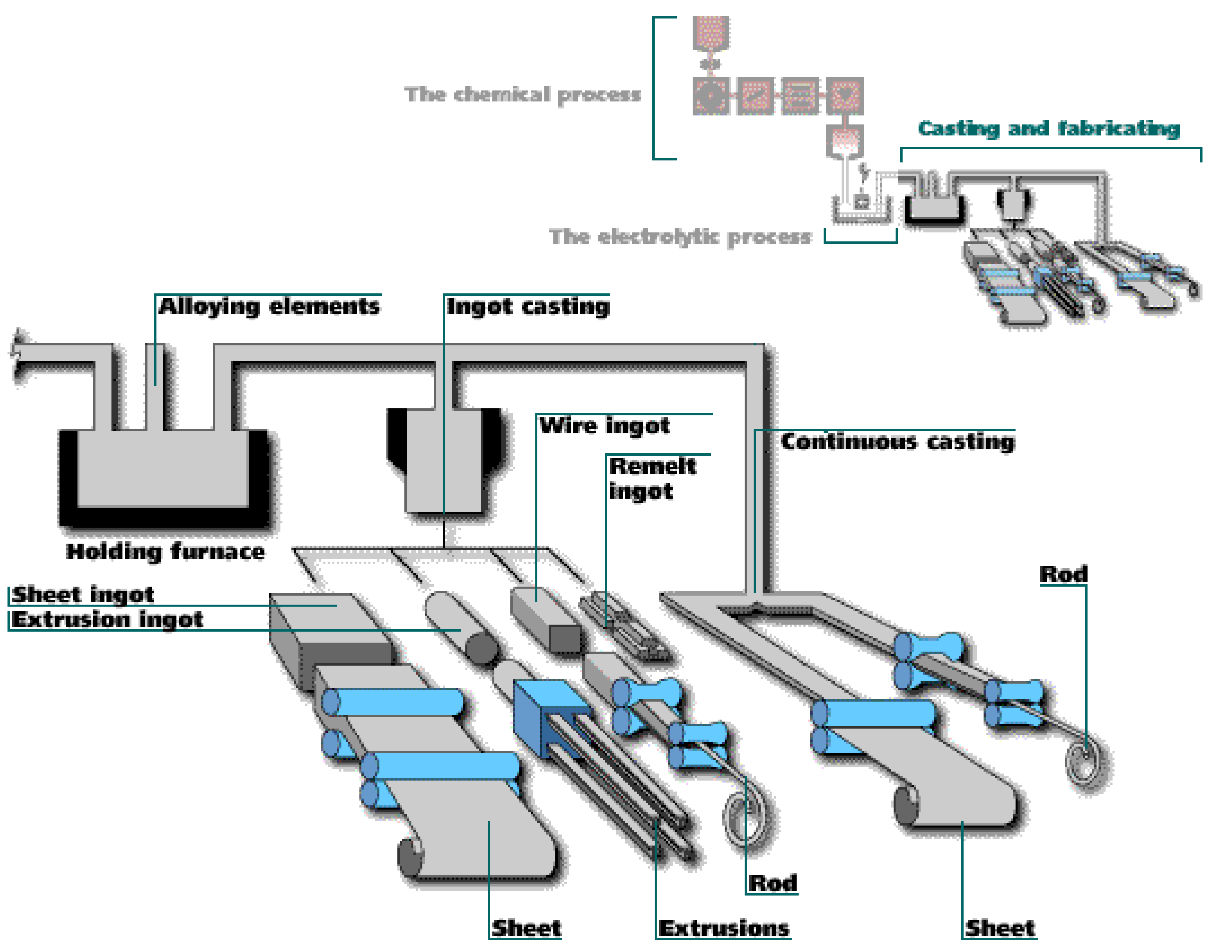

Figure 29. The aluminum casting and fabrication process. (Photo from Alcan Aluminium Limited, from their web site at http://www.alcan.com/markets.nsf/Topics-E/Making. (Accessed October 27, 2000.)

RECYCLING TECHNOLOGY

One of the advantages of aluminum is that it is easily recyclable. The aluminum recycling industry, also called the secondary aluminum industry, began about 1904 to process scrap from the primary aluminum industry. The amount of energy required to produce one ton of recycled aluminum is about five percent of the energy required to produce one ton of primary aluminum from bauxite (Wilburn and Wagner, 1993). 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 favorable economics. Figure 30 shows aluminum production for both the U.S. primary and secondary aluminum industries.

Some technical advances in alloying and die casting during World War II were developed specifically for the aluminum recycling industry (The Aluminum Association, 1985). Technology also was developed during the 1950's that allowed improved separation of aluminum from scrapped automobiles. Recycling of aluminum products increased dramatically in the 1970's when the recyclable aluminum beverage can began to be widely used. Increased public concern for the environment, and State beverage container deposit legislation and resulting consumer aluminum recycling programs in the 1980's, further increased aluminum recycling efforts. Between 1950 and 1974, aluminum recovered from old (post-consumer) scrap accounted for approximately five 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

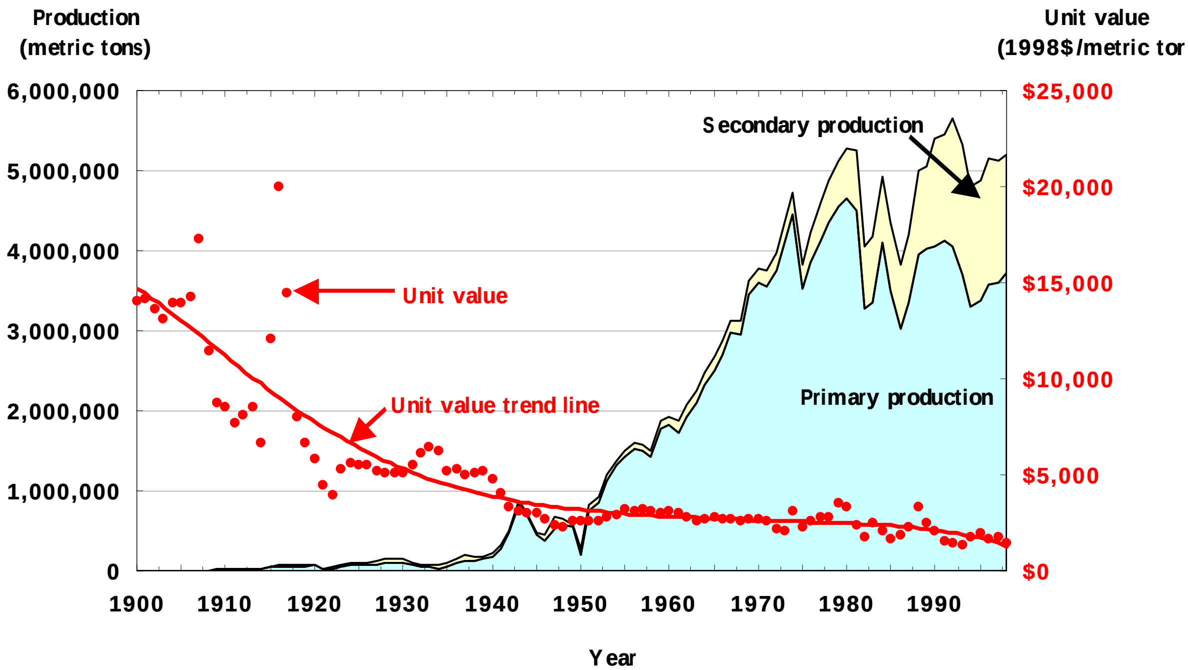

Figure 30. U.S. primary and secondary aluminum production and primary aluminum unit value, 1900 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94; and the U.S. Geological Survey, 1900-27, 1995-2001). The unit value (1998$/metric ton) is defined as one 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 U.S. Geological Survey, 1999a, divided by the Consumer Price Index for that commodity with a base year of 1998. The unit value trend line was fitted as sixth-order polynomial. Area charts for primary and secondary production are cumulative.

metal (U.S. Geological Survey, 1999). As shown in figure 30, there has been a general decline in U.S. primary aluminum production over the past 20 years; however, production of secondary aluminum has generally increased, allowing the industry as a whole to grow

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FUTURE DIRECTIONS

The driving force for developing new processes for aluminum smelting usually centers around one of three factors: electrical energy reduction, capital 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. Electric current efficiencies in excess of 96 percent can be obtained from new technologies, and equipment using older technologies can be retrofitted to perform at 95 percent efficiency. Emphasis is currently on developing plant designs with a low capital cost per unit production while complying with environmental requirements.

Since 1980, five alternative aluminum processing types have been under study, and each faces challenges similar to those of 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. Current 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 small but cumulative improvements. The aluminum industry initially was stimulated by the development of Hall-Héroult and Bayer processing technologies at the end of the 19th century. Since then, small gradual improvements on basic technology have allowed the U.S. industry to grow and remain competitive. Technological developments during World War II increased the adaptability and versatility of aluminum, leading 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 has grown 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. Near-term technological advances are likely to be incremental and expensive.

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APPENDIX 3 – COPPER CASE STUDY

COPPER PRODUCTION HISTORY

Humankind has found uses for copper metal for 6,000 years. At first, copper was used for simple weapons, tools, and ornaments. Today, copper is a critical metal in electrical transmission, electronic equipment, pipes for fluid transport, and many other products (Arbiter and Fletcher, 1994, p. 118).

Figure 31 shows, by decade, the growth in the per capita consumption of copper over a 90-year period, beginning in 1900. Per capita consumption is defined here as world copper produced from mines, 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. However, this has not been the case, and this appendix explains how copper production has managed to keep pace with copper demand.

Throughout the 20th century, copper resources and metal production have expanded to meet an ever-growing demand for copper. Technological advances[1] 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.

Figure 32 shows world copper production for the 20th century. World production reflects both increased demand based on population growth and increased intensity-of-use.

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

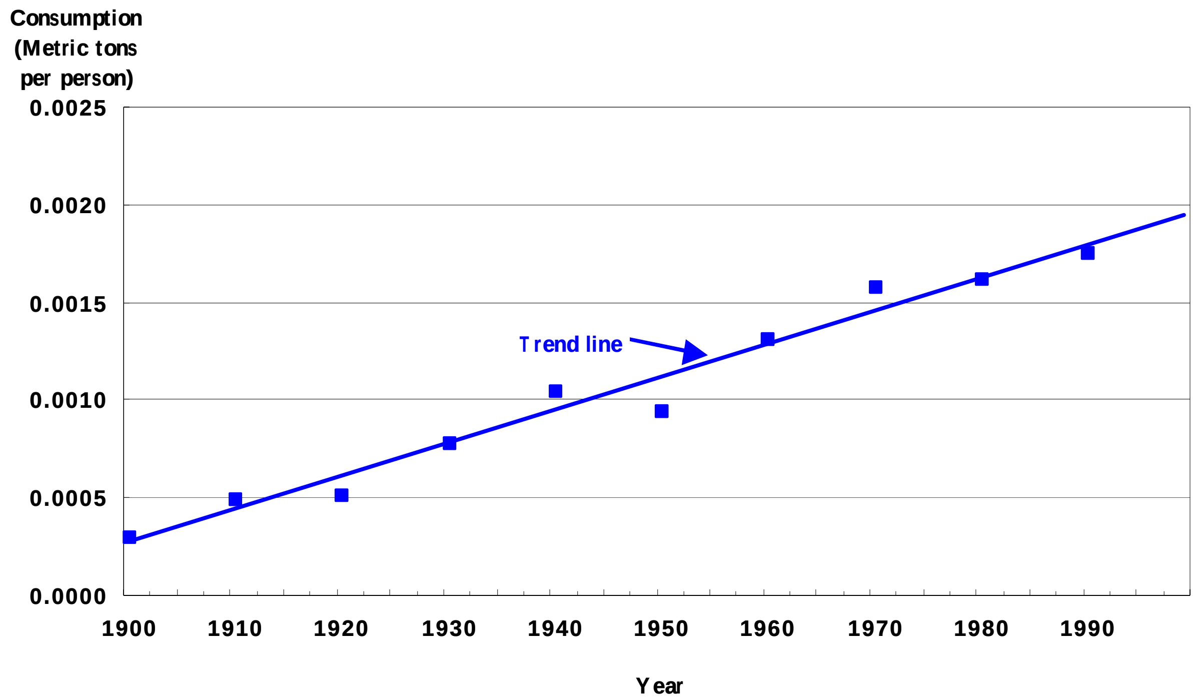

Figure 31. World copper per capita consumption, 1900 to 1990. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001); and U.S. Bureau of the Census, 2000, Historical Estimates of World Population, from their web site at http://www.census.gov/ftp/pub/ipc/www/worldhis.html. (Accessed November 21, 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.

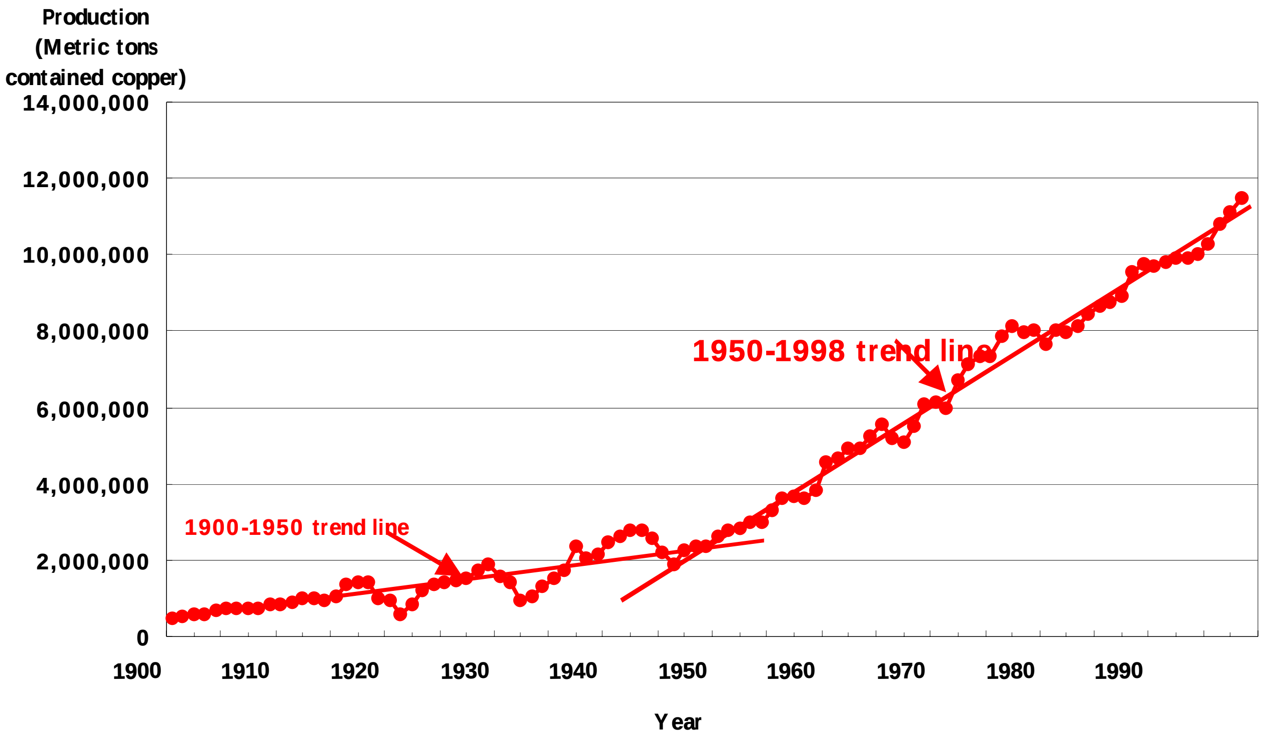

Figure 32. World copper mine production, 1900 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001). Linear trend lines were plotted.

In 1900, world copper mine production was about 500,000 metric tons[2] of contained copper, and it came mainly from high-grade (around 2.5 percent copper) veins and contact zones found in or near deposits containing large quantities of much lower grade copper ore. By 1930, world mine production had quadrupled to approximately 2,000,000 tons 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 substantially beginning in 1950, growing from 2,400,000 tons to 12,200,000 tons in 1998.

Figure 33 shows the growth of U.S. copper production from 1900 to 1998, together with the change in constant dollar (1998) copper unit values (prices) over the period. The linear trend lines

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[2] Tons, when used throughout this report, refer to metric tons.

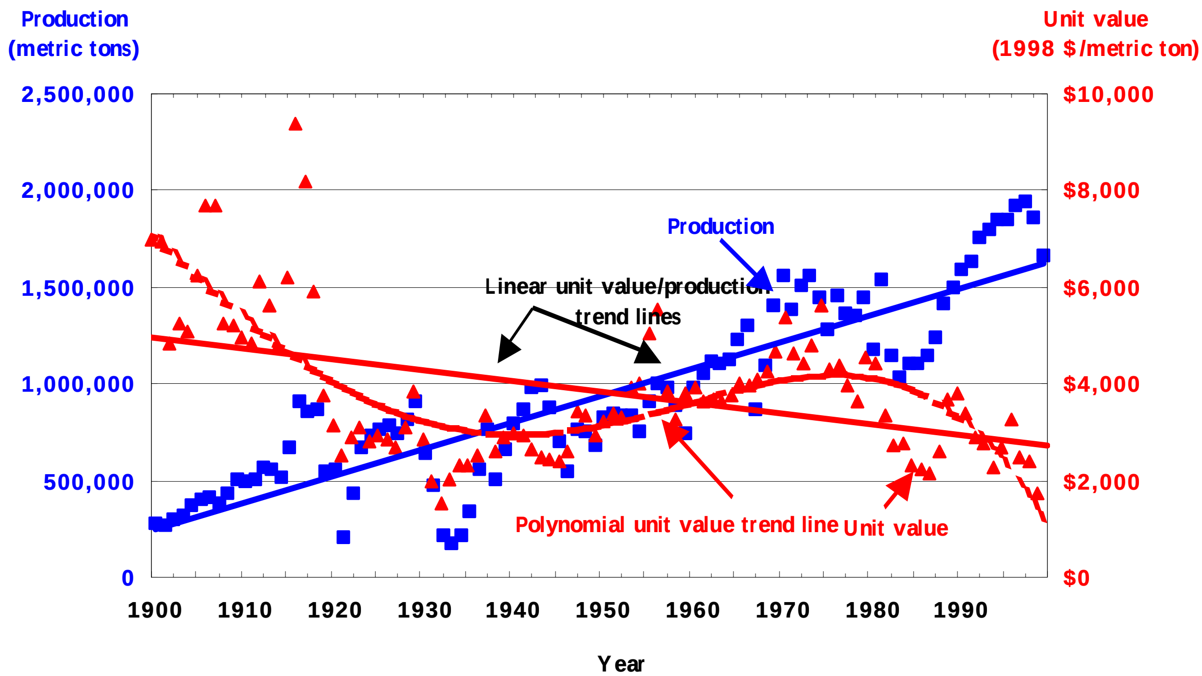

Figure 33. U.S. mine production of copper and U.S. unit value, 1900 to 1998. The unit value (1998$/metric ton) is defined as one metric ton of copper apparent consumption, estimated from the "Annual Average U.S. Producer Copper Price" in U.S. dollars, as reported by U.S. Geological Survey, 1999a, p. 42, divided by the Consumer Price Index with a base year of 1998. The unit value trend line was fitted as a fourth-order polynomial.

for production and price show that supply has increased while prices have fallen. The polynomial trend line shows that the overall downward trend in prices is segmented with periods of rapidly falling prices, and periods of stagnant, or even slightly rising prices.

In figure 33, one can see that constant dollar (1998) prices between 1900 and 1999 for copper might be characterized as follows: 1, volatile, as shown by the variance from the trend lines; 2, trending variably, as shown by the slope changes of the polynomial trend line; and 3, generally trending downwards, as shown by the slope of the linear trend line. From 1900 to 1932, constant dollar copper prices trended downwards, decreasing at the rate of about 3.2[3] percent per year. Between 1933 and 1974, constant-dollar copper prices showed an upward trend, increasing at the rate of about 1.8 percent per year. Between 1975 and 1998, constant-dollar copper prices again trended downwards, decreasing at the rate of about 2.0 percent per year. Over the entire 1900-1998 period, constant-dollar copper prices have shown a generally downward trend, decreasing at the rate 0.6 percent per year. For each period, whether price increased or decreased, there was short-term price volatility. For example, when the United States became involved in World War I, 1916 – 1917, copper prices almost doubled (see figure 33).

U.S. mine production of copper was 275,000 tons in 1900, 56 percent of world mine production, and 1,660,000 tons 1999, 13 percent of world mine production. The reduction in U.S. market share, even while copper production was increasing, can be attributed to the proliferation of mining investment, technology, and opportunity throughout the world, especially in Latin America. Until about 1932, over half of world mine production was from the United States; since 1932, however, growth in world mine production, which has been about 4 percent, compounded annually. World mine production growth has outpaced the growth in U.S. production, which is about 2.4 percent, compounded annually.

[3] The rate calculated is a compound rate for the period 1900 – 1999, and was calculated by taking the values at the ends of the linear trend line running through the price data as estimates for the present and future value parameters.

Figure 34 shows U.S. production by process and material type. U.S. refined copper production grew from 300,000 tons in 1900 to about 2,500,000 tons in 1998, a compound annual growth rate of 2.2 percent.

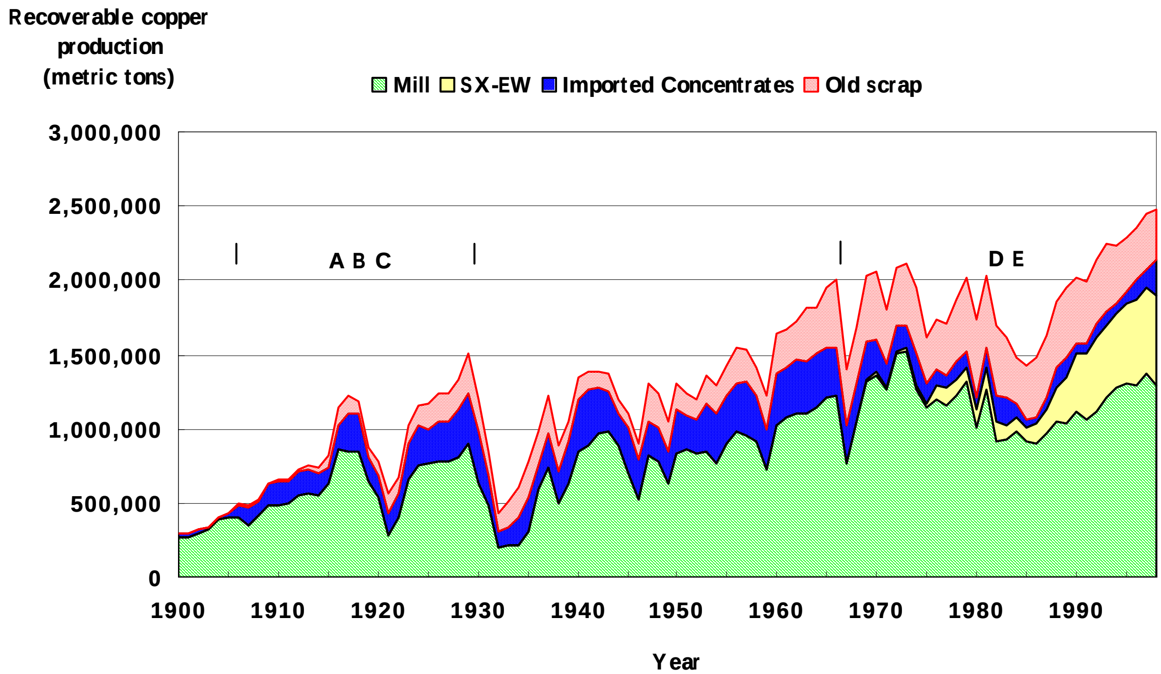

Figure 34. U.S. copper production, by component, 1900 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001). The unit value (1998$/metric ton) is defined as one metric ton of copper apparent consumption, estimated from the "Annual Average U.S. Producer Copper Price" in U.S. dollars, as reported by U.S. Geological Survey, 1999a, p. 42, divided by the Consumer Price Index with a base year of 1998. Letters A-E indicate major turning points in the history of copper production: A, Large-scale open-pit mining techniques were first demonstrated 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; and E, Oxygen "flash" smelting began production in 1970.

In general, prices reflect the momentary relationship of supply to demand. If supplies were restricted, one would expect that increasing demand would lead to an upward price trend over time. The general trend for metals demand has been upwards, and U.S. copper production has

> 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. (Lambert, 1996).

followed that trend (figures 33 and 34). Since prices for most metals have been trending downwards (See figure 2), 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 – 1932, and 1975 - 1998) correspond to the periods of investment in technology that allowed the processing of increasingly lower grade copper ores.

With perhaps the exception of technology that is mandated for environmental or other regulatory reasons, the introduction of new technology is generally aimed at improving overall productivity and reducing costs. When the differential between market prices and production costs narrows, one possible response is to look to technology for cost reductions.

TECHNOLOGY AND MANAGEMENT OVERVIEW

“Capital investment is usually the route by which technical advance is put into practice. This often means that its effect is time-lagged. The capital intensity of the [copper] industry makes it hard to adopt new processes on a wholesale basis. The rate at which capital stock is added or replaced is constrained by lead-time for approvals and permits. For these reasons, technology management within the minerals industry is often a process of ‘adaptation’ rather than outright ‘adoption’” (Groeneveld, 1998).

While technological improvement is mainly incremental, it remains true that the copper industry has seen some major breakthroughs. Between the years 1905 and 1930, three major technological advances were concurrently implemented. These were large-scale open-pit mining, Pierce-Smith converters, and sulfide flotation, (A, B, and C shown in figure 34, respectively).

Large-scale open-pit mining techniques were first demonstrated by Daniel C. Jackling at Bingham Canyon, Utah, starting in 1906, and have come to dominate world copper mining. (Utah History Encyclopedia, 2000). This mining method is discussed in greater detail in the next section.

For many years, only the high-grade veins and igneous contact zones in porphyry deposits were mined. However, utilization of large-scale open pit mining beginning in 1906 allowed the efficient, economical recovery of millions of 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, and by 1920 had spread throughout the world. Taken together, these extractive and process advances are responsible for the growth in worldwide porphyry copper reserves as shown, for the years where data are available, in the accompanying box.

Estimated World Copper Reserves (Million metric tons contained metal)					
1930	1950	1960	1970	1982	1998
80	91	154	280	350	330

(Source: Daniel Edelstein, USGS, oral commun., 2000)

According to Hyde (1998), investment in materials processing equipment for U.S. copper production between 1920 and 1970 was incremental and included such advances as block caving for underground mining, larger shovels, and diesel-electric motors for haul trucks. As a result, productivity improvement was also incremental. Nonetheless, the largest capital outlays during this period were for foreign properties having higher ore grades. The period also includes innovation in the area of organizational and administrative technology, beginning with an attempt to form a domestic copper production cartel during the 1920’s, and later an international copper cartel to restrict production. During the 1950’s, efforts were made to get the U.S. government to stockpile copper. Large corporations paid out as much as 80 percent of earnings to stockholders. Several porphyry copper deposits were discovered by the oil industry in their search for oil (Hyde, 1998).

Since 1970, oxygen “flash” smelting (E, figure 34), has reduced energy input at copper smelters and improved air quality by lowering smelter emissions. 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 (SO_2) 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. However, the combined operating-cost savings and capacity increases were insufficient to recover the capital investment (E&MJ, 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 (see D, figure 34).

Technological advances have permitted the economic recovery of copper from progressively lower grade, more chemically diverse ores. Figure 35 shows the apparent decline in world copper ore grades since 1750. At the time of the American Revolution (1775 – 1783), the average grade of copper ore processed was about 13 percent. During the War of 1812 (1812 – 1815), the average grade had dropped to about 9 percent, and at the time of the Mexican War (1846 - 1848), the

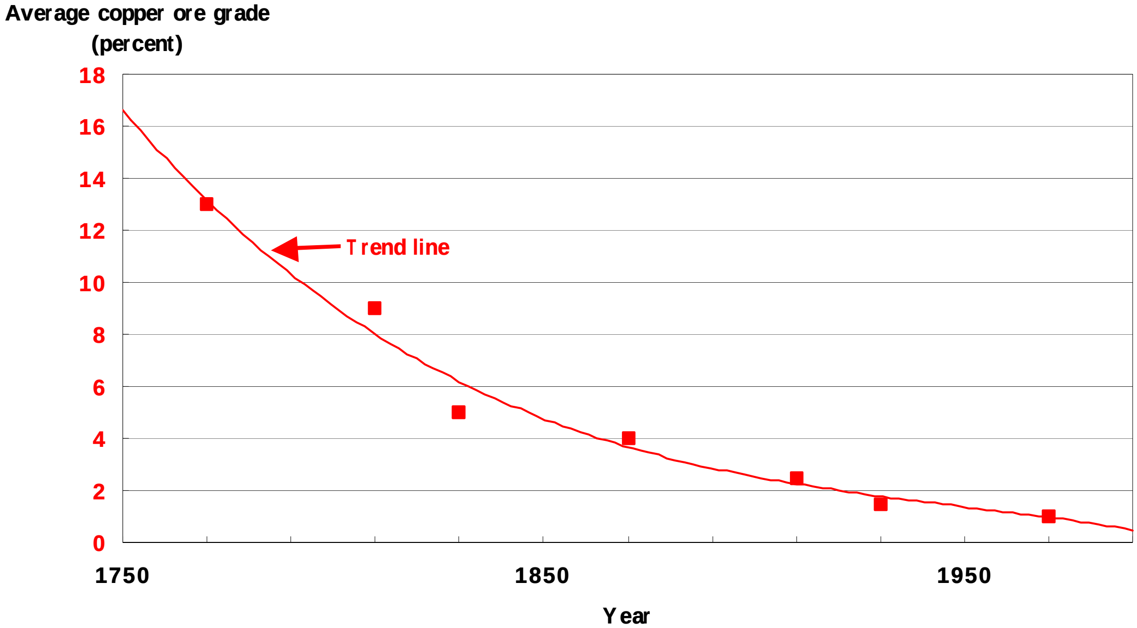

Figure 35. Historical copper industry ore grades. Data adapted from Groeneveld, Oscar, 1998, Technology – The technology environment for the 21st century—the mining industry: In Australia's future: new technology for traditional industries. The Australian Academy of Technological Sciences and Engineering web site at http://www.atse.org.au/publications/symposia/proc-1998p1.htm. (Accessed October 31, 2000.) The trend line was fitted as a third order polynomial.

average grade had decreased to about 5 percent. During the Civil War (1861 – 1865), 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 contain less than 0.5 percent copper, and some oxide ores containing less than 0.2 percent copper are being mined using SX-EW.

Figure 36 shows the overall trend of decreasing copper mill yields[4] for the 20th century. Yield is not equivalent to ore grade, but it is close enough to be an indicator of grade. Figure 36 shows the same trend as figure 35, that is, downward trends in copper ore grades over time. The large peak associated with the Great Depression, 1932 – 1933, results from mines taking steps to

[4] Yield (in copper mill lexicon) = all of the copper coming out of the mill in a given year as a percentage of total ore input to the mill. The calculation for the years 1960 – 1998 was adjusted to exclude leach ores, because of data reporting anomalies.

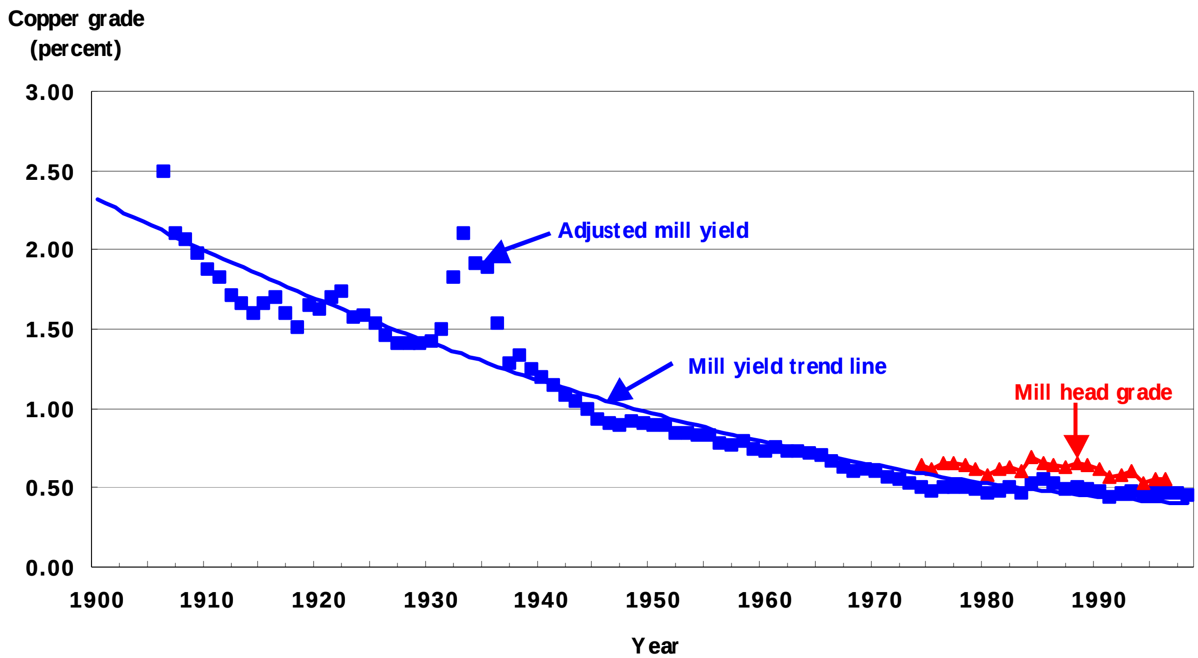

Figure 36. U.S. adjusted mill copper yields, 1906 to 1998, and head grades, 1974 to 1996. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001).

improve short-term yield. Such steps included high-grading ores, closing marginal facilities, or leaching waste dumps.

As discussed previously, copper prices are determined by many factors, one of which is the need for producers to recover costs. Decreasing ore grades normally could be expected to lead to increased production costs, as 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 another way to maintain or lower production costs. Copper prices, in constant dollar terms, gradually declined through the 20th century (see figure 33). Declining copper prices, and (or) increasing production costs, narrow profitability and tend to stimulate copper companies to invest in productivity-increasing technologies. Management technologies such as reorganization and improved administration are directed primarily towards improving labor productivity. By contrast, improved process equipment technologies work directly on production methods and usually are directed towards improving yield, decreasing materials handling costs, and (or) decreasing inputs of materials and energy.

RECYCLING

Scrap recycling, including the scrap industry organization, supporting infrastructure, and equipment selection and use, can be considered to be a technology that decreases commodity scarcity through a process of revaluing obsolete commodities-in-use. For that reason, a brief description of old copper scrap recycling is included here. Old copper scrap is post consumer scrap composed of obsolete or discarded products. Figure 37 shows the history of old copper scrap use as

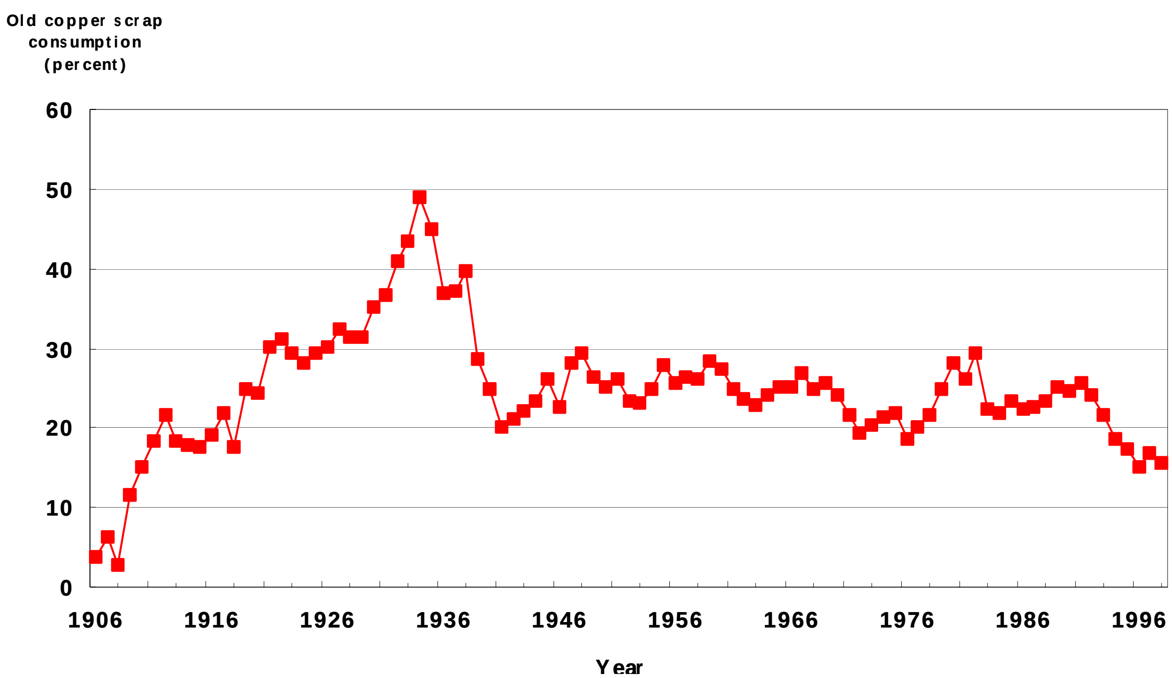

Figure 37. U.S. use of old scrap as a percent of U.S. apparent consumption of copper, 1906 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001).

a percentage of total U.S. apparent consumption of copper. Apparent consumption is defined mathematically as being equal to primary production + secondary production + net imports + stock changes.

As shown in figure 37, recycling of old copper scrap grew from a level of one percent to a level of 30 percent of total U.S. copper apparent consumption between 1906 and 1920. Except for the period 1929 to 1938, the time of the Great Depression, old copper scrap recycling has ranged mainly between 20 and 30 percent, averaging 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. Beginning in 1991, use of old copper scrap, as a percent of apparent consumption, apparently has decreased. Although this may be attributed to increasing copper consumption and longer lasting products, the principal reason for this decrease is that there has been an erosion of domestic processing capacity, and an increase of scrap exports. Depressed copper scrap prices during the 1990's discouraged collection and processing of scrap**.**

COPPER PRODUCTION TECHNOLOGIES (FIGURE 34, A – E)

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

OPEN PIT MINING (A)

Incremental improvements in bulk materials-handling equipment helped to 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 those illustrated in figure 38. By 1985, production had reached 60 percent. Most of the mine closures that have occurred during the 1980's and 1990's have been higher-cost underground mines, and most of the new mine expansions have been open pit. Currently, over 80 percent of the world's copper comes from open-pit mines.

Open Pit Mine Startups	
Bingham Canyon, Utah	1905
Ely, Nevada	1908
Cananea, Mexico	1910
Chuquicamata, Chile	1910
Miami, Arizona	1910
Morenci, Arizona	1937

Accompanying the growth of open pit mining were increases in equipment size and efficiency. Trucks, which today have payloads in excess of 300-tons, move material from deep open pits to processing facilities at the surface. As the pits have become deeper and deeper, in-pit crushing and conveyor transportation of crushed ore became prominent in the mid-1980's replacing trucks and trains. Investments in computerization helped to improve mine development, dispatch of equipment, and recovery-circuit yields. In the United States, open pit

Figure 38. Morenci open pit, Arizona.
(Phelps-Dodge Corp.)

mining methods like those for copper mining have been used extensively to mine industrial minerals, iron, and uranium.

Such improvements mainly are incrementally generated in response to the continuing need to increase productivity and 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 (B)

Pierce-Smith copper converting (see figure 39) was a technological breakthrough in copper smelting. It was implemented beginning in 1910 to treat copper mattes (metal mixtures) containing upwards of 45 percent copper, which typically are 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 39. Pierce-Smith converter, Chino operation, New Mexico. (Phelps-Dodge Corp.)

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 a gas, SO_2, 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 95 to 98 percent copper.

With the ability to produce 95 to 98 percent copper at lower cost than in the past, and with electro-refining resulting in a 99.999 percent copper product, this metal became available for applications requiring higher purity. Technology, therefore, was instrumental in meeting the expanding demand for high-purity copper for electronics and electrical transmission wire.

COPPER TECHNOLOGY ON THE DEMAND SIDE

While the bulk of this case study focuses on the relationship of technology to increased supply while maintaining, or even lowering production costs, it also is true that technology developments on the demand side, for example, the electric light and motor driven appliances, have significantly increased the demand for copper, spurring the search for ways to increase production.

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

More recently, the evolution of copper wire drawing has been toward ever-finer (smaller diameter) wires. Nano-size wires are smaller in diameter than a human hair and find application in the evolutionary development of faster, smaller, more powerful, and productive 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, one can expect that as long as there is an electrical services market and a major investment in copper production infrastructure, copper technologists will search for ways to recover any market share losses to silica and to find ways to expand copper production.

FLOTATION SEPARATION OF SULFIDE ORES (C)

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).

Sulfide flotation, illustrated in figure 40, 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 sulfides from the other metallic sulfides. Using sulfide flotation, copper can be concentrated from less than one percent to greater than 25 percent, making them economical to smelt. It also stimulated research into bulk crushing, grinding, and materials handling equipment. Chemical research into the surface forces that exist between dissimilar materials in close proximity led to new methods like 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).

Figure 40. Flotation cells, Chino, New Mexico. (Phelps Dodge Corp.)

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. But by the early 1920's, when the patent problems were overcome, sulfide flotation technology expanded throughout the world. The first large-scale application of a process similar to present flotation practice in the United States was begun 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 poly-metallic ore bodies, that otherwise would have been too complex to process. The San Martin deposit in Zacatecas, Mexico, for example, uses flotation to recover metals from ores containing 1 percent copper, 4 percent zinc, and 0.5 percent lead, together with byproduct silver, cadmium, gold, 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 mineable copper veins. With the advent of sulfide flotation and open pit mining techniques, the porphyry copper deposit that underlay the area became the dominant target of mining and such that the site is now one of the world's largest copper mines (Mikesell, 1979). By making these complex types of deposits attractive for exploration, world copper resources were expanded. By 1916, output from porphyry copper mines accounted for 35 percent of U.S. copper production (Hyde, 1998, p. 149).

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

OXYGEN AND FLASH SMELTING (D)

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 with Pierce-Smith converters. However, the 78 percent nitrogen in natural air used in the Pierce-Smith converters reduced its oxidizing affects proportionately. This inert element required energy to move and heat, but contributed nothing to the smelting process.

Cryogenic (extremely low temperature) technology developed during World War II 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 more could efficiently react with iron and sulfur already available in the copper mattes and thereby generate sufficient heat to power the smelting process. Any substance that releases heat upon oxidation can be used as a fuel. Thus, iron and sulfur already present replaced coal as the primary fuel for copper smelting.

Several proprietary smelting processes based on the principle that mixtures of gases and fine particles react together more efficiently have been implemented worldwide since the 1950's (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.

U.S. Copper Smelter Capacity		
Pyrometallurgical process	Smelter Capacity (tons copper blister)	
	1975	1987
Outokumpu flash	--	160,000
Inco flash	--	288,000
Noranda modified	--	210,000
Electric	336,000	112,000
Reverberatory (primary)	1,444,500	386,000
Reverberatory (secondary)	208,400	281,000
Total	1,988,900	1,437,600

Source: U.S. Bureau of Mines, 1989, p. 299

Smelting using pure oxygen produces a more concentrated SO_2 off-gas, 25 percent SO2 versus 6 percent formerly, which can be processed more economically in an acid plant to produce the useful sulfuric acid byproduct. The sulfuric acid can be sold on the open market or used on-site for the leaching of oxide ores and waste dumps to recover low-grade copper. Before oxygen flash smelting was developed, the standard copper smelting technology produced stack gases containing low levels of SO_2 that were not recovered. This dilute SO_2 gas was toxic in confined areas. Consequently, tall stacks, the technology of the day, became the signature of metal smelters and the polluting gases were disbursed over wide areas. Thus, the most important factor driving the rapid implementation of oxygen smelting was environmental protection legislation that mandated ambient air quality standards requiring the capture of SO_2. Now, after the switch to flash smelting, the tall stacks are being removed or are becoming historic relics.

SOLVENT EXTRACTION-ELECTROWINNING (SX-EW) (E)

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. Leaching of copper from waste dumps and low-grade ores has a long history that reaches back prior to the industrial revolution (Arbiter, 1994). Copper dissolves in weak acid solutions. For the first 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, similar to the addition of scrap.

In 1968, the first commercial application to recover copper from solutions using solvent extraction with electrowinning (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 electro-refined copper. Figure 41 shows one portion of the process. SX-EW hydrometallurgical methods to produce copper have been implemented throughout the southwestern United States where desert conditions (rainfall dilutes leaching solutions), oxide ores, and sulfuric acid from pyrometallurgical smelters all are available. Chile and the United States are the leaders in use of this technology for these reasons.

Figure 41. Electrowinning tankhouse. (Phelps-Dodge Corp.)

Benefits of SX-EW include: (1) economic copper recovery from low-grade oxide ores, thereby expanding the reserve base; (2) mine plans were re-evaluated and ores previously processed through flotation concentrators were redirected to leaching, which raised mill-head grades and improved overall economics (Phelps Dodge's Chino mine in New Mexico is an example); (3) wastes such as low-grade copper-oxide stocks and caved areas became new reserves; and (4) the overall cost of copper production was lowered, particularly when used in conjunction with conventional processing of sulfide ores.

Figure 42 shows the development of SX-EW copper production in the United States from 1968 through 1998. As a result, U.S. copper reserves increased from 36 million tons in 1989 to 42 million tons in 1993 (U.S. Bureau of Mines, 1989-95), illustrating benefit (1) above.

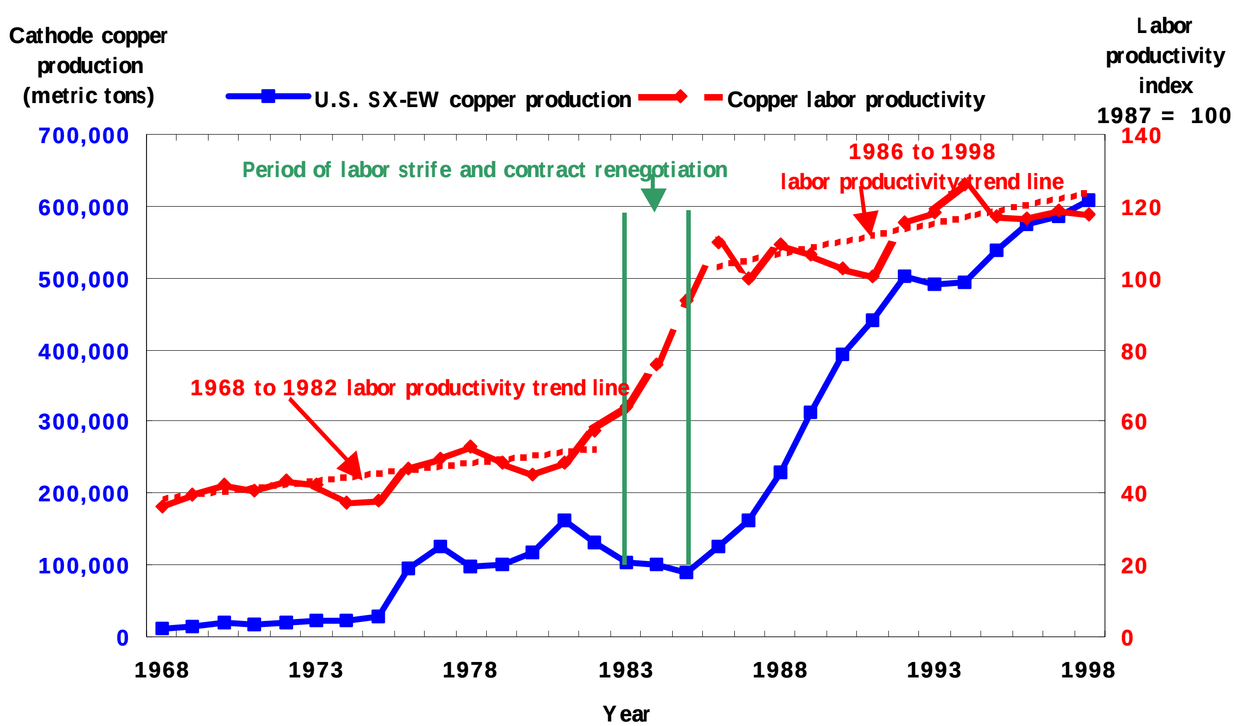

Figure 42. U.S. solvent extraction-electrowinning (SX-EW) copper production and copper industry labor productivity, 1968 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001) and Bureau of Labor Statistics, 2000, Data from Industry Productivity Database, from their web site at ftp://ftp.bls.gov/pub/special.requests/opt/dipts/oaehhiinin.txt and ftp://ftp.bls.gov/pub/special.requests/opt/dipts/oaehaiin. (Accessed November 30, 2000.)

Also shown in figure 42 is copper industry labor productivity for the same period. Note the parallel trend with growth in SX-EW production for the periods 1968 - 1982, and 1986 –1998, signifying incremental improvement, probably related to incremental improvements to the physical plant. The intervening years, 1983 – 1985, were very tumultuous with respect to industry-labor relations. Tilton and Landsberg (Simpson, 1999, p. 119-120) characterize the early 1980s as follows: "…real hourly wages in the mining and milling, 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." Tilton and Landsberg continue, "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."

In the early 1980s, it appears that labor productivity improvement was 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.

CURRENT RESEARCH

The ultimate target of process research often is cost reduction, even when there is another goal such as environmental improvement. Cost reduction is accomplished through new efficiencies in separation of high-value from low-value materials, reductions of inputs of labor, energy, and materials, and quality (metal purity). 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).

Breakthrough technology is still sought through fundamental research. Presently, important research is underway on bio-leaching 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 whole 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. However, this technique 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 protect groundwater. The Pinto Valley division of Broken Hill Proprietary Company Limited (BHP) is recovering copper from in-situ leaching of the block-cave area of the old Miami mine. This area contains 172 million tons of ore grading 0.40 percent copper (Arizona Department of Mines, 2000, p. 3)]. In-situ leaching has the potential to improve resource recovery and expand reserves, but this potential is still unrealized.

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 our most essential non-metallic minerals. Potash ore is a generic term that refers to a group of naturally occurring minerals containing between 7 and 25 percent potassium, one of the three essential nutrients for plant growth, the others being nitrogen and phosphorous. These three elements are the chief components of agricultural fertilizers. Fertilization is necessary to replace soil nutrients that are taken up by plants. Although there are many industrial uses for potassium, over 90 percent is used in agricultural fertilizers (Searls, 2000, p. 128).

Early uses for potash were mostly for soap making, glass making, fabric dyeing, baking, and making saltpeter for gunpowder (Williams-Stroud and others, 1994). Prior to the mid-1800's, before potash ore was discovered, manufacturers produced potash by burning hardwood trees, then gathering the ashes and leaching out the salts contained in the ash. By evaporating the leachate in a pot, the water-soluble part of the ashes containing 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 for an improvement in producing potash was issued in 1790 by President George Washington, as head of the U.S. Patent Office (Paynter, 1990). The process required three to five acres of timber to produce about one ton of potash from wood ashes (IMC Global Inc., 1978). Potash was America's first industrial chemical, and up until the 1860's the United States was one of the leading producers in the world. Wood and kelp met part of the domestic supply of potassium into the twentieth century. Demand surged in the 1840's when a German scientist discovered that potash was a vital soil nutrient for plant growth and could significantly increase crop yields (Williams-Stroud and others, 1994).

Most of the world's potash today is recovered from salt deposits that formed from the natural evaporation of ancient oceans, seas, and lakes. The deposits usually are 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. Significant technological challenges for mining these deposits occur when the deposits occur at great depths or are structurally complex. Potash also is extracted from salt brines in today's lakes and seas, sometimes in inhospitable environments like the Dead Sea, which is at the lowest elevation on earth. Another example is potash brines in the harsh climate of the high deserts of Chile.

The first discovery of potash ore occurred in Germany in 1857 while a shaft was being dug to mine salt beds. When first encountered, the potash beds were considered worthless and an obstruction to extracting edible rock salt (U.S. Bureau of Mines, 1927, p. 19). It was only after learning that potash could increase crop yields that additional shafts were developed with potash as the primary target. Deposits in France were discovered in the early 1900's during drilling for coal and oil. These two countries supplied nearly the entire world's demand for potash, and Germany supplied virtually all American needs until the beginning of World War I when shipments stopped. It was at this time that 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. Saltpeter, a product containing potassium, was used in gunpowder, explosives, fireworks, matches, fertilizers, and as a food preservative. By 1918, when the United States was embroiled in World War I, potash was recovered from the evaporation of lake water in Nebraska

(Nebraska State Historical Society, 1999) and brines in California (Gerard, 1917). During World War I, potash shortages were so severe that needs were supplemented by processing kelp beds on the Pacific Coast and high potassium feldspars in Utah (Gerard, 1917), and by returning to the earliest industrial source, wood ash. Costs, of course, were much higher. The price of potash increased from about $1,700 per ton just prior to World War I to over $10,000 per ton during the war (constant 1998 dollars). The amount of potash resources available during this period expanded because of the high price and newly developed technologies permitting potash to be recovered from more diverse sources. In 1920, 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 of the Nebraska potash plants were closed (Nebraska State Historical Society, 1999). Many other operations also closed at this time. During World War II, the price of potash did not increase as dramatically because of federally mandated price caps.

In 1920, world potash production was approximately 100,000 tons, and by 1998 had increased to 25 million tons (see figure 43). The 250-fold increase in production resulted from potash's effectiveness at increasing crop yields at relatively low cost.

Since 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-1920's, oil exploration drilling in the Carlsbad area of New Mexico intercepted large resources of high-grade bedded potash. In the early 1940's, one of the largest known potash deposits in the world (exceeding 5 billion tons) was discovered at depths between 1 and 2 kilometers in Saskatchewan, Canada. This deposit also extends south into Montana and North Dakota (Natural Resources Canada, 1999).

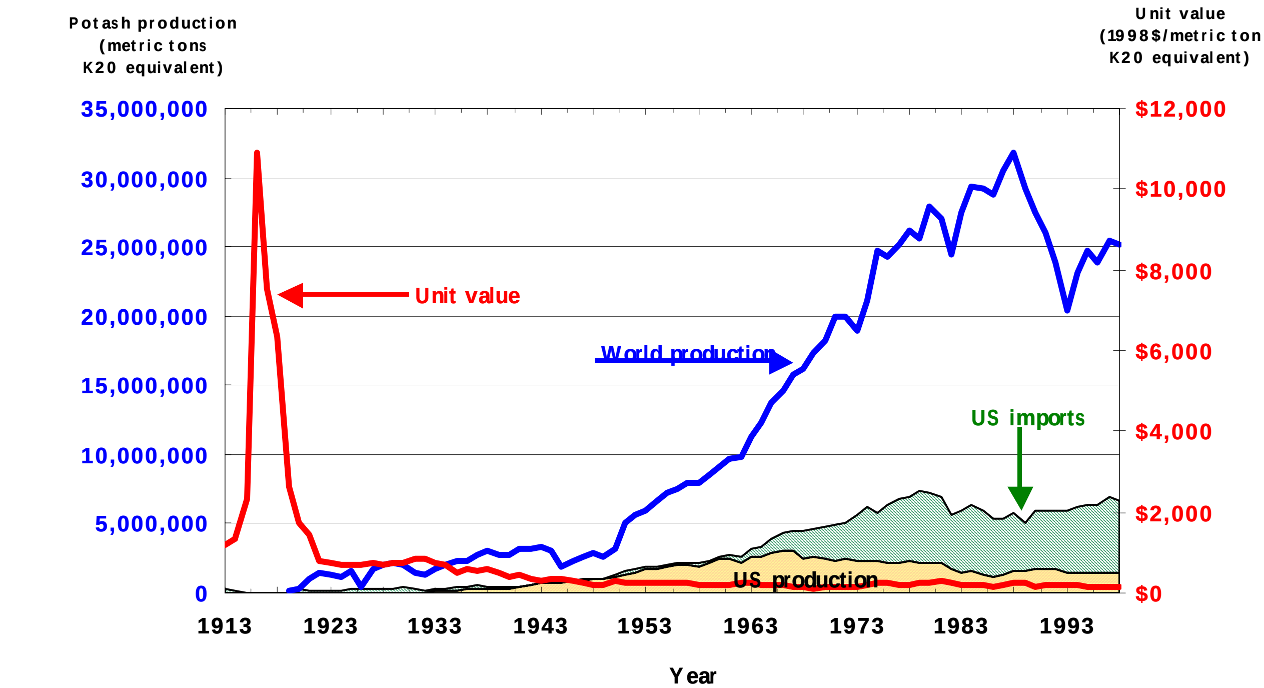

Figure 43. Potash production and unit value, 1913 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001). The unit value (1998$/metric ton) is defined as one metric ton of potash apparent consumption, expressed in terms of K_2O, as reported by U.S. Geological Survey, divided by the Consumer Price Index for that commodity with a base year of 1998.

Canadian and U.S. potash ores have considerably higher and more consistent K_2O grades. Furthermore, the mineralogy and geologic structure are less complex than deposits in Europe. The Canadian mines have a competitive edge over other deposits in the world. The Canadian reserves are huge, of high quality, and easy to mine. They are located in one of the largest agricultural areas in the world and are accessible to railroad networks connecting with the Great Lakes and St. Lawrence Seaway, as well as Pacific Coast ports. Development of the Canadian potash mines in the early 1960's had a nearly immediate and profound impact on U.S. potash imports. In 1960, less than one percent of total potash imports to the United States were from Canada while about 40 percent were from France and 30 percent were from East and West Germany (U.S. Bureau of

Mines, 1961). By 1964, the percentage from Canada had increased to nearly 70 percent and in the late-1990's approached 95 percent (U.S. Bureau of Mines, 1965; Searls, 2000).

Over the last half-century, billions of metric tons of underground resources of potash have been discovered through the use of sophisticated geophysical, geochemical, and geological techniques. These deposits in Brazil, Canada, and Russia, coupled with 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 1998, apparent consumption of potash in the United States, expressed in tons of K_2O, increased from 117,100 tons to 6,220,000 tons. This increase reflects the material's use as a fertilizer in agriculture. In constant dollars, the price of potash in the 1990's was less than 25 percent of the price in the 1930's. The price of the material continues downward as a result of: the abundant supply 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.

MINING

Early potash mining activities in Germany and France consisted of labor-intensive underground mines using conventional pick and shovel methods. 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 using 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 groundwater.

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

Mining and beneficiation methods to recover potash have become diverse and highly mechanized, resulting in very high productivity gains. An underground potash mine uses methods similar to those employed in mining other bulk commodities like 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, thickness of the ore, thickness and type of associated rocks, geologic complexities such as faulting and folding, and grade and type of ore. Technologies in shaft sinking have advanced dramatically. Early mine shafts were constructed using picks and shovels, and waste and ore were lifted to the surface using hand winches. Later, with the invention of steam engines, ore could be lifted to the surface by machine.

Figure 44. The Lanigan Potash Mine, Saskatchewan, Canada. (Photo courtesy of Potash Corporation of Saskatchewan Inc.)

The Lanigan mine (figure 44) is over 1,000 meters below the Saskatchewan prairie. It produces nearly 4 million tons of potash per year (Potash Corporation of Saskatchewan Inc., 2000a). Development of the mine in the early 1950’s presented major engineering challenges. Accessing the ore in Saskatchewan was delayed nearly 10 years because advanced engineering technology was not available to develop shafts through water-saturated unconsolidated material, under high pressure, thousands of meters below the surface, without flooding the shaft or the developing mine. The first shaft was not constructed until 1962. Construction of the shaft was accomplished first by freezing water in the saturated zones by drilling from the surface and circulating refrigerants. The frozen, solidified 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).

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

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 meters wide and as much as 1,000 meters 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 threat of flooding and roof collapse is carefully monitored. Mining potash beds results in an overall extraction 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 measuring up to 2.74 meters by 8.23 meters (9 feet by 27 feet), advancing at a rate of 30 centimeters per hour (1 foot per minute), and producing nearly 900 tons of potash ore per hour (see figures 45 and 46). These machines can weigh more than 250 tons. (IMC Global Inc., 1978).

Continuous miners initially were used in U.S. coal mines in the late 1940's to increase productivity and mine safety, but were quickly adapted for use in potash mining. Continuous miners can be designed to perform "real time" sampling and measuring of ore grades, in order to ensure that the highest-grade material is mined. This equipment also can be designed to operate 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 to underground storage bins capable of holding tens of thousands of 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 over 1,100 meters per minute (3,600 feet per minute). Some potash mines in Canada have more than 57 kilometers (35 miles) of conveyors and 4,000 kilometers (2,500 miles) of tunnels (IMC Global Inc., 1978). In some mines, ore is brought to the surface by high-speed conveyor belts through inclined shafts.

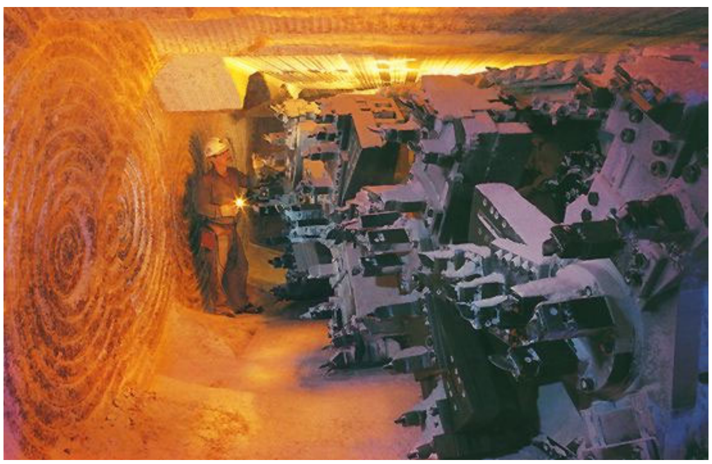

Figure 45. Each continuous miner rotor cuts a circular profile to produce a combined width of 20 meters. (Photo from Mining Technology, 2000, from web site at http://www.mining-technology.com/projects/rocanville/rocanville4.html. (Accessed April 12, 2000.)

Figure 46. Continuous miner in action. (Photo courtesy of Cleveland Potash Ltd., 2000, from their web site at http://www.clevelandpotash.ltd.uk/world.htm . (Accessed September 14, 2000.)

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 1920's, sacked potash ore was sent to chemical plants for further treatment to produce higher purity products such as potassium chloride and potash fertilizer using methods similar but less sophisticated than those used today.

The German potash industry was mining complex ores, which were difficult to process using the relatively simple technologies of the 1920's. 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, a major technological advance resulting in higher quality products and greater efficiency, was first used at the Carlsbad, New Mexico, potash operation in the early 1930's, and gradually spread worldwide (Williams-Stroud and others, 1994). The process, 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 this section. This technology forms the foundation for the most commonly employed treatment of potash ore.

In the 21st century, technologies previously unavailable are employed to ensure that potash specifications are constantly met at the lowest cost for customers. All steps in the processing of potash ore are monitored with computers. Ore is processed at the mine site with the goal of producing numerous high-grade potassium products, some of them through patented processes. An outline of the entire processing sequence is shown in figure 47.

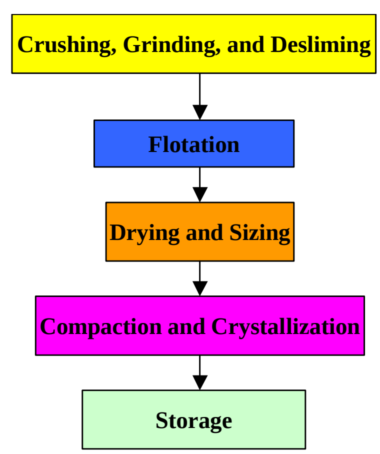

Figure 47. Typical potash mill process. (Photo courtesy of Potash Corporation of Saskatchewan Inc., 2000, from their web site at http://www.potashcorp.com. (Accessed September 14, 2000.)

The typical potash processing plant starts by crushing the ore and splitting it into individual particles of potash and salt, each less than 3/8 inch in diameter. The crushed ore then is mixed with brine, a salty solution, 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. A detailed description of ore treatment in figure 48 follows.

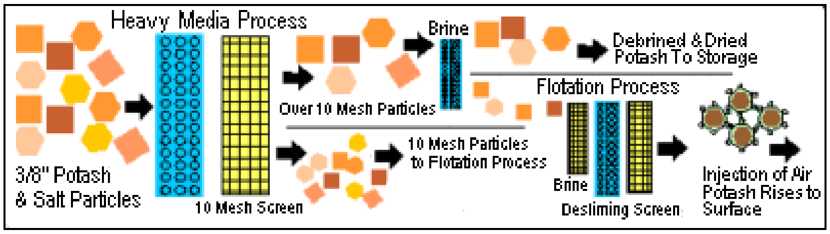

Figure 48. Potash processing sequence. (Photo courtesy of IMC Global Inc., 1978, The story of potash: IMC Global Inc. web site at http://www.imcglobal.com/potash/historyframe.html. (Accessed August 14, 2000.)

HEAVY MEDIA

Some mining operations use a treatment process in which the 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-size particles of floating potash are then washed, de-brined, dried, and prepared for storage and shipment. Some particles, called middlings, are not separated in the heavy media process. They are re-crushed, screened, and directed to flotation.

FLOTATION

First, insoluble materials and brine are removed from the small particles of ore in a process called desliming. Next, the ore is conditioned with chemical reagents that are added to a brine solution and 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, de-brined, and dried. The unaffected salts remain, sinking to the bottom.

The potash recovered from flotation is the operation's most important product and is called standard potash.

CRYSTALLIZATION

Potash dust 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, producing larger, purer crystals of potash called white muriate. Dissolution-recrystallization was a major technological advancement in the recovery of potash and is used in numerous potash operations including underground, solution, and solar evaporation mines. Developed by the French in the early 1910's, the process was developed to treat potash ores that contained more impurities than the ores being processed by the German potash industry. The white muriate next is de-brined and dried and can be refined through recrystallization to 99.9 percent pure potassium chloride called potassium muriate which is used in the fertilizer and chemical industry.

COMPACTING

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

STORAGE AND SHIPPING

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

SOLUTION MINING

The technology currently used to recover potash from brines injected through deep wells is adapted from the petroleum industry; however, the recovery of soluble materials from wells is not a new mining method. The Chinese performed solution mining for salt about 1,500 years ago (see figure 49) using wells drilled to depths exceeding 100 meters. (Adshead, 1991, p. 39; National Geographic Magazine, 1944, p. 329). Chinese technology included drilling at least two holes: one hole to feed and flood fresh water from a nearby source into salt deposits, and the second hole to allow the water to “well” up after dissolving the salt. Pumps using 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.

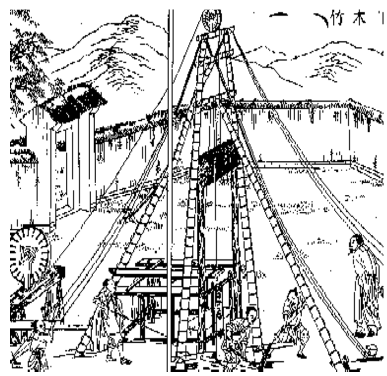

Figure 49. Drilling for salt circa 400 A.D. (Photo courtesy of Salt Institute, 2000, from their web site at (http://www.salt.org.il/. (Accessed Sept. 14, 2000.)

Potash From Solution Mining
The Patience Lake mine, in Saskatchewan, Canada has a capacity to produce over 1 million t of potash annually 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 exceeding 1,000 meters (3,280 feet). The mine workings extend up to 18 km (11 miles) from the shaft (Potash Corporation of Saskatchewan Inc., 2000b).

Solution mining for potash is currently used when deposits are geologically too complex to mine profitably 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 waters from underlying or overlying rock strata and conventional mining is no longer feasible. Solution mining of flooded mines is accomplished by injecting heated brines through wells up to several thousand meters deep. The brines circulate throughout the flooded mine workings dissolving 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, sylvite, potash, and other salt crystals form and settle to the bottom of the pond. The cooled brine is then reheated and re-injected into the mine to repeat the process. The potash crystals in the pond are pumped to a plant for further processing, sometimes using a floating dredge (see figure 50).

SOLAR EVAPORATION MINING

Potash and other salts have been recovered from salt water since ancient times. Salt mining probably started when ponds of seawater evaporated naturally, leaving behind salts that could then be collected. Emulating this natural process, people built shallow ponds to collect seawater, or lake water containing a very high salt content, and allowed it to evaporate. This process is still employed for local needs. Major industries involved in international trade use more advanced technologies. Operations using solar evaporation to recover potash are located in numerous countries including Israel and Jordan on the Dead Sea, the high deserts in Chile, and in Utah at the Great Salt Lake. The first major potash recovery plant using solar evaporation was initiated on the Dead Sea in Israel in 1934.

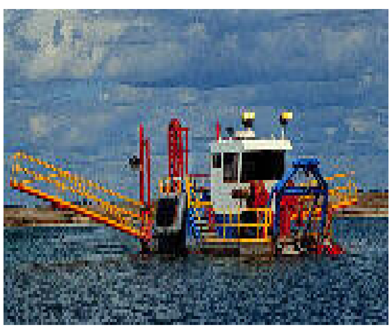

Figure 50, A floating dredge recovers potash crystals from the bottom of a 130 acre cooling pond at the Belle Plaine solution mine in Canada. (Photo courtesy of IMC Global Inc., 2000, Production techniques: IMC Global web site at http://www.imcglobal.com/potash/production/techniques.html. (Accessed August 24, 2000.)

At the Great Salt Lake, the process uses solar evaporation to concentrate the natural lake brine by pumping it through a series of shallow ponds covering 86,000 hectares (35,000 acres). Figure 51 is a photograph of 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 (400,000 gallons) of water per minute evaporates from the pond system. To accomplish the same amount of work using coal as the heat source would require about 6 million tons of coal per year.

Figure 51. Solar evaporation pond at Ogden, Utah. (Photo courtesy of IMC Global Inc., 2000, The story of potash: IMC Global Inc. web site at http://www.imcglobal.com/potash/historyframe.html. (Accessed August 14, 2000.)

The Dead Sea Works in Israel also uses the energy of the sun to concentrate brines through evaporation. The solar energy used at this operation is equivalent to about 7 million tons (54 million barrels) of oil per year (Bodenheimer and Zisner, 1998) or 10 million tons of coal (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 carnallite, a mineral from which potash also is recovered. All of these salts are allowed to dry and then are harvested using front-end-loaders and trucks that transport the salt to the processing plant. The process from this point on is similar to that used in other potash mines. If the potassium content of the salts is above 10 percent, they are fed directly to the plant where they are washed and sized, dried, and shipped. If the potassium content is below 10 percent, the salt must first be processed through a flotation plant in order to separate the impurities that passed through the dissolution-recrystallization process. Some brine operations recover more than 3 million tons of potash per year. Brine operations generally produce other products in addition to potash. These products include sodium chloride, magnesium chloride, sodium sulfate, chlorine, bromine, and magnesium metal.

RECYCLING

Unlike most metals and many other materials, potash is not directly recycled, except as animal waste used as a natural fertilizer. As a salt and as a fertilizer, it either is absorbed by plants or is dissipated into the environment, and it is not commercially recoverable.

CONCLUSIONS

Between 1905 and 1998, apparent consumption of potash in the United States, expressed in tons of K_2O, increased from 117,100 tons to 6,220,000 tons. This increase reflects the growing of potash as a fertilizer in agriculture. In constant dollars, the price of potash in the 1990's was less than 25 percent of the price in the 1930's. The price continued downward 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, specifically more efficient transport by rail. Abundant potash at low prices should continue for the foreseeable future, barring unforeseen events. Meeting the anticipated need for more potash fertilizer to grow more crops to feed an ever-increasing population is achievable.

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APPENDIX 5 – SULFUR CASE STUDY

PRODUCTION HISTORY

Sulfur, 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 refers to its use as a fumigant in the Odyssey. During the Peloponnesian War, in the fifth century B.C., the Greeks used burning sulfur and pitch to produce suffocating gases. The Romans combined brimstone with tar, pitch, and other combustible materials to produce the first incendiary weapons. Muslims, through the use of alchemy during the “Golden Age of Arabic Science” from A.D. 700, probably were 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 made sulfur an important mineral commodity for the first time (U.S. Bureau of Mines, 1985). 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).

It was not until the birth of the science of chemistry in the 1700’s, and the growth of chemical industries in the 1800’s, that sulfur became 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).

Reflective of the industrial era, world sulfur production in 1930 had risen to about 6.4 million tons[1] (see figure 52). By 1965, world production had quadrupled to approximately 27.5 million tons. The greatest production growth occurred between 1963 (24.9 million tons) and 1973 (52.5 million tons). This growth resulted from two forces: (1) accelerated demand and production of phosphate fertilizers, taking about 60 percent of the sulfur production; and (2) large quantities of sulfur produced as by-product from newly discovered Canadian natural gas. Since 1977, however, world sulfur production essentially has been flat, averaging about 54.0 million tons in 1998 (U.S. Bureau of Mines, 1933-96, Minerals Yearbook, 1932-94, chapter on sulfur and U.S. Geological Survey, 1997-2000, Minerals Yearbook, v. 1, 1995-98, chapter on sulfur). Sulfur production dropped in the former Soviet Union but increased in other areas. Between 1984 and 1996, sulfur production in some countries shifted from discretionary to non-discretionary sources, and world production outpaced increasing demand. Overall, between 1900 and 1998, while sulfur production and demand were rising, the constant-dollar (1998) unit value for sulfur was decreasing. Government price controls for sulfur existed both during World War II and the Korean conflict.

Discretionary sulfur is produced under market conditions.

Non-discretionary sulfur is produced because of regulatory mandates.

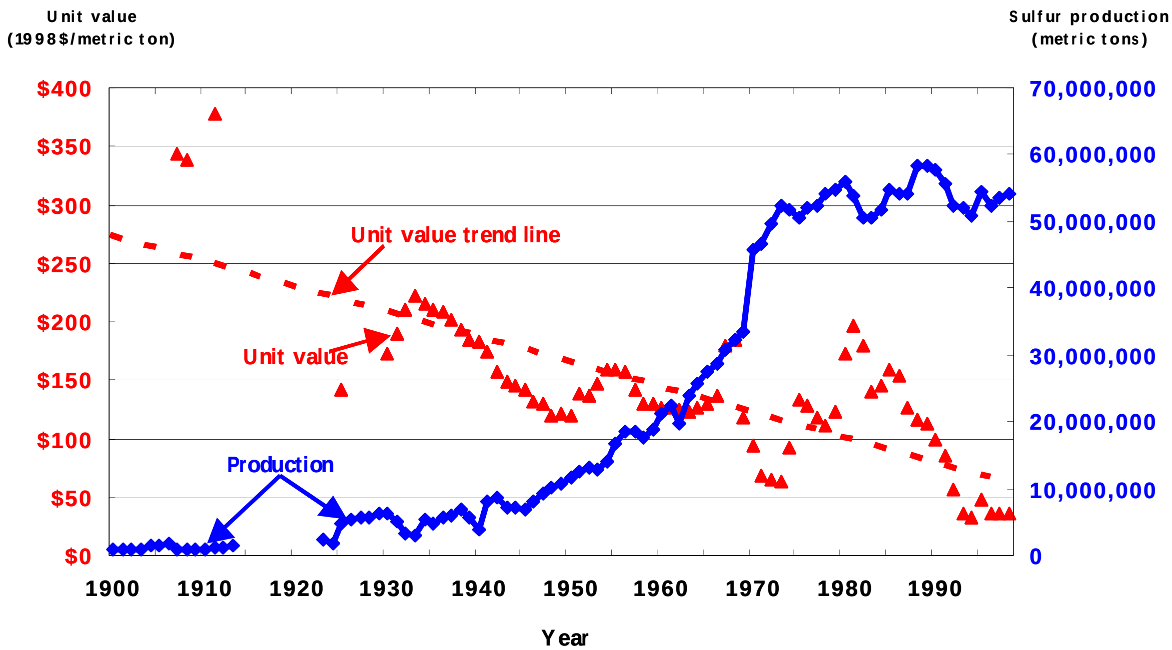

Figure 52. World sulfur production and U.S. unit values, 1900 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001). The unit value (1998$/metric ton) is defined as one metric ton of sulfur apparent consumption as reported by U.S. Geological Survey, divided by the Consumer Price Index for that commodity with a base year of 1998.

TECHNOLOGY

Figure 53 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 pertaining to deposits in the Gulf of Mexico. This process, which grew steadily in use from 1904 to 1975, was the principal source of U.S. sulfur until 1982 when processes relying on recovery of sulfur from oil and gas processing started to take substantial market share.

Around 1950, the Claus process began to be used to recover sulfur from oil and gas. This process, which produces elemental sulfur from hydrogen sulfide (H_2S), was added to oil refinery infrastructure to recover sulfur from H_2S separated during the refining process. There were several reasons why this process became attractive: (1) hydrogen sulfide is an odorous, toxic, substance for

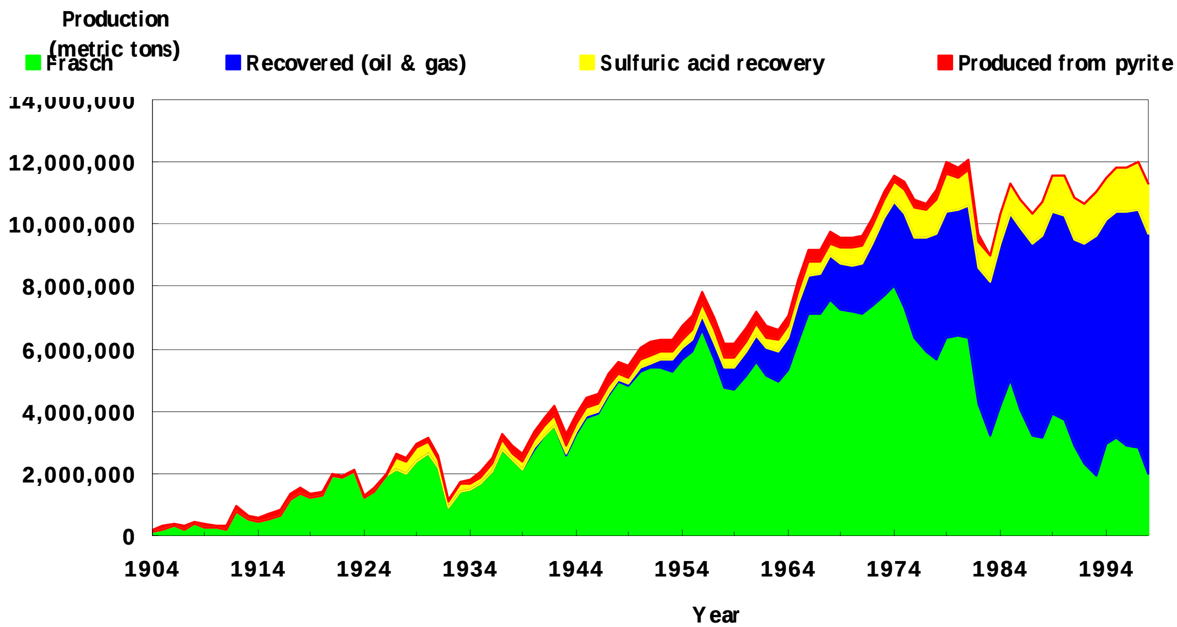

Figure 53. U.S. sulfur production by source, 1904 to 1998. Data from the Minerals Yearbook, v. 1, and its predecessors (published by the U.S. Bureau of Mines, 1927-94, and the U.S. Geological Survey, 1900-27, 1995-2001).

which incidental human contact should be limited; (2) hydrogen sulfide, if left in the refining operation, causes corrosion and caking, and produces foul smelling products; (3) the increasing gasoline consumption increased the need for lower sulfur levels in the final product; and (4) 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 has grown 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. This was a less costly approach than collecting sulfur combustion products after the fuel was burned. Second, the U.S. 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 lower 48 states. Sulfur recovered from oil refining, natural gas production, and metallurgical processes has come to dominate U.S. sulfur production.

Figure 54 shows how world sulfur recovery from industrial processes has grown through the decade of the 1990's, 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 the years 1994 and 1995 is an artifact of data reporting for that period. The most likely assumption is that sulfur generated from natural gas grew at a constant rate through that period.

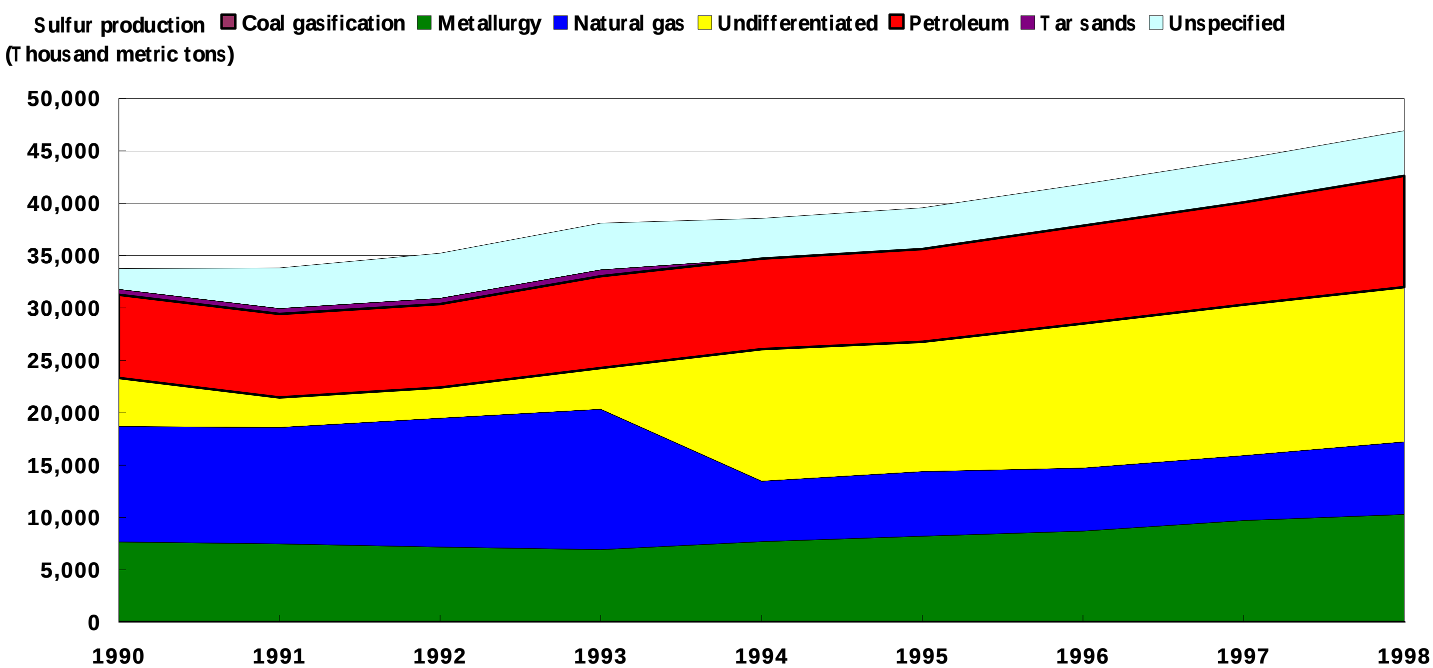

Figure 54. World sulfur production recovered from industrial processes, 1990 to 1998. Data from the Minerals Yearbook, v. 1, (published by the U.S. Bureau of Mines, 1990-94, and the U.S. Geological Survey, 1995-1998). Sulfur production from coal gasification during this period amounted to just 2000 metric tons, too small a quantity to show up on this figure.

Recovery of sulfur and some by-product iron from the mineral pyrite has always been small, and ended in the 1980's because of the depletion of economically mineable deposits. In 1997, sulfur from non-discretionary (mandated) sources represented more than 80 percent of the sulfur produced in all forms worldwide (Ober, 1998).

PRODUCTION TECHNOLOGIES

Except for the Frasch process, the technologies for production of discretionary sulfur from native sulfur and sulfide mineral deposits are common mining practices. The technologies for sulfur recovery, including those for non-discretionary recovery of sulfur during processing of other materials are explained below. Each technology has a history of its own. While this story of technological advance has some breakthroughs, sulfur production technology is more about continuous incremental improvement.

Regardless of social priorities, whether they are wealth building, ecosystem health, or something else, commodity producers in a free-market system will respond to the priorities of the moment by developing and implementing technologies to make materials available to serve consumer needs. For example, when the health of the environment and humans became preeminent social priorities, the Clean Air Act was passed in 1970. The technologies for recovering sulfur from industrial waste streams were already available, but were more costly than the Frasch process then in wide use. Nonetheless, with the passage of the Clean Air Act, sulfur recovery from industrial waste streams became the dominant mode of sulfur production. Sulfur is now being produced in excess of demand, and at a price that

> Consumers do not buy commodities for their own sake, but rather for the utility their physical properties provide.

has been falling steadily, recently reaching new lows – a clear triumph for technology (see figure 52).

FRASCH TECHNOLOGY

Frasch mining, 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 (See figure 55). 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. Both water and air 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. Compressed air then is injected into each well forming sulfur foam, which is propelled to the surface. At the surface, the sulfur foam is de-aerated and treated with a mixture of sulfuric acid and diatomaceous earth, which is composed of the siliceous shells of algae. The diatomaceous earth removes organic impurities (Buckingham, 1991, p. 11). The molten sulfur then is delivered to vats to solidify. In this way, blocks of pure sulfur weighing more than a million tons are obtained (Sander and others, 1984).

Figure 55. The Main Pass Mine is the largest Frasch sulfur mine in the world and the largest structure in the Gulf of Mexico. (Photo courtesy of Freeport-McMoRan Sulphur Inc.)

Frasch mining is an example of a method called in-situ mining whereby desirable materials are separated from their host rocks while those rocks are left in place undisturbed. In-situ mining saves the cost of breaking and moving these rocks, and avoids unsightly above-ground waste piles.

NATIVE SULFUR AND PYRITE RECOVERY TECHNOLOGIES

The following text describing native sulfur and pyrite recovery technologies is taken directly from Buckingham (p. 11): "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 with the resulting SO_2 gas converted to sulfuric acid. Low-grade ores are treated by a wide variety of processes, including direct melting, distillation, agglomeration, solvent extraction, and flotation to produce elemental sulfur." These methods generally are higher cost than the Frasch process, so they have difficulty competing with non-discretionary production.

TECHNOLOGY FOR RECOVERING SULFUR FROM H_2S

Average crude oil contains about 84 percent carbon, 14 percent hydrogen, 1-3 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 (OSHA), 2000). Hydrogen sulfide is a highly toxic gas that is also a primary contributor to corrosion in refinery processing units (OSHA, 2000, p. 8).

The process of hydrodesulfurization in petroleum refineries uses a fixed-bed catalytic reactor to convert the sulfur and nitrogen compounds in the crude oil to H_2S and NH_3 (OSHA, 2000, p.31) (See figure 56). The H_2S then is recovered by converting it to elemental sulfur. The most widely used recovery system is the Claus process, which uses both thermal and catalytic-conversion reactions. Typically, the process produces elemental sulfur by burning H_2S in the presence of a catalyst and recovering the sulfur from the resulting vapor as a condensate (OSHA, 2000, p. 40).

Figure 56. H_2S stripping plant. (Photo used with permission of Gas Technology Institute.)

Hydrodesulfurization was introduced to petroleum refining in 1954 (OSHA, 2000, p. 4). In figure 2 (page 15 in the main text), one can observe that the production of sulfur from fuel desulfurization began to grow steadily after 1954. However, around 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 SO_2 GAS

The technology of choice for capturing SO_2 depends upon the concentration of SO_2 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, together with sulfur and oxygen. With additional processing, some of this material can be made suitable as a substitute for natural gypsum ($CaSO_4$).

The treatment of H_2S and pyrometallurgical processing of metal sulfide ores both generate highly concentrated SO_2 gas. These sulfur resources are ideal for production of sulfuric acid, which often is used in other processes in the same plant that made the acid. For example, petroleum refiners use sulfuric acid for their alkylation processes. Copper producers use the acid as a leachate in the solvent extraction processes that recovers copper form very low-grade ores. 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 supplies have kept pace or exceeded demand. Technological change has increased production and the number of production sources. There is no foreseeable shortage of sulfur for the world economy. Sulfur supplies probably will increase even further as the worldwide effort to control sulfur emissions continues to expand.

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