Innovation, Productivity Growth, and the Survival of the U.S. Copper Industry

John E. Tilton and Hans H. Landsberg

Discussion Paper 97-41

September 1997

RESOURCES
FOR THE FUTURE

1616 P Street, NW
Washington, DC 20036
Telephone 202-328-5000
Fax 202-939-3460

This paper is one of a series of studies on "Understanding Productivity Change in Natural Resource Industries" undertaken by Resources for the Future with the assistance of a grant from the Alfred P. Sloan Foundation. Titles in this series are:

- PRODUCTIVITY TRENDS IN THE NATURAL RESOURCE INDUSTRIES, by Ian W. H. Parry, RFF Discussion Paper 97-39;

- PRODUCTIVITY CHANGE IN U.S. COAL MINING, by Joel Darmstadter with the assistance of Brian Kropp, RFF Discussion Paper 97-40;

- PRODUCTIVITY GROWTH AND THE SURVIVAL OF THE U.S. COPPER INDUSTRY, by John E. Tilton and Hans H. Landsberg, RFF Discussion Paper 97-41;

- THE FOREST SECTOR: IMPORTANT INNOVATIONS, by Roger A. Sedjo, RFF Discussion Paper 97-42;

- CHANGING PRODUCTIVITY IN U.S. PETROLEUM EXPLORATION AND DEVELOPMENT, by Douglas R. Bohi, a book from Resources for the Future (forthcoming);

and

- UNDERSTANDING PRODUCTIVITY CHANGE IN NATURAL RESOURCE INDUSTRIES, edited by R. David Simpson, a book from Resources for the Future (forthcoming).

Innovation, Productivity Growth, and the Survival of the U.S. Copper Industry

John E. Tilton and Hans H. Landsberg

Abstract

Mining is widely viewed as an old industry with mature and stable technologies. Companies and countries with the best deposits are the most productive and efficient producers. As these deposits are depleted, mining shifts to countries with the next best deposits. This tendency to exploit poorer quality ores tends to push productivity down and the prices of mineral commodities up over time.

Copper mining in the United States, however, calls into question this conventional view. After leading the world in output for decades, the U.S. industry lost its ability to compete and suffered a major decline during the 1970s and early 1980s. In the face of predictions of complete collapse, it staged a remarkable revival, and today mines more copper than in 1970.

A handful of companies achieved this recovery, in large part through their efforts to introduce a wide range of cost-reducing innovations. These efforts, in turn, helped double labor productivity in copper mining during the 1980s. The known copper endowment of the United States hardly changed over this period, aside from the depletion arising from mining, and had little to do with either the decline or the recovery.

The experience of copper mining in the United States holds a number of lessons for countries competing in global mineral markets and for countries striving to raise their labor productivity and standard of living. In particular, it highlights the stimulating influence of global competition on industry productivity and comparative advantage, even in the mining sector where mineral endowment is widely thought to be of overriding importance.

Key Words: copper industry, productivity, technological change, comparative advantage

JEL Classification Nos.: Q30, L72, O31, F14

Table of Contents

List of Figures and Tables

INNOVATION, PRODUCTIVITY GROWTH, AND THE SURVIVAL OF THE U.S. COPPER INDUSTRY

John E. Tilton and Hans H. Landsberg*

Productivity isn't everything, but in the long run it is almost everything. A country's ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker.

Paul Krugman (1994, p. 13)

Mining in general and copper mining in particular go back a long way, back to the Bronze Age, possibly even the Stone Age. The Romans mined copper in Spain and tin in England some two thousand years ago. The writings of Agricola in the 16th century show that mining was important in the Middle Ages, and that Medieval Europe made significant contributions to the art of mining and metal processing. Today the world mines more mineral commodities in greater tonnages than ever before.

This long and fascinating history so closely tied to the development of human civilization is one of the charms of the mining industry. It also, unfortunately, gives rise to some widespread misconceptions about mining. Old industries are generally considered stodgy with mature and stagnant technologies. Costs do not decline as in the newer, high technology industries, and may even increase with real wages. Costs are particularly expected to rise in the case of mining, as the depletion of the best mineral deposits causes labor productivity to fall (Young, 1991).

In fact, however, the mining of copper, and other metals as well, is a highly competitive global industry, where the successful firms aggressively pursue new technologies and other cost-reducing innovations. Costs over the longer term have fallen substantially--indeed, more than the production costs of non-extractable goods--despite the increasing need to exploit lower grade, more remote, and more difficult to process deposits (Barnett and Morse, 1963; Tietenberg, 1996, chapter 13).

In the pages that follow we examine changes in labor productivity in the U.S. copper mining industry over the past several decades along with their causes and consequences. Such an inquiry seems worthwhile given the widespread misconception that mining is a

---

* William J. Coulter Professor of Mineral Economics, Colorado School of Mines, and Senior Fellow Emeritus, Resources for the Future. We are grateful to the Sloan Foundation and the William J. Coulter Foundation for their financial support, and to Rio Tinto Plc and Brook Hunt and Associates Limited for sharing proprietary data. We would also like to acknowledge the many helpful comments we received from Michael Bailey, Ross R. Bhappu, David W. J. Coombs, Phillip C. F. Crowson, Daniel L. Edelstein, Merton J. Peck, Jane Robb, Simon D. Strauss, and Richard Wilson.

mature industry with relatively static technology. Copper mining in the United States is of particular interest as it has in recent years enjoyed a remarkable revival, largely the result of a dramatic jump in labor productivity, following what many predicted was a terminal decline.

Though the scope of the analysis is limited to the U.S. copper industry, the implications that flow from the findings extend to other mineral commodities and to other countries. The focus is on the first two stages of copper production, namely, mining and milling, though it is not always feasible to exclude downstream processing at the smelting and refining stages. For the most part, the time period covered runs from 1970 to the mid-1990s, though in a few instances data back as far as 1950 are noted.

The first section following this introduction provides a brief description of the U.S. copper mining industry, focusing mostly on its decline and subsequent recovery. The second section explores possible explanations for the recovery, and highlights the importance of the rapid surge in labor productivity that occurred during the 1980s. The third section attributes this rise in labor productivity largely to new technologies and other labor-saving innovations. The fourth section looks in some depth at the development and adoption of one important innovation--the solvent extraction electrowinning (SX-EW) process. The fifth and final section examines the implications of the findings for mineral producing countries striving to increase their comparative advantage in an increasingly competitive global economy and for all countries trying to raise their living standards by accelerating productivity growth.

DECLINE AND REVIVAL

The United States was the world's largest producer of copper in 1970, as it had been throughout most of the 20th century. In that year, as Table 1 (below) indicates, its mine output contained some 1.56 million tons of copper, accounting for 30 percent of total western world production. At the mining and milling stages alone, it employed 37 thousand people. The industry as a whole was quite profitable. Adjusted breakeven costs (as defined in Table 1, note d), averaged $1.04 in real (1990) dollars, considerably below the prevailing copper price of $1.83, again measured in real (1990) dollars. Net imports of copper in concentrates, blister, and refined metal supplied only 8 percent of the total U.S. market.

The 15 years that followed, however, threatened the industry's very survival. Mine output fell by nearly a third. The country's share of western world output shrank from 30 to 17 percent. Net imports rose. Adjusted breakeven costs, though they did decline, did not fall as much as the price of copper. As a result, few producers were recovering their full production costs, including the fixed costs of capital. Many were not even covering their variable or cash costs. In these depressed conditions, a number of mines curtailed production or shut down completely. Employment in copper mining and milling fell to 13 thousand, a 70 percent decline from its 1970 level.

Producers twice petitioned the government for protection under the Trade Act of 1974, first in 1978 and then again in 1984. Both times their request was denied. The government maintained protection would cost more jobs in the copper fabrication industry than it would save in copper mining and processing. Skeptics noted that, unlike the steel industry which did receive protection, the copper industry was concentrated in Arizona, Utah, New Mexico, and Montana, states with relatively little political influence.

Table 1. Mine Output, Share of Western World Output, Net Imports, Adjusted Breakeven Costs, and Prices for the U.S. Copper Industry, 1970, 1975, 1980, 1985, 1990 and 1995

Year	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**
Mine Output[a]	1.56	1.28	1.18	1.10	1.59	1.89
Output Share[b]	30	22	20	17	22	23
Net Imports[c]	0.12	0.06	0.39	0.19	-0.07	0.08
Costs[d]	1.04	1.02	0.90	0.70	0.65	0.61
Price[e]	1.83	1.43	1.57	0.80	1.23	1.19

Notes:

[a] Mine output is measured in millions of metric tons of contained copper. Copper mine output was depressed by an unusually severe economic recession in 1975 and by and industry strike in 1980.

[b] Output share is the ratio of U.S. to western world copper mine output multiplied by 100. The western world includes all countries except those currently or formerly with centrally planned economies.

[c] Net imports reflect U.S. imports of copper minus U.S. exports of copper contained in ores, concentrates, blister, and refined metal, measured in millions of metric tons.

[d] Costs are the weighted-average adjusted breakeven costs for U.S. producers, measured in real (1990) U.S. dollars per pound. Breakeven costs are the costs of producing copper to refined metal minus capital costs (specifically, depreciation, amortization, and interest on external debt) minus any credits for coproduct and byproduct revenues. Adjusted breakeven costs are breakeven costs minus the difference, if any, between reported revenues and the product of the world copper price times mine output. Thus, adjusted breakeven costs reflect the lowest market price for refined copper at which the mine can operate without cash losses. The figure shown for 1995 is actually for 1993. Costs in nominal dollars are converted to real (1990) dollars using the U.S. GDP implicit price deflator.

[e] Price is the average U.S. domestic producer price, measured in real (1990) U.S. dollars per pound. Prices in nominal dollars are converted to real (1990) dollars using the U.S. GDP implicit price deflator.

Sources:

Mine output, output share, net imports, and prices: *Metal Statistics* (Frankfurt am Main: Metallgesellschaft AG, annual); U.S. Bureau of Census; U.S. Bureau of Mines.

Costs: Rio Tinto Mine Information System.

Nor was it just the industry seeking government assistance that saw a bleak future for domestic copper mining. The media was also pessimistic. In the mid-1980s, *Business Week* in a cover story declared the death of mining in the United States.

A number of companies, including Amoco Minerals, Arco/Anaconda, Cities Service, and Louisiana Land and Exploration, left the industry. Their copper properties were sold to other firms, spun off as independent companies, or simply shut down.

Within the U.S. industry, however, a handful of companies refused to quit. Aware they could not influence the market price, their managers nevertheless believed that copper mining in the United States could once again be made profitable by controlling costs. The decisions these companies took during the bleak years of the 1980s produced one of the most dramatic turnarounds in mining history.

By 1995, copper mine output had jumped to 1.89 million tons of contained copper, an amount 21 percent above its 1970 level and 72 percent above its 1985 level. The U.S. share of western world production at 23 percent was back to its 1975 level, though still below its 1970 level as copper demand and western world copper production continued to grow over the 1970-95 period. More important for producers, net imports had fallen to only 4 percent of domestic demand, and the gap between average breakeven costs and the market price for copper had widened sufficiently to make domestic mining once again profitable.

While the U.S. industry as a whole was enjoying a renaissance, recovery at the individual mine level was mixed. Table 2 (below), which shows the significant copper mines in the United States along with their output in 1975, 1985, and 1995, reflects several notable characteristics of the recovery.

First, it was not ubiquitous. Of the 26 significant mines producing copper in 1975, seven were shut down by 1995. Another seven had sharply curtailed their output.

Second, only two mines--Flambeau and Cyprus Tohono--producing copper in 1995 were opened after 1970. Together they accounted for 3 percent of U.S. output in 1995.[1] The rest came from mines that had been in operation for 20 years or more.

Third, the recovery of the U.S. copper industry was largely the result of expanding output at a few mines--Morenci, Bingham Canyon, Chino, Ray, San Manuel, Sierrita, and Bagdad. Five companies--Phelps Dodge, Kennecott, Asarco, Magma Copper, and Cyprus Amax--owned, and still own, these mines. These are the companies that refused to abandon what many considered a dead or dying industry.

BEHIND THE REVIVAL

How did this handful of companies manage during the 1980s and 1990s to reestablish the global competitiveness of copper mining in the United States? This section examines five possible explanations--an increase in the production costs of foreign producers, a surge in

[1] Cyprus Tohono was shut down in early 1997 due to high production costs. Flambeau is expected to close within the next several years as its reserves are depleted.

copper prices, a rise in byproduct revenues, a decline in the real wages of domestic copper workers, and finally an increase in U.S. labor productivity.

Table 2. U.S. Copper Output in Thousands of Metric Tons of Contained Metal by Mine, 1975, 1985, and 1995

Mine	1975	1985	1995
Morenci	121.9	243.1	403.5
Bingham Canyon	167.8	30.6	307.5
Chino	51.2	108.5	156.9
Ray	46.9	80.9	149.9
San Manuel	89.1	88.9	116.9
Sierrita	82.2	97.8	112.4
Mission	103.0	53.4	101.8
Bagdad	17.8	78.4	97.2
Pinto Valley	60.5	78.7	88.7
Tyrone	70.8	135.8	67.9
Cyprus Miami	42.9	69.9	58.5
Butte	88.1	0.0	51.2
Flambeau	0.0	0.0	39.3
White Pine	68.7	1.1	33.9
Superior	38.0	0.0	18.4
Cyprus Tohono	0.0	5.9	15.4
Miami East	10.6	3.7	10.5
Continental	14.2	0.0	7.4
Yerington	30.8	0.0	6.5
Silver Bell	27.8	4.2	3.2
Mineral Park	16.5	1.7	1.4
Ajo	31.0	0.0	0.0
Battle Mountain	14.1	1.4	0.0
Bisbee	10.5	1.6	0.0
Esperanza	12.8	4.5	0.0
Ruth McGill	27.1	0.0	0.0
Sacaton	19.0	0.0	0.0
Twin Buttes	13.8	15.2	0.0
All other mines	40.9	36.7	25.6
Total	**1318.0**	**1142.0**	**1874.0**

Source: Brook Hunt and Associates Limited.

Higher Production Costs Abroad

Over the longer run the costs of producing copper abroad have fallen, and fallen substantially. Figure 1 (next page) shows adjusted breakeven costs in real 1990 dollars over the 1972-93 period for western world copper producers as a whole (including the United States) and for Chile. The latter is currently the largest copper mining country, accounting for about 30 percent of western world output, and the most important competitor of the U.S. industry. Adjusted breakeven costs for the western world fell from 87 to 58 cents between 1972 and 1993, a decline of 33 percent. The drop in production costs was even more spectacular for Chile. The U.S. industry, thus, has had to reduce its costs substantially over the past couple of decades just to keep pace with producers in the rest of the world.

Since the mid-1980s, however, production costs abroad have risen somewhat, reversing at least for a time the longer-term downward trend. Western world breakeven costs, for example, rose from 47 to 58 cents per pound between 1986 and 1993. This helped domestic producers compete both at home and abroad, and contributed to the revival of U.S. copper industry.

Some of the factors behind the recent rise in production costs abroad--and the long run decline--are easy to identify. The sharp appreciation of the dollar over the 1979-85 period, in large part the result of macroeconomic policies that raised domestic interest rates to curb inflation, lowered production costs abroad when expressed in dollars. Subsequently, however, the depreciation of the dollar, which by 1988 had returned the dollar exchange rate to roughly its late 1970s level, helped the U.S. industry by increasing the costs expressed in dollars of foreign producers. In addition, there is now considerable evidence that state mining companies in Zambia, Zaire, and elsewhere by the mid-1980s were encountering higher costs as a result of their failure in earlier years to invest sufficiently in development and maintenance (Chundu and Tilton, 1994).

Surge in Copper Prices

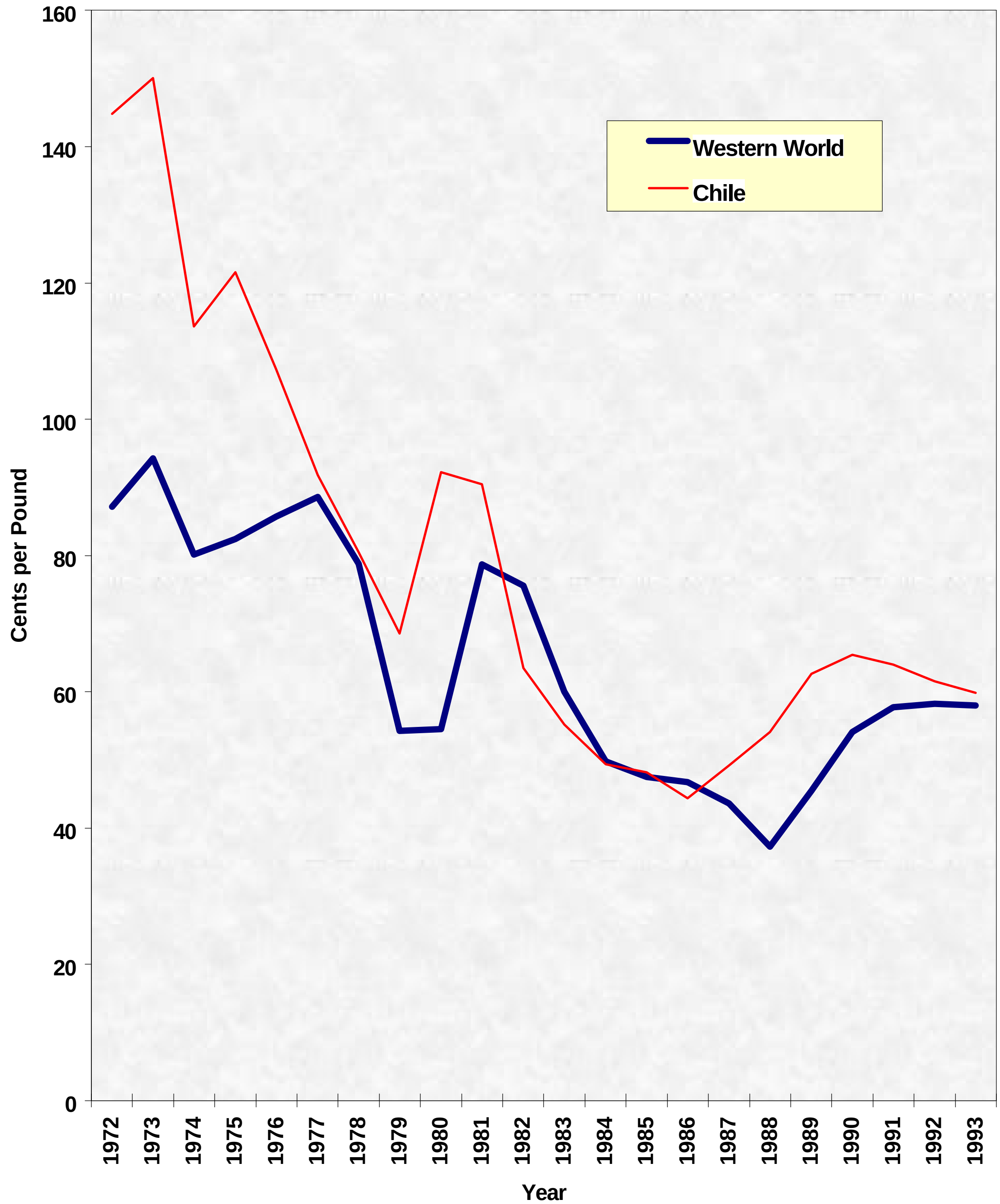
While copper prices over the longer run presumably follow production costs,[2] in the short run they, like the prices of other metals, are known for their volatility. A surge in demand caused by a boom in the business cycle or an interruption in supply caused by a mine closure can cause the market price of copper to rise and for some time to remain significantly above its long run trend. Similarly, during recessions and other periods of excess supply the price may languish far below the full production costs of many producers.

This raises the possibility that cyclical fluctuations in copper prices contributed to the decline of the U.S. copper industry during the 1970s and early 1980s, and then to its subsequent recovery. Figure 2 provides some support for this. It shows the London Metal Exchange (LME)

---

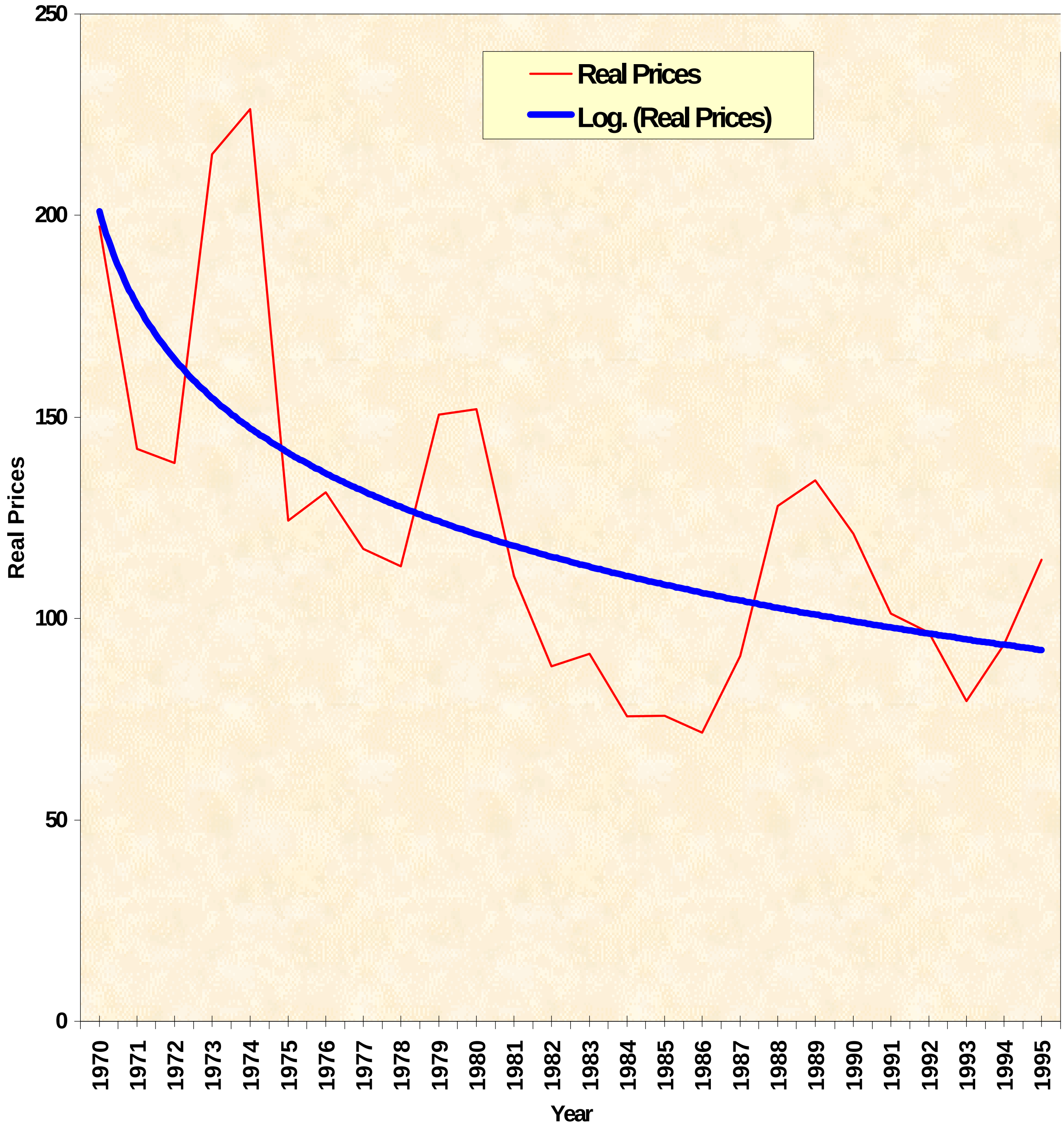
[2] More specifically, in competitive industries prices over the long term should follow the production costs including capital costs of the marginal producer, that is, the highest cost producer whose output is necessary to satisfy demand. While costs affect price, the reverse is also true. When the market price falls, producers increase their efforts to reduce their costs, as the experience of the U.S. copper industry in the early 1980s illustrates.

Figure 1. Average Adjusted Breakeven Costs for the Western World and for Chile in Real 1990 Dollars, 1972-1993



Source: RTZ Mine Information System.

Figure 2. Real and Trend Copper Prices in 1990 Dollars, 1970-95



Note: The price shown is for high grade and grade A copper on the London Metal Exchange.

Sources: Commodity Exchange of New York, Metals Week, and American Metal market as reported by the U.S. Geological Survey.

price of copper in real 1990 dollars over the 1970-95 period along with its logarithmic trend. The long run trend in prices, like that for production costs, is downward. Actual prices, however, are below the trend for many years between 1970 and 1985, while the opposite is the case for several years after 1987.

The sharp rise in real prices in the late 1980s, which was largely unexpected, provided a boost to U.S. and foreign producers alike. It reflected a tightening of supply and demand caused in part by unusually strong growth in the consumption of copper in Asia and the United States. The closure of the Bougainville mine in Papua New Guinea, the result of a local insurrection, in 1989 along with the collapse of production in Zambia and Zaire simultaneously constrained the available supply.

Greater Byproduct Revenues

Where gold, silver, molybdenum, and other byproducts are recovered along with copper, they reduce the adjusted breakeven costs of producing copper. Such byproduct credits, which can vary greatly from year to year due to the volatility of metal prices noted earlier, may help explain the changing fortunes of the U.S. copper industry over the past quarter century.

Figure 3 (next page) shows the average byproduct revenues realized by U.S. copper producers over the 1970-93 period as a percentage of their cash costs. (Cash costs are breakeven costs plus byproduct revenues.) This figure indicates that byproduct revenues covered about the same portion--roughly one-fifth--of the cash costs of producing copper in the United States in the early 1970s as in the early 1990s. So changing byproduct revenues have not affected the competitiveness of U.S. producers over the long run.

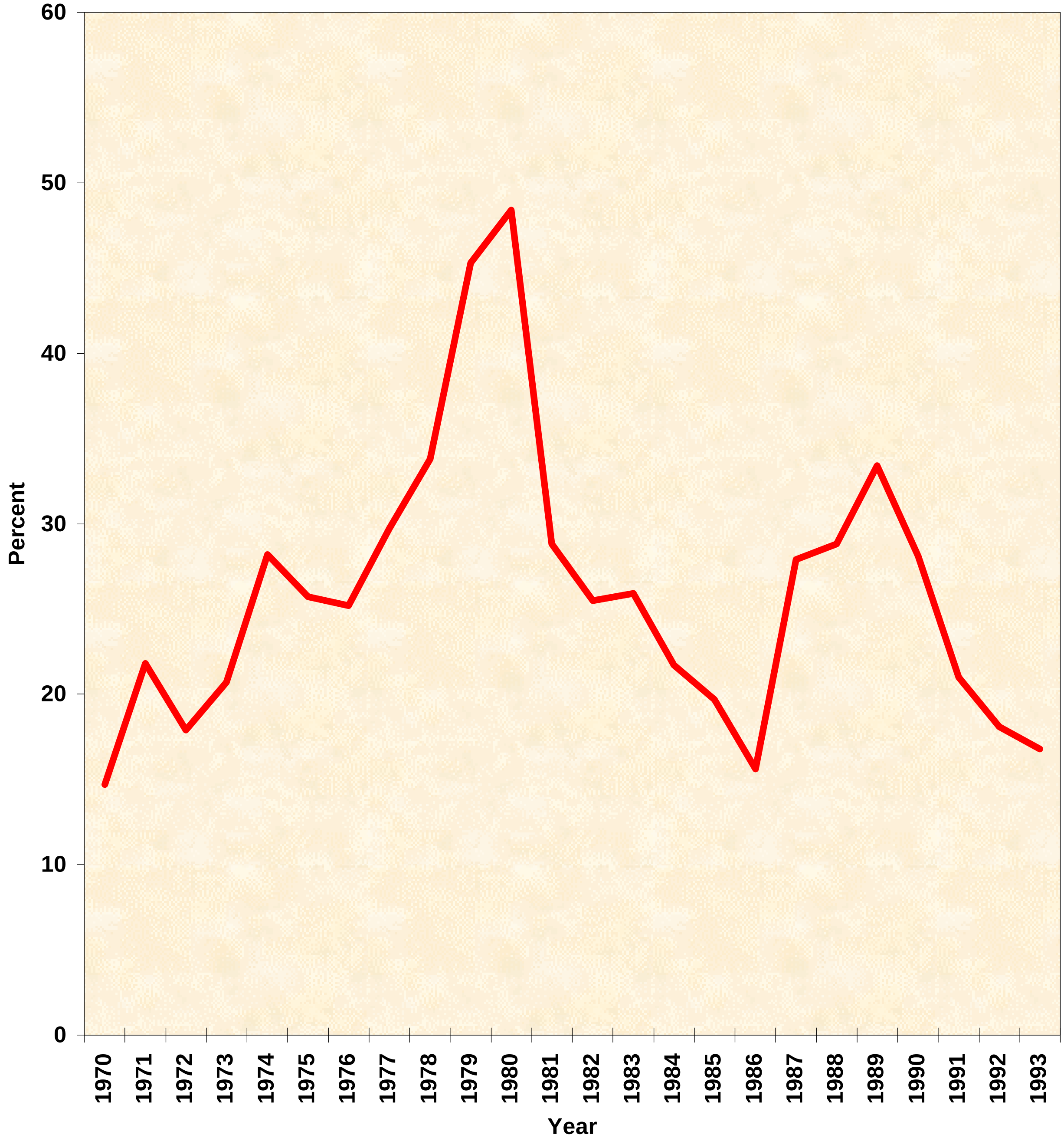
Between the early 1970s and early 1990s, however, byproduct revenues followed two pronounced cycles. The percent of byproduct revenues to cash costs rose sharply during the 1970s, reaching nearly 50 percent by 1980. This favorable trend offset to a considerable degree the rise in real wages and other costs over these years. It was not to last, however. During the early 1980s the percentage of cash costs covered by byproduct credits dropped as rapidly as it had risen in the late 1970s, contributing in the process to the industry's troubles during this period.

The second cycle was more modest. It began in 1987, and for several years contributed to the industry's revival. The decline set in about 1990. Part of this decline can be attributed to the growing importance of a new production process, solvent extraction electrowinning (SX-EW), which is discussed more fully below. This process does not recover any byproducts.

Lower Wages

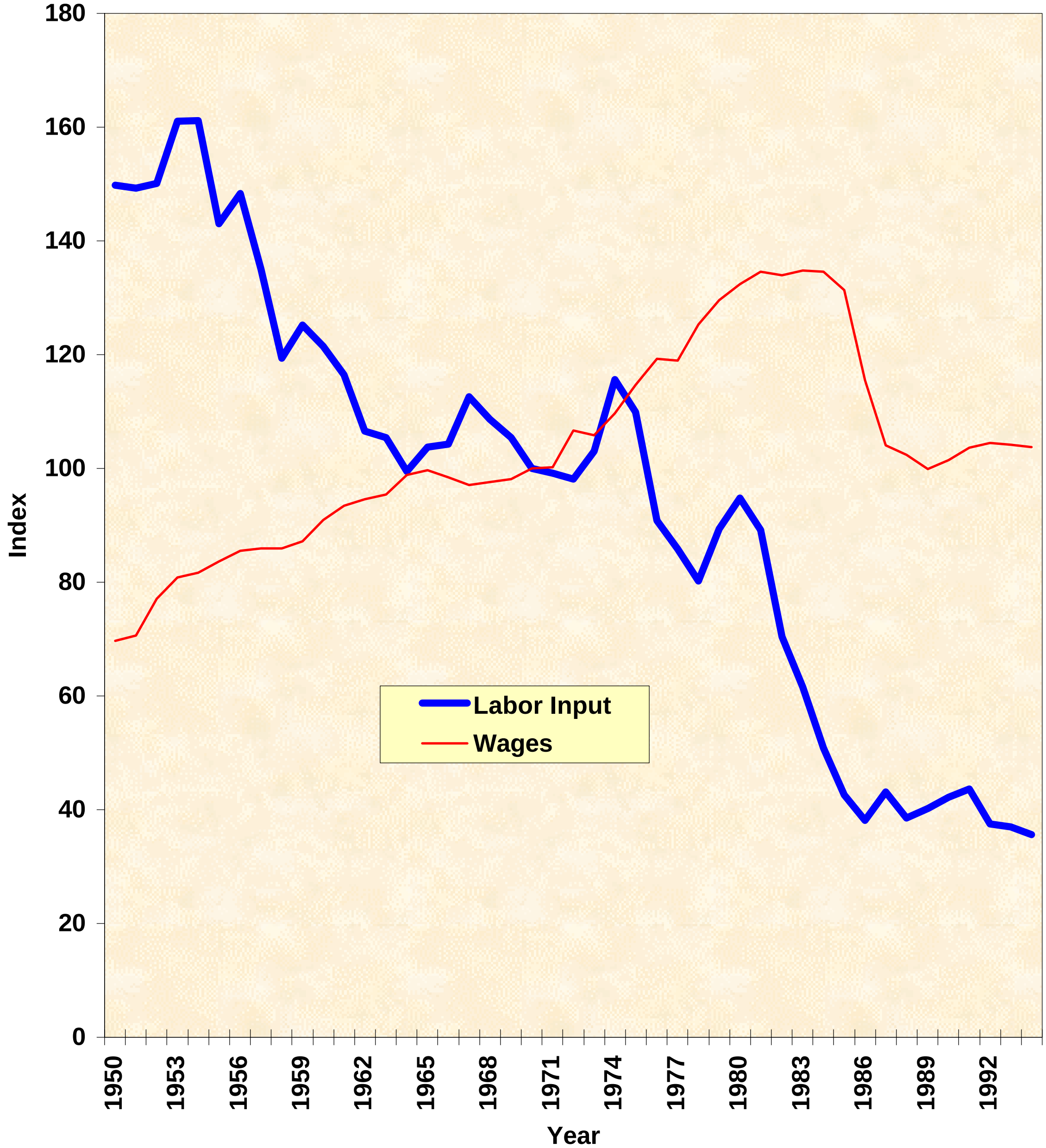
Trends in real wages also affected the changing fortunes of the U.S. copper industry over the past several decades. As Figure 4 (below) illustrates, real hourly wages in copper mining and milling, after rising persistently for over three decades, plummeted by more than 25 percent between 1984 and 1989. They have since remained fairly constant at levels similar to those of the early 1970s.

Figure 3. Byproduct Revenue as a Percent of Cash Costs for the U.S. Copper Industry, 1970-1993



Source: RTZ Mine Information System.

Figure 4. U.S. Real Hourly Wages and Labor Input per Unit of Output for Copper Mining and Milling, 1950-1994 (1970 = 100)



Source: U.S. Bureau of Labor Statistics.

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 at its properties in Arizona. It continued to produce during the strike, and ultimately union members who resisted the elimination of the cost of living adjustment and other concessions were permanently replaced.

Kennecott shut down Bingham Canyon in early 1985 after five years of consecutive losses, and started a $400 million modernization program later the same year. 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. According to the president of the United Steelworkers of America Local 392 at the time (Hamilton, 1988, p.1):

> We paid dearly to come back to work, but we had to do it. Changes had to be made . . . . I think we did the right thing, but a lot of people think we sold out to Kennecott.

Some companies, including Magma Copper and Inspiration Consolidated Copper, offered profit sharing plans tied to the price of copper to help convince workers to accept a reduction in salary and other concessions.

These arrangements produced sizable bonuses in the later 1980s when copper prices rose sharply (Regan, 1988, p. 1). This raised the possibility that a relapse in prices and profits might adversely affect worker morale and productivity. Magma, as a result, shifted in 1989 from a profit sharing plan to what it called a gain sharing plan. The latter tied bonuses directly to productivity and cost performance, rather than to profits and thus the price of copper, over which managers and workers have no control.

At the White Pine Mine in northern Michigan, the union's hard line against any concessions led to a strike in 1983. The mine remained shut for two years. During this period, Louisiana Land and Exploration sold the mine along with the other assets of the Copper Range Company to Echo Bay Mines, which in turn resold the mine to the mine's employees led by a former president of the Copper Range Company. In return for a share of the company and perhaps more importantly an opportunity to return to work, workers accepted a cut in pay of nearly $4.00 per hour, or about 33 percent (McDaniel, 1989). In addition, the cost of living adjustment was dropped. While these conditions caused some consternation at the time, most workers realized the old pay schedules were no longer feasible. Moreover, four years later when the mine was sold to Metallgesellschaft, the large German mining company, the average worker received $60,000 for his ownership shares (Stertz, 1989, p. 1+).

Increased Labor Productivity

While the fall in real wages, the increase in byproduct revenues, the jump in copper prices, and the rise in production costs abroad during the 1980s played a part in the recovery of the U.S. copper industry, the surge in labor productivity between 1980 and 1986 was particularly important. The hours of labor required to mine and mill a ton of copper, as Figure 4 shows, fell by over 50 percent during this period. This means one worker in 1986 was producing copper at a rate equivalent to that of two workers just six years earlier.

This rise in labor productivity is part of a longer run trend that has dramatically reduced the hours of labor to mine and mill a ton of copper since 1950. The long run trend, however, follows a series of downward steps, rather than a continuously declining curve, with major increases in productivity occurring in the 1950s and then, as just noted, in the early 1980s. In the 1960s and 1970s, labor productivity changed little. The same is true as well for the decade since 1985.

FACTORS AFFECTING LABOR PRODUCTIVITY

The critical role played by rising labor productivity in the revival of the U.S. copper mining industry leads naturally to a search for possible causes--increases in capital and other inputs available per worker, changes in the quality of the copper ore being mined, and new technology and other innovative activities.

Capital and Other Inputs per Worker

During the 1980s, Kennecott increased labor productivity at its Bingham Canyon mine by nearly 400 percent. The $400 million modernization program, mentioned earlier, that the company began in 1985 is credited with much of this increase (Goldberg, no date; Carter, 1990). This raises the question: how much of the increase in labor productivity in copper mining in the United States over the past several decades is simply the result of workers having more capital and other inputs with which to work.

Efforts to answer this question, and in turn to measure trends in total or multifactor productivity, are hampered by the absence of data on the capital stock and intermediate goods used in copper mining in the United States. The only attempt of which we are aware to estimate non-labor inputs and multifactor productivity for copper mining in the United States is Parry's chapter in this book. By making a number of assumptions, Parry's study derives estimates of the capital stock (structures, equipment, inventories, and land) and intermediate inputs (energy, purchased services, and raw materials) for copper on the basis of data available for the U.S. metal mining industry as a whole.

The findings, which Table 3 (below) highlights, are quite interesting. Between 1972 (the first year reported in the Parry study) and 1980, copper mine output fell by 22 percent in the United States. Hours of labor fell by nearly the same percentage, leaving labor productivity little changed over this period. In contrast, the estimated capital stock rose by 10 percent and inputs of intermediate goods by about 12 percent. As a result, multifactor productivity in copper mining declined by 22 percent.

Table 3 also reflects the recovery of U.S. production during the 1980s and early 1990s. Because the jump in output was achieved with substantially smaller inputs of labor, labor productivity nearly tripled between 1980 and 1992. Multifactor productivity also rose, though less dramatically, as inputs of labor, intermediate goods, and capital per unit of output all declined.

Table 3. Indices of Production, Labor Input, Capital Stock, Intermediate Goods Input, Labor Productivity, and Multifactor Productivity for the U.S. Copper Mining Industry, Selected Years (1972 = 100)

	1972	**1975**	**1980**	**1985**	**1990**	**1992**
Production	100	84	78	73	105	116
Labor Input	100	104	80	35	41	41
Capital Stock	100	114	110	95	79	81
Intermediate Goods Input	100	99	112	65	130	119
Labor Productivity	100	81	97	208	257	284
Multifactor Productivity	100	81	78	104	103	123

Source: Parry 1997.

The faster growth in labor productivity over multifactor productivity implies that some of the increase in labor productivity came about because labor had more capital and intermediate goods with which to work. While this finding is consistent with casual observation and anecdotal evidence, two caveats should be noted:

First, the numbers in Table 3, as pointed out earlier, are proxies based on data for all metal mining. While they represent the best estimates available of multifactor productivity, they rest on a number of critical assumptions, and in particular do not take account of the writing off of capital that occurred as many copper mines were closed prematurely.

Second, while Table 3 reflects an increase in the quantity of capital and intermediate inputs per unit of labor, the most dramatic trend it highlights is the drop in all inputs per unit of output between 1980 and 1992. This suggests that new technologies and other innovative activities have had a major impact on both labor and multifactor productivity since 1980.

Moreover, investments in structures and equipment often embody new technologies and other innovative developments. Thus, in practice, the effects of an increase in capital on productivity cannot easily be separated from those of new technology. The $400 million that Kennecott invested in Bingham Canyon during the 1980s, for example, paid for a mobile in-pit crusher, a five-mile long coarse-ore conveyor system, a 17 mile slurry pipeline that transports the concentrate from the mill to the smelter, three autogenous grinding mills, six ball mills, and 97 large-capacity flotation machines--all of which embodied state-of-the-art technology. Thus, some of the effect of capital deepening on labor productivity reflects the influence of better technology as well.

Quality of Copper Deposits

One additional factor of production still to be considered is the quality of the mineral reserves being exploited. Companies interested in maximizing shareholder value, it is widely presumed, will tend to mine the highest quality (and hence lowest cost) ores first. Thus, over time the remaining reserves will decline in quality, causing labor and multifactor productivity to fall, unless new technology, capital investment, or some of the other developments already considered offset this adverse effect.[3]

This tendency toward poorer reserves at individual mines, however, does not necessarily mean the average reserve quality across all mines has to fall. For the country as a whole, the average can rise as a result of (a) developing new mines with above average reserves, (b) closing down or cutting back production at mines with poor reserves, and (c) expanding output at mines with above average reserves. Thus, the jump in labor productivity and multifactor productivity since 1980 could in part reflect the mining of higher quality ores.

The first possibility, the discovery and development of new mines, we already know has been of little or no importance. As pointed out earlier, Flambeau and Cyprus Tohono were the only two significant mines producing copper in 1995 that were not in operation in 1975, and together they accounted for but 3 percent of U.S. mine output.

This implies that the quality of U.S. copper reserves either declined over time or at best remained largely unchanged. Still, the quality of the ores actually being mined may have increased as production shifted among mines. As noted above (and shown in Table 2), the United States had 26 significant copper mines in 1975. Seven of these mines were shut down and production at another seven sharply curtailed over the following two decades. Many of the remaining mines increased their output, some significantly, over this period. If the latter possess the better ores, which seems likely, this shift may have more than offset the decline in reserve quality at the level of individual mines.

Figure 5 (below) allows us to assess this possibility. It shows the average grade of the copper ore mined--commonly called the head grade--at all mines and at open pit mines in the United States over the 1971-93 period. While grade does not alone determine reserve quality, it is a major consideration.

The average head grade for all types of copper mining declined from 0.73 to 0.60 percent between 1971 and 1993, suggesting that the quality of the reserves mined in the United States has fallen, not risen, over the past couple of decades. The decline, however, was not monotonic. Average head grade rose in 1976-77 and over the early 1980s when copper prices were depressed. The second increase contributed to the jump in labor productivity and the revival of the U.S. copper industry during the 1980-86 period. This stimulus, however, was short lived, as average head grade fell over the second half of the 1980s, reaching a historic low by the early 1990s.

---

[3] There, of course, are exceptions. Ore location and other constraints may at times require mining lower grade and poorer quality ore early on in the life of a mine.

Figure 5. Average Copper Head Grades for All Mines and for Open Pit Mines in the United States, 1971-1993

Source: RTZ Mine Information System.

These figures, though, may be somewhat misleading, since some of the decline in head grade for all mines in part arises from the shift away from underground mining and toward leach mining over time. The high grades associated with underground mining reflect the inherently greater costs of such operations (which require high-grade ore to be profitable), while the low grades of leach mining similarly reflect its inherently lower costs. However, since the trend in average head grade for open pit mines alone follows closely that for all mining, the magnitude of this distortion is not great.

Thus, changes in the grade of ore mined--the rise during the early 1980s and the decline during the late 1980s--help explain the sharp jump in labor productivity during the first half of this decade and the stagnation in labor production thereafter. Over the entire 1971-93 period, however, changes in head grades, since head grades have fallen, do not explain the dramatic rise in labor and multifactor productivity.

Innovative Activity and New Technology

As noted earlier, significant declines in the labor, intermediate goods, and capital required to mine and process a ton of copper after 1980 (Table 3) suggest that innovative activity and new technology contributed greatly to the growth in labor productivity and the recovery of the U.S. copper industry. A number of studies (U.S. Congress, Office of Technology Assessment, 1988; National Material Advisory Board, 1990; Witzig, 1982; Queneau, 1985) provide further support for this proposition by documenting the changes across the entire spectrum from exploration to recycling that have taken place in the way copper and other metals are produced and consumed.

One particularly important development over the past several decades has been the increasing use of the solvent extraction electrowinning (SX-EW) process. The big advantage of this new technology lies in its low operating and capital costs. Pincock, Allen & Holt (1996), on the basis of its review of SX-EW facilities in the United States and abroad, estimates the average operating costs of producing SX-EW copper in 1995 at 39 cents per pound--8 cents for mining and handling, 13 cents for leaching, 16 cents for SX-EW recovery, and 2 cents for general and administrative costs. This total compares quite favorable with the 60 cents per pound the study estimates as the average operating costs for copper produced with the traditional technology. Capital costs of building new SX-EW capacity--estimated at 3,400 dollars at greenfield plants and 1,700 dollars at existing plants per annual ton of additional capacity--also are considerably lower than those for traditional facilities.

U.S. companies, as the next section shows, helped pioneer the development of this new technology, and led the world in its adoption. Between 1980 and 1995, the share of total U.S. copper output accounted for by the SX-EW process increased from 6 to 27 percent. By the end of this period the country possessed over half of the world's SX-EW capacity.

SX-EW technology is just one of many innovative activities U.S. producers undertook to increase labor productivity and reduce costs. Porter and Thomas (1988) estimated that new mine plans led to a drop in the average stripping ratio, measured as the tons of waste removed per ton of ore mined, from 2.11 in 1981 to 1.33 in 1986.

Other innovations came about as a result of the increased flexibility in work rules and manning assignments that new agreements with labor made possible. At Morenci and Bingham Canyon, the ore handling system was improved. Large trucks and in-pit mobile crushers with conveyor belts replaced rail haulage, once favored in very large mines for its ability to handle huge tonnages. The computerization of truck scheduling and real time process controls in mills produced significant economies at some sites. New work schedules helped at other operations. Larger trucks, shovels, and drills coupled with more cost effective explosives also generated savings. The concentration of U.S. production at a smaller number of large mines produced savings from economies of scale.

SOLVENT EXTRACTION ELECTROWINNING

While innovative activity and new technology clearly can and do increase labor and multifactor productivity, can they reduce any particular company's or country's comparative costs, that is, its costs relative to its competitors' costs? Skeptics point out that new innovations, such as larger trucks and better drills, are often produced by equipment makers who are not only willing to sell their products abroad but actually promote such sales. For this and other reasons, new innovations diffuse very rapidly, particularly in what is becoming an increasingly global economy, and any cost advantage a firm realizes from introducing a new technology will be short lived at best.

This validity of this view, however, depends on two implicit assumptions. First, new innovations are one-time, discrete events, rather than an on-going series of minor and major advances. Where development is continuous over an extended period of time, innovators can maintain a technological lead and in turn a cost advantage. Second, new innovations are neutral in the sense that they possess the potential to reduce all producers' costs similarly. This need not be the case. Large trucks, for example, are particularly cost-effective in large open-pit mines, and simply unusable in small underground operations.

While these two assumptions or conditions may be satisfied for some innovations, anecdotal evidence, to us at least, suggests that they frequently do not hold, and thus that innovative activity often shifts the comparative costs of producers, favoring some at the expense of others, while raising labor and multifactor productivity.

To illustrate this point, we will delve in some depth into the early development and subsequent evolution of the SX-EW process. Before doing so, however, we examine the nature of the SX-EW process, and compare it with the traditional technology for processing copper ores.

Copper Technology

The traditional technology entails mining sulfide copper ore in underground or open pit mines. The ore is then moved by truck, rail, or conveyor belt to a mill where it is crushed and the copper bearing minerals separated from the waste material or gangue by flotation. The resulting concentrate (25 to 40 percent copper) is shipped to a smelter for partial purification (97 to 99 percent copper), and then on to a refinery for electrolytic purification (99.99 percent copper).

The SX-EW process involves leaching existing mine dumps, prepared ore heaps, or in situ ore with a weak acidic solution. The solution is recovered, and in the next stage, the solvent extraction stage (SX), mixed with an organic solvent (referred to as an extractant), which selectively removes the copper. The copper-loaded extractant is then mixed with an aqueous acid solution, which strips it of the copper. The resulting electrolyte is highly concentrated and relatively pure, and is processed into high quality copper in the third and final stage by electrowinning (EW).

The leaching of existing mine dumps does not require mining since these dumps are already in place from past operations. Mining is similarly not necessary for in situ leaching, where copper is extracted from fractured ore remaining in place within the original deposit. The leaching of prepared ore heaps, however, does require that the ore be removed from the deposit, in some cases crushed, and then placed on prepared heaps or "lifts." Mining, of course, adds to costs.

SX-EW is a hydrometallurgical process, while the traditional technology is referred to as a pyrometallurgical process since it entails smelting. There are, however, other hydrometallurgical processes for treating copper ores. For centuries copper has been leached and then recovered by precipitation with iron. This process produces cement copper (85-90 percent copper), which then must be smelted and electrorefined. Direct electrowinning involves leaching and electrowinning, but skips the solvent extraction stage. It produces a lower-quality copper contaminated with iron and zinc, which is considered more of a substitute for high-grade (number 1) copper scrap than for electrorefined copper.

Evolution of SX-EW Technology[4]

The leaching of copper ores can be traced back to 15th century Hungary, and until earlier in the 20th century leaching and precipitation by iron was the only hydrometallurgical method available to process copper. With the commercial development of electricity, the direct electrowinning of copper became possible. The first commercial application of this technology took place in 1915 at Ajo in Arizona and at Chuquicamata in Chile. As noted earlier, neither of these processes produced copper of sufficiently high quality to compete directly with electrorefined copper. This became possible only with the development of solvent extraction technology during and after World War II.

Solvent extraction was first employed during the war to separate and recovery uranium. It is now widely use to treat a variety of metals--copper, zinc, nickel, gold, silver, rare earth metals, and others. It typically concentrates the metal in solution and acts as filter to remove impurities.

---

[4] This and the following subsections draw heavily from Pincock, Allen & Holt (1996), Biswas and Davenport (1994), Arbiter and Fletcher (1994), Coombs (1995), Jeric (1995), Lake (1996), Townsend and Severs (1990), and Hopkins (1994).

Ranchers Exploration and Development Company began operating the first commercial SX-EW facility for copper at its Bluebird Mine in Arizona in March 1968. It worked closely on this project with the General Mills Corporation (whose chemical division developed the necessary extractants during the early 1960s), with Hazen Research Incorporated (which as a consulting engineering firm helped develop the process), and with the Bechtel Corporation (which designed and constructed the production plant).

The second SX-EW facility started in 1970 at the Bagdad mine of Cyprus Mines. Subsequent installations occurred during the 1970s at Nchanga in Zambia, at Cerro Verde in Peru, and at Johnson Camp, Twin Buttes, Miami, Battle Mountain, Inspiration, and Ray in the United States.

By the early 1980s, SX-EW was rapidly replacing direct electrowinning and leaching with iron precipitation. The quality of SX-EW copper did not yet rival that of electrorefined copper. It was generally sold at a discount, and used by alloy producers and other customers who did not need the highest quality copper.

Shell, Acorga Limited, and Ashland Chemicals joined General Mills as suppliers of extractants. Henkel Corporation purchased the operations of General Mills and Shell, and along with Acorga remains a major supplier of extractants. These companies developed second and third generation extractants that enhanced the removal of impurities. The new extractants also extended the range of treatable leach solutions, in particularly allowing the upgrading and purification of much more acidic solutions with a wider range of copper concentrations. This greatly increased the dump and heap materials from which copper could be processed. At the same time, improvements in equipment design permitted the more rapid and effective mixing of the extractant with the leach solution and then the recovery or stripping of the copper from the extractant.

The successful introduction of SX-EW stimulated a search for better technologies at the leaching and electrowinning stages of production. For example, although electrowinning and electrorefining are similar, electrowinning uses a lead rather than copper anode. Early problems with lead contamination were eventually overcome by the addition of cobalt salts to the electrolyte.

At the leaching stage, important advances have occurred in the acid solutions or lixiviants used to dissolve the copper in a continuing effort to extend the range of copper minerals suitable for SX-EW processing. Copper is recovered from both primary and secondary copper-bearing minerals. The former are the primary sulfides (chalcopyrite, bornite). The secondary minerals, produced by natural processes over extended periods of time from the primary minerals, include carbonates (azurite, malachite), oxides (cuprite, tenorite), hydroxy-silicates (chrysocolla), sulfates (antlerite, brochantite), native copper (copper metal), and secondary sulfides (chalcocite, covellite). The non-sulfide ores are typically the easiest and quickest to leach. The sulfide ores, both primary and secondary, require that an oxidant be added to the acidic leach solution. The process takes longer, for some ores literally years longer, and is less complete. Bioleaching, which uses bacteria as a catalyst, has shortened the leaching time for sulfide ores. Even though most of the world's copper reserves are primary sulfide minerals and thus still best processed with the traditional pyrometallurgical technology, these efforts have expanded, and continue to expand, the use of SX-EW.

Other advances include the recent addition of surfactants to the leach solution, which allows the solution to spread more completely over the copper bearing minerals, increasing the amount of copper recovered. For some time efforts have also been underway to improve in situ leaching techniques, which eliminate the need and cost of mining. In arid regions, producers have replaced sprinklers with drip irrigation and covered their heaps with plastic sheeting to reduce solution losses from evaporation.

Technological advances in SX-EW technology over the past several decades have reduced production costs at all three stages of production--leaching, solvent extraction, and electrowinning. They have also extended the range of ore sources from which copper could be economically extracted. In the 1970s and early 1980s, SX-EW was primarily used to recover copper from existing waste piles, which required no mining and contained copper minerals that were quick and easy to leach. In recent years, the process has been increasingly used in mine-for-leach operations, where certain types of copper minerals are mined for leaching. Though not yet successful, efforts continue to develop techniques to use SX-EW in place of the traditional pyrometallurgical technology to process the primary sulfide minerals which account for the bulk of the world's copper reverses.

This review, though it identifies only some of the important advances in the SX-EW process over the past several decades, illustrates the dynamic nature of this technology. With such technologies, innovative firms can maintain a technological lead even though competitors adopt any particular advance within a few years or even months of its introduction. Maintaining such a lead, however, requires a persistent commitment to innovation, to the development and use of new technologies.

Effects on Comparative Costs

The SX-EW process has in two ways helped the U.S. copper producers reduce their costs relative to those of their foreign competitors. First, the technological lead in this field the U.S. firms have enjoyed since the introduction of the solvent extraction process in the late 1960s has allowed them to benefit from the cost savings derived from new advances in SX-EW technology sooner than other producers. If the U.S. producers maintain their technological lead, and continue to pioneer important new advances in the SX-EW process, this advantage can continue indefinitely.

Second, the SX-EW process is not a neutral innovation. It reduces the costs of some copper producers much more than others. In particular, it tends to favor:

- Countries, such as the United States, that have historically been important copper producers and that have over the years accumulated substantial waste piles of oxide copper minerals. These minerals, as pointed out earlier, are often found near the surface of porphyry deposits. As the traditional pyrometallurgical technology can not process such ores, they have been removed and place into waste dumps. SX-EW technology can now treat these dumps quite inexpensively. In addition, the SX-EW process allows the recovery of copper from low-grade ores which producers in established mining districts have not found economic to extract with the traditional technology.

- Countries, such as the United States, that are currently important producers of copper and that enforce stringent environmental regulations. Producers in these countries are forced to recover the sulfur emissions from their smelting operations, typically in the form of sulfuric acid. This provides a low-cost source of leach solution, as diluted sulfuric acid is the prevailing acid used at this stage of the SX-EW process. There is, thus, a strong symbiotic relationship between the new SX-EW process and traditional technology.
- Countries, such as the United States, whose copper deposits are located largely in arid regions. Where precipitation is heavy, maintaining the desired characteristics of the leach solution is difficult.
- Countries, such as the United States, that possess substantial copper reserves with little or no byproducts of value. One current shortcomings of the SX-EW process is its inability to recover gold, molybdenum, and other valuable byproducts. The SX-EW process is also not suitable for treating primary sulfide minerals, such as chalcopyrite, given the lengthy periods required to leach these minerals.

The inherent advantages that the SX-EW process bestows on the United States are not accidental. U.S. producers pushed the development of this new technology because of the potential benefits it offered for their operations. While future developments may strengthen or weaken these advantages, as long as U.S. producers remain the major innovators they will have strong incentives to pursue most actively those developments that particularly favor their activities.

Others, of course, may benefit as well. Indeed, the conditions that make SX-EW advantageous to U.S. producers exist in other countries. This is especially so for Chile, which may soon surpass the United States in the production of SX-EW copper. The important point, however, is that SX-EW has reduced the costs of some producers more than others. The United States has benefited from this non-neutral effect on comparative costs, and may continue to do so for some time.

LESSONS

The story of the U.S. copper industry over the past three decades--its decline and dramatic revival--is of some intrinsic interest, particularly for those whose welfare is significantly affected by the fortunes of this particular industry. We, however, have studied this industry in the hope of finding implications and lessons that extend beyond copper mining in the United States. This final section first looks at the implications for mining and mineral producing countries competing in increasingly competitive global markets, and then for all countries striving to increase the productivity of their workforce.

Comparative Advantage in Global Mineral Markets

Why countries produce and export the goods they do has interested economists for centuries. Modern explanations, based on the doctrine of comparative costs that David Ricardo introduced nearly two hundred years ago, contend that states will produce and export those commodities whose production costs are low relative to the costs of other domestic products when compared with production costs in other countries.

The doctrine of comparative costs is just the first step in accounting for comparative advantage. To be useful, it must be coupled with an explanation of why differences in comparative costs arise among countries. In the first attempt to answer this question, Ricardo and other classical economists pointed to differences in labor productivity.

The factor endowment theory, advanced by the Swedish economists Eli Heckscher and Bertil Ohlin in the early years of the 20th century, provides a second explanation for differences in comparative costs. This theory contends that differences in production costs are due largely to differences between countries in the price of capital, labor, and other factors of production, which arise because countries enjoy different factor endowments.

Over the past several decades, numerous other explanations for differences in comparative costs have emerged. These theories stress the importance of differences among countries in the generation and diffusion of technology, in human capital, in opportunities to exploit economies of scale, in regional externalities, in domestic market conditions, in strategic trade policies capitalizing on learning economies, and in the opportunities to realize economies of scope.

They arose to explain trade between the industrialized countries in manufactured goods and services. While differences in factor endowments and productivity exist among these countries, they are small compared with the differences between the developed and developing countries. Moreover, developed countries with similar domestic conditions, such as those of Western Europe, often import and export the same or similar final goods with each other. This has produced considerable uneasiness over the validity and usefulness of the neoclassical and factor endowment theories in explaining trade between such countries in automobiles, farm machinery, computers, and other manufactured products.

This dissatisfaction, however, does not extend to trade in primary products. Here, one still finds widespread acceptance of the factor endowment theory as the most useful explanation for international differences in production costs. In the words of Haberler (1977, p. 4):

> The most obvious factors that explain a good deal of international trade are 'natural resources'--land of different quality (including climatic conditions), mineral deposits, etc. No sophisticated theory is required to explain why Kuwait exports oil, Bolivia tin, Brazil coffee and Portugal wine. Because of the deceptive obviousness of many of these cases economists have spent comparatively little time on 'natural resource trade.'

Intuitively, the hypothesis that mineral endowment is the overriding determinant of comparative advantage in mining and mineral processing is very appealing. It also has some important implications.

First, all other determinants of comparative advantage in mining are of second order importance compared with resource endowment. In particular, the generation and diffusion of new technology along with other innovations are relatively insignificant. This is either because the production process changes little over time, or because new technologies and innovations diffuse quickly and effortlessly around the world providing little opportunity for individual mines, companies, or countries to exploit such developments to achieve a cost advantage.

Second, it suggests that comparative advantage in mining and mineral processing is largely a transitory gift of nature. Countries with the best deposits and the lowest production costs are the most competitive in world markets. Once their deposits are exhausted, comparative advantage shifts to those countries with the next best deposits. From time to time, new discoveries may also produce shifts in comparative advantage.

Third, and a corollary of the second, corporate managers and labor can do little to maintain or enhance the comparative advantage of a particular mine. As long as it possesses reserves, it will operate. Once its reserves are gone, it will close. Companies can maintain their comparative advantage only by ensuring new high quality deposits are discovered or otherwise acquired to replace those being depleted.

Fourth, governments of mineral producing and exporting countries are similarly limited in their ability to promote comparative advantage. While they can encourage domestic exploration for new deposits (through favorable land use policies, taxation, permitting requirements, and so on) to slow the decline, eventually the depletion of the best deposits will encourage firms to look abroad for new reserves. Governments can capture and invest some of the rents or profits their domestic reserves generate so that the public welfare can be sustained once the mineral wealth is gone. They cannot, however, prevent mineral exhaustion and the ultimate loss of comparative advantage this effects.

This picture of comparative advantage is largely deterministic. One exogenous factor (mineral endowment) governs the evolution over time of production and trade. Other than finding and developing new high quality deposits, management, labor, and governments can do little to reduce their relative costs and enhance their comparative advantage.[5]

The interesting policy issues are now how long the endowment will last and how to divide the resulting rents among workers, equity holders, the state as a whole, and other

---

[5] An interesting public policy issue that lies beyond the scope of the analysis here concerns the effectiveness of U.S. government in promoting the discovery of new mineral deposits. The U.S. copper industry, as pointed out earlier, has discovered and developed very few new mines since 1970. Moreover, in recent years the country's share of world mineral exploration has declined. These developments may reflect a deterioration in the industry's perception of the country's geological potential as well as increasingly favorable mineral polices in many countries abroad, particularly developing countries. There is, however, widespread concern within the U.S. mineral industry that domestic regulatory policies are also discouraging the search for new mineral deposits within the United States.

interested parties. These issues lead inevitably to concerns over sustainability, intergenerational equity, and the complexities of green accounting.

On the other hand, if extending mineral endowment by developing known marginal deposits or by discovering new deposits is not the overriding determinant of costs, but simply one of many activities mineral producers pursue in an unrelenting struggle to reduce costs, the set of important issues changes. The whole process becomes much more endogenously driven. There are still rents to be captured, but they are no longer predetermined gifts of nature, fixed in size, that firms and countries can effortlessly gather up. They are instead created by mining companies, specifically those companies that succeed in the global competition to reduce production costs.

In this scenario, managers and workers are not helpless bystanders watching external forces unravel their predetermined fate, but instead are crucial players who through their innovative efforts significantly control their own destiny. The role of government shifts from ensuring society as a whole gets its fair share of the externally given rents and that these are used in a manner that ensures intergenerational equity, to providing an economic climate that encourages the innovative activities of firms and individuals.

In this scenario, human ingenuity can keep the real prices of mineral commodities falling indefinitely, making concerns over sustainability and intergenerational equity less pressing. Interestingly, the forces shaping comparative advantage for mineral commodities are not all that different from the forces determining which firms and countries will produce and export high technology goods and services.

The U.S. copper industry demonstrates that the second scenario, at least in some instances, is more relevant and useful in understanding the nature of production and trade in mineral commodities than the traditional paradigm based on the factor endowment theory. Moreover, while the dramatic turnaround of the U.S. industry may be exceptional, the experience of the successful U.S. firms in other respects is not all that unusual. Around the world, mineral companies are constantly searching for new technologies and other innovations to reduce costs, knowing that maintaining competitiveness in the future means producing at ever lower costs. The discovery and development of high quality deposits is only one of many possible avenues for reducing costs, and often not the most important.

Public Policy and Productivity

The story of copper mining in the United States also has implications for countries striving to raise living standards by promoting productivity growth. The U.S. government denied the copper industry's request for protection from imports in 1978 and 1984 on the grounds that the costs to fabricators would exceed the benefits to copper producers. While there is no way to know for certain how copper mining in the United States would have fared with protection, with the benefit of hindsight several conjectures seem reasonable.

Competition from the world's most efficient producers left U.S. firms--their managers and workers--with little choice. They either had to shut down or pursue a range of innovative activities to enhance their productivity and efficiency.

Protection would have limited and constrained the stimulating effects of this competition, weakening the push for new and better production methods. The sharp jump in labor productivity and fall in costs during the 1980s would have come more slowly, perhaps much more slowly. The revival of the industry would have been less spectacular. Copper mining in the United States would now almost certainly be less efficient, less competitive in global markets, and possibly still dependent on government protection or subsidies for its survival. It appears, ironically, that the domestic copper producers were fortunate their requests for protection in 1978 and 1984 went unheeded.

It is important, of course, to remember there were costs. Mines closed, and some three-quarters of the workforce lost jobs. Such costs are the price an economy pays to sustain productivity growth and international competitiveness in dynamic, high technology industries, including mining. Fortunately, these costs are temporary, while the benefits are long lasting. Still, for societies that care both for those hurt by change and for their children, the challenge is to find ways to help the former without impeding growth in output per worker. For as Paul Krugman so succinctly notes, over time labor productivity and little else matters in determining a country's standard of living.

REFERENCES

Andrews, David H., Jr. 1989. "Cost Reductions by U.S. Mineral Producers: Real or Illusory?" unpublished MS thesis, Mineral Economics Department, Colorado School of Mines, Golden, Colorado.

Arbiter, Nathaniel, and Archie W. Fletcher. 1994. "Copper Hydrometallurgy--Evolution and Milestones," *Mining Engineering*, February, pp. 118-23.

Barnett, Harold J., and Chandler Morse. 1963. *Scarcity and Growth* (Baltimore, Md.: The Johns Hopkins University Press for Resources for the Future).

Biswas, A. K., and W. G. Davenport. 1994. *Extractive Metallurgy of Copper*, Third edition (Tarrytown, N.Y.: Pergamon and Elsevier Science).

Campbell, Gary A. 1989. "The Response of US Copper Companies to Changing Market Conditions," *Resources Policy*, December, pp. 321-337.

Carter, Russell A. 1990. "Kennecott Utah Copper Modernization Pays Off," *E&MJ*, January, pp. C22-C29.

Chlumsky, Gregory F., and Toni L. Wallis. 1996. "Sx/Ew: Technology, Quality and Cost Update," unpublished paper prepared for Metal Bulletin, 9th International Copper Conference, April 16.

Chundu, Askim, and John E. Tilton. 1994. "State Enterprise and the Decline of the Zambian Copper Industry," *Resources Policy*, vol. 20, no. 4 (December), pp. 211-218.

Coombs, David. 1995. "The SxEw Factor," *Mine & Quarry*, October, pp. 30-36.

Crowson, Phillip. 1987. "Some Aspects of Copper Production Costs," John M. Olin Distinguished Lecture in Mineral Economics, Colorado School of Mines, February 2.

Doyle, James. J. 1982. "Analysis of the Productivity Trends in the Strategic and Critical Minerals Industries: The Case of Copper," unpublished final report submitted to the U.S. Bureau of Mines (Fort Washington, Pa.: JACA Corporation), October 9.

Goldberg, Gary J. Undated, circa 1991. "Productivity at Bingham Canyon," Mine Operations Superintendent, Kennecott, Utah Copper, 9 pp.

Haberler, Gottfried. 1977. "Survey of Circumstances Affecting the Location of Production and International Trade as Analysed in the Theoretical Literature," in Bertil Ohlin and others, eds., *The International Allocation of Economic Activity* (New York: Holmes and Meier Publishers).

Hamilton, Martha M. 1988. "U.S. Copper Industry is Lesson in Survival," *The Washington Post*, January 17.

Hopkins, Wayne R. 1994. "SX-EW," *Mining Magazine*, May, pp. 256-265.

Jeric, Steve. 1995. "The Impact of Solvent Extraction on World Supply of Copper," unpublished paper, Colorado School of Mines, December 12.

Krugman, Paul. 1994. *The Age of Diminished Expectations: U.S. Economic Policy in the 1990s*, revised and updated edition (Cambridge, Mass.: MIT Press).

Lake, James L. 1996. "A Better Way to Make Copper," *Pay Dirt*, December, pp. 4-10.

McDaniel, Kirk Haley. 1989. "The New Copper Range Company: Its Regeneration and the Factors Influencing It," unpublished MS thesis, Department of Mining Engineering, Colorado School of Mines, Golden, Colorado.

National Material Advisory Board, National Research Council. 1990. *Competitiveness of the U.S. Minerals and Metals Industry* (Washington, D.C.: National Academy Press).

Parry, Ian. 1997. *Productivity Trends in the Natural Resource Industries*, RFF Discussion Paper 97-39, Resources for the Future, Washington, D.C., July.

Pincock Allen & Holt. 1996. *Copper Technology to Year 2000*, Information Bulletin 96-1 (Lakewood, Colo.).

Pincus, William J. 1994. "Low Costs Boost SX-EW's Image,' *MBM Copper Supplement*, May, pp. 30-35.

Porter, K. E., and Paul R. Thomas. 1988. "Competition Among World Copper Producers," *EM&J*, November, pp. 38-44.

Queneau, Paul Etienne. 1985. "Innovation and the Future of the American Primary Metals Industry," *Journal of Metals*, February, pp. 59-64.

Regan, James G. 1988. "Miners Share $10M at Two Copper Firms," *American Metal Market*, June 27.

Stertz, Bradley A. 1989. "A Once-Poor Town Gets a Lot of Advice Now That It's Rich," *Wall Street Journal*, June 29.

Takeuchi, Kenji, and others. 1987. *The World Copper Industry: Its Changing Structure and Future Prospects*, Commodity Working Paper No. 15, The World Bank, Washington, D.C.

Tietenberg, Tom. 1996. *Environmental and Natural Resource Economics*, Fourth Edition (New York, Harper Collins).

Townsend, B., and K. J. Severs. 1990. "The Solvent Extraction of Copper--A Perspective," *Mining Magazine*, January, pp. 26-35.

U.S. Congress, Office of Technology Assessment (OTA). 1988. *Copper: Technology and Competitiveness*, OTA-E367 (Washington, D.C.: Government Printing Office), September.

Young, Denise. 1991. "Productivity and Metal Mining: Evidence from Copper-Mining Firms," *Applied Economics*, No. 23, pp. 1853-1859.