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The Availability of Primary Copper in Market Economy Countries

A Minerals Availability Appraisal

By Kenneth E. Porter and Gary R. Peterson

UNITED STATES DEPARTMENT OF THE INTERIOR

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PREFACE

The U.S. Bureau of Mines Minerals Availability Program is assessing the worldwide availability of nonfuel minerals. The Bureau identifies, collects, compiles, and evaluates information on active and developing mines, explored deposits, and on mineral processing plants worldwide. The program's objectives are to classify domestic and foreign resources; to identify by cost evaluation resources that are reserves, and to analyze the availability of mineral resources.

This report is a continuation of previous Division of Resource Evaluation reports in which the availability of copper resources from domestic and foreign sources and the factors affecting availability were evaluated. This report updates and expands upon the first report that was published in 1983.

Analyses of other metals and minerals are in progress. Questions about the Minerals Availability Program should be addressed to Chief, Division of Resource Evaluation, U.S. Bureau of Mines, 810 7th Street, NW., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

kg	kilogram	mt	metric ton
kmt	thousand metric ton	Mmt	million metric ton
lb	pound	tr oz	troy ounce

THE AVAILABILITY OF PRIMARY COPPER IN MARKET ECONOMY COUNTRIES

A Minerals Availability Appraisal

By K.E. Porter,[1] and G.R. Peterson[2]

ABSTRACT

The U.S. Bureau of Mines has estimated the potential availability of copper from 204 mines and deposits in market economy countries (MEC's). The evaluated properties have demonstrated resources totaling 436.4 million metric tons of contained copper and account for 90% of the Bureau of Mines reserve base for copper in market economy countries.

Total recoverable MEC copper resources are 340.8 million metric tons, 69% of which is from producing mines and 31% from nonproducing mines and deposits. Chile had the lowest estimated average total cost from producing mines of $0.48 per pound of recoverable copper at a 0% discounted cash-flow rate of return (DCFROR), with estimated average total costs ranging from $0.40 to $0.81 per pound. The estimated average total cost of production, per pound of copper, for producing mines in the United States amounts to $0.57 in January 1988 dollars at a 0% DCFROR, with estimated total costs ranging from $0.36 to $0.85 per pound.

In both real and nominal terms, the United States has, on average, significantly lowered its copper production costs since 1981. Rationalization of the industry and significant increases in productivity have made a strong improvement in the competitiveness of the U.S. copper industry to the extent that the United States should no longer be considered as a marginal producer of copper.

[1]Mining Engineer.
[2]Mineral Economist.
U.S. Bureau of Mines, Minerals Availability Field Office, Denver, CO.

INTRODUCTION

The world copper industry was severely affected by the period of low metals prices from 1982 to 1987. The oversupply of copper and low prices caused producers worldwide to institute rationalizations and cost-reduction measures in order to improve their relative competitiveness and profitability. The U.S. copper industry was particularly hard hit by the drop in consumption associated with the recession of the early 1980's. World copper consumption had begun to decrease after 1979, and dropped even further during the following recession. Copper prices peaked in 1980, then plunged almost 50% in real terms before leveling off in 1984. Despite the slumping copper market, copper production continued to increase in countries such as Chile, and world inventories swelled. The strong U.S. dollar over this period favored imported copper over domestic production.

By the mid-1980's, domestic mine production had fallen to its lowest level in two decades, and the United States lost its position as the world's largest mine producer of copper for the first time in a century. Between March 1981 and January 1983, 28 U.S. mines closed or cut back production, and domestic mine capacity utilization was down to about 65%. By the end of 1982, the domestic copper industry had laid off about 42% of the total work force.

Caught in the vise of rising costs versus low commodity prices, the copper industry was faced with the unwelcome choices of cutting costs or going out of business. Although some of the mines were closed, the majority managed to find ways to cut costs and improve efficiencies. The initial method used to cut operating costs was to convince labor to accept lower wages and benefits, and to cross-train workers for more than one job. Technological improvements included the installation of in-pit crushers and conveyors to reduce energy costs and costly truck haulage; the use of larger equipment to take advantage of economies of scale; initiate leaching of old and new waste dumps and to erect SX-EW plants to treat the copper leaching solutions.

In concentrators, new and larger SAG mills (semiautogenous grinding) were installed, and many copper cleaner flotation circuits were converted to column flotation to enhance recoveries and to reduce energy consumption. As a result of cost-cutting efforts, the U.S. copper industry reestablished its competitive position within the world copper industry. Cost reduction measures are detailed in the appendix.

This study evaluates the potential availability of copper from 204 mines and deposits in market economy countries, 112 of which were producing as of January 1988, and 92 properties which were under development, temporarily shut down, or explored.

ACKNOWLEDGMENTS

Much of the data for the domestic deposits and properties analyzed in this study were developed at Bureau of Mines Field Operations Centers in Denver, CO, Juneau, AK, and Spokane, WA. Richard R. Beard of the Arizona Department of Mines and Mineral Resources was extremely helpful in providing insights into the Arizona copper industry.

WORLD COPPER PRODUCTION

In 1988, copper was mined in 51 countries, with the top six producing countries in MEC's accounting for almost 58% of world mine production and more than 72% of mine production in MEC's. The six leading MEC mine producers in 1988 were Chile (21.8%), the United States (21.0%), Canada (11.2%), Zaire (7.8%), Zambia (5.9%), and Peru (4.4%). Mine production and smelter/refinery production of copper as well as refined consumption, by country, in 1988 is shown in table 1.

RESERVES/RESOURCES

Demonstrated resources of the 204 properties in MEC's evaluated for this study as of January 1, 1988, are presented in table 2. The comparison of demonstrated resources evaluated in relation to the Bureau reserve base for copper is illustrated in figure 1 (*1*).[3] The list of properties evaluated appears in table 3. The total demonstrated resource amounted to 55.4 billion metric tons of ore containing 436.4 million metric tons of copper metal. Of that amount, approximately 341 million metric tons of copper is estimated to be recoverable. In terms of recoverable copper, 29.0% is in Chile, 16.5% is in the United States, 8.0% is in Australia, and 6.7% is in Peru.

[3]Italic numbers in parentheses refer to items in the list of references at the end of this report.

The United States has the largest known in situ resource of 15.1 billion metric tons of ore, followed by Chile with 11.5 billion metric tons, but the average copper grade in the United States is much lower (0.52% compared to 1.0%), resulting in Chile having a contained copper resource that is significantly higher than in the United States, amounting to 115.5 million metric tons compared to 78.3 million. In terms of recoverable copper, Chilean deposits contain 98.9 million metric tons, compared with 56.2 million metric tons for the U.S. deposits. The Americas dominate the copper resource picture for the MEC's, with 67.9% of total recoverable copper. Chile and the United States combined account for 45.5% of total recoverable MEC copper.

Table 1.—World production and consumption of refined copper, by country, in 1988
(Thousand metric tons of contained copper)

Country	Mine[1,2] production	Smelter production[1,3]		Refinery production[1,4]		Refined[5] consumption primary and secondary
		Primary	Secondary	Primary	Secondary	
Albania	15.0	14.5	—	13.0	—	11.0
Argentina	.5	—	—	—	—	60.0
Australia	238.3	177.8	9.0	191.2	26.7	125.6
Austria	—	—	34.5	3.6	38.4	37.0
Belgium	—	1.2	93.2	364.3	140.0	306.5
Bolivia	.2	—	—	—	—	—
Botswana	24.4	—	—	—	—	—
Brazil	44.4	147.9	—	147.9	38.1	259.6
Bulgaria	80.0	87.0	5.0	75.0	20.0	71.0
Burma	13.8	—	—	—	—	—
Canada:						238.5
Concentration/leaching	753.5	537.0	14.0	490.7	38.0	—
Leaching (electrowon)	5.0	—	—	—	—	—
Chile	1,472.0	1,189.4	—	1012.7	—	42.7
China	375.0	400.0	—	510.0	—	470.0
Congo (Brazzaville)	1.0	—	—	—	—	—
Cuba	3.0	—	—	—	—	2.8
Cyprus	.3	—	—	—	—	—
Czechoslovakia	5.0	5.0	22.1	5.0	22.1	96.0
Ecuador	.1	—	—	—	—	—
Egypt	—	—	—	—	2.5	6.5
Finland	20.2	79.0	12.0	47.9	6.0	73.7
France	.3	—	8.5	7.2	36.0	395.1
German Democratic Republic	10.0	25.0	—	18.0	62.0	131.5
Germany, Federal Republic of	.7	171.5	50.0	192.2	234.2	796.1
Greece	—	—	—	—	—	51.0
Honduras	.6	—	—	—	—	—
Hungary	—	—	.1	19.2	—	25.8
India	55.7	44.8	—	44.8	—	130.0
Indonesia	121.5	—	—	—	—	33.0
Iran	51.0	52.0	—	32.0	—	20.5

See footnotes at end of table.

Table 1.—World production and consumption of refined copper, by country, in 1988—Continued
(Thousand metric tons of contained copper)

Country	Mine[1,2] production	Smelter production[1,3]		Refinery production[1,4]		Refined[5] consumption primary and secondary
		Primary	Secondary	Primary	Secondary	
Italy	—	—	—	.0	71.4	437.3
Japan	16.7	854.6	139.4	854.6	100.5	1,330.7
Korea, North	15.0	15.0	3.0	18.0	4.0	22.0
Korea, Republic of	—	123.5	—	168.3	0.7	289.0
Malaysia	22.0	—	—	—	—	18.8
Mexico:						105.2
Concentration/leaching	268.8	151.8	—	98.9	19.9	—
Leaching (electrowon)	11.4	—	—	11.4	—	
Mongolia	160.0	—	—	—	—	—
Morocco	14.5	—	—	—	—	
Mozambique	.1	—	—	—	—	—
Namibia	40.9	42.2	—	—	—	—
Netherlands	—	—	—	—	—	20.1
New Zealand	—	—	—	—	—	1.8
Norway	15.9	31.7	—	31.7	—	11.9
Oman	17.1	16.8	—	16.5	—	—
Papua New Guinea	218.6	—	—	—	—	—
Peru:						46.8
Concentration/leaching	301.7	246.9	—	179.6	—	
Leaching (electrowon)	21.1	—	—	21.1	—	
Philippines	218.1	159.2	—	132.2	—	8.3
Poland	437.0	385.0	25.0	401.0	—	220.0
Portugal	5.2	2.5	2.0	6.0	—	26.0
Romania	26.0	28.0	8.0	30.0	12.0	42.0
Saudi Arabia	.3	—	—	—	—	17.0
South Africa, Republic of	168.5	180.0	—	139.4	—	75.1
Spain	18.1	95.6	50.0	108.8	50.0	135.0
Sweden	74.4	90.4	25.5	68.3	22.0	104.6
Switzerland	—	—	—	—	—	12.0
Taiwan	—	43.3	—	43.3	10.0	217.5
Thailand	—	—	—	—	—	26.2
Turkey	31.2	12.8	.1	68.4	—	75.6
U.S.S.R	640.0	800.0	150.0	850.0	150.0	1,290.0
United Kingdom	.7	—	—	49.3	74.7	327.7
United States:						2,203.0[r]
Concentration/leaching	1,191.7	1,043.0	320.2	1,178.0	446.0	—
Leaching (electrowon)	228.0	—	—	228.0	—	—
Venezuela	—	—	—	—	—	21.8
Vietnam	—	—	—	—	—	2.0
Yugoslavia	103.5	106.5	65.5	105.6	39.8	145.4

See footnotes at end of table.

Table 1.—World production and consumption of refined copper, by country, in 1988—Continued
(Thousand metric tons of contained copper)

Country	Mine[1,2] production	Smelter production[1,3]		Refinery production[1,4]		Refined[5] consumption, primary and secondary
		Primary	Secondary	Primary	Secondary	
Zaire:						2.4
Concentration/leaching	250.0	160.0	—	202.6	—	
Leaching (electrowon)	280.0	306.8	—	—	—	
Zambia:						8.0
Concentration/leaching	284.1	308.9	—	397.7	—	
Leaching (electrowon)	147.7	95.9	—	51.8	—	
Zimbabwe	16.9	16.1	—	16.1	11.4	9.6
Others	—	—	—	—	—	16.4
Total	8,536.7	8,247.5	1,037.1	8,655.4	1,676.2	10,653.2
	Of which:			Of which:		
	Electrowon		402.7	Primary		8,126.2
	Other		7,513.1	Undifferentiated		529.2
	Undifferentiated		169.0			

[1]Source: BuMines Copper Minerals Yearbook (*2,3*).
[2]Data represents copper content by analysis of concentrates produced except where otherwise noted.
[3]Data represents total production of copper metal at the unrefined stage.
[4]Data represents total production of refined copper from pyrometallurgical, electrolytic, and electrowinning processing and from primary unrefined copper and scrap.
[5]Source: World Bureau of Metal Statistics (*4*).
[6]Data may not add to totals shown because of independent rounding.
Note:—A dash indicates negligible production.

METHODOLOGIES AND COST EVALUATION

To determine the potential availability and supply of copper, geologic and operating data were collected and analyzed for each of the 204 mines and deposits evaluated. These data include: demonstrated resource estimates; actual or estimated mine and mill operating capacities, including future expansions and development plans when reported; estimated mine life based on reserves and capacity utilization; all capital expenditures including reinvestment costs; operating costs for mining, milling, and transportation; material balances for each concentrate produced in the mill; and estimates of smelting and refining charges for each concentrate and the pay-fors (credits and deductions) associated with each commodity treated. Smelting and refining charges and the pay-for schedules used in the study are for typical smelters and refineries within each country or region. For example, one smelter schedule was used for all concentrates processed in Japan, another was used for all concentrates processed in Europe, and so forth. Smelter schedules used for the United States were more site specific. For undeveloped deposits, future materials flows were estimated based on historical patterns, and estimates of where plants for future smelting and refining capacity are likely to be constructed.

The costs used in this study were collected or developed using various methodologies. Operating parameters and cost data for producing U.S. operations were collected by the Bureau's Field Operations Centers in Denver, CO, Spokane, WA, and Juneau, AK. Engineering cost estimates for foreign properties were developed by personnel at the Minerals Availability Field Office based on data from a number of sources including company annual reports, published articles and reports, and personal correspondence with company and Government contacts. Several foreign copper-zinc mines were evaluated by Pincock, Allen & Holt, Inc., under contract.

For each mine or deposit included in the evaluation, capital expenditures were estimated for exploration, mine plant and equipment, mill plant and equipment, and all necessary reinvestments in mine or mill. Capital expenditures for mining and processing facilities include the costs of mobile and stationary equipment, construction, engineering, infrastructure, and working capital. Infrastructure includes

Table 2. —Summary of MEC demonstrated copper resources from evaluated properties as of January 1988[1]
(Million metric tons unless otherwise specified)

Country	Number of deposits	In situ resource[2]			Minable resource[3]	
		Tonnage	Average grade, % copper	Contained copper	Tonnage	Recoverable copper
North America:						
Canada	33	4,110	0.56	23.0	4,064	19.4
Mexico	3	3,933	.49	19.3	3,933	15.1
United States[4]	48	15,127	.52	78.3	14,890	56.2
Total or average[5]	84	23,170	.52	120.6	22,887	90.7
Central and South America:						
Chile	13	11,548	1.00	115.5	11,780	98.9
Peru	14	3,561	.78	27.8	3,262	22.9
Other	8	3,253	.80	26.0	3,040	18.9
Total or average[5]	35	18,362	.92	169.3	18,082	140.7
Europe	13	1,518	.74	11.2	1,506	9.0
Middle East	9	544	1.42	7.7	512	6.0
Asia:						
India	3	448	1.33	6.0	430	4.5
Philippines	17	2,913	.46	13.4	2,854	10.6
Other	6	702	.85	6.0	701	4.9
Total or average[5]	26	4,063	.62	25.4	3,985	20.0
Africa:						
Zaire	5	605	4.09	24.7	629	19.9
Zambia[6]	10	815	2.19	17.8	927	11.1
Other	10	495	.78	3.9	516	3.0
Total or average[5]	25	1,915	2.43	46.4	2,072	34.0
Oceania:						
Australia	7	2,225	1.71	38.0	1,732	27.2
Papua New Guinea[7]	5	3,562	.50	17.8	3,352	13.0
Total or average[5]	12	5,787	.96	55.8	5,074	40.2
Grand total or average[5]	204	55,359	.79	436.4	54,128	340.8

[1]Includes oxide and leach material.
[2]In situ resource is the in-place mineralized material prior to mining.
[3]Minable resource: Recoverable copper is that quantity that can be extracted and recovered to a finished product i.e., copper cathode) after making allowances for mining, concentration, and smelting and refining losses. Tonnage is that quantity of material delivered to the concentrating plant and may have allowances for mining dilution.
[4]Includes 6,666 million mt oxide and silicate material at 0.31% Cu. Sulfide resources averaged 0.68% Cu.
[5]Data may not add to totals shown because of independent rounding.
[6]Includes 352 million mt oxide material at 0.87% Cu in Nchanga Stage III leach project. Primary resources averaged 3.17% Cu.
[7]Includes Namosi deposit in Fiji.

the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance. Working capital is typically estimated as 3 months of operating costs.

Mine and mill operating costs for each foreign operation were estimated in local currencies and then converted to U.S. dollars. Operating costs are a combination of direct and indirect costs. Direct operating costs include production and maintenance labor, operating supplies, utilities, and payroll overhead. Indirect operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research. Other costs in the analysis are fixed charges, including local taxes, insurance, depreciation, deferred expenses, interest payments (if any), and return on investment.

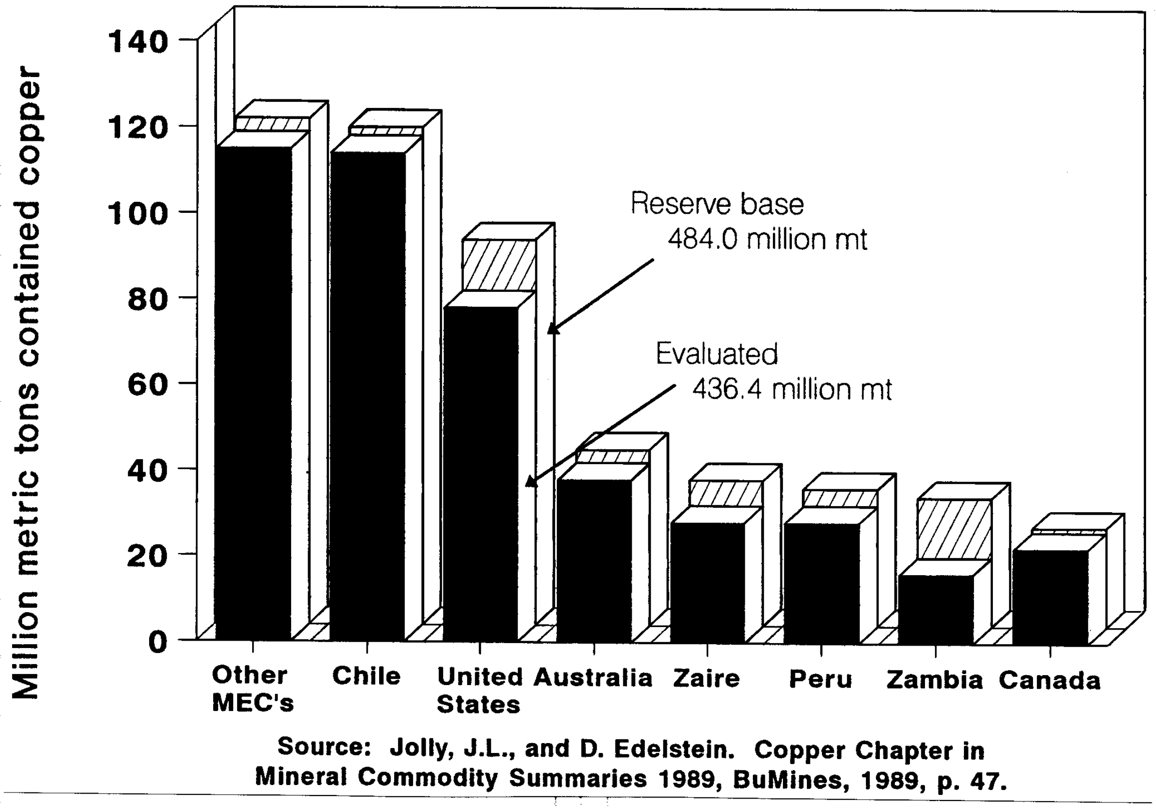

Figure 1.—Estimates of demonstrated world copper resources.

Transportation charges were derived from actual data when available, or were estimated from data for similar cargoes in the same geographical area. Transportation costs include the in-country transportation cost required to ship concentrates to the smelter or port, and ocean freight charges for exported concentrates.

All costs were initially developed in January 1987 U.S. dollars based on January 1987 resource estimates. These costs were then updated for the analyses performed in 1988 and 1989 dollars using the Bureau's International Mining Cost Indexation System (*5*). The index system includes updating factors for 12 separate components of mining and milling costs (e.g., mining labor, mining equipment, diesel fuel, steel, and chemicals) for foreign countries and the United States. The index values for each component in each country take account of whether the expenditure is in local or foreign currency and what the traditional sources are for needed imports such as equipment, and certain operating and maintenance supplies. A time series of exchange rates is used to translate the cost index values developed in local currencies into values expressed in U.S. dollars. Operating costs for producing mines were estimated in 1987 dollars and updated to 1988 and 1989 dollars. Average total costs over the life of the mine for each operation and total availability of copper are reported in January 1988 dollars.

After production parameters and cost estimates were determined for each mine and deposit, all of the operating data were entered into the supply analysis model (SAM). The Bureau developed the SAM (*6*), to perform discounted-cash-flow rate of return (DCFROR) analyses in order to determine the long-run constant dollar price at which the primary commodity must be sold (f.o.b. refinery) to recover all costs of production including a prespecified DCFROR on all investments. The DCFROR is commonly defined as the rate of return that makes the present worth of cash-flow from an investment equal the present worth of all aftertax investments (*7*). For this study, a 15% DCFROR was considered the necessary rate of return to provide the incentive to develop a mineral property or to continue producing over the long run. The determined value for the primary commodity price is equivalent to the average total cost of production for the operations over its producing life under the

Table 3.—MEC copper properties included in this study

Country/property name State	Ownership	Current[1] status	Mining[2] method	Milling[3] method	First year	% Government ownership
ARGENTINA:						
Bajo La Alumbrera	Yacimentos Agua Del Dionisio	E	OP	F	NA	100
Pachon	Cia. Minera Aguilar S.A.	E	OP	F	NA	—
Paramillos Sur	Fabricacionces Militares	E	OP	F	NA	100
AUSTRALIA:						
C S A	Cobar Mines/CRA	P	OS	F	1907	—
Cadia	Pacific CU Ltd./Homestake Australia	E	OP	F	NA	—
Chesney	Cobar Mines/CRA	E	OS	F	NA	—
Golden Grove	Murchison Zinc/Esso/Aztec	D	SL	F	1990	—
Mount Isa	Mount Isa Mines Ltd.	P	SL	F	1931	—
Mount Lyell	Renison Goldfields Cons. Ltd.	P	SL	F	1935	—
Olympic Dam	Western Mining/BP Australia	P	SL	F	1988	—
BOTSWANA:						
Selebi - Phikwe	BCL Ltd.	P	C&F,OS	F	1974	15
BRAZIL:						
Camaqua	CIA Brazileira Do Cobre	P	OP,SL	F	1982	100
Jaguari (Caraiba)	Caraibas Metais S.A.	P	OP,SL	F	1980	100
Pedra Verde	Promisa/Caraiba Metais S.A.	P	OS	F	1982	100
Salobo	CIA Vale Do Rio Doce (CVRD)	D	OP	F	1993	100
BURMA:						
Monywa	Government of Burma	P	OP	F	1984	100
CANADA:						
Afton/Ajax	Teck Corp/Metallgesellschaft	P	OP	F	1977	—
Ansil	Minnova, Inc.	D	SL	F	1989	—
Bell	Bell Copper/Div. Noranda Mines	P	OP	F	1972	—
Berg	Kennco Expl. (Canada), Ltd.	E	OP	F	NA	—
Brenda	Brenda Mines/Noranda	P	OP	F	1970	—
Casino	Casino Silver Mines, Ltd.	E	OP	F	NA	—
Catface	Falconbridge Ltd.	E	OP	F	NA	—
Copper Rand	Northgate Exploration, Ltd.	P	C&F	F	1959	—
Coppermine River	Coppermine River, Ltd.	E	OP	F	NA	—
Equity Silver	Equity Mining/Placer Development	P	OP	F	1980	—
Falconbridge (Sudbury)	Falconbridge, Ltd.	P	SL,C&F	F	1928	—
Galore Creek	Stikine Copper, Ltd.	E	OP	F	NA	—
Gaspe	Mines Gaspe/Noranda	P	OS	F,L	1955	—
Geco	Noranda Mines, Ltd.	P	OS	F	1957	—
Gibraltar	Gibraltar Mines, Ltd.	P	OP	F,L	1972	—
Great Lakes Nickel	Boliden Canada, Ltd.	E	OS	F	NA	—
High Lake	Kennarctic Explorations	E	SH	F	NA	—
Highland Valley Complex	Cominco/Lornex/Highmont	P	OP	F	1962/72	—
Huckleberry Mountain	Kennco Exploration (Canada), Ltd.	E	OP	F	NA	—
INCO (Sudbury)	INCO	P	SL,C&F	F	1900	—
Island Copper	Utah Mines, Ltd.	P	OP	F	1971	—
Izok Lake	Kidd Creek Mines, Ltd.	E	OP	F	NA	—
JA Zone	Cominco, Ltd.	E	BC	F	NA	—
Kidd Creek	Falconbridge, Ltd.	P	OS	F	1966	—

See footnotes at end of table.

Table 3.—MEC copper properties included in this study—Continued

Country/property name State	Ownership	Current[1] status	Mining[2] method	Milling[3] method	First year	% Government ownership
CANADA:—Continued						
Maggie	Cominco, Ltd.	E	OP	F	NA	—
Myra Falls	Westmin Resources, Ltd.	P	C&F	F	1967	—
Poison Mountain	Lac Minerals, Ltd.	E	OP	F	NA	—
Ruttan	Hudson Bay Mining & Smelting	P	OS	F	1973	—
Schaft Creek	Teck Corp/Liard Copper Mines	E	OP	F	NA	—
Selbaie	BP Canada/Esso Mineral/TCPL	P	OP,SL	F	1981	—
Similkameen	Newmont Mining Corp.	P	OP	F	1972	—
Sustut	Falconbridge, Ltd.	E	OP	F	NA	—
Trout Lake	Hudson Bay Mining & Smelting	P	C&F	F	1982	—
CHILE:						
Andacollo	Enami	E	OP	F	NA	100
Andina	Codelco-Chile	P	BC	F	1970	100
Cerro Colorado	Rio Algom, Ltd.	E	OP	L	1993	10
Chuquicamata	Codelco-Chile	P	OP	F,L	1915	100
El Abra	Codelco-Chile	E	OP	F	NA	100
El Salavdor	Codelco-Chile	P	BC	F	1959	100
El Soldado	Exxon Minerals Co.	P	SL	F	1800's	—
El Teniente	Codelco-Chile	P	BC	F,L	1906	100
La Escondida	Utah Int., RTZ Corp., Mitsubishi	D	OP	F	1992	—
Los Bronces	Exxon Minerals Co.	P	OP	F	1962	—
Los Pelambres	Antofagasta Holdings/Midland Bank	E	SL,OP	F	1991	—
Mantos Blancos	Empresas Sudamericana Consolidated	P	OP	F,L	1961	—
Quebrada Blanca	Cominco, Ltd./Enami	E	OP	F	NA	10
FIJI:						
Namosi	Viti Copper, Ltd.	E	OP	F	NA	—
FINLAND:						
Pyhasalmi	Outokumpu Oy	P	SL	F	1962	81
INDIA:						
Indian Copper Complex	Hindustan Copper, Ltd.	P	R&P,C&F	F	1919	100
Khetri/Kolihan/Chandmari	Hindustan Copper, Ltd.	P	SL,OS	F	1973	100
Malanjkhand	Hindustan Copper, Ltd.	P	OP	F,L	1982	100
INDONESIA:						
Ertsberg/Grasberg	Freeport Indonesia Inc.	P	OP,SL	F	1973	9
IRAN:						
Sar Cheshmeh	Natl. Iranian Copper	P	OP	F	1982	100
JAPAN:						
Hanaoka	Dowa Mining Co., Ltd.	P	R&P	F	1965	—
Kosaka	Dowa Mining Co., Ltd.	P	C&F	F	1898	—
JORDAN:						
Wadi Dana	Jordan National Resource Authority	E	OP	L	NA	100
MALAYSIA:						
Mamut	Mamut Dev. Co./Malaysian Government	P	OP	F	1975	49

See footnotes at end of table.

Table 3.—MEC copper properties included in this study—Continued

Country/property name State	Ownership	Current[1] status	Mining[2] method	Milling[3] method	First year	% Government ownership
MAURITANIA:						
Akjoujt	Arab Mining/Mauritanian Government	D	OP	F	1989	100
MEXICO:						
Cananea	CIA Minera De Cananea S.A.	P	OP	F,L	1899	90
El Arco	Indust. Mineria Mexico/Asarco	E	OP	F	NA	—
La Caridad	Mexicana De Cobre S.A.	P	OP	F	1979	—
MOROCCO:						
El Bleida	Societe Miniere De Bou Gaffer	P	C&F	F	1979	40
NAMIBIA:						
Kombat/Asis West	Tsumeb Corp. Ltd.	P	COMBINE	F	1965	—
Otjihase	Tsumeb Corp/Otjihase Mining	P	R&P	F	1975	—
Tsumeb	Tsumeb Corp. Ltd.	P	C&F	F	1905	—
NORWAY:						
Tverrejellet	Outokumpu Oy	P	SL	F	1968	100
OMAN:						
Sohar Project	Oman Mining Company	P	SL	F	1983	100
PAKISTAN:						
Saindak	Resource Development Corp.	E	OP	F	NA	100
PANAMA:						
Cerro Colorado	Codemin/Riotinto Zinc Corp.	E	OP	F	NA	—
PAPUA NEW GUINEA:						
Bougainville	Papua New Guinea Government/ CRA Ltd	P	OP	F	1972	20
Freida River	Conzinc Rio Algom	E	OP	F	NA	—
OK Tedi	Broken Hill Pty./Amoco Papua New Guinea Government	P	OP	F	1984	20
Yandera	Triako/Buka/Broken Hill	E	OP	F	NA	—
PERU:						
Antamina	Minero Peru	E	OP	F	NA	100
Berenguela	Minero Peru	E	OS	L	NA	100
Cerro Verde	Minero Peru	P	OP	F,L	1977	100
Cobriza	Centromin	P	C&F	F	1967	100
Coroccohuayco	Minero Peru	E	SL	F	1994	100
Cuajone	Southern Peru Copper Corp.	P	OP	F,L	1976	—
La Granja	Minero Peru/Metallgesellschaft	E	OP	F	1994	50
Michiquillay	Minero Peru	E	OP	F	NA	100
Pashpap	Minero Peru	E	OP	F	NA	100
Quellaveco	Minero Peru	E	OP	F	NA	100
Tambo Grande	Coframines/Minero Peru	E	OP	F	1993	25
Tintaya	Minero Peru/Centromin/Cofide	P	OP	F	1985	100
Toquepala	Southern Peru Copper Corp.	P	OP	F	1960	—
Toromocho	Centromin	E	OP	F	NA	100
PHILIPPINES:						
Amacan (North Davao)	North Davao Mining Corp.	P	OP	F	1982	—
Atlas	Atlas Consolidated Mining and Development Corp.	P	BC	F	1962	—

See footnotes at end of table.

Table 3.—MEC copper properties included in this study—Continued

Country/property name State	Ownership	Current[1] status	Mining[2] method	Milling[3] method	First year	% Government ownership
PHILIPPINES:—Continued						
Basay	CDCP Mining Corp.	T	BC	F	1979	100
Batong-Buhay	Development Bank of Philippines	T	BC	F	1983	100
Boneng-Lobo	Western Minolco Corp.	T	OP	F	1970	—
Copper Shield	Benguet Exploration, Inc.	T	BC	F	1969	—
Dizon	Benguet Corp.	P	BC	F	1980	—
Far South East	Lepanto Consolidated/Galactic Resources	E	SL	F	1993	—
Hinobaan	Lepanto Consolidated Mining Co.	E	OP	F	1992	—
Ino-Capayang	Consolidated Mines, Inc.	T	OP	F	1978	—
Lepanto	Lepanto Consolidated Mining Co	P	C&F	F	1975	—
Marcopper	Marcopper Mining Corp.	P	OP	F	1969	—
Philex	Philex Mining Corp.	P	BC	F	1957	—
Sabena	Sabena Mining Corp.	T	OP	F	1979	—
Sipalay	Maricalum Mining Corp.	P	OP	F	1957	—
Taysan	Benguet Consolidated, Inc.	E	OP	F	1992	—
Trident	Trident Mining & Industrial Co.	E	OP	F	1992	—
PORTUGAL:						
Aljustrel	Pirites Alentejanas S.A.R.L.	D	C&F	F	1991	90
Neves-Corvo	EDMA/RTZ Metals, Ltd.	P	C&F	F	1988	51
SAUDIA ARABIA:						
Jabal Sayid	Saudi Arabian Government	E	OS	F	NA	100
SOUTH AFRICA:						
Messina	African Finance Corp.	P	SH	F	1906	—
O'Okiep	O'Okiep Copper Co., Ltd.	P	SL	F	1965	—
Palabora	Palabora Mining Co., Ltd.	P	OP	F	1965	—
SPAIN:						
Aznal Collar	Banco Central De Espana	P	OP	F	1979	100
Cerro Colorado	Rio Tinto Minera S.A.	P	OP,R&P	F	1967	—
Sotiel	Enmasa	P	R&P	F	1983	—
SWEDEN:						
Aitik	Boliden Metall AB	P	OP	F	1968	100
Viscaria	Outokumpu Oy	P	SL	F	1983	100
TURKEY:						
Cayeli	Etibank/Metall Mining Corp.	E	C&F	F	1991	51
Ergani-Madeni	Etibank	P	OP	L	1980	100
Espiye	Etibank/Kbi	E	COMBINE	F	1980	100
Murgul	Etibank/Black Sea Copper	P	OP	F	1972	100
Siirt	Etibank/Preussag Metall	E	SH	F	1983	51
UNITED STATES:						
Alaska:						
Arctic Camp	Bear Creek Mining Co.	E	OP	F	NA	—
Orange Hill/Bond Creek	Bear Creek Mining Co.	E	OP	F	NA	—
Arizona:						
Casa Grande	ASARCO/Freeport McMoran	E	BC	F	NA	—
Christmas	Cyprus Minerals Co.	T	OP,C&F	F	1962	—
Cochise	Phelps Dodge Corp.	E	OP	L	1994	—
Copper Basin	Phelps Dodge Corp.	E	OP	F	1993	—

See footnotes at end of table.

Table 3.—MEC copper properties included in this study—Continued

Country/property name State	Ownership	Current[1] status	Mining[2] method	Milling[3] method	First year	% Government ownership
UNITED STATES:						
Arizona:—Continued						
Cyprus Bagdad	Cyprus Minerals Co.	P	OP	F,L	1940	—
Cyprus Sierrita	Cyprus Minerals Co.	P	OP	F,L	1959	—
Cyprus Twin Buttes	Cyprus Minerals Co.	T	OP	F	1969	—
Dos Pobres (Safford)	Phelps Dodge Corp.	E	BC	F	NA	—
Dubacher Canyon	Occidental Minerals Corp.	E	OP	L	NA	—
East Helvetia	ASARCO, Incorporated	E	OP	F	NA	—
Florence	Conoco	E	OP	F,L	NA	—
Inspiration	Cyprus Minerals Co.	P	OP	F,L	1915	—
Lone Star (Safford-KCC).	Phelps Dodge Corp.	E	In-Situ	L	NA	—
Miami (Leach)	Magma Copper Co.	P	OP	L	1954	—
Miami East	Magma Copper Co.	E	C&F	F	1993	—
Mission Complex	ASARCO, Incorporated	P	OP	F	1961	—
Morenci/Metcalf	Phelps Dodge Corp./Sumitomo	P	OP	F,L	1942	—
New Cornelia	Phelps Dodge Corp.	T	OP	F	1917	—
Pinto Valley	Magma Copper Co.	P	OP	F,L	1974	—
Ray	ASARCO, Incorporated	P	OP	F	1955	—
Red Mountain	Kerr McGee Corp.	E	BC	F	NA	—
San Manuel	Magma Copper Co.	P	BC,OP	F,L	1955	—
Sanchez	The Arizona Copper Company	D	OP	L	1992	—
Silver Bell	ASARCO, Incorporated	P	OP	F,L	1954	—
Van Dyke	Kocide Chemical	P	In-Situ	L	1988	—
Vekol Hills	Papago Indian Tribe	E	OP	F	NA	—
West Helvetia	ASARCO, Incorporated	E	OP	F	NA	—
California:						
Lights Creek	Placer Amax	E	OP	F	NA	—
Maine:						
Bald Mountain	Chevron Resources Co.	E	OP	F	NA	—
Michigan:						
Presque Isle Syncline	Amax Inc.	E	R&P	F	NA	—
White Pine	Copper Range Co.	P	R&P	F	1953	—
Montana:						
Butte Copper	Montana Resources, Inc.	P	OP	F	1952	—
Noxon	Noranda/Montana Reserves	E	R&P	F	1993	—
Rock Creek	ASARCO, Incorporated	E	R&P	F	1993	—
Troy	ASARCO, Incorporated/Bear Creek Mining	P	R&P	F	1982	—
Nevada:						
Lyon	Plexus Resources Corp.	E	SL,R&P	F	NA	—
New Mexico:						
Chino	Phelps Dodge Corp/Mitsubishi	P	OP	F,L	1912	—
Copper Flat	Several Banks	E	OP	F	NA	—
Tyrone	Phelps Dodge Corp.	P	OP	F,L	1970	—
Puerto Rico:						
Rio Vivi	Puerto Rican Government	E	OP	F	NA	100

See footnotes at end of table.

Table 3.—MEC copper properties included in this study—Continued

Country/property name State	Ownership	Current[1] status	Mining[2] method	Milling[3] method	First year	% Government ownership
UNITED STATES:—Continued						
Utah:						
Bingham Canyon	Kennecott Corp.	P	OP	F,L	1906	—
Bingham Canyon Underground	Kennecott Corp.	E	C&F	F	NA	—
Washington:						
Sunrise	International Brenmac Development Corp.	E	SL	F	NA	—
Wisconsin:						
Crandon	Exxon Minerals Co.	E	OS	F	NA	—
Flambeau	Kennecott Corporation	D	OP,C&F	F	1991	—
Wyoming:						
Kirwin	Amax Inc.	E	OP	F	NA	—
YUGOSLAVIA:						
Bor	RTB BOR	P	OP,SL	F	1965	100
Bucim	Bucim Rudnik Za Bakar	P	OP	F	1978	100
Majdanpek	RTB BOR	P	OP	F	1965	100
Veliki Krivelj	RTB BOR	P	OP	F	1981	100
ZAIRE:						
Gecamines Central Division	Gecamines	P	OP	F	1962	100
Kipushi	Gecamines	P	SL,C&F	F	1925	100
Gecaminez Western Division	Gecamines	P	OP,SL	F	1942	100
Musoshi/Kinsenda	Sodimiza	P	SL	F	1972	100
Tenke-Fungurume	Gecamines	E	OP	F	NA	100
ZAMBIA:						
Baluba	ZCCM	P	SL	F,L	1973	60
Chambishi	ZCCM	P	SL	F	1965	60
Chibuluma	ZCCM	P	C&F	F,L	1956	60
Konkola	ZCCM	P	OS	F,L	1957	60
Luanshya	ZCCM	P	OS	F	1927	60
Mufulira	ZCCM	P	SL	F	1933	60
Nchanga Cobalt Ores	ZCCM	P	OP	F,L	1980	60
Nchanga Primary Ores	ZCCM	P	OP	F	1936	60
Nchanga Tailing & Leach	ZCCM	P	OP	L	1973	60
Nkana	ZCCM	P	OP,SL	F,L	1932	60
ZIMBABWE:						
Mhangura	Mhangura Copper Mines	P	SL	F	1958	60

NAp Not applicable.
[1]Current status: P, producing; T, temporarily shut down; D, developing; E, explored.
[2]Mining method: OP, open pit; BC, block cave; C&F, cut and fill; R&P, room and pillar; SL, sublevel stoping; OS, open stope; SH, shrinkage.
[2]Milling method: F, flotation; L, leach.

Note.—Dashes indicate no Government ownership.

set of assumptions and conditions (e.g., mine plan, full capacity production, and a market for all output) necessary to perform a full economic evaluation.

A DCFROR analysis for each operation was also performed at a 0% rate of return, and both sets of results are analyzed in the "Total Production Costs and Availability" section. Prices received for byproducts are assumed to be the average market prices for each byproduct commodity existing in January of each year of the operating cost analysis—1987, 1988, and 1989. Prices for major byproducts shown in table 4 were the January averages appearing in Metals Week for each analysis year. Prices for the years 1984 through 1986 are shown in table 4 for comparison purposes. Revenues received for byproducts are credited against the cost of

Table 4.—Commodity prices used in the economic evaluations, representing the January average price for each year listed

Commodity	Units	1984	1985	1986	1987	1988	1989
Cobalt[1]	US$/lb	$7.41	$11.70	$11.70	$7.00	$7.50	$8.65
Copper:							
U.S. Producer-cathode[2]	US$/lb	.66	.64	.70	.65	1.32	1.58
LME grade A cash[3]	US$/lb	.62	.62	.64	.61	1.21	1.54
Gold - Handy & Harmon[4]	US$/tr oz	370.89	302.79	345.49	408.26	476.58	404.02
Lead:							
U.S. Producer	US$/lb	.25	.19	.18	.28	.38	0.40
LME cash	US$/lb	.18	.19	.17	.21	.30	0.31
Molybdenum (in concentrate)	US$/lb	3.45	2.70	2.90	2.80	2.40	2.75
Nickel - New York Dealer	US$/lb	3.20	3.20	2.34	3.20	3.60	7.92
Silver - Handy & Harmon4	US$/tr oz	8.18	6.10	6.05	5.53	6.73	5.97
Zinc:							
U.S. - High grade	US$/lb	.49	.43	.33	.41	.44	.79
LME - High grade	US$/lb	.43	.39	.28	.34	.40	.79

[1]Cobalt price for shot, 99.5%, 250-kg drums.
[2]Weighted average based on estimated U.S. refined copper production and published prices for delivered full-plate cathodes.
[3]Cathode grading 99.9935% Cu on the London Metal Exchange (LME).
[4]Lowest price at which offers can be obtained by Handy & Harmon for gold and silver for nearby delivery at New York in quantities sufficient to meet its daily requirements.

Source: Metals Week.

production. Copper prices over the same period are included in the table for comparison with the average total costs determined in the analysis. A more detailed discussion of byproduct credits is included in the Appendix.

A separate tax records file, maintained for each particular State or nation, contains the relevant tax parameters under which a mining firm would operate. Tax parameters include corporate income taxes, property taxes, royalties, severance taxes, or other taxes that pertain to the production of copper. Deductibles such as depreciation, depletion, deferred expenses, investment tax credits, and tax-loss carry forwards are also included in the analysis. These tax parameters are applied to each mineral deposit under evaluation under the implicit assumption that each deposit represents a separate corporate entity.

Upon completion of the individual property analyses, the results for all 204 properties included in the study were aggregated onto resource availability curves. Two types of resource availability curves have been generated for this study: (1) total availability curves, and (2) operating cost curves reflecting the average estimated operating cost, by country, in January 1988 dollars.

CAPITAL COSTS TO DEVELOP NONPRODUCING DEPOSITS

For purposes of the DCFROR methodology, all capital investments incurred 15 years before the year of analysis (either 1987, 1988, or 1989) are treated as fully depreciated costs. Capital investments incurred less than 15 years before the study date have the undepreciated balances carried forward to the study date. All subsequent investments, reinvestments, operating costs, and transportation costs are expressed in January 1987 dollars, updated to January 1988 or January 1989 dollars depending on the study date.

Capital cost estimates were made for each of the nonproducing copper properties evaluated for this study. Estimates include preproduction development, mine equipment, mine plant, mill plant and equipment, and associated infrastructure. Table 5 presents potential average annual production and capital costs for nonproducing properties in the major countries included in this study.

At an estimated average $7,400 per metric ton of annual capacity, capital costs per annual metric ton of copper output for surface mines evaluated are higher than for the average for the underground mines evaluated, which have an estimated capital cost of $5,800 per metric ton of annual capacity. Lower ore grades for surface deposits are a major contributing factor for higher costs on a metric ton of annual capacity basis because more tons of ore have to be mined in order to produce 1 ton of metal. Also, the surface deposits evaluated tend to be in more remote locations that necessi-

Table 5.—Average capital costs per metric ton of annual copper capacity to develop nonproducing deposits in MEC's
(In January 1987 U.S. dollars)

Country	Number of mines	Average annual Mt ore	Average annual Mt Cu	Average annual $/mt Cu	Distribution % Mine	Distribution % Mill	Distribution % Infrastructure
Surface Deposits							
Argentina	3	12,200,000	63,700	$11,700	22	28	50
Canada	9	8,800,000	33,500	6,000	48	43	9
Chile	4	11,650,000	119,400	5,300	30	35	35
Peru	7	8,700,000	67,900	8,100	27	40	33
Philippines	3	5,100,000	18,700	6,500	47	34	19
Papua New Guinea	3	21,200,000	71,700	12,500	23	37	40
United States	5	8,000,000	37,700	7,900	31	57	12
Other Latin America	3	22,700,000	144,500	5,700	35	39	26
Total or average	37	11,100,000	63,200	7,400	30	39	31
Underground deposits							
United States	9	6,500,000	51,000	5,700	47	49	4
Other	13	2,000,000	18,300	5,900	49	31	20
Total or average	22	3,900,000	31,700	5,800	47	43	10

tate higher infrastructure costs. Due to their remote locations, properties in Papua New Guinea and Argentina have average infrastructure costs amounting to 40% and 50%, respectively, of total capital cost estimates.

Average capital costs for capacity expansions at existing mines average about $3,200 per metric ton of additional annual copper capacity (*8*). This is approximately one-half of the average greenfields capital cost estimate.

OPERATING COSTS

Production costs were estimated for 202 copper properties in MEC's; 107 of the evaluated mines were producing and 95 properties were either developing, temporarily shut down, or explored as of January 1987. The Sudbury operations of both INCO and Falconbridge in Canada are not included in the operating cost analysis because copper values are overshadowed by nickel revenues in the economic analysis. Recent increases in nickel prices cause an economic analysis based on copper as the primary product to result in negative total production costs for copper at the Sudbury operations. However, the Sudbury operations were evaluated and included in the total cost and availability section of this report, as well as in a recently completed Bureau of Mines Information Circular on nickel (*9*).

For the January 1988 operating cost analysis, 110 mines were producing, and 92 properties were developing, temporarily shut down, or explored. The January 1989 analysis included 110 producing mines, and 91 properties that were developing, temporarily shut down, or explored. The nonproducing properties in 1989 included eight developing mines and nine operations that were temporarily shut down. All of the temporarily shutdown operations included in the study were located in the Philippines, the United States, and Zambia.

Cash cost is defined as the sum of mining, milling, smelting/refining, SX-EW, and transportation costs in U.S. dollars per pound of recovered copper. *Net operating cost* is defined as cash cost minus byproduct credits per pound of recovered copper. This definition of operating costs avoids problems concerning interest, marketing, corporate overhead, depreciation and taxation, all of which are highly variable and difficult to define for each operation. Operating costs can vary greatly depending on such factors as size of the operation, mining method, deposit location, stripping ratio for open pit mines, depth of the ore body, mill feed grades, complexity of mill feed, processing losses, energy and labor rates, and productivity. A discussion on ore feed grades is included in the appendix.

Estimated operating costs were aggregated on a weighted-average basis to determine the average cost of production per pound for each producing country. Estimated average net operating costs, by country, from producing mines in selected MEC's in 1987, 1988, and 1989 dollars are shown in table 6. Table 7 presents copper production and the estimated cost breakdowns for each stage of production, by country, in 1988. The average net operating cost and 1988 copper production, by country, from table 7 is illustrated graphically in figure 2.

Table 6. —Weighted average net operating costs in 1987, 1988, and 1989, by country, in selected MEC's (Costs in U.S. dollars per pound of refined copper)

Country	1987	1988	1989
Australia	$0.40	$0.39	$0.50
Brazil	.92	1.19	.35
Canada	.41	.40	.35
Chile	.31	.34	.38
India	1.24	1.28	1.29
Mexico	.43	.45	.43
Namibia	.48	.60	.68
Papua New Guinea/Indonesia[1]	(.19)	.09	.42
Peru	.52	.76	.10
Philippines	.35	.39	.56
South Africa, Republic of	.35	.46	.46
Spain	.68	.94	.84
United States	.53	.52	.52
Yugoslavia	.63	.35	.04
Zaire	.56	.45	.37
Zambia	.65	.76	1.04

[1]Net operating costs are strongly affected by byproduct credits for gold produced at the OK Tedi Mine. Where byproduct credits are greater than cash operating costs, the average net cost is negative. Refer to the byproduct credit column in table 7.

Table 6 shows the relative changes in average net operating costs for copper between countries in nominal U.S. dollar terms for 1987, 1988, and 1989. It is interesting to note that estimated average net operating costs in the United States remained constant over the 1987-89 period, whereas the estimated average net operating cost increased $0.11 per pound in Australia between 1988 and 1989, and by $0.28 per pound in Zambia between 1988 and 1989, but decreased by $0.67 per pound in Peru over the same period. Much of the difference between changes in operating costs, in U.S. dollar terms, between 1988 and 1989 was caused by differences in the relative rates of inflation and currency exchange existing in January 1989. Countries such as Brazil and Peru, which are undergoing hyperinflation with resultant mega-devaluations of their currency, show indexed net costs for January 1989 which may be unrepresentative of the actual costs of production over the entire year. For this reason, the 1989 estimates, particularly for Brazil, Peru, and Zambia may be misleading compared with cost estimates for 1987 and 1988. As a result, the total cost and availability analyses appearing in the following section will focus on 1988 cost estimates only.

The countries with the lowest net operating costs (per pound of copper) in 1988 were Papua New Guinea and Indonesia, Chile, the Philippines, Australia, Canada, Zaire,

Table 7. —Estimated 1988 copper production and average production costs, from evaluated operations in selected countries

Country	Number of mines	Estimated production (kmt)		Operating costs[1]				Less byproduct credit	Total net[3]
		Ore	Recoverable copper	Mine	Mill	Smelter-refinery[2]	Total cash		
Australia	4	9,250	234	$0.33	$0.14	$0.16	$0.62	$(0.23)	$0.39
Brazil	3	7,706	65	.37	.54	.29	1.20	(.01)	1.19
Canada	16	113,660	564	.30	.28	.34	.92	(.52)	.40
Chile	7	107,600	1,371	.15	.16	.09	.39	(.05)	.34
India	3	5,100	54	.62	.45	.24	1.32	(.04)	1.28
Mexico	2	54,000	278	.11	.17	.25	.53	(.08)	.45
Namibia	3	1,869	37	.39	.21	.37	.98	(.37)	.60
Papua New Guinea/Indonesia	3	71,060	368	.28	.33	.23	.84	(.75)	.09
Peru	5	38,012	344	.21	.30	.33	.83	(.07)	.76
Philippines	7	63,498	211	.28	.37	.24	.89	(.49)	.39
South Africa,Republic of	3	31,925	158	.23	.19	.13	.55	(.09)	.46
Spain	3	9,050	48	.84	.76	.92	2.53	(1.59)	.94
United States	18	209,779	1,351	.18	.28	.17	.62	(.10)	.52
Yugoslavia	4	33,100	153	.22	.19	.16	.56	(.22)	.35
Zaire	4	17,035	551	.27	.14	.29	.70	(.25)	.45
Zambia	9	23,890	449	.32	.26	.25	.83	(.08)	.76
Other	16	42,138	334	.40	.34	.40	1.14	(.55)	.59
Total or average[3]	110	838,672	6,571[2]	.24	.24	.22	.70	(.22)	.47

[1]Cost and credits are in U.S. dollars per pound of refined copper.
[2]Includes transportation costs.
[3]Data may not add to totals shown because of independent rounding.

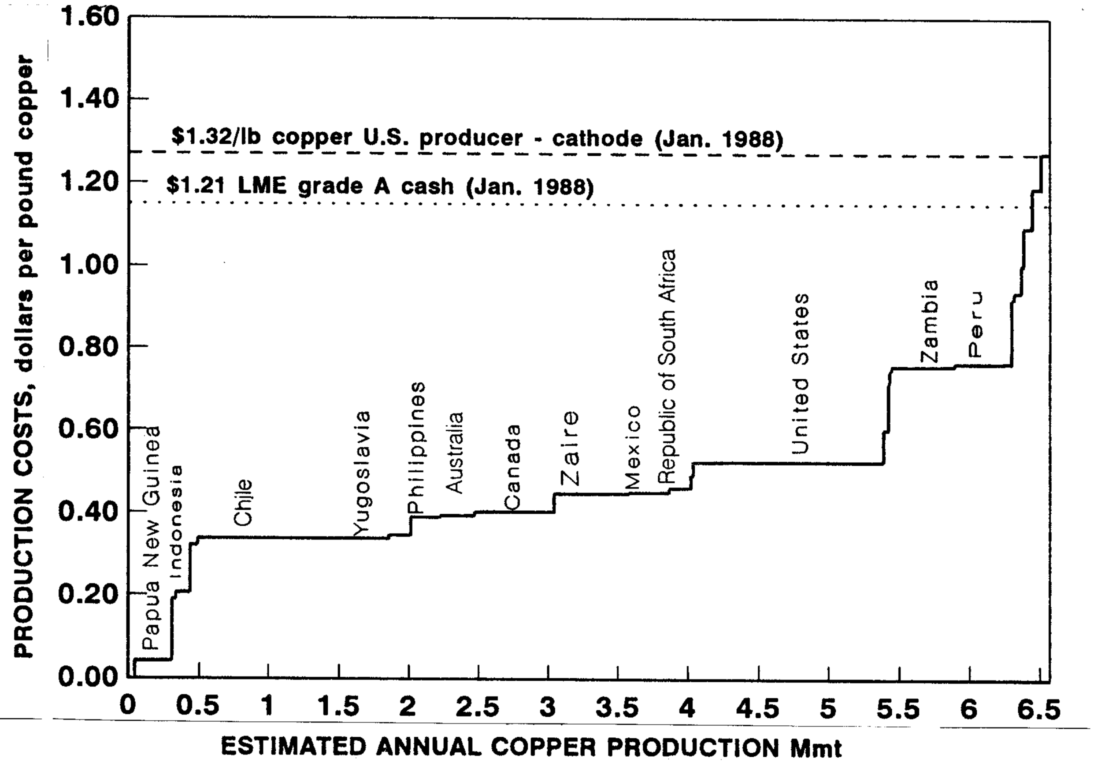

Figure 2.—Copper production costs in 1988 for major MEC producers.

and the United States. Zaire had an average operating cost in 1988 ($0.45 per pound), which is less than the average for the United States ($0.52 per pound), largely due to devaluation of the local currency. On an operating cost basis, nearly all of the major operating copper mines in MEC's are profitable at 1988 prices. The exceptions were a few mines in countries such as Brazil and India which continue to produce as a matter of government policy for import substitution, employment, and savings of foreign exchange.

Nominal Versus Real Operating Costs for Copper

Comparisons of operating costs for copper between countries over time is difficult because costs (in U.S. dollar terms) and each country's relative competitiveness are significantly influenced by differing rates of inflation and fluctuating foreign exchange rates. The major copper-producing countries have experienced very different rates of inflation during the past decade. The United States and Canada had cumulative inflation from January 1981 to January 1988 of 37.9% and 55.4%, respectively. In Chile, cumulative inflation amounted to 275.7% and Mexico's was 4,625% over the 7-year period. Over the same period, foreign currencies were devalued against the U.S. dollar at extremely different rates. The Canadian dollar was devalued relative to the U.S. dollar by about 14% in nominal terms over the period, whereas devaluation of the Mexican peso amounted to 5,900%.

Nominal average cash costs of copper production (excluding byproduct credits) for eight major producing countries (Australia, Canada, Chile, Mexico, the Philippines, the United States, Zaire, and Zambia) in January 1981, 1986, 1987, and 1988 dollars are shown in table 8. All of the countries shown in the table with the exception of Zaire and Zambia experienced reductions in average cash operating costs between 1981 and 1988. Reductions were especially significant in the United States, Chile, and Australia. Reductions in average cash operating costs were more moderate in Mexico, Canada, and the Philippines.

Reductions in nominal cash operating costs, however, include the combined effect of inflation differentials and devaluation of local currencies relative to the U.S. dollar, which is the currency in which copper prices are denominated. Real cash operating costs expressed in January 1988 dollars were thus calculated to remove this effect. A quick

Table 8. —Nominal and real cash operating costs in 1981, 1986, 1987, and 1988 for producing mines in selected MEC's

	United States	Australia	Canada	Chile	Mexico	Philippines	Zaire	Zambia
Recoverable copper, kmt:								
1981	1,662	205	613	813	227	375	519	607
1986	1,114	192	594	1,115	189	335	517	497
1987	1,277	216	554	1,323	228	178	501	458
1988	1,351	234	564	1,371	278	211	552	449
Nominal cash cost,[1] U.S. dollars/lb:								
1981	0.96	0.78	0.99	0.55	0.63	0.93	0.69	0.70
1986	.63	.52	.86	.35	.58	.88	.76	.53
1987	.62	.47	.91	.37	.51	.79	.79	.72
1988	.62	.62	.92	.39	.53	.89	.70	.83
Percent change, 1988 from 1981	-35.4%	-20.5%	-7.1%	-29.1%	-15.9%	-4.3%	1.4%	18.6%
Real cash cost:[2] 1988 U.S. dollars								
1981	1.33	.84	1.35	.37	.49	.90	.30	.34
1986	.66	.62	.96	.37	.47	.83	.94	.35
1987	.65	.54	.99	.39	.53	.81	.80	.84
1988	.62	.62	.92	.39	.53	.89	.70	.83
Percent change, 1988 from 1981	-53.4%	-26.2%	-31.9%	5.4%	8.2%	-1.1%	133.3%	144.1%

[1]Cash operating costs are the sum of mining, milling, smelting, refining, and transportation costs in U.S. dollars per pound of copper. They do not include depreciation, interest, profit, or taxes. Byproduct credits have not been deducted.
[2]Real cash costs expressed in 1988 U.S. dollars = nominal cash costs for operations as of 1981, 1986, and 1987 and adjusted for inflation and exchanges to Jan. 1988; byproduct credits have not been deducted.

estimation of real cash costs in January 1988 dollars was done by converting estimated average nominal cash costs for operations as of 1981, 1986, and 1987 and adjusting for inflation (based on the consumer price index) and exchange rate changes up through January 1988. Byproduct credits have not been deducted in the real cost analysis. Real average cash operating costs for the eight selected countries in January 1981, 1986, 1987, and 1988, expressed in January 1988 dollars also appear in table 8. In January 1988 dollar terms, the United States, Canada, and Australia experienced significant decreases in average cash operating costs between 1981 and 1988, while the Philippines had a minor decrease in average cash operating costs. Chile and Mexico have experienced a small real increase in average cash costs since 1981, and average cash costs in Zaire and Zambia have increased tremendously in real terms over the same period.

The large real cost reductions in the United States, Canada, and Australia and the small real increase in Chile demonstrate the degree that cost-reducing measures have been masked by exchange rate and inflationary movements. Moreover, exchange rate and inflationary movements can hide real cost increases caused by operating problems and inefficiencies in countries such as Zaire and Zambia, whose cost increases in nominal terms are a fraction of the real increases in the cash operating cost over the past 8 years. Although the Chilean operations made significant improvements in productivity during the 1980's, the small real increase in cash operating costs was caused by such factors as declining ore grades over the past 7 years, haulage problems at Chuquicamata, and harder ore at El Teniente. In addition, the significant decrease in nominal cash operating costs in Chile between 1981 and 1986 indicates that the Chilean peso was overvalued in 1981 and that the subsequent devaluations of the peso against the U.S. dollar in excess of inflation lowered the average nominal cash operating cost by a substantial amount. Similarly, Mexico, the Philippines, Zaire, and Zambia devalued their currencies in excess of inflation between 1981 and 1988.

In real terms, copper producers in the United States had the greatest success in lowering average cash operating costs, with a decrease of 53.4% between 1981 and 1988. Canadian producers achieved a real reduction in average cash operating costs of 31.9% between 1981 and 1988, and Australian producers achieved a real reduction of 26.2%.

Mining, Milling, and G&A Costs, On a Per Ton of Ore Basis

Mining, milling, and G&A (general and administrative) costs, on a per metric ton of ore basis for surface and underground mines in selected MEC's are shown in table 9, and costs per pound of leach copper from selected countries are shown in table 10. For some producers, such as the San Manuel open pit and Miami leach operations, which produce leach copper exclusively, the costs for mining, crushing, haulage, dump preparation, leaching, and SX-EW are included in the estimated costs. Where leaching is secondary compared to sulfide copper production, such as at Pinto Valley and Morenci, the mining costs were arbitrarily burdened against the sulfide operation. Dump preparation, leaching, and SX-EW costs constitute the leach costs averaged in the table.

Over three-quarters of the copper ore mined (and about two-thirds of the recoverable copper) is produced by open pit mining. Mine operating costs for surface mines are considerably lower per ton of ore than operating costs for underground mines. The cost to mine 1 ton of material (ore and waste) appears to be relatively consistent worldwide from major mines using similar technology. Variances in open pit mining costs are largely the result of local or regional differences in the cost of diesel fuel, labor, spare parts, and operating efficiency (or lack thereof). Of more importance, on a cost-per-ton-of-ore basis, is the stripping ratio (tons of waste rock per ton of ore) of an open pit mine. Average stripping ratios at producing surface copper mines range from 0.67:1 in the Philippines to 13.6:1 in Zambia. Average stripping ratios in Mexico are currently under 1:1 (excluding leach ore and the capitalized prestripping program at Cananea), and the average stripping ratio in Canada and Peru is currently about 1:1. The average stripping ratio in the United States runs about 1.5:1 compared with about 2.7:1 in Chile. The highest stripping ratios occur in Zaire and Zambia where the average stripping ratios currently amount to 7.8:1 and 13.6:1, respectively. Unlike the copper porphyry deposits, the folded and steeply dipping African stratiform deposits are covered at depth with thick overburden, resulting in high stripping ratios and high mining costs, necessitating eventual underground mining. The current average ore grades in Zaire and Zambia are among the highest in the world, however, enabling the economic use of open pit mining at a number of operations.

Table 9. —Estimated production and average mining, milling, and G&A costs in 1988 for producing copper mines, in selected MEC's
(All costs are in January 1988 U.S. dollars per metric ton of sulfide ore milled)

Country	Sulfide ore treated (kmt)	Sulfide recoverable copper (mt)	On site cash operating cost			
			Mine	Mill	G&A	Total
SURFACE MINES						
Canada	102,975	335,200	$1.23	$2.15	$0.32	$3.70
Chile	49,600	655,400	3.28	2.16	1.76	7.20
Mexico	54,000	260,800	1.00	1.46	0.49	2.95
Peru	34,812	278,000	2.41	3.09	2.76	8.26
Philippines	37,100	118,700	1.48	2.28	0.44	4.20
United States	187,599	909,700	1.88	2.68	0.35	4.91
Yugoslavia	33,100	153,500	2.25	1.89	[1]—	4.14
Other	150,999	1,059,000	3.61	4.01	1.43	9.05
Total or average	650,185	3,770,300	2.24	2.72	0.84	5.80
UNDERGROUND MINES						
Australia	9,250	233,600	16.53	6.20	3.27	26.00
Canada	10,685	219,800	19.24	6.45	5.25	30.94
Chile	58,000	592,600	3.17	2.86	1.92	7.95
Philippines	26,398	92,200	2.25	2.61	0.63	5.49
United States	22,180	151,700	5.80	2.92	0.74	9.46
Zaire	8,435	249,300	14.80	7.30	6.56	28.66
Zambia	17,640	240,500	12.90	5.46	4.95	23.31
Other	35,899	435,500	11.13	5.21	2.53	18.87
Total or average	188,487	2,215,200	8.97	4.58	2.77	16.32

[1]Included with mining and milling cost.

Table 10. —Estimated production and average net operating cost in 1988 for producing leach operations, in selected MEC's
(All costs are in January 1988 U.S. dollars)

Country	Recoverable copper (mt)	Operating cost	
		$/mt Copper	$/lb Copper
Chile.	123,200	848	0.38
United States.	289,400	777	.35
Zambia	114,500	827	.38
Others	58,200	1,458	.66
Total or average	585,300	868	.39

TOTAL PRODUCTION COSTS AND COPPER AVAILABILITY

Total production costs were determined for all of the 204 copper mines and deposits evaluated in market economy countries. The INCO and Falconbridge massive sulfide nickel operations in Canada were not included in the total cost analysis (table 11) but their copper output is included in the total availability analysis (fig. 3). Costs are presented on a dollar per pound recoverable metal basis over the life of the operation including net operating costs as presented above and include recovery of capital to arrive at a net production cost. Total production cost is the net production cost as defined previously, plus all property, severance, State or Province, and Federal taxes plus a return on all investments to achieve a specified DCFROR. The total production cost represents the long-run constant dollar price that an operation would have to receive in order to recover all of its capital investments and achieve a specified DCFROR.

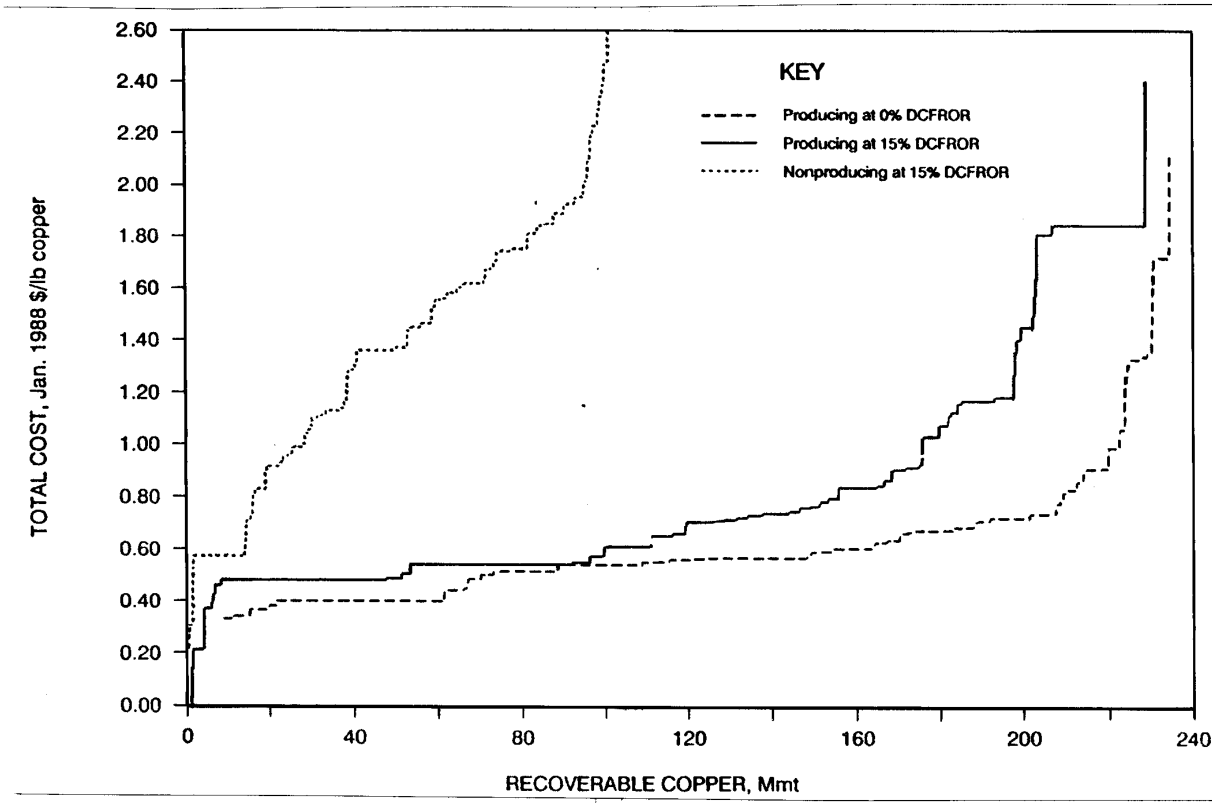

Figure 3.—Total potential copper available from MEC's.

During 1988, 112 of the evaluated mines were in production (18 were in the United States) and 9 mines (2 in the United States, 6 in the Philippines, and 1 in Zambia) were temporarily shut down. Three mines were included in the analysis that commenced production in 1988: the Van Dyke operation in Arizona (now closed), Neves Corvo in Portugal, and Olympic Dam in Australia.

Total refined copper potentially available from producing and nonproducing mines and deposits is illustrated in figure 3 where total production costs in January 1988 dollars were estimated at a 15% DCFROR for nonproducing properties and estimated at both a 0% and a 15% DCFROR for producing mines. The results of the total production cost analyses that underlie the availability curves of figure 3 are shown, by country, in table 11.

Table 11.—Estimated average total copper production costs for producing mines and nonproducing deposits, by country, in selected MEC's

(All costs are in January 1988 U.S. dollars per pound of refined copper over each mine's operating life)

Country	Number of deposits	Total kmt[1] Ore	Total kmt[1] Recoverable copper	Operating cost Mine	Operating cost Mill	Costs ($/lb) Smelter-refinery[2]	Cash operating	Byproduct credit	Net operating	Recovery capital	Net production	Total[3] production at 0%	Total[3] production at 15%
Producing mines													
Australia	4	1,652,725	26,268	$0.47	$0.22	$0.19	$0.88	$(0.44)	$0.44	$0.05	$0.49	$0.51	$1.24
Brazil	3	37,497	327	.36	.54	.29	1.19	(.01)	1.18	.21	1.39	1.56	1.75
Canada[4]	16	1,664,746	7,403	.28	.26	.31	.84	(.38)	.47	.09	.56	.59	.73
Chile	7	8,664,864	77,202	.18	.21	.09	.48	(.05)	.42	.03	.45	.48	.56
India	3	430,257	4,523	.55	.44	.28	1.28	(.06)	1.21	.07	1.28	1.35	1.54
Mexico	2	2,650,447	12,142	.10	.19	.22	.51	(.09)	.42	.08	.50	.67	1.01
Namibia	3	16,487	316	.40	.23	.34	.97	(.33)	.64	.08	.72	.74	.80
Peru	5	1,326,972	9,341	.19	.30	.36	.85	(.22)	.63	.10	.73	.80	1.10
Philippines	7	1,847,734	6,667	.24	.31	.24	.80	(.28)	.52	.07	.58	.65	.74
South Africa, Republic of	3	396,106	1,828	.22	.20	.13	.54	(.10)	.44	.14	.58	.58	.68
Spain	3	151,045	695	1.09	.87	1.36	3.33	(2.12)	1.21	.14	1.35	1.35	1.62
United States	18	5,085,247	32,333	.16	.26	.17	.59	(.09)	.50	.05	.55	.57	.67
Yugoslavia	4	1,014,895	4,407	.26	.23	.16	.64	(.20)	.43	.07	.50	.53	.63
Zaire	4	572,970	17,609	.29	.15	.25	.69	(.19)	.51	.02	.53	.54	.60
Zambia	9	888,790	10,577	.35	.26	.25	.85	(.08)	.77	.05	.82	.91	1.00
Others	19	2,634,339	18,486	.32	.44	.32	1.08	(.71)	.37	.08	.45	.68	.79
Total or average	110	29,035,121	230,123	.23	.25	.19	.68	(.17)	.50	.05	.55	.60	.74
Nonproducing mines and deposits													
Argentina	3	1,315,900	6,281	.15	.26	.15	.56	(.24)	.31	.21	.53	.95	1.70
Australia	3	79,424	969	.44	.21	.44	1.09	(.79)	.30	.14	.44	.57	1.51
Canada	15	1,956,068	7,762	.28	.33	.32	.93	(.24)	.69	.15	.84	.94	1.24
Chile	6	2,103,224	21,707	.14	.22	.20	.55	(.06)	.49	.10	.59	.68	.86
Peru	9	1,935,016	13,576	.22	.34	.30	.87	(.17)	.69	.18	.87	1.16	1.69
Philippines	10	1,006,180	3,960	.33	.32	.23	.87	(.57)	.30	.35	.65	.65	.97
Turkey	3	48,952	1,405	.18	.07	.49	.74	(.81)	(.07)	.09	.01	.07	.50
United States	30	4,824,252	23,817	.33	.35	.24	.92	(.17)	.75	.15	.90	1.04	1.80
Others	13	4,653,805	27,016	.24	.30	.28	.82	(.23)	.59	.14	.73	.93	1.47
Total or average	92	17,922,821	106,492	.24	.30	.26	.79	(.20)	.59	.14	.73	.91	1.41

[1]Ore tonnages include feed treated in the primary concentration process. Oxide material treated as a secondary process to sulfide copper recovery is not included here but is accounted for in Reserves/Resources shown in table 8.

[2]Includes transportation costs for copper concentrates plus coproduct/byproduct concentrates. Also includes smelting and refining costs for coproducts and byproducts.

[3]Equal to net production costs plus loan repayments, all pertinent taxes, and return on investment (at 15% DCFROR).

[4]Does not include Inco and Falconbridge Sudbury operations.

Note: Data may not sum to totals due to independent rounding.

A total of 340.8 million metric tons of copper is potentially recoverable from 204 evaluated MEC mines and deposits (69% from producing mines and 31% from nonproducing mines and deposits). Chile remains the largest potential source of copper in the MEC's with 98.9 million metric tons of recoverable copper (78% from producing mines), followed by the United States with 56.2 million metric tons (58% from producing mines), Australia with 27.2 million metric tons (96% from producing mines), and Peru with 22.9 million metric tons (41% from producing mines).

All of the MEC copper-producing nations with the exception of Brazil, India, and Spain have average total production costs (0% DCFROR) from producing properties below the average LME cash wirebar price of $1.15 per pound. Based on either the estimated 1988 operating costs for producing mines in MEC's shown in table 8, or the average total costs for producing operations evaluated in January 1988 dollars (table 12), 1988 was a banner year for copper producers, particularly in comparison with the early to mid-1980's.

Table 12. —MEC copper production estimates, by region and country, 1987 through 1995[1]
(Thousand metric tons of contained copper)

Country	1987	1988	1989[e]	1990[2]	1991[2]	1992[2]	1993[2]	1994[2]	1995[2]
North America:									
Canada	794.1	758.5	798.1	813.0	780.8	776.3	768.8	748.8	696.2
Mexico	253.7	280.2	310.5	330.1	328.0	313.3	313.3	313.3	313.3
United States	1,284.9	1,419.7	1,551.7	1,599.1	1,653.0	1,715.8	1,817.8	1,881.8	1,887.2
Total	2,332.7	2,458.4	2,660.3	2,742.2	2,761.8	2,805.4	2,899.9	2,943.9	2,896.7
Central and South America:									
Chile	1,412.9	1,472.0	1,636.3	1,728.4	1,874.2	2,094.5	2,222.4	2,300.0	2,306.0
Peru	406.4	322.8	339.6	415.1	472.0	469.6	515.4	619.6	634.9
Other	41.1	45.8	51.1	56.8	57.1	47.2	84.8	84.8	84.8
Total	1,860.4	1,840.6	2,027.0	2,200.3	2,403.3	2,611.3	2,822.6	3,004.4	3,025.7
Europe	290.7	249.0	364.9	423.5	450.8	443.6	439.0	426.6	408.5
Middle East	100.1	99.9	157.5	190.5	194.7	198.8	207.1	215.4	223.7
Asia:									
India	56.5	55.7	58.5	58.5	58.5	58.5	58.5	58.5	58.5
Philippines	216.1	218.1	225.7	239.8	252.3	252.4	275.6	267.8	266.6
Other	71.4	52.5	63.0	59.5	55.1	55.1	55.1	55.1	55.1
Total	344.0	326.3	347.2	357.8	365.9	366.0	389.2	381.4	380.2
Africa:									
Namibia	37.6	40.9	40.0	40.0	37.0	37.0	37.0	37.0	37.0
South Africa, Republic of	188.1	168.5	196.9	190.9	189.5	189.2	189.2	182.5	182.5
Zaire	525.0	530.0	550.0	550.0	566.8	565.9	565.9	565.9	562.1
Zambia	463.1	431.8	451.0	447.2	451.8	479.0	470.9	468.6	486.6
Other	56.9	56.9	61.8	59.8	59.8	55.2	47.4	47.4	47.4
Total	1,270.7	1,228.1	1,299.7	1,287.9	1,304.9	1,326.3	1,310.4	1,301.4	1,315.6
Oceania:									
Australia	232.7	238.3	273.0	281.0	283.5	300.0	298.5	313.5	267.0
Other	319.7	340.1	343.7	326.5	362.2	562.0	633.0	625.0	599.0
Total	552.4	578.4	616.7	607.5	645.7	862.0	931.5	938.5	866.0
Grand total	6,751.0	6,780.7	7,473.3	7,809.7	8,127.1	8,613.4	8,999.7	9,211.6	9,116.4

[e]Estimated.
[1]1989-95 is based on estimated projections from literature, and does not necessarily reflect capacity or actual production.
[2]Projected copper production.

The 92 nonproducing mines and deposits evaluated in 1988 dollars have a weighted average total cost at a 0% DCFROR of $0.91 per pound of refined copper, increasing to $1.41 per pound of refined copper at a 15% DCFROR. All of the countries evaluated with nonproducing mines and deposits have an estimated weighted average total cost at a 0% DCFROR, which is under the January 1988 LME grade A cash cathode price. At a 15% DCFROR, Chile, the Philippines, and Turkey have weighted average total costs under the January 1988 LME copper price.

Chile had the lowest estimated average total cost from producing mines of $0.48 per pound of recoverable copper (0% DCFROR), with estimated total costs ranging from $0.40 to $0.81 per pound. Nonproducing deposits in Chile had average estimated potential total costs of $0.68 per pound at a 0% DCFROR and $0.86 per pound at a 15% DCFROR. At a 15% DCFROR, nonproducing deposits in Chile had estimated potential total costs of production ranging from $0.57 to $1.88 per pound. The average estimated total cost of production for U.S. producing mines in January 1988 dollars at a 0% DCFROR amounted to $0.57 with estimated total costs ranging from $0.36 to $0.85 per pound. For nonproducing deposits, potential average total costs of production were estimated to be $1.04 per pound at a 0% DCFROR and $1.80 at 15%.

It is worthwhile to note that the estimated average total cost of production of $0.57 per pound in the United States at a 0% DCFROR from producing mines as of January 1988 is $0.13 per pound lower than the average total cost estimated in January 1985 dollars of $0.70 published in BuMines Bulletin 692 (*10*). In average 1981 dollars, the Bureau estimated an average total cost for producing mines in the United States of $0.92 per pound (*11*) which is $0.35 higher than the estimate for January 1988.

The producing operations in Canada had an estimated weighted average total cost of $0.38 per pound ($0.59 per pound excluding the Sudbury operations) at a 0% DCFROR, with estimated total production costs ranging from less than $0.00 to $0.91 per pound. Nonproducing deposits had an estimated potential average total production cost of $0.94 per pound at a 0% DCFROR and $1.24 at 15%.

If the curve for producing mines at a 0% DCFROR in figure 3 is divided into quartiles, approximately 51% of potential production from producing mines in Chile lie in the first quartile, 31% is in the second quartile, 17% is in the third quartile, and 1% is in the upper quartile. For the United States, 20% of potential production of copper is in the first quartile, 29% is in the second quartile, 8% is in the third quartile, and 43% lies in the upper quartile. In Canada, 7% of potential production is in the first quartile, 19% is in the second quartile, 55% lies in the third quartile, and 19% lies in the upper quartile. None of the potential production from Zaire is included in the first quartile, 82% is in the second quartile, 11% is in the third quartile, and 7% is in the upper quartile. The distribution of potential production from Zambia is more heavily weighted toward the upper quartile, with 0% in the first two quartiles, 21% in the third quartile, and 79% in the upper quartile.

The total cost distributions for each quartile discussed in the above paragraph are as follows: The first quartile contains potential production at total costs ranging from $0.00 to $0.41 per pound of recoverable copper; the second quartile contains potential production with total costs ranging from $0.42 to $0.55 per pound; the third quartile contains potential production with total costs ranging from $0.56 to $0.66 per pound; and the upper quartile contains potential production at total costs exceeding $0.67 per pound. It should be noted that 80% of the potential production in the upper quartile has estimated total costs of under $1.00 per pound, which remains well below the current copper price. The highest cost producer in the United States has an estimated total cost of $0.85 per pound; all of the other U.S. producers falling in the upper quartile have estimated total costs of between $0.67 and $0.72 per pound.

PLANNED EXPANSIONS AND ESTIMATED COPPER PRODUCTION

The following primary copper production estimates are based on current production capacities and planned expansions at producing mines and estimated production at developing mines expected to come on stream by 1995. Explored deposits are included where plans have been announced by companies for development and production by 1995. Primary copper production estimates, by country, through 1995 are shown in table 12. Changes in estimated production between 1988 and 1995 for major producing countries are illustrated in figure 4.

The average annual rate of production growth in MEC's is projected at 4.4% through 1994 with a slight decrease predicted in 1995. The largest production increases are projected to occur in Chile where an average annual growth rate is estimated to be 7.9% through 1995. The largest increase in Chile will result from the development of mines owned by private corporations. The La Escondida Mine, which will come on-stream in late 1990, will have a capacity of 320,000 metric tons of contained copper per year. The La Candelaria project is planned to produce 90,000 metric tons of copper per year by 1993. Other projects expected to commence production by 1993 include Quebrada Blanca, Zaldivar, Los Pelambres, El Lince, and Collahuasi. Major expansions are planned at Los Bronces and Mantos Blancos.

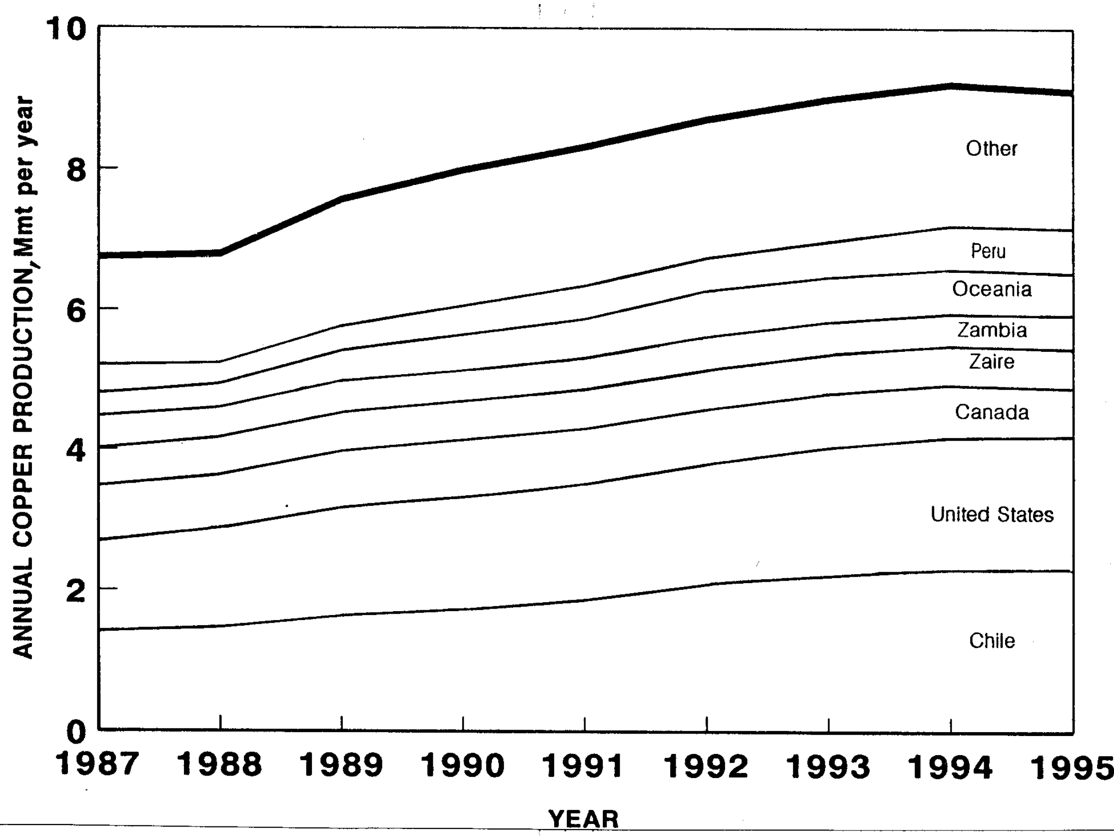

Figure 4.—Changes in estimated MEC copper production between 1987 and 1995.

The United States is projected to have a slightly lower production growth rate of 5.9% per year. Expansions are planned at Bagdad, Bingham Canyon, Mission complex, Ray, and White Pine for sulfide ore, as well as Cyprus Miami, Morenci, and Pinto Valley (including Miami tailings project) for increased SX-EW production. New projects expected to be in production between 1992 and 1994 include Cochise, Copper Basin, and Sanchez in Arizona; Bald Mountain in Maine; Montanore (Noxon) and Rock Creek in Montana; and Flambeau in Wisconsin.

Oceania, consisting of Australia, Papua New Guinea, and Indonesia was estimated to have the highest growth rate at 10.9% per year, over the 8-year period. The increase in production is not gradual, with an estimated 14.6% growth rate over the 1987 through 1992 period, then dropping at a 3.2% annual rate for the next 3 years because of declining ore grades at OK Tedi. However, with the closure in 1989 of Bougainville in Papua New Guinea owing to terrorist activity, the original production estimates will not be realized until Bougainville returns to full production (perhaps by 1992). Accounting for the loss of production from Bougainville, estimated production from Oceania will remain relatively stable through 1991, then increase dramatically in 1992 as Bougainville returns to full production. The current loss of production from Bougainville is being offset by increases at the Ertsberg-Grasberg complex in Indonesia. Production at the Ertsberg-Grasberg operation increased rapidly in 1990 due to the development of the Grasberg deposit and is expected to increase to about 285,000 metric tons per year by mid-1992. The Olympic Dam Mine in South Australia commenced production in 1988 with phased capacity increases up to 55,000 metric tons per year planned by 1994.

Canada's production growth is not at a uniform rate either, with a 0.8% annual increase through 1990 followed by an average decline of 2.9% per year over the next 5 years for an overall 1.5% annual decline from 1987 through 1995. The only significant production increase in Canada will be from

Ansil mine, which commenced production in 1989, will attain full production of about 29,000 metric tons of copper in 1990.

Peru has the potential for major production increases if the country's economic, political, and labor problems are alleviated. Taking an optimistic view, Peru could increase production by 7% per year by bringing several properties into production from a long list of potential candidates. The expansion project by Minero Peru at Cerro Verde is continuing, and the Tambo Grande and La Granja projects could add about 135,000 metric tons of copper per year to Peru's total by 1995 if development proceeds as planned. The unsettled political and economic climate in Peru remains a serious drawback to major investments, however.

Zaire and Zambia are projected to maintain the status quo with only a slight growth rate in annual production of less than 1% estimated through 1995. Efforts are being made to improve efficiency at operations in both countries through modernization and cost cutting programs.

In light of the continued strong copper market, additional properties could conceivably be brought into production by 1995 but would typically have to be smaller operations requiring shorter lead times. A major development would have to have been announced by 1989 with plans for development already made in order to be in production by 1995. Expansion plans are more difficult to project, however, and annual production projections will have to be revised periodically as a result.

CONCLUSIONS

A total of 204 mines and deposits were evaluated for the availability of copper; 112 were producing, 9 mines were on temporary shutdown, and 8 were being developed as of January 1988. The remaining 75 deposits were explored with no finalized development plans. Total demonstrated copper resources evaluated for MEC's contain 340.8 million metric tons of recoverable refined copper (69% from producing mines and 31% from nonproducing mines and deposits). The countries with the largest copper resources are Chile with 98.9 million metric tons of recoverable copper (78% from producing mines), the United States with 56.2 million metric tons (58% from producing mines), Australia with 27.2 million metric tons (96% from producing mines), and Peru with 22.9 million metric tons (41% from producing mines).

Chile not only has the largest recoverable copper resource, but also has the lowest estimated weighted average total production costs in MEC's. The estimated average total cost of production of copper from producing mines in Chile as of January 1988 amounted to $0.48 per pound at a 0% DCFROR, with costs ranging from $0.40 to $0.81 per pound. Nonproducing deposits in Chile have estimated average potential total costs of $0.68 per pound of copper at a 0% DCFROR and $0.86 per pound at a 15% DCFROR.

The estimated average total cost of production, per pound of copper, for producing mines in the United States amounts to $0.57 in January 1988 dollars at a 0% DCFROR, with estimated total costs ranging from $0.36 to $0.85 per pound. For nonproducing deposits, potential average total costs of production were estimated to be $1.04 per pound at a 0% DCFROR and $1.80 at 15%.

Mine production of copper from MEC's is estimated to be 9.12 million metric tons in 1995, an increase of 2.32 million metric tons (34.2%) over 1988 production levels. The largest increases are estimated to be from Chile (834,000 metric tons), the United States (468,000 metric tons), Peru (336,600 metric tons) and Papua New Guinea-Indonesia (258,900 metric tons). Based on these estimates, Chile's share of MEC production would increase from 21.7% in 1988 to 25.3% in 1995. The United States would essentially maintain its market share, which amounted to 20.9% in 1988 and is estimated to be 20.7% in 1995. Oceania (Australia, Papua New Guinea and Indonesia) would increase its share of MEC production from 8.6% in 1988 to 9.5% in 1995, with most of the increase accounted for by Indonesia and Papua New Guinea.

Africa will continue its decline in market share, from 18.1% in 1988 to 14.3% in 1995 although African production is estimated to increase slightly. Canada's production is estimated to decrease to 696,000 metric tons in 1995 from production of 756,400 metric tons in 1988. Canada's share of MEC production would decline from 11.1% in 1988 to 7.6% in 1995.

The largest unknowns pertaining to the production estimates presented in this report involve the political and economic situation in Peru and the future status of the Bougainville operation in Papua New Guinea. If production from these two countries in 1995 lags behind current production estimates, the relative importance of Chile and the United States will increase.

In both real and nominal terms, the United States has, on average, significantly lowered its copper production costs since 1981. Rationalization of the industry and significant increases in productivity have made a strong improvement in the competitiveness of the U.S. copper industry. The U.S. copper industry's ability to compete in the world copper market has improved to the point that the United States should no longer be considered as a marginal producer of copper. The U.S. industry is well-placed to face future downturns in the copper market and remain a viable and growing segment of the world industry.

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APPENDIX

COST REDUCTION MEASURES TAKEN BY THE COPPER INDUSTRY DURING THE 1980's

The methods used to cut operating costs were numerous, including one or more in the following categories:

1. Convince labor to accept lower wages and benefits, and to cross-train for more than one job;
2. Install in-pit crushers and conveyors to reduce energy costs and costly truck haulage;
3. Eliminate direct-loading of railroad cars to permit more leeway in pit planning and waste removal;
4. Steepen pit slopes to delay waste handling;
5. Purchase larger equipment to take advantage of economies of scale;
6. Rebuild equipment rather than replace units;
7. Establish trolley lines for trucks to reduce fuel usage;
8. Initiate leaching of old and new waste dumps;
9. Begin heap leaching of selected lower grade material;
10. Start or continue in situ leaching;
11. Erect SX-EW plants to treat the copper leaching solutions;
12. Convert cleaner flotation circuits to column flotation;
13. Install new and larger SAG mills; and
14. Automate wherever possible.

Labor Costs and Training

The obvious place to slash costs for most companies, particularly in the developed countries, was in labor. The mining projects were overstaffed, and most wages were higher than average wages in the local economy.

In general, the work force was asked to take a reduction in direct wages and in benefits, such as health insurance and cost of living adjustments (COLA). At some properties, the workers went on strike. At other properties, a spirit of conciliation was in the air. Most of the new contracts contained clauses which affirmed the company's intention to raise the wages again in a few years, or included incentive bonuses based on the prevailing copper price.

Following a general reduction in force, the remaining workers were asked to gain proficiency in more than one job. For example, a drill operator could learn to handle a bulldozer, and a mechanic might be expected to handle minor electrical repairs. This action of crosstraining resulted in a smaller, more efficient work force.

In-Pit Crushers and Conveyors

As open pits become deeper, the cost of truck hauls can exceed 50% of the total mining cost. One method for reducing this high cost is to install primary crushers and ore conveyors in the pit. With the primary crusher in the pit instead of at the mill or on the pit rim, the haulage distance for run-of-mine ore is drastically shortened, and the truck fleet can be cut back. Conveying material is cheaper than trucking because the conveyor uses less body weight to carry a load (less deadweight to haul around), and the returning empty belt can regenerate power. The conveyor also uses comparatively fewer workers. Furthermore, power from a central powerplant is more efficient and less expensive than diesel truck engine power.

The in-pit crusher/conveyor does have disadvantages. Capital costs can be high, although the depreciation period is longer than that for trucks. The operable slope of the conveyor requires a flatter pit slope at one end of the mine, or a notch in the working slope, or possibly a tunnel through the pit wall.

The first in-pit crushers, such as at Sierrita and Twin Buttes, were permanently entrenched on the pit slope a few hundred meters below the pit rim. As technology advanced, mobile or semimobile crushers became available; they were not permanently located, and could be moved as often as necessary, usually every 2 years.

The mobile crusher typically is composed of three main parts. The first is a dump hopper and apron feeder, which conveys the run-of-mine material from trucks or front-end loaders to the crusher. The second is the primary crusher itself, which is almost always a gyratory, and the control tower. The third part is the discharge conveyor system, which transfers the crushed rock to the transport conveyor.

The three parts of this system are moved by a mobile transporter, similar to the vehicles used at Cape Canaveral to move rockets. The transporter maneuvers under the section to be moved, raises a hydraulic jack topped by a bolster plate (which locks into a receiving box on the bottom of the section) until the supporting legs of the section are raised off the ground, and then moves off to the new site at a slow and safe speed. The bolster plate can be angled hydraulically to compensate for steep road grades.

Eliminate Railroad System

Both Morenci and Bingham Canyon have stopped direct-loading of railroad cars by shovels, and have removed most of their in-pit track systems. Parts of the systems are being retained for the sole purpose of loading some cars from trucks at a dock.

A railroad system imposes severe restrictions on mine planning because of the forced sequence of track shifts, and the space taken up by the 3% access ramps. Removal of the railroad permits more opportunistic planning, and reduces the stripping ratio (at Bingham Canyon, a 30% reduction to a 1:1 strip ratio).

Steepen Pit Slopes

Many mining engineering departments have been reexamining their criteria for pit design. Some are finding that their slopes have been overdesigned, and can safely be steepened to a higher angle. This will result in less waste being moved, and a lower mining cost. It is reported that Morenci was able to change one section from 37° to 51°, thus cutting the strip ratio from 1.7:1 to 1.4:1.

The normal way for steepening slopes is to reduce the width of the safety benches. In some cases, every other bench can be eliminated, especially on the final slope. Rock bolts, cable bolts, and cable nets can be used to strengthen the pit walls, much as they are used underground to unify the backs. Where water is a weakening source, it can be removed by drainpipes or pumping.

Larger Equipment Units

As a general rule of thumb, the larger the piece of equipment, the cheaper the operating cost per metric ton of material handled. Thus, most mines, when ordering new equipment, will specify the largest unit available that has undergone thorough testing. When properly matched with the rest of the mine equipment, the larger units will effectively contribute to lower capital and operating costs.

There are a few drawbacks to the larger units. If one should break down in a scheduled operation, the other units in the activity will not come close to maintaining the target production. Also, if the larger unit is a truck, it must be able to fit into the existing maintenance shop bays. If the unit is a shovel or dragline, the on-site cranes must be able to service it.

Rebuilding Versus Replacing

In the past, most mines replaced old equipment with new units at the appropriate time. Now, under the burden of lower budgets, the mines are finding that rebuilt units are just as dependable, but less costly, than new ones. In some foreign countries, the import duties alone negate the potential for acquiring new equipment.

In a typical rebuild, the machine is stripped down to the basic frame, which is inspected and tested for cracks and warps. New or rebuilt components are then added until the rebuild job is completed. Usually, the rebuilds are conducted in the shops of the manufacturer, or at the mine by the manufacturer's representative. Sometimes the mine itself will undertake the rebuilding. In a few cases, the manufacturer will buy old units, then rebuild them and sell them again as remanufactured machines. In all cases, the rebuild cost is less than a new-unit cost, and the life is about the same.

Trolley-Assisted Haul Trucks

The trolley-assist works more or less like an electric streetcar or train. For a truck, electric current is fed from an overhead wire to the truck's electric wheel motors and blowers; the diesel engine then has less load, and converts to the idle mode at this time. In general, the overhead lines are suspended from poles that are lined up along the side of the inclined haul ramp. The loaded truck leaves the shovel and travels to the ramp under its own power. While still rolling, the truck driver elevates a pantograph (the connecting device) to the cable, and electricity powers the truck while it is on the ramp. At the top of the ramp, the cable stops, and the truck proceeds to the crusher or dump under its own power again. On the return downhill trip, it is possible to employ a second cable, which can be used for regeneration of electricity.

Advantages of trolley-assist are many. Diesel consumption of a loaded truck drops by about 95%, due to idle versus full-power engine status. Central powerplants can supply electricity much more cheaply than that furnished by a truck engine. Truck speed is higher on the ramps with the trolley, which means that production can be sustained with fewer trucks. The truck engines do not work as hard, and engine life is doubled. Wheel motors spend a shorter time on the grade, and can last more than twice as long as in the past. There are a few disadvantages to trolley-assist. The overhead lines, once in place, are difficult to move, meaning that the haul ramps must stay put for many years, which may hinder mine planning. The lines are also vulnerable to flying rock from blasting. Finally, truck drivers may become bored and lose attention, which could lead to accidents.

The only mine committed to the trolley-assist is Palabora, in South Africa. Project personnel are happy with the results of this program, and fully intend to prolong it. Other mines that have tested the system have discontinued it.

Increased Leaching of Waste Dumps

Much of the waste rock (not alluvium) that has been, or is being, placed in waste dumps carries some copper values in the form of oxides and sulfides which have grades that are too low for profitable extraction by flotation. Normally, dilute acid is fed to the top of these dumps, by sprinkling or ponding, and will percolate downward dissolving some of the copper, which is part of the pregnant solution collected at the base of the dump. Copper is recovered from the solution by contacting it with scrap iron or by solvent extraction. Costs are not high, because delivery of the rock to the dump has been charged against normal ore production. Pumping of water or weak acid solutions to the dump is not expensive.

There are two factors, which may distract from a dump leach operation. The first is that the rock is usually run-of-mine, which means that it is not crushed. As a consequence, boulders cannot be thoroughly leached, resulting in a low copper recovery. The second factor is that exiting solutions may sink into the underlying soil, where they cannot be captured, but may pollute the ground water.

Some copper properties have been reviewing the status of their waste dumps, and have been installing copper-recovery systems. The decision is easier to make if a solvent extraction plant is already on site.

Heap Leaching of Low-Grade

Heap leaching is similar to dump leaching in that copper is leached out of low-grade material. However, in heap leaching, the rock, either run-of-mine or crushed, is placed on a heap in layers of a specified depth, much like a blending pile. Placement can be by trucks or conveyors. There is usually a bulldozer on assignment to spread out the rock, and possibly rip the layers to avoid compaction.

Costs for heap leaching can be significantly higher than for dump leaching in those cases where the rock is mined specifically for leaching rather than as a part of a stripping program. Otherwise, additional costs are incurred only for crushing the rock and shaping the layers in the leach pile.

In Situ Leaching

An in situ leaching operation carries the leaching solution to the rock, rather than the rock to the leaching solution. The in-place rock may be broken, or solid; it can be in old mines, such as pit bottoms or block-caves, or it can be in virgin ground. The leaching solution is usually delivered to the site via a pipeline network and drilled holes. The solution diffuses throughout the rock, dissolving copper as it spreads. Eventually, the solution accumulates in one location, and is then pumped to a solvent extraction plant.

The major advantage of this type of operation is that there are no costs involved in moving the rock; for virgin ground, there are no drilling and blasting costs, either. There is no disfigurement of the surface, such as open pits, shaft headframes, waste dumps, or tailing ponds.

A major disadvantage is the potential for the leaching solution to escape into aquifers, and render them unsuitable for human, animal, or agricultural consumption. Thus, many tests have to be run on the site to determine pumping pressures and hydraulic gradients; a protective fence of wells may have to be established. There are also a few other points to consider for testing purposes: Is the rock leachable? Will dissolved copper reprecipitate before it can be pumped out? Will alkalies neutralize the acidity of the leach solution, rendering it impotent?

SX-EW Plants

The standard method of extracting copper from copper-bearing rock is to form a concentrate by flotation, blister copper by smelting, and salable copper by refining. However, for the recovery of oxide ores and some low-grade sulfides, leaching-solvent extraction-electrowinning has become a viable alternative.

The first method for extracting copper from acidic solutions was by deposition of the copper on iron scrap (cementation). This was initiated as a means of recovering copper from natural mine and drainage dumps. At some properties, this process became a valuable adjunct to the main facilities, while at others, it was the only source of revenue. However, iron scrap can be expensive and difficult to find, and the precipitated copper needed further treatment at a smelter.

Research for a cheaper way to extract copper from solutions resulted in the solvent-extraction/electrowinning process, known as SX-EW. Costs are less than from conventional flotation-smelting-refining of sulfide ore, and the end product is a highly marketable electrolytic copper.

The leaching solutions treated by SX-EW can originate from several types of copper minerals. Oxide copper minerals, such as malachite and chrysocolla, are the most suitable. Native copper and some of the sulfides, like chalcocite and bornite, are also good sources. Other sulfides, i.e., chalcopyrite and enargite, will leach, but relatively slowly.

Many of the major copper producers, including the United States, Chile, and Zambia have implemented hydrometallurgical technology for treatment of oxide ores and tailings. In heap leaching, the raw material is layered on waterproof pads and a lixiviant (solvent) is applied to the top and allowed to percolate through the layers. Dump leaching involves the treatment of existing waste dumps. In either case, the leach liquor is collected at the bottom and pumped to a storage pond. From storage, the leach liquor is pumped to the solvent extraction circuit. Solvent extraction is a form of liquid ion exchange, which purifies and concentrates the copper sulfate solution in a two-stage operation. The two stages are called extraction and stripping.

In the extraction stage, the aqueous leach liquor is contacted by an organic liquid ion exchange agent in a series of vessels (mixsettlers). The two liquid phases are well mixed and then allowed to settle. The copper is absorbed from the aqueous phase into the organic phase. Because the aqueous and organic phases are immiscible, they separate and the copper ions are selectively removed with the organic phase. The depleted liquor, or raffinate, is recycled to the leaching operation.

The loaded organic phase from the extraction stage next enters the second series of mix-settlers, termed the stripping stage. In this operation, the organic is mixed with spent electrolyte from the electrowinning operation. By virtue of its lower pH, the spent electrolyte replaces the copper ions in the organic phase with hydrogen ions. The strong electrolyte produced in this operation advances to the electrowinning section.

Electrowinning resembles electrolytic refining in many respects. The key differences are that the copper is "won" from a leach solution rather than recovered from anodes. The anodes are of inert, insoluble lead. Cathodes may be either pure copper "starter sheets" or inert stainless steel.

The SX-EW process is now recognized as crucial to obtaining low operating costs at leach operations. Besides dump and heap leaching, some mines are retreating their tails, while others are prestripping and treating oxide material overlying sulfide ores. In several cases, the whole project is committed to leaching and SX-EW treatment.

Column Flotation

Standard flotation cells in mills have increased in size and efficiency. However, they are still a suitable target for cost reduction. The column flotation cell is becoming more popular as its attributes become known. Essentially, it is a tall cylinder that can replace two to five stages of cleaner cells. It is not yet suitable for rougher flotation.

Operation of the column cell is simple. Feed and water enter at the top, and compressed air is blown in at the bottom. Concentrate froth overflows at the top, and tails escape through a hutch at the bottom. Adjustments of feed, water, and air inflows control the froth quantity and quality.

Advantages of the column are many. Required floor space is much less than for normal cell banks, leading to reduced capital costs for the mill building and ancillaries; as a corollary, production expansions would also be cheaper. Powering of the flotation process by air instead of mechanical paddles cuts electricity and maintenance costs. Personnel requirements are also lower. Best of all, concentrate grades can improve by as much as 5%, resulting in lower concentrate transport and smelting costs.

SAG Mills

Semiautogenous grinding (SAG) mills are becoming more popular and bigger. In new projects, they are installed after the primary crusher and in front of the ball mill, replacing the standard series of secondary/tertiary crushers and rod mill. Capital savings can be as much as 30%. Operating cost savings can also be as much as 30%, due to lower maintenance requirements, lower media consumption, and fewer operators.

It would not be advantageous to change an existing circuit, just for the purpose of inserting a SAG mill. However, for production expansions and new concentrators, the SAG mill should definitely be considered, especially for high-tonnage operations and for damp, sticky material.

SAG mills are an intermediate design between fully autogenous mills, which use natural hard rock as grinding media, and rod/ball mills, which use manufactured steel rods/balls as media. The SAG mill uses a media mix of hard rocks and balls, with the percentage and amount of each changed to suit the particular type of ore and throughput required. Size and hardness of the ore should be fairly uniform in order to maintain consistent output.

As SAG mills become larger, the standard powertrain design has become inadequate. To resolve this problem, the wraparound motor was developed. In this system, the mill serves as the motor rotor, revolving inside a stationary stator; i.e., the poles on the mill shell rotate within a nonmovable collar containing the stator. Advantages attributed to the wraparound motor are many. Gears, drivetrain, and clutches are eliminated. There are no power surges at startup. Mill speed is continuously variable: this permits "inching" for maintenance purposes, and can also be used to compensate for changing ore characteristics.

Automation

The main function of automation for machinery and operations is to eliminate the chances for human error. A welcome side effect can be a reduction in personnel, coupled with enhanced safety. One of the major advances in mine and mill machinery has been automatic lubrication systems for the larger units, such as shovels and trucks. Each friction point receives the proper amount of grease at the appropriate scheduled time. Oilers, who used to be full-fledged members of the operating crew, are no longer needed on a full-time basis, although in some cases they have been retained as samplers, trainees, or for safety reasons. In some large mines, an oiler is given a pickup truck and is expected to circulate among the shovels and drills working that shift. From the safety point of view, the engine deck is no longer slippery with spilled lube, which contributed to some serious accidents when the oiler lost his footing and fell against moving machinery parts.

Many mining activities are beyond the scope of reasonable automation. Shovels are faced with numerous varieties of digging conditions. Trucks must be expected to travel in any direction with equal facility. On the other hand, there have been some other successes: drilling of blastholes is now almost entirely automatic; engines have diagnostic features which tell the operator and mechanic where and what the trouble is; and, concentrators are essentially completely automated. There are also automated trains (in another mining industry) which shuttle railcars between loading bins and dumpers.

The foregoing discussion cannot hope to cover all of the recent cost-saving advances that have been made in the copper industry. However, it does demonstrate that management can continue to improve operations and reduce costs at the same time.

DECLINING ORE GRADES

The long-term trend in ore feed grades is gradually declining as higher grade, easier to mine material is exhausted. This is a reflection of the tendency for ore grades to decline over the life of the mine in porphyry deposits such as in Chile, Papua New Guinea, Mexico, Peru, and the United States. Also, mining companies will generally try to exploit the higher grade material in the early years of mine life in order to shorten the payback period of capital investments and, thus, increase the DCFROR of the project. During periods of low prices, mine operators, in many cases, will attempt to exploit higher grade portions of the mine to counter the lost revenues from lower commodity prices.

Average sulfide ore feed grades, by country, from selected mines for the years 1980-88 are shown in table A-1. The classic trend of declining ore grades with depth is exemplified by Chile and Peru. In Chile, there has been a rapid decline in ore feed grades as the major Chilean mines are going through the transition from enriched supergene ores to primary ore. The average feed grade for Chuquicamata has declined from 2.26% copper in 1980 to 1.6% in 1988. A more gradual decline will continue for the CODELCO mines with average feed grades estimated to decline to 1% by the end of the century. Major investments have been made by CODELCO to offset this trend in terms of total copper production by expanding annual ore capacities. The startup of new mines such as La Escondida will increase the average ore grade in the future, because new mines to be brought into production will have higher ore grades than the prevailing average. In Peru, the two principal porphyry copper mines exhibit a classic decline in average ore grades and are expected to continue this decline throughout their operating lives. The average feed grade in Mexico increased dramatically in 1981 and 1982 as La Caridad achieved capacity production mining supergene ore. Feed grades for both Cananea and La Caridad have declined annually since 1983.

Ore grades in the United States, on average, increased annually from 1980 through 1984, then began to decline slightly from 1986 through 1988. Many operators practiced high-grading during the worst of the recession of the 1980's in order to continue producing. High-grading is a short run solution to economic pressures. Changes in mine plans have a longer term effect on operating efficiency and feed grades. Increased cutoff grades, steeper pit slopes, and changes in mining sequence serve to enhance feed grades but will ultimately shorten the life of the mine. For example, feed grades at Bingham Canyon increased from 0.58% in 1980 to 0.75% in 1985 (prior to the mine shutdown) as a result of high-grading. The revamped operation reopened at the end of 1986, and operated through 1988 with an average feed grade of 0.71% as a result of the revised mine plan.

Copper deposits in Zambia and Zaire are metasedimentary stratiform deposits and are much higher grade than the more common disseminated porphyry deposits. Feed grades in these countries have declined only slightly over the 1980-88 time period and should remain relatively constant in the future. The largest Australian producers are also high grade

Table A-1. —Weighted average sulfide ore feed grades, by country, from selected mines, 1980-88
(Percent copper)

Country	1980	1981	1982	1983	1984	1985	1986	1987[e]	1988[e]
Australia	2.96	2.54	2.64	2.61	2.72	2.71	2.73	2.78	2.88
Canada[1]	.59	.58	.52	.58	.65	.69	.64	.63	.63
Chile	1.74	1.71	1.64	1.56	1.56	1.46	1.40	1.40	1.40
Mexico	.72	.80	.86	.78	.73	.70	.69	.64	.64
Papua New Guinea	.46	.51	.47	.46	.42	.42	.42	.47	.55
Peru	1.04	1.01	1.00	1.00	.98	.96	.92	.91	.87
Philippines	.44	.45	.44	.42	.39	.39	.43	.43	.43
United States	.58	.59	.61	.63	.68	.65	.66	.64	.63
Zaire	4.21	4.41	4.11	4.04	4.10	4.06	4.04	4.09	4.10
Zambia	2.38	2.28	2.13	2.13	2.21	2.20	2.08	2.10	2.12

[e]Estimated.

[1]Averages do not include Falconbridge's and INCO's Sudbury operations.

stratiform deposits. Average feed grades fluctuated slightly during the decade, but there is no indication of declining ore grades, and with the addition of Olympic Dam, and the closure of Mount Lyell and the CSA mine, the average feed grades are expected to increase in the future.

Mines in the Philippines and Papua New Guinea are copper-gold porphyry operations with relatively low copper grades. These mines are currently mining primary material, meaning that feed grades are not expected to decline significantly in the future.

The large mines in the United States have reached a point where ore grades are no longer declining rapidly, whereas Chile is still faced with significant decreases in average ore grades through the end of the century as operations mine increasing amounts of primary ore. The development of new mines in Chile will somewhat counteract this downward trend on a country average basis, but ore grades from the current major producers will continue to consistently decrease.

BYPRODUCT CREDITS

Byproduct revenues play an extremely important part in the profitability of many copper operations. The significant increase in base metal prices beginning in mid-1987 has had a major impact on the net operating cost for copper. Table A-2 shows the average byproduct revenues, by country, estimated for the producing mines evaluated for this study for 1986 through 1989. Average commodity prices used in the economic evaluations were shown in table 4.

In Canada, where polymetallic deposits contribute a large share of copper production, the increase in lead and zinc prices are primarily responsible for doubling of the average byproduct revenue. Australia shows a significant jump in byproduct revenues in 1988, partially as the result of higher lead and zinc prices. Of more importance is the start of production at Olympic Dam with large uranium, gold, and silver revenues to offset the high production costs at the mine. In the Philippines, where gold is the principal byproduct, a significant increase in the gold price combined with a modest increase in byproduct gold production resulted in a sharp increase in byproduct revenues.

The high cobalt price in effect in early 1986 led to anomalously high byproduct credits in Zaire and (to a lesser extent) Zambia. The cobalt price dropped from $11.70 to $7.00 per pound during 1986, and in turn caused byproduct revenues to plummet nearly 40% in Zaire by 1987. Cobalt prices had gradually rebounded to $8.65 per pound by January 1989.

Copper producers in Chile, Peru, and the United states receive most of their byproduct revenues from molybdenum and, to a lesser extent, gold and silver. Molybdenum and silver prices have remained depressed throughout the 1986-89 period with gold making only modest improvement from 1986-88, declining again in 1989. This has resulted in only a marginal increase in byproduct revenues for these countries.

Table A-2. —Average byproduct revenue from producing copper operations in selected MEC's
(Dollars per pound recoverable copper)

Country	1986	1987	1988	1989
Australia	0.03	0.07	0.23	0.18
Canada[1]	.30	.49	.52	.63
Chile	.05	.06	.05	.06
Peru	.05	.07	.07	.07
Philippines	.20	.47	.49	.42
United States	.08	.10	.10	.11
Zaire	.37	.23	.25	.29
Zambia	.08	.07	.08	.09
Other	.30	.45	.42	.42
Average	.17	.22	.23	.24

[1]Excludes Falconbridge's and INCO's Sudbury operations. Average byproduct revenue for Canada in 1988 would be $0.92 per pound with these operations included.