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Availability of Primary Nickel in Market-Economy Countries

A Minerals Availability Appraisal

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PREFACE

The Bureau of Mines Minerals Availability Program assesses the availability of nonfuel minerals. The program identifies, collects, compiles, and evaluates information on active, developed, and explored properties, deposits, and mines and on mineral-processing plants worldwide. Objectives are to classify domestic and foreign resources, to identify by cost evaluation resources that are reserves, and to analyze the availability of minerals.

This report is part of a continuing series of reports by the Division of Minerals Availability analyzing the availability of minerals from domestic and foreign sources and the factors that affect availability. It is a revision of a report based on 1981 data that was published in 1984.

Analyses of other metals and minerals are in progress. Questions about the Minerals Availability Program should be addressed to: Chief, Branch of Minerals Availability, Bureau of Mines, 2401 E Street, N.W., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

bbl	barrel
Bmt	billion metric tons
°C	degree Celsius
km	kilometer
km^2	square kilometer
kmt	thousand metric tons
kmt/yr	thousand metric tons per year
kW-h	kilowatt hour
lb	pound
Mmt	million metric tons
mt	metric ton
mt/yr	metric tons per year
pct	percent
psi	pounds per square inch
tr oz	troy ounce

ACRONYMS

BCL	Botswana Concession Limited
BP	British Petroleum
CPE	Centrally planned economy (country)
DCFROR	Discounted cash flow rate of return
LME	London Metal Exchange
MAP	Minerals Availability Program
MEC	Market-economy country
MFN	Most favored nation
PGM	Platinum group metals
PM	Precious metals
RSA	Republic of South Africa
SAM	Supply Analysis Model
SLN	Eramet-SLN
VCR	Vertical crater retreat
WMC	Western Mining Corporation

AVAILABILITY OF PRIMARY NICKEL IN MARKET-ECONOMY COUNTRIES

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By Donald I. Bleiwas[1]

ABSTRACT

The U.S. Bureau of Mines has evaluated the potential availability of nickel from 36 deposits or districts in 16 market-economy countries (MECs), analyzing more than 95 percent of production in those countries. This study indicates the quantity of nickel available on the basis of net production costs and total costs with a 0-pct and a 10-pct discounted cash flow rate of return (DCFROR). Costs of production are expressed in dollars per pound of recovered nickel. The study also indicates sensitivities of the cost of production to energy, labor, and other factors.

The studied deposits and properties contain approximately 33 Mmt of recoverable nickel. About 26 Mmt of nickel is potentially recoverable from laterite deposits, of which 4.5 Mmt can be produced at $2.50/lb or less with a 0-pct DCFROR. Approximately 7 Mmt of nickel is potentially recoverable from sulfide deposits, of which about 6.3 Mmt could be produced at $2.50/lb or less at a 0-pct DCFROR. The price of nickel averaged above $6.00/lb in 1988.

Sensitivity studies performed for both laterite and sulfide deposits indicate that the total cost of producing nickel from laterites is most sensitive to increases in energy costs and that the total cost of producing nickel from sulfide deposits is most sensitive to increases in labor costs; sulfides are also affected by changes in revenues from byproducts.

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INTRODUCTION

Nickel is considered a strategic material, a commodity whose lack of availability during a national emergency or strategic situation would seriously affect the economic, industrial, and defensive posture of the United States. This study assesses the position of the United States in relation to other nickel-producing nations to determine the availability of nickel in MECs and to provide a perspective on the resources and industry structures of the centrally planned economy (CPE) countries (see list in appendix A).

Nickel, primarily in the form of refined metal and ferronickel, is derived from the mining and processing of nickel sulfide and laterite deposits. Most of the nickel consumed in the world originates from sulfide ores in Canada, Australia, and the Soviet Union and from laterite ores in Cuba, New Caledonia, Indonesia, South America, and the Dominican Republic. In 1987, nearly 65 percent of U.S. requirements for primary nickel were met by imports from Canadian mines. Through April 1988, nearly 70 percent of requirements for domestic nickel were met from Canadian nickel. The United States is dependent on foreign sources for its primary nickel.

The evaluation and analysis of nickel resources and production and the estimation of production costs and their sensitivities permit the assessment of the United States position with respect to the availability of nickel. The initial task in accomplishing this goal was to identify and perform engineering and economic analyses of significant nickel producers and potential producers in the MECs. The results are presented on curves and tables illustrating availability of resources, capacity, actual and potential production, and costs. Portions of the data used in the evaluations are derived from NICKDATA, Inc. (*1*).[2]

Sulfide deposits are generally mined by underground methods, while laterites are mined by surface methods. Laterite resources occur regionally, are subequatorial for the most part, and represent a larger segment of total resources than sulfides. In general, sulfide deposits are more labor intensive and benefit from revenues received from byproducts. Laterite deposits generally require larger amounts of energy to recover nickel than sulfides and usually do not benefit from revenues received from byproducts.

The cost and competitive relationship between sulfides and laterites are affected to various degrees by the cost of labor, energy, materials and supplies, debt on new projects, foreign exchange, transportation, and revenues from byproducts. The effect of these costs on the availability of nickel from both sulfides and laterites is analyzed.

This report is a revision of a report published in 1984 that was based on 1981 data. The cost of production has changed throughout the industry, owing in large part to improved productivity and changes in energy and labor costs, values of byproducts, and exchange rates. Other factors have changed: Canada's production has increased dramatically, new mines have been brought on line in Colombia, and significant mines have been closed, including Agnew, Eximbal, Nonoc, and Hanna's Riddle, Oregon.

The previous study evaluated 126 mines and prospects, but the consolidation of Western Mining's mines in Australia into one production center, Inco's Canadian mines into two production centers, and Falconbridge's Canadian operations into one production center significantly reduced the number of separate evaluations. Multiple operations in Greece and New Caledonia and prospects in the Republic of the Philippines and Zimbabwe were also consolidated. A number of prospects that were included in the previous study were deleted from the current analysis because additional data indicated that the resources are inferred and not demonstrated. Nickel production from the Merensky Reef in the Republic of South Africa and potential production from the Great Dyke were not included in the economic analyses because of their nature as byproducts.

ACKNOWLEDGMENTS

Data for the domestic deposits and properties analyzed in this study were developed at Bureau of Mines Field Operations Centers in Denver, Colorado, Juneau, Alaska, and Spokane, Washington. The assistance of William Kirk, Bureau of Mines Nickel Specialist, is acknowledged.

[2]Italic numbers in parentheses refer to items in the list of references preceding the appendixes.

WORLD NICKEL INDUSTRY

During the past three decades, significant changes in nickel production have had a major impact on the nickel industry and the overall availability of nickel. The following sections describe forms, uses, pricing structures, major changes in key primary nickel mines and processing facilities, and general consumption patterns for nickel products.

NICKEL PRODUCTS AND APPLICATIONS

Nickel's most important use is as an additive to other metals to form alloys. Nickel imparts strength, heat resistance, and corrosion resistance. Nickel alloys generally can be divided into three types: general technical alloys, high-performance alloys (superalloys), and special-performance alloys.

Primary nickel products are divided into two classes based on their nickel content. Class I products have a nickel content of at least 99 percent. Products of this type generally can be used without constraints for many applications. The most common Class I products include electrolytic cathodes (99.9 percent nickel) and carbonyl pellets (99.7 percent nickel).

Class II products, suitable for specific limited applications, contain some residual elements and have a nickel content ranging from 20 percent to 96 percent. The most common Class II product forms are ferronickel, which generally ranges from 25 percent to 45 percent nickel, and nickel oxide sinter, containing 76 percent to 90 percent nickel. A Class II product introduced in 1976 is Incomet (a trademark of Inco Ltd.), containing 94 percent to 96 percent nickel. Nickel salts containing 20 percent to 25 percent nickel are also included with Class II products.

More than 80 percent of the use of nickel in its primary forms is as an alloying agent to add corrosion resistance and strength to other metals. The steel industry uses more than 60 percent of these alloys. Stainless steel production reached an all-time high in 1988; it consumed approximately 400 kmt or 60 percent of total nickel demand in the MECs, compared to about 45 percent in the late 1970s and 35 percent in the late 1960s (*2*). Other primary forms are used in nickel alloys other than stainless steel or alloy steels. They include superalloys, other high-temperature alloys, and nonferrous alloys. Pure nickel is also used in electroplating.

The general technical alloys include pure nickel, nickel-copper, and nickel-iron-chrome. Depending on use, these metals are distinguished by their corrosion- and/or heat-resistant qualities.

The superalloys are used primarily in the aerospace industry because of their ability to withstand very high temperatures, strength, and resistance to corrosion. To form these alloys, nickel is combined with numerous metals, including cobalt, molybdenum, tungsten, and iron.

The special-performance alloys are produced by combining nickel with chromium or iron. They are used primarily in electrical resistance and magnetic alloys.

Nickel salts and nickel oxides are used as catalysts in batteries, fuel cells, and insecticides. Ferronickel, a Class II product, has its greatest application in the production of stainless and alloy steel, and, as a result, its production and share of total nickel demand have increased dramatically since the 1960s.

Until the mid-1980s, the prices of ferronickel and nickel oxide were generally 6 and 15 percent, respectively, below the price per pound of nickel in electrolytic cathodes, but these differences have lessened since ferronickel and nickel oxide have gained greater acceptance for steel production.

U.S. STRATEGIC NICKEL STOCKPILE

The current inventory of nickel in the U.S. strategic stockpile is approximately 33.8 kmt. Although the congressionally mandated goal for the stockpile is approximately 181.4 kmt, it is unlikely that it will be attained in the foreseeable future. About 4.5 kmt of the nickel is excellent quality electrolytic nickel, purchased in 1984 and 1985 from Norway and Canada. The remaining tonnage is of mixed origin and of various qualities, all below standards for superalloys acceptable to the aerospace industry. The material is, however, suitable for use in iron alloys, stainless steel, and other corrosion-resistant alloys. In 1985, the administration proposed a new goal of 4.5 kmt for the stockpile. This proposal would require selling all but the highest-quality metal. Through 1988, no action had been taken.

PRICING STRUCTURE

Historically, the market price of all primary nickel products was related to the price and nickel content of Inco Ltd.'s (Inco's) electrolytic cathodes (Inco is the largest producer of nickel in the MECs), which produced a relatively stable market structure for the metal. In recent years, however, increased sales from the CPE countries to the West, a greater number of producers in the MECs, increasing demand and tight supplies, and Inco's decision to play a less important role in price setting have made prices more volatile. The average price for nickel on the London Metal Exchange (LME) in 1986 was approximately \$1.85/lb, but in 1987 the price increased to an average of about $2.20/lb and ended the year at over $4.00/lb. During the same period, producers' stocks decreased from about 110 kmt to just under 75 kmt (*3*). Based on data through the third quarter of 1988, the U.S. Bureau of Mines estimates that nickel prices will average above $4.00/lb for the year.

The cash price on the LME in late August 1988 was about $6.50/lb. High prices in 1988 were caused by high demand, low inventories, and the threat of interruptions to production by strikes and technical and political problems at several major nickel producers. Demand, fueled by vigorous economic growth, resulted in depletion of producers' stocks as demand exceeded production. Nickel prices reached all-time highs in 1988 ($10.84/lb on March 28) as a result of very tight market conditions and depleted stocks. Nickel demand in 1989 will probably not continue to increase at the same rate as late 1987 and 1988. Mining companies like Inco are signing longer-term contracts (up to 3 years), and barring shortfalls in the supply from production losses (strikes or political problems, technical complications, and so on), production in 1989 should increase slightly. For these reasons, nickel prices will remain more stable and probably decrease in 1989, perhaps averaging significantly more than $4.50/lb.

NICKEL SCRAP

The industries that rely on nickel for their products acquire it from either newly mined ores or scrap. The ratio of nickel consumed for production of stainless steel in the United States between primary sources and scrap has been about 45:55. If Japan and West Germany were included, the ratio would shift to 55:45. In 1987, total U.S. nickel consumption (primary and scrap) was approximately 200 kmt, of which at least 25 percent was scrap. In 1987, consumption of stainless steel scrap increased about 45 percent over 1986. Primary stainless steel production increased about 20 percent in 1987 as a result of increased demand. Historically, U.S. demand for primary nickel increases proportionately during periods of increasing production of stainless steel and subsequently declines when higher amounts of scrap become available or production of stainless steel declines.

TARIFFS

Few taxes are applied to imports of nickel into the United States. Countries with most-favored-nation (MFN) status do not impose any import tax on nickel or its associated products (nickel ore and concentrates, nickel oxide, ferronickel, unwrought nickel, waste and scrap, and nickel powder). Non-MFN countries can import nickel ore and concentrates and nickel oxide duty free but must pay a $0.03/lb tariff on ferronickel, nickel powders, unwrought nickel, and waste and scrap. A $0.14/lb tariff is charged on nickel flakes.

GENERAL CONSUMPTION

The general pattern of nickel consumption has changed significantly over the past 30 years. In 1987, industrialized countries accounted for about 70 percent of total world consumption. Specifically, the United States and Japan accounted for about 50 percent, the CPE countries about 26 percent. Table 1 and figure 1 show primary nickel consumption in the MECs in 1950, 1981, and 1987 and distribution by country, respectively. In 1950, the United States was a major force in world steel production and a major exporter of goods. As a result, the United States was the world's largest consumer of nickel. By 1981, although the tonnage of nickel had increased, the United States' percentage share of consumption in the MECs had decreased from 69 percent in 1950 to 27 percent. During the same period, Japan's share increased from a negligible portion of production in the MECs to about 22 percent as a result of growth in the country's steel industry. Since 1981, only incremental changes have occurred.

Table 1.—Estimated primary nickel consumption in the MECs

Country or Region	1950 Production (kmt)	1950 Share (pct)	1981 Production (kmt)	1981 Share (pct)	1987 Production (kmt)	1987 Share (pct)
Europe	38	31	182	37	248	39
Japan	1	0	105	22	156	24
United States	85	69	131	27	148	23
Other MECs	NA	NA	68	14	90	14
MEC Total	124	100	486	100	642	100

NA Not available.

SOURCES: Manshreck-Head (*3*), Telewiak (*4*), and World Bank (*5*).

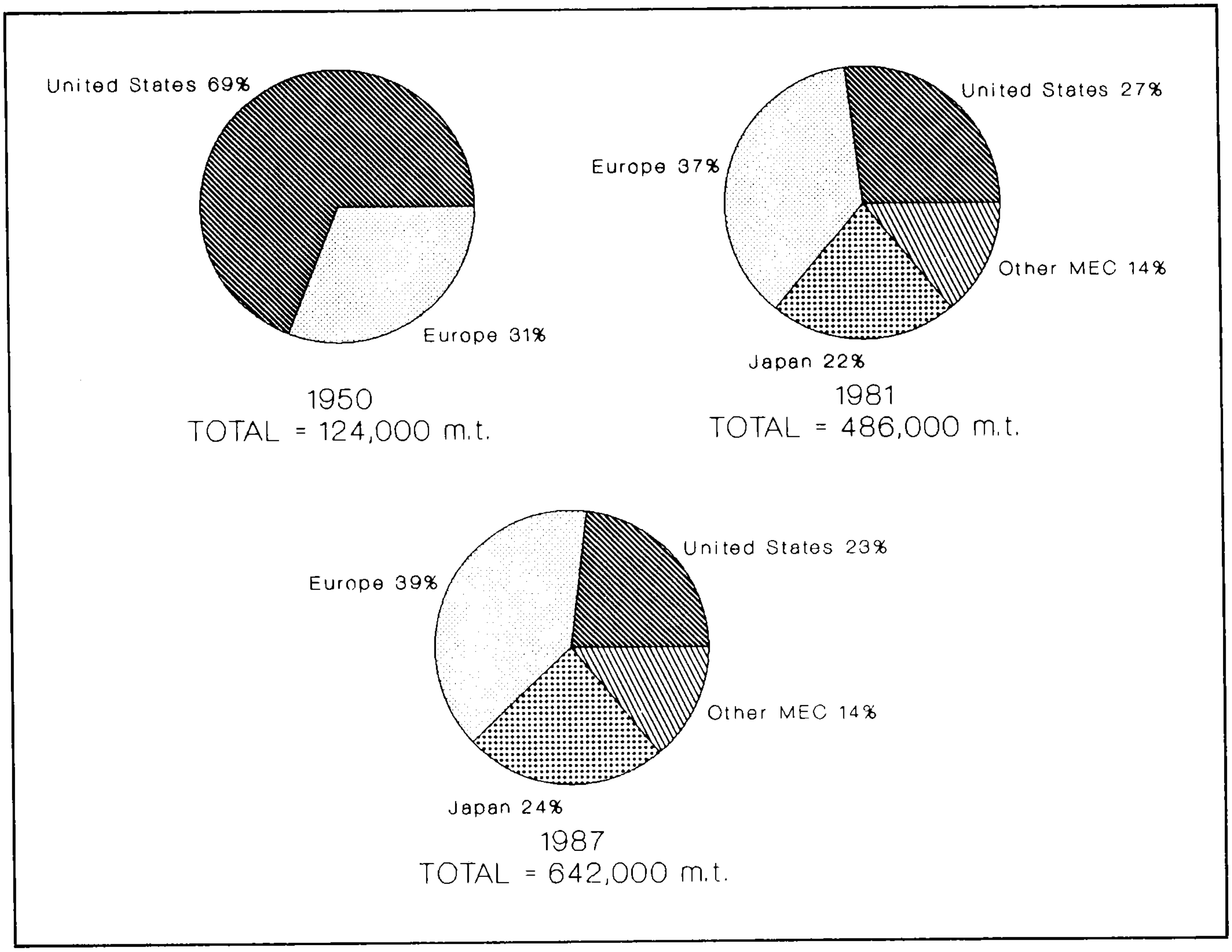

Figure 1.—Distribution of nickel consumption in the MECs.

Sales of primary nickel originate from mining operations and sales from inventories. The average annual growth rate in consumption for MECs from 1987 through 1995 is estimated for this study at between 1 and 1.5 percent. At these rates, annual consumption could reach 695-723 kmt of primary nickel by 1995.

From the mid-1970s to about 1986, the average annual growth in domestic nickel consumption was quite flat, but in 1987 and 1988, domestic demand was fueled by increased orders from the domestic automotive, petrochemical, and food-processing industries. The weakened U.S. dollar decreased demand for foreign manufactured goods and increased demand for U.S. manufactured goods. Increased consumption in the United States over the last few years is the result of several factors: increased capital spending encouraged by low interest rates, low inventories, low nickel prices, and high productivity. In 1987, production of stainless steel totaled 1.8 Mmt, about 20 percent higher than 1986 (*3*). In 1987, shipments of stainless steel by U.S. manufacturers were up almost 25 percent over the previous year. In 1987, the United States exported approximately 84 kmt of stainless steel, compared with 49 kmt in 1986. In 1987, the United States imported most of its demand for primary nickel, in various forms, from Canada, Norway, Botswana, Australia, New Caledonia, and the Dominican Republic. Most of the Norwegian nickel originates from Canadian matte; therefore, total imports from Canadian ore were nearly 65 percent of total annual domestic consumption of primary nickel. Consumption in 1989 will probably be close to that of 1988.

Japan is the world's second leading consumer of nickel products, accounting for about 16 percent of world consumption. Japan has no domestic mine production and must import all its primary nickel, mostly in the form of partially dried ore from Indonesia, New Caledonia, and the Philippines. It also imports matte from Australia and Indonesia. Japan's average annual growth rate in nickel consumption since the 1950s has been the highest for any of the world's industrialized countries.

Western Europe consumes nearly a third of the world's nickel, with an average annual growth rate of about 1.2 percent since the mid-1970s. Germany is the largest European consumer and, along with France, leads the European nations in average annual growth rate. The consumption of nickel in other countries, such as the Republic of Korea and Taiwan, has increased greatly as a result of the development of industrialization, especially in the automotive and steel industries. Increased consumption in India and Brazil was caused by the expansion of their domestic economies, which resulted in development of the domestic stainless steel and consumer product industries. For example, India's domestic output of stainless ingots increased from about 43 kmt in the early 1980s and is estimated to have exceeded 150 kmt in 1987 (*2*). Production of finished stainless steel was approximately 140 kmt in 1987 and is projected to approach 250 kmt by 1990 (*2*). India has no significant domestic production of nickel.

MAJOR NICKEL PRODUCERS IN THE MECs

Four firms, Inco Ltd., Falconbridge Ltd., Eramet-SLN (SLN), and Western Mining Corp. (WMC), account for about 70 percent of production from nickel mines in the MECs. Table 2 represents historical nickel production for the major producers in the MECs for 1975, 1985, and 1988 (estimated).

Inco was incorporated in 1916 as the International Nickel Co. of Canada Limited. Its name was changed to Inco in 1976. Inco is the largest producer of nickel in the MECs, accounting for about 39 percent of production in the MECs in 1988, and probably has the lowest average net production cost of any nickel producer in the MECs. In 1982, poor markets influenced Inco not to participate in severe price discounting. As a result, the company's production share among the MECs declined to a historical low of 25 percent. Inco is also a major producer of byproduct copper, cobalt, gold, and the platinum group metals (PGM). Inco's and Falconbridge's principal mines (table 3) and processing centers are located at or near Sudbury, Ontario, and in the Thompson, Manitoba, district of Canada. The company began production at an open-pit operation at Thompson in 1986, becoming the lowest-cost nickel operation among MECs. Production should continue for about 8 more years. Inco also operates a very large laterite mining and smelting facility in Indonesia. Matte produced at the Indonesian operation currently is refined in Japan, although a portion may be sent to a new facility in the Republic of South Korea by 1989. Inco has smelters and refineries at Copper Cliff and at Port Colborne, Ontario, and Thompson, Manitoba, Canada; Taiwan, China; Acton, England; Indonesia; and Clydach, Wales. The plants in Port Colborne and Taiwan produce nickel oxide (utility nickel), while the one in Thompson produces electrolytic nickel. The Clydach and Copper Cliff plants produce nickel carbonyl pellets and powder.

Table 2.—Estimated production from major nickel producers in the MECs

Company name	Primary mining locations	1975 Production (kmt)	1975 Share (pct)	1985 Production (kmt)	1985 Share (pct)	1988 Production (kmt)	1988 Share (pct)
Inco	Canada						
	Indonesia[1]	209	40	154	28	211	39
SLN	New Caledonia	65	13	44	8	45	8
Falconbridge	Canada						
	Dominican Rep.	55	11	57	11	67	12
WMC	Australia	32	6	40	7	45	8
Other	MECs	154	30	249	46	177	33
Total		515	100	544	100	545	100

[1]Indonesia's P.T. Inco property did not begin operating until 1977.

Table 3.—Status and mine type of Inco's and Falconbridge's Canadian nickel properties by province (as of 5/88)

Province	Owner	Active properties[1]	Properties on standby or inactive	Mine type
Ontario	Falconbridge	East (1988)		Underground
		Fraser		Do.
		Lockerby (1992)		Do.
		Strathcona (1992)		Do.
		Craig[2]		Do.
			East Falconbridge	Do.
			Falconbridge (1987)[2]	Do.
			Falconbridge (1985)	Open pit
			Fecunis (1977)	Do.
			Hardy (1977)	Do.
			North (1978)	Underground
			Lindsley	Do.
			Longvack South (1977)	Do.
			Onaping (1976)	Do.
	Inco	Clarabelle		Open pit
		Copper Cliff North		Underground
		Copper Cliff South		Do.
		Creighton		Do.
		Crean Hill		Do.
		Frood		Do.
		Levack		Do.
		Little Stobie		Do.
		McCreedy West		Do.
		Stobie		Do.
			Coleman	Do.
			Garson (1987)	Do.
			Levack West (1988)	Do.
			Murray (1976)	Do.
			Shebandowan (1986)	Do.
			Totten (1972)	Do.
Manitoba	Falconbridge		Manibridge (1977)	Do.
	Inco	Thompson		Do.
		Thompson		Open pit
			Birchtree (1974)[2]	Underground
			Pipe 1	Do.
			Pipe 2	Do.
			Soab North	Do.
			Soab South	Do.

[1]Years in parentheses are actual or estimated dates of closure, suspension of mining, or exploration.
[2]Being rehabilitated for production within 2 years.

Inco's Canadian operations are confronted with high costs associated with meeting air-quality standards. Canadian legislation requires that by 1994 emissions be reduced to a maximum of 265 kmt, about one-third the 1985 levels (*4*).

In addition to cutting production costs, Inco has made strides in reducing emissions by improving the separation of pyrrhotite from concentrates before smelting. Inco is actively modifying its operations to reduce operating costs. The Crean Hill Mine, now in production, is being converted to an all-electric mine.

Falconbridge, also a Canadian company, is the second largest nickel producer in the MECs, providing nearly 12 percent of the total production for the MECs. The company has been involved in mining, processing, and marketing metal products since 1928. Falconbridge produces electrolytic nickel, ferronickel, cobalt, copper, zinc, and precious metals. Its nickel mining operations are located near Sudbury, Ontario, Canada (table 3), and the Dominican Republic. Falconbridge maintains its own cargo ship, which transports Canadian nickel-copper matte to Falconbridge's Kristiansand refinery in Norway. Like Inco, Falconbridge is also confronted with air-quality legislation and additional costs to reduce air emissions. Falconbridge is actively exploring for additional resources in the Sudbury District to avoid potential depletion of reserves before the turn of the century. The company's Dominican Republic operations depend totally on imported oil as a source of energy. As a result, the operation's economics are very vulnerable to increases in energy costs. In addition, the operations have recently been affected by higher taxes based on nickel prices. Falconbridge sells approximately one-third of its nickel production to the United States, 45 percent to Europe, and the remainder to customers in Australia, Canada, India, Japan, Latin America, and the Far East.

SLN is a vertically integrated French company whose nickel laterite mining and smelting operations are located primarily on the west coast of New Caledonia at Nepoui Center. The company's Doniambo smelter, the world's largest ferronickel plant, had an original annual capacity of about 90 kmt of nickel, but after major cost-cutting measures, furnace closings, and renovation, the current design capacity is approximately 45 kmt. More than 80 percent of the facility's production is in ferronickel. The ferronickel, which assays approximately 25 percent nickel, is shipped to France, Japan, and the United States. The remaining nickel, contained in a high-grade matte, is shipped to the company's hydrometallurgical refinery at LeHavre, France, although some has been shipped to refineries in Japan. SLN also ships minor amounts of lateritic ore to Japan for production of ferronickel. Overall, SLN produces about 8 percent of the nickel production in the MECs and is the third largest nickel producer among companies in the MECs. The company's operations are vulnerable to high energy costs, sabotage by rebels, and the potential increase in value of the French franc relative to the U.S. dollar.

WMC averaged 6 percent of world nickel output from 1972 to 1975 and by 1987 increased its share to about 8 percent. It produces matte from several Australian sulfide deposits (table 4) and ships a portion of it for refining to Sherritt Gordon's Fort Saskatchewan refinery and to Japan. Most of WMC's mining operations are centered in the Kambalda District of Western Australia; its processing facilities are located in Kalgoorlie and Kwinana, also in Western Australia.

The United States has no nickel mining, primary smelting, or refining operations. Two nickel producers were active in the mid-1980s, but neither was a major, world-scale producer. The Hanna Mining Company was the only U.S. company to exploit a North American laterite deposit. The mine and ferronickel plant at Riddle, Oregon, was temporarily shut down in April 1982, reopened in 1983, and then closed in 1987. Some interest was expressed in reopening the facility in 1989. The mine accounted for only about 1.2 percent of production in the MECs in 1981 and met approximately 7 percent of U.S. demand. The only other nickel producer in the United States was AMAX, which refined nickel and its associated byproducts from imported nickel mattes, mostly from Australia and Botswana, at its Port Nickel Refinery in Louisiana. The operation closed in 1985 because of high production costs and low metal prices.

Table 4.—Status and mine type of WMC's nickel mines (as of 1987) in Western Australia

Mine status	Mine	Mine type
Active:	Carnilya Hill	Underground
	Foster	Do.
	Kambalda	Do.
	Lanfranchi	Do.
	Otter-Juan	Do.
	Windarra	Do.
	South Windarra	Open pit
Suspended:[1]	Fisher(1986)[2]	Underground
	Hunt (1986)	Do.
	McMahon (1986)	Do.
	Mt. Edwards (1986)	Do.
	Wannaway (1986)	Do.
	Western	Open pit
	Jan (1986)	Underground
In development	Long	Do.

[1]Suspended mines are those that have been closed two years or less and could possibly reopen without major capital expenditure or lengthy rehabilitation.

[2]Dates in parentheses refer to actual or estimated date of closure or suspension of mining or exploration.

The Canadian-based mining operations have numerous advantages over most of their competitors in the MECs. The companies have successfully undertaken aggressive cost-cutting programs over the last 5 or 6 years and have greatly increased productivity. In addition, they receive high byproduct credits and use relatively low cost mining methods, making Canadian nickel less expensive to produce than in some other countries, and the country is politically stable. Markets for Canadian nickel products are well developed, large resources are available near most processing facilities, and the country's infrastructure is well established.

COUNTRY AND REGIONAL NICKEL PRODUCTION

The structure of the world nickel industry has changed dramatically since 1950, as illustrated in table 5 and figure 2. The production share of nickel from the industrialized MECs of Australia, Canada, the Republic of South Africa (RSA), and the United States dropped from 77 percent in the early 1950s (5) to 36 percent in 1987 and 1988. The share from the developing countries (New Caledonia, countries in Central and South America, Indonesia, and others), however, increased from 4 percent to 22 percent in the same period.

Table 5.—Comparison of estimated world primary nickel production by country

Country	1950-51 Avg. annual production (kmt)	1950-51 Share (pct)	1987-88 Avg. annual production (kmt)	1987-88 Share (pct)
MECs:				
Australia	NA	0	69	8
Botswana	NA	0	19	2
Brazil	NA	0	14	2
Canada	119	75	209	25
Colombia	0	0	20	2
Dominican Republic	0	0	30	4
Finland	0	0	7	1
Greece	0	0	9	1
Indonesia	0	0	42	5
New Caledonia	6	4	59	7
Philippines	0	0	7	1
South Africa, Rep. of	1	1	25	3
United States	1	1	0	0
Yugoslavia	0	0	5	1
Zimbabwe	0	0	10	1
Total MEC	127	81	525	63
CPE countries:				
China	0	0	25	3
Cuba	0	0	37	4
U.S.S.R.	31	20	250	30
Other CPEs	NA	NA	6	1
Total CPE	31	20	318	38
Total World	158	[1]100	843	[1]100

NA Not available, but assumed to be negligible.

[1]Numbers may not total 100 because of independent rounding.

SOURCE: World Bank (5).

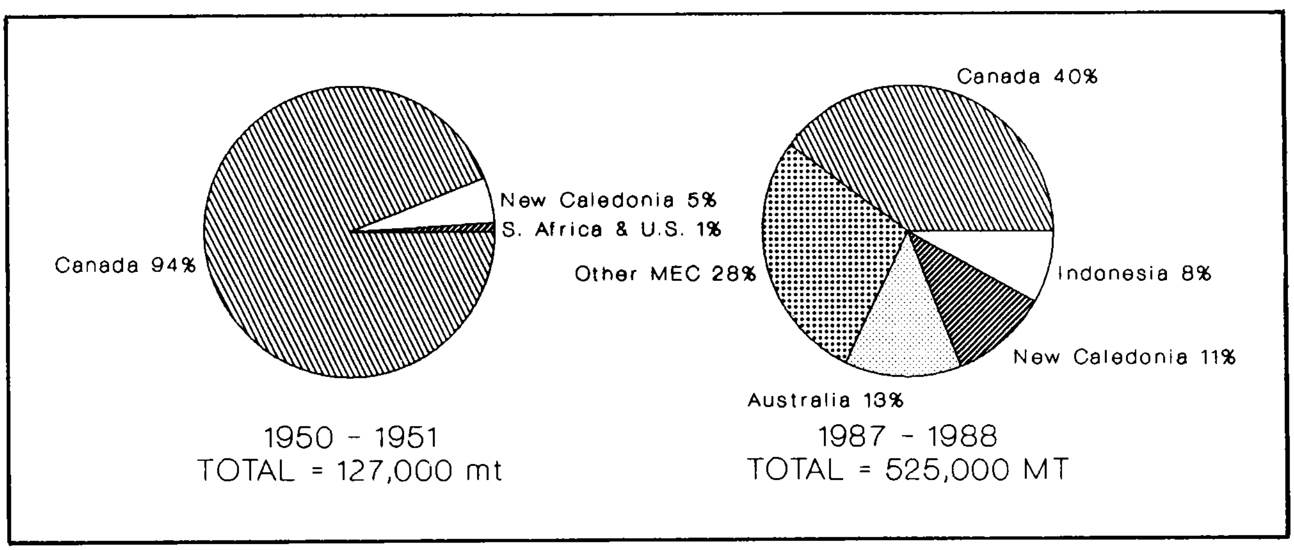

Figure 2.—Distribution of nickel production in the MECs.

Canada's share of production was affected dramatically between the 1950s and the 1980s. In the 1950s, Canada provided about 75 percent of the total world's mine output of nickel but in 1987 accounted for only about 25 percent. The decrease in Canada's share of the market occurred partly because of production from new operations in Greece and Australia but primarily because of the rise in production from developing countries, specifically New Caledonia, Indonesia, the Philippines, the Dominican Republic, and the CPE countries of Cuba and the People's Republic of China.

Production in the CPE countries as a percent of world nickel production rose from 20 percent in 1950-51 (*5*) to 38 percent in 1987-88.

New Caledonia accounted for about 5 percent of world production in 1950-51, increasing to about 15 percent in 1961 but dropping to a 7 percent share in 1987. Three other countries, Australia, Indonesia, and the Philippines, did not begin to produce nickel until the 1970s. In 1981, they collectively accounted for about 19 percent of world mine output and as of 1987 represented about 14 percent. Inco was a prime force in the development of laterites in Indonesia.

Virtually all of the world's primary nickel production originates from 18 countries, 15 of which are MECs. (A list of operations and deposits evaluated in this study is provided in the section titled "Nickel Resources and Geology.") In 1987, about 70 percent of the world's nickel was produced in MECs; the MECs with the largest production presently are Canada, Australia, and New Caledonia. Canada is a major supplier of nickel to both the United States and other MECs; however, as table 5 illustrates, growth of the nickel industry in the Pacific region, specifically New Caledonia and Indonesia, has dramatically affected Canada's market share and world trade patterns for the entire industry. In 1973, nearly 50 percent of primary nickel production in the MECs originated from Canada, about 23 percent from New Caledonia, and about 8 percent from Australia. The Dominican Republic, Greece, and Indonesia represented less than 6 percent each. In 1988, Canada's portion was projected to be reduced to less than 40 percent of total production in the MECs, New Caledonia's to about 11 percent. Australia's production share was expected to increase to about 13 percent, the Dominican Republic's and Indonesia's to increase slightly. Production in the MECs operated at near capacity through most of 1987 and was expected to continue through 1988. High demand caused sustained high market prices. Virtually all nickel producers operated at a profit in 1988. Estimated world primary nickel production for 1987 and 1988 is presented in table 6. Production estimates for 1987 and 1988 were derived from discussions with company personnel and industry specialists and from the author's judgment.

Table 6.—Estimated 1987 and projected 1988 primary nickel production (kmt)

Country	1987	1988
MECs:		
Canada	202	215
Australia	65	72
Caribbean and South America[1]	66	66
New Caledonia	57	62
Africa[2]	52	54
Indonesia	43	45
Greece	8	10
Finland	7	7
Philippines	6	8
Yugoslavia	4	6
Total MEC	510	545
CPE countries:		
Soviet Union	250	250
Cuba	35	40
China, P.R.	25	25
Other	6	6
Total CPE	316	321
Total World	826	866

[1]Includes Dominican Republic, Colombia, and Brazil.

[2]Includes Botswana, Republic of South Africa (byproduct nickel from PGM), and Zimbabwe.

Canada

Canada's 1987 primary nickel production of approximately 202 kmt originated from two Canadian companies, Inco and Falconbridge. Inco produced approximately 85 percent, or 172 kmt, of Canadian nickel from its Sudbury and Thompson operations in 1987, compared to 136 kmt in 1986. Five years of successful cost-cutting measures, the startup of the Thompson open pit in September 1986, high prices for byproducts, and relatively high prices for metal may have placed Inco in its best competitive position since the mid-1970s, and the potential exists for Inco to increase production and its market share. Inco also owns numerous inactive mines, such as Birchtree, which is being rejuvenated, and excellent prospects that can replace lost production from the Thompson open pit upon its exhaustion in the mid-1990s or sooner. These properties could also add to the company's production if necessary.

In 1987, Falconbridge produced about 32 kmt of nickel from Canadian ores, with plans to expand production by as much as 3 kmt in 1988. Falconbridge has also been very successful in cost-cutting measures but is confronted with high costs associated with exploration and development of additional reserves. (See table 3 for information on the status of Falconbridge and Inco nickel properties.)

By late 1988, development was expected to be completed on the Namew Lake prospect in Manitoba, owned in partnership by Hudson Bay Mining and Smelting and Outokumpu Oy. The capital cost of the property was

U.S. $60 million. The property is scheduled to begin full-scale operation in 1989 with an annual production capacity of about 9 kmt of nickel (*6*).

The Raglan prospect in northern Quebec is probably the largest undeveloped high-grade sulfide deposit in North America. The isolated location of the deposit, however, would require very high development costs. Total Canadian production in 1988 was likely to be higher than in 1987 by approximately 13 kmt.

Australia

Australian nickel production in 1987 was approximately 65 kmt and was expected to increase by about 10 percent in 1988. Production originates from WMC's operations (table 4) and Dallhold Investments's Greenvale nickel project. The Agnew operation has been on a care-and-maintenance basis since 1986; WMC, which has processing facilities nearby, bought it from British Petroleum (BP). The mine was never a low-cost mine to operate, however, and although the ore is high grade in places, the nature of mineralization may not lend itself to less costly bulk mining methods. WMC operated at or very near capacity in 1987, producing about 45 kmt of nickel. WMC has large resources and numerous mines, some of which have suspended operations. With continued high prices, some of them may be reactivated.

Greenvale's local resource is nearly exhausted. In 1987, the operation produced approximately 20 kmt of refined nickel and, assuming continued availability of ore, was expected to maintain the same level of production in 1988. The company has located additional domestic resources, but major capital expenditures for infrastructure would be required to make them accessible. In an effort to locate additional feed, the company has tested ore from New Caledonia with favorable results and from Indonesia and has contacted officials at Rio Tuba in the Philippines. Greenvale contracted to process ores from New Caledonia for 1988.

Caribbean and South America

The Caribbean and South American nickel producers include Falconbridge's operation in the Dominican Republic (32 kmt of nickel in ferronickel in 1987), Cerro Matoso, Colombia (20 kmt of nickel in ferronickel in 1987), and several properties in Brazil, totaling about 14 kmt/yr of nickel. Combined, these laterite properties produced approximately 66 kmt of nickel in 1987 and were expected to produce about the same amount in 1988. For several months in 1988, Falconbridge and the Government of the Dominican Republic disagreed about duty payments, resulting in delayed shipments.

Operators of the Cerro Matoso ferronickel operation solved several technological problems in 1987, although problems recurred with deterioration of the furnace linings. Production was expected to total approximately 20 kmt of nickel in 1988.

Several Brazilian nickel producers have announced intentions to expand, which could increase annual production capacity by 10 kmt in the next several years. Production in 1987 was 4.5 percent higher than in 1986. With continued development of infrastructure (including inexpensive hydroelectric power), expanding production of stainless steel, expansions of current producers, and the probable near-term development of the proposed BP Mineracao's Fortaleza (O'Toole) nickel sulfide deposit (10 kmt/yr), Brazilian production could increase to almost 35 kmt/yr by the early 1990s. Brazil will become a significant nickel producer and potentially an important exporter.

New Caledonia

New Caledonia possesses very large, high-grade resources. Development of hydroelectric power could provide the necessary incentive for development of additional vertically integrated facilities. New Caledonian nickel is produced by SLN, which processes laterite ores into ferronickel and minor amounts of matte, and by the Petit Mineurs (small independent miners), who ship most of their lateritic ore to Japan for processing into ferronickel. Nickel production in New Caledonia in 1986 totaled approximately 62 kmt of nickel contained in ore, matte, and ferronickel. Nickel production in 1987 was estimated at 57 kmt, 40 kmt for SLN and 17 kmt for the independent miners. SLN's original installed capacity was about 90 kmt of nickel in ferronickel and matte, but the current effective capacity is approximately 45 kmt (*5*). Any significant increase in production would require a large infusion of capital. SLN has experienced production problems in recent years, including high operating costs, technical problems, strikes, and sabotage by rebel separatists. A protectorate-wide referendum in September 1987 indicated that residents favored remaining a French overseas territory. The vote was originally seen as a possible end to interruptions caused by sabotage at the company's facilities, but in mid-1988 operations were again affected by rebel activity. The drop in New Caledonian production from 1986 into 1987 came as a result of reductions in Japanese ferronickel production from purchased ore and less production of ferronickel and matte by SLN.

Production in New Caledonia could have decreased in 1988 if exports of ore to the Japanese were affected by increasing costs for transportation and processing costs or problems continued as a result of political instability. An offsetting factor, however, could be shipments of ore to

Greenvale in Australia. Any major drop in production caused by either low prices or decreased Japanese demand will probably affect the independent miners more than SLN. In 1988, SLN's production was expected to return to its full capacity of 45 kmt of nickel (*7*), and total production in 1988 for New Caledonia was estimated to increase to about 62 kmt.

New Caledonia possesses very large, high-grade resources. Development of hydroelectric power could provide the necessary incentive for development of additional vertically integrated facilities.

Africa

In 1987, the southern African region (Botswana, RSA, and Zimbabwe) produced approximately 52 kmt of nickel. Botswana Concession Limited (BCL) of Botswana produced approximately 17 kmt of nickel, lower than its original goal, owing to a furnace breakdown during the early part of the year. BCL's production in 1988 was expected to be about 20 kmt.

The RSA's production originates as a byproduct of PGM production. The mining companies are expanding their production of PGM, a portion of which originates from the UG2 Reef, which contains lower-grade nickel than the Merensky Reef. Production in 1986 was estimated at approximately 23 kmt of nickel, and production in 1987 and 1988 was expected to show only slight increases, perhaps to 25 kmt. The relationship between expanding production from the UG2 Reef and the Merensky Reef and development of new mines complicates estimates of byproducts. The potential continues for interruptions in mining as a result of social instability leading to strikes. Several companies, however, are planning significant increases in production of PGM, perhaps by up to 50 percent by the early 1990s, thereby producing additional byproducts.

Zimbabwe produced less than 10 kmt of refined nickel in 1987, and only about 9 kmt of nickel was expected to be produced in 1988 because of decreasing ore grades and escalating costs. As it now stands, it is unlikely that production from currently active mines will continue much beyond 1990. Although exploration continues, no major development is currently under way. Nickel may eventually be produced as a byproduct if PGM are produced from the Great Dyke.

Indonesia

Total nickel production (as ferronickel and matte) in 1987 from Indonesian laterites was estimated at 43 kmt. Overall production in 1988 was expected to be about the same or slightly higher. Production of nickel in Indonesia originated from state-owned operations and from P.T. Inco, Inco's Indonesian operation. P.T. Aneka Tambang, the government-owned operation, produced about 14 kmt of nickel in ore and ferronickel in 1987. A major furnace failure in May 1987 interrupted its ferronickel production, and continued technical problems could have had major effects on its 1988 output.

Exports of laterite ore also could have decreased in 1988 as a result of reductions in demand by Japan. The Indonesian Government has expressed interest in at least two plans to expand production of value-added products (as opposed to shipping ore to Japan): the construction of additional ferronickel facilities, which could provide an additional 14 kmt of ferronickel, and the addition of a hydrometallurgical plant, increasing output by up to 5.5 kmt of nickel plus cobalt as a byproduct. By the early 1990s, total production from government-owned operations could total 30 kmt, especially if natural gas or hydroelectric power can be further developed and if the necessary capital becomes available.

P.T. Inco produced 28 kmt of recoverable nickel from matte in 1986 and increased production to about 29 kmt in 1987, which is near capacity. Production in 1988 was expected to approach 31 kmt as a result of continued technological improvements, although damage from a recent earthquake could possibly affect overall production for the year. The technical improvements resulted in lower costs. Because P.T. Inco exports all of its nickel matte to Japan for refining, however, high transportation costs and the strong yen have eroded a portion of the cost-cutting efforts. This situation may have influenced P.T. Inco's decision to develop a plant with a capacity of 12 kmt/yr of utility nickel (96 percent nickel) in Korea, with Korean Zinc Co. as a partner (*8*). P.T. Inco recently announced plans to expand capacity by 30 percent in partnership with Sumitomo of Japan at a cost exceeding U.S. $70 million. Construction is expected to be completed by 1991 (*9*).

Greece

Production of ferronickel in Greece has been decreasing since 1985 as a result of high energy costs, declining ore grades, high labor costs, and labor problems. In an effort to cut costs and increase efficiency, Larco (a government-owned corporation) has converted part of the ferronickel facility to experimental production of stainless steel and ferrochrome. The Greek Government is considering selling the operation to private owners or possibly shutting it down. Social pressures could prevent closure, and, with the economic state of the operations and conditions of sale, it is unlikely a private company would purchase it. Further, high market prices for nickel in late 1987 and 1988 may have deferred any decision to shut down. The Greek Government was making plans to hold an open auction by the end of 1988. Larco's debt, as of the first half of 1987, was about U.S. $220 million (*10-11*). Production in 1987 was estimated at 8 kmt of nickel in ferronickel, down from 1986's production of nearly 15 kmt. Depending on the outcome of these issues, the production of nickel in ferronickel was estimated to be 10-15 kmt in 1988.

Finland

Finnish production of nickel from domestically produced ores was less than 7.5 kmt in 1987. Outokumpu Oy closed the Kotalahti mine in the second quarter of 1987 (*12*), while production continued from its new nickel mine, Enonkoski, as well as from the Vammala Mine. The Hitura Mine produced small quantities intermittently. Rapidly decreasing reserves and underutilized smelter and refinery capacity have forced the company to expand explorations, both domestically and abroad. The company originally hoped that it would be able to supply its domestic smelting-refining industry with feed from its joint venture at Namew Lake, Canada, but recently negotiated to have its share of concentrates processed by Inco because of high transportation costs to Finland. Finland's decreasing domestic production may eventually result in only a custom (toll) industry based on smelting and refining. Finland's primary nickel production in 1988 was expected to be about the same as in 1987.

Philippines

Annual nickel production in the Philippines dropped dramatically as a result of the shutdown of the Nonoc operation in 1986. In 1985, the Philippines produced approximately 27 kmt of nickel, but in 1986 production dropped to 1.7 kmt at Nonoc and to 7 kmt at Rio Tuba. Total Philippine nickel production in 1987 was expected to total approximately 6 kmt, virtually all of it from Rio Tuba. Rio Tuba's lateritic ore is shipped to Japan for conversion to ferronickel, and production in 1988 would depend on demand by the Japanese. An expansion to 8 kmt is possible if Japanese production of ferronickel increases. While it is unlikely that a ferronickel plant will be constructed in the Philippines in the near future, it is probable that new high-grade laterite ore mines will be developed in order to export ore to Japan. The unstable political environment in the Philippines reduces the chances of significant expansion or new development in the very near future. Several companies and the Soviet Union have evaluated the potential for reactivating Nonoc. It is unlikely, however, that production will occur during the 1980s because of the very high costs of rehabilitation and the political climate. The Philippine Government placed Nonoc on its list of state-owned companies that it hoped to sell to a private company by the end of 1988.

Yugoslavia

Yugoslav production in 1987 was estimated at 4 kmt of nickel in ferronickel, significantly below 1985's reported capacity of about 12 kmt and below 1986's production of about 5.5 kmt. The major reason for the drop in production since 1985 was the closure of the Kavadarci smelter in 1985; another reason for the low estimated production in 1987 was the suspension of operations at the Kosova plant in July. The exact reason for the shutdown was not available, although a furnace failure is a likely possibility. With successful reactivation of the operation in 1988, a return to about 6 kmt was likely.

U.S.S.R. and Cuba

The U.S.S.R. and Cuba currently are the world's first and sixth largest nickel producers, respectively. In 1950, the U.S.S.R. produced approximately 31 kmt of nickel, while Cuba produced none. Combined, they currently produce about 385 kmt of nickel, almost 30 percent of the world's total primary nickel.

The Soviet nickel industry started a program of modernization in 1983 with the installation of Outokumpu-type flash furnaces at Norilsk. Outokumpu Oy recently won a contract to supply equipment to the Pechenga concentrator on the Kola Peninsula to modernize grinding, flotation, and chemical preparation plants through 1989 (*13*), but how it will increase capacity in the short term is not known. Information relating to Soviet nickel production is difficult to acquire. Estimates range from 300 kmt to 350 kmt of nickel annually. Some of the Soviet Union's nickel production is actually a product of PGM production. It is possible that PGM production will increase, with a commensurate increase in production of nickel.

In 1986, from 36 kmt to 42 kmt of Soviet nickel was exported to the MECs. That year, the Soviet Union entered into a marketing agreement with Philipp Brothers, whereby the trading company committed to marketing between 20 kmt and 40 kmt of electrolytic nickel in Europe and elsewhere (*14*). The Soviets might have increased exports in 1988 because of higher metal prices and loss of revenue from petroleum sales (the Soviet Union's major source of currency exchange). Decreased demand for nickel from the military as a result of demilitarization could result in an increase in exports or increased use in the industrial sectors such as transportation, food processing and/or consumer products. In addition, exports to the West could increase as technical problems at Cuban facilities are solved, thereby creating less demand on Soviet nickel operations to meet domestic requirements.

Cuba is one of the few countries where a major expansion in production is expected. The country produced about 35 kmt of nickel (about 70 percent of currently installed capacity) in 1987 and might have improved to over 45 kmt in 1988 as technological problems plaguing Punta Gorda were slowly resolved. Labor and technical problems have occurred at Punta Gorda, and the startup date of Las Camariocas (30 kmt/yr) has been delayed until about 1995 (*14*). The country has targeted a capacity of 100 kmt by 1995 when projects financed by the U.S.S.R., Hungary, East Germany, and other Eastern Bloc nations are scheduled to be in production (*15*).

About 10 kmt of Cuban nickel was traded directly to the West in 1986.

People's Republic of China

Except for importing and exporting small amounts, China was historically self-sufficient in nickel, but in the last several years, it has become a net exporter. Nickel production in 1988 was expected to be approximately 25 kmt, about the same level as 1987. By 1990, China could consume as much as 70 kmt/yr; by 2000, it could consume approximately 120 kmt/yr (*16*). To guarantee self-sufficiency, the Chinese are instituting high-capacity, advanced mining techniques at their Jin Chuan operations and are planning a major expansion of processing facilities. They are undertaking these projects with the assistance of Soviet and Western experts, including Atlas Copco, Boliden, Inco, and, most recently, WMC. WMC will assist in the operation of a licensed Outokumpu nickel flash-smelting facility. When implemented, about 1990, the vertically integrated operation will have the capacity to increase production to about 40 kmt/yr of nickel (from the 1987 level of 25 kmt/yr) and 80 kmt/yr by 1995. Potential nickel production of the Jin Chuan district is such that the People's Republic of China could eventually become one of the world's largest nickel producers.

PATTERNS IN SMELTING, REFINING, AND TRADE

Despite the dramatic increase in nickel production from developing countries, industrialized countries still dominate the critically important smelting and refining industry (see table 7). Recently announced expansions and development of processing facilities in Brazil, Indonesia, and the Republic of South Korea illustrate the shifting of a portion of the industry from the highly industrialized nations to several developing countries.

Canada has the largest nickel smelting and refining capacity of the MECs. In 1987, it produced over 200 kmt of nickel from domestic sources. Canada's smelter capacity is limited to approximately 210 kmt of nickel because of clean air standards. Without this constraint, capacity probably exceeds 250 kmt. Canada has four refineries with a combined capacity of nearly 180 kmt. Inco shipped about 25 kmt of nickel in matte to its Clydach, Wales, plant to be refined, and Falconbridge shipped 33 kmt of nickel in matte to its refinery in Kristiansand, Norway. The Norwegian refinery also receives matte from BCL's operation in Botswana (15 kmt of nickel) and processes some scrap and Soviet matte. In 1985, the refinery had an annual capacity of approximately 45 kmt of nickel, 32 kmt of copper, 2 kmt of cobalt, plus gold, silver, and PGM. Over the last 3 years, a U.S. $43 million expansion program was implemented, increasing the annual capacity to about 55 kmt of nickel. Most of the production is sold to Western Europe and the United States. The Sherritt-Gordon hydrometallurgical plant in Alberta receives concentrates from Inco's Canadian operations as well as some Australian feed from WMC. The facility processed about 800 mt of nickel from Australia's Agnew operation until the mine shut down. Sherritt-Gordon's contract to process Thompson's concentrates (15 kmt annually) expires in 1990. The facility is to process 60 percent of the concentrate from the Namew Lake, Manitoba, mine when it is put into production (*6*). The remaining concentrate will go to Inco. The Sherritt-Gordon facility has an annual capacity of about 25 kmt of nickel, 1 kmt of cobalt, and some copper (which is refined elsewhere).

Although Japan does not have any domestic nickel mines, it is the second leading producer of smelted and refined nickel products among MECs. Japan's ferronickel capacity in 1986 was approximately 74 kmt (from four ferronickel facilities), but by 1987 the permanent closure of Nippon Mining's Saganoseki ferronickel plant reduced the company's capacity by approximately 10 kmt. In 1988, Japan was expected to produce approximately 55 kmt of nickel in ferronickel, or about 65 percent of total available capacity. Laterite ores for Japan's ferronickel industry originate from Indonesia (40 percent), New Caledonia (40 percent), and the Philippines (20 percent). In 1987, Japan produced about 43 kmt of nickel in nickel oxide (97 percent nickel) and electrolytic nickel. The refineries receive their matte primarily from P.T. Inco's operation in Indonesia (65 percent) and WMC (35 percent) in Australia. Plant capacity is estimated to be 48 kmt of contained nickel per year.

Japan's nickel processing industry has been producing well below capacity for several years as a result of the strength of the yen relative to other currencies and high transportation and energy costs. Part of these higher costs can be absorbed in value-added products.

Table 7.—Major processing operations and available annual capacities for contained nickel in MECs and CPE countries

Country	Company	Location	Primary product[1]	Operation	Annual capacity[2] (kmt)	Byrpoduct/ coproduct[3]
MARKET ECONOMY COUNTRIES:						
Australia	Dallhold and others	Yabulu	Ni	Refinery	22	Co, Ni
	WMC	Kalgoorlie	Matte	Smelter	50	Cu, PM[4]
		Kwinana	Ni	Refinery	30	Do.
Botswana	BCL	Selebi	Matte	Smelter	20	Cu, Co
Brazil	Codemin	Goias	FeNi	do.	5	Do.
	Morro do Niquel	Petropolis	FeNi	do.	3	Do.
	Tocantinas	Sao Paulo	Ni	Refinery	5	Co, MgO
		Tocantins	Ni	do.	6	Co
Canada	Inco	Copper Cliff	Matte	Smelter	[5]120 (155)	Co, Cu, PM
		do.	Nickel	Refinery	57	Do.
		Port Colborne	Nickel	do.	30+	Do.
		Thompson	Matte	Smelter	50	Do.
		do.	Ni	Refinery	50	Do.
	Sherritt-Gordon	Fort Saskatchewan	Ni	do.	25	Do.
	Falconbridge	Falconbridge	Matte	Smelter	45	Do.
Colombia	Cerro Matoso	Monteliban	FeNi	do.	23	
Dominican Republic	Falconbridge	Bonao	FeNi	do.	32	Energy[6]
Finland	Outokumpu Oy	Harjavalta	Matte	do.	18	Cu, Co
		do.	Ni	Refinery	15	Do.
France	SLN	LeHavre	Ni	do.	10	Co
Greece	Larco	Larymna	FeNi	Smelter	14	
Indonesia	P.T. Inco	Soroako	Matte	do.	[7]34	
	P.T. A. Tambang	Pomalaa	FeNi	do.	4	
Japan	Nippon Yakin	Oeyama	FeNi	do.	13	
	Pacific Mtls.	Hachinonhe	FeNi	do.	31	
	Sumitomo	Hyuga	FeNi	do.	20	
		Niihama	Ni	Refinery	24	
	Tokyo	Matsuzaka	Ni	do.	24	Co
Korea, Rep. of	Korea Zinc[8]	Onsan	Ni	do.	12	
New Caledonia	SLN	Doniambo	FeNi	Smelter	40	
		do.	Matte	do.	10	Co
Norway	Falconbridge	Kristiansand	Ni	Refinery	55	Cu, Co, PM
Philippines	Nonoc[9]	Nonoc Island	Ni	do.	28	Co
South Africa	Impala		Ni[10]	Smelter & refinery	10	
	Matthey	Rustenburg	Ni	do.	19	
Taiwan	Taiwan-Inco	Ta Nun	Ni	do.	NA	
United Kingdom	Inco	Clydach	Ni	do.	[11]25	Cu, Co, PM
Yugoslavia	Kosova	Kosova	FeNi	Smelter	12	
CENTRALLY PLANNED ECONOMY COUNTRIES:						
Cuba	CPE Partnership	Las Camarioca[12]	Ni	Refinery	[13]30	
	Cubaniquel	Moa Bay	Ni[14]	do.	20	Co
		Nicaro	Ni	do.	20	
		Punta Gorda	Ni	do.	[15]30	
U.S.S.R.	State Owned	Various	Ni	do.	[16]300	Cu, Co, PM

NA Not available.
[1]Ni = Refined nickel, nickel oxide, etc. FeNi = Ferronickel. Matte = an intermediate smelter product.
[2]Contained nickel.
[3]May not be recovered at the same facility.
[4]PM = Precious metals.
[5]Capacity is based on constraints of air quality standards. Number in parentheses represents estimated capacity without constraints.
[6]Excess electricity is reportedly sold to the national grid.
[7]A 30-pct expansion is planned to be operational by 1990.
[8]Scheduled to be operational by end of 1988.
[9]Closed, no immediate plans for reactivation.
[10]Nickel is a byproduct of platinum group metal mining.
[11]Capacity may be as high as 45 kmt.
[12]In development. Production planned for 1995.
[13]Proposed annual capacity.
[14]Nickel in sulfide.
[15]Only 3.6 kmt produced in 1987. Capacity may be reached by 1992.
[16]Estimated capacity for total refined nickel and nickel in ferronickel.

SLN operates the world's largest ferronickel facility, the Doniambo plant in New Caledonia. The plant has an annual capacity of about 50 kmt of nickel contained in ferronickel and nickel matte. Production has occasionally been interrupted by strikes and sabotage. Barring any major interruptions, close to 100 percent of capacity was expected to be used in 1988. The majority of the ferronickel production is sent to Japan, although minor amounts are sold to France, Taiwan, India, West Germany, and the United States. Through April 1988, the United States imported about 3 kmt of nickel from New Caledonia. The matte is sent primarily to LeHavre, France, where it is refined.

In 1987, Australia produced approximately 25 kmt of nickel (from matte) and concentrates at WMC's Kwinana ammonia leach refinery (Sherritt-Gordon process), and 20 kmt of nickel from laterite ore from Greenvale's Yabulu plant. The majority of Australia's nickel sulfide concentrates is smelted at WMC's flash smelter at Kalgoorlie, which has a capacity of about 65 kmt of matte containing approximately 50 kmt of nickel. A relatively small portion of WMC's matte production and some excess concentrates are shipped for refining by Sherritt-Gordon in Alberta, Canada, Sumitomo, Japan, and Outokumpu, Finland. WMC's refinery at Kwinana has a design capacity of 30 kmt of nickel per year but is operating at about 25 kmt.

Greenvale's laterite operation consists of a mine and hydrometallurgical plant (Yabulu). The refinery has an annual capacity of about 22 kmt of nickel metal in oxide and about 1.1 kmt of cobalt in sulfide concentrate. The mixed sulfide concentrates, which contain cobalt and some nickel, are exported to Finland, where they are refined into salts, powder, and metals.

Laterite operations in Indonesia produce ore, matte, and ferronickel. Inco's operation is by far the largest. The facility produces a 70 percent nickel matte, which is shipped to Japan for processing. Some nickel matte may also be shipped to Clydach, Wales, for refining. In 1988, P.T. Inco was to ship approximately 44 kmt of matte, from which about 31 kmt of nickel was to be recovered. An Inco partnership is constructing a U.S. $4 million utility nickel facility in the Republic of Korea to treat Canadian matte (*8*). The plant was scheduled to be on line by the end of 1988 with an annual capacity of 12 kmt. Aneka Tambang, a government-owned operation, produces between 4 kmt and 5 kmt of nickel, in ferronickel, which is sold to Japan.

Significant amounts of ferronickel are produced in Brazil, Colombia, and the Dominican Republic. Falconbridge's Dominican Republic operation is currently producing at a full capacity of 32 kmt of nickel, contained in about 80 kmt of ferronickel. The plant was completed in 1971 at a cost of approximately U.S. $180 million. The facility has potential for expansion. The high dependency on oil as a source of energy and recent political problems with the Government present a risk to a large investment. The plant's product is marketed worldwide.

Cerro Matoso's plant in Colombia is producing at a rated capacity of 23 kmt of nickel in ferronickel. Preliminary discussions have been held regarding a possible 30 percent expansion. The product grade is about 35 percent nickel.

Brazil has two ferronickel plants with a combined annual capacity of 8 kmt. Tentative plans, however, are to expand capacity by about 50 percent in the next few years. In 1987, approximately 90 percent of capacity was used. Brazil has one hydrometallurgical refinery in Sao Paulo, which processes laterite into nickel carbonate, which is further refined at an electrowinning plant. Current annual capacity is approximately 5 kmt, with plans to double capacity by 1990. Production in 1987 was approximately 4 kmt. The other two producers are Codemin and Morro do Niquel, which produce ferronickel. Nearly all of Brazil's nickel production is consumed in the domestic steel industry and is therefore not exported. Brazilian producers are required by law to sell nickel at a price below 1988 market levels, making them less profitable than if they sold their nickel on the open market.

Although the United States is the world's largest consumer of nickel, it has no mining, primary smelting, or refining operations. The only recent production was from the Nickel Mountain, Oregon, laterite mine and ferronickel plant operated by the Hanna Mining Co. and AMAX's Port Nickel facility in Louisiana. The annual design capacity of the Oregon plant was approximately 14 kmt of contained nickel. Low metal prices, depletion of resources, high costs (labor and energy), and a shrinking domestic steel market contributed to the plant's closure in 1986. The facility will reopen at the end of 1989 because of high market price.

The Port Nickel refinery at Port Nickel, Louisiana, closed in 1985 as a result of high costs. It processed matte from Botswana, Australia, and other countries. The refinery had an annual capacity of about 40 kmt of nickel as nickel briquettes and powders, 20 kmt of copper, and 600 mt of cobalt. Although most of the production was exported (33 kmt in 1986), some was for domestic consumption.

CHANGES IN THE PROCESSING INDUSTRY

The geographic distribution of nickel processing in the MECs has changed dramatically over the last 25 years (tables 8-10). In 1965, production was approximately 320 kmt, of which about 13 percent was ferronickel, all of which was produced from laterite deposits and the remainder of which was refined nickel, produced primarily from sulfide ores. Over 60 percent of production in the

MECs originated from Canadian ores. By 1975, production of ferronickel had more than quadrupled. Increased production of ferronickel in Japan and in the Dominican Republic resulted in response to increased demand for nickel for stainless steels. Ferronickel's use in making steel is seen by some as acquiring free iron because the ferronickel price is based, for the most part, on the contained nickel value. New Caledonia's production increased to a record high in 1975 because of the modernization and expansion of the facility's furnaces.

In 1975, production of refined nickel totaled approximately 342 kmt, with the largest increase resulting from the development of the Australian nickel industry. WMC's Kwinana Refinery opened in 1970, the Kalgoorlie smelter in 1972. The laterite operation at Greenvale started operation in 1974 and became fully operational in 1976. Approximately two-thirds of Australia's production in 1975 was from WMC's Kambalda operations. The Republic of South Africa's nickel production has increased considerably since the 1960s as a byproduct of the country's expanding PGM industry.

Table 8.—Estimated ferronickel production (contained nickel)

Country	1965		1975		1988	
	Production (kmt)	Share (pct)	Production (kmt)	Share (pct)	Production (kmt)	Share (pct)
Brazil	1	2	2	1	9	5
Colombia	0	0	0	0	20	12
Dom. Republic	0	0	27	15	32	19
Greece	0	0	15	8	10	6
Indonesia	0	0	0	0	4	2
Japan	12	29	65	35	55	32
New Caledonia	16	38	54	29	31	18
Philippines	0	0	9	5	5	3
United States	13	31	13	7	0	0
Yugoslavia	0	0	0	0	6	3
Total	42	100	185	100	172	100

SOURCES: Manshreck-Head (*3*), World Bank (*5*), and Mohide, Warden, and Mason (*17*).

Table 9.—Estimated refined nickel production (contained nickel)

Country	1965		1975		1988	
	Production (kmt)	Share (pct)[1]	Production (kmt)	Share (pct)	Production (kmt)	Share (pct)
Australia	0	0	33	10	45	11
Brazil	0	0	0	0	5	1
Canada	160	58	158	46	159	40
Finland	3	1	7	2	16	4
France	8	3	11	3	7	2
Japan	15	5	13	4	46	12
Korea, Rep. of[2]	0	0	0	0	1	1
Norway	32	12	38	11	55	14
Philippines	0	0	9	3	0	0
RSA	3	1	14	4	25	6
United Kingdom	41	15	39	11	25	6
United States	13	5	7	2	0	0
Zimbabwe	3	1	13	4	10	3
Total	278	100	342	100	394	100

[1]Percentages may not total 100 as a result of independent rounding.

[2]Plant expected to be in production at end of 1988. Production is for one month. Planned capacity is 12 kmt of nickel in utility-grade nickel oxide.

SOURCES: Manshreck-Head (*3*), World Bank (*5*), Mohide, Warden, and Mason (*17*).

Table 10.—Estimated ferronickel and refined nickel production (contained nickel)

Country	1965 Production (kmt)	1965 Share (pct)[1]	1975 Production (kmt)	1975 Share (pct)	1988 Production (kmt)	1988 Share (pct)
Australia	0	0	33	6	45	8
Brazil	1	0	2	1	14	2
Canada	160	50	158	30	159	28
Colombia	0	0	0	0	20	4
Dominican Rep.	0	0	27	5	32	6
Finland	3	1	7	2	16	3
France	8	3	11	2	7	1
Greece	0	0	15	3	10	2
Indonesia	0	0	0	0	4	1
Japan	27	8	78	15	101	18
Korea, Rep. of[2]	0	0	0	0	1	1
New Caledonia	16	5	54	10	31	5
Norway	32	10	38	7	55	10
Philippines	0	0	18	3	5	1
RSA	3	1	14	3	25	4
United Kingdom	41	13	39	7	25	4
United States	26	8	20	4	0	0
Yugoslavia	0	0	0	0	6	1
Zimbabwe	3	1	13	2	10	2
Total	320	100	527	100	566	100

[1]Percentages may not total 100 as a result of independent rounding.

[2]Plant expected to be in production at end of 1988. Production is for one month. Planned capacity is 12 kmt of nickel in utility-grade nickel oxide.

SOURCES: Manshreck-Head (3), World Bank (5), Mohide, Warden, and Mason (17).

By 1988, the nickel market in the MECs had progressed from the boom of the 1970s and passed through the recessionary period, low metal prices, low demand, and increasing inventories of the early 1980s. While new participants had entered the processing industry, others closed or redesigned their operations in response to increasing costs of energy and labor. As a result of economic growth, total refined nickel and ferronickel production reached all-time highs in 1987 and 1988.

Since 1985, production of ferronickel has decreased as a result of the permanent closure of Hanna's ferronickel facility in Oregon, a redesign and consequent decrease in capacity in New Caledonia, and a lowering of Japanese production because of high costs associated in part with the strength of the yen. Since 1983, Brazil's ferronickel industry expanded and Yugoslavia's ferronickel industry initiated production.

Production of refined nickel for 1988 was estimated at 394 kmt. Most of the increase came as a result of expansion of the Australian, Japanese, Norwegian, and South African industries. Japan's continued expansion of domestic industries requiring stainless steel and other nickel-bearing alloys encouraged construction of smelters and refineries in the late 1970s. South African nickel production also increased as a result of high demand for PGM.

In summary, over the last 20 years, production of ferronickel has increased almost fourfold as the product has become an acceptable addition for the production of stainless steels. During the same period, production of refined metals increased about 40 percent.

Production of nickel and ferronickel in the developing countries of Brazil, Colombia, the Dominican Republic, Indonesia, New Caledonia, the Philippines, Republic of Korea, and Zimbabwe increased dramatically—from 20 kmt, or about 6 percent of production in the MECs, to approximately 117 kmt (which does not include P.T. Inco's 30 kmt of nickel in matte or Nonoc, which could reopen), now about 21 percent of production in the MECs. At the same time, Falconbridge's and Inco's market share of processed nickel from Canadian operations (including the Canadian portion of Norwegian production) decreased from about 60 percent of production in the MECs in 1965 to about 36 percent in 1988. This trend may continue into the 1990s as air-quality legislation limits Canadian production, while P.T. Inco expands production of matte by 30 percent in Indonesia (for processing in Japan and supplying a 12 kmt/yr utility nickel plant recently constructed in the Republic of Korea). As developing countries possessing nickel resources and/or stainless steel fabricating facilities become increasingly industrialized, countries like Brazil and the Republic of Korea will likely develop additional capacity to produce value-added products. These shifts could threaten the U.S. steel manufacturers' share of the market.

Construction of new plants or expansion of existing plants is difficult to predict at this time. To commit funds for projects requires consideration of the demand for nickel, inventory levels, price fluctuations, the quality of resources, the effects of energy prices, byproduct credits, and labor costs. These factors are discussed in later sections of this report.

The development of sufficient hydropower may also be a critical factor in some regions. The People's Republic of China's nickel industry is expanding rapidly, and Cuba's production, although hampered by technical problems, will eventually be very large. Recent estimates of the capacity of Soviet nickel refineries have been as high as 350 kmt, significantly higher than previous estimates. Depending upon how much nickel is used in consumer products (transportation, food processing, etc.), an increase in nickel exports to the MECs may result, owing to the de-emphasis on military spending, decreased oil revenues, relatively flat gold prices, and very high nickel prices. These countries could have a large effect on production in the MECs through displacement of market shares.

EVALUATION METHOD

Figure 3 is a flowchart of the Bureau's Minerals Availability Program (MAP) evaluation process from the identification of deposits to the development of availability curves. Properties were selected for this study with the aim of including at least 95 percent of current production from key nickel-producing areas in the MECs. Significant developing and explored deposits and past producers were also included. The CPE countries were not included in the availability study owing to the difficulty of acquiring data.

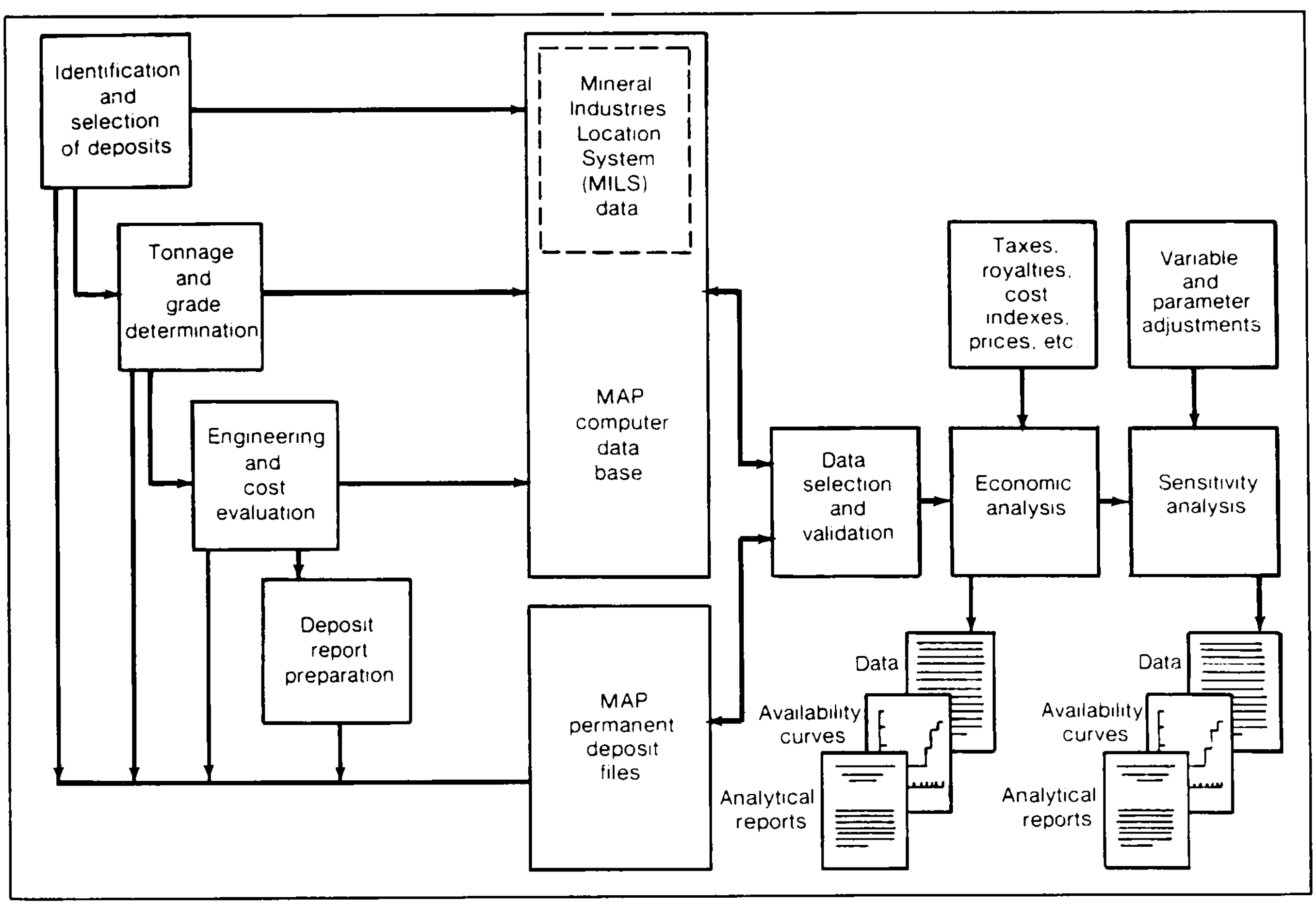

Figure 3.—Flowchart of MAP evaluation procedures.

Each deposit selected for analysis was evaluated to estimate the costs to recover nickel. For producing properties, the designed mining and milling capacities were used. For deposits not in production, appropriate parameters for mining, concentrating, smelting, refining, transportation, and other aspects of production were assigned based on applicable engineering principles, feasibility studies, and discussions with industry personnel to estimate costs.

Capital expenditures were determined for exploration, acquisition, development, mine and mill plant and equipment, and a smelter and/or refiner if required. All capital costs include mobile and stationary construction and engineering equipment, support facilities and utilities, and working capital. Facilities and utilities (infrastructure) include access, water facilities, power supply, port facilities, and accommodations for personnel. Working capital is a revolving cash fund required for operating expenses, such as labor, supplies, taxes, and insurance. Operating costs for 30, 60, or 90 days were most commonly used as an estimate for working capital in the evaluations.

Based on the MAP methodology, all capital investments incurred 15 years or more before the initial year of the analysis (January 1987) were treated as sunk costs. Capital investments incurred fewer than 15 years before January 1987 had the undepreciated balances carried forward to January 1987, with all subsequent investments reported in constant January 1987 dollars. This method generally contributes to a lower total cost for currently producing operations. All reinvestment, operating, and transportation costs were converted to January 1987 dollars. No escalation of either costs or byproduct prices was included, because, it was assumed any increase in costs would be offset by an equivalent increase in product prices.

Mine and mill operating costs were calculated for each deposit, with the total operating cost the sum of direct and indirect costs. Direct production costs include materials, utilities, direct and maintenance labor, and most of payroll overhead. Indirect operating costs include research, technical and clerical wages, administrative costs, facilities and maintenance supplies, marketing costs, and research. Costs for transportation and any processing after mill operations were included separately. These costs resulted in the determination of total operating costs, which, after byproduct credits, is defined as the net production cost.

Other costs not included in the net production costs but used in the analysis include taxes and royalties, insurance, depreciation, deferred expenses, and return on investment.

After capital and operating costs were determined, the data were entered into the MAP Supply Analysis Model (SAM) (*18*). The U.S. Bureau of Mines developed SAM to perform economic analyses; it presents the results as the primary commodity price (total production cost) needed to provide a stipulated rate of return. The rate of return used in this study is the discounted cash flow rate of return, most commonly defined as the rate of return that makes the present worth of cash flows from an investment equal to the present worth of all after-tax investments. For this study, 0- and 10-pct DCFROR analyses were performed. A 0-pct DCFROR analysis was used to evaluate the break-even point, where revenues are sufficient to recover total investment and production costs over the operation's life but provide no rate of return. This rate would satisfy a company interested in developing a market share.

A 10-pct DCFROR was considered an acceptably attractive rate of return to cover the opportunity cost of capital plus risk. For some government-owned operations, a 0- or 10-pct DCFROR may not be required for continued production, but for purposes of comparison, each deposit was analyzed at these rates of return.

A separate file of tax records, maintained for each state, province, and country, contains relevant fiscal parameters under which mining firms operate. This file includes corporate income taxes, property taxes, and any royalties, severance taxes, or other taxes pertaining to the production of nickel. These tax parameters were applied to each mineral deposit under evaluation, with the implicit assumption that each deposit represents a separate corporate entity.

The SAM system contains all the deposits studied. The results of these analyses are presented as availability tables and curves, discussed in a later section of this report.

NICKEL RESOURCES AND GEOLOGY

Thirty-six deposits and/or districts in 16 MECs were selected for inclusion in this study. Table 11 lists the ore type, status, mining method, product type, and owner for each deposit for which complete evaluation was made, and figure 4 illustrates the general location of the deposits. Selection was limited to deposits having a minimum demonstrated nickel resource of 40 kmt of recoverable nickel that could be mined and processed using currently practiced technology.

Table 11.—Analysis of nickel deposits evaluated

Country: Deposit name	Ore type	Status as of January 1988	Mining method	Product[1]	Owner	Map location number
Australia:						
Agnew	Sulfide	Suspended	Underground	Class I	Agnew Mining Corp.	1
Greenvale	Laterite	Producer	Surface	do.	Dallhold Metals Expl., Std. Charter Bank	2
Western Mining[2]	Sulfide	do.	Underground	do.	Western Mining Corp.	3
Botswana:						
Selebi-Phikwe	Sulfide	do.	do.	Class II	BCL	4
Brazil:						
Fortaleza (O'Toole)	Sulfide	Nonproducer	Underground	Class I	British Petroleum	5
Morro do Niquel	Laterite	Producer	Surface	Class II	Mineracao Sartenejo S.A.	6
Tocantin	do.	do.	do.	Class I	Companhia Niguel de Tocantins (CNT).	7
Codemin	do.	do.	do.	Class II	Codemin	8
Canada:						
Expo Ungava	Sulfide	Nonproducer	Surface	Class I	Falconbridge	9
Inco - Sudbury[3]	do.	Producer	Underground	do.	Inco	10
Inco - Thompson[4]	do.	do.	Combined	do.	do.	11
Falconbridge[5]	do.	do.	Underground	do.	Falconbridge	10
Namew Lake	do.	Developing	do.	do.	Hudson Bay & Outokumpu Oy	12
Raglan	do.	Nonproducer	do.	do.	Expo Ungava Mines Ltd.	9
Colombia:						
Cerro Matoso	Laterite	Producer	Surface	Class II	Econiquel/Billiton/Hanna	13
Ure district	do.	Nonproducer	do.	Class II	Colombian Government	13
Dominican Republic:						
Falcondo Bonao	do.	Producer	do.	do.	Falconbridge	14
Finland:						
Outokumpu Group	Sulfide	do.	Underground	Class I	Outokumpu Oy	15
Greece:						
Larco	Laterite	Producer	Combined	Class II	Larco (Greek Government)	16
Indonesia:						
Aneka Tambang	do.	do.	Surface	Class II	Indonesian Government	17
Gag Island	do.	Nonproducer	do.	Class I	P.T. Pacific Nickel	18
Soroako	do.	Producer	do.	Class I	P.T. Inco	19
Ivory Coast:						
Biankouma region	do.	Nonproducer	do.	Class II	Indonesian Government	20
Madagascar:						
Ambatory/Analamy	do.	do.	do.	do.	Malagasy Government	21
Valozoro	do.	do.	do.	do.	do.	21
New Caledonia:						
SLN	do.	Producer	do.	Class I, II	Eramet-SLN	22
Petit Mineurs	do.	do.	do.	Class II	Petit Mineurs	22
Philippines:						
Nonoc Mine	do.	Nonproducer	do.	Class I	Nonoc Dev (Philippine Government)	23
Rio Tuba	do.	Producer	do.	Class II	Rio Tuba Mining Co.	24
Undeveloped	do.	Nonproducer	do.	Class II[6]	Various owners	24
United States:						
Duluth Gabbro	Sulfide	do.	Combined	Class I	State of Minnesota, et. al.	25
Gasquet	Laterite	do.	Surface	do.	Cal Nickel Corp., Cook Int'l.	26
Guanijibo	do.	do.	do.	do.	Government of Puerto Rico	27
Red Flat	do.	do.	do.	do.	Hanna Mining Corp.	28
Yugoslavia:						
Kosova	do.	Producer	do.	Class II	State-owned corporation	29
Zimbabwe:						
Bindura Group	Sulfide	do.	Underground	do.	Bindura Nickel Corp.	30

[1]Class I products include cathode nickel, nickel pellets, etc. Class II products include nickel matte and ferronickel. Products are either actual or in the case of nonproducers, anticipated.

[2]Combined WMC operations.

[3]Combined operations for Inco's Sudbury, Ontario, operations.

[4]Combined operations for Inco's Thompson, Manitoba, operations.

[5]Combined operations for Falconbridge's Sudbury, Ontario, operations.

[6]A portion of this resource is amenable to leach methods.

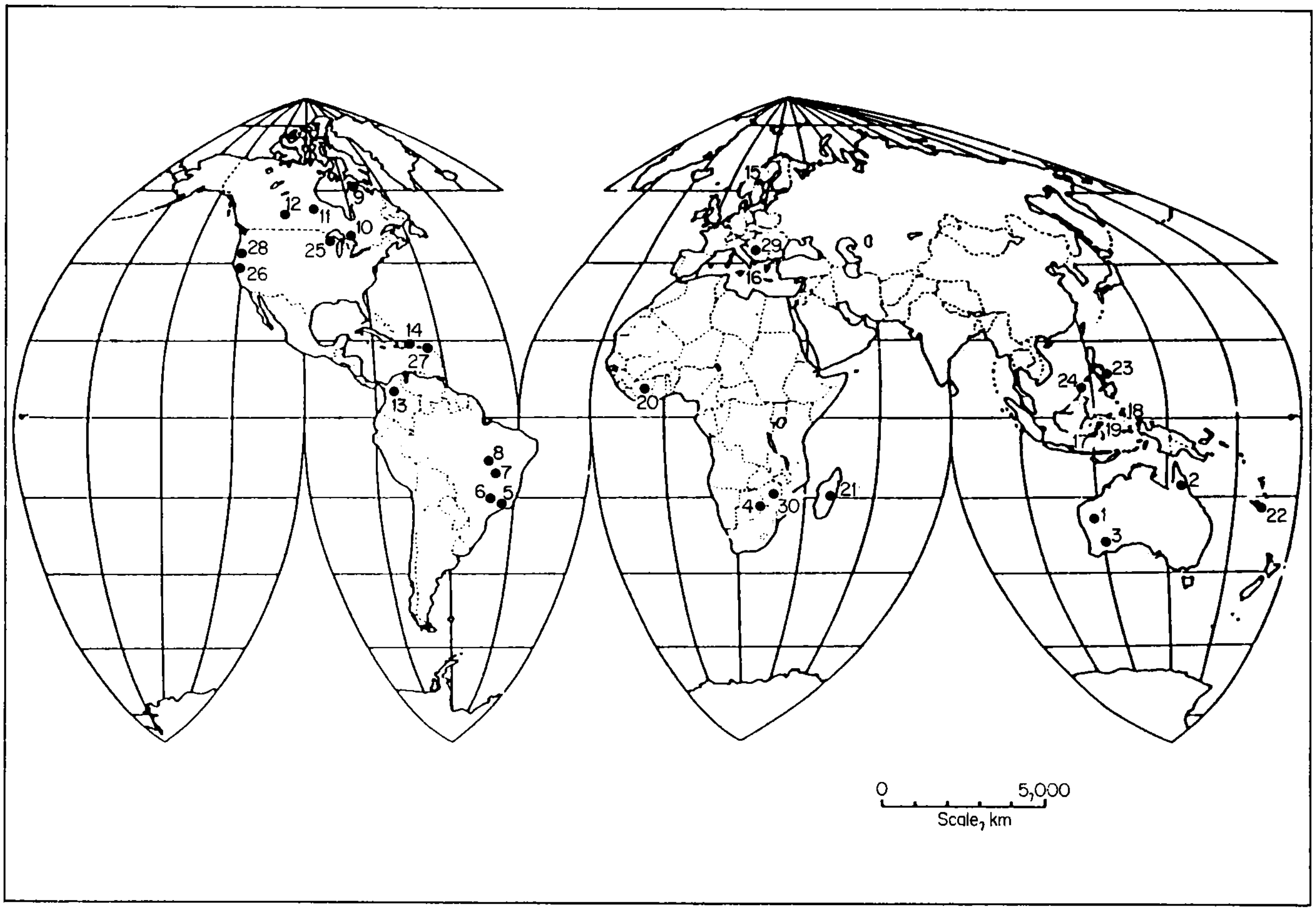

Figure 4.—Distribution of evaluated deposits.

For each deposit, a demonstrated resource was estimated. A demonstrated resource is defined by the mineral resource classification system developed jointly by the U.S. Geological Survey and the U.S. Bureau of Mines as presented in figure 5. Demonstrated resources used in this evaluation include measured plus indicated tonnage and are defined as those resources whose quantity is computed from site inspections, drill data, and mine workings and whose grade is determined from sampling (*19*).

Information on average grades, resource tonnages, and physical characteristics affecting potential production from the deposits was obtained from numerous sources, including independent contractors, U.S. Bureau of Mines files, U.S. Geological Survey and state publications, professional journals, annual reports, company 10K reports, prospectuses filed with the Securities and Exchange Commission, and data made available to the U.S. Bureau of Mines by private companies. The knowledge and expertise of

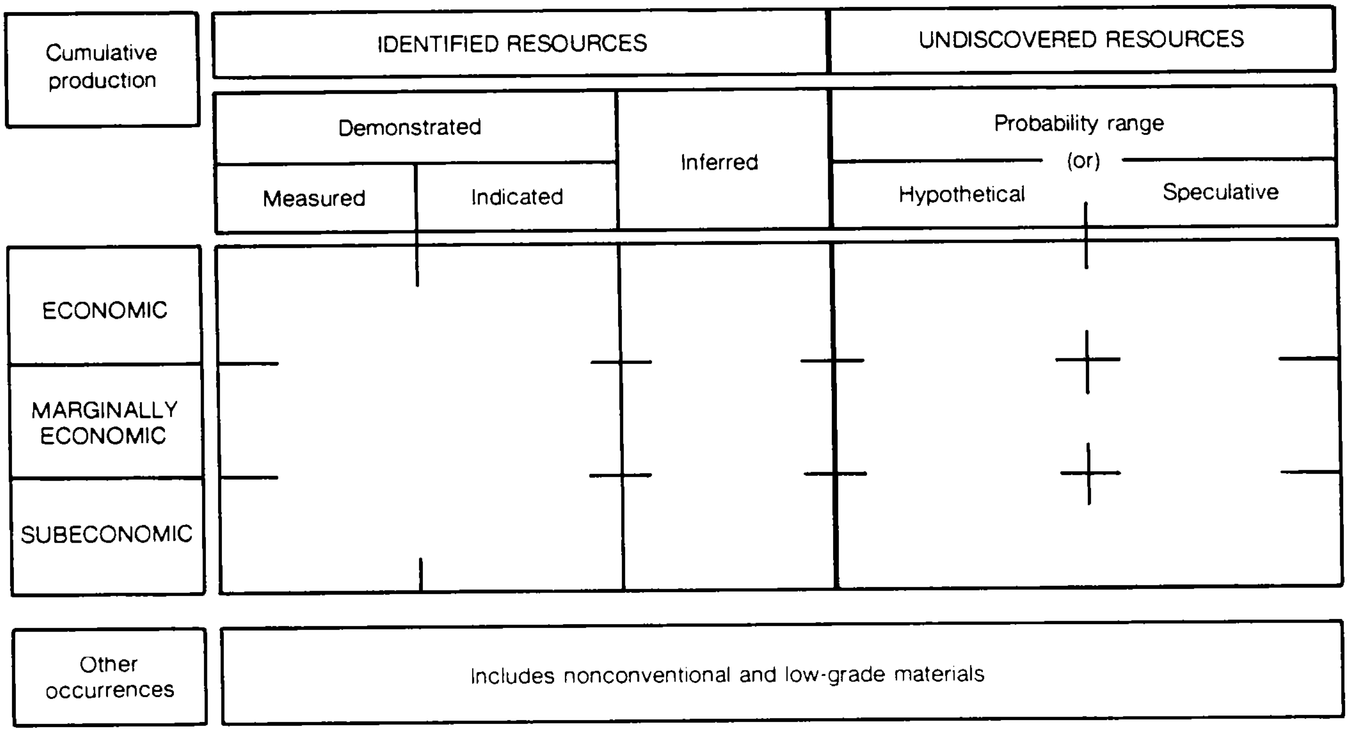

Figure 5.—Classification categories of mineral resources.

U.S. Bureau of Mines personnel helped to determine each deposit's potential resources.

This study evaluates deposits in MECs containing 33 Mmt of recoverable nickel at the demonstrated (measured plus indicated) level. The 20 producing operations account for just over 50 percent of that total, or 16.7 Mmt. The remaining 16.3 Mmt are in the 16 nonproducing deposits. Geologic and specific descriptions of deposits are included in appendix B.

In 1950, only 5 percent of nickel production in the MECs originated from laterites, but by 1988 about 40 percent originated from these ores, owing to wider acceptance in the steel industry. Nearly 80 percent of the demonstrated nickel resources from deposits in the MECs evaluated in this study are contained in laterites, while only 20 percent are contained in sulfides. This relationship has important implications for the future of the nickel industry. Canada has more than 70 percent of the recoverable nickel from sulfide deposits.

Laterite deposits in the Philippines contain 40 percent of the recoverable nickel in laterites. The Southwest Pacific countries of Indonesia, New Caledonia, and the Philippines account for nearly 80 percent of the recoverable nickel from laterite deposits and about 60 percent of the nickel resources evaluated. Table 12 lists evaluated properties and potentially recoverable nickel. Approximately 17 Mmt of nickel, or about 50 percent of the total recoverable nickel resource, is in producing mines. Nearly 11 Mmt of this amount is in laterite mines, mostly in the Southwest Pacific region, while about 5.5 Mmt is in sulfides, mostly in Canada and Australia.

Table 12.—Primary recoverable nickel from demonstrated reserves and resources[1] (kmt)

Region: Country	Producing mines[2] Sulfides	Producing mines Laterites	Producing mines Total	Nonproducing deposits Sulfides	Nonproducing deposits Laterites	Nonproducing deposits Total	Grand Total
Africa:							
Botswana	243	0	243	0	0	0	243
Zimbabwe	41	0	41	0	0	0	41
Others[3]	0	0	0	0	3,196	3,196	3,196
Total Africa	284	0	284	0	3,196	3,196	3,480
Southwest Pacific:							
Australia	679	40	[4]719	660	0	660	1,379
Indonesia	0	1,452	1,452	0	858	858	2,310
New Caledonia	0	7,500	7,500	0	0	0	7,500
Philippines	0	390	390	0	9,783	9,783	10,173
Total SW Pacific	679	9,382	10,061	660	10,641	11,301	21,362
Europe:							
Finland	40	0	40	0	0	0	40
Greece	0	280	280	0	0	0	280
Yugoslavia	40	367	87	0	0	0	87
Total Europe	40	367	407	0	0	0	407
Central and South America:							
Brazil	0	488	488	92	0	92	579
Colombia	0	522	522	0	177	177	699
Dominican Rep.	0	385	385	0	0	0	385
Total Central and South America	0	1,395	1,395	92	177	269	1,663
North America:							
Canada	4,559	0	4,559	396	0	396	4,955
United States[5]	0	0	0	306	439	745	745
Total North America	4,559	0	4,559	702	439	1,141	5,700
World Total[6]	5,562	11,142	16,704	1,454	14,451	15,905	32,609

[1]Estimates of reserves and resources were derived from published material and personal communications. Estimates are considered conservative for most deposits.
[2]Mines, districts or regions.
[3]"Others" includes Ivory Coast and the Malagasy Republic.
[4]Includes 2 years of recoverable nickel in ore at Greenvale.
[5]Includes Puerto Rico.
[6]Numbers may not add to totals due to rounding.

NICKEL PRODUCTION COSTS

Production costs in this study are based on actual data or are estimated by comparison with similar mining operations. (Appendix C discusses mining and processing technologies for sulfide and laterite operations.) Production costs, estimated as dollars per pound of recovered nickel, for selected producing and nonproducing sulfide and laterite operations are discussed in this section. Costs presented are averages for the deposits in individual countries; costs for specific deposits may vary from country averages. Costs for mining, milling, smelting, refining, and transportation were calculated along with credits for byproducts. Costs of beneficiation for sulfides include the costs of recovery for all commodities by flotation. In the case of laterites, the costs include mining, screening, washing, drying, and calcining plus other steps required to produce ferronickel, matte, or refined nickel. Postmill processing for byproduct commodities is included in smelter and refinery costs. The total of these costs is called "total production costs." They often vary greatly, depending on such factors as size of operation, method of mining, location of deposit, stripping ratio, depth of ore body, grade of nickel and byproducts, processing losses, and energy and labor costs. Revenues generated from coproduct and byproduct commodities have also been computed and subtracted from "total production cost" to determine "net production cost."

Net production cost is an average cash cost of production, not including taxes, interest, recovery of capital, or profit. It can be compared to the average nickel price at which a mine could break even by recovering all current production costs. Many mines operate at these costs with the expectation that market price will improve in the short term.

Often some costs exist that, if expended, may prevent an operation's closing immediately if the price of nickel falls below the net production cost for a period of time. The initial and continuing costs associated with closure and reactivation may be significant. Closing costs may result in the loss of market shares, payouts for financial commitments to labor, electricity, and other contracts, care and maintenance, loss of skilled employees, political costs resulting from unemployment, loss of support facilities for local towns, and loss of foreign exchange. Reactivation costs include locating, rehiring, and training labor, renegotiating new contracts and loans if necessary, and rejuvenating facilities. If the operation is owned by the government, the sales revenue generated by the mining operation may be needed to purchase other needed materials.

Once closed, a facility may wait for metal prices to exceed net production costs before reentering the market to ensure that the reactivation costs can be recovered.

Taxes may also be forgiven or deferred during periods of economic difficulties. Government-owned operations are an exception in that they may continue to produce for long periods at a loss because of social benefits derived through employment, foreign exchange, and support of infrastructure.

"Total cost" is defined as the net production cost, plus taxes and royalties, plus the cost of recovery of capital at a 0- or 10-pct DCFROR. Total cost could be compared to a long-run market price to indicate which properties have sufficient return of and on capital to provide an incentive to operate. For some producing mines, no great difference exists between the net production cost and the total cost, because the mine has been producing long enough that a large portion of the capital has already been amortized. For other producing mines, and for most nonproducing deposits, the difference is significant, because relatively large amounts of capital remain to be amortized.

INTEREST COSTS

Nearly all producing nickel operations are burdened with debt payable to either private institutions (sometimes within their own corporation), international lending organizations, such as the World Bank, or government agencies. At prices above $3.00/lb of nickel and high prices of associated byproducts, most facilities can meet their debt obligations. Over the last few years, however, when metal prices were very weak, some operations could not meet their debt service. It is rare, however, for a creditor to force an operation to shut down when it defaults on debt. Instead, most mines continue to operate as long as net production costs meet or come close to market prices.

In general, laterite mining operations are more burdened with debt per pound of nickel recovered than are sulfide mining operations. Laterite mines are generally newer operations, and significant amounts of debt remain.

The weighted average debt for producing laterites per pound of nickel recovered is approximately $0.30, compared to about $0.20 for nickel from sulfides. Significant amounts of debt affect the total cost of several properties. Several noteworthy examples of interest per pound of nickel recovered include Inco's and Falconbridge's Sudbury operations ($0.20/lb of nickel), WMC ($0.15/lb of nickel), Falconbridge's laterite operations ($0.35/lb of nickel), Inco's Indonesian operation ($0.25/lb of nickel), and SLN ($0.25/lb of nickel).

The creditor, in cooperation with the lending institution, may opt to convert debt into equity, roll debt into the remaining principal, or generate some other plan to prevent foreclosure. The complexity of terms associated with loans precluded the inclusion of interest costs in this study, but as mentioned earlier, debt could add an average of $0.20/lb to $0.30/lb to the production costs presented in this section.

PRODUCING SULFIDE OPERATIONS

Table 13 illustrates costs from selected operations associated with production of nickel from sulfide ores per pound of nickel. The weighted-average mining cost for producing sulfide operations is $0.60/lb of nickel. Cost differences for individual mines are the result largely of variations in stripping ratios, productivity, ore grade, dilution, recovery factors, and costs of energy and labor.

The lower Australian and Canadian costs per pound of nickel reflect the higher grade of nickel and high productivity resulting largely from bulk mining techniques. Zimbabwe's high cost results from very low grade ore, high mining costs, and low productivity.

Australian operations have the lowest milling cost because of high ore grades, efficient technology, and high productivity. Canada's costs are higher than Australia's because of lower ore grades and higher labor costs. The costs for Bindura, Zimbabwe, are high owing to low grades and generally low productivity.

Table 13.—Estimated costs for selected producing nickel operations (January 1987 dollars/lb of nickel)

Ore type: Operation: Country	Production costs					Byproduct credits	Net production cost[1]	Total cost including a 10-pct DCFROR[2]
	Mine	Mill	Smelting refining	Transportation	Total			
Sulfides:								
Bindura: Zimbabwe	$1.85	$0.65	$1.35	$0.10	$3.95	$0.25	$3.70	$3.80
Canadian operations (wt avg)	.65	.30	1.20	.10	2.25	.85	1.40	1.45
Western Mining: Australia	.50	.20	.90	.05	1.65	.10	1.55	1.70
Selebi Phikwe: Botswana	.90	.40	1.20	.20	2.70	.80	1.90	2.05
Weighted average	.60	.30	1.20	.10	2.20	.70	1.50	1.65
Laterites:								
Greenvale: Australia[3]	.70	NAp[4]	1.30	.25	2.25	.40	1.85	2.10
Larco: Greece	.60	do.	1.40	.25	2.25	.00	2.25	2.30
Indonesia (wt avg)[5]	.30	do.	1.40	.20	1.90	.00	1.90	2.20
New Caledonia (wt avg)[5]	.35	do.	1.65	.30	2.30	.05	2.25	2.45
Rio Tuba: Philippines	.40	do.	1.45	.20	2.05	.00	2.05	2.35
Colombia and Dominican Republic (wt avg)[6]	.20	do.	1.30	.10	1.60	.00	1.60	1.90
Brazil (wt avg)	.35	do.	1.30	.10	1.75	.05	1.70	2.10
Kosova: Yugoslavia	.35	do.	1.45	.05	1.85	.00	1.85	2.40
Weighted average	.30	do.	1.40	.20	1.90	.00	1.90	2.25

NAp Not applicable.
[1]Total production cost less byproduct credits.
[2]Net operating cost plus taxation, royalties, and capital recovery determined at a 10-pct DCFROR.
[3]Mining cost incudes ores purchased from New Caledonia.
[4]Postmine processing of laterite is included in smelting-refining cost.
[5]Includes production of matte and ferronickel, and processing of ore shipped and processed in Japan.
[6]Average weighted to avoid disclosure of proprietary data.

Smelting and refining costs for producing sulfides range from $0.90/lb of nickel in Australia to $1.35/lb of nickel in Zimbabwe. Australia's flash furnace technology and high grades contribute to the low costs. Zimbabwean concentrates are very low grade; therefore, more energy, labor, materials, and supplies are expended to recover 1 lb of nickel than at the other operations evaluated.

Transportation costs for Selebi-Phikwe are relatively high because the majority of its operations matte is refined in Norway.

Of the primary-nickel-producing countries, Canada, on a weighted average basis, is the lowest-cost producer. Canada's low net production cost is a result of revenue generated by coproducts and byproducts.

Total cost, including a 10-pct DCFROR, ranges from a low of $1.45/lb of nickel for the Canadian operations to a high of $3.80/lb for Bindura. Canada's low total cost results from relatively low capital expenditures, high-grade ores, and revenues from byproducts. Bindura has a high total cost because of low-grade ore and poor productivity.

PRODUCING LATERITE OPERATIONS

Mining costs for producers of nickel from laterite ores range from $0.20/lb of nickel for the average of Colombia and the Dominican Republic to $0.60/lb of nickel for Larco and $0.70/lb at Greenvale. The variation in costs results from the wide range of ore grades, depth of mining (underground for a portion of the production), and poor productivity in Greece. Australia's high cost represents mining of local ores and the cost of importing ores from New Caledonia. The average mine operating cost for laterite operations is $0.30/lb of nickel.

Laterite ores are not milled or concentrated as are sulfide ores. They are instead screened and dried to reduce moisture content. These costs are included in smelting. Smelting and refining costs for laterites include all postmine costs to produce ferronickel and matte through production of refined nickel. Processing costs of byproducts are included in smelting and refining costs. The lowest estimated processing costs are in Australia, which produces nickel oxide and byproduct cobalt, and Colombia and the Dominican Republic, which produce ferronickel. Brazil's estimate is based on a weighted average of refined nickel and ferronickel produced from several laterite operations. Transportation is a major cost associated with shipping laterite ores for processing, as it is a high-bulk, low-grade "concentrate" that often contains 25-30 percent moisture. It costs from $10-$15/wet mt ($0.25-$0.40/lb of nickel) to transport ore to Japan from Indonesia, New Caledonia, and the Philippines. A large portion of the cost for smelting and refining reflects high energy consumption to reduce the moisture content of ores. Recovery of byproducts, mainly cobalt, and transportation are additional costs for some properties.

Byproduct metals, mainly cobalt, are recovered from some laterite ores in Australia, Brazil, and New Caledonia. Byproduct credits average \$0.05/lb of nickel (mostly from cobalt) in New Caledonia, exclusive of production from the Petit Mineurs, and Brazil to \$0.40/lb in Australia. Because SLN recovers only a small amount of nickel matte for refining in France, the byproduct credit per pound of total nickel recovered is minimal. Australia's Greenvale operation recovers cobalt in a sulfide residue, which is shipped out of the country for refining.

Total costs, at a 10-pct DCFROR, average \$1.65/lb of nickel for sulfides and \$2.25 for laterites. The Canadian producers have the lowest total costs among the evaluated producers.

NONPRODUCING SULFIDE DEPOSITS

The weighted average mining cost for nonproducing sulfide operations in Canada is estimated at \$0.90/lb of nickel. Table 14 illustrates that the lowest mine cost estimated for a nonproducing sulfide is Fortaleza, Brazil, the highest cost estimate for the Duluth Gabbro. The variation in costs results primarily from the high-grade ores at Fortaleza as compared to the low grades in the Duluth Gabbro.

Mill costs for nonproducing sulfides are generally comparable to producing properties except in the cases of Fortaleza, where the ore is very high grade, and the Duluth Gabbro, where the low grades, fine grain size, and other characteristics of the resource result in poor recoveries.

Smelting and refining costs for nonproducing sulfide operations vary from \$0.55/lb of nickel for Brazil's Fortaleza deposit to \$2.15 for the Duluth Gabbro in the United States. The higher costs result from low concentrate grades and high environmental costs, while Fortaleza benefits from very high-grade ores and relatively low energy costs.

Byproduct credits at the Duluth Gabbro are primarily from copper (actually a coproduct) with additional credits from cobalt and precious metals.

Total cost, including a 10-pct DCFROR, was selected to indicate and provide insight to what sustained nickel price would be required for a company to commit capital to ensure profit. The large increase in cost between net production cost and total cost results from recovery of and on capital.

Table 14.—Estimated costs for selected nonproducing nickel deposits (January 1987 dollars/lb of nickel)

Ore type: Operation: Country	Production costs: Mine	Mill	Smelting refining	Transportation	Total	Byproduct credits	Net production cost[1]	Total cost including a 10-pct DCFROR[2]
Sulfides:								
Agnew: Australia	\$0.80	\$0.20	\$0.90	\$0.05	\$1.95	\$0.10	\$1.85	\$2.05
Canada[3]	.90	.30	1.10	.20	2.50	.65	1.85	5.80
Duluth Gabbro: United States	4.00	2.10	2.15	.10	8.35	4.45	3.90	8.60
Fortaleza: Brazil	.25	.15	.55	.05	.95	.30	.65	2.60
Weighted average	1.20	.50	1.10	.15	2.95	1.00	1.95	5.10
Laterites:								
Africa	.45	NAp[4]	2.30	.65	3.40	.00	3.40	5.65
Pacific Islands	.40	do.	1.90	.05	2.35	.60	1.75	4.30
United States	.40	do.	3.10	.05	3.55	.80	2.75	5.80
Weighted average	.40	do.	2.25	.25	2.90	.40	2.50	5.00

NAp Not applicable.
[1]Total production cost less byproduct credits.
[2]Net operating cost plus taxation and royalties and recovery of capital at a 10-pct DCFROR.
[3]Canada includes Expo Ungava, Namew Lake, and Raglan.
[4]Postmine processing of laterites is included in smelting-refining cost.

NONPRODUCING LATERITE DEPOSITS

Estimated mine costs per pound of nickel for nonproducing laterite deposits range narrowly from $0.40-$0.45/lb of nickel (table 14). Costs per mt of ore could vary quite a bit, however, because of factors like grade of ore, moisture content, stripping ratios, and productivity. Costs for smelting and refining range from $1.90/lb of nickel in the Pacific Islands to $3.10 in the United States. The lower cost represents nickel from potential ferronickel producers; the higher cost results from refined nickel and production of byproduct cobalt.

The low net production cost in the Pacific Islands results from high-grade ores and high potential byproduct credits. The high cost for the African laterites results from high energy and transportation costs and lack of revenues from coproducts or byproducts.

Total cost (including a 10-pct DCFROR) ranges from a low of $4.30/lb of nickel in the Pacific Islands to $5.80/lb in Africa.

FACTORS AFFECTING THE COST OF NICKEL PRODUCTION

Costs associated with mining and processing ores to recover nickel have been dramatically affected by energy and labor costs. Net production costs have also been affected by changes in prices of byproduct commodities. These changes have caused major shifts in market shares, especially in 1973 and 1981, when energy costs dramatically escalated. This section analyzes the impact of energy and labor costs and byproduct prices on sulfide and laterite deposit economics.

Energy

Energy costs have varied dramatically during the last decade, from a high exceeding $40/bbl in 1981 to below $10/bbl in 1986. The evaluations in this study are based on approximately $15/bbl. As illustrated in figure 6, recovering nickel from laterites is significantly more energy intensive than recovering nickel from sulfides, and as a result, the cost of nickel recovered from laterites is generally higher. Despite government energy subsidies for some producers, increases in energy costs have contributed to closures, plant conversions, and reduced production, especially for some laterite operations. Some laterites have decreased their reliance on oil by converting to coal, natural gas, and hydroelectric power. The impact of increased fuel cost on producing nickel operations was estimated by determining the type of energy used when possible and the amount of consumption per pound of nickel recovered.

Sulfides

It is generally accepted that approximately 10 kW-h of energy is required to produce 1 lb of nickel from sulfides (*20*). Of that amount, 3-4 kW-h is used for underground mining and beneficiation and the remainder for smelting and refining.

Canadian nickel companies, particularly Inco, consume hydroelectric power for part of their energy requirements and expend 10-15 percent of total operating costs on energy, whereas most other producers spend 15-20 percent of their operating costs for energy. Hydroelectric power, especially when company owned, offers several advantages:

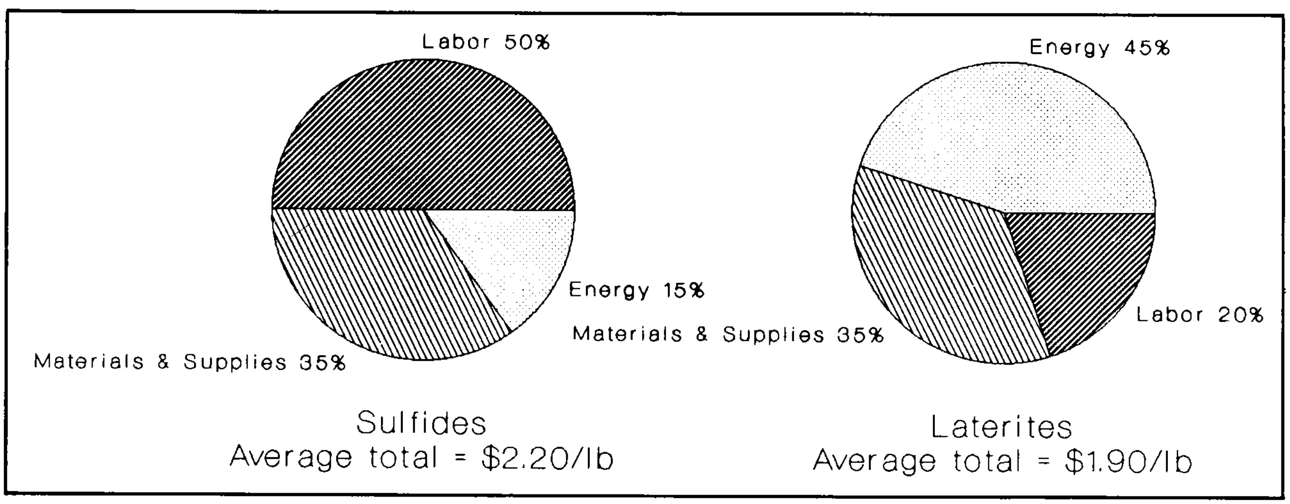

Figure 6.—Average distribution of production costs for producing sulfide and laterite operations, 1987.

It is a reliable source of power, inexpensive, and essentially unaffected by increases in costs of fossil fuels. In 1987, energy costs for sulfide operations ranged from $0.15-$0.40/lb of recovered nickel and averaged about $0.30/lb. Inco generates about 14 percent of the energy required for its Sudbury operations by company-owned hydroelectric plants. Inco also generates electricity from two waste steam generators. Therefore, an increase in petroleum-based energy costs would result in a somewhat lesser impact on Canadian producers than on mines with no access to hydroelectric power. Canadian mining companies are increasing their efforts to electrify mining operations to reduce costs. An increase in the price of oil from $15/bbl to $20/bbl would result in a $0.02-$0.05/lb increase in the cost of production of nickel from sulfide ores.

Laterites

Operating costs associated with laterite deposits have a large fuel component. Energy costs can account for 35-60 percent of total operating costs, more than three times that of Inco's Canadian sulfide mines. For an operation that depends totally on fuel oil for its energy requirements, such as Falconbridge's operation in the Dominican Republic, a $0.05/lb increase in the price of nickel is required to offset a $1.00/bbl increase in the price of oil.

Analyses indicate that energy costs account for about 45 percent of total production costs. The burden of these costs is on the postmining stages (drying, calcining, smelting, and refining). Changes in fuel costs, therefore, have a greater impact on the profitability of laterite operations than those that produce nickel from sulfide ores.

Energy costs, which represented about 60 percent of total operating cost, were a major reason for the closure of Eximbal in Guatemala. Approximately 4,000 bbl of fuel oil per day was required to operate the turbogenerators. The facility produced about 28 million lb of nickel in matte annually at full capacity. When the property started production in 1977, oil cost approximately $12/bbl, but when the operation was closed in 1981, it had increased to about $30/bbl. Assuming full capacity, the cost for fuel of $16 million in 1977 increased to $40 million in 1981. Although high capital costs are a major issue, low fuel costs and a high but stable nickel price could encourage the rejuvenation of the Guatemalan operation.

The decision in 1982 not to proceed with the development of the proposed Gag Island laterite project (approximately 45 kmt of refined nickel per year) in Indonesia was significantly affected by the increased costs for fossil fuels. To reduce energy costs, the Nonoc operation in the Philippines converted from an oil-fired plant to a coal-fired facility. Soon afterward, the Greenvale facility also converted from oil to coal.

The economics of Falconbridge's laterite operation in the Dominican Republic is greatly affected by fuel costs (table 15). From the project's startup in 1973 through 1981, energy costs per barrel of oil had risen more than tenfold ($3.60 to $41/bbl), while the market price of nickel had increased only 2.3 times. As a result, energy costs increased as a proportion of total operating costs from 9 percent to 64 percent (*22*). The company has successfully reduced energy requirements by using only two electric furnaces rather than three and is still able to maintain capacity. In 1987, fuel costs accounted for about 50 percent of total production costs.

Table 15.—Effect of oil price on nickel production cost at Falconbridge Dominicana operation (Falcondo Bonao)

Year	Total energy consumption (10^6 bbl)	Average cost per barrel	Total energy cost, million dollars	Energy cost per pound of nickel produced
1975	3.2	$11.70	$36.8	$0.62
1980	1.8	29.45	53.0	1.46
1987	2.4	22.00	52.8	.78
1988[1]	2.5	16.25	40.6	.58

[1]Estimated, based on a 6-month reporting period.

SOURCE: Berry (*21*).

As with sulfides, laterite operations that use hydroelectric power are probably in the best position for consistently lower energy costs. P.T. Inco's Indonesian laterite-nickel matte plant at Soroako uses hydroelectric power for approximately 50 percent of its energy needs. The availability of hydroelectric power lowers operating costs by 54 percent compared to what would have been incurred if P.T. Inco depended completely on oil. The facility has also reduced oil consumption by adding coal to the ore feed and not drying the ore as much as previously. Energy requirements account for about 40 percent of the production cost for the operation. The company's matte is exported to Japan, where it is toll refined. Processing costs in Japan are relatively expensive, in part owing to high energy costs. If oil prices were to increase to $20/bbl from $15/bbl, P.T. Inco's net production costs for nickel production (ore through final product) would increase about $0.10/lb of nickel.

Cerro Matoso in Colombia also uses hydroelectric power and other inexpensive local fuel sources (coal). The World Bank has insisted, however, that the hydroelectric project (which used World Bank financing) yield a commercial rate of return. As a result, the rate for electricity has increased 10-15 percent annually. Costs are still considered reasonably low, however, at about $0.45/lb of product or about 40 percent of total production cost.

In New Caledonia, SLN's oil requirements have dropped as a result of technical improvements and use of coal and hydroelectric power. The operation's demand for energy is currently met by oil (60 percent), coal (20 percent), and hydroelectricity (20 percent). An increase in the price of oil from $15/bbl to $20/bbl would result in an increase in net production costs of approximately $0.10/lb of nickel in ferronickel and up to $0.20/lb for refined nickel (SLN exports matte to France for refining).

In summary, increases in energy costs generally have a greater impact on laterite operations than on sulfide operations. Canadian sulfide producers in particular, which use hydroelectric power for a portion of their energy requirements, consume less oil and are therefore less affected by increases in fuel costs than most other sulfide producers. An increase from $15/bbl to $20/bbl of oil would result in an increase in average total production cost of about $0.05 for sulfides and about $0.15/lb for laterites. If energy costs were to dramatically increase, laterite operations could be closed and their market share lost to sulfide operations (providing the price of nickel does not increase commensurately).

Labor

The cost of labor can account for 10 percent to 60 percent of total operating costs. Labor costs are directly related to labor rates, productivity, and mining methods. Operations that recover nickel from sulfide ores are more labor intensive because of the complexities associated with underground mining. Figure 6 illustrates the relationship of labor costs for sulfide and laterite operations.

Sulfides

Labor costs per pound of recovered nickel from producing sulfide operations evaluated in this study range from $0.55 to $1.25. The weighted average in 1987 was approximately $0.95, or 45-50 percent of the total production cost. In 1980, labor accounted for nearly 55 percent of total direct underground mine operating costs in the Sudbury District. In 1987, productivity increased dramatically because of the development of more efficient mining and processing methods. For example, Inco's productivity at Sudbury increased by more than 65 percent between 1980 and 1987. During the same period, the work force decreased from more than 15,000 to fewer than 9,000. Application of bulk mining methods at the company's Sudbury operations rose from 33 percent of total ore mined in 1980 to more than 80 percent in 1987. Since 1981, productivity in the Copper Cliff smelter increased about 80 percent, primarily through a reduction in labor. In other countries, labor costs can account for 60 percent of the operating cost because of a lesser degree of mechanization and nonselective mining techniques.

In mid-1988, Inco Ltd. and United Steel Workers Union members approved a new three year contract that affected about 6,000 employees in Sudbury and Port Colborne. The agreement included a 21.8 percent wage increase over the life of the contract in addition to a bonus when the averaged realized nickel price reaches $2.25/lb. Some industry analysts expect that the agreement could add $0.35/lb to Inco's production cost (the estimate does not include the bonus). The increase in labor cost alone will add approximately $.10/lb to the company's world production cost. The U.S. Bureau of Mines analyses indicate that net production costs in the Sudbury district could increase by approximately $0.30/lb, excluding the bonus program, over the life of the labor contract.

Laterites

Relatively simple, usually efficient surface-mining methods and generally lower salaries in countries that have laterite mining operations provide an advantage in labor cost over mining underground sulfides. Labor costs required to recover nickel range from 10-50 percent of the total operating cost (*21*). The average labor cost represents about $0.40/lb of nickel, or about 20 percent of total operating costs. Approximately 75 percent of total labor costs is in the postmining stages of nickel processing.

Coproducts and Byproducts

Revenues from coproducts and byproducts, primarily those from copper, cobalt, and precious metals, significantly affect competitiveness in the nickel industry. These revenues play an important role in offsetting total operating costs for most sulfide operations but have less significance for laterites. The evaluations in this study included revenues from byproducts generated at prices listed in table 16 (included later in the section titled "Methodology").

Sulfides

Nickel sulfide deposits characteristically contain several recoverable metals. The most common coproduct or byproduct is copper. In 1987, for example, Inco produced more than 150 kmt of copper from the Sudbury District. In addition, it also recovered important amounts of cobalt, PGM, gold, and silver. The PGM recovered from the

Sudbury region make Canada the third largest producer in the world. In 1988, byproducts were expected to generate significantly higher revenues because of higher average metal prices. Deposits in Australia, Finland, Botswana, and Brazil recover all or some of the following metals: cobalt, copper, gold, PGM, and silver. Sulfuric acid is also recovered. The weighted average byproduct credit for nickel recovered from sulfide ores in 1987 was approximately $0.70/lb of recovered nickel.

Laterites

Laterite operations most often produce ferronickel, from which little or no value in byproducts is realized. Any byproducts produced are usually cobalt. An exception is Falconbridge Dominicana's operation in the Dominican Republic, which distributes electricity to the national grid as a byproduct. An agreement with the government requires a payment resulting in a $0.05/lb of nickel "byproduct" credit. The analysis presented in this section is based only on those laterite deposits that recover metal byproducts, which includes Greenvale, Australia, Tocantins, Brazil, and SLN, in New Caledonia, among producers. In 1987, Greenvale produced approximately 1.2 kmt of cobalt, which produced a byproduct credit of approximately $0.40/lb of recovered nickel. SLN's operations in New Caledonia received only a minor byproduct credit against its total production, because cobalt is recovered from the small amount of matte refined in France.

In summary, revenues from byproducts benefit the economics of sulfide operations and improve their competitive position with ferronickel operations during periods of low nickel prices. Record high prices for copper and attractive prices for precious metals in 1988 significantly lowered net production costs of most sulfide operations. The laterites have not benefited as much for three reasons: (1) the majority of nickel production from laterites is in the form of ferronickel, from which byproducts are generally not recovered or for which credits are not given; (2) byproducts that are recovered, primarily cobalt, have generally low feed grades and poor metallurgical recoveries; and (3) the price of cobalt has remained relatively stable despite increases in most other metals.

Materials and Supplies

Materials and supplies are major components in the recovery of nickel. They include ammonia, naphtha, acid, sulfur, electrodes, and other materials. On average, materials and supplies represent approximately the same percentage, about 35 percent, of total production cost for sulfides and laterites, but their cost varies by operation and technology used to recover nickel and any byproducts.

CAPITAL COSTS

Capital costs for nonproducing operations include acquisition of land, exploration, mine development, mine and mill plant and equipment, smelters and refineries, and infrastructure, where required. Capital costs therefore reflect the total investment required for those deposits not producing at the time of the study to develop the mine, construct all facilities, and begin production. Capital costs for producing mines are not discussed in this section because most of the sulfide and some of the laterite operations have been producing for long periods and a large portion of the initial cost has been depreciated.

A vertically integrated, surface/underground sulfide operation (similar to those proposed in the Duluth Gabbro) capable of producing approximately 7-10 kmt of nickel annually might require an average capital cost of about $350 million (in 1987 dollars), or about $23 lb/yr of recovered nickel. Approximately 6 percent of the cost is for development, 55 percent for mine plant and equipment, and the remainder for mill plant and equipment. Infrastructure is an additional cost.

In the United States, a laterite operation with a proposed annual ore capacity of 1.1 Mmt that would produce about 10 kmt of nickel plus byproduct cobalt would require estimated $325 million, or about $16/lb of recoverable nickel. The distribution is as follows: 3 percent for development and infrastructure, 8 percent for mine plant and equipment, and the remainder for mill plant and equipment. Plant costs include facilities for a roast-reduction leach process. U.S. costs are generally higher than other countries owing to environmental and permitting costs, land purchases, construction costs, and so on.

Inflation caused capital costs to increase dramatically in the late 1970s and early 1980s. As an example, in 1971, the Falcondo smelter, which processes laterite to ferronickel, was completed at a cost of $182 million dollars (1971 U.S. dollars), excluding working capital, at a design capacity of 63 million lb of nickel annually (*21*). The efficient overall design of the Falcondo plant allowed an annual capacity of 68 million lb, thereby lowering the capital cost per annual lb from $2.90 to $2.70. In 1981, a capital cost of about $1 billion would have been required to replace the operation or $14.70/lb of annual capacity (*21*), in 1987 a capital cost of about $1.2 billion. Another example of capital costs is Cerro Matoso. The property was completed in 1981 at a cost exceeding $225 million. The plant has a capacity of about 23 kmt of nickel in ferronickel, resulting in a capital cost per pound of capacity of greater than $4.50/lb. P.T. Inco's operation exceeded $12 per annual lb in 1978. In 1988, a greenfields laterite operation would average an estimated $12/lb of annual capacity, but costs would vary, depending on requirements for infrastructure.

Capital costs required for sulfide operations are more difficult to estimate owing to the complexities of underground mining, infrastructure, and variations in process technology. The total capital cost for the Namew Lake deposit in Manitoba is estimated at $80 million (1987 U.S. dollars), and development costs for the Fortaleza deposit are projected at approximately U.S. $200 million (1987 dollars). The capital cost per pound of annual nickel capacity is approximately $9.00.

Capital costs relating to environmental factors have significantly affected production costs. In 1980, Falconbridge completed an environmental smelter improvement program at Sudbury, Ontario, at a capital cost of U.S. $83 million. Inco plans to implement a sulfur dioxide reduction program costing U.S. $350 million that includes the implementation of fluid bed roasters at Sudbury as a means of reducing gas emissions.

Another example of the effects of environmental legislation results from a decision of the Ontario Minister of Environment to require additional reductions in sulfur dioxide emissions. Sulfur dioxide emissions have constrained production at Sudbury. Inco is spending about U.S. $50 million (1987 dollars) to consolidate concentrating of ores. In addition to improving efficiency, the upgrading program will improve removal of pyrrhotite from the concentrate, thereby reducing annual sulfur dioxide emissions from the smelter by 100 kmt (*20*).

NICKEL AVAILABILITY ANALYSES

METHODOLOGY

Analyses presented in this section indicate the availability of nickel from the deposits evaluated in this study. Total availability curves relate quantities of recoverable nickel from each of the deposits to net production costs and total costs of production. Annual availability analyses are also presented illustrating annual production capabilities and taking into account time lags involved in reaching full production. Other curves presented in later sections illustrate the impact of changes in revenues from byproducts, energy costs, and labor costs on production cost and availability of nickel.

Certain assumptions are inherent in these analyses:

(1) All deposits produce at or near design capacity throughout their life.

(2) Each operation is assumed to be able to sell all of its output at the determined total cost.

(3) Startup dates for some nonproducing deposits were assumed.

(4) Time lags related to permitting, environmental impact statements, and other possible delays affecting production are minimized.

(5) It is assumed that all of the byproducts are sold at January 1987 market prices (table 16).

Some evaluated deposits could be prevented from development because of a lack of capital, environmental problems or issues, political reasons, a poor economic climate, or other constraints not known at this time.

Table 16.—Commodity prices used in analysis

Commodity	Units	January 1987
Cobalt	lb	$7.00
Copper	lb	.64
Gold	tr oz	408.26
Iridium	tr oz	400.00
Palladium	tr oz	200.00
Platinum	tr oz	600.00
Rhodium	tr oz	700.00
Ruthenium	tr oz	45.00
Silver	tr oz	5.53

TOTAL RESOURCE AVAILABILITY

Total recoverable nickel from evaluated deposits in terms of total cost, including 0- and 10-pct DCFRORs, is illustrated in figure 7; it also relates the total cost of production with a 0- and 10-pct DCFROR to the amount of nickel potentially recoverable from the evaluated properties and their type of ore by status of production. Bodies of ore are not homogenous, and costs can vary throughout the mine's production life. For example, during periods of high metal prices, operations are likely to mine lower-grade ores; the opposite is true when metal prices are low. The cost of transportation and processing to a final product is included for the properties that export raw ore to Japan (Aneka Tambang, Petit Mineurs, and Rio Tuba).

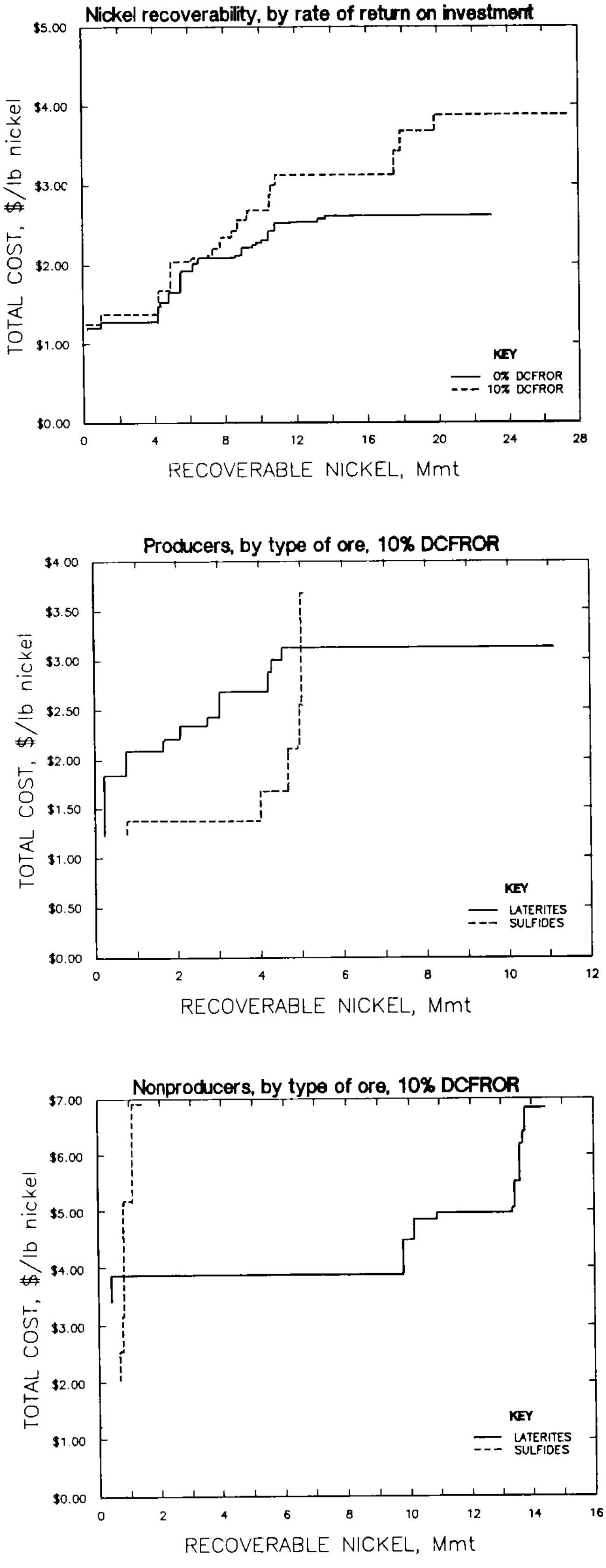

Figure 7.—Potentially recoverable nickel.

The analyses indicate that just over 32 Mmt of nickel is potentially recoverable. A price exceeding $5.00/lb of nickel would be required for all of the properties to produce at a 0-pct DCFROR, however. A 0-pct DCFROR was selected to illustrate the lowest average cost where an operation could break even on its costs and still recover capital. It is unlikely that a company would commit capital for a greenfields project at this rate of return. Table 17 lists the amount of potentially recoverable nickel within selected cost ranges.

Approximately 4.3 Mmt of nickel is available at a total cost, including a 0-pct DCFROR, of up to $1.50/lb. Of that amount, 4.2 Mmt is entirely controlled by Inco's Canadian operations. The Fortaleza prospect is the only nonproducer that could potentially operate in this cost range.

About 65 percent of the tonnage available between $1.51/lb and $2.00/lb is from producing operations, primarily WMC's operations and Cerro Matoso. Agnew is the only nonproducer in this category. A little more than 70 percent of the total resource is in sulfide deposits. All of the resource between $2.01 and $2.50/lb is in mines that are currently producing. Over 80 percent is in laterite resources, the largest being Inco's Indonesian operations, SLN, and the Falcondo operation. The sulfide deposits include Falconbridge's Canadian operations and Selebi-Phikwe.

Twelve operations were determined to have a total cost, at a 0-pct DCFROR, between $2.51 and $4.00 per pound of recovered nickel. Three operations—Bindura, Morro do Niquel, and the Petit Mineurs—are the only producers. The largest resources among the nonproducers are laterite deposits: the undeveloped Philippine laterites, the Ivory Coast, Gag Island, and Nonoc. The Raglan sulfide deposit in northern Quebec and the Namew Lake sulfide deposit in Manitoba are also in this cost range.

Six properties, none of which has produced, were estimated to have a total cost exceeding $4.00/lb, at a 0-pct DCFROR. Three of these properties, Gasquet, Duluth Gabbro, and Red Flat, are located in the United States. The other properties include Expo Ungava and the laterites in the Malagasy Republic.

The upper, dashed curve on figure 7 represents the analysis at a 10-pct DCFROR. The proximity between the 0-pct and the 10-pct curves depends on the amount of capital expended per pound of nickel produced over the life of the property. The older, more established operations are generally less capital intensive, and, because of depreciation, most capital has been written off. As a result, the costs at 0- and 10-pct are quite close. For economic evaluations of a prospect, however, costs for recovery of capital and profit are often significant and result in large differences between the 0- and 10-pct curves. The resource tonnages available at a 10-pct DCFROR within selected cost categories are shown in table 18.

Table 17.—Estimated potentially recoverable nickel at a 0-pct DCFROR (kmt)

Total cost range, dollars per pound	Producers			Nonproducers			Grand total	Cumulative total
	Sulfides	Laterites	Total	Sulfides	Laterites	Total		
< $1.51	4,004	222	4,226	92	0	92	4,318	4,318
$1.51-$2.00	679	522	1,201	660	0	660	1,861	6,179
$2.01-$2.50	838	3,794	4,632	0	0	0	4,632	10,811
$2.51-$4.00	41	6,604	6,645	328	13,525	13,853	20,498	31,309
> $4.01	0	0	0	374	926	1,300	1,300	32,609
Total	5,562	11,142	16,704	1,454	14,451	15,905	32,609	NAp

NAp Not applicable.

Table 18.—Estimated potentially recoverable nickel at a 10-pct DCFROR (kmt)

Total cost range, dollars per pound	Producers			Nonproducers			Grand total	Cumulative total
	Sulfides	Laterites	Total	Sulfides	Laterites	Total		
< $1.51	4,004	222	4,226	0	0	0	4,226	4,226
$1.51-$2.00	679	522	1,201	0	0	0	1,201	5,427
$2.01-$2.50	283	2,288	2,571	660	0	660	3,231	8,658
$2.51-$4.00	596	8,110	8,706	141	9,783	9,924	18,630	27,288
> $4.00	0	0	0	653	4,668	5,321	5,321	32,609
Total	5,562	11,142	16,704	1,454	14,451	15,905	32,609	NAp

NAP Not applicable.

Three producing operations can produce at an average total cost, at a 10-pct DCFROR, less than $1.51/lb: Inco's Sudbury and Thompson sulfide operations and Tocantin, a laterite operation. Over 95 percent of the evaluated resource in this cost range is available from Canadian operations.

At a total cost, with a 10-pct DCFROR, from $1.51-$2.00/lb, about 1.2 Mmt of nickel is potentially recoverable. About 43 percent is in the Cerro Matoso laterite, the remainder from the sulfide ore body at WMC.

The tonnage available from $2.01-$2.50/lb originates from eight producing operations and from Agnew, which is currently on standby. The largest resources belong to SLN, Agnew, Aneka Tambang, Falcondo, and Larco. Agnew is the only sulfide deposit in the group.

Eleven properties, three of them nonproducing, can supply nickel at a total cost from $2.51-$4.00/lb. The resources in this category represent over 50 percent of the total potentially recoverable nickel included in this study. About 95 percent of the resource is in laterites, approximately 90 percent of which is at P.T. Inco, the Petit Mineurs' holdings, and in undeveloped Philippine laterites. The most significant sulfide operation in this cost range belongs to Falconbridge, in Canada. The three nonproducers are Fortaleza, Namew Lake, and Nonoc, which is in the lower part of the cost category.

Eleven properties can produce at a total cost above $4.00/lb, including a 10-pct DCFROR. None of these properties have produced, although several have been extensively explored. Approximately 90 percent of the resource is in laterites. The most significant properties are in the Ivory Coast laterites, Gag Island, and the four U.S. properties.

In summary, the African region, Canada, and the southwest Pacific region (Australia, Indonesia, New Caledonia, and the Philippines) account for nearly 30 Mmt or 90 percent of the nickel potentially recoverable from deposits evaluated in MECs. Of this resource, 72 percent is in the southwest Pacific countries, 16 percent in Canada, and 12 percent in Africa. Based on demonstrated resources, the total nickel potentially recoverable is divided almost equally between producing operations and nonproducing deposits. Laterites account for approximately 80 percent of total potentially recoverable nickel, evaluated in this study, almost 70 percent of the total resource in producing properties and 90 percent of the total resource among nonproducers.

POTENTIAL ANNUAL NICKEL PRODUCTION

Annual nickel production, based on total costs including 0-pct and 10-pct DCFRORs, is presented to indicate the effects associated primarily with the return of capital. A 0-pct DCFROR is considered a break-even cost and includes a return of, but not on, capital. Some companies would not continue to operate at this rate of return for an extended period of time. A 10-pct DCFROR includes a 10-pct return on invested capital. Ten percent was selected to represent an attractive rate of return to cover the opportunity cost of capital plus risk. The results of the evaluation are illustrated in figure 8 for producers and figure 9 for nonproducers and in tables 19 and 20 for

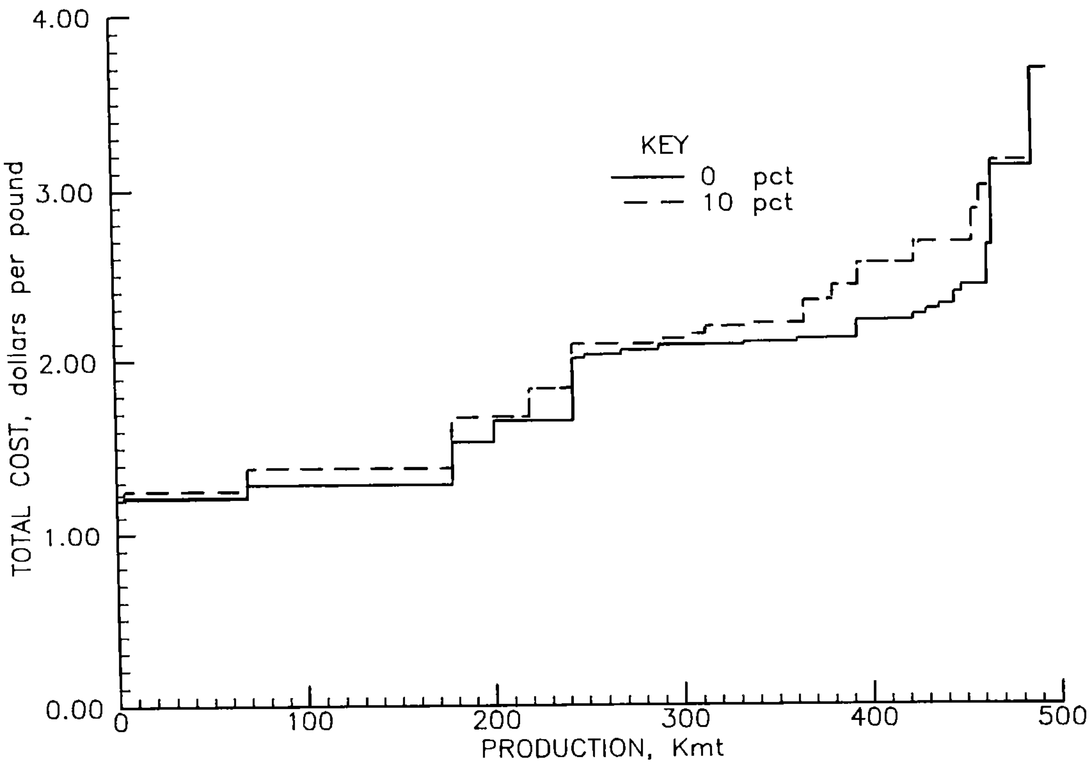

Figure 8.—Potential annual nickel production from producing mines at a 0- and 10-pct DCFROR.

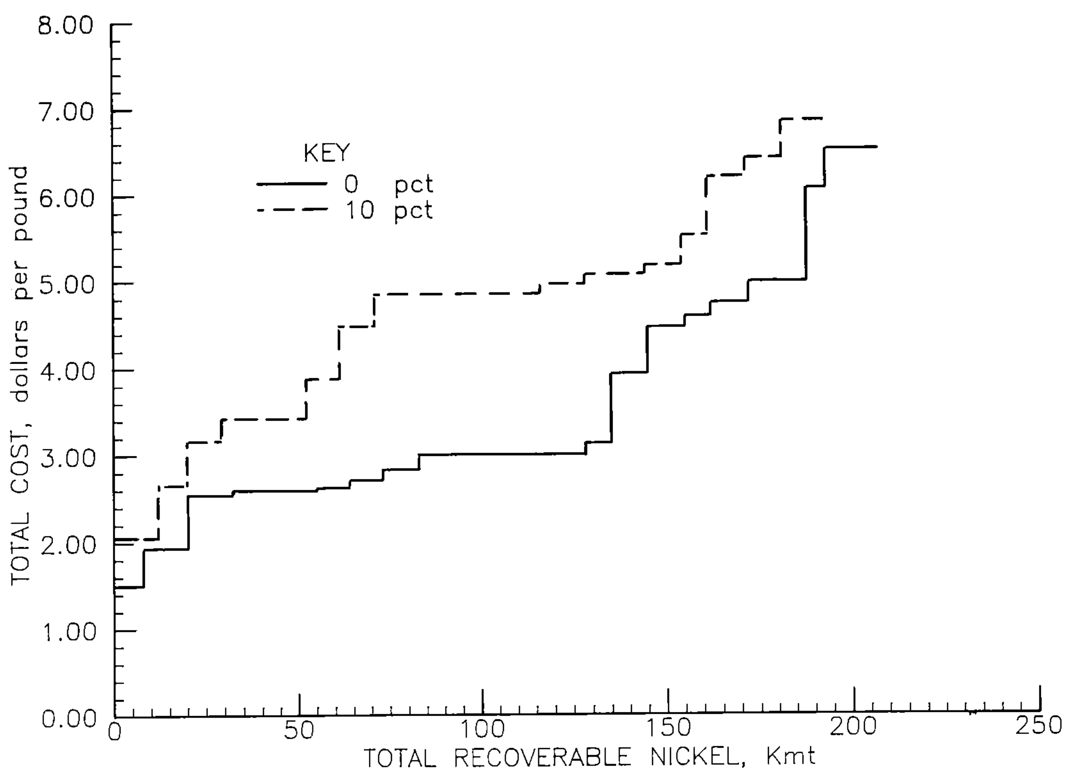

Figure 9.—Potential annual nickel production from nonproducing deposits at a 0- and 10-pct DCFROR.

0- and 10-pct DCFRORs, respectively. The curves are based on data from 1987 and early 1988. All operations are evaluated at full capacity.

Producing Mines

Nearly 98 percent of recoverable nickel available at an average total cost below $1.51/lb at a 0-pct DCFROR originates from Inco's Canadian operations. The remaining nickel is produced by Tocantin, in Brazil. Only two operations, Cerro Matoso (35 percent) and WMC (65 percent), can produce at $1.51-$2.00/lb of nickel.

At a 0-pct DCFROR from $2.01-$2.50/lb, 45 percent of the annual production of the evaluated producing mines could be supplied by 12 operations. Major producers and their share of capacity are Falconbridge's operations in Canada (15 percent), the Dominican Republic (15 percent), Inco's Indonesian operation (15 percent), SLN (20 percent), and Greenvale and Selebi-Phikwe (nearly 10 percent each). Other producers are Outokumpu, Rio Tuba, Niquelandia, Larco, Kosova, and Aneka Tambang.

Only two producers, New Caledonia's ore exporters (evaluations included transportation and processing in Japan) and Bindura, Zimbabwe, produce nickel at costs above $2.50/lb.

A total cost, including a 10-pct DCFROR, was determined to indicate the relative competitive positions for producing mines evaluated in this study.

Three properties, Inco's two Canadian operations and Tocantin, produce about 35 percent of the primary nickel in the MECs at a cost of less than $1.51/lb. In 1988, these companies were expected to produce significantly greater rates of return than the 10-pct DCFROR previously discussed.

At $1.51-$2.00/lb, production from WMC and Cerro Matoso is potentially available.

About 50 percent of the production in the MECs can be supplied at a cost of up to $2.00/lb, at a 10-pct DCFROR at least. All of these properties are relatively established (except for Cerro Matoso), are vertically integrated, and are less capital intensive per pound of nickel.

Table 19.—Estimated primary nickel production at a 0-pct DCFROR (kmt)

Total cost range, dollars per pound	Producers			Nonproducers			Grand total	Cumulative total
	Sulfides	Laterites	Total	Sulfides	Laterites	Total		
< $1.51	174	4	178	8	0	8	186	186
$1.51-$2.00	42	23	65	12	0	12	77	263
$2.01-$2.50	56	165	221	0	0	0	221	484
$2.51-$4.00	9	24	33	19	106	125	158	642
> $4.00	0	0	0	12	50	62	62	704
Total	281	216	497	51	156	207	704	NAp

NAp Not applicable.

Table 20.—Estimated primary nickel production at a 10-pct DCFROR (kmt)

Total cost range, dollars per pound	Producers			Nonproducers			Grand total	Cumulative total
	Sulfides	Laterites	Total	Sulfides	Laterites	Total		
< $1.51	174	4	178	0	0	0	178	178
$1.51-$2.00	42	23	65	0	0	0	65	243
$2.01-$2.50	26	126	152	12	0	12	164	407
$2.51-$4.00	39	63	102	17	23	40	142	549
> $4.00	0	0	0	22	133	155	155	704
Total	281	216	497	51	156	207	704	NAp

NAp Not applicable.

Eight properties produce a combined total of about 30 percent of production in the MECs at $2.01-$2.50/lb. Nearly 85 percent of this tonnage originates from laterite deposits, primarily owned by SLN in New Caledonia, Falconbridge in the Dominican Republic, Greenvale in Australia, and Aneka Tambang in Indonesia. The nickel from sulfide operations is produced by properties in Botswana and Finland.

About 20 percent of production is available at $2.51-$4.00/lb. The two largest producers in this category, Falconbridge's Sudbury operations and Inco's Indonesian operations, which combined produce approximately 60 kmt, are below $2.70/lb. Falconbridge's costs could drop significantly if ongoing exploration programs are successful in increasing the operation's production life. The remaining tonnage originates from the relatively high-cost, small syndicate miners in New Caledonia and several other small producers.

Nonproducing Deposits

Figure 9 illustrates the relationship of the potential annual production from the prospects and other nonproducers evaluated in this study. The curves are based on expected or assumed capacities.

Potential annual production from nonproducing properties was evaluated at a 0-pct DCFROR to determine a minimum rate-of-return cost for which an operation will be able to recover its investment. A company would not commit capital for development unless it were trying to increase its market share or expected a sustained increase in nickel price. For this reason, analyses at a 10-pct DCFROR are more representative for nonproducers.

Except for Agnew and Namew Lake, approximately 2-3 years of development would be required for each property before production could be initiated.

Fortaleza, in Brazil, is the lowest-cost potential operation among nonproducers. The mine could produce 8-10 kmt of nickel annually for less than $1.50/lb at a 0-pct DCFROR. The Brazilian government recently enacted a policy that discourages foreign participation, which has delayed development.

The Agnew mine, on standby since 1986, could produce nickel for $1.51-$2.00/lb at a 0-pct DCFROR. Production was expected to resume during the third quarter of 1989. Cumulatively, about 20 kmt of nickel could be potentially produced annually at costs below $2.00/lb.

Potential producers from $2.51-$4.00/lb of nickel include Guanajibo, Namew Lake, Nonoc, undeveloped Philippine laterites, and Gag Island. Their combined production could be nearly 100 kmt. Nonoc requires major capital investment to be reactivated. Investments in the Philippines are considered risky because of political instability.

At a total cost over $4.00/lb, about 62 kmt of annual nickel production is potentially available. Almost 45 percent of the total tonnage could originate from several deposits evaluated in the United States (Gasquet, Duluth Gabbro, and Red Flat), the remainder from the African laterites.

A 10-pct DCFROR is used to represent a minimum rate-of-return incentive for commitment of capital required for most greenfield projects.

Agnew has the lowest total cost among the nonproducing operations evaluated. The property can potentially produce about 12 kmt annually at a cost of $2.01-$2.50/lb, including a 10-pct DCFROR. The low cost results, in part, from reactivation costs much lower than initial capital investments associated with a greenfield project.

Four properties can potentially produce at $2.51-$4.00/lb. They are, in order of increasing costs, Fortaleza, Namew Lake, Nonoc, and undeveloped Philippine laterites. The remaining 11 nonproducing properties evaluated in this study require an average price of nickel over $4.00/lb. Although nickel prices were expected to average over $4.00/lb in 1988, it is doubtful that they will remain at a sustained high level long enough to encourage near-term development of properties in this cost category.

POTENTIAL ANNUAL PRODUCTION FROM OPERATING MINES AND SELECTED NONPRODUCERS

Figure 10 illustrates potential annual production from 1987 to 1995 at selected costs through time from 20 primary nickel producers and three nonproducing properties with excellent potential for production in the near future. The nonproducers included are Agnew, Fortaleza, and Namew Lake. Agnew is on standby, Fortaleza is undeveloped, but have excellent potential for near-term production, and Namew Lake was expected to be fully operational in 1989.

A 0-pct DCFROR was selected to illustrate the minimum total cost for an operation. This rate of return, however, may not be acceptable to some companies over an extended period of time.

The most apparent aspect of the curves is that resources are sufficient to maintain current capacity levels through 1995. Between 80-85 percent of potential production can be attained at or below $2.25/lb (in constant January 1987 dollars).

The increase between 1987 and 1992 results from current producers' increasing capacity through technology and capital expenditures that attain higher productivity in

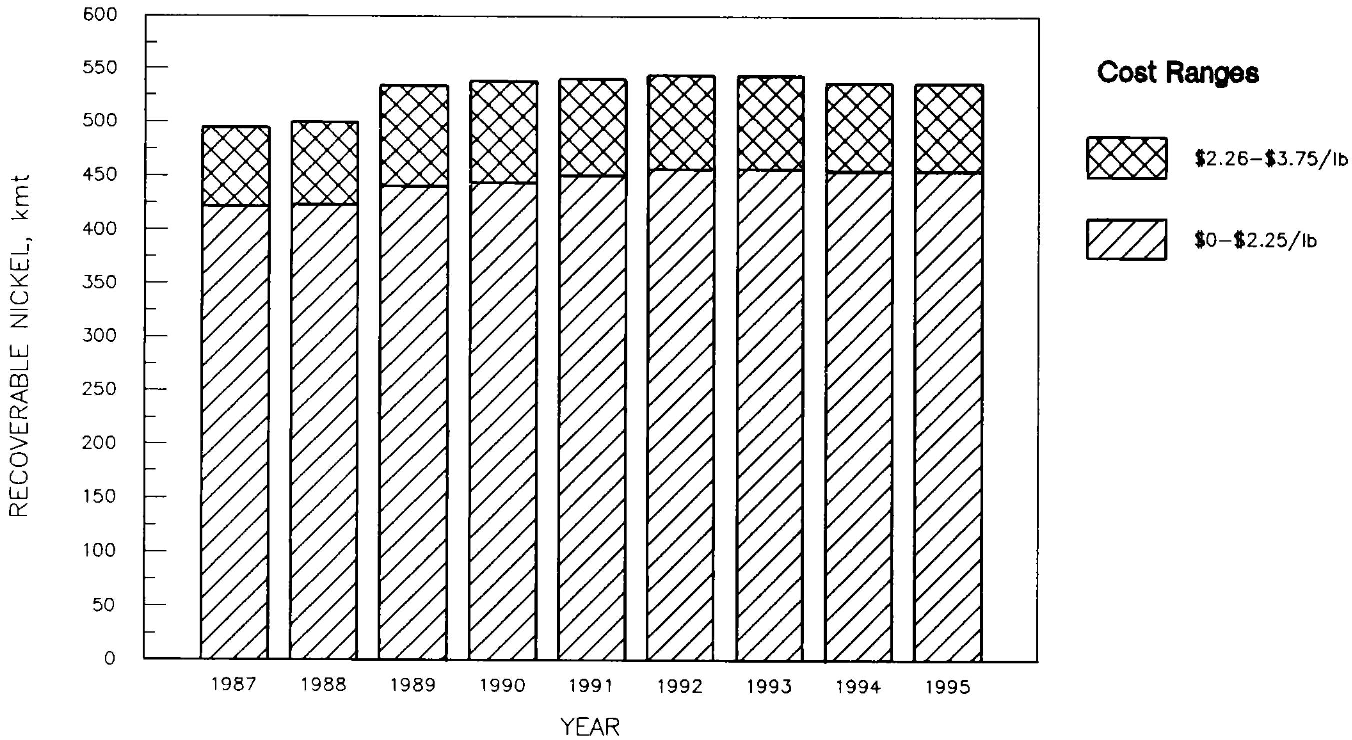

Figure 10.—Potential annual nickel production from operating mines and selected nonproducers at a 0-pct DCFROR.

Canada and expansions at Brazilian operations and Inco's Indonesian facilities into the early 1990s. The commissioning of Namew Lake in late 1988 and full production in 1989, the reactivation of Agnew in 1990, and the development and production from Fortaleza by 1991 are also assumed. Closures resulting from depletion of reserves and resources are also likely for Outokumpu operations in Finland and Bindura in Zimbabwe. Inco's Thompson open pit will be nearing exhaustion by 1995, but to maintain the company's production level, it is likely that another open pit will be developed. A possible decrease in production from 1994 to 1995 results from the exhaustion of currently demonstrated resources at Namew Lake, although additional resources are possible.

In 1987, primary nickel consumption in the MECs was about 642 kmt. At an assumed annual growth rate of 1-1.5 percent in the MECs, by 1995, between 695 kmt and 723 kmt of primary nickel may be consumed. In 1995, based on known resources and currently proposed development plans, production from primary nickel producers in the MECs would be approximately 535 kmt. No shortage of resources exists, but for producers in the MECs to meet projected demand, existing mines will need to expand (as resources are sufficient) or new discoveries will be necessary. Additional expansions are likely in Australia, Canada, and Indonesia. Brazilian expansion will be fueled by increased industrialization, improved infrastructure, and availability of hydroelectric power. Japanese interests may also decide to construct ferronickel plants in the Philippines and in other Asian countries. Preliminary plans are to construct a ferronickel plant in New Zealand. Sustained high nickel prices could encourage exploration and development of new mines. Nickel sales to the West from the CPE countries will become significant contributors in filling the gap between production and consumption of primary nickel, especially as Cuban production increases to perhaps 100 kmt (about 2.5 times current production) by the late 1990s. Increased recovery of scrap could also offset some demand for primary nickel.

POTENTIAL TOTAL RESOURCE AVAILABILITY AND NET PRODUCTION COSTS

Total potentially recoverable nickel at various net production costs is illustrated in figure 11 and listed in table 21 for all of the evaluated producing operations. Net production costs are most applicable for understanding relative competitiveness, after capital has been committed.

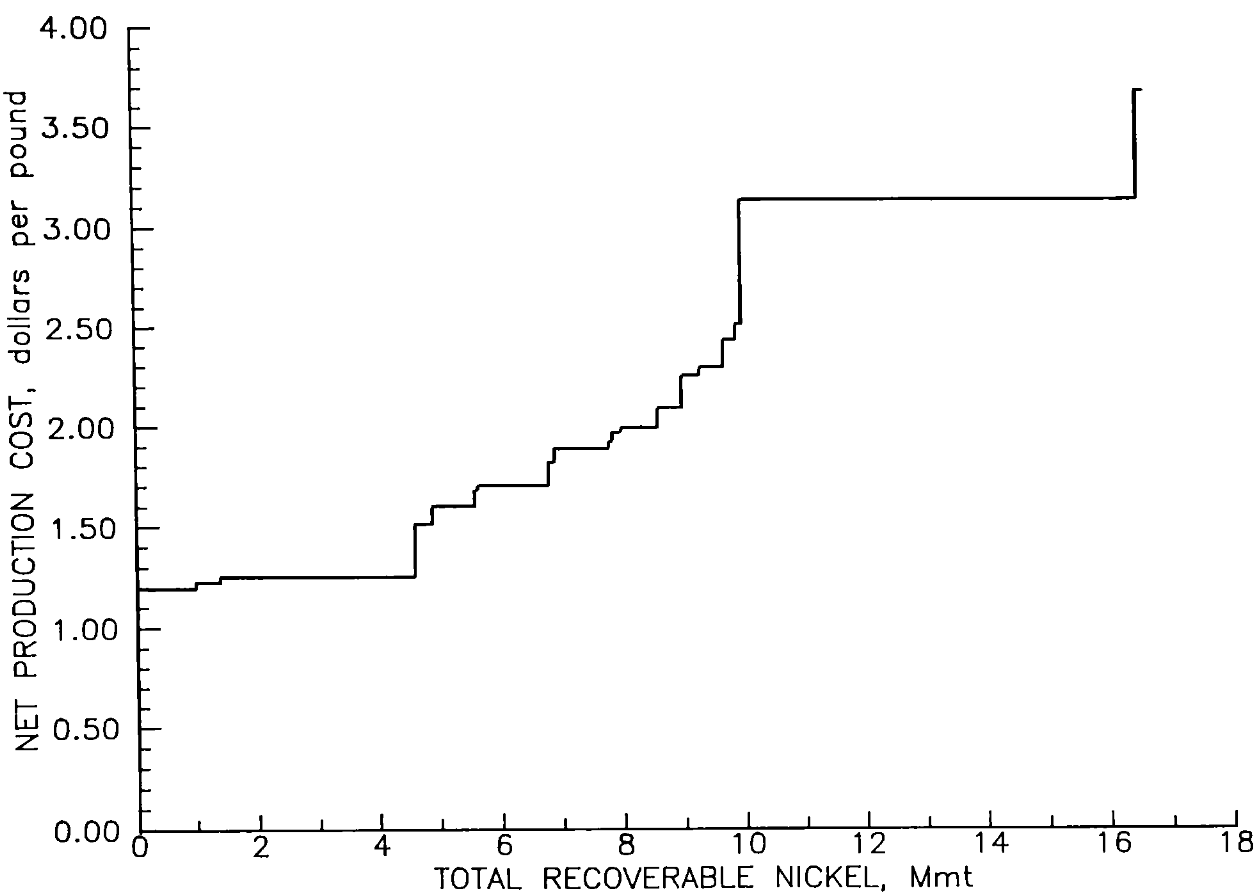

Figure 11.—Potential resource availability and net production cost from producing operations.

Table 21.—Estimated total potentially recoverable nickel from producers at selected net production cost ranges (kmt)

Total cost range, dollars per pound	Producers: Sulfides	Producers: Laterites	Producers: Total	Cumulative total
< $1.51	4,004	744	4,748	4,748
$1.51-$2.00	1,517	2,455	3,972	8,720
$2.01-$2.50	0	1,339	1,339	10,059
$2.51-$3.75	41	6,604	6,645	16,704
Total	5,562	11,142	16,704	NAp

NAp Not applicable.

Approximately 85 percent of the tonnage available at a net production cost of $1.50/lb or less is in Inco's Canadian operations. The remaining nickel is in Cerro Matoso and Tocantin. Although not included because they are nonproducers, Fortaleza and Namew Lake were also determined to have net production costs in this range.

Approximately 90 percent of the resource is in Inco's Indonesian and Falconbridge's Sudbury operations, Selebi-Phikwe, SLN, and WMC's operations at net costs of $1.51-$2.00/lb. (The Agnew mine, currently on standby, and the Raglan deposit in Canada would likely be included in this category if they were operational.)

All of the nickel available at $2.01-$2.50/lb is contained in Falconbridge's laterite operation in the Dominican Republic, Larco, Aneka Tambang, and Rio Tuba.

New Caledonia's Petit Mineurs, which export ore for processing in Japan, accounts for 99 percent, or 6.6 Mmt, of the recoverable nickel resource at $2.51-$3.75/lb. This estimate is conservative owing to limited exploration, but extensive nature, of the laterites. Bindura, also in this category, has the highest net production cost among the evaluated producers.

NET PRODUCTION COSTS AND POTENTIAL ANNUAL PRODUCTION

Figure 12 and table 22 illustrate estimated potential primary nickel production in the MECs and net production costs (including all direct production costs for mining, beneficiation, smelting, refining, and transportation, less byproduct credits) for the 20 producing operations analyzed in this study, imported nickel originating from CPE countries, and byproduct nickel (primarily from the RSA).

Exports from CPE countries and nickel originating as a byproduct, such as in South Africa, are shown separately on figure 12 at a net production cost of $0, because the imports, for the most part, are not sensitive to costs. An important aspect of exports from CPE countries is the need for foreign exchange, especially in the face of low petroleum costs (the U.S.S.R. is one of the world's largest exporters), relatively stable gold prices, and weak domestic economies. Byproduct nickel from South African PGM operations will continue to be produced as long as the cost for nickel recovery from matte (less than $1.00/lb) is less than the market price for nickel. Figure 13 illustrates estimated potential production against net production costs and does not include imports from CPE countries or byproduct nickel. These figures are useful in that they indicate the relative economic position of nickel production to net production cost and can be used to indicate the potential loss of production (because of closure or reduced production) when nickel prices fall. In 1988, all producing primary nickel operations could potentially produce at net production costs lower than world nickel prices.

Table 22.—Estimated primary annual nickel production at selected net production cost ranges (kmt)

Total cost range, dollars per pound	Producers			Cumulative total
	Sulfides	Laterites	Total	
< $1.51	174	27	201	201
$1.51-$2.00	98	104	202	403
$2.01-$2.50	0	61	61	464
$2.51-$4.00	9	24	33	497
> $4.00	0	0	0	497
Total	281	216	497	NAp

NAp Not applicable.

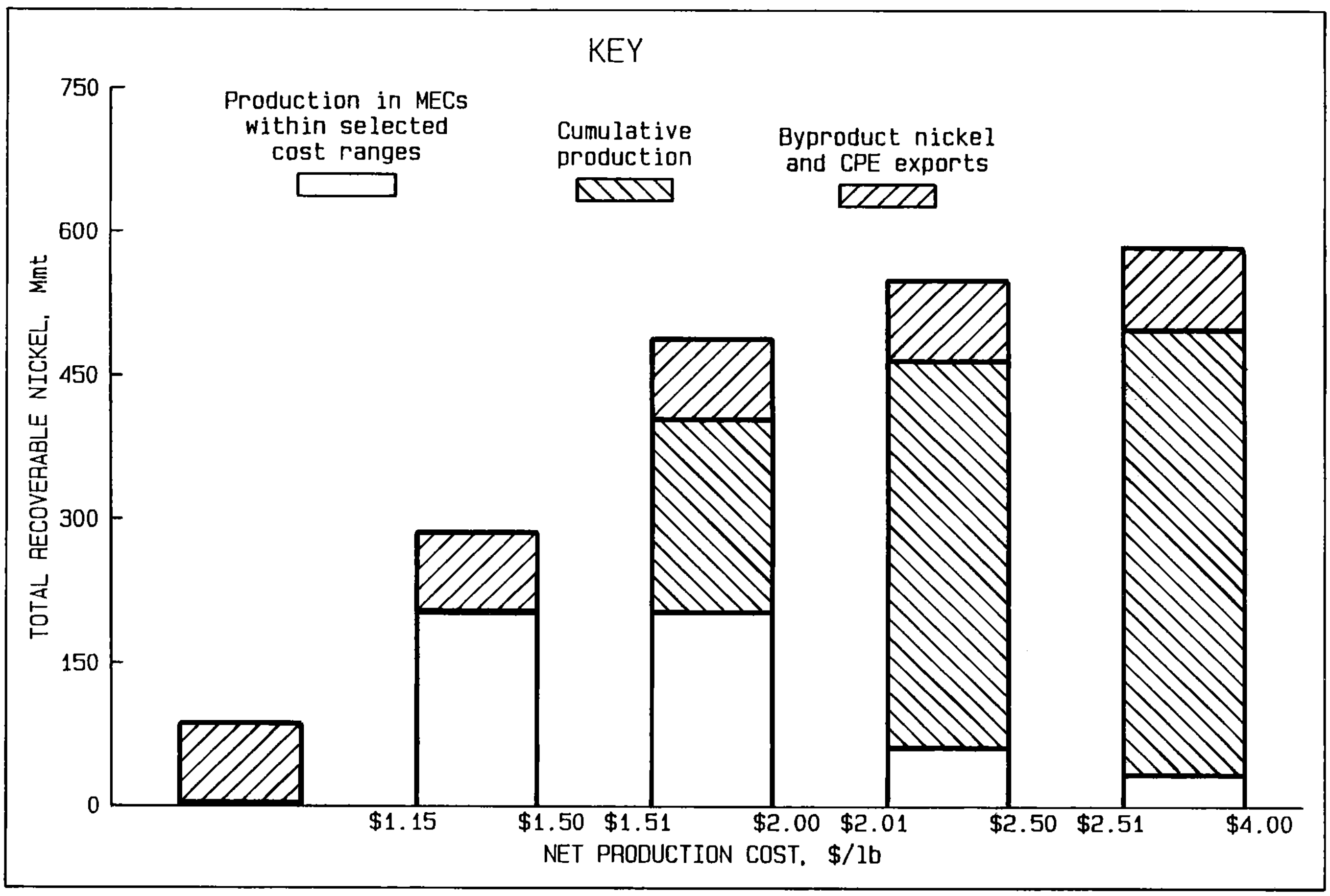

Figure 12.—CPE exports, byproduct nickel, and production in MECs at selected net production costs.

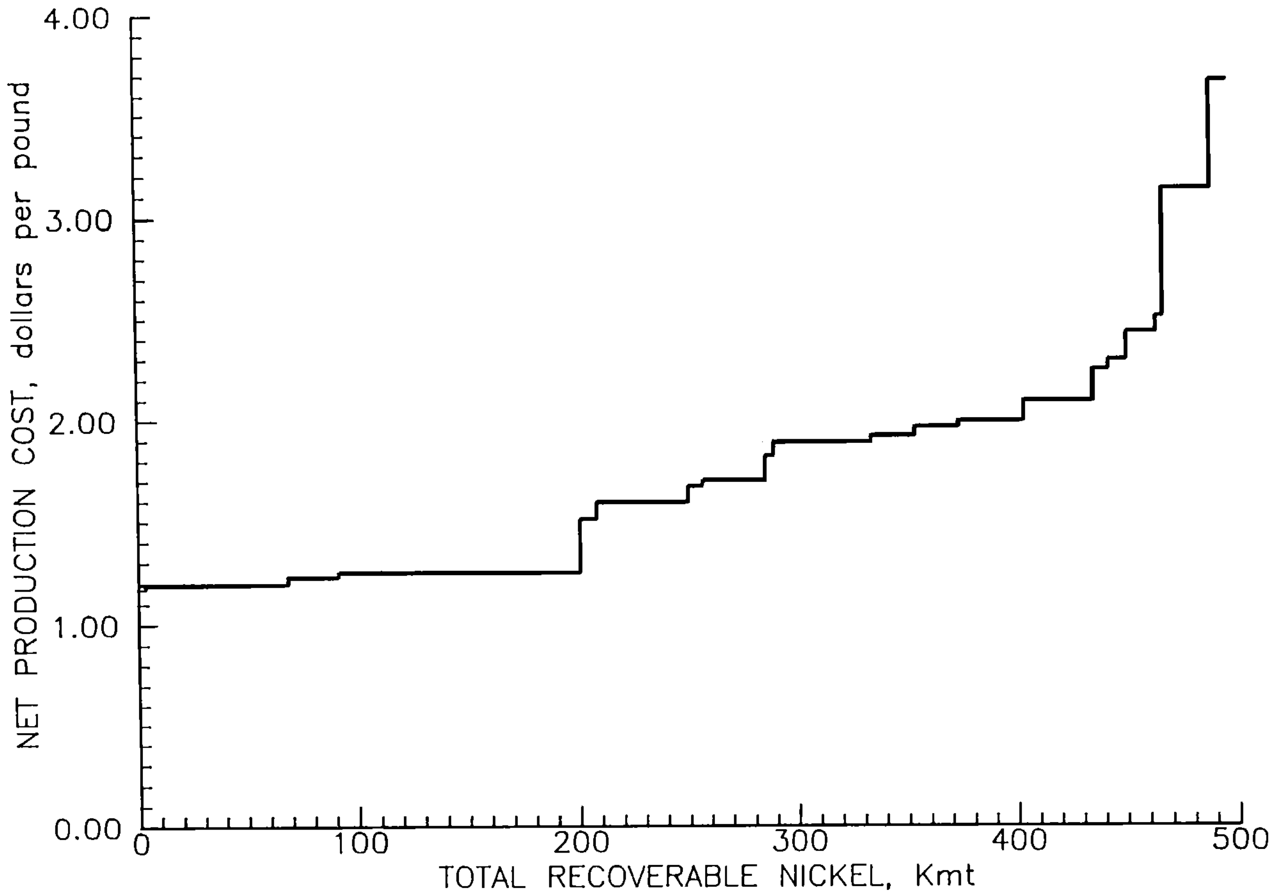

Figure 13.—Estimated production and net production costs in 1987.

From 1983 through 1986, the average annual nickel price was approximately \$2.15/lb. In 1986, the average price was approximately \$1.85. At these market prices, a significant portion of production in the MECs (approximately 42 percent) could not cover net production costs. About 40 percent of primary nickel production in the MECs is produced at net production costs below \$1.50/lb. Approximately 87 percent originates from Inco's Canadian operations, the remainder from Cerro Matoso and Tocantin.

Canada's Falconbridge operations, Inco's Indonesian operations, SLN, and Australia's Greenvale and Western Mining operations produce nickel at net production costs of \$1.51-\$2.00/lb. These operations account for nearly 85 percent of the total production in this category.

Twelve percent of nickel production in the MECs is available at net production costs of \$2.01-\$2.50/lb. All of this nickel originates from laterites. About 50 percent of it is from Falconbridge's operation in the Dominican Republic, 25 percent from Aneka Tambang, and the remainder from Larco and Rio Tuba.

CONCLUSIONS

The industrialized world remains dependent upon nickel as an alloying agent because it imparts strength and resistance to corrosion and heat. At the level of demonstrated resources, the 36 deposits and districts analyzed in the MECs have an estimated 33 Mmt of nickel potentially recoverable using current technology. Of this total, just over 50 percent is from mines producing at the time of this study. According to estimates of the countries studied, the Philippines, New Caledonia, Indonesia, Africa, and Canada have the largest demonstrated nickel resources, accounting for over 70 percent of the potentially recoverable nickel. Laterite resources in the Pacific Islands, Africa, and South America are undoubtedly much larger than estimates provided in this study but have not been proven at demonstrated levels.

Although the United States contains large domestic nickel resources, no primary nickel is produced. The resources are generally low grade and therefore costly to mine and process. A nickel price exceeding $4.50/lb would be required for any of them to generate a 10-pct DCFROR on the required investment. Development of these resources could be impaired or delayed as a result of several factors. The extremely high capital outlays required and critical balance between supply and demand, which greatly affect nickel prices, produce a high-risk investment. Environmental constraints and social issues related to the proximity of potential mines to the Boundary Waters Canoe Wilderness area in Minnesota may delay or totally prevent future development of the Duluth Gabbro. The laterites in California may also be negatively affected by environmental and social issues, and the proposed technology for recovering nickel and cobalt has not been used on a commercial scale.

Owing to record high nickel prices in 1988, virtually all producers in the MECs can supply nickel and its associated byproducts at a profit. At market prices below $2.50/lb, however, a significant portion are unprofitable. Approximately 10 Mmt is potentially available from producers at net production costs at or below $2.50/lb.

In 1987, mines in the MECs produced approximately 500 kmt of primary nickel. Results of this study indicate that at $2.50 or less, about 30 percent of that amount could be potentially produced and attain a 10-pct DCFROR. Most of this production originates from Canada, Australia, New Caledonia, the Dominican Republic, and Colombia. Most of the nickel produced above this cost originates from Pacific Island laterites.

In 1987, consumption of primary nickel in the MECs was about 642 kmt. By 1995, 695-723 kmt of primary nickel could be consumed each year. In 1995, based on known resources and currently proposed development plans, production in the MECs from primary nickel producers would be approximately 535 kmt. No shortage of resources exists, but for producers in the MECs to meet projected demand, existing mines will need to expand (as resources are sufficient) or new deposits discovered. Additional expansions are likely in Canada and Indonesia. Expansion in Brazil will be fueled by increased industrialization, improved infrastructure, and availability of inexpensive hydroelectric power. Japanese investors may construct ferronickel plants in the Philippines and in other Asian countries. Higher prices could fuel exploration and result in the development of new mines. Sales to the MECs from the CPE countries will also become more significant, especially as Cuban production increases to perhaps 100 kmt (about 2.5 times current production) by the mid-1990s.

In 1988, nickel prices reached all-time highs because of unexpectedly high demand and tight supplies. Barring disruptions in supply or shortfalls from production losses, production in 1989 may increase slightly. Nickel prices were expected to remain more stable and probably average over $4.50/lb in 1989. Prices could drop below this estimate if demand suddenly drops. Increasing nickel production among the CPE countries, especially in Cuba, over the next several years and demilitarization in the U.S.S.R. could result in substantially higher sales to the MECs. If this situation occurs, nickel prices could erode significantly.

As mining and processing facilities (smelters and refineries) in less developed countries and stainless steel manufacturing plants are developed and used in value-added goods for export at relatively low costs, the survival of U.S. manufacturers is increasingly threatened and the United States becomes more dependent on imports.

The cost of energy for laterite deposits and labor costs and revenues from byproducts for sulfides are important factors affecting cost of production. Presently, most sulfide operations can produce nickel at lower costs than laterites. This condition has developed primarily as a result of the increases in fuel costs since 1973 and the fact that much of the capital associated with sulfide operations has been amortized. If energy costs decrease, however, laterites will become increasingly competitive. Transportation of moisture-laden laterite ores to Japan can add a significant cost to the production of ferronickel. Transportation costs coupled with the strength of the yen and high labor costs could encourage development of vertically integrated nickel-processing facilities (mine through ferronickel or stainless steel) by Japanese investors in Indonesia, New Caledonia, the Philippines, and other countries.

It is apparent from the results of this study that Canada, relative to other MECs, has a secure position in the primary nickel market and will continue to maintain this position for the foreseeable future.

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APPENDIX A.—CENTRALLY PLANNED ECONOMY COUNTRIES

Albania

Bulgaria

Cuba

Czechoslovakia

German Democratic Republic

Hungary

Kampuchea

Laos

Mongolia

North Korea

People's Republic of China

Poland

Romania

U.S.S.R.

Vietnam

APPENDIX B.—GEOLOGY AND RESOURCES

This appendix addresses regional and deposit geology, resources, and mine characteristics of sulfides and laterites.

SULFIDE DEPOSITS

Nickel-bearing sulfide deposits are formed by several geologic processes; however, the great majority are of igneous origin. A brief discussion of sulfide resources by country follows.

Australia

The Agnew deposit and WMC's Kambalda District deposits have an estimated total recoverable resource of about 1.3 Mmt of nickel. The majority of these Precambrian deposits were discovered during the "nickel rush" in the late 1960s and early 1970s. They appear to be nearly always associated with ultramafic rocks that are generally within metavolcanic belts. Nickel grades of currently producing mines often exceed 3 percent. Some byproduct copper and lesser amounts of cobalt, silver, and gold are also recovered. WMC operates 6 or 7 small nickel mines using highly mechanized mining techniques. Several other large nickel deposits, such as Sherlock Bay, were not included in this study owing to lack of information about demonstrated resources.

Botswana

The Selebi-Phikwe mine is the only primary nickel-copper producer in Botswana. The ore bodies are hosted in Precambrian mafic and ultramafic rocks; the mineralization ranges from disseminated to massive pyrrhotite, chalcopyrite, and pentlandite contained in an amphibolite sill. Besides nickel, the property produces byproduct copper and cobalt. Surface operations were discontinued in 1980, and only the underground operations remain. Approximately 2.3 Mmt of ore was mined in 1987 at an average grade of about 1 percent nickel and 0.82 percent copper. Remaining resources are estimated at approximately 245 kmt of recoverable nickel, and the likelihood exists that additional resources will be developed.

Canada

Ontario

The Sudbury District in Ontario is currently the world's largest single producing source of nickel. It has produced over $25 billion of minerals over the past 95 years (*17*).

Geologically, the Sudbury District is within a Precambrian bowl-shaped basin. Nickel-copper mineralization may have taken place during norite formation. The ore is associated with the "nickel intrusive," also called the "nickel irruptive," emplaced as a 1.5-km-thick igneous body at an unconformity between metavolcanics and plutonic rocks (granites) and a Precambrian series of slates and quartzites known as the Whitewater Group.

Generally, nickel is primarily recovered from the mineral pentlandite, but chalcopyrite and pyrrhotite are also contributors. Besides the production of nickel, the district ranks number three in the world in production of PGM and also contributes large amounts of cobalt, copper, and silver. The bowl-shaped structure of the mineralized zone permits some of the deposits on the margins to be mined by open-pit method, but nearly all production has originated from underground methods. The ore intervals are generally located along the outer edge of an oval 32 km wide and 55 km long.

Ownership of producing mines and properties in the Sudbury District is divided into a complex pattern between primarily two companies, Inco and Falconbridge. The pattern and complexities of ownership have required in some cases that the two companies mine ore on an exchange basis.

A total demonstrated reserve of nearly 4 Mmt of recoverable nickel has been estimated in the district, with ore grades averaging about 3 percent combined copper and nickel divided in roughly equal portions. Inco's Sudbury in situ reserves are over 300 Mmt of ore averaging about 1.5 percent nickel and 1.4 percent copper. Falconbridge's Sudbury in situ reserves are estimated at 46 Mmt averaging 1.7 percent nickel and 1.5 percent copper. Cobalt grades at Falconbridge's mines are considerably higher than Inco's, at about 0.05 percent. Inco's and Falconbridge's resources are undoubtedly larger, but detailed information on much of the additional resource is not available owing to the lack of data about development drilling and the company's strict policies relating to information about resources.

Manitoba

The Thompson District in north central Manitoba is located along the boundary of the Precambrian Superior Province to the southeast and the Precambrian Churchill Province to the northwest. Several nickel deposits have been discovered along a 140-km belt. The Thompson ore body, which is mined by open-pit and underground methods, is probably the best known. Several known deposits, such as Birchtree and Pipe, could be mined if high metal prices continue. The majority of mining is underground using cut-and-fill and other mining methods similar to those used at Sudbury.

The Thompson Belt ore bodies are generally of two types: (1) uniformly disseminated sulfides or sulfide veinlets in peridotites and (2) sharply defined breccia zones in metasediments. The ore bodies of the second type are generally higher grade (2.5 percent nickel) although less common. Mineralization is generally confined to a narrow zone of schist within a series of folds. Mineralization in the district has been located along 5,000 meters of strike. Like most nickel sulfide ore bodies, the ore minerals of the Thompson Belt are pentlandite, chalcopyrite, and pyrrhotite. In addition to nickel, the district produces some byproduct copper and small amounts of cobalt.

The Namew Lake deposit, which was planned for initial production in late 1988, has a resource estimated at 2.5 Mmt averaging 2.4 percent nickel and 0.9 percent copper (*4*).

United States

The Duluth Gabbro Complex is one of the world's largest basic igneous intrusions and contains the largest known sulfide nickel resource in the United States. The intrusion covers an area greater than 1,200 km^2 in northeastern Minnesota and contains an estimated inferred resource of 4.2 Mmt of potentially recoverable nickel. This Precambrian intrusion consists generally of strongly layered gabbros. Mineralization is the result of magmatic differentiation during the crystallization process. The principal nickel mineral is pentlandite, and copper-bearing minerals are chalcopyrite and cubanite. Minor amounts of cobalt and PGM are also present. Average feed grade was estimated at about 0.15 percent nickel and 0.45 percent copper.

Several areas were leased in the late 1970s and early 1980s by Inco, AMAX, Bear Creek Exploration, and other companies. Most of the lease holdings have now been relinquished, except for the immediate area surrounding the Minnamax shaft. Most properties were explored to varying degrees by performing drilling, magnetic surveys, small test pitting, outcrop sampling, and so on. The Ely Spruce and Minnamax deposits were extensively explored. An exploration shaft was constructed at Minnamax, from which bulk ore samples were recovered for metallurgical testing.

In general, the resource is very low grade. In addition, potential environmental problems and associated political and social pressure from environmental interest groups would complicate or preclude exploitation of these deposits. The Duluth Gabbro Complex extends into the Boundary Waters Canoe Area, a Federally established wilderness area, and several areas of mineral interest were within a few miles of its southwest boundary. High costs would be associated with precautions to ensure water and air quality. Stringent legislation would require that smelters and refiners be located some distance away.

For this study, a smaller area of demonstrated resources containing approximately 300 kmt of recoverable nickel was considered. The Brady Glacier and Yakobi Island deposits in Alaska are also associated with ultramafic intrusives. Brady Glacier is a vertically oriented cylindrical deposit. The nickel and copper mineralization is associated with disseminated pentlandite with chalcopyrite and cubanite. These properties were explored, and some preliminary mining plans developed in the mid- to late 1970s, but development in the near future appears unlikely owing to the high cost of mining and infrastructure and environmental issues associated with exploiting these deposits. For example, the Brady Glacier deposit is under a glacier in Glacier Bay National Monument. For these reasons, the deposits were not analyzed in this study. Additional nickel resources are located in Maine, Missouri, and Montana.

Zimbabwe

Nickel is produced from four mines in central Zimbabwe—Madziwa, Trojan, Epoch, and Shangani. The Trojan, Epoch, and Shangani mines are situated in Precambrian ultrabasic lavas that have been altered to talc-carbonate and serpentinite; the Madziwa is hosted in a massive mafic intrusive. Mineralization is generally in the form of disseminated pentlandite with pyrrhotite and chalcopyrite. Nickel grades are the lowest of the evaluated sulfide deposits and probably the lowest among all world primary nickel producers. Nickel content ranges from 0.3-0.8 percent nickel, with some minor massive sulfide occurrences containing 1-3 percent nickel in the footwalls. As much as 20 percent of the nickel may be refractory, suggesting difficult recovery. Minor amounts of copper, cobalt, and precious metals are recovered as byproducts. All of the mines are operated using underground methods. Only about 40 kmt of nickel is potentially recoverable. Zimbabwe's nickel industry is negatively affected by low grades, high beneficiation costs, and increasing labor costs.

Additional nickel resources in Zimbabwe were not analyzed for this study. The U.S. Bureau of Mines estimates that a demonstrated resource of approximately 1.2 Mmt of contained nickel is located in the Great Dyke. The Great Dyke is considered the second largest resource for PGM in the world, after South Africa (which produces approximately 25 kmt of byproduct nickel per year), containing over 85 million tr oz of platinum. Nickel grades average about 0.25 percent and would only be recovered as a byproduct of mining PGM. Some interest currently exists in developing a portion of the Hartley lease, which is located on the northern half of the Great Dyke (*23*). Preliminary feasibility plans call for production beginning in the early 1990s, with an annual production of 210,000 tr oz of PGM and approximately 3 kmt of byproduct nickel.

Other Countries

Nickel deposits are also exploited in Finland. These deposits are relatively small and are associated with Precambrian ultramafic rocks. The deposits average less than 1 percent nickel with byproduct copper and cobalt. Total evaluated resources are estimated at about 40 kmt of recoverable nickel. A significant sulfide deposit was recently discovered in Brazil, and the Fortaleza (O'Toole) prospect has been explored extensively (*24*). Nickel mineralization is in the form of pentlandite and is associated with Precambrian metavolcanic rocks. The demonstrated resource is estimated at 91 kmt of recoverable nickel and averages 2.3 percent nickel with byproduct copper, cobalt, and PGM. Exploration indicates that very large additional resources probably exist.

LATERITE DEPOSITS

For nickel-bearing laterites to develop, subtropical to tropical climatic conditions must have existed. Nickel laterites result from a gradual decomposition of ultrabasic rocks, particularly peridotites, in which nickel for the most part is contained in the mineral olivine.

Laterite ores are formed by the combined action of mechanical and chemical weathering. As nickeliferous olivine decomposes, nickel is released and mobilized into solution by the downward percolation of rainwater and/or the movement of groundwater. Nickel is redeposited at depth by precipitation. This repeated action, known as lateritization, results in a "zone of enrichment" that in some cases can be mined at a profit. Saprolite, the lowermost lateritic zone, overlies the parent rock.

Lateritic nickel ores can be divided primarily into siliceous and limonitic ores. The silicate ores (garnierites) contain less than 30 percent iron, about 30 percent silica, and a nickel grade generally exceeding 1.5 percent. Garnierite laterites are desirable for ferronickel production owing to their high content of silicon dioxide and magnesium oxide. A portion of the laterite ores in Indonesia, New Caledonia, the Philippines, and the United States falls into this general classification. Iron-rich limonitic laterites form when the leaching of nickel is not as favorable or complete, as with the garnierite laterites, resulting in a mixed iron-nickel zone. Limonitic ores, which occur throughout much of the world, contain approximately 45 to 55 percent iron and about 1 percent nickel. Limonitic ores are often amenable to hydrometallurgical processing.

The distinction between the two types of laterite ores is clear; however, because of various degrees of lateritization, field classification is often difficult. In some cases, a layered ore body containing limonitic material overlying garnieritic ore is mined, and the overlying limonitic material is stockpiled for later processing.

Laterites are generally large deposits and represent the largest land-based source of nickel. A brief description of the major laterite deposits in important nickel-producing countries follows.

Australia

One laterite occurrence was evaluated in Australia. Greenvale, in northeast Queensland, consists of three main zones developed on Ordovician ultramafic country rock. The uppermost zone consists of overburden of clay and other detritus, the middle zone is a limonitic laterite about 5 meters thick averaging about 1.5 percent nickel and cobalt combined, and the lower zone consists of highly weathered rock containing up to 5 percent nickel. The lower and middle zones are mined using draglines, shovels, and trucks; however, resources are nearly exhausted and the mining operation will likely become dependent on imported ores from New Caledonia and possibly other Pacific Islands.

Two laterites were examined but not evaluated in this analysis. The Ora Banda laterite in Western Australia has been intermittently mined using surface methods. The laterite has been used as flux in the Kalgoorlie smelter and contains about 1 percent nickel.

Wingellina, a relatively high-grade occurrence, is located on the borders of Western Australia, South Australia, and the Northern Territory. Although exploration has been undertaken on this property, no significant development has taken place.

Dominican Republic

The laterites of the Dominican Republic are developed on Cretaceous through Eocene serpentinized peridotites. Lateritization appears to have begun during the Miocene period and continued for about 20 million years. Deposits measure up to 60 meters thick and are strongly zoned.

Minable ore zones are about 1.2 percent nickel and measure about 8 meters thick. The waste-to-ore-stripping ratio ranges from 6:1 to 11:1.

Three zones of ore are currently blended to produce ferronickel, each reflecting different compositions. The zones range from about 0.5 percent to 3 percent nickel. The ultramafic host rock assays about 0.3 percent nickel and is sometimes mined for garnieritic fracture fillings in the bedrock. Limonitic ore near the surface is up to 20 meters thick, with nickel grades of approximately 1.2 percent. This ore has the highest iron content of the three zones, about 35 percent. The middle ore, a limonitic laterite with serpentine, is about 1.5-2 percent nickel and about 15 percent iron and measures up to 16 meters thick. The third and deepest zone consists of soft and hard serpentine, serpentinized peridotite, and ultramafic rock and is low grade, about 0.5 percent. Falconbridge Dominicana, which operates the island's only nickel-mining operation, has located numerous nickel deposits that will eventually be developed.

Approximately 385 kmt of potentially recoverable nickel was estimated for the Dominicana operation, and additional resources are present.

Greece

The nickel laterites in Greece are developed on Cretaceous ultramafic rocks. Although primarily high-iron laterites, some garnierites are also mined. The average in situ nickel content of the ore ranges from 1-1.5 percent nickel. Generally, two areas are mined for laterites—the island of Euboea, northeast of Athens, and St. John, northwest of Athens. Combined, the properties conservatively contain 280 Mmt of recoverable nickel. The ore is mined using surface and, to a lesser extent, underground methods. The surface operation uses standard shovel and truck methods.

Indonesia

Although the laterites on the island of Sulawesi have been well explored, most of Indonesia's nickel laterite resources have yet to be defined. Approximately 2.3 Mmt of recoverable nickel, or about 10 percent of total recoverable nickel from laterite deposits analyzed, was estimated for Indonesian resources. In situ reserves at P.T. Inco's operation exceed 70 Mmt of ore averaging approximately 1.5 percent nickel. Laterite deposits range from 5-30 meters thick and developed as a result of weathering of Cretaceous ultramafic complexes. A larger, inferred resource undoubtedly exists. Both garnierites and limonitic laterites are found on the island. Garnierites contain about 2.5 percent nickel and are processed to matte and ferronickel. The limonitic ore averages from 0.5-1.5 percent nickel.

New Caledonia

The nickel-bearing laterites of New Caledonia were first discovered in 1865. Garnieritic laterite was initially mined in 1875 and continues to this date. The ore grade has declined from 10 percent nickel to about 2.5 percent because the highest-grade ores have been removed.

Laterites cover a third of New Caledonia's 19,000 km^2 to an average depth of about 20 m. The deposits resulted from the weathering of Oligocene peridotites, primarily harzburgite and dunites. Although both limonitic and garnieritic (saprolites) laterites exist on the island, only garnieritic ores are presently mined. The primary product for these ores is ferronickel, which is produced from SLN's Doniambo ferronickel plant; ores are shipped to Japan. In addition to SLN's operation, the Petit Mineurs, small syndicate miners, were evaluated, including those at Kouaova, Moneo, and Nakety, which combined contain a nickel resource exceeding 6.5 Mmt of recoverable nickel. This estimate is considered conservative. The New Caledonian laterites contain approximately 30 percent of the total recoverable nickel in laterites evaluated in this study and nearly 25 percent of total potentially recoverable nickel.

The Philippines

Philippine laterites are developed on Cretaceous ultramafics. The laterite profile generally consists of three zones: overburden, limonitic laterites, and saprolites. Nickel content of the ores ranges from about 0.4 percent to about 2.1 percent. A well-developed laterite profile is developed throughout most of the islands underlain by ultramafics. Ore bodies average about 8 meters thick and are mined by surface methods using shovels and trucks. Depending on the chemical nature of the ore, either ferronickel or nickel and cobalt can be produced. The ore with a low iron content (saprolites) is dried and shipped to Japan for production of ferronickel. The ore with high iron content (limonitic), containing up to 0.2 percent cobalt, was processed by Nonoc to recover nickel and cobalt. Resources in the Nonoc-Dinagat area are believed to be over 55 Mmt of ore averaging 1.22 percent nickel and 0.1 percent cobalt.

Reliable data about resources are difficult to acquire, but total potentially recoverable nickel from the Philippine deposits evaluated in this study is over 10 Mmt of nickel. More than 50 percent of the potentially recoverable nickel is on the islands of Mindanao and Palawan.

South America

Very large high-grade nickel resources are located in Brazil and Colombia. Ferronickel is produced at several Brazilian properties and at Cerro Matoso in Colombia. Ore feed grades at these operations range from about 1.5-3 percent nickel, dry weight. The ores contain from 20-25 percent moisture.

One leach operation, Tocantin, produces nickel and some cobalt from ores assaying between 1.5 and 2 percent nickel, dry weight. Evaluated Brazilian resources exceed 450 kmt of contained nickel. Most of these ores exceed 1.4 percent nickel, dry weight. Although not demonstrated, estimates of Brazilian resources of 200 Mmt have been reported (*25*).

Cerro Matoso has reserves sufficient for more than 25 years of production. Additional resources have not been fully evaluated.

United States

The laterites evaluated in the United States account for nearly 2 percent of total nickel in the MECs from all properties studied. Approximately 439 kmt of recoverable nickel was evaluated among the 3 nickel laterite deposits. The evaluated domestic laterite deposits are in California, Oregon, and Puerto Rico. Other deposits in these states and in Washington were not evaluated. These deposits were formed by weathering of ultramafic, often serpentinized, peridotite bodies. Garnierite is the principal nickel mineral. The Nickel Mountain Mine near Riddle, Oregon, which permanently closed in 1986, was the only recent domestic primary nickel producer. The Gasquet deposit in northwestern California has been fully explored. Production was originally scheduled to begin in spring 1982, but difficulty in acquiring capital delayed the venture. The hydrometallurgical process proposed for the operation has never been commercially tested. Coastal Mining Company, a subsidiary of Hanna, has also investigated laterite properties with the potential of producing nickel and cobalt. Resources at the Oregon property are estimated at about 27 Mmt of ore assaying 1 percent nickel and 0.13 percent cobalt.

Surface mining would be used to extract the ore from these deposits. Most of the U.S. laterite resources are located in environmentally sensitive areas, so that attempts to develop them would meet strong local opposition.

Other Countries

Other laterite deposits evaluated in this study are located in the Ivory Coast and the Malagasy Republic. All of these laterite resources have been explored to varying degrees but are undeveloped. The deposits are generally 5-30 meters thick and have iron contents of 10-25 percent and nickel grades of about 1 percent. Several deposits contain cobalt grades high enough to be potentially recoverable.

MANGANESE NODULES

Significant nickel resources occur in deep seabed nodules, also known as manganese nodules. These nodules occur on large areas of the ocean floor from 300-9,000 meters below sea level. The highest concentrations occur in the central East Pacific Ocean between 5° and 20° north latitude and 110° to 160° west longitude. Estimated resources range from 27 Mmt to 39 Bmt of nickel along with cobalt, copper, gold, manganese, and silver (*26*). Mining and lifting systems have been tested at one-fifth and one-tenth scale; however, technologies for mining and recovery are in preliminary stages. Hydrometallurgical and pyrometallurgical treatments have been extensively investigated. Within the context of this study, seabed nodules are considered a resource for future exploitation and are not included.

APPENDIX C.—MINING AND PROCESSING TECHNOLOGIES

The nature of the geologic occurrence of sulfide and laterite ores usually dictates underground mining for sulfides and surface mining for laterites. In addition, differences in chemistry of the ores require specific processing methods to produce a final marketable product. Following is a brief discussion of the mining and processing methods for sulfide and laterite ores.

SULFIDE TECHNOLOGIES

The majority of nickel sulfide ores is taken through four basic steps to recover nickel and associated coproducts and byproducts: mining, beneficiation, smelting, and refining. In some cases, concentrates can be processed hydrometallurgically.

Mining

Nickel sulfide ore is mined by surface and underground methods. Surface or open-pit mining is based on standard engineering practices using power shovels and trucks and generally does not present any special problems. Virtually all nickel sulfide mines use underground mining.

The Sudbury District is the largest and one of the most efficient nickel mining districts in the world. Inco and Falconbridge use vertical retreat mining or vertical crater retreat (VCR), mechanized undercut and fill, and large-diameter underground blasthole mining bulk methods at Sudbury. From the late 1970s through the 1980s, mining productivity increased significantly owing to the development of bulk-mining techniques, resulting in lower costs. In 1987, about half as many miners were required as in 1981 to produce an equivalent amount of ore. In 1981, about a third of the underground ore production in the District originated from VCR methods, but by 1987, almost 85 percent of the ore was recovered using this method. VCR has numerous advantages over conventional mining: Mining activities are concentrated, mining is continuous, secondary recovery is not necessary because no pillars are left, recovery is improved, drilling is reduced, secondary blasting is required less often, and mine safety is improved. Mining costs for underground operations are relatively high and are a major component of the total cost to recover nickel from sulfide deposits.

Beneficiation

Beneficiation of sulfide ores is generally more complicated than of laterites. Sulfide ore is crushed, ground in ball or rod mills, and floated. (Underground track-mounted crushers have also been installed in the Sudbury District and have contributed to lower costs). Magnetic separation may precede flotation. Depending upon the complexity of the ore, the flotation circuits may be designed to recover high-grade nickel-copper and/or high-grade copper-nickel concentrates. Nickel recovered averages about 90 percent, concentrate grades approximately 12 percent. Pyrrhotite may also be recovered as a separate concentrate. Depending on the ore content, the various concentrates may contain variable amounts of cobalt, gold, silver, and PGM.

Pyrometallurgical Postmill Processing

Most nickel sulfide concentrates are processed to a matte in three stages: roasting, smelting, and converting. Roasting is applied to concentrates that contain more iron than nickel and serves as a preparatory step to smelting. Roasting is accomplished by heating the concentrate in an oxygen-enriched atmosphere, which results in the oxidation of the contained metal sulfides and in the removal of up to 50 percent of the sulfur. Roasting also preheats the material before smelting.

Most smelting of a roasted concentrate takes place in flash smelters and/or electric furnaces. The term "smelting" refers to melting of the ore or concentrate under conditions that separate the desired metal from other constituents. The flash smelting process entails the injection of concentrate and flux with oxygen or preheated air into a furnace chamber. The term "flash" is derived from the high-heat-producing reaction between the furnace atmosphere, iron, and sulfur.

Electric furnace smelting operates by passing an electrical charge through the feed concentrate. The electrical resistance caused by the concentrate produces heat, which results in melting. The energy-intensive nature of this method often requires a low-cost energy source, such as hydroelectric power, to remain cost competitive.

Conversion is the process by which the remaining iron and sulfur are oxidized to eliminate residual iron sulfide. Conversion of the matte is generally carried out in Pierce-Smith converters combining heat and an oxygen-enriched atmosphere. Smelting produces mattes containing about 50 percent nickel. Over 90 percent of the nickel contained in the concentrate is recovered. The matte is usually cast into anodes for electrolytic refining to nickel metal. Other constituent metals may be recovered by processing the slimes resulting from the electrolytic process.

Hydrometallurgical Postmill Processing

Hydrometallurgical methods are also an efficient and economically attractive method for the treatment and recovery of nickel and byproduct metals from nickel sulfide concentrates. The principal purpose of a hydrometallurgical method is to selectively leach the desired metals into solution. Ammonia, although a relatively expensive reagent, is most desirable as a leaching agent because of its selectivity of leaching nickel, copper, and cobalt while not reacting with carbon steel equipment, as do acid leach solutions. The ammoniacal pressure leaching process was first developed on a commercial scale by Sherritt-Gordon at its Fort Saskatchewan refinery in Alberta, Canada. This hydrometallurgical process can be used directly on primary nickel, copper, and cobalt sulfide concentrates, in most cases eliminating the need for roasting.

Leaching is carried out in a solution of ammonia, oxygen, and water at 70°-90° C and at 100-150 psi. Nickel, cobalt, and copper are converted to soluble ammines, iron is converted to an insoluble hydrated ferric oxide, and the sulfur is oxidized to various soluble sulfur-oxygen ions. Metals dissolved in the leach solution are then individually separated. The solution is heated to boil off free ammonia, and a copper sulfide precipitate is formed and later refined. The pregnant solution is then treated in an "oxydrolysis" autoclave to convert unsaturated compounds into ammonium sulfate. Nickel and cobalt are separately precipitated out of the solution in an autoclave with an atmosphere of hydrogen at 500 psi. The nickel powder (precipitate) is either briquetted or rolled to form nickel strip, and the cobalt is marketed as powder. The remaining ammonium sulfate, recovered by evaporation as ammonium sulfate crystals, is marketed as Sherritt ammonium sulfate fertilizer.

Refining of Nickel

Electrowinning, electrorefining, and a vapometallurgical process are techniques used for refining nickel into high-purity metal. Electrowinning is a process for recovering a metal previously dissolved in an electrolyte. An electric current passing through the solution causes the metal to deposit on a cathode. Sometimes an impure cathode must be purified by electrorefining.

Electrorefining of nickel anodes is accomplished by placing the anodes in a cell or tank containing an electrolyte solution. An electric current dissolves the anodes and causes them to plate on cathodes. Impurities collect in the sludge and are periodically removed and processed further to recover other products, including precious metals.

The vapometallurgical process, or carbonyl gas process, uses impure metallic nickel granules as feed. These granules are fed into a rotating carbonyl reactor and converted to nickel-iron carbonyl vapor by heating at 50°-80° C in a high-pressure carbon monoxide atmosphere. The vapor is condensed to a nickel iron carbonyl liquid, which is decomposed to high-purity nickel.

LATERITE TECHNOLOGIES

Laterites, which are usually mined by conventional surface methods, have high free moisture contents (up to 30 percent) and have no effective preconcentration methods. Postmine processing is dictated by the chemistry of the ore, either limonitic or garnieritic, which can also determine the product, either ferronickel or matte.

Mining

Most laterite deposits are mined by open-cut and modified open-pit methods. The soft nature of most laterite ores allows for mining with power shovels, draglines, front-end loaders, and bulldozers, and usually little blasting is required. Laterite mining operations strongly resemble simple earth-moving operations. A major problem associated with mining laterites is the high percentage of moisture content, up to 30 percent, in the ore. This high moisture content adds weight and significantly reduces equipment traction and ground support, thus dictating the size of the equipment. Other problems are related to removal of boulders, maintaining grade control because of zonation of ore bodies, and topography.

Underground mining of laterites is rarely undertaken owing to ground support problems and associated higher operating costs. An exception is Larco's St. John Mine in Greece, where underground cut-and-fill and sublevel caving methods are employed.

Postmine Processing

The selection between pyrometallurgical and hydrometallurgical treatment of laterite ores is dictated largely by the composition of the ore, and the primary criterion is the ratio of magnesium to iron. Ores in the limonitic zone are treated by hydrometallurgical methods, the garnieritic ores by pyrometallurgical methods. Processing of material in a transition zone, using either method, can create problems in recovering metals and result in higher costs.

Pyrometallurgical Methods

The major pyrometallurgical methods consist of direct reduction to ferronickel and smelting to a nickel matte. Each method is briefly discussed in the following sections.

Production of Ferronickel

The majority of laterites is processed to ferronickel, which generally consists of the following four steps: drying, calcining, smelting, and refining.

Drying the ore consists of loading the wet laterite ore into rotary dryers, which reduce the moisture content by more than half (typically 30 percent to 5 percent). In some cases, the ore is sun dried to reduce moisture and lower costs. After the ore is dried, it can be crushed and screened. From the crushing and screening plant, the ore is fed to calciners to remove or decompose carbonates and moisture. The hot calcine is transported to the smelter and is fed, with reducing agents, to melting furnaces to produce ferronickel. Following smelting, the molten ferronickel is fed to refining furnaces for dephosphorizing and deoxidizing.

A final ferronickel composition is generally 20-40 percent nickel, with the remainder primarily iron with traces of cobalt, sulfur, carbon, and silicon. No byproduct credit is given for cobalt content.

Production of Matte

Approximately 18 percent of nickel produced from laterite ore is processed to a nickel sulfide matte. This process is used on a small portion of New Caledonian ores (approximately 20 percent of total nickel production) and all of P.T. Inco's production from Indonesia. Production of matte consists of smelting a charge comprised of laterite ore, coke, limestone, and a source of sulfur, usually gypsum or liquid sulfur. This process results in high-iron nickel sulfide matte, which is refined in a converter to remove the iron and some sulfur. The refined nickel sulfide matte contains up to 75 percent nickel and 25 percent sulfur with some impurities. The matte is shipped to refineries for processing to nickel metal.

Hydrometallurgical Methods

Limonitic laterite ores and some mixed laterites with low magnesia and silica content are amenable to processing by hydrometallurgical methods. Two primary methods are used for processing these ores: reduction roasting followed by ammoniacal leaching, and sulfuric acid leaching.

The ammoniacal leaching process (Nicaro) consists of drying, grinding, reducing in multiple-hearth roasters, leaching out ammonia carbonate, separating out cobalt, precipitating nickel carbonate, and recovering ammonia. The nickel carbonate precipitate is then calcined to produce a nickel oxide. The roast-reduction ammonia leaching process is used on the Greenvale, Australia, laterite ore. The final nickel product averages about 90 percent nickel, with an estimated 75 percent overall recovery. The Nonoc operation, which closed in 1986, used the roast-reduction ammonium carbonate leaching method. The closure resulted from problems with extraction, availability of labor, and high costs. At its peak, the mine produced 24 kmt of nickel per year, only 65 percent of its design capacity.

The sulfuric acid leaching (Caron) process used at Moa Bay, Cuba, does not require drying. The wet ore is pumped to leaching towers, where it is exposed to high-temperature sulfuric acid. Nickel, cobalt, and magnesium are dissolved and then precipitated by the addition of hydrogen sulfide gas. The resulting concentrate is sent to a refinery, where it is dissolved through a series of precipitation and dissolution steps, and refined metals (e.g., nickel, copper, and cobalt) are recovered. Nickel sinter and metal are produced. Overall nickel recovery is usually 60-90 percent of the nickel in the ore. The sulfuric acid leaching process is presently used in Cuba and in Niquelandia, Brazil.

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