

Information Circular 9085

Columbium Availability—Market Economy Countries

A Minerals Availability Appraisal

By Federick W. Miller, R. J. Fantel, and D. A. Buckingham



UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
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As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environment and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

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PREFACE

The Bureau of Mines is assessing the worldwide availability of selected minerals of economic significance, most of which are also critical minerals. The Bureau identifies, collects, compiles, and evaluates information on producing, developing, and explored deposits, and on mineral processing plants worldwide. Objectives are to classify both domestic and foreign resources, to identify by cost evaluation those demonstrated resources that are reserves, and to prepare analyses of mineral availability.

This report is one of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources. Questions about, or comments on, these reports should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., NW., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	mt/h	metric ton per hour
g	gram	mt/yr	metric ton per year
g/mt	gram per metric ton	mm	millimeter
h	hour	Mmt	million metric tons
kg	kilogram	μm	micrometer
m	meter	pct	percent
min	minute	lb	pound
mt	metric ton	yr	year

COLUMBIUM AVAILABILITY—MARKET ECONOMY COUNTRIES

A Minerals Availability Appraisal

By Frederick W. Miller,¹ R. J. Fantel,¹ and D. A. Buckingham²

ABSTRACT

The Bureau of Mines has investigated the availability of columbium from 19 deposits (3 producers and 16 nonproducers) in 7 market economy countries (MEC's). Brazil has the largest recoverable columbium resource, possessing approximately 2.39 million metric tons (Mmt), or 69 pct of the MEC total (3.47 Mmt). The Western Hemisphere countries of Brazil, Canada and the United States contain 3.14 Mmt of recoverable columbium or 90 pct of the MEC total. Columbium recovered as a byproduct of tin mining is not included as part of MEC resources in this study.

Currently producing mines are Araxa and Catalao in Brazil, and Niobec in Canada. These three mines have 2.42 Mmt of recoverable resources or approximately 69 pct of the MEC total. It is estimated that these mines, operating at full capacity, could satisfy cumulative MEC demand (based on an annual growth rate of 5.1 pct) for the next 20 yr.

The United States is totally dependent upon foreign sources for its columbium supply. The majority of U.S. columbium is imported from Brazil in the form of steelmaking-grade ferrocolumbium. Canada has been the sole source of pyrochlore concentrates since Brazil discontinued exports in 1981. The United States also imports small (but important) quantities of columbium as columbite concentrates from Nigeria and Brazil, as columbite contained in tin slags from Thailand and Malaysia, and as synthetic concentrates from the Federal Republic of Germany.

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INTRODUCTION

The primary use of columbium (niobium) is as an alloying element in steels and superalloys. It has been estimated that 85 to 90 pct of columbium production in market economy countries³ (MEC's) is presently consumed by the steelmaking industry in the form of ferrocolumbium (1).⁴

Columbium occurs primarily in two mineral forms, pyrochlore (Na, Ca)₂Cb₂(O, OH, F)₇ and columbite⁵ (Fe, Mn)(Cb, Ta)₂O₆. Mill concentrates produced from either mineral form contain approximately 60 pct columbium pentoxide (Cb₂O₅), equivalent to about 42 pct Cb (2). Columbium concentrates are principally recovered from pyrochlore minerals and, to a lesser extent, from columbite minerals.

The most common upgraded form of columbium produced from pyrochlore concentrates is steelmaking-grade ferrocolumbium. Recently, technology has been developed to convert this ferrocolumbium to columbium oxide suitable for the manufacture of high-purity ferrocolumbium, nickel-

columbium, and columbium metal (2). Prior to this technology, production of high-purity oxides was possible only through the processing of columbite ores. This development has greatly increased the market importance of pyrochlore ores.

The purpose of this study is to evaluate columbium resources of the MEC and to assess the production costs of recovering ferrocolumbium. Table 1 lists 19 columbium deposits in 7 MEC's included in this study; figure 1 shows their locations. The majority of MEC columbium resources are found in Brazil and Canada.

The United States is a major consumer of columbium products, totally dependent upon foreign sources for all of its columbium. More importantly, the U.S. ferrocolumbium industry could be threatened by the tendency of major columbium mine owners to further vertically integrate their operations to produce upgraded columbium products. If these producers were to supply upgraded columbium products at significantly lower costs, the U.S. columbium industry could be at a distinct economic disadvantage. Subsequently, if the United States lost a major share of its processing capability because of increased competition from abroad, it would become totally dependent upon imports for both columbium concentrates and upgraded columbium products (2).

³Information on columbium resources located in the U.S.S.R. or other centrally planned economy countries (CPEC's) is not available and is not addressed in this evaluation.

⁴Italic numbers in parentheses refer to items in the list of references at the end of this report.

⁵Columbite is the columbium-rich member of the columbite-tantalite isomorphous series.

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The authors would like to thank Larry D. Cunningham, Columbium Specialist of the Bureau's Division of Ferrous

Metals in Washington, DC, for his assistance in the review of the data used in this report.

Table 1.—Columbium deposit ownership and status data

Nation and deposit name	Owner	Status ¹
United States:		
Gem Park Complex ²	Coca Mines, Inc.	NP
Iron Hill ²	Buttes Gas and Oil Co.	NP
Brazil:		
Araxa	CBMM	P
Catalao	Mineracao Catalao de Goias S.A.	D
Catalao Ouidor	Goias Niobio S.A.	P
Canada:		
Crevier	SOQUEM	NP
James Bay	Esso, Morrison, Canray, Argor	NP
Lackner Lake	Mertec Resources Develop Ltd.	NP
Martison Lake	New Ventura Equities/Cambell Resources	NP
Nemegosenda	Gulf Agric Chem. Co. Ltd.	NP
Niobec	Teck Corp., SOQUEM	P
Oka	St. Lawrence CB, Metals Corp.	NP
Strange Lake	Iron Ore Co. of Canada	NP
Thor Lake	Highwood Resc, Calabros Ltd.	NP
Kenya: Mrima Hill	Mrima Industrial Minerals	NP
Tanzania: Panda Hill	State Mining Corp. (STAMICO)	NP
Uganda: Sukulu Hills	Sukula Mines Limited	NP
Zaire:		
Bingo	Somikivu	NP
Lueshedo	NP

¹P producing. D Developing. NP Nonproducing.

²Colorado.

COLUMBIUM INDUSTRY

Columbium serves as an alloying element in high-strength, low-alloy (HSLA) steels and superalloys. HSLA's are so named because of their relatively high strengths, obtained by the addition of very modest amounts of alloying elements (less than 1 pct alloying, other than carbon and manganese). This strengthening effect has led to widespread use of HSLA steels in oil and gas pipeline steels, in lighter, more fuel-efficient automobiles, and in the construction of massive structures such as skyscrapers, bridges, and nuclear reactors (3). Columbium is also used as a "carbide

stabilizer" in stainless steels to improve their resistance to corrosion when used in exhaust manifolds, fire walls, and pressure vessels.

Cobalt-, nickel- and iron-based superalloys, containing between 1.0 to 5.0 pct Cb, are used to make gas-turbine engine components, rocket-nozzle subassemblies, and heat-resistant combustion equipment.

New applications of columbium-containing superconductors are being tested for future energy generation and transmission needs (2). Superconductors have the ability to

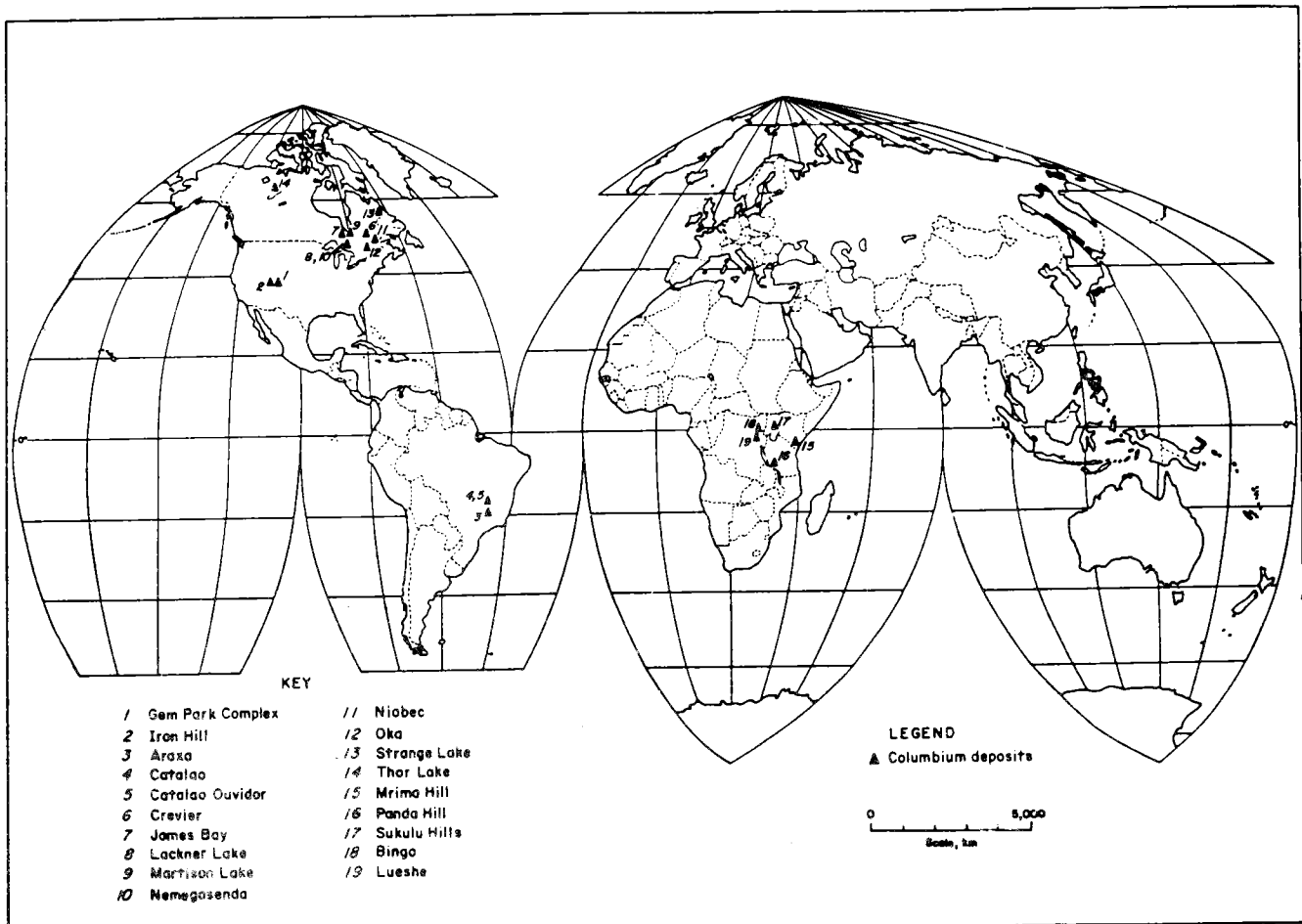


FIGURE 1.—Location of MEC pyrochlore deposits.

lose all resistance to direct electrical current at temperatures near absolute zero (3), and columbium has unrivaled properties of superconductivity relative to other pure metals. Therefore, most commercial superconductor devices use columbium alloys such as columbium-titanium (CbTi) or columbium-tin (Cb₃Sn).

The majority of columbium concentrates are derived from the beneficiation of pyrochlore ores. Columbite ores, including columbite and columbite-tantalite mineral ores, were once the primary source of columbium, but their significance has diminished in recent years. Advances in technology have made possible the production of high-purity oxides through further processing of ferrocolumbium produced from pyrochlore concentrates (2). Previously, columbite ores were the major source of the oxides necessary for columbium-based alloys and superalloys. New technology, combined with the immense resource of pyrochlore ores, has almost totally replaced the use of columbite minerals as a source of columbium.

Brazil is the world's largest producer and processor of columbium (fig. 2), most of which is recovered from two pyrochlore deposits.⁶

The pyrochlore deposit at Araxa, owned by Campanhia Brasileira de Metalurgia e Mineracao (CBMM), has been in operation since 1961 and is the world's largest known columbium deposit. CBMM is owned by Campanhia Metropolitana de Comercio e Participacoes (55 pct) and Molycorp Inc. (a subsidiary of Union Oil Co. of California) of the United States (45 pct). Brazil's other operating pyrochlore mine, located at Catalao and owned by Mineracao Catalao de Goias S.A. (MCG), began operation in 1976. A 70-pct share of MCG was purchased by the Anglo-American Group in November 1984, with the balance (30 pct) held by Unamina, a local group of investors. Development of a third pyrochlore mine, Catalao Ouidor, began in 1981. This deposit is owned by Goias Niobio S.A., and was tentatively slated to begin production in 1985. Partners of Goias Niobio S.A. include Produtos Metallurgico S.A. (51 pct), Metais de Goias (24 pct), and Fibase, a subsidiary of National Economic Development Bank (25 pct).

The majority of Brazilian mine production concerns the manufacture of steelmaking-grade ferrocolumbium. By 1980, Araxa had vertically integrated its operation to include production of high-grade columbium oxides and by 1982, it had discontinued exporting pyrochlore concentrates (4).

Canada is the second largest MEC producer and its only exporter of pyrochlore concentrates. The Niobec Mine, located near the town of St. Honore in Quebec Province, has been Canada's only operating pyrochlore mine since it began production in 1976. Ownership of Niobec is split evenly between Societe Quebecoise d'Exploration Miniere (SOQUEM, a corporation of the Quebec Provincial Government) and Teck Corporation. The Oka Mine, also in Quebec, is owned by the St. Lawrence Columbium & Metal Corp. It began operation in 1961 but was closed in 1976 because of labor and economic problems. Substantial reserves remain at Oka and are included in this evaluation.

Owners of the Leushe deposit in Zaire completed construction of a 2 mt/h pilot plant in March 1984. The pilot plant was set up by a joint venture of Somnikubi (Societe Miniere Zairoise de Nyamukubi), Coframines, and Metallurg Inc. Commercial production is expected to begin

⁶Less than 1 pct of the columbium mined in Brazil is recovered as columbite from pegmatite mines that were not examined in this study.

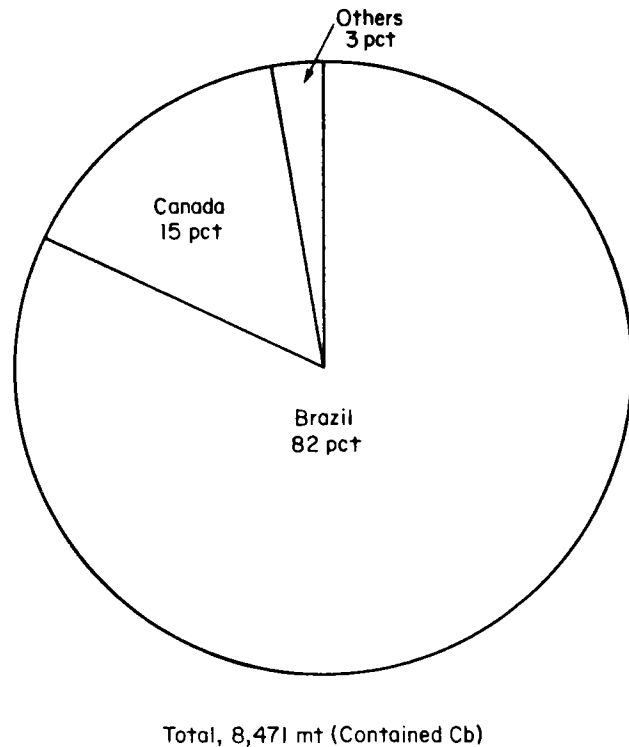


FIGURE 2.—Estimated MEC mine production, 1983.

by the end of 1986 (5). The Leushe deposit is owned by Somnikivu (Kivu Mining Co.) in which Metallurg holds a 70-pct share, the Zaire Government 20 pct, and Sominki (Societe Miniere et Industrielle du Kivu) 10 pct.

Columbium is considered a strategic and critical mineral to U.S. interests because of its defense-related uses in the aerospace, energy, and transportation industries. Columbium has not been mined commercially in the United States since 1959, except for small unreported quantities of columbium-bearing concentrates produced in 1980-82 (4). Therefore, the United States is totally dependent upon foreign imports of columbium, primarily in the form of ferrocolumbium or columbium oxides from Brazil and pyrochlore concentrates from Canada. The United States imports smaller amounts of columbium in the form of columbite concentrates from Nigeria, tin slags from Malaysia and Thailand, and synthetic concentrates made by upgrading low-grade tin slags from the Federal Republic of Germany. Imports of columbite, especially from Nigeria, have been declining steadily.

The U.S. columbium processing industry consists of eight companies with nine plants integrated through the processing of columbium concentrates to upgraded end products, including columbium metal (2). U.S. industry is potentially threatened by the continued vertical integration of foreign mines, principally in Brazil, through the production of high-grade columbium products. Brazil's share of the U.S. ferrocolumbium market has increased from 0 pct 20 yr ago, to nearly 75 pct (4). It is possible that this trend will lead to total U.S. dependence on foreign sources for all columbium products.

Columbium stored in the National Defense Stockpile, as of November 30, 1984, amounts to 1,271 mt (2.8 M lb) contained columbium, primarily in the form of concentrate and ferrocolumbium, with smaller amounts contained in carbide

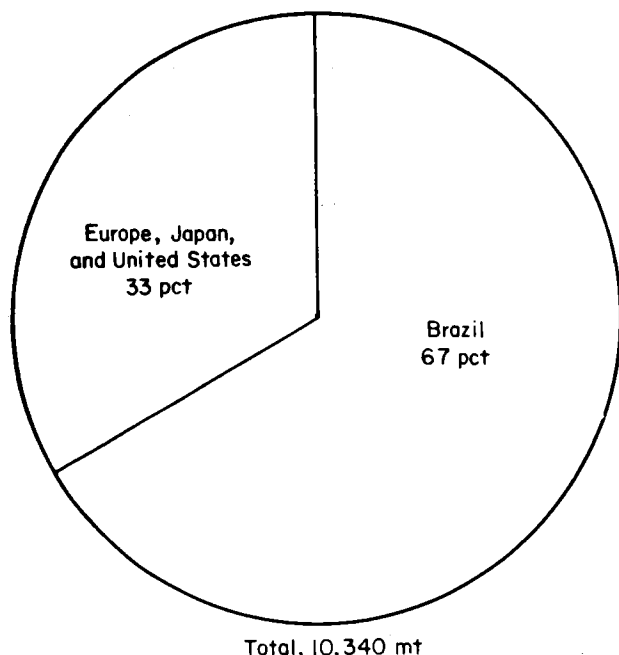


FIGURE 3.—Estimated MEC ferrocolumbium production, 1983.

powder and columbium metal (4). The last sale from this stockpile was in 1976. In 1984, bids solicited by the General Services Administration to supply up to 400,000 lb of columbium contained in concentrates for the stockpile were rejected because they were too expensive and did not conform to prevailing market conditions. (4).

In 1983, MEC production of ferrocolumbium was estimated by the Bureau of Mines Columbium Specialist at 10,340 mt (6). Figure 3 shows the breakdown of MEC ferrocolumbium production by country and illustrates Brazil's control of an estimated 67 pct of the industry. Important amounts of ferrocolumbium are also produced using imported pyrochlore and columbite concentrates in the United States, Western Europe, and Japan. European producers of ferrocolumbium include Austria, Belgium-Luxembourg, the United Kingdom and the Federal Republic of Germany. The United States is currently the largest producer of columbium metal.

Overall U.S. consumption of columbium increased from 2,600 mt in 1983 to 3,500 mt in 1984, owing to increased consumption by steel and automotive industries (4). This reverses the 30-pct decrease reported in overall U.S. consumption in 1982 from the record high established in 1981 (7).

EVALUATION METHODOLOGY

METHODOLOGY

Data collected for this report are stored, retrieved, and analyzed in a computerized component of the Minerals Availability Program (MAP). Data for foreign mines and deposits used in the evaluation were collected by Pincock, Allen & Holt, Inc., under Bureau of Mines contract J0225022 (8). Data for domestic deposits were collected by the Bureau's Intermountain Field Operations Center in Denver, CO. After a deposit was selected for the analysis, an evaluation of the operation began. The flow of the Minerals Availability evaluation process from deposit identification through analysis of availability information is illustrated in figure 4. The following evaluation and analysis methodology was used in this study:

1. The quantity and grade of columbium resources from each deposit were evaluated in relation to physical and technological conditions affecting production as of the study date, January 1984.

2. Actual mining, concentrating, and processing (smelting) methods employed at producing mines, along with appropriate methods used at nonproducers, were described. Related capital investments and operating costs for each operation were then estimated in 1984 dollars.

3. An economic analysis of each operation was performed to determine: (a) the average total production cost at a specified discounted cash flow rate of return (DCFRR) on invested capital for each operation over its entire producing life and (b) the ferrocolumbium potentially recoverable on a total and annual basis.

4. Following individual property analysis, all properties in the study were aggregated into columbium availability curves. These curves represent total potential columbium contained in ferrocolumbium producible over the life of each operation, arranged in order from the lowest to highest cost

deposits. The curves illustrate the comparative costs associated with any given level of potential total output, and provide an estimate of what the average long-run ferrocolumbium price (in January 1984 dollars) would have to be for a given tonnage to become potentially available. This long-run price would provide enough revenue to cover the average total cost of production including an investment return high enough to attract new capital. A 15-pct real DCFRR on the total investment of each operation was used in this study. Additional curves were generated at a break-even or 0-pct DCFRR.

5. Annual availability curves are also presented in the report. These curves show amounts of columbium potentially available each year at various levels of average total cost of production. These curves reflect the current installed capacity levels of producing deposits, including known expansion and development plans, and assumed capacity levels and development schedules of undeveloped deposits.

DEPOSIT SELECTION CRITERIA

Deposit selection criteria was limited to known deposits with demonstrated resources of columbium. Ownership and current status information of individual columbium mines and deposits in this study are presented in table 1.

For the 19 deposits evaluated, tonnage estimates were based on resource values considered demonstrated according to definitions established by the Bureau of Mines and the U.S. Geological Survey (9) (fig. 5). Demonstrated resource data presented in this paper were available from published sources (Bureau, U.S. Geological Survey, State and industry publications, professional journals, and company annuals reports and 10K's), and personal contacts (deposit owners, individuals or government agencies with personal knowledge of the deposit).

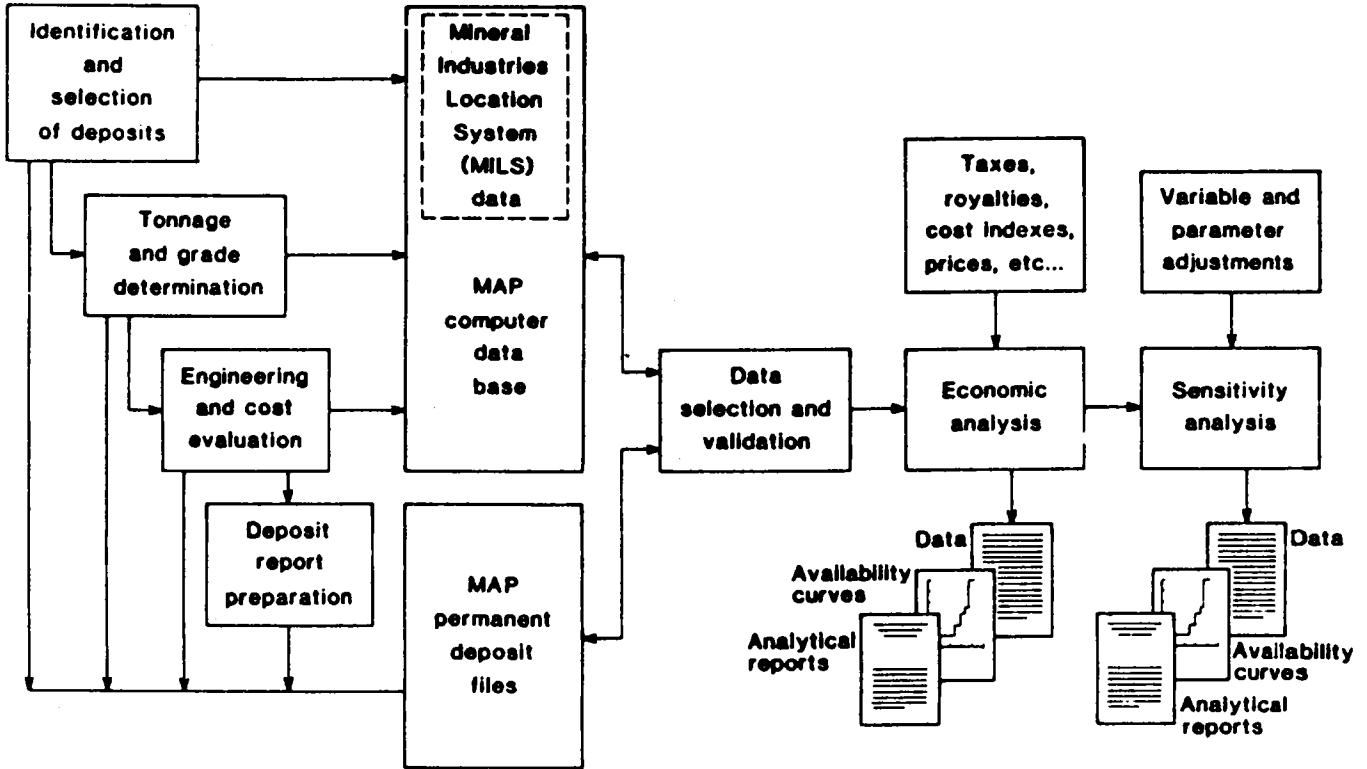


FIGURE 4.—Flow chart of evaluation procedure.

Cumulative production	IDENTIFIED RESOURCES		UNDISCOVERED RESOURCES		
	Demonstrated		Inferred	Probability range	
	Measured	Indicated		Hypothetical	Speculative
ECONOMIC	Reserve		Inferred		
MARGINALLY ECONOMIC	base		reserve	+	
SUB-ECONOMIC			base	+	
Other occurrences	Includes nonconventional and low-grade materials				

FIGURE 5.—Mineral resource classification categories.

Resources for analysis had to be recoverable using current mining, milling, and processing technologies. In addition, the deposits had to meet the following criteria:

1. Producing properties included must account for at least 85 pct of the columbium production from each significant producing country.

2. Developing and explored deposits and past producing deposits needed a demonstrated columbium reserve-resource quantity equivalent to at least the lower limits of the reserve-resource quantity of the producing deposits. Inferred or hypothetical resource levels could not be included in the economic evaluations.

3. Columbium produced as a byproduct of tin mining operations, such as in Nigeria, Thailand, and Malaysia, totals less than 5 pct of current world's production figures and was not included in this evaluation.

For this study, a total of 3 producing mines, 1 developing mine, and 15 nonproducing deposits were evaluated. All deposits evaluated in the study are from MEC's Information on columbium resources in CPEC's such as U.S.S.R. and China was not available. Additionally, properties at which columbium is produced as a byproduct of tin mining are not addressed in this evaluation.

RESOURCES

Estimates of in situ demonstrated resources amount to over 946 Mmt of material (5.36 Mmt of contained Cb) from studied deposits in the Western Hemisphere countries of the United States, Canada, and Brazil (collectively referred to in this study as the Americas), and the four African nations of Zaire, Uganda, Tanzania, and Kenya. A detailed breakdown of MEC resources is given in table 2 and figure 6. Inferred resources from studied deposits contribute an additional 655 Mmt of material, containing 6.41 Mmt Cb. Approximately 79 pct of the inferred resources of contained Cb are found in Brazil, with Africa and North America containing 10 and 11 pct, respectively.

Regionally, carbonite deposits in Brazil account for 60 pct of the contained columbium resources at the demonstrated level. Another 26 pct is located in the United States and Canada with the remaining 14 pct found in the four African countries. Thus, 86 pct of these columbium resources are available in the Americas alone.

Reserve base figures reported by the Bureau's columbium specialist (2, 4) were based largely on the data in this report. The following figures represent contained columbium:

Brazil 3.6 Mmt
 North America:
 United States Negligible
 Canada 0.3 Mmt
 Africa 0.2 Mmt

Differences in Brazilian resource tonnages reported by the columbium specialist and those reported here resulted from rounding up of the figures (by the columbium specialist) from 7.5 to 8.0 billion lb of contained columbium. The differences in resource tonnages reported for Canada and Africa resulted from exclusion of several deposits based on the columbium specialist's judgmental interpretation of their current economic feasibility.

Table 2.—Summary of columbium resources in market economy countries

	In situ, Mmt	Av grade Cb, pct	Contained Cb, Mmt
Demonstrated:			
Brazil	207	1.57	3.25
North America	472	.29	1.37
Africa	268	.28	.75
Total	946	.57	5.36
Inferred:			
Brazil	290	1.75	5.08
North America	250	.28	.70
Africa	115	.52	.60
Total	655	.97	6.38

NOTE.—Data may not add to totals shown because of independent rounding.

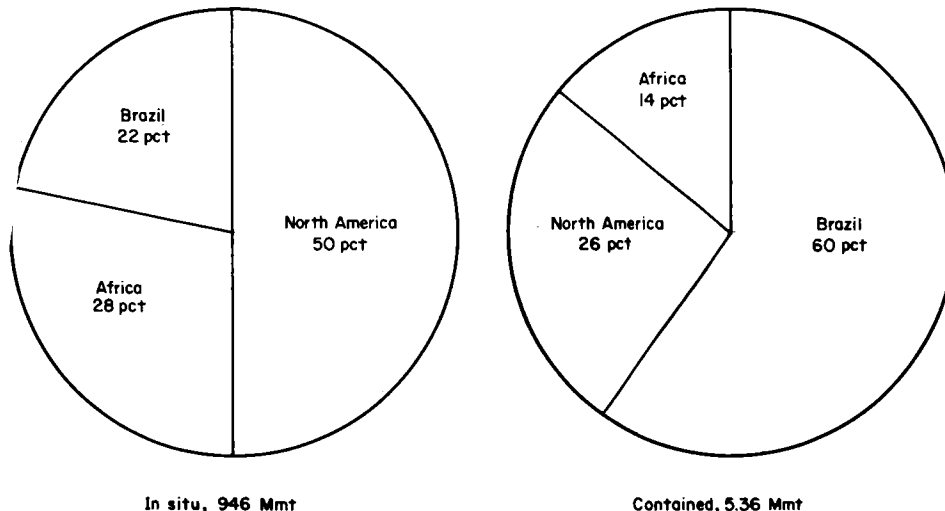


FIGURE 6.—Demonstrated columbium resources.

GEOLOGY

Columbium minerals chiefly occur in nature as oxides, multiple oxides, and hydroxides (10). Principal ore minerals include:

Pyrochlore (Na, Ca)₂ Cb₂ (O, OH, F)₇
 Pandaite (Ba, Sr) (Cb, T) (O, OH)₇
 Columbite-tantalite (Fe, Mn) (Cb, Ta)₂O₆
 Loparite (Ce, Na, Ca)₂ (Ti, Cb)₂O₆
 Ixiolite (Ta, Nb, Sn, Fe, Mn)₄O₈

Economic concentrations of columbium minerals occur predominantly in the following related members of intrusive alkaline rock complexes:

- a. carbonatites.
- b. alkaline granites.
- c. pegmatites.
- d. nepheline syenites.

Alkalic rock complexes are commonly restricted to the stable Precambrian cratons of continents (11). These complexes are often found in spatial relationship with fault lineaments such as the Kapuskasing-Moosonee High and the St. Lawrence River Fault in Canada, and the marginal fault of the East African rift system (12). However, some occurrences are less obvious where the spatial relationship may not in fact exist. Alkaline complexes commonly occur as small circular or elliptical bodies (usually less than 5 miles in diameter), arcuate ringlike structures, cone sheets, or crosscutting dikes.

Carbonatites provide the overwhelming source of columbium in the world. In fact, all current producers included in this study recover columbium from carbonatites. Carbonatites usually occur central to the alkaline complex in the form of a plug or an irregularly shaped body up to 3 mi² in area, or as a crosscutting dike (13).

Carbonatites are chemically unique igneous rocks that contain an anomalous amount of carbonates and resemble marble (13). The majority show an excess of calcite and are called sovites; those dominated by magnesium carbonates are called ankerites. Pyrochlore characteristically reaches peak abundance in sovites, though it has been reported in practically all associated rock types of the alkaline granitic suite (12). In addition, carbonatites may contain significant concentrations of phosphate, titanium, rare earths, uranium, thorium, fluorite ore minerals, and others.

The combination of radioactive thorium and uranium has greatly aided in the discovery of carbonatites. Radiometric reconnaissance using a gamma ray scintillometer was instrumental in discovering the Niobec property. Magnetometer surveys have also proven useful in the discovery of carbonatites enriched in magnetite.

Pyrochlore minerals predominantly occur in either primary or secondary carbonatites. Primary deposits repre-

sent the hard-rock ore body usually found in more temperate climates in which weathering has not been significant. Columbium is manifested as pyrochlore and concentrations range from 0.5 to 0.7 pct. The Niobec and Oka deposits in Canada are examples of this type.

Secondary deposits are found typically in tropical regions characterized by abundant rainfall. Deep in situ weathering results in strong residual enrichment of the more resistant columbium, phosphate, and iron minerals (14). Under these conditions, columbium may occur in an altered mineral form of pyrochlore called pandaite (more correctly known as bariopyrochlore) in which the sodium and calcium ions are replaced in varying percentages by barium and/or strontium. Enrichment of the columbium ore is 2 to 10 times greater than the concentrations found in primary deposits. The highest concentration of columbium ore is in the alluvial or laterized material which forms a cap overlying the carbonatite body. All Brazilian deposits have undergone this columbium enrichment process. African deposits, especially the Zairian, have undergone similar enrichment, but to a lesser extent. The importance of this grade enrichment becomes most obvious when comparing in situ demonstrated resources to the contained columbium. Figure 6 shows that Brazil, which contains 22 pct of the studied in situ demonstrated resources, actually possesses 60 pct of the studied contained columbium.

Alkaline granites and related ultramafics are a potential source of columbium in Canada. Deposits apparently associated with later stages of the alkaline intrusive event characteristically contain higher concentrations of tantalum in the columbite-tantalite minerals. If this tantalum can be economically recovered, alkaline granites might become significant sources of tantalum as well as columbium. Crevier and Thor Lake are examples of such deposits.

Pegmatites and their respective placer deposits once served as the major source of columbium in the mineral columbite-tantalite. Columbium was often produced as a coproduct with tantalum, both of which are byproducts of tin mining. The Jos Plateau in Nigeria is an example of such an operation (a tin mine producing byproducts of columbium and tantalum). The importance of columbite as a source of columbium has diminished in recent years with the increased utilization of pyrochlore ores. As such, pegmatites and their respective placer deposits currently contribute less than 5 pct of the MEC supply of columbium and are not included in this study.

Columbium deposits in the U.S.S.R. are principally derived from nepheline syenites, which comprise 1 pct of the exposed rock in that country. The main area of concentration is on the Kola Peninsula. The principal columbium mineral is loparite, which contains approximately 12 pct (Nb,Ta)₂O₆ (10-11).

MINING AND PROCESSING OF COLUMBIUM

MINING METHODS

All but 2 of the 19 columbium properties examined in this study are amenable to open-pit mining techniques. Of the three producing properties, Niobec is the only underground operation. Open-pit mining is performed at both Araxa and

Catalao and is proposed for use in development of the Catalao Ovidor deposit. Because of the highly weathered nature of the ore at these three operations, blasting is not required, allowing actual mine recoveries to exceed 90 pct. Ore material is mined using crawler tractors and loaded by front-end loaders onto either conveyor systems (used at

Araxa) or trucks (used at Catalao) to facilitate haulage to the mill. At Catalao, various degrees of weathering have resulted in inconsistent ore grades throughout the deposit. Drilling and metallurgical tests of drill-hole samples are required to determine ore grade in advance of mining. The ore is stockpiled according to grade and blended prior to beneficiation to achieve a constant feed grade.

Drilling and blasting have been proposed for the Canadian deposits because of their hard-rock ore bodies. Blasting is expected to require over 300 g of explosives per metric ton of material.

African deposits, though highly weathered, will require blasting to fracture the more resistant zones estimated to occupy 10 to 20 pct of each ore body. This blasting is estimated to require approximately 200 g of explosives for each metric ton of material mined. Expected mine recoveries range between 85 and 95 pct of the Canadian and African deposits.

Underground mining at Niobec is accomplished using a large-diameter blasthole stoping method. Mine development extends to a depth of 402 m and is serviced by a timbered shaft. Development levels are situated at 91, 137, 229, and 259 m. Primary crushing is carried out underground at the 350-m level. Mechanized, trackless mining equipment is used for the extraction of ore from the large vertical stopes. Mining equipment includes jumbos used to drive most headings, scissor lifts for rock bolting, and a combination of trucks and scooptrams (diesel and electric) for mucking. During stoping, in-the-hole drill rigs perform the drilling. Blasting of the bedrock requires a powder factor of 300 g of explosives per metric ton of material.

Sublevel stoping is proposed to replace surface mining in the Leushe deposit in Zaire after the sixth year of production. Underground haulage would be accomplished using trackless equipment. Jumbos would be used to drive the sublevel drifts. Blasting is expected to require 360 g of explosives per metric ton of material mined.

BENEFICIATION METHODS

Current columbium producers use a milling process to concentrate pyrochlore. This process includes crushing and grinding, magnetic separation, desliming, flotation, leaching, and calcining. An idealized mill process flow diagram is shown in figure 7. Most of the nonproducing properties included in the study were evaluated based on similar flowsheets, with some modifications due to ore metallurgy. Mill recoveries ranged from 20 to 80 pct based on variations in feed grade and physical characteristics of the ore (including fine-ness of pyrochlore minerals and the presence of impurities).

Depending on the type of ore, one to three stages of crushing are necessary. Laterized ores, such as Araxa's require less crushing than hard-rock ores, such as Niobec's. Crushing circuits consist of various vibrating screens, which feed jaw and impact crushers in open or closed circuits. Crushing circuit output ranges from minus 10 to minus 50 mm depending on optimum pyrochlore crystal liberation size.

Ball and rod mills are used in the grinding circuit, usually in one or two stages, to reduce the ore to optimum liberation size. Araxa pyrochlore is very fine grained with the majority of crystals smaller than 1 mm. Optimal liberation requires grinding 95 pct to minus 104 μm (minus 150 mesh) (14). This product is then sent through magnetic separation.

Magnetic separation is not carried out at every operation and may serve different purposes when used. Deposits with high magnetite concentrations like Araxa and Catalao use magnetic separation to remove the magnetite, which can amount to as much as 25 pct of the ore. This magnetite is approximately 67 pct Fe and is stockpiled for potential future recovery of the contained iron (14). Magnetic separation may also be used to concentrate the slightly magnetic pyrochlore ore. This process usually precedes desliming at most operations; however at Niobec, this step follows the desliming and the carbonate and pyrochlore flotation circuits.

During pyrochlore concentration, the desliming circuit is considered the most critical stage. Large quantities of slimes may inhibit the recovery of columbium as a pyrochlore flotation concentrate. Therefore, a three-stage desliming circuit is used, consisting of various sized classification and desliming cyclones along with scrubbers. Three desliming products are discharged from this circuit: a coarse fraction (greater than 30- μm), a slime fraction (between 3 and 30 μm) and a tails fraction. At Araxa, columbium is concentrated in the minus 37- +5- μm fraction. A minus 5- μm split eliminates 12 pct of the slimes, but only 5 to 7 pct of the columbium (14).

The columbium mineral is recovered by selective froth flotation of the pyrochlore. If coarse and slime products of desliming are discharged, a separate circuit is used for the flotation of fine particles from the desliming cyclones. Niobec uses a carbonate flotation circuit prior to pyrochlore flotation. Conditioning of the pyrochlore concentrate takes place in the desliming stage or just prior to flotation in a separate conditioning stage. Each flotation section consists of one rougher stage followed by three to five stages of cleaners. Final pyrochlore concentrates from both sections are combined and sent to thickening and filtration prior to calcining and leaching. The Niobec pyrochlore concentrate is not leached; instead it is sent to a sulfide flotation circuit to remove pyrite (fig. 7).

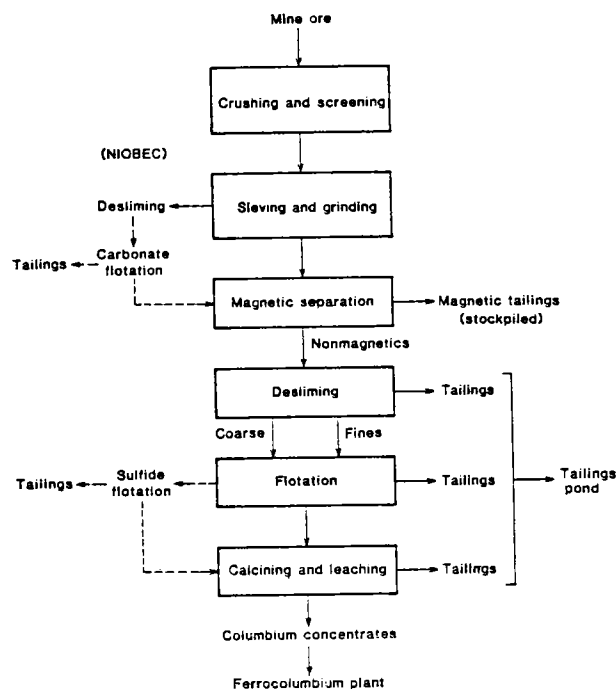


FIGURE 7.—Typical process flowsheet for pyrochlore mill.

A calcining and leaching stage may be necessary to reduce high concentrations of phosphate to meet market specifications. This is the situation at the Brazilian mines where two stages of leaching are used; a HCl acid leach and a NaOH leach. At Araxa, pyrochlore is calcined prior to the leaching steps, while at Catalao, calcining follows both leaching steps.

SMELTING METHODS

Aluminothermy is a batch process used for producing ferrocolumbium from pyrochlore concentrates. A typical reaction charge at CBMM's Araxa ferrocolumbium operation as reported by de Souza Paraiso and de Fuccio (14) follows:

Pyrochlore concentrate (60 pct Cb_2O_6) . . .	18,000 kg
Iron oxide (as hematite) (68 pct Fe)	4,000 kg
Aluminum powder	6,000 kg
Fluorspar	750 kg
Lime	500 kg

This charge is thoroughly mixed and then poured into a magnesite-brick-lined, steel cylinder. This cylinder, or reactor vessel, is placed into a silica sand bed lined with a mix-

ture of lime and fluorspar. A fuse mixture of aluminum powder and barium or sodium peroxide, ignited by a flame or small quantity of water, is used to start the exothermic reduction. Reaction time lasts 15 to 20 minutes and reaches a maximum temperature of 2,400°C. During this reaction, gangue material, along with other impurities forming the slag, separates from the columbium-iron alloy. After the reaction is completed and slag is drained off the top, the reaction cylinder is lifted, leaving columbium metal in the sand pit. After several hours of cooling and solidification, this metal "button" is removed from the pit, crushed, sieved, sized (depending on market specifications), and packaged for shipping. A typical charge will produce approximately 11 mt of ferrocolumbium containing 66 pct Cb (14). A similar grade of ferrocolumbium is produced at the Catalao smelter and expected from the developing Catalao Ouidor operation.

A ferrocolumbium smelter costing model was developed by Pincock, Allen & Holt, Inc. (8) for the Niobec Mine and subsequently applied to all nonproducing deposits for costing purposes. The model is very similar to the aluminothermic process used by the Brazilian operation except that it produces a ferrocolumbium product containing 60 pct Cb.

COLUMBIUM DEPOSIT COSTS AND EVALUATION

COSTING METHODOLOGY

For each property included in this study, a capital and operating cost evaluation was made, to reflect (as nearly as possible) actual operations or, in the case of nonproducers, to reflect expected operational technologies and capacities. Costs for U.S. deposits were developed by the Bureau's Intermountain Field Operations Center, Denver, CO, based either (1) on actual reported company data, (2) scaling from similar known operations, or (3) using the Bureau's Cost Estimating System (CES) (15). Costs from all foreign deposits were collected and developed by Pincock, Allen & Holt, Inc. (8). Some of the foreign deposits costs were actual company reported data; others were contractor estimates.

All costs presented in this report are in terms of January 1984 U.S. dollars, using appropriate exchange rates. The cost estimates reflect a prefeasibility estimate of ± 25 pct.

Capital expenditures were calculated for exploration, acquisition, development, mine plant and equipment, construction of the mill plant, and installation of the mill equipment. Capital expenditures for mining and processing facilities include the costs of mobile and stationary equipment, engineering design, facilities and utilities, and working capital. Facilities and utilities (infrastructure) includes the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance.

Mine and mill operating costs are calculated as a combination of direct and indirect costs. Direct operating costs include materials, utilities, direct and maintenance labor, and payroll overhead. Indirect operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research. Other costs, not included in operating costs but used in the analysis, include depreciation, insurance and taxes, and royalties. Operating

costs of ferrocolumbium plants and costs to transport the concentrates to the nearest plants were also included in this analysis.

OPERATING COSTS

Total operating costs are composed of mining, milling, and smelting costs; taxes (including property, state, Federal, and severance); and royalties. The percentages contributed to total operating cost by each principal operating component are shown in table 3 and figure 8. Actual operating costs for producers (not reported to protect the confidentiality of information) are significantly less than those for nonproducers. Total operating costs for Canadian and African nonproducers have been estimated at \$9.27 and \$7.34, respectively, per pound of contained columbium in ferrocolumbium.

For most of the examined properties, total operating costs decrease with increasing mill feed grades. Exceptions occur in cases where unique ore mineralogies do not permit efficient beneficiation. Table 3 shows feed grade as a weighted average calculated on a yearly production basis.

For producing surface mines in Brazil, operating costs are greatest in the milling and smelting area because the highly laterized Brazilian ores do not require blasting and can easily be mined at relatively low costs. Conversely, in Canada, mining costs estimated for nonproducing deposits include, blasting expenses required to fracture the hard-rock ore bodies and the more resistant, unweathered zones in the laterized African deposits. As expected for underground mines, mining costs comprise a major percentage of the total cost. Taxes and royalties are generally greater for nonproducers in this study because of the increased revenues required to cover the higher overall costs (including profit). Nonproducers require a higher taxable income (leading to

TABLE 3.—Breakdown of operating cost expressed as a percentage of total costs

	Producers		Nonproducers	
	Brazil (surface) ¹	N. America (underground)	N. America (surface)	Africa (surface) ²
Feed grade ³	1.40	0.47	0.27	0.65
Ore capacity ⁴	9,240	3,406	2,430	2,275
Total operating cost ⁵	W	W	\$9.27	\$7.34
Operating cost, pct of total:				
Mining	9	34	28	23
Milling	36	26	35	32
Taxes and royalties ⁶	17	6	25	29
Transportation	0	5	2	3
Smelting	38	29	10	13
Total	100	100	100	100

W Information withheld to avoid disclosing individual deposit data.
¹Includes 2 producing and 1 developing mine in Brazil.
²Leushe deposit is included as surface operation.
³Weighted average of ore grade to mill based on yearly production.
⁴Annual ore capacity as contained columbium.
⁵All costs are expressed as January 1984 U.S. dollars per pound of columbium contained in ferrocolumbium product on a weight-averaged basis.
⁶Includes all property, State, Federal, and severance taxes plus any royalty. The nonproducing deposits would require higher income in order to provide the stipulated 15-pct DCFROR; thus, aggregate tax payments are generally higher than for producing mines.

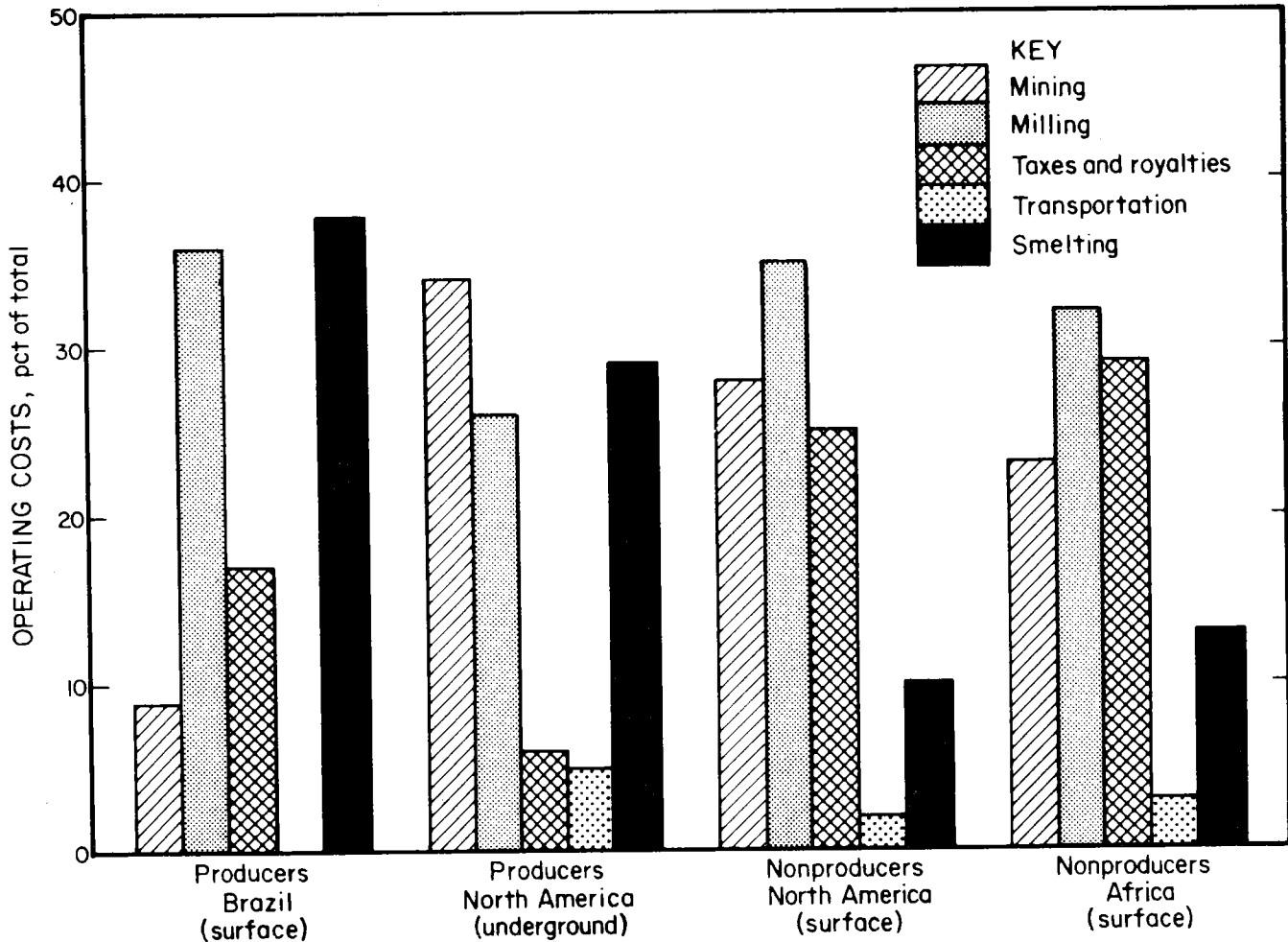


FIGURE 8.—Operating cost comparison for columbium mines and deposits.

TABLE 4.—Mine, mill, and smelter operating cost by principal component, percent

	Labor	Parts	Fuel	Blasting powder	Material	Electrical
PRODUCERS¹						
Surface:						
Mine	70	15	15	1	NAP	NAP
Mill	37	10	11	NAP	15	27
Smelter	13	2	1	NAP	83	1
Underground:						
Mine	56	16	6	15	1	7
Mill	37	21	2	NAP	31	9
Smelter	11	3	NAP	NAP	85	1
NONPRODUCERS (SURFACE)²						
North America:						
Mine	60	20	6	6	7	1
Mill	48	14	2	NAP	29	7
Smelter	11	3	1	NAP	85	1
Africa:						
Mine	50	25	12	5	8	NAP
Mill	43	15	1	NAP	25	16
Smelter	11	3	1	NAP	85	1

NAP Not applicable.

¹Includes 2 producing and 1 developing mine in Brazil.

²Leushe deposit is included as surface operation.

NOTE—Data may not add to totals shown because of independent rounding.

higher tax payments) to cover all operating costs and provide a 15-pct DCFROR on all investments. Operating costs for all properties, except in Brazil, also include the cost of transporting concentrates to a ferrocolumbium smelter. Brazilian operations include a smelter on site.

Mine, mill, and smelter operating costs for all studied deposits are broken down by percentage and shown in table 4. Both mine and mill operating costs are shown to be heavily weighted towards the cost of labor. Smelter costs are heavily weighted by the cost of industrial materials. This is directly related to the large quantities and high cost of aluminum used in the aluminothermic process.

CAPITAL COSTS

Table 5 and figure 9 show the average capital investments necessary to develop nonproducing columbium deposits in North America and Africa. For all deposits, mill investments comprise the greatest share of total investment—61 pct for North American deposits and 65 pct for African deposits. This is expected since similar concentrating processes are proposed for practically all operations. Notice the total capital cost is slightly less for the North American deposits, which have higher ore capacities.

COLUMBIUM AVAILABILITY

ECONOMIC EVALUATION METHODOLOGY

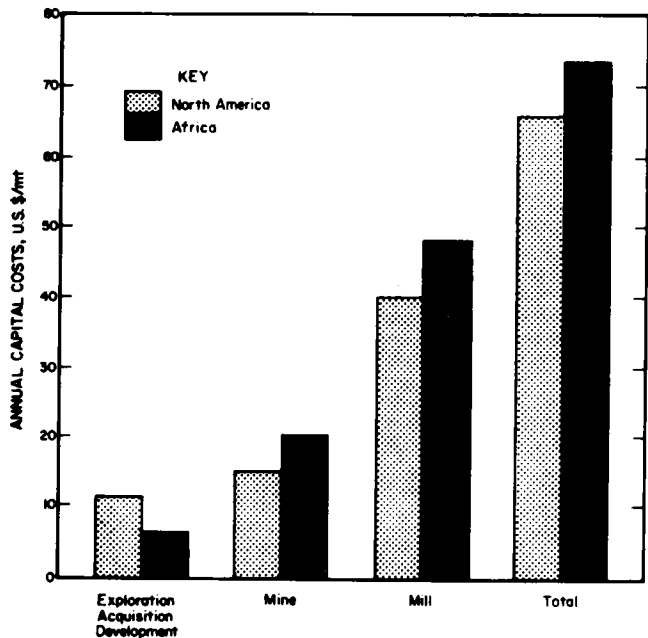
After establishing cost and engineering data, production parameters and cost estimates for each mine and deposit were entered into the Bureau's Supply Analysis Model (SAM). The Bureau has developed the SAM to perform DCFROR analyses to determine the long-run constant dollar price at which the primary commodity must be sold to recover all costs of production and investments (16). The DCFROR is defined as the rate of return making the pres-

TABLE 5.—Breakdown of capital cost required to develop non-producing columbium deposits in North America and Africa¹

	North America	Africa
Av ore capacity per deposit 10 ³ mt/yr	900	350
Total capital (10 ³ U.S.\$)	59	26
Annual capital costs, U.S.\$/mt ore:		
Exploration, acquisition, development	11	6
Mine	15	20
Mill	40	48
Total	66	74
Cost item share of total investment, pct:		
Exploration, acquisition, development	16	8
Mine	22	27
Mill	61	65

NOTE.—Data may not add to total shown because of independent rounding.

¹All deposits are anticipated to be surface mines. The Leushe deposit in Zaire is included as a surface mine although underground mining will begin following the 6th year of production.

**FIGURE 9.—Estimated capital cost required to develop non-producing deposits.**

Capital costs for the nonproducers in both Canada and Africa primarily reflect equipment cost (60 to 65 pct). The remaining capital is split between the construction costs for materials and labor.

ent worth of after-tax cash flow from an investment equal to the present worth of all investments (17). For this study, a 15-pct DCFROR was considered the necessary rate of return to cover the opportunity cost of capital plus risk. The determined value for columbium is equivalent to the average total cost of production (less credits for byproducts) for the operation over its producing life under the set of assumptions and conditions necessary to make an evaluation (e.g., mine plan, full-capacity production, and a market for all output).

If an operation has more than one product, each is priced according to the January 1984 market price. Revenues generated from each byproduct are credited to the proposed operations if, at the time of the study, their recovery was economically feasible. The following byproduct prices were used in this analysis:

<i>Byproducts</i>	<i>Market price, \$/mt</i>
Beryl ore	1,212.75
Phosphate	18.00
Rare-earth oxides	362.25
Tantalum	130.00

¹Contained.

Potential byproducts for specific deposits are listed below:

<i>Deposit name</i>	<i>Byproduct</i>
Canada:	
Crevier	Tantalum.
Martison Lake	Phosphate.
Strange Lake	Beryl ore, rare earths.
Thor Lake	Tantalum.
Uganda: Sukulu Hills	Phosphate.

None of the producing columbium mines in this study recover byproducts.

Although tantalum is present in the Canadian Crevier and Thor Lake deposits, a mill concentrate of sufficient marketable Ta₂O₅ grade could not be produced to justify applying a credit. An estimated minimum tantalum grade of 20-pct Ta₂O₅ would be required to justify a credit.

Based on the Bureau's methodology, all capital investments incurred prior to January 1969 are presumed to be fully depreciated and are treated as sunk costs. Capital investments incurred since January 1969 have the estimated undepreciated balance carried forward to January 1984. All reinvestment, operating, and transportation costs are expressed in January 1984 U.S. dollars. No escalation of either costs or prices was included because any increase in costs would be offset by an increase in market price of the commodities (16).

Detailed cash-flow analyses were generated by the SAM for each preproduction and production year of an operation beginning with the initial year of the analysis, 1984. Upon completion of the individual property analyses for each mine or deposit, all properties included in the study were simultaneously analyzed and aggregated into resource availability curves. Two types of curves have been generated for this study: (1) total availability curves at a 15-pct and 0-pct DCFROR, and (2) annual curves at selected production costs. Potential tonnage and estimated average total cost for each mine and deposit evaluated have been aggregated into columbium availability curves to illustrate the comparative costs associated with any given level of potential total output.

Total resource availability curves show the total quantity of recoverable columbium potentially available at each operation's average total cost of production (less byproduct credits) over the life of the mine, determined at the stipulated (15-pct) DCFROR. Thus, the curve shows an aggregation of the total potential quantity of columbium producible over the life of each operation, ordered from operations with the lowest to highest average total cost of production. The curve provides a concise, easy-to-read, graphic

analysis of the comparative costs associated with any given level of potential output and provides an estimate of what the average long run price of columbium (in January 1984 dollars) would have to be for a given tonnage to be potentially available to the marketplace.

Annual curves are simply a disaggregation of the total curve to show annual columbium availability at varying costs of production. Each curve represents an amount of material potentially available annually at, or below, a specific cost level. The horizontal axis represents time, in either actual years (for producers) or the number of years following the commencement of development (for non-producers.) The vertical axis represents annual production levels based upon an aggregation of proposed capacities of each property within a specified cost range.

Certain assumptions are inherent in all curves. First, each deposit produces at full operating capacity throughout its productive life. Second, each operation is able to sell all of its byproducts at the market prices and all of its primary products at a price sufficient to generate total revenues equal to or greater than its average total production cost. Third, development of each nonproducing deposit is assumed to begin in the same base year (N) (unless the property was developing at the time of the evaluation).

Since it is difficult to predict when the explored deposits are going to be developed, an assumption is necessary to illustrate the maximum potential annual availability with minimum lag time. It is doubtful that this potential would be reached in the short term since it is unlikely all non-producers would start preproduction in the same year. The preproduction period allows for only the minimum engineering and construction period necessary to initiate production under the proposed development plan. Consequently, the additional time lags and potential costs involved in filing for and receiving required permits, financing, etc., have not been included in the individual deposit analyses.

TOTAL AVAILABILITY

Nineteen columbium deposits located in the United States, Brazil, Canada, Zaire, Uganda, Tanzania, and Kenya are included in the evaluation of MEC total recoverable columbium resources. These properties contain a total of 5.36 Mmt Cb in demonstrated resources; at an average recovery rate of 65 pct, a total of 3.47 Mmt is recoverable. The Bureau of Mines estimates that up to 90 pct of the columbium recovered is consumed by the steelmaking industry in the form of ferrocolumbium (1). For this study, it is assumed that all (100 pct) of the columbium recovered goes to the production of ferrocolumbium. Therefore, using an average grade of 64-pct Cb contained in ferrocolumbium, a total of 5.42 Mmt of ferrocolumbium is potentially available from the 19 deposits.

Table 6 and figure 10 clearly show Brazil as the MEC largest potential source of recoverable columbium, containing 2.39 Mmt or 69 pct of the studied total recoverable columbium. In addition, recent reports have claimed discovery of a columbium deposit at Seis Lagos, in the Amazon region, which could contain 38 Mmt of ore containing as much as 1.75 pct Cb (18, 19).

North America accounts for 11 of the 19 deposits evaluated, which amounts to 21.7 pct or 0.75 Mmt of the MEC total recoverable columbium resources. Combined with resources of Brazil, the Americas resources total 3.14

TABLE 6.—Total recoverable tonnage of columbium and ferrocolumbium

	Total recoverable columbium, 10 ⁶ mt	Total ferro-columbium, 10 ⁶ mt	Av Cb content, pct
Brazil	2.39	3.62	65.9
North America ..	.75	1.25	60.0
Africa33	.55	60.0
Total or wtd av	3.47	5.42	64.0

NOTE.—Data may not add to totals shown because of independent rounding.

Mmt of recoverable columbium or slightly less than 91 pct of studied MEC resources.

African resources are all from five deposits, containing a total of 0.33 Mmt of recoverable columbium, accounting for the remaining 9 pct of MEC recoverable columbium.

Figure 11 is a graphic representation of total availability of potentially recoverable columbium resources as related to total production cost. At a total cost (including a 15-pct DCFROR) of \$5 and below, the curve is masked to insure the confidentiality of information concerning lower cost operations.

At a cost of production comparable to the January 1984 market price of \$6/lb for columbium contained in ferrocolumbium, slightly over 2.50 Mmt Cb is potentially available. This amounts to approximately 72 pct of studied recoverable resources. All producing deposits are capable of profitably operating below the market price. Present producers have recoverable columbium resources totaling 2.42 Mmt or slightly less than 70 pct of the MEC resources.

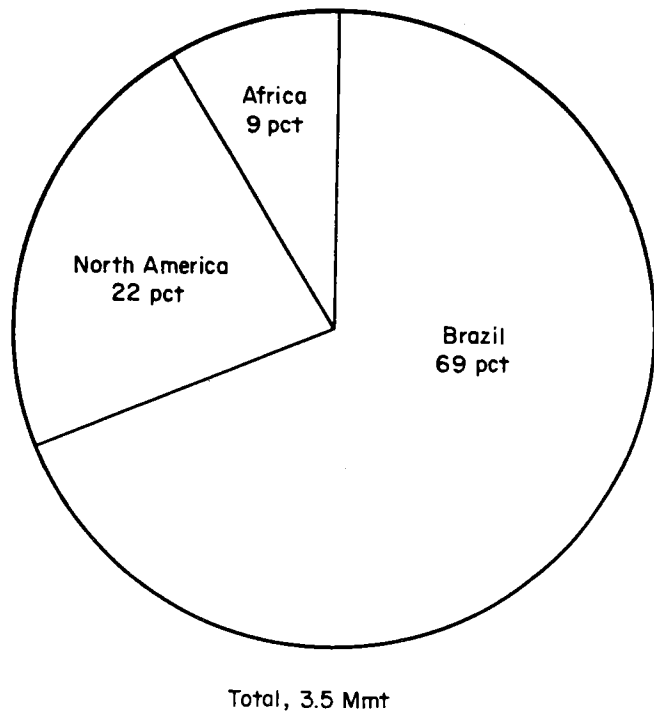
Cumulative MEC demand for columbium between the years 1981 to 2000 was estimated by the Bureau of Mines to be 415,000 mt (2). This estimate was based on an annual growth rate in the demand for columbium of 5.1 pct. Therefore, adequate supplies of columbium from currently producing mines should be available well beyond the year 2000. According to the 1982 report of the National Research Council (20), the Araxa mine in Brazil contains sufficient resources to alone "supply world needs for decades if not centuries."

At a total production cost comparable to doubling the market price to \$12/lb, figure 11 shows only a 9.7-pct increase or 0.34 Mmt of additional recoverable columbium from studied properties. This means that most of the MEC known resources can economically be produced at, or below, the present market price. The abundance of low-cost columbium from producing mines might inhibit incentives to begin development of new mining projects targeting columbium.

Figure 12 is a comparison between resources available in the Americas and the total recoverable resource from all studied deposits. The Americas total recoverable resource of 3.14 Mmt comprises over 90 pct of MEC potential resources. Brazilian resources alone total 76 pct of the total Americas resources or 2.39 Mmt recoverable columbium.

At a cost of production comparable to the January 1984 market price, approximately 78 pct (2.45 Mmt) of the Americas recoverable columbium resources are potentially available. In comparison to the MEC availability at this price, 97.8 pct is present in the Americas. At a total production cost comparable to double the market price, only an additional 10 pct would become available in the Americas, resulting in 2.73 Mmt of recoverable columbium.

The difference between the Americas and the MEC total availability curve represents the four African nations contribution to MEC columbium resources. This difference in

**FIGURE 10.—Recoverable columbium from evaluated mines and deposits.**

total recoverable columbium availability at the maximum total cost (shown in figure 12) is 0.33 Mmt.

The relationship between total cost and availability of recoverable columbium from nonproducers at both a 15- and a 0-pct DCFROR is shown in figure 13. Recoverable resources from studied nonproducers total 1.05 Mmt Cb of which 68 pct or 0.71 Mmt is located in the Americas. Further examination of the graph shows that at a cost of production comparable to the January 1984 market price (\$6/lb), only 0.08 Mmt are available assuming a 15-pct DCFROR. This is only 8 pct of total available resources from nonproducers and 2.4 pct of resources from all studied properties. At a cost level comparable to a doubling of the market price, an additional 0.34 Mmt of potentially recoverable columbium could be economically available. This amounts to 0.42 Mmt of recoverable columbium or 40 pct of the total available from nonproducers, but only 12 pct of that available from all studied deposits.

Figure 13 compares the effect of imposing a 15-pct DCFROR as opposed to a 0-pct DCFROR (break-even cost) on the total cost of production for nonproducers. This comparison is most relevant to deposits in which a 15-pct profit may not be a crucial factor for development.

Figure 13 shows a majority of potentially recoverable columbium from nonproducers at the break-even level is available at costs between \$6 and \$11.50. Conversely, at the 15-pct DCFROR, to produce the same amount of recoverable columbium involves costs of between \$11.50 and \$19.50. Therefore, doubling the market price to cover the total cost of production up to \$12/lb at the break-even level could result in the development and recovery of 1.02 Mmt, or 97 pct, of available columbium from nonproducers.

In summary, nonproducing columbium deposits have much lower total costs at the break-even level than at a specified 15-pct DCFROR. This fact may provide incentive for development of a columbium property assuming a situation arises in which a 15-pct DCFROR is not pursued.

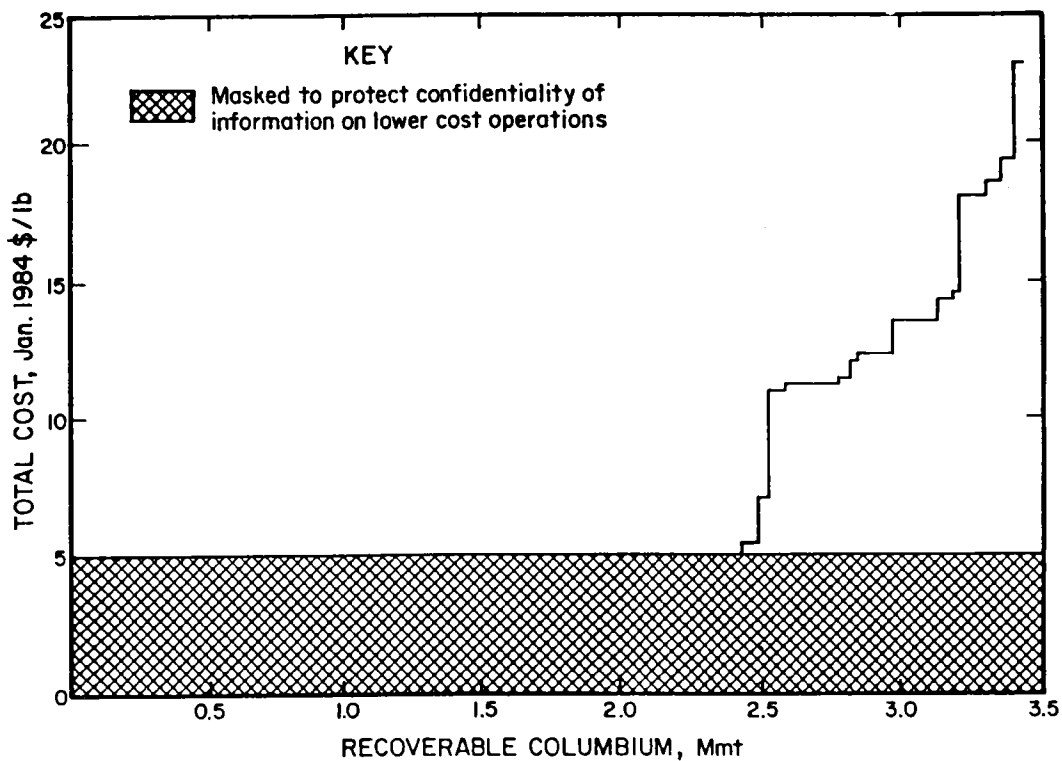


FIGURE 11.—Total cost and total recoverable columbiuM from MEC mines and deposits.

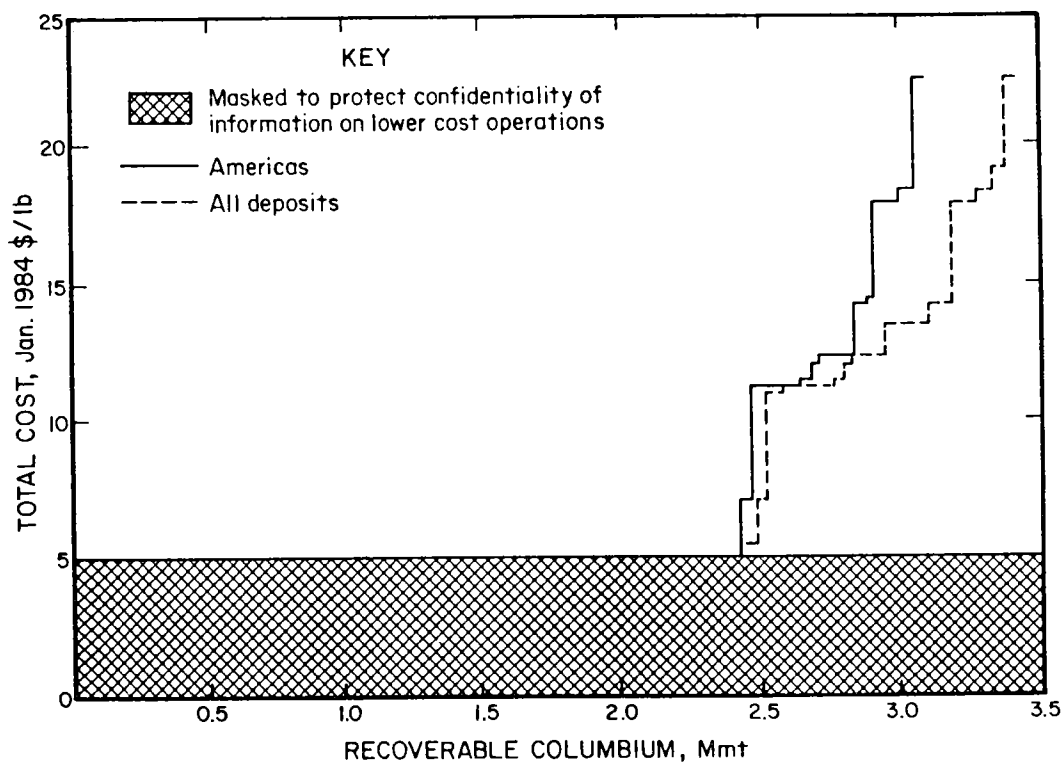


FIGURE 12.—Total cost and total recoverable columbiuM from Americas as compared with data for all selected deposits.

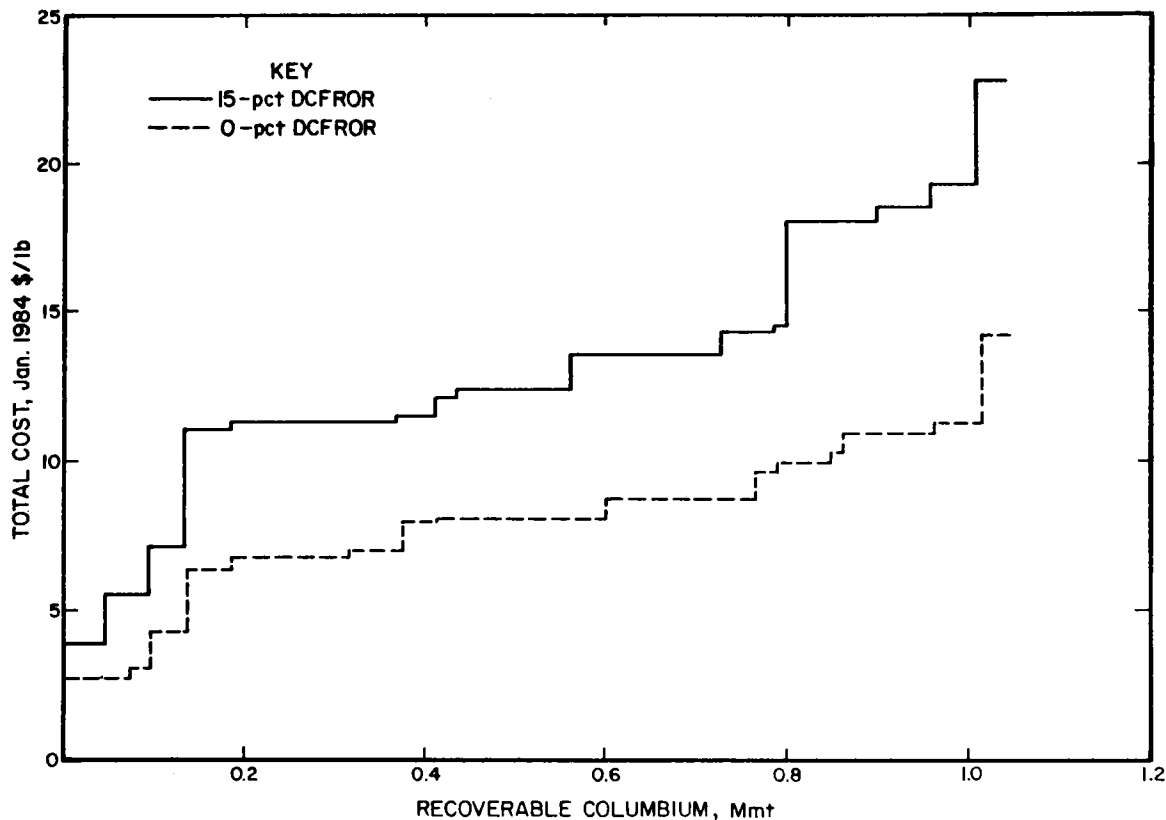


FIGURE 13.—Total cost and total recoverable columbium from nonproducers at 0- and 15-pct DCFROR.

However, the dominance of the Brazilian and Canadian producers, in terms of low-cost levels and sizable resources would likely inhibit any such development even at the break even level.

ANNUAL AVAILABILITY

Annual availability curves portray the potential annual availability of recoverable columbium contained in ferrocolumbium within a specified range of total cost. Annual curves as presented assume each operation will produce at full capacity over its life and should not be interpreted as true supply curves.

An annual availability curve for the three producing mines is presented in figure 14. At a total cost of less than \$6/lb, current producers have the capacity to produce up to 20,800 mt/yr Cb as contained in ferrocolumbium. However, due to low demand, estimates of actual production for 1983 amounted to only 10,000 mt from the three producing operations (6). Obviously, operating mines are producing at greatly reduced levels; in fact, at less than 50 pct of capacity. Figure 14 demonstrates that at full capacity and current demand levels, producers of columbium have the potential to supply projected annual MEC demand into the next century.

Annual availability curves for nonproducing deposits at a total cost of \$6/lb, \$12/lb and \$24/lb. (including a 15-pct DCFROR) are shown in figure 15. This figure demonstrates that significantly higher prices than current levels must prevail in order to cover the high costs of production

associated with these properties. At a total cost of \$6/lb or less for columbium contained in ferrocolumbium, nonproducers have a combined capacity of nearly 4,000 mt/yr. An additional 7,000 mt/yr is potentially available at a cost of production up to \$12/lb. At a maximum total cost of \$24/lb, the potential availability from nonproducers could increase to 20,000 mt/yr.

Figure 16 shows potential annual availability of columbium and total cost for nonproducers 5, 10, and 20 yr from the study date 'N'. Figures 15 and 16 show production from nonproducers would peak 8 to 15 yr after the base year 'N', then gradually decrease. This decline in production would continue as current resources were depleted, assuming additional resources were not discovered and technological improvements were not made to process lower-grade materials.

Though unlikely, it is important to consider the effects of a cut off of production by Brazil on MEC availability of columbium and its ramifications regarding U.S. industries (fig. 17). Brazilian production presently accounts for almost 70 pct of MEC ferrocolumbium. This figure assumes that the only remaining producer, Niobec, would maintain a stable level of production but could not respond to such an increased demand. To maintain the estimated 1983 production levels of 10,000 mt (fig. 16) would require a total cost of production of up to \$12/lb contained columbium. In addition, it would require approximately 6 to 8 yr to achieve this production level. A total cost of approximately \$24/lb would be required to reach existing capacity levels. This scenario reiterates Brazil's importance to the MEC columbium industry.

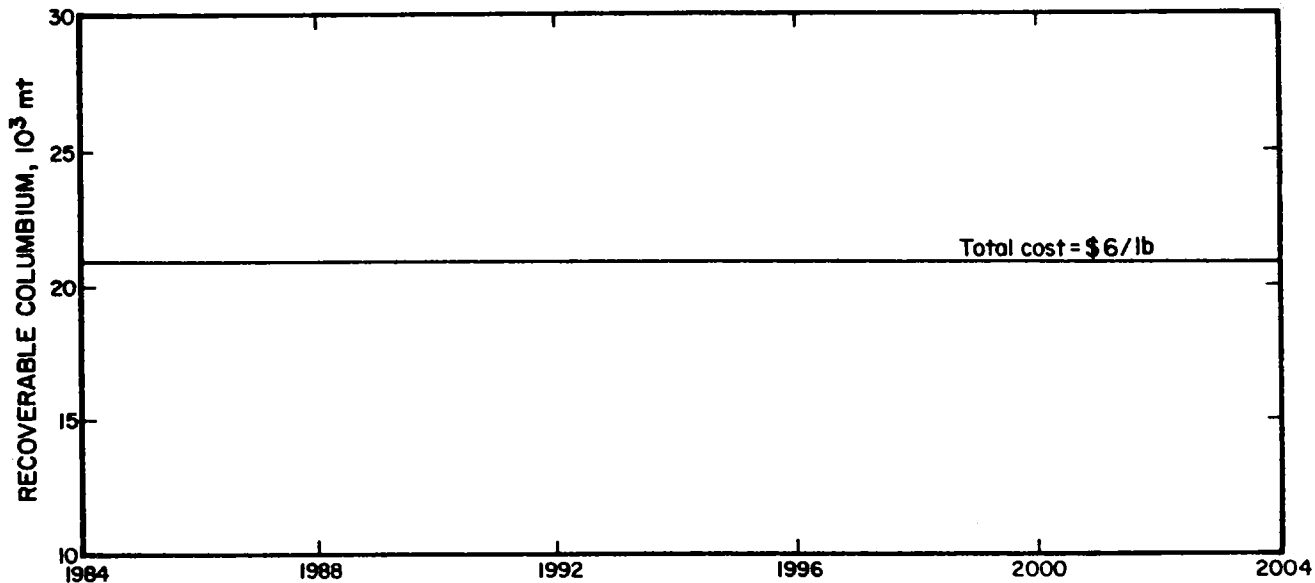


FIGURE 14.—Potential annual production from producing mines.

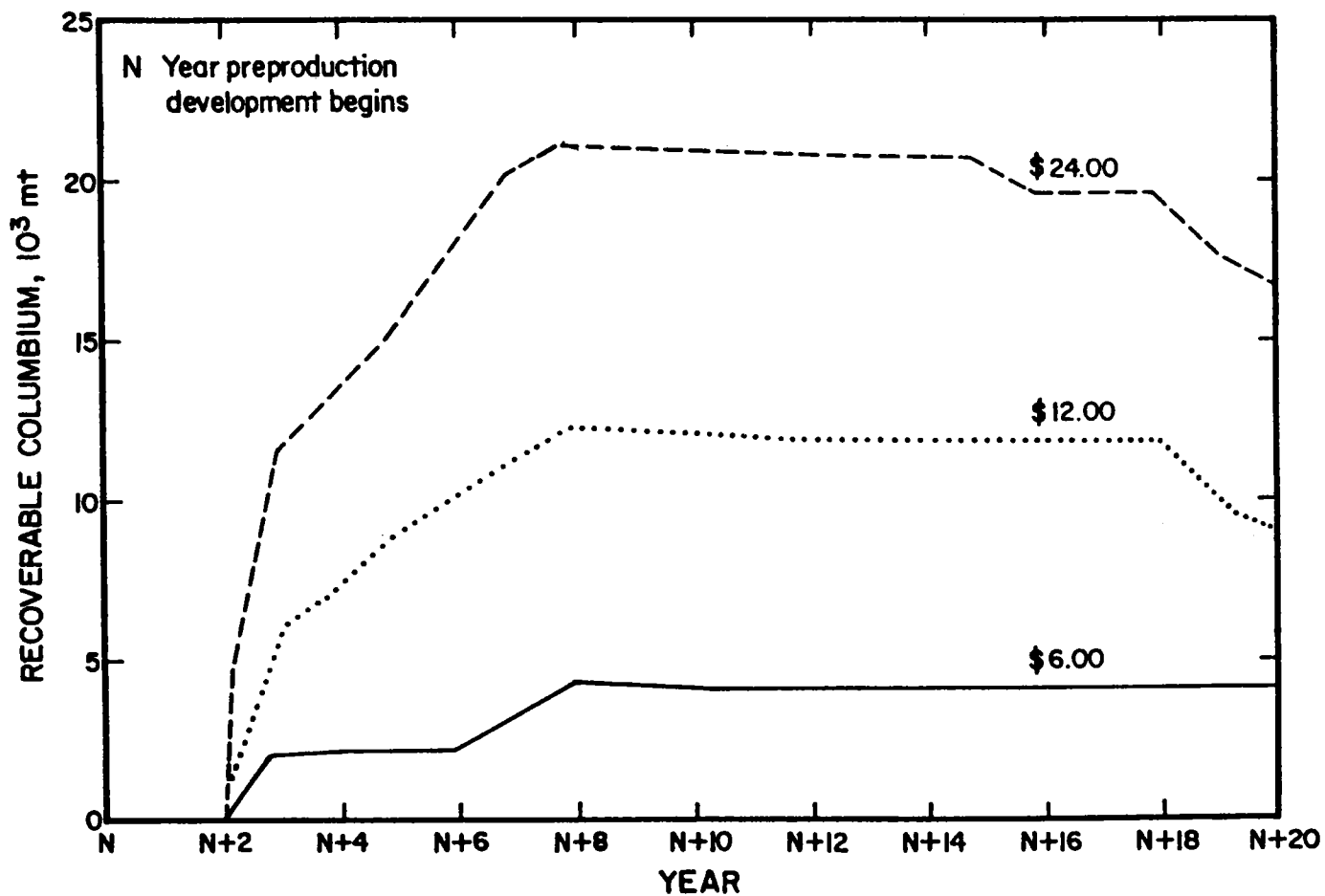


FIGURE 15.—Potential annual production from selected nonproducers at selected ranges of total production costs.

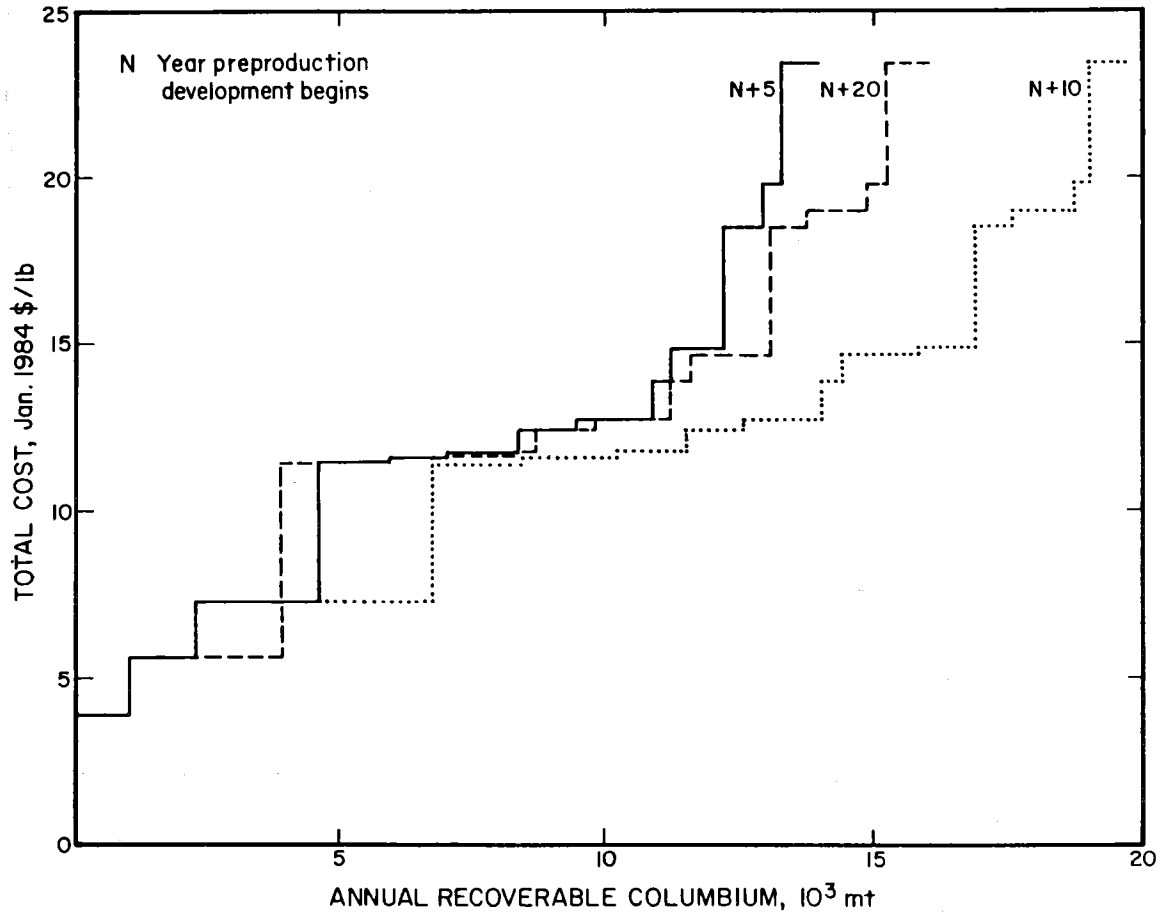


FIGURE 16.—Potential annual production from nonproducers for selected years.

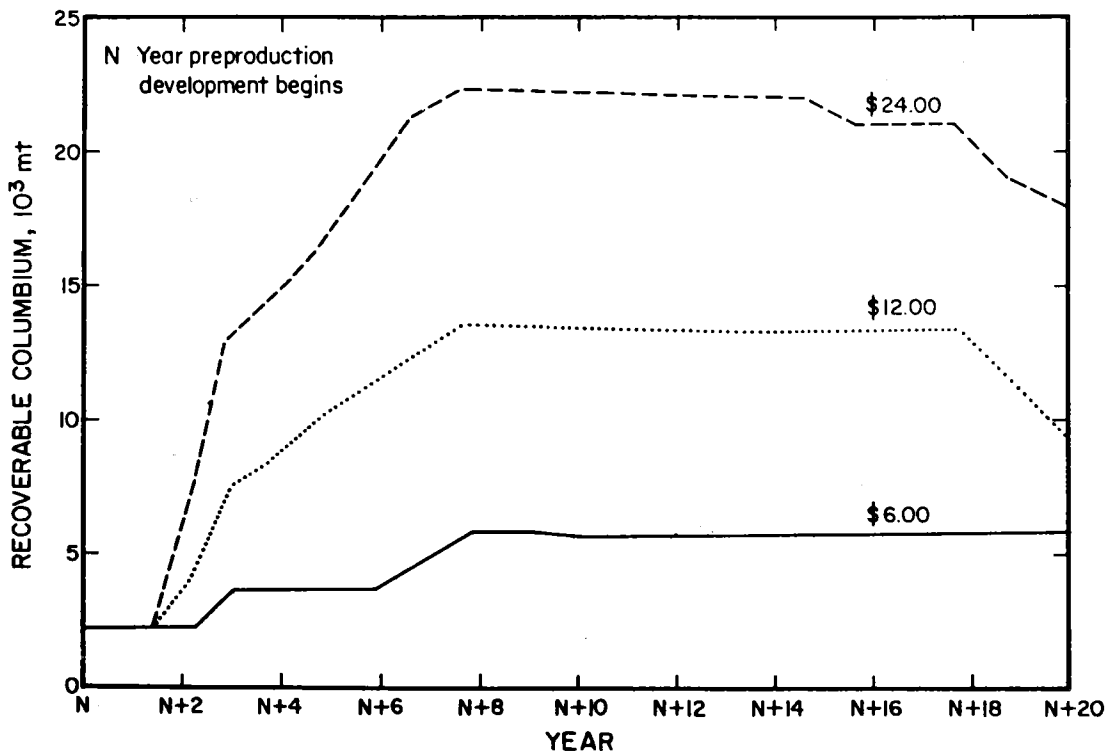


FIGURE 17.—Potential annual production from selected mines and deposits excluding Brazil.

CONCLUSION

Columbium is used primarily as an alloying element in high-strength, low-alloy steels and superalloys. For this purpose, approximately 85 to 90 pct of the columbium consumed is processed to ferrocolumbium for use in the steel industry. Most of the remainder is upgraded to high-purity columbium products for use in cobalt, nickel, and iron-based superalloys and superconductors. Columbium has not been mined commercially in the United States for many years, and U.S. ferrocolumbium producers rely solely on columbium imports.

A total of 19 deposits (3 producing mines and 16 non-producers) were examined to determine MEC availability of columbium. The selected deposits included all known resources of columbium, meeting the criteria for this study.

In situ demonstrated resources total over 946 Mmt for the 19 deposits. Total columbium contained in these resources amounts to approximately 5.36 Mmt. This figure includes 3.25 Mmt in Brazil, 1.37 Mmt in North America (Canada and the United States), and 0.75 Mmt in Africa (Kenya, Uganda, Tanzania, and Zaire). In all cases, columbium occurs in the mineral form of pyrochlore or its barium-strontium analog, pandaite, and is found in association with the carbonatite member of alkalic-granite complexes. All pyrochlore is currently mined from carbonatite deposits.

In the past, pegmatitic rocks have served as the principal source of columbium as contained in the mineral columbite. However, due to the abundance and increased utilization of pyrochlore ore, pegmatitic sources of columbite have been reduced to a less than 5-pct share of the MEC market for columbium.

In terms of potential total availability, Brazil is the largest and lowest-cost source of recoverable columbium in the MEC. Total recoverable columbium (contained as 65 to 66 pct in ferrocolumbium) in Brazil amounts to 69 pct (2.39 Mmt) of the MEC supply. Recoverable columbium resources

from the Americas account for over 90 pct of the total MEC resources studied, totaling 3.14 Mmt.

Current producers of columbium examined for this study include the Araxa and Catalao mines in Brazil, and the Niobec mine in Canada. Combined, these mines contain sufficient resources to supply the estimated cumulative MEC columbium demand through the year 2000, based on a 5.1-pct annual growth rate.

Potentially recoverable columbium resources from MEC nonproducers total 1.05 Mmt. Of this, only 8 pct or 0.08 Mmt are available at a total cost of production (including a 15-pct DCFROR) at, or below, the January 1984 market price of \$6/lb Cb contained in ferrocolumbium. A cost of \$12/lb, comparable to twice the current market price, is required to make available 40 pct of the recoverable columbium contained in nonproducing deposits. Even then, this amounts to only 12 pct of the total available from all studied deposits.

The United States is totally dependent upon foreign sources of columbium, principally in the forms of ferrocolumbium for steelmaking from Brazil and pyrochlore concentrates from Canada. Furthermore, Brazil has increased its production of ferrocolumbium and other high-grade columbium products in recent years, resulting in a decrease in U.S. production. Twenty years ago, the United States produced nearly all its ferrocolumbium; today, U.S. production has declined to 25 pct. Brazil's abundant, low-cost supplies may continue to increase U.S. dependency on that country for the high-grade columbium products used in superalloys. Analyses indicate that columbium is available from undeveloped deposits outside of Brazil but at costs of production significantly greater than current costs (even at a 0-pct DCFROR). Also, these deposits require a period of up to 8 yr to develop. As a result, Brazil is expected to maintain its position as the world's major columbium producer, into the foreseeable future.

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