CHAPTER 5

Strategic Material Supply

Contents

Contents–continued

List of Tables

List of Figures

CHAPTER 5

Strategic Material Supply

Introduction

Strategic material supply vulnerability could be reduced by developing domestic sources of ores and maintaining domestic processing capability or by sufficiently diversifying foreign suppliers to reduce the likelihood that any supply disruption would adversely affect U.S. national security or industrial stability. Prospects for changes in the existing distribution of mineral supply sources depend primarily on whether future demand for various commodities encourages expansion by current suppliers or the opening of new mines in new areas. Other factors include shifts in consumption patterns in the developing nations—e.g., a growth in internal use of resources that result in fewer or higher processed forms of exports—and the decline of production as reserves are depleted. Although market forces and, increasingly, government action in mineral-rich developing countries determine which mineral deposits are chosen for exploitation, neither has contributed or will necessarily contribute to a lessening of vulnerability by promoting either domestic or diversified foreign production.

This chapter discusses the existing lack of diversity of supply and the corresponding lack of adequate domestic supply of the first-tier strategic materials. It also presents an overview of the technology employed in strategic materials supply. (International political factors, which relate to the likelihood of disruptions and their possible durations, are not discussed.) The first section of the chapter considers mining and processing in general and is followed by sections on the specific ore production and processing environments and supply patterns of each of the first-tier strategic materials. The prospects for reduction in vulnerability are assessed. The last section discusses, in terms of U.S. lands and the ocean floor, the possibilities for new mineral finds and improved exploration technology and their effects on expanding the knowledge and availability of strategic materials.

Summary of Supply Prospects

While today's pattern of supply for chromium, cobalt, manganese, and platinum group metals (PGMs) will not change in any appreciable way in the near and, most likely, long-term future, there are some opportunities for direct and targeted government action to diversify foreign sources of these materials away from politically sensitive areas. A concentrated push to diversify foreign sources of supply, however, would inevitably open marginally economic deposits and, in the long run, might do nothing more than simply delay an even greater reliance on the abundant deposits—e.g., those in southern Africa.

Of the first-tier strategic materials, only PGMs are now produced from domestic ores; and in 1982 the amount produced represented less than 1 percent of that year's consumption. Other domestic PGM and some cobalt resources have been under consideration for commercial exploitation. Known chromium and manganese ore resources in the United States are considered improbable candidates for commercial production at any time in the near or long-term future. Without Federal subsidies, production may be possible for larger amounts of PGMs, but is less likely to initiate production of cobalt, and appears unlikely for chromium and manganese even under supply disruption conditions when market prices can rise dramatically. In all cases, only a portion of U.S. needs could be supplied by domestic production. All of these resources, though, represent important in-place stockpiles of strategic materials.

Chromium

Foreign alternatives to the major chromium producers, South Africa and the Soviet Union, are limited in number and in the amount of chromium they could provide. Prospects include the expansion of output from producing deposits in the eastern Mediterranean and the Philippines and the development of laterite and beach sand deposits in the Western Pacific region. These sources might provide an additional 10 to 20 percent of U.S. needs.

Domestic resources could provide up to 50 percent of needs (in a low consumption year such as 1982) for 11 years if four deposits were simultaneously developed at costs about double prevailing rates. One of these deposits, which could supply up to 4 percent of U.S. chromium consumption, has been under recent consideration by a private firm, but production would be contingent upon significant increases in the prices and demand for nickel and cobalt.

Cobalt

If foreign production of cobalt is to diversify, it will most likely result from the opening of cobalt-containing nickel laterite deposits in such countries as New Caledonia and Papua New Guinea, possible expansion of output from the Philippines, and production of cobalt as a byproduct from iron ore mining in Peru.

Four cobalt deposits in the United States could supply up to 10 million pounds annually, if producing simultaneously; this production rate would decline after about 20 years, Private firms investigating three of these properties have suggested that Federal subsidies in the form of price guarantees could assist them in overcoming a prime barrier to production—low and volatile market prices for cobalt. The fourth deposit is not under consideration for production.

Manganese

The greatest opportunities for diversifying the foreign supply of manganese lie in increased production of manganese ore in Australia and Mexico. Mexico's ores require more extensive processing than Australia's and would represent a larger investment to promote increased production. Neither producer will decide to increase production without clear market signals of increasing and sustained demand. Increases from these producers plus Gabon (with transportation improvements) might be able to meet U.S. needs.

The cost of producing ores from known domestic manganese deposits ranges from 2 to 18 times the market price; commercial activity is nonexistent. Simultaneous development of eight domestic deposits could theoretically cover most of U.S. needs over a 10-year period.

Platinum Group Metals

There are no known foreign alternatives to PGMs. South Africa, the Soviet Union, and to a much lesser extent, Canada, will continue to supply the world.

Private development of and production from the Stillwater Complex in Montana appears possible given slight increases in market prices for platinum and palladium and evidence of increased, sustained demand. Initial production would supply about 9 percent of domestic needs, based on 1982 consumption of PGMs.

Exploration

The relatively low economic value of many strategic materials and ample foreign supplies combine to inhibit any domestic commercial exploration for new deposits of these materials. Advances in exploration technology are not specifically directed at finding strategic materials, but general improvements could increase the likelihood of locating deposits, if they exist.

Processing and the Ferroalloy Industry

U.S. ferroalloy production capacity has declined over the last decade. This erosion is expected to continue at a slower pace, resulting in a lean domestic industry that can supply a portion of domestic needs.

Factors Contributing to Change in Supply

It is a consequence of the economics of mining that there are no known "world class" mineral deposits that are not producing. Known deposits that are not producing, whether foreign or domestic, are small in size and / or contain low-grade material. These factors, plus others such as labor and energy costs, accessibility, the effect of perceptions of political risk on investment, and environmental concerns, contribute to these deposits' marginal economic value. Some producing deposits are not considered to be economic by free market standards. The less developed nations that own many of the known deposits consider them such critical sources of jobs and foreign exchange that they are often exploited even if operations must be subsidized.

Mineral activity encompasses a time-consuming, sequential chain of activity: exploration, mine development, ore production and processing, and international trade. Normal changes in supply patterns evolve slowly. Dramatic changes, when they do occur, are the result of perturbations to the system, Two ongoing evolutions in international mineral trade are now affecting mineral supply and the ways in which vulnerability is measured, The first is a shift from export production to domestic consumption. Many producer countries (e.g., Brazil and India) are increasingly using their mineral resources, just as the United States did, as a contribution to their own industrial development. Internal demands for these resources affect the trading relationship these nations maintain with their mineral customers by the reduction of market supplies during high internal growth periods and the dumping of excess supplies on the world markets during recessionary times.

A second and related factor is that producing nations are deciding that it is in their own best interests to promote the export of processed ores rather than raw materials. Since their newer facilities appear to have a competitive edge over traditional processing facilities in industrialized centers, the vulnerability of the West to imported materials is shifting from ores to higher processed forms of strategic materials.

This shift in trade from ores to ferroalloys and from semiprocessed ores to cobalt and PGMs is accompanied by a change in transportation requirements. Ferroalloys contain double to triple the chromium or manganese content of the mined ores, so that shipping the same amount of chromium or manganese as ferroalloys rather than as ores requires less space, fewer ships. While prior processing allows the shipment of a greater amount of chromium or manganese in fewer vessels, PGM and cobalt metal products can be shipped by air at no great increase in cost to the consumer, The growth in cobalt and PGM refining capability in mining countries increases the flexibility of transportation systems (and reduces the overall processing time), resulting in a lowering of the vulnerability of cobalt and PGMs to sea and land transportation problems,

Concern about the vulnerability of transportation routes from producing to consuming nations usually focuses on the problem of open sea lanes in time of war. Consideration must also be given the less dramatic problem of whether land transportation services are and will remain adequate. Mines are often located far inland, in isolated areas. Transportation of ores to a shipping port usually involves an initial overland route (by railroad, truck, aerial tramway). The costs of developing and operating such systems can be a significant factor in the economics of a potential source of minerals. Transportation bottlenecks could prove the most time-consuming aspect of any rapid expansion required in a supply emergency. In addition, land transport is a weak link between producer and consumer in terms of possible terrorist operations,

Technological Advances in Mine Production and Processing'

Into the 1990s, the overall picture for mining technology applicable to first-tier strategic

---

[1] See the following section for a description of various exploration, ore mining, and processing procedures and technologies.

material resources should differ only in a few respects from that of today.

Technology will only marginally enhance the likelihood for domestic production. Changes in technology affect the cost of materials by reducing the capital investment and the unit cost of mining and processing operations. However, low-grade domestic resources of strategic materials are not unique geologically, and any innovations would apply to foreign deposits of higher grades, as well. New technology would not be likely to make domestic sources more competitive. Unless there are discoveries of higher grade ore bodies in the United States or the development of mining and processing technologies that selectively improve the economics of low-grade deposits, marginally economic deposits will remain as such.

If foreign supplies were restricted or unavailable, new technology could provide for domestic production at lower costs than would be possible otherwise. Development costs in open pit and underground mines might be reduced by as much as 15 percent with the use of rapid excavation and continuous material-handling methods and in situ (solution) mining could realize savings of up to 50 percent over today's conventional open pit and underground mine installations. Mine operating costs per unit of material could be reduced by as much as 20 percent in relation to the costs of applying current technologies, with in-situ operation costs perhaps 40 percent below those of conventional methods.[2]

Mechanization of age-old mining methods is the key change now underway in production. Open pit mining, which employs technology to drill, blast, and load rock is expected to use more continuous conveying systems in deeper and steeper pits, and continuous bucket-wheel excavators will come into use. Hard rock underground mining will still be a cyclic operation of drilling, blasting, and loading but there should be increased remote control, rapid conveyor haulage, and mining methods that break rock on remote levels. Machines used to bore shafts (called "raise-boring") will be in general use, but other continuous mining innovations in shaft sinking, tunnel boring, and mining methods will probably be used in only a few mines.

In specific instances, new mining concepts could be applied. Solution mining of manganese deposits is now under investigation and is being conceptualized for other strategic materials. Bioengineering, which uses bacteria in leach treatment of ores, may provide a mining innovation for the future. It is expected, however, only to supplement existing mining and processing techniques.

The low grades of domestic deposits and the attendant costs involved in processing their ores to produce the high-grade industry standard material is a major contributor to their uneconomic status. There are no major changes in processing technologies expected to be available in the future to alter that picture substantially. Domestic cobalt and PGM ores, if in production, are expected to be processed with modifications of today's technologies,

Strategic Material Environments, Mineral Activity, and Technology

Geology of Strategic Materials

Chromium, cobalt, manganese, and platinum group metals are found in greatest concentration in certain classes of rocks (called "mafic" and "ultramafic")[3] which were formed eons ago by solidification from a molten state. Ta-

---

[2] A. Silverman, et al., *Strategic and Critical Mineral Position of the United States With Respect to Chromium, Nickel, Cobalt, Manganese, and Platinum*, contractor report prepared for the Office of Technology Assessment, June 1983.

[3] Rocks that are dominately composed of iron and magnesia silicate (SiO_4) minerals. Ultramafic rocks contain less than 45 percent SiO_2.

ble 5-1 identifies by deposit type and location the major worldwide known deposits of the first-tier materials. The significance of the different deposit types is explained in each of the individual mineral sections below.

A troublesome aspect of any discussion of mineral supply is in establishing agreement over the meaning and use of the basic terms, "resources" and "reserves." Reserves include deposits that were known and were technically and economically feasible to mine at a profit at the time the data was analyzed. Reserves are the only deposits that are immediately available to be developed to meet the need for materials. Resources, on the other hand, include reserves and deposits that are known but are not currently economic to mine, as well as deposits that are merely inferred to exist from geologic evidence. Numbers for both are estimates and should be used only with caution. The Bureau of Mines and the U.S. Geological Survey, which calculate and report the numbers, rely on their own research, the reporting of private data that is often purely voluntary, and data from various publicly available sources. Moreover, the degree of information and commitment to maintaining current estimates of resources and reserves varies greatly among nations. Countries with limited mineral assessment programs may, for instance, not distinguish between resources and reserves, estimate only from operating mines, or fail to conduct economic analyses.

Table 5-1.—Deposit Types and Locations of First-Tier Strategic Materials

Chromium:	
Stratiform	**South Africa (Bushveld Complex), Zimbabwe** (Great Dyke), Finland, Brazil, U.S. (Stillwater Complex)
Podiform	Albania, New Caledonia, Philippines, Turkey, Zimbabwe
Laterite	U.S. (Gasquet Mountain), Philippines, New Caledonia
Cobalt:	
Stratabound	Zaire, Zambia
Laterite	Australia, New Caledonia, Philippines, Cuba
Hypogene	Australia, Botswana, Canada (Sudbury), Soviet Union (Noril'sk), U.S. (Duluth Gabbro)
Hydrothermal	U.S. (Blackbird, Madison)
Manganese:	
Sedimentary	Australia, Brazil, Gabon, India, Mexico, South Africa (Transvaal)
Platinum group metals:	
Stratiform	South Africa (Bushveld), Soviet Union, Canada (Sudbury), U.S. (Stillwater)
Placer	Colombia, U.S. (Goodnews Bay)

SOURCE Office of Technology Assessment

Reserves and resources are often given in terms of ore tonnage. An important qualifier is the "grade" of the desired mineral, the amount of that mineral that is estimated to be contained within the ore. Grades are usually presented in percentages or parts per million (ppm).

Prospecting to Production

Mineral activity[4] can be divided into successive mineral exploration, development, and production phases, all accompanied by ongoing analysis of information accumulated during these phases. The full sequence of activity occurs for only a few projects, as a project will be shelved or abandoned at any stage if the results are not encouraging or if economic conditions become unfavorable. The full sequence, subdivided into six stages, is shown in table 5-2. Although there may be some overlap between stages, they each involve a decision by mining companies or other investors to expend time and resources that grow significantly with each stage. Revenue is not generated until the activity reaches the production phase.

Exploration involves the identification and investigation of target areas with the intent to discover an economic mineral deposit. An analysis of exploration findings of the mineral deposit, combined with a determination of the applicability of mining procedures and capability of ore processing techniques, and marketing studies will determine the initial economic viability of a mineral project. After this

---

[4] For more information on this subject, see U.S. Department of Agriculture Forest Service, *Anatomy of a Mine From Prospect to Production*, General Technical Report INT-35, June 1977; and U.S. Congress, Office of Technology Assessment, *Management of Fuel and Nonfuel Minerals in Federal Lands*, OTA-M-88 (Washington DC: U.S. Government Printing Office, April 1979).

Table 5-2.—Mineral Activity

Phase	Stage	Activity
Exploration		
Target identification		
	1.	Regional appraisal
	2.	Reconnaissance of region
Target investigation		
	3.	Detailed surface investigation and chemical analysis of samples
	4.	Detailed 3-dimensional analysis of site by drilling, testing of samples. Project feasibility studies
Development	5.	Drilling to block out deposit. Construction of mine workings, ore processing plants, support facilities
Production	6.	Operation of mine, ore processing, and shipment of material to market

SOURCE: U.S. Congress, Office of Technology Assessment, *Management of Fuel and Nonfuel Minerals in Federal Lands*, (Washington, DC: U.S. Government Printing Office, April 1979), p. 47.

determination has been made, development work proceeds to bring a deposit to the point of *production* —the actual mining, ore processing, and shipment of material to market.

During target identification (stages 1 and 2), a large area is surveyed to locate areas of promise. Research is based largely on previously collected industry and government data and geologic theory and is supplemented by field inspection by air or on the grounds Successful conclusion is marked by a decision, usually made by the exploration experts, to focus on particular areas of high potential,

The objective of target investigation (stages 3 and 4) is to locate a deposit of a desired mineral that has potential for commercial exploitation. This involves the gathering of data from the region selected during the previous stages and proceeding with sampling and mapping of geologic features, geophysical surveys (usually conducted from the air), limited drilling to determine the nature of the layers below the surface, and laboratory analysis of samples obtained in the region. If a promising deposit is found during stage 3, then a decision is made as to whether the potential of the deposit justifies the expenditure of further funds for stage 4. If so, a process begins to define the grade and extent of the deposit and to determine the detailed composition of the minerals in the deposit. It is at this stage that sufficient information is obtained to determine whether the deposit is of commercial value and whether development activities are advisable. Three-dimensional mapping of the deposit, with drilling samples taken at close intervals, provide detailed maps of the ore and the surrounding rock. This information and analysis of mineral content of the ore are used to develop mine plans. Samples are used to test prospective ore processing systems. In addition to providing the information for the design of the mine and the ore processing plants, feasibility studies during this stage provide the basis for the final company decision to commit funds to a mining project and provide investment groups with the information they need to justify loans for or equity involvement in a project,

Mineral activity then moves into the development stage during which the mine and ore processing plant are constructed and transportation and other support facilities are installed. This stage is the greatest expense of the mineral activity process. Once the final production stage commences, it continues for as long as the project can produce on commercial terms. Should economic conditions change, perhaps due to depressed market prices or depletion of high-quality ore, the facilities are closed either temporarily (“placed on care and maintenance”) or permanently. In addition, the mining industry is quite accustomed to delaying partially completed projects when market conditions change. There can be a considerable time gap between the end of the exploration and the beginning of the development stages.

This process of mineral activity is long-term, risky, and expensive. In general, each successive stage is more expensive and takes more time than prior stages. The costs and time involved vary and are dependent on a number of factors. For instance, both will increase if a deposit is buried rather than exposed on the

---

[1] Remote sensing (exploration by satellite), while it has not yet located ore deposits, is a tool which provides basic scientific data which can be coordinated with geologic concepts to assist in the process.

surface. In 1977, according to an earlier OTA report,[6] estimates of average U.S. exploration costs per mineral project ranged from $1.7 million to $5.4 million and took up to 5 years to complete; mine development costs varied from millions to several hundred millions of dollars with times ranging from less than 1 up to 13 years. A 1980 report[7] stated that major international mining projects take at least 7 to 8 years after the time of discovery and often cost up to $1 billion to reach the production stage. Once production begins, mining ventures may need years of continuous operation to show an adequate return on the capital investment.

Exploration Technology

The geologist's search for a specific mineral is aided by knowledge of the environment in which it is likely to be found. Thus, expected host rock, trace metal, and gangue[8] mineral associations, wall rock alteration occurrences, and the age of a mineralization can all be keys to discovery. Exploration technologies which help to identify these environments as well as the mineral itself include three types: visual, geophysical, and geochemical. Visual methods are the oldest, simply being the surveying of an area for geologic formations and features known to be favorable to the desired minerals, Such methods are still used in the first stage of mineral activity in the search for regions deserving of more detailed study.

Technology has now taken the explorer beyond the powers of eyesight to advanced geophysical methods. Physical properties of mineral formations such as density, magnetic behavior, electrical conductivity, and radioactivity provide characteristic patterns which can be used for identification. Some of these measurements are taken on the ground, some "down hole" and others can be conducted by air. Geochemistry involves trace metal analysis of air, water, soil, and rock materials in the region of mineral exploration.

Mining Technology

The mining method selected for a particular project will vary according to the size, type, and position of the deposit; the grade of the ore, its strength and the strength of the surrounding waste rock; and the unit value of the desired mineral.

There are two general classes of mineral deposit: surface and vein. Vein deposits are formed by the deposition of minerals by molten rock as it moves upward from deep below the surface through cracks in the surface rock. As the molten rock cools, the contained metals (under the action of pressure and heat) can concentrate in particular locations to form veins of minerals. Although some vein deposits may be accessible by removing the surface rock, generally such deposits must be mined by underground methods.

Surface deposits are found at or near the surface. Some, known as placer deposits, occur as concentrations of mineral or metal particles that have washed away from an exposed deposit to mix with sand and gravel in river beds or ocean beaches. (Placer deposits have been an important source of PGMs and gold.) The metals are recovered by dredging river beds or beaches and using flowing water and gravity to separate the heavier precious metals from the lighter sand and gravel.

Another important class of surface deposit is formed by the weathering of surface rock that contains dispersed metals such as nickel and chromium. Through a continual process of changing temperatures and rainfall, these metals are washed to lower levels of the rock formation where they concentrate in amounts that are attractive for commercial exploitation. (Deposits of nickel, known as nickel laterites, are formed in this way. Such deposits may also contain concentrations of chromite, the mineral from which chromium is obtained.) Laterite deposits are generally mined from the surface by open pit methods.

---

[6] *Management of Fuel and Nonfuel Minerals in Federal Lands*, op. cit.

[7] The Brandt Commission, *North-South." A Program for Survival* (London: Pam Books, 1980), p. 156.

[8] Gangue is that part of an ore body which contains the undesirable minerals—i.e., waste material.

Mining processes thus fall into two general classifications: underground and surface mining. In underground mines a complex system of shafts are sunk and tunnels bored which selectively follow the ore veins or pockets of minerals with highest grade material. Blasting techniques must be used to remove the ore, which is often crushed within the mine prior to hauling above ground, Underground mining methods (called "stoping" by American miners) are age old and highly varied. They include open stoping (room and pillar, for instance, is a form of open stoping), shrinkage, cut and fill, and square-set stoping and block caving. Today, underground mining is becoming increasingly mechanized in order to improve productivity.

Placer and open pits are surface mining techniques, both of which take advantage of large and efficient earthmoving machinery. In dredging operations, a form of placer mining, the gravel containing minerals is scooped up by bucket lines or a dragline onto a floating plant which separates the gravel into a mineral concentrate and tailings (waste product). In an open pit mine access to the ore body is accomplished by removal of the waste overburden (upper layer of earth lacking in economic concentration of metals). The material in the ore body is then removed, as the pit is formed, top to bottom by sequentially blasting (in hard rock[9] mines) and then mechanically loaded into equipment for hauling up out of the pit for processing, A choice whether to use open pit or underground mining methods is based, in part, on the cost of removing the overburden and whether the waste rock can sustain the sloping sides of the pit.

Solution mining techniques are now used for extracting soluble materials such as potash and salt in situations where conventional mining methods would not be economic. There are two general versions. In the first, "heap leaching," ores are mined and spread on the surface. A solvent is then applied and the resultant solution of minerals is collected and processed, The second version—"in situ leaching"--involves the introduction of the solvent into the orebody in place, followed by pumping out of the resultant mineral solution. The application of in situ leaching in hard-rock mining requires an initial fracturing of an ore body before leaching solvents can effectively produce a solution of the desired minerals to be extracted from the ground. These techniques for hard-rock mining are under active research but have not yet been attempted on any virgin deposits. They may offer a possible solution to the problem of the poor economics of low-grade domestic deposits if they can reduce the overall recovery costs of producing a high-grade material. Research areas include equipment, solvents, technologies for fracturing ore bodies in place and for controlling the movements of fluids through them.

Bioengineering may provide mining with a technique to recover metals from ores too low in grade to process conventionally or from existing tailings dumps.[10] Certain bacteria will liberate and concentrate small grades of metals, and natural bacterial leaching is used currently to recover copper and uranium from sulfide deposits. A major drawback of bacterial leaching is the slow rate of the process compared with chemical extraction. The hope is that genetic manipulation can enhance the natural leaching properties of bacteria.

Potential for Change in the Supply of Strategic Materials

Once a mineral activity moves into the development stage, its details are generally widely known. Given the time-consuming development process, it is not difficult to project world ore production (a total of existing and developing new sources) at least a decade into the future. Even beyond 10 years, potential new

---

[9] Hard rock refers to material that has a strong bonded structure and must be excavated by using blasting techniques in which an explosive charge is placed in a hole bored in the rock and detonated, Most first-tier strategic materials are mined from hard-rock ore bodies.

[10] See U.S. Congress, Office of Technology Assessment, *Commercial Biotechnology: An International Analysis*, OTA-B-218 (Washington DC: U.S. Government Printing Office, January 1984), pp. 226-228; Joann Dennett, "Microbe Miners, " *AMM Magazine*, July 2, 1984; and Joseph Alper, "Bioengineers Are Off to the Mines, " *High Technology*, April 1984.

sources can be readily identified because there are only a limited number of known deposits, undergoing investigation, that could be opened or expanded to capture a share of the ore market. Discoveries of major, new deposits are possible but unpredictable. Thus, projections of production beyond about 20 years become unreliable.

Any change in the existing mine production of strategic materials will be determined by market demand and by the efforts of mineral producer governments to provide employment for their citizens, obtain foreign currency, and promote industrial development. Extraordinary conditions, such as a prolonged supply disruption of a substantial portion of any one mineral, could also encourage increased production from existing or the development of new sources of supply.

Table 5-3 presents a summary of the supply prospects of the first-tier strategic materials, a picture of the geographic distribution of the United States' major sources of the first-tier strategic materials along with the relative present and estimated future contribution of the producers. (The ranking system is based on the magnitude of each producer's output combined with the extent of its participation in Western trade.) The table also identifies the major barriers to expansion of production and initiation of new sources of supply.

constraints include limited knowledge about the extent of the resource base; the equipment and skilled labor needs to mine, process, and refine the ores; and the limits of support systems such as energy sources and transportation facilities. Direct economic constraints include the need for massive capital to finance development work and uncertainty about future markets. Political risk (contractual instability, threat of nationalization without compensation, uncertainty over guarantees of sufficient mine life to attain expected rate of return) is a component of the economic analysis of any mining project located in a developing country.

Available mine capacity for chromium, cobalt, manganese, and PGMs has been highly underused in the early 1980s, the effect of several years of worldwide economic recession. While the fortunes of the mining industry have historically been cyclical, the recent sustained oversupply and low prices have adversely affected new investment in these commodities. Although some new mining ventures for these materials are being evaluated, few are going forward. It is expected that any increase in demand in the near future will be supplied by current mines operating at capacity and the reopening of recently shut mines.

Even under healthy market conditions, the ample reserves and resources of the South African mines for chromite, manganese, and PGMs and of the Zairian/Zambian mines for cobalt serve as impediments to investment in the development of new mining areas. All new ventures must compete for markets against the strength of the existing producers and their ability to increase production easily to meet any new market demands.

The immediate response capability of existing producers to a supply disruption depends on the status of mining at the time and the corresponding extent of development needed. For instance, during such periods as the early 1980s, when mining operations generally were operating at as little as 50 percent of capacity, an expansion to full capacity could be simply a matter of hiring personnel for more shifts in a mine or for reopening mines. This could be done in a matter of weeks, or at most, in a few months. On the other hand, a mine already operating at full or close-to-full capacity during a tight market would require substantially more time to expand production, even though the plans for expansion would be available. Any producing mine is continually upgrading its reserves and blocking out future production areas to open, given a change in market conditions. In an underground mine, however, new shafts might have to be prepared by extensive blasting and boring, a time-consuming process. An open-pit mining operation with simple ore concentrating equipment can increase output much more rapidly by adding blasting and hauling equipment. Ultimately, however, limitations could be imposed by avail-

Table 5-3.—First-Tier Strategic Materials Supply Prospects

Regions	Minerals	Country producers	Importance[b]		Primary constraints to increased availability[c]
			Now	Potential	
North America	Chromium	NA			
	Cobalt	CANADA	2	2	nickel demand, refinery limits
		United States	—	3	high cost deposits, demand for various primary metals
	Manganese	MEXICO	3	2	customer acceptance of quality
	PGM	CANADA	3	3	nickel/copper demand, refinery limits
		United States	—	3	demand for PGMs, competition
South America	Chromium	NA			
	Cobalt	Peru	—	2	processing facilities
	Manganese	BRAZIL	2	2-3	local demand
	PGM	NA			
Australia and Oceania	Chromium	PHILIPPINES	2	2	infrastructure
		Pacific rim	—	3	proof of feasibility
	Cobalt	PHILIPPINES	2	2	demand for nickel
		AUSTRALIA	2	2	demand for nickel
		New Caledonia	—	3	demand for nickel
		Papua New Guinea	—	2	demand for cobalt/chromium
	Manganese	AUSTRALIA	2	1-2	hauling equipment
	PGM	Pacific rim	—	?	proof of feasibility
Eurasia	Chromium	FINLAND	3	3	possible resource limits
		ALBANIA	2	1-2	unknown
		GREECE	3	3	resource limits
		TURKEY	3	3	improved knowledge of resources and technology
		INDIA	3	3	resource limits, infrastructure, local demand
	Cobalt	FINLAND	2-3	2-3	possible resource limits
	Manganese	INDIA	3	3	resource limits, infrastructure, local demand
	PGM	NA			
Africa	Chromium	SOUTH AFRICA	1	1	transportation
		ZIMBABWE	2	1	transportation
		MADAGASCAR	3	2-3	seasonal operation, infrastructure
	Cobalt	ZAIRE	1	1	processing, refinery limits
		ZAMBIA	1	1	processing, refinery limits
		Morocco	—	3	resource evaluation
		BOTSWANA	3	2-3	transportation
	Manganese	SOUTH AFRICA	1	1	transportation
		GABON	2	2	transportation
	PGM	SOUTH AFRICA	1	1	refinery limits
Eastern Bloc	Chromium	SOVIET UNION	2	2-3	unknown
	Cobalt	SOVIET UNION	3	3	unknown
		CUBA	3	2	unknown
	Manganese	SOVIET UNION	3	3	unknown
	PGM	SOVIET UNION	1	1	unknown

NA—Not applicable.

[a] UPPERCASE indicates a current producer.

[b] Key: 1 = major
2= medium
3 = minor
7 = unknown

Based on assessment of relative production levels and contributions to Western trade.

[c] Any expansion/development would require capital investment, to a varying degree, in mining, Processing, and refining infrastructure.

SOURCE: Office of Technology Assessment, 19S4.

able processing facilities, such as smelting and refining operations,

Processing of Strategic Materials

Once removed from the ground, all ores undergo some level of processing. Technologies chosen will be based on the extent of processing required due to the condition of the ore (e.g., the amount of upgrading necessary to produce a salable product and the level of difficulty involved in separating out the unwanted minerals) and the intended end use of the mineral.

At the mine site, preliminary processing will take place in order to separate the desired minerals from the unwanted rock (gangue) that accompanies them, thereby, increasing the grade and value of the sought-after mineral. These "beneficiation" techniques to produce "ore concentrates" include simple hand-sorting, mechanical crushing, and gravity concentration methods, A more sophisticated and widely used method is flotation. Crushed ore is passed through vats of water containing reagents which make one or more of the ore minerals water repellent. These particles attach to air bubbles and float to the top of the vats where they can be selectively removed.

Even after the minerals are concentrated, further processing steps are required to alter their form. Manganese carbonate minerals, for instance, must be heated to convert them into manganese oxides. Manganese oxides and chromite (chromium ores) are smelted into ferroalloys.[11] Cobalt and PGMs, once in metal form, must be highly purified before they are useful for certain applications. Finally, metal alloys such as stainless steels and superalloy are manufactured from ferroalloys or relatively pure metals and used in applications such as hubcaps and jet engines.[12]

This multistep processing of ores into useful forms of metals takes a variety of paths; the appropriate choice depends on the nature of the ore and the type of product desired. Processing facilities are often tailored to a particular ore body or type, production rate, and metal production. Other than the initial beneficiation steps, processing does not necessarily take place at the mine site. However, there is an increasing tendency to combine mine production and downstream processing of minerals. This tendency and the consequences to U.S. import vulnerability is discussed more fully below and in the appropriate mineral sections which follow.

Processing Technology

Extractive metallurgy involves the recovery of metals and metal compounds from ores and mineral concentrates. Either a pyrometallurgical or hydrometallurgical method is used, followed in some cases by an electrolytic refining process.

In pyrometallurgy, heat is used to melt the concentrate and, in some cases, to promote a chemical reaction that will change the ore mineral into an alternate chemical compound. Metals are separated out in gaseous form, collected as they rise from the "melt" or in their liquid state, by differences in densities. Smelting—the technique used to produce ferroalloys—is a pyrometallurgical process.

Hydrometallurgy is chemical processing in which metals are selectively leached (dissolved) from ores and concentrates. The variety of minerals to be separated determines whether an acid or alkaline solvent is applied. Hydrometallurgical processes are increasingly selected over pyrometallurgical processes because they use considerably less energy and produce less air pollution.

In an electrolytic process, a metal is "won" (separated out) from a solution and deposited on a cathode (the negative side of an electrical flow) in a relatively pure form.

No technology ever completely recovers all the desired metal contained in the ores in which they are found. Recovery rates (the amount of contained metal that is liberated)

---

[11] Ferroalloys, alloys of iron, contain a sufficient amount of one or more other chemical elements (in this case, chromium or manganese metal] to be used as an agent for introducing these elements into molten metal, usually steel. Ferroalloys are produced by smelting ores in electric arc furnaces. See the chromium and manganese sections that follow for more discussion on processing.

[12] For a discussion of metal processing, such as steelmaking, see U.S. Congress, Office of Technology Assessment, Technology *and Steel* Industry Competitiveness, OTA-M-122 (Washington, DC: U.S. Government Printing Office, June 1980).

can range from about 25 to 95 percent and depend on both the physical limits of the processing methodology and value attached to each specific metal in an ore body.

Production and Processing of the First-Tier Materials

The United States is not a producer of chromium, cobalt, manganese, or PGM[13] ores, although this has not always been the case. At some stage, however, domestic plants still enter the processing chain of such ores.

The worldwide chromium industry is characterized by a large number and variety—big and small, public and private sector—of ore producer firms. Chromite deposits also vary widely in size and are mined by underground and surface methods and concentration methods range all the way from simple manual sorting to flotation systems.

Manganese deposits are fewer in number and the producing industry is more concentrated than that for chromium. The deposits are generally abundant and can be relatively easily expanded in bulk terms. Often their expansion capabilities are restricted by equipment and transportation systems, rather than the size of their reserves. The majority of the world's producing manganese deposits are oxide, rather than carbonate minerals, and are mostly mined by surface methods. Oxide ores need only to be concentrated; while carbonate ores must be reacted with oxygen to form manganese oxide compounds prior to the ferroalloy stage of processing.

Most of the chromium and manganese mined is consumed by the steel industry. Manganese is a processing agent, and both are used as alloying agents. Producers of these ores have traditionally engaged in the initial processing of the ores they mine—sorting and concentrating them by grades of mineral, chemical content, and physical condition—and leaving the downstream processing to the steel industry. World trade in both chromium and manganese, however, has been shifting in the past decade from concentrated ores to ferroalloys.

The growing ferroalloy production capacity of ore producers (and the steel industries of developing nations) competes with rather than supplements traditional ferroalloy plants in the United States, Western Europe, and Japan. Important factors identified as contributing to this shift are lower labor and energy production costs and lower transportation costs for higher metal content ferroalloys. It is not clear whether the competitive edge of new producers offerroalloys is due to free market economics or whether government subsidies have promoted economically unsound competitors, In any case, as ore producer countries receive the benefits of exporting a higher value product, the shift in production away from the industrialized West is forcing adjustments (due to unemployment from plant closings, and reduced availability of capital for modernization which further diminishes competitiveness) and resulting in a reduction in U.S. ferroalloy production capability.

It is not clear whether trend toward the importation of higher processed material increases the import vulnerability of the United States. At the same time this processing shift is occurring, Western Europe and the United States are importing increasing amounts of final steel products from ore producer nations and others, and their needs for raw and semiprocessed forms of chromium and manganese are decreasing. It is true that, as integration increases in ore-producing countries, system dependencies increase—i.e., concern now must include not only the assurance that a foreign mine will continue to produce and concentrate ores, but also maintain the operation of a smelting plant, Lack of adequate domestic ferroalloy processing capacity could complicate and add considerably to the costs involved in efforts to cope with any emergency ore supply disruption and would probably increase the response time to an emergency, On the other hand, the higher value of processed ores means that an overt act of a supply interruption becomes more costly to producers and a growing number of proc-

---

[13] Current domestic production of PGMs evolves from the refining of copper ores.

essors and might affect such an event's likelihood, In addition, processed ores contain higher amounts of metal per unit volume than ore concentrates and therefore larger amounts can be transported at a time. It is economically feasible to airship refined cobalt and PGMs and avoid supply disruptions caused by surface transport interdictions. Ferroalloys, like ore concentrates, are still confined to ocean shipment due to their weight and volume.

Cobalt is only a secondary product of any current mining operation, therefore, its supply is tied to the demand for the nickel and copper with which it usually occurs. The ore producers control a substantial amount, but not all, of the downstream processing of cobalt, PGMs are primary products, coproducts, or byproducts; and the industry is highly concentrated and is expected to remain so. Almost the entire downstream processing of PGM ores is controlled by the ore producers, As cobalt and PGMs often occur in the same ore bodies, their processing paths are often the same.

Cobalt and PGMs are consumed in metal or chemical form. The ores for both materials usually contain a variety of metals in either oxide or sulfide forms, and their processing paths are complex and tailored to the mineral content of the individual mines, The United States has always had a limited ability to process cobalt and PGM ores, relying instead on importing these materials in their usable forms. (An increasing interest in recycling catalytic converters, however, is promoting the development of domestic refining capacity for platinum that may be usable for virgin PGM ores.) Europe, the first consumer of these metals, was also the home of companies that controlled most mining operations during the colonial era; semiprocessed forms of the ore were physically transferred from the ore-producing countries to northern Europe for the final refining processes. This flow still occurs, but mining countries are gradually developing refining capability. This new capacity does not yet appear to be replacing the existing refining capacity, but is absorbing growth in demand, Meanwhile, more diversified sources of refined cobalt and PGM products are being created and the overall time required to process the ores and produce the metal forms is being shortened.

Chromium Production and Processing

The chromite industry is concentrated in the Eastern Hemisphere and includes a large number and variety of firms–big and small, public and private sector. These producers are now shifting from simply mining and trading chromium ore to producing and trading ferrochromium as well.

The only mineral form of chromium ore is chromite. Most of the chromite resources of the world occur in stratiform deposits—layered, long continuous seams that are often visible on the surface. Podiforms are the second major geologic deposit type for chromite. They are small in comparison with stratiform deposits and are discrete, lens-shaped, and usually undetectable without the use of sophisticated exploration tools unless a portion of the deposit happens to appear on the surface. Lesser deposits of chromite are found in laterite formations and alluvial (placer) deposits. Laterites are principally found in tropic or warm temperate zones and are not exploited today as a source of chromite due to general low grades of contained chromite and its granular form.

Any analysis of chromium production is complicated by the multiplicity of ways in which the commodity is reported: chromite, chromite concentrates, contained chromic oxide or chromium, recovered chromic oxide or chromium, etc. Chromite is primarily iron, chromium and aluminum oxides with varying amounts of silica and magnesium.[14] Chromite ore is usually defined in terms of its chromic

---

[14] Naturally occurring chromite is a combination of minerals described by the chemical formula $(Fe, Mg)O \bullet (Cr, Al, Fe), O_3$.

oxide (Cr_2O_3) content (rarely more than 50 percent), as well as its chromium-to-iron ratio and aluminum oxide content. Once mined, chromite is usually concentrated to increase its chromic oxide (or, chromium) content. These "chromite concentrates" are sold, in part, on the basis of their chromic oxide content. The chromium content of chromic oxide is 68 percent by weight, and the Bureau of Mines defines its chromite data as 22 to 38 percent contained chromium.[15] Throughout the following discussion, an attempt has been made–wherever possible—to convert data into *chromium* units so that comparisons can easily be made by the reader. In addition, the reader should note that the chromium contained in chromite ores and concentrates ("chromium content") is greater than that which will ever be extracted from the ores by any metallurgical process. Thus, "recovered chromium" is the true estimate of the amount that would be available for use.

Each chromite mine differs in the type of product it offers: the ore grade and its chemical composition and physical characteristics. Historically, the ores have been classified into three groups, reflecting primary end uses: "metallurgical" (minimum 46 percent chromic oxide with a chromium-to-iron ratio greater than 2:1), "chemical" (40 to 46 percent chromic oxide and chromium-to-iron ratio of 1.5:1), and "refractory" (high aluminum content). Other considerations affecting end use feasibility of various ores are their other chemical characteristics (e.g., silica content) and physical characteristics (e.g., size and condition). South African ores are of both refractory and chemical grades, and tend to be friable (i.e., breakup easily). The Philippine deposits are principally refractory grade, but its ores are used for other applications by blending. Turkey's and Zimbabwe's deposits primarily provide metallurgical ores.

The distinction between chemical and metallurgical grades has become less important due to the adoption of the argon-oxygen-decarburization (AOD) process for producing stainless steel. This process allows the use of high-carbon ferrochromium (made from chemical ores) rather than low-carbon ferrochromium (from metallurgical ores) and has boosted the importance of the South African deposits at the expense of higher priced metallurgical ores from Zimbabwe and Turkey.

Foreign sources supply all of the U.S. requirements for chromite (there has been no domestic mine production since 1961) and supply an increasing share of its ferrochromium needs at the expense of the domestic ferroalloy industry. In 1971 the United States obtained 87 percent of its chromium imports in the form of chromite and 12 percent in the form of ferrochromium; by 1981, the imports were roughly equal.[16] Because no Western Hemisphere ore producer supplies chromite or ferrochromium in substantial quantities to the United States, most imports must transit the Atlantic or Pacific Oceans.

While 19 countries contributed to the production of chromite in 1982, almost 75 percent of the world's total was provided by South Africa, Zimbabwe, the Soviet Union, and Albania. Table 5-4 lists 12 major producers and their reserves and production for 1982. South Africa is the principal source of ore for the United States, Western Europe, and Japan. Other major suppliers to the United States are the Soviet Union, the Philippines, and Albania. Turkish and Greek ores are shipped primarily to Western Europe. France is Madagascar's major customer. Brazil, the only substantial Western Hemisphere producer, exports mainly to Japan.

The Soviet Union long played a significant role as chromite supplier to the world. In the mid-1970s, however, its exports to areas outside the Eastern bloc began to decline, until by 1982 they were a fraction of those a decade earlier. Decreasing reserves, increased costs of production, and political control over export policies are the major reasons that have been suggested for this change.

---

[15] U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries, 1984.*

[16] U.S. Department of the Interior, Bureau of Mines; *Mineral Commodity Profiles 1983: Chromium,* p. 4.

Table 5-4.—World Chromite Reserves and Production by Country (thousand short tons, gross weight)[a]

Producer country	Reserves 1981	Production 1982	Percent of world production
Albania	2,000	1,320	12
Brazil	9,000	1,050	10
Finland	19,000	440	4
Greece	1,000	46	<1
India	15,000	375	3
Madagascar	230	100	1
New Caledonia	2,000	25	<1
Philippines	23,000	390	4
South Africa	910,000	2,385	22
Turkey	5,000	410	4
Soviet Union	17,000	3,750	34
Zimbabwe	19,000	470	4
Other		146	1
Total	1,000,000	10,907	100

[a] Chromite typically contains from 22 to 38 percent chromium.

SOURCE: Reserves—Bureau of Mines, *Mineral Commodity Profile 1983: Chromium*, table 3, p. 8.
Production—Bureau of Mines, *Minerals Yearbook 1982*, table 14, p. 213.

Producer countries currently export between 35 and 100 percent of their chromite as ores with ferrochromium production taking an increasing share for consumption by local steel industries, as well as export. From South Africa, exports of chromite ore, as opposed to ferroalloys, were 76 percent of production in 1969 and only 35 percent in 1980. South Africa is now the major supplier of ferrochromium to the free world market and provided 49 percent of U.S. imports in 1982. Of the ore producers listed in table 5-4, only Madagascar and New Caledonia have not yet developed ferrochromium production capability. The majority of Zimbabwe's ores are now converted to ferrochromium before export to the United States, Europe, and Japan. In 1982, Yugoslavia—which must import most of its chromite feed—supplied 11 percent of the United States' ferrochromium imports, placing it a distant second to South Africa. Soviet exports of ferrochromium products, like those of ores, are primarily to the Soviet bloc countries.

Extending this vertical integration trend, several South African firms and one Finnish firm now mine ores, process ferrochromium, and produce stainless steel. Greece's recent ore expansion and ferrochromium plant development is aimed at achieving a similar vertically integrated industry, Table 5-5 shows how the ferrochromium industry has shifted over 6 years between 1974 and 1980. For the most part, the traditional centers of ferroalloy production in the industrialized West have declined in total output and have lost market shares to vertically integrated ore producers,

Foreign Production of Chromium

In market economy countries, as shown in table 5-6, chromite production is spread among many private and some public sector firms. Central economy countries (the Soviet Union, Albania, and Madagascar) operate their mines and market production through a central agency. In South Africa, Turkey, and Zimbabwe there is considerable multinational firm involvement. South Africa's ore is produced by 10 companies, operating some 20 mines along parallel seams in the Bushveld Complex, The combined production of Transvaal Mining, Transvaal Consolidated, and Samancor dominates South African output, and the majority interest in these firms is held by four of the six local investment houses ("groups"). U.S. firms engaged in South African chromite mining are Union Carbide, Metallurg, and International Mineral & Chemical. Great Britain is represented in South Africa by investors with long-term interests in the group houses, while West Germany's Bayer Group owns and operates one mine. Eighty percent of Zimbabwe's out-

Table 5-5.—Ferrochromium Production by Country (thousand tonnes, gross weight)

Country[a]	1974	Percent of total	1980	Percent of total	Percent change 1974-80
BRAZIL	38.1	2.0	93.4	3.2	145
FINLAND	48.1	2.6	49.9	1.7	4
France	111.6	6.0	86.2	2.9	–23
INDIA	15.5	0.8	16.3	0.6	5
Italy	39.9	2.1	40.8	1.4	2
JAPAN	541.6	29.1	427.3	14.4	–21
Norway	30.8	1.7	11.8	0.4	–62
SOUTH AFRICA	193.2	10.4	565.2	19.1	193
Spain	20.9	1.1	19.1	0.6	– 9
Sweden	100.7	5.4	188.7	6.4	87
United States	305.7	16.4	216.8	7.3	–29
SOVIET UNION	184.1	9.9	698.5	23.6	279
YUGOSLAVIA	39.0	2.1	64.4	2.2	65
ZIMBABWE	181.4	9.7	199.6	6.7	10
Other[b]	12.0	0.6	282.2	9.5	2,252
Total	1,862.5	100.0	2,960.2	100.0	59

[a] Upper case indicates country was ore producer in both years, but did not necessarily cover its needs.

[b] In 1980: ALBANIA, Czechoslovakia, East Germany, West Germany, PHILIPPINES, Poland, and TURKEY.

SOURCE: Charles River Associates *Processing Capacity for Critical Materials,* OTA contract report January 1984

Table 5-6.—Chromite Mining Industry by Country

		Ownership		
Country	Major firms	Sector	Major holders[a]	Primary national identity
Brazil	Cia. de Ferro-Ligas da Bahia S.A. (Ferbasa)	Private	Various	Local
Finland	Outokumpu Oy	Government	(81)	Local
		Private	(balance)	Local
Greece	Hellenic Ferroalloys S.A.	Private and government	Hellenic Industrial Mining & Investment (HIMIC) (96)	Local
India	Various	Private and government		Local
Madagascar	Kraoma	Government	(loo)	Local
New Caledonia	Societe de la Tiebaghi	Private	Inco (55)	Canada/U.S.
			Various	French
Philippines	Acoje Mining Co.	Private		Local
	Consolidated Mines Inc.[b]	Private		Local
	Trident Mining & Industry Corp.	Private	c	Local
	Phil chrome	Private	Kawasaki (15)	Japan
South Africa[d]	Transvaal Mining and Finance	Private	Gencor (100)	Local
	Transvaal Consolidated Land and Exploration	Private	Barlow Rand	Local
	UCAR Chrome Co.	Private	Union Carbide	Us.
	Cromore Ltd. & Bathlako Mining Ltd.	Private	Samancor[e] (100)	Local
	Waterkloof Chrome Mines	Private	Metallurg	Us.
	Chrome Chemical S.A.	Private	Bayer Group	W. Germany
	Lavino S. A., Ltd.	Private	International Minerals & Chemical Corp. (100)	Us.
Turkey	Etibank	Government	(loo)	Local
	Egemetal Madencilik A.S.	Private	Metallgesellschaft	W. Germany
	Turk Maadin Sirketi	Private	Metallurg	Us.
Zimbabwe	Zimbabwe Mining & Smelting	Private	Union Carbide (100)	Us.

[a] With approximate percentage of control, if available.

[b] Operated by Benquet Corp. (local Philippine firm).

[c] A U.S. firm invested in Trident's operation in 1984.

[d] There are six finance houses (the "Groups") which dominate the South African industry: The Anglo American Corp. of S.A. Ltd. (AngloAmer); Gold Fields of S.A Ltd., General Mining Union Corp. Ltd. (Gencor); Rand Mines/Barlow Rand; Johannesburg Consolidated Investment Co. Ltd (JCI); and Anglo-Transvaal Consolidated Investment Co. Ltd. (AngloTC).

[e] Samancor is owned by Gencor, Anglo American, and Iscor, which is a state-owned, integrated steel corporation.

SOURCES: E&MJ 1983 *International Directory of Mining;* Bureau of Mines, *Mineral Commodity Profile 1983: Chromium;* Office of Technology Assessment put is generated from two mines east of the Great Dyke deposit by a firm owned by Union Carbide. Albania's government operates more than a dozen mines located in four areas along its eastern border with Greece and Yugoslavia.

Among the middle-level producers, Turkey has three major firms with eight mines, along with numerous smaller (many one-person) operations. Half of Turkey's output, however, comes from mines operated by a state-owned firm. U.S. (Metallurg) and West German (Metallgesellschaft) firms are involved in the other two important Turkish ventures. There are 125 chromite deposits scattered among the islands of the Philippines, but only 12 mines were operating in 1980. The majority of these are locally owned and operated; two are considered major producers. (Japan's Kawasaki Steel has a minority interest in a recently initiated beach sand operation on Palawan Island in the Philippines. An American firm operates the mine for Kawasaki.) Madagascar's government firm has two open pit mines, one of which is a primitive operation accessible only in the dry season. Finland's government-controlled firm produces from a mine along a stratiform deposit. Greece has one major, primarily government-owned operation. Three of India's four firms are private and locally owned; the fourth is a state government firm. Canada's Inco has a controlling interest in New Caledonia's new chromite mining firm, Societe de la Tiebaghi.

In the past 20 years, there have been shifts in the relative output among chromite producer countries, as shown in table 5-7. Overall, the group of 12 major producers has steadily increased its share of the world market. By 1980 it was providing 98 percent of the world's total production of chromite, up from 90 percent in 1960. During this period, two new producers (Finland and Madagascar) appeared; they now hold 5 percent of the world market. While Albania, Brazil, South Africa, and the Soviet Union have increased their production shares, the shares of the Philippines, Turkey, and Zimbabwe have decreased. The shift from Turkey and Zimbabwe to South Africa is due to the advent of the AOD process and to the accompanying development and aggressive sales by South African firms of "charge chrome, " a form of high-carbon ferrochromium particularly suited to South African ores.[17]

The major producer and exporting countries are likely to maintain their current positions in world production for the near future and can be expected to continue reducing the export of ores in favor of ferroalloys. The integration of ore mining with ferroalloy production and the accompanying decline of independent ferroalloy producers may force the remaining nonintegrated ore producers, witnessing shrink-

---

[17] See table 5-13 for a comparison of various ferrochromium products.

Table 5-7.—Historical Production—Chromite, 1960-80, by Country
(thousand short tons, gross weight, percent of world total)

	1960		1965		1970		1975		1980	
Producer country	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
Albania	319	7	342	6	516	8	859	9	1,190	10
Brazil	6	<1	19	<1	30	<1	191	2	919	7
Finland	0	0	0	0	133	2	365	4	376	3
Greece	38	1	56	1	29	<1	39	<1	47	<1
India	110	2	66	1	299	4	551	6	354	3
Madagascar	0	0	3	<1	144	2	214	2	198	2
New Caledonia	43	1	0	0	0	0	2	<1	2	<1
Philippines	810	17	611	12	624	9	573	6	547	4
South Africa	851	17	1,038	20	1,573	24	2,288	25	3,763	30
Turkey	531	11	625	12	572	9	790	9	431	3
Soviet Union	1,010	21	1,565	30	1,930	29	2,290	25	3,748	30
Zimbabwe	668	14	646	12	400	6	650	7	608	5
Subtotal	4,386	90	4,971	94	6,250	93	8,812	96	12,183	98
Other	499	10	330	6	422	6	3,324	4	203	2
Total	4,885	100	5,301	100	6,672	100	9,136	100	12,386	100

SOURCE U S Department of the Interior, Bureau of Mines, *Minerals Yearbooks 1964, 1968, 1972,* 1977, and 1982 ing markets, to integrate. Turkey, India, Greece, Albania, and Madagascar, among other countries, are currently expanding or planning to expand or introduce ferrochromium capacity. While some construction has been held up by weak worldwide demand for ferroalloys, expansion will probably resume as the steel industry recovers from the early 1980s recession period. Given chromium's primary use in steelmaking, certain producer countries with growing domestic and export-oriented steel industries—e.g., India and Brazil—may reduce their participation in both ore and ferroalloy export markets.

The 1981-82 worldwide recession caused low-capacity usage in chromite mines (see table 5-8) and ferroalloy plants, and low world prices. These market conditions and the competitive strength of the South African producers inhibit the pursuit and development of new sources of chromite ore. In addition, the only known, nonproducing deposits of chromite are considered marginally economic even under more favorable market conditions due to low grades and/or smallness of overall deposit.

In 1982 one new chromite source entered the world market when a firm resumed production at a previously abandoned area in New Caledonia. A project in Papua New Guinea has been fully explored and evaluated by an international mining firm but is not considered economically viable and will not be developed in the near future. Together, these new producers, while diversifying the world's sources of chromium, will add only about 5 percent, at maximum output, to the world's total production. More important, perhaps, is that new sources of chromite will be unconventional unless new stratiform or podiform deposits are discovered. The Papua New Guinea project, for instance, may undertake mining from a sand and laterite deposit.

In the long term, two developments could alter the current pattern of chromite production. Almost 90 percent of the world's known reserves of chromium are contained in stratiform, as opposed to podiform, deposits. This is explained in part by the fact that stratiform chromite deposits are continuous over large areas, making estimation of reserves relatively easy and the exploration costs to prove large tonnages of reserves small compared to those for podiform deposits. Scattered, discontinuous podiform deposits, on the other hand, are difficult and therefore expensive to locate, even using the most sophisticated geophysical exploration techniques.[18] This implies that areas

Table 5-8.—Chromite Mine Capacity and Usage in 1981 by Country (thousand short tons, contained chromium)

Producer country	Estimated annual capacity	Percent in use	Estimated unused capacity
Albania	300	50%	150
Brazil	130	83	22
Finland	130	82	23
Greece	15	73	4
India	170	47	90
Madagascar	50	48	26
New Caledonia	5	20	4
Philippines	150	85	23
South Africa	1,500	63	555
Turkey	170	97	5
Soviet Union	1,000	93	70
Zimbabwe	325	43	185
Other	55		
Total	4,000	70	1,160

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Commodity Profile 1983: Chromium*.

---

[18] U.S. International Development Cooperation Agency, Trade and Development Program, *The Chromite Project Definition Mission of the Philippines*, February 1983; Charles J. Johnson and Jean A. Brady, *Chromite Potential of the Southwest Pacific*, a summary of research in progress at the Resource Systems Institute of the East-West Center, Honolulu, Hawaii. August 1982, p. 13.

of podiform deposit concentration—e.g., in Turkey, Albania, and the Philippines—that have not been systematically surveyed are potential locations for increased reserves. Location of these podiform deposits could benefit from developments in the use of geochemistry as a prospecting tool and an infusion of funding to finance exploration efforts.

The other possible development is exploitation of two deposit types found in the southwest Pacific Basin area—the Philippines, Indonesia, New Caledonia, New Guinea; that is, nickel laterite deposits overlain by low-grade chromite, and alluvial deposits of chromite sands in shallow offshore areas. No laterites have yet been exploited for chromite, and only one beach sand operation has been opened (in the Philippines). The mining and extraction of chromium from either type of deposit is prevented not by a lack of technology, but by economics. An American mining company studied the possibility of joining in the Philippine beach sand operation and decided that the economics, based on South African competition, did not warrant the investment. The U.S. Bureau of Mines has conducted successful research up to the pilot plant stage on processing laterites ores (from U.S. sources) and concluded that existing technologies, with adjustments for the different minerals encountered in foreign ores, could be applied. Analyses at the East-West Center concluded[19] that economic mining of some known laterite resources would require a chromite concentrate price of $100 to $150 per tonne, f.o.b.[20] (The 1984 price for South African 44 percent chromic oxide chromite ore was $40 to $55 per ton, f.o.b., or $44 to $60 per tonne.)[21] Ongoing work by the U.S. Geological Survey on PGMs contained in laterites (see the PGM section) offer a possibility of changing the economics of laterite deposits if PGMs could be mined as a primary or coproduct.

While expansion of chromite production awaits increased steel industry production, many ore producers have announced plans to add ferrochromium capacity. In some countries, such as Zimbabwe, this would require additional ore production, but in many it could simply mean a greater diversion of ore production from exports into ferroalloy production. Some of the constraints to increased production, such as lack of energy sources and transportation facilities, are given below in brief country-by-country reviews.

Albania

Chromite is one of Albania's chief export commodities and most important sources of foreign exchange.” Since 1976, Albania's production has been steadily increasing. The nation now ranks as the world's third largest producer. The last completed 5-year plan period (1976-80) called for an output of 1.25 million tonnes (1.14 tons) by 1980, a goal that was not quite met. The 1981-85 plan calls for a 9.7-percent annual increase in chromite output. Albania has one ferrochromium plant in operation, with total estimated capacity of 30,000 tons per year.

Albania's chromite trade patterns have shifted over the past 30 years. Its production once served as a supplemental source for Eastern European nations that relied primarily on exports from the Soviet Union. China bought half of Albania's output from the mid-1950s to 1978, when relations were broken due to ideological conflicts. Since then, an increasingly large portion of Albania's exports have gone to Western countries, Recently, relations with China have improved, and renewed ties could bring resumed chromite trade. Yugoslavia has been an important buyer of Albanian ores for conversion into ferroalloys for the world market.

While Albanian ore reserves and resources are not known with great certainty, current estimates are considered too low to support current and planned production levels. The possibility of finding new deposits is likely because large areas have yet to be explored for

---

[19] Charles J. Johnson, personal communication, August 1983.

[20] Free on board, means price at embarkation—i. e., without transportation charges,

[21] "AMM Closing Prices, " *American Metal Market,* June 21, 1984.

[22] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook,* **1981,** vol. 111, p. 42.

the discontinuous, podiform deposits common to Albania.

Brazil

Due to the volume of unexplored area in Brazil, the potential exists for improved chromite reserves but the uncertainty factor is high. Ferbasa is Brazil's major producer of ore and its sole producer of ferrochromium. Brazil exports more of its chromium as ferrochromium than as ore. Most has been destined for Japan, which assisted Ferbasa in the development of its ferrochromium facilities, In 1972 a Japanese consortium formed a joint venture (Mineracao Serra de Jacabina S. A.) with Ferbasa to mine another deposit, in the state of Bahia. The mine was opened in 1976 and was Japan's first captive overseas chromite mine. Heavy losses forced the Japanese to sell their 48-percent interest to Ferbasa in 1980.

Finland

Finland's sole producer of chromite, Outokumpu Oy, is a highly integrated firm that mines, explores, trades, smelts, and refines a variety of minerals and produces both ferrochromium and stainless steel. In addition, it is involved worldwide in the development and sale of mineral industry technology. Currently, all of Outokumpu's chromite production comes from its Kemi deposit, located in northwestern Finland near the Gulf of Bothnia. Another deposit is being developed for future production and would allow, under the proper economic conditions, a 25-percent increase in Finland's output. A constraint on expansion is the need to import energy resources—mainly petroleum. Shipping during the winter months is often hampered by frost and ice conditions.

Greece

An expansion in chromite mining and in development of a ferrochromium industry has been underway in Greece since 1976, when government geologic research verified that chromite resources were adequate for ferrochromium production. Hellenic Ferroalloys S.A. has expanded an underground mine at the Skoumtsa deposit in the Mt. Vourinos region (northern Greece, near the Albanian border) to serve as feed for a new ferrochromium plant at Tsigeli. This plant, which began operation in February 1983, was constructed by Outokumpu Oy. Until Hellenic Industrial Mining & Investment Co. (parent firm of Hellenic Ferroalloys) follows through with plans for a steel plant at Tsigeli, the ferrochromium output (potential total capacity of about 90,000 tons per year) is destined for the export market, primarily other European Economic Community (EEC)[23] countries.

India

The principal ore-producing area in India is in the state of Orissa. In recent years, the Indian government has actively encouraged the development of the ferrochromium industry to increase the value of its exports and to reduce its dependence on imported ferroalloys for growing domestic steel needs. Four new plants were under construction in 1982 for two private firms and one public firm. Ongoing mining industry upgrading and geological survey work to improve the ore reserve base is intended to support the ferroalloy industry rather than increase ore exports. production has been hindered at times in recent years because of power shortages caused by droughts. Indian power needs are heavily dependent on the monsoon rains to provide necessary energy. Transportation bottlenecks and production inefficiencies are traditional constraints to India's assuming a greater role in providing world needs.

Madagascar

Chromite is this country's most important mineral commodity, and all production is for export. Although feasibility studies have been conducted, no ferrochromium plant has yet been built, owing to unresolved financial and technical problems. The necessary power source, a hydroelectric dam, was completed in 1983. Two open pit mines, each with a capacity of 300,000 tons of chromite ore per year, are operated. The Adriamena mine was developed by the French firm Comina before it was

---

[23] Common Market.

nationalized in 1976. Its ores must be processed to reduce an unacceptably high phosphorus level. The newer mine, Befandriana, is a primitive setup consisting of several small open pits and no concentrator, Ores from this mine do not have a high phosphorus level and are simply screened to produce two separate grades, During monsoon season, December to April, the Befandriana pits cannot be operated. Transportation from Adriamena is by truck and railroad to the port of Toamasina (Tamatave). From Befandriana, ores are trucked about 100 miles to Narinda Bay for shipment, Due to the shallowness of the bay, ores must be transferred by small vessels to ocean freighters; loading of one shipment can take 3 weeks.

The area has the potential to expand production easily by 50 percent due to the extent of the reserves. Transportation is the weakest link; lack of sufficient railroad cars, poor roads, and the undeveloped port at Narinda Bay impede expansion. While France is Madagascar's major customer for chromite, one U.S. ferroalloy firm, Interlake, had a 2-year contract, ending in 1982, to take all of the annual output of the Befandriana mine. The contract has not been renewed due to the weak market for ferroalloys.

New Caledonia

All of New Caledonia's lateritic nickel deposits contain chromite. Much of the chromite, however, occurs in low grades and is currently considered uneconomical. Two firms operate mines from podiform deposits in New Caledonia. Societé de la Tiebaghi started full-scale production in 1982, with an output of 50,000 tons of chromite concentrates (containing 51 percent chromic oxide), eclipsing Calmine's 2,000 tons-per-year operation. Capacity of the Tiebaghi mining operation is 85,000 tons per year of concentrates. The new mine, for which development work began in 1976, underlies a Union Carbide operation that closed in 1962. The island has no domestic energy source, creating a potential barrier for any expansion. Societe le Nickel (SLN), the large nickel producer on the island, already consumes 85 percent of the country's industrial electricity in its mining and smelting operations. A hydroelectric powerplant has been considered but is not yet planned.

Philippines

The Philippines is the principal source of refractory grade chromite for the Western world. The Coto deposits in the Zambales district on the main island of Luzon are the largest such group in the world. Reports on the Philippines continually predict reserve depletion, but further exploration has always extended mine life by another 10 years. Two major firms conduct operations at Zambales. Consolidated's Masinloc mines are operated by the Benquet Corp. and contribute 95 percent of the country's refractory ores; Acoje Mining is the country's major metallurgical ore producer. A third firm, Trident Mining & Industrial Corp., has produced metallurgical ores from mines on the southern Palawan Island. Its operations have been shut down since 1981 due to financial problems. Representatives from Trident were in the United States in 1983 seeking new capital to resume production and reportedly secured it. In late 1983, Acoje was seeking debt relief from the Philippine government and the private sector in order to maintain operations. These financial difficulties will delay plans for exploration and new mine development.

Two ferrochromium plants in the Philippines produce primarily for the Japanese market. The newest plant began operating in 1983, and some startup problems caused by erratic power supplies and ore quality were reported.

Theoretically, the extensive ultramafic formations of the Philippines could hold up to 105 million tons of 32-percent chromic oxide in laterite formations.[24] Extensive, systematic geological field and exploration work, however, must be completed in order to prove the theory.

South Africa

The Bushveld Complex in the Transvaal Province is the largest known chromite deposit

---

[24] *The Chromite Project Definition Mission of the Philippines,* op. cit.

in the world. Most of the chromite is produced in two districts within the complex: the Eastern Belt (Lydenburg district, five mines) and Western Belt (Rustenburg district, eight mines). Competition among the many firms and mines for increased market shares is strong. The slackness in world chromite markets, rising costs, and stable prices in recent years have caused some of the least efficient mines to be placed on "care and maintenance" status.

The UG2 (upper group seam of the Bushveld) chromium-platinum reef in Rustenburg is currently mined for PGMs by Western Platinum and has chromite resources estimated by South Africa to total *650* million tonnes. Tapping certain sections of this reef for chromium requires new metallurgical and smelting techniques in order to separate and recover the individual minerals. The South African government's Mintek (Council for Mineral Technology, a research arm of the Ministry of Mines and Energy) has conducted research and development and plasma technologies, which provide high-temperature processing, have been tested. Western Platinum has reportedly opened a smelter in 1984 capable of processing these complex ores and is considering the addition of a ferrochromium plant.

As in many areas, transportation bottlenecks could limit any effort to rapidly increase output from the Bushveld. Ores from the mines are currently trucked 5 to 10 miles to a railhead. Once there, the ores are moved to the heavily used port of Maputo in Mozambique *(480* miles from the Western Belt and *350* miles from the Eastern Belt). Perennial congestion at the port has been relieved by recently installed mechanized facilities. The port can now handle *2,500* tonnes of chromite per hour and store up to 1.1 million tonnes. Alternate ports in South Africa, at Durban and Richards Bay, could be used if Maputo was not available (for instance, due to transborder conflicts) although significant lead-time would be required to accommodate chromite at these ports. It has been estimated that for a typical underground South African mine, 50-percent expansion would require little more than 1 year; however, port expansions to handle such increased output could take 4 years.[25]

Soviet Union

The Soviet Union is still the world's second largest chromite producer, although its ore exports have declined during the past decade. Most of its deposits are podiform and located in the Ural Mountains. Virtually all its metallurgical-grade ores originate in the Western Kazakhstan (southern Ural region). Ninety percent of production comes from the Donskoye mining and concentration complex in Khrom-Tau. A new underground mine there started producing in *1982* with an expected ore capacity of *2* million tons per year by *1985.*

Turkey

Exports of ore from Turkey have declined in recent years as a result of increasing internal consumption, world market oversupply, and an inability to meet price competition. Turkish podiform deposits are widely scattered (occurring in *40* of the country's *67* provinces), limiting the output and mechanization potential of many mines. The presence of podiform rather than stratiform deposits, however, makes the total resource picture uncertain because such pockets are difficult to locate. With economic incentives, a 50-percent increase in production (a return to the 1975 production level) could take place in 3 to 12 months. Any further increase would be limited by available and willing investment and would require an increase in reserves. Constraints would include lack of mining equipment and transportation bottlenecks. The main ports (Mersin and Iskenderun, on the Mediterranean Sea) are 400 miles from the mineheads and have maximum loading capacities of 3,000 tonnes per day, each.

Several ferrochromium plants are now online in Turkey, and additional capacity (to a total 150,000 tons per year) is expected by 1986. Etibank, the state-owned mining company that

---

[25] Charles *River Associates, Processing Capacity for Critical Materials,* contractor report prepared for the Office of Technology Assessment, January 1984.

supplies half of Turkey's chromite output and all of its ferrochromium, has a reputation for making policy decisions removed from political influence, Under the most recent government it has become very active in seeking investment partners from the private sector, Owing to market conditions, most of Turkey's existing private producer mines, which mainly contribute ores for export, were closed during 1982. Overall, Turkey's chromite industry could improve its position in the world market with an infusion of capital and substantial technology transfer to upgrade its mining and processing procedures.

Zimbabwe

Most of the chromium reserves in Zimbabwe lie in the Great Dyke, an elongated, elevated geological structure that runs 300 miles or more in a northeast-southwest direction across the country, However, about 80 percent of current output comes from the Selukwe mines in related lode deposits along the Great Dyke's southern section. The Dyke's thin seams require labor-intensive mining methods and are underdeveloped due to high costs. The Selukwe mines are operated by Union Carbide's Zimbabwe Mining & Smelting Co. Since Western trade sanctions against the importation of Rhodesian (now Zimbabwean) chromium were lifted in 1979, the emphasis has been on exporting ferrochromium rather than ores. Union Carbide and Anglo American (of South Africa) own the two ferroalloy plants in Zimbabwe. Their combined ferrochromium capacity in 1980 was 240,000 tons per year, and expansion plans have been announced. As with most chromite mining areas, transportation is a major physical barrier to increased production. Zimbabwe would prefer to use direct rail routes through black Mozambique, but while the border was closed between 1975 and 1980, the rail link deteriorated, forcing reliance on routes through the ports in South Africa.

Potential **Producers**

PAPUA NEW GUINEA-RAMU RIVER

A nickel laterite deposit containing chromite and cobalt has been under development at Ramu River, The mineral deposit is in three layers, with chromite in the top two layers, Estimates give a reserve of 80 million to 100 million tons of ore with about 9 percent metallurgical grade chromite in the first, sandy clay layer, and about 81.5 million tons at 6 percent in the second. These 14 million tons of chromite would place Papua-New Guinea alongside most of the major ore-producing countries, if classified as a reserve and assuming a chromic oxide content of 46 percent. Nickel (1.14 percent] and cobalt (0.16 percent) are concentrated in the third layer of the deposit. In 1983 Nerd Resources Corp. (U. S.) held a 69.5-percent share of the mining concession and Mount Isa Mines Ltd. (Australia), the balance. (Mount Isa Mines is owned by the Australian corporation M.I.M. Holdings, in which Asarco Inc. holds a 49-percent interest.) Technical viability of the project has been confirmed, and economic studies were conducted in 1982. An executive of Nerd Resources stated in early 1984 that the earliest possible date to start the development phase of the project was 2 years away due to the depressed markets for both chromite and cobalt, and that once a decision to go ahead was made—if ever—it would take 5 years to reach the production phase.[26]

The first phase of production will be to mine the chromite, which can be recovered from the ore by gravity concentration methods, Nickel and cobalt, which will require a hydrometallurgical acid leaching process for recovery, will be mined in the second stage of the project. Annual production of chromite concentrates has been estimated at 500,000 tons. Japan, Australia, and the United States are considered the most probable markets. The U.S. Bureau of Mines tested the chromite concentrate product and, using conventional technology, produced high- and low-carbon ferrochromium.[27]

CANADA–BIRD RIVER

Of hundreds of documented chromite occurrences in Canada, few contain measured re-

---

[26] Richard Steinberger, Executive Vice-President, Nerd Resources, Dayton, OH, personal communication, February 1984.

[27] "More on Ramu River," *Mining Journal,* Mar. 19, 1982, p. 211 and U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982,* vol. III, p. 1237.

sources. One deposit, considered the most likely candidate if development plans arise, is Bird River in Manitoba, Resources for the four Bird River properties total 4 million tons at 18 to 25 percent chromic oxide and 15 million tons at 5 to 7 percent chromic oxide.

The low grade and chromium-to-iron ratio of these deposits have mitigated against their development in the past. Research into technologies to process the ores has determined that only with high-cost chemical treatment can a sufficiently high-grade product be attained to meet conventional specifications. Recent research by the Ontario Research Foundation has produced a chromium carbide that could be used to produce chromium metal or be used as an alloying agent.

Domestic Production of Chromium

Known resources of domestic chromite are the stratiform deposits in the Stillwater Complex of Montana and the small podiform bodies in northern California, Oregon, and Alaska. Chromite is also associated with nickel-cobalt laterite ores of northern California and southern Oregon and found in placer beach and stream sands located in Oregon, Maryland, and Pennsylvania.

As tables 5-9 and 5-10 show, the United States has an estimated 337 million tonnes (371 million tons) of identified resources[28] of chromite with chromic oxide grades ranging from 1 to 25 percent (or, 13.8 million tons of contained chromium). Of these identified resources, 80.4 million tonnes (88.6 million tons) of chromite are considered to be demonstrated resources (a subdivision of identified resources with the highest degree of geologic certainty) containing 3.9 million tons of chromium. As a comparison, South Africa is credited with a "reserve base" (total demonstrated resources but excluding the subeconomic tonnages) of 910 million tons of shipping grade chromite ores normalized to 45 percent chromic oxide, or 279 million tons of chromium.

In a Minerals Availability Appraisal[29] published in 1982, the U.S. Bureau of Mines concluded that none of the U.S. identified resources of chromite in stratiform or podiform deposits were economically recoverable at January 1981 market prices ($128 to $144 per tonne for a metallurgical grade product, CIF[30] in the Eastern United States), Instead, production at that time would have required a minimum price of $237 per tonne, almost double the prevailing market price.

Laterite deposits were not analyzed in the Bureau of Mines' study in terms of potential production because of "technological and cost uncertainties."[31] Unlike laterite deposits, the other deposit types have previous production history in the United States.

The mining and beneficiation methods upon which the study was based were those methods used in past domestic production of chromite ores; no new technologies were considered. For each deposit included in the appraisal (table 5-11), the engineering and cost (capital and operating) analyses were followed by an economic evaluation using a 15 percent rate of return on the capital investment. Some costs were not considered—e.g., the time lags involved in filing environmental impact statements, receiving necessary permits, financing, etc., as it was felt that such delays "would be minimized in consideration of strategic availability."[32]

Up to 235,000 tons per year (table 5-12) of contained chromium could theoretically be produced from the most probable U.S. sources. This assumes simultaneous production and would most likely require government incentives, Mine lifetimes range from 3 to 46 years.

---

[28] "Identified" resources are those for which location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic, and subeconomic components. To reflect varying degrees of geologic certainty, identified resources are divided into "demonstrated" [both measured and indicated) and "inferred" resources.

[29] Jim Lemons, Jr., et al., U.S. Department of the Interior, Bureau of Mines, *Chromium Availability—Domestic: A Minerals Availability System Appraisal*, Information Circular No, 8895, 1982, p. 1.

[30] Cost, insurance, and freight paid by the shipper.

[31] Ibid., p. 1.

[32] Ibid., p. 7.

Table 5-9.—U.S. Chromite Deposit Resources

State	Property	Grade (percent Cr_2O_2)	Demonstrated[a] (thousand tonnes) Mineralized material	Demonstrated[a] (thousand tonnes) Contained Cr_2O_2	Identified (thousand tonnes) Mineralized material	Identified (thousand tonnes) Contained Cr_2O_2
Alaska	Claim Point	17.6	267	47.6	267	47.6
	Red Bluff Bay	12,0	30	3.6	30	3.6
	Red Mountain	25.8	0	0.0	183	47.2
California	Bar Rick Mine	7.6	5,065	384.9	44,512	3,382.9
	McGuffy Creek	W	w	w	w	w
	North Elder Creek[b]	11.9	0	0.0	104	12.4
	Pilliken Mine	5.0	0	0.0	30,975	1,548.8
	Seiad Creek/Emma Ball	5.0	4,546	227.3	10,826	541.3
Georgia	Louise Chromite	.4	131	.6	131	.6
Maryland-Pennsylvania	West Placer Area[c]	1.4	729	10.1	729	10.1
Montana	Stillwater Complex:					
	Mouat/Benbow	W	W	W	W	W
	Gish Mine	15,0	500	75.0	854	128.1
North Carolina	North Carolina Area[b]	1.9	108	2,1	178	3.5
Oregon	Southwest Oregon Beach Sands	5.6	10,827	604.1	45,772	2,554.1
Pennsylvania	Renshaw Placer	1.7	209	3.5	209	3.5
Wyoming	Casper Mountain	2.5	3,774	92.5	3,774	92.5
Total[d]		NA	46,604	5,620,6	194.019	19.333.2

W—Withheld to avoid disclosing individual company proprietary data, included in total
NA—Not applicable
[a] Domestic chromite reserve base
[b] Includes 3 deposits that have been combined for analysis
[c] Includes 13 deposits that have been combined for analysis
[d] Includes resources withheld to avoid disclosing individual company proprietary data

SOURCE U S Department of the Interior, Bureau of Mines Information Circular No 8895, 1982, *Chromium Availability—Domestic A Minerals System Appraisal*, tables 1 and 2, pp 4 and 5

Table 5.10.—U.S. Chromite Laterite Deposit Resources

State	Property	Grade (percent Cr_2O_2)	Demonstrated (thousand tonnes) Mineralized material	Demonstrated (thousand tonnes) Contained Cr_2O_2	Identified (thousand tonnes) Mineralized material	Identified (thousand tonnes) Contained Cr_2O_2
California	Gasquet Laterite	W	w	w	w	w
	Little Rattlesnake	W	w	w	w	w
	Lower Elk Camp	W	w	w	w	w
	Pine Flat Mountain	2.8	6,382	178,7	15,052	421.5
	Red Mountain	W	w	w	w	w
Oregon	Eight Dollar Mountain	1.1	0	0	13,023	145.9
	Red Flat	W	w	w	w	w
	Rough and Ready	1.5	0	0	5,931	90.7
	Woodcock	1.3	0	0	8,587	112.5
Total		NA	33,813	640.0	143,126	2,995.4

W—Withheld to avoid disclosing Individual company proprietary data, Included in total
NA—Not applicable

SOURCE U S Department of the Interior, Bureau of Mines Information Circular No 8895, 1982, *Chromium* Avai/abi/ity—Domestic *A Minerals System Appraisal*, tables 1 and 2, pp 4 and 5

Table 5-11.—Proposed Mining and Processing Methods U.S. Chromite Deposits

Property	State	Type of deposit	Minimum lead time years	Annual capacity tonnes of ore	Mining method	Beneficiation method
Claim Point	Alaska	Podiform	4	18,000	Open pit	Gravity
Red Bluff Bay	Alaska	Podiform	2	9,000	Open pit	Gravity
Red Mountain	Alaska	Podiform	2	18,000	Overhand shrinkage	Gravity
Bar Rick Mine	California	Podiform	2	350,000	Sublevel slope	Gravity
McGuffy Creek	California	Podiform	2	787,000	Open pit	Gravity
North Elder Creek[a]	California	Podiform	1	25,000	Open pit	Gravity
Pilliken Mine	California	Podiform	2	2,100,000	Open pit	Gravity-magnetic
Seiad Creek/Emma Bell	California	Podiform	3	562,500	Open pit	Gravity
Louise Chromite	Georgia	Placer	1	25,000	Open pit	Gravity-electrostatic
West Placer Area[b]	Maryland-Pennsylvania	Placer	1	50,000	Placer mining	Gravity-electrostatic
Stillwater Complex:						
Mouat/Benbow	Montana	Strati form	3	525,000	Shrink slope	Gravity
Gish Mine	Montana	Strati form	2	175,000	Shrink slope	Gravity
North Carolina Area[a]	North Carolina	Placer	1	25,000	Open pit	Gravity-electrostatic
Southwest Oregon Beach Sands	Oregon	Placer	2	1,000,000	Strip	Gravity-magnetic-electrostatic
Renshaw Placer	Pennsylvania	Placer	1	50,000	Open pit	Gravity-electrostatic
Casper Mountain	Wyoming	Strati form	3	377,260	Open pit	Gravity

[a] Includes 3 deposits combined in the analysis

[b] Includes 13 deposits combined in the analysis.

SOURCE: U.S Department of the Interior. Bureau of Mines Information Circular No. 8895, 1982, *Chromium Availability—Domestic: A Minerals Availability System Appraisal*, 'tables 1 and 2, pp. 4 and 5.

All of these areas, with the exception of Gasquet Mountain in California, have been mined previously, providing a backlog of information and infrastructure upon which to base operating decisions. Gasquet Mountain has benefited from considerable recent commercial evaluation.

The most recent U.S. production of chromite was from the Gish and Mouat/Benbow Mines at Stillwater from 1953 until 1961, subsidized by the Federal Government under the Defense Production Act. The contract with the American Chrome Co. called for 900,000 tons of chromite ore (36 to 38 percent chromic oxide) over an 8-year period (an average annual rate of 113,000 tons), during which the government advanced $1.8 million for machinery and equipment and guaranteed the company a price of $34.98 per ton of ore (about $140 per ton of chromium). (During the period 1954-61, the weighted average yearly price ranged from *$124* to *$147* per ton.)[33] Approximately 400,000 tons of the ore produced—half of the contract—remained unused and was sold by the government to Metallurg, Inc., in 1974 for $7.64 per ton. In 1984, this "stockpile" sat in the town of Columbus, nearby the Stillwater mine site.

Chromite was also mined from Stillwater and from podiform deposits in Alaska under World War II production subsidies. At Stillwater, development efforts began in 1941 under the Reconstruction Finance Corp. 's Metals Reserve Co. After spending $15 million on the development of two mines (only one of which actually started producing), all operations were closed down in 1943 when foreign trade routes became more secure. Domestic chromite production reached a historic peak of about 140,000 tons in 1943, and consumption that year was

---

[33] U.S. Department of the Interior, Bureau of Mines, *Mineral Facts and Problems, 1975* edition, p. 248.

Table 5-12.—Potential U.S. Chromite Production

	Demonstrated resources			Estimated annual production		
Known resources by deposit type	Grade (percent Cr_2O_3)	Ore (thousand tonnes)	Chromium content (thousand tonnes)	Ore (thousand tonnes)	Chromium content (thousand tonnes)	Estimated minelife (years)
Stratiform:						
Stillwater Complex:						
Mouat/Benboe	w	w	w	525	72[a]	46
Gish	15.0	500	51	175	16	3
Pod/form:						
California:						
Bar Rick Mine	7.6	5,065	262	350	16	13
McGuffy Creek.	w	w	w	788	NA	4
Pilliken Mine[b].	5.0	30,975	1,053	2,100	65	4
Seiad Creek/Emma Bell . . .	5.0	4,546	155	563	17	9
Beach Sands:						
Southwest Oregon	5.6	10,827	412	1,000	35	11
Laterite	Grade (percent chromium)	Proven reserves (thousand tonnes)		Chromite concentrates (thousand tonnes)		
Gasquet Mountain.	2.0	16,000	320	50	14	18

[a] Estimated assuming 15 percent grade
[b] Inferred resources only
W—information withheld for proprietary reasons
NA—Date not available

SOURCES Resources, ore grades, proposed mining rate, minelifes from U.S Department of the Interior, Bureau of Mines, *Chromium Availability—Domestic*, IC8895/1982 Gasquet Mountain data provided by California Nickel Corp; balance calculated by OTA.

Chromium data	1979	1982
Reported chromite consumption (tons) (22 to 38 percent chromium)	1,209,000	545,000
Apparent chromium consumption (tons)	610,000	319,000

SOURCE U S Department of the Interior, Bureau of Mines, *Mineral Commodity Summaries, 1984*

965,000 tons. More than 200,000 tons has been reported as domestic "shipments" for 1956, but some 45,000 tons of this amount came from government stockpiles.

Before 1958, scattered small chromite deposits were mined in California, Oregon, and Washington. The Pilliken Mine near Sacramento, CA, for instance, was operated intermittently from 1950 to 1957. Total production from these mines was, however, never more than 45 percent of the Stillwater Complex production in the same years.[34]

Stillwater Complex

The chromite deposits at the Stillwater Complex in Montana are the largest known, single potential U.S. source of chromium. Although there are no current plans to resume commercial production of chromite at Stillwater, these deposits would most likely be the first to be considered for production during any emergency situation. Several companies, including Anaconda Minerals Co., which has patented mineral holdings on the Mouat/Benbow Mine, have been involved in the area since the late 1960s in investigating various Stillwater properties for their potential mineral values. (See the domestic PGM section, p. 196 for details.)

Available resource data for the two chromite deposits, the Gish and Mouat/Benbow mines,

---

[34] For more information about past domestic production see, Silverman, et al., op. cit., and *The Stillwater Citizen-Sun*, Apr. 26, 1974, sec. 2, p. 8.

are not complete since for proprietary reasons only the numbers for the Gish mine have been published (see table 5-9). The Mouat/Benbow deposit is reportedly the much larger of the two. This is evident from the fact that the Bureau of Mines projected a mine life for the Mouat/Benbow deposit of 46 years with a production rate of 525,000 tonnes (477,000 tons) of ore per year; whereas, production at the Gish mine was projected at a third of that rate for only 3 years.

Combined potential output of 65,000 tons of contained chromium (table 5-12) from these Stillwater mines amounts to about 11 percent of U.S. needs when compared with a peak consumption year such as 1979 or 20 percent when compared with 1982.

Gasquet **Mountain Project**

California Nickel Corp. has proposed to produce nickel, cobalt, and chromium from a lateritic deposit at Gasquet Mountain in northern California, The project's economic viability is dependent on the market prices of all three metals, and in 1982 the firm was using a chromite price of $40 per ton in its economic evaluations, The estimated output (50,000 tons per year of chromite concentrates with 14,000 tons of contained chromium) would be small relative to the other metals involved in the project and in relationship to Stillwater as analyzed by the Bureau of Mines. However, this is the only domestic mining project which includes chromium that has been under recent scrutiny by a mining firm, Perhaps of greater importance is the processing technology that this firm is developing for recovery of metals from laterite ores, Such ores have the possibility of being a future worldwide source of metals such as chromium, nickel, cobalt, PGMs, etc. (The Gasquet Mountain Project is discussed in more detail in the cobalt section on p. 170, See also the following chromium mining and processing technologies section on p. 153.)

Lateritic deposits generally offer one of the lowest metal grades, and chromite at Gasquet is thought to be extremely erratic. Exploitation thus requires considerable movement of ore in order to reclaim any substantial tonnages of the desired metal.

Other Potential U.S. Sources

Other chromite deposit types in the United States are the podiform bodies in northern California, southern Oregon and Alaska and beach sands in Oregon, Maryland, and Pennsylvania. Table 5-12, using the Bureau of Mines' analysis, shows the estimated production from the most likely candidate areas, California's podiforms and Oregon's beach sands.

Although the chromium content of the possible output of the Pilliken Mine was calculated as the largest, the information base is the weakest since all resources fall into the "inferred" category. Except for the Bar Rick Mine, these podiform properties have short mine lifes which reduces their economic viability,

The Oregon beach sands contain a comparatively large amount of identified resources. These resources are dispersed over a large area (some 5,000 acres) which is now either public beaches or land used in Oregon's forestry industry, The low grades present means that a lot of material would need to be displaced in order to acquire the contained chromite, disturbing not only the beaches but an established Oregon economic base.

The Alaskan podiform deposits are considered the most expensive to mine, due to their location, low grades and short mine lifes. One area of podiform deposits, stretching south from Anchorage through the Kenai Peninsula along the Chugach Arch, may contain sufficient chromite for several years supply, but is not of commercial interest due to the high cost of production. as Anaconda Minerals explored one such deposit area, Red Mountain near Seldovia, as a possible PGM resource but results have proved disappointing. Conceivably, chromite might be a byproduct of any future PGM production there, Other potential occurrences of chromite in Alaska are at Kanuti River, Red Bluff Bay, Baranof Island, in southeastern

---

[35] John Mulligan, Chief, Alaska Field Operations Center, Bureau of Mines, persona] communication, July 9, 1984,

Alaska, and the western Brooks Range deposits. Present information on these occurrences is inadequate to suggest any level of expectation.[36] After surface occurrence investigations in the Kanuti River area, the Bureau of Mines recommended in 1983 that subsurface exploration be employed to establish the extent of chromite occurrences .[37]

Domestic Mining and Processing Technology Prospects

Rather straightforward mining and beneficiation technologies are applicable for the exploitation of U.S. chromite deposits, and their composition—while primarily chemical grade—is suitable for a variety of current uses. Future breakthroughs in beneficiation and smelting technologies might lead to the possibility of mining of lower grade ores common to the United States. Plasma arc furnace technology (see the following processing section), for instance, uses finely ground chromite as is found in laterite deposits. Successful application of new methods would not necessarily make U.S. deposits more competitive with other world deposits, unless innovations can be selectively applied to U.S. deposits.

Improved mining technology offers several possible applications for chromite ore mining, In hardrock ore bodies, open pit and underground mining systems would be similar to those used in other ore bodies; the trends toward increased mechanization and to continuous mining systems would apply, The new vertical crater retreat system for underground mining would be especially applicable in narrow and steeply dipping veins and podiform bodies, In shallow lateritic material and beach placer type sands, open pit mining would very likely involve continuous mining by bucket wheel machines or by shovels without the need for drilling and blasting,

Solution mining of chromite is only in the conceptual stage, but could provide an approach to the mining of hardrock chromite with explosive fracturing or to the mining of lateritic deposits that are inaccessible by open pit mining.

The minimum grades required for metallurgical use (at least 46 percent chromic oxide and a chromium-to-iron ratio greater than 2.5:1) have not ordinarily been obtained from the processing of domestic chromite deposits. Low-cost methods of beneficiating domestic deposits to an acceptable concentrate have been studied for a number of years by the Bureau of Mines, The methods have involved combinations of gravity and electrostatic separation plus flotation to obtain a higher chromium content, and leaching to reduce the iron content, The Bureau of Mines has recently introduced a chromite beneficiation program that has provided encouraging results, Research has not yet provided for an economic method of upgrading, however, A direct smelting process for Stillwater Complex ore has been investigated; this would provide a high-iron alloy, but still not comparable in grade and cost with imported ferrochromium.

The Albany Research Laboratory of the Bureau of Mines has been exploring the recovery of chromite from the residue of laterites that have been chemically processed to recover cobalt and nickel. Lateritic ores containing chromium are ordinarily roasted and leached, An experimental plan by the Bureau of Mines for the recovery of chromium from laterite ores, as at Gasquet Mountain, involves roasting and leaching after gravity beneficiation, with final electrowinning for nickel and cobalt and final recovery of chromium from the leach residue. The concentrate produced contains about 35 percent chromic oxide. Future research and experimentation in chromite recovery and chromium extraction will most probably involve such hydrometallurgical processing.

Another Bureau of Mines project is evaluating the low-grade podiform deposits of California, These ores range from 3 to 10 percent chromic oxide and contain tonnages that can potentially be mined by open pit and underground methods. Preliminary results suggest that these podiform ores can be concentrated

---

[36] U.S. Department of the Interior, Bureau of Mines, *Critical and Strategic Minerals in Alaska,* Information Circular No. 8869, 1981.

[37] Jeffrey Y. Foley and Mark M. McDermott, U.S. Department of the Interior, Bureau of Mines, *Podiform Chromite Occurrences in the Caribou Mountain and Lower Kanuti River Areas, Central Alaska,* Information Circular No. 8915, 1983.

to a range of 37 to 45 percent chromic oxide; and with improved gravity process techniques, a marketable concentrate might be produced if smelter facilities were located nearby and local steel markets were accessible to the product.

Foreign and Domestic Chromium Processing

The major use of chromium is as an alloying agent in chromium and stainless steels and in superalloy. In steels, chromium is consumed primarily in the form of a chromium ferroalloy, principally high-carbon ferrochromium or "charge chrome. " In the production of superalloys with little or no iron content, a metallic form of pure chromium is consumed. The various types of chromium ferroalloys and metals and their compositions are shown in table 5-13.

Figure 5-I provides a simplified flow chart of chromium from ore to industrial use. Ore, as produced from today's mines, contains from 35 to 48 percent chromic oxide. An exception is Finland which has the lowest grade economic deposits at 27 percent Cr_2O_3. Where necessary, mined chromite is concentrated (gravity or magnetic separation is usually employed to increase the chromic oxide or reduce the silicon content), sized, and classified at the mine site. This concentrate, typically 40 to 46 percent chromic oxide (27 to 31 percent contained chromium), is then processed by smelting into ferrochromium products or begins a multistep process for conversion into pure metal.

Table 5-13.—Composition of Chromium Ferroalloys and Metal (weight percent)

Type	Chromium	Carbon	Silicon
Ferrochromium:			
High carbon	52-72	4.0-9.5	3-14
Charge.	58-60	6-7	4-5
Low carbon, ...	60-75	.025-.75	1-8
Silicon	34-42	.05-.06	38-45
Metal:			
Aluminothermic			
Vacuum melting grade . .	99.5	.05	.04
Carbothermic (chrome 98) .	≈98.5	NA	NA
Electrolytic , ...	99.1	.02	.01

NA—Not available.

SOURCE: Ferrochromium content, U.S. Department of the Interior, Bureau of Mines, *Minerals Commodity Profile 1983: Chromium*.
Metal content, appropriate manufacturers.

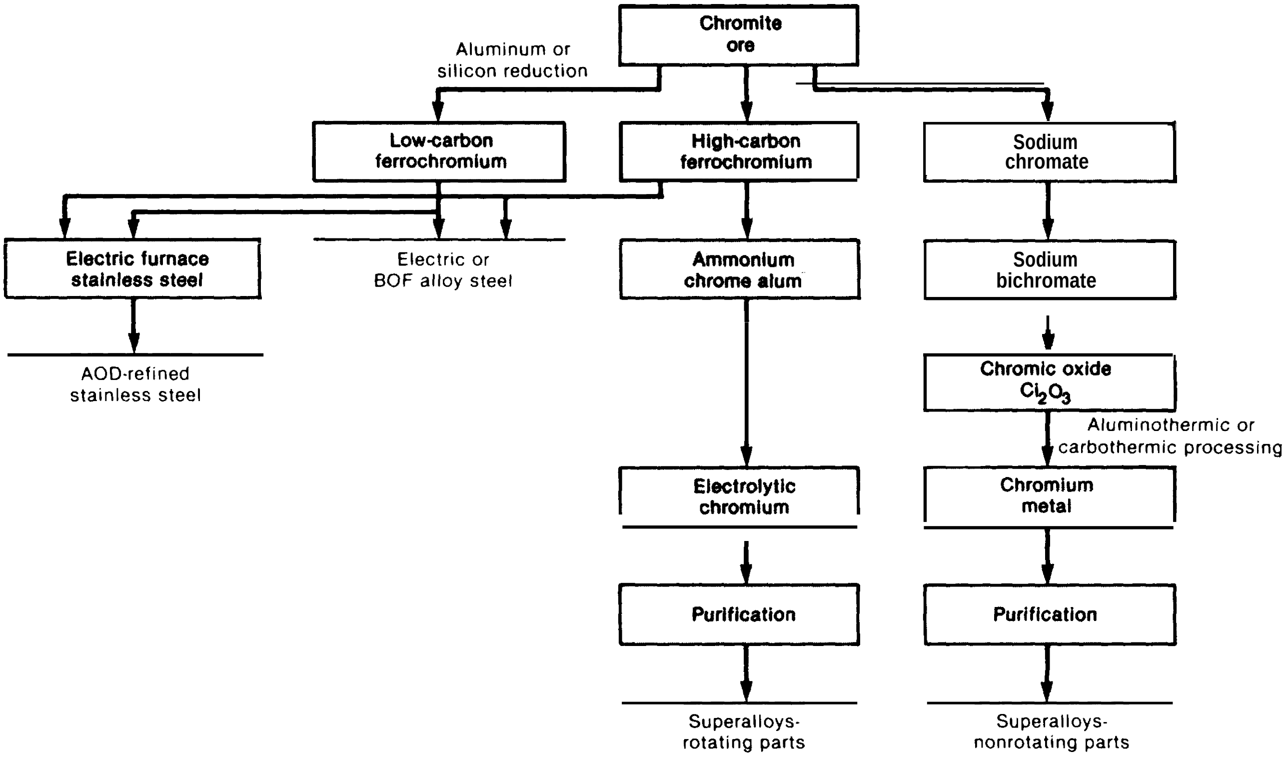
Ferrochromium

High-carbon ferrochromium is usually produced in a submerged arc electric furnace. These furnaces, shown in figure 5-2, use vertical electrodes that are suspended into the charge material (principally chromite and coke, a form of coal). A pass of electric current through the charge provides the heat to sustain a reaction in which the oxygen content of the chromite is removed (by combining with the carbon in the coke) and an iron-chromium alloy is produced.

Low-carbon ferrochromium can be produced from high-carbon ferrochromium or from chromite ores. In the Simplex process, an oxide material is mixed with the ferrochromium and heated in a vacuum furnace, where the carbon and oxide combine and are driven off, reducing the carbon content of the ferrochromium. In another process, silicochromium (a silicon-chromium alloy) is first produced in a submerged arc furnace and then used to reduce the carbon content of ferrochromium in an open arc furnace. (In open arc furnaces the electrodes are not suspended deep within the charge).

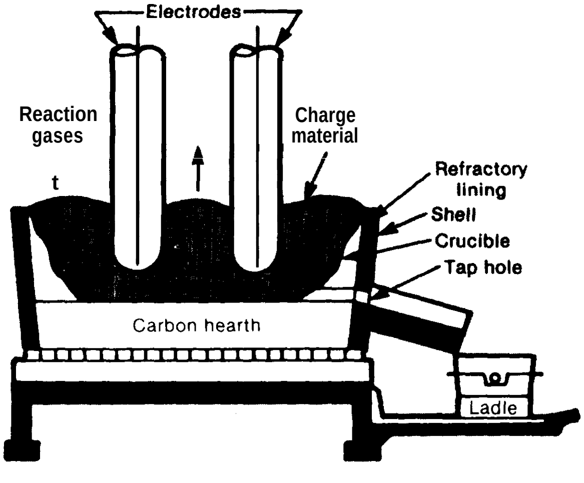
Ferromanganese (see manganese processing section) is produced in electric submerged arc furnaces similar to those used for ferrochromium, and there is a degree of convertibility between chromium and manganese ferroalloy furnaces. The United States has, consequently, some flexibility in production capacity for both ferroalloys. Ferromanganese production requires a wider electrode spacing than that used for ferrochromium, which has a less conductive slag. Other important differences in design parameters of the furnaces include electrode diameter, hearth diameter, crucible depth, and voltage range of the transformer. A ferromanganese electric furnace could technically be used to produce ferrochromium. By techniques such as modifying the composition of the slag to decrease its resistance, the furnace would be operating at less than optimum conditions and would probably not be economic. Modification of these furnaces for alternative uses may be physically and process constrained by the existing pollution abatement equipment.

Figure 5-1.—Simplified Flowchart, Chromium Ore to Industrial Use



SOURCE: Charles River Associates, *Processing Capacity for Critical Materials*, OTA contract report, January 1984

Figure 5-2.—Submerged Arc Furnace



SOURCE Charles River Associates, *Processing Capacity for Critical Materials*, OTA contract report, January 1984

ADVANCED TECHNOLOGY

While the submerged-arc electric furnace process predominates in the production of ferroalloys, other methods are being explored. Most attention is directed at the development of plasma furnaces.[38] This furnace is basically an electric arc furnace in which carbon electrodes are replaced by metallic electrodes and the electric arcs by plasma arcs.[39] An essential difference in design is the installation of plasma torches in the wall of the furnace, rather than

---

[38] Charles River Associates, *Processing Capacity for Critical Materials,* contractor study prepared for the Office of Technology Assessment, January 1984.

[39] A plasma is a gas of sufficiently high energy content that many of its molecules split into atoms, which then become ionized and electrically conducting. Such a gas can develop and deliver heat as high as 20,000° C. Fossil fuels, on the other hand, limit combustion processes to 2,000° C. See "The Promise of Plasma, " 33 *Metal Producing,* February 1984.

the roof as with carbon electrodes. A plasma furnace used for the production of ferrochromium can be used to produce ferromanganese or other ferroalloys.

The major advantages claimed for the plasma furnace process are: increased economy due to longer life electrodes, fewer environmental problems (e.g., less dust and waste gas are generated, noise level is extremely low), reduced cost of charge material (e. g., use of small particle–''fines" –feed material rather than lumps, eliminating the need for preliminary processes to compact such material, and fine coal rather than more expensive coke), higher product quality (e.g., a lower carbon content), and increased product yield due to lower losses into the waste material.

In the production of ferroalloys, the plasma furnace can either be used for the reduction of ore (as in the submerged arc furnace) or for melting metallic fines. Such a melting operation has been installed by Voest-Alpine of Austria at Samancor (a major manganese ore and ferroalloy producer) in South Africa, Middelburg Steel & Alloys, a major ferrochromium producer in South Africa, has been investigating plasma furnace technology for a number of years and in late 1983 installed a Swedish-designed 20 megawatt (MW) reduction furnace at its plant in Krugersdorp. This is the first commercial application of plasma technology in the ferroalloys field,[40] and Middelburg expects to take 2 years to evaluate the efficiency of the operation before committing to a conversion of its other furnaces (which could result in a doubling of its output capacity) to plasma operation. South Africa appears to be in an excellent position to adopt the plasma technology since its chromite ores tend to break up into fine material, its coal is generally of the lower grade applicable, and electric power is the main energy source. Plasma technology does not yet appear to be able to compete in areas where fossil fuel is available.

Relative to Western Europe, South Africa and the Soviet Union, the United States has seen little activity in plasma technology for process metallurgy (reduction). Westinghouse is one U.S. firm involved in developing the technology, especially the initial torch systems which were a spinoff of the U.S. space program.[41] Foster Wheeler Corp. holds a U.S. license for European plasma furnaces and was involved in setting up the Middelburg furnace. Its estimates have shown that capital costs for the system would be 40 percent less than for a conventional electric arc furnace and operating costs, about 25 percent lower.[42] A major inhibiting factor to U.S. interest in plasma technology is the relatively high cost of electrical power compared with fossil fuel in most parts of the country .43 However, since ferroalloy processing is an electric power consumer, plasma technology has the potential to be economically viable in this particular application.

Plasma arc reduction processes have occasioned a good deal of interest, but they have yet to be proven in full scale for ferroalloy production, It is not known, for instance, if they can compete with submerged arc furnaces on the basis of energy consumed per ton of ferroalloy produced. They would seem to merit attention, however, if the high-intensity heat source used would permit economical operation of smaller scale units (as compared with the large, 50 MW, submerged arc furnaces). Small-scale, adaptable units could provide flexible production capacity for a new, lean domestic ferroalloy industry.

Chromium Metal

Aluminothermic, carbothermic, and electrolytic processes are used to produce metallic chromium. Each process results in a different quality of product, which determines its possible value to industry. Electrolytic chromium is the purest and used in the most demanding

---

[40] SKF Steel of Stockholm announced i n June 1984 intentions of building a 78,000-tonne per year ferrochromium plant in southern Sweden using plasma technology. Overall savings of SKF'S Plasmachrome process compared to costs of conventional ferrochromium production in Sweden has been estimated at 15 to 20 percent.

[41] K. J. Reid, "Plasma Tech Potential Best in High-Value Goods," *American Metal Market,* May 15, 1984, p. 22. Excerpts from a speech "Plasma Metallurgy in the 80s" given at an international symposium—Mintek 50—in Johannesburg, South Africa, in April 1984.

[42] Charles River Associates, op. cit., p. 78.

[43] Reid, op. cit., p. 22.

applications. The most widely used method is the aluminothermic (A-T) process. The same equipment can be used to produce other alloys —e.g., ferrovanadium, ferrocolumbium, or ferromolybdenum—providing a wide range of furnace flexibility, but also making it difficult to estimate total aluminothermic capacity.

The A-T process is relatively simple. High-purity aluminum powder is mixed with Cr_2O_3, charged into a reaction vessel, and ignited, The reaction of aluminum and oxygen produces chromium metal and a slag that contains the oxidized aluminum. The metal is separated from the slag, cooled rapidly, and crushed to specified sizes for sale.

Two products are made by the A-T process, One, known as Chrome 99, is suitable for processes using open vessels in contact with air, but residual oxygen and nitrogen in Chrome 99 limit its use to less demanding end-use applications. The other product, called vacuum melting grade (for use in vacuum furnaces), is produced with excess aluminum to drive down the levels of oxygen. This high purity grade is interchangeable with electrolytic chromium in all but the most stressful applications, e.g., the rotating hot sections of the jet engine.

The A-T process requires high-purity chromic oxide as feed material. This chromic oxide is produced by roasting chromite. Care must be taken during this process to minimize the sulfur, oxygen, and nitrogen content of the end product. producing this oxide is the capital-intensive phase of chromium metal production,

Another chromium product, Chrome 98, also uses Cr_2O_3 as the input material. Carbon is mixed with the oxide to form briquettes, which are then heated in a vacuum furnace at close to the melting point for several days. The carbon and oxygen form carbon monoxide gas, which leaves behind briquettes of chromium metal, The vacuum furnaces used for this carbothermic process are used for the production of other alloys (e. g., low-carbon ferrochromium) so that total production capacity is difficult to measure. Chrome 98 competes with A-T chromium for use in superalloy.

Chromium metal of the highest purity, consumed in the most demanding superalloy applications, is produced by the electrolytic method. This process, based on developments by the U.S. Bureau of Mines in the 1950s, uses ferrochromium as a feed material. Chemical processing removes the iron content of the ferrochromium, and this “chrom alum” (chromium aluminum sulfate) is then dissolved in water to provide the feed for electrolytic cells. Chromium, deposited on cathodes, is periodically removed. This product is sold as regular grade (99.1 percent chromium) or further purified.

Production Capacity and Distribution

The worldwide distribution of production capacity for ferrochromium and chromium metal is shown in tables 5-14 and 5-15. In 1979, the United States had more than 225,000 tonnes (205,000 tons) of ferrochromium capacity among seven firms, Of the six firms now credited with capacity, only two were operating in 1983, functioning at low levels of production or only intermittently, Early in 1984, temporary respite was provided to one bankrupt firm with the award of a contract from the General Services Administration to upgrade 121,173 tons of chromite in the national defense stockpile to ferrochromium. Table 5-16 shows the increasing U.S. reliance over the past decade on imports of both chromium ferroalloys and metal.

In the past, the West’s supply of chromic oxide, the precursor for aluminothermic chromium metal production, was supplied almost entirely by a single firm, the British Chrome & Chemical Co., which has an annual capacity of 12,700 tonnes of chromic oxide. In 1982, however, a subsidiary of the British firm, the American Chrome & Chemical Co., began operating a plant in Texas that produces chromic oxide, along with various chromium chemicals. Shieldalloy Corp. has been producing chromic oxide in the United States, but has used it for internal consumption in the production of A-T metal. It has an annual output capacity of 1,400 tons of chromium metal, with the possibility of expanding capacity to 1,800 tons, if equipment normally used in the production of

Table 5-14.—Ferrochromium Capacity, 1979 (in tonnes)

Country	Charge chrome	High carbon	Medium carbon	Low carbon	Ferro-silico
Brazil	90,000	–	—	—	—
Canada	50,000	–	—	—	—
Finland	50,000	–	—	—	—
France	—	—	—	—	2,000
West Germany	●	●	●	●	35,000
India	10,000+	●	●	5,000 +	1,000
Italy,	—	40,000 (incl. charge)	—	15,000	—
Japan	172,000	344,100	12,000	106,000	81,400
Mexico	—	—	—	6,000	–
Norway	—	20,000	18,000	—	—
Philippines	—	●	●	●	—
South Africa	270,000	30,000	–	10,000	55,000
Spain	—	28,000	–	10,000	—
Sweden	—	240,000	–	33,000	53,000
Turkey.	—	50,000	–	15,000	–
United States.	●	136,000+	●	36,000+	53,000+
Yugoslavia	—	68,000	–	15,000	5,500
Total	642,700+	956,100+	30,000	251,300+	285,900+

● —Capacity notavallable.

SOURCE: Charles River Associates, Processing Capacity for Critical Materials, OTA contract report, January 1984

Table 5-15.—Production Capacities for Chromium Metal in the Non-Communist Countries-1981 (tonnes per year)

Country	Electrolytic	Aluminothermic[a]
France		900-1000
Japan	3,000-4,000	300-1,000
West Germany[b]		600,1,200
Luxembourg		0- 500
Great Britain		2,000-4,000
United States	2,800-3,000	0-1,800

[a] A-T capacity is difficult to estimate Since some facilities that are used forthe production of other alloys can be used for the production of A-T chromium The wide range of capacity estimates reflects this difficulty.

[b] There is an additional "captive" producer of A-T chromium in West Germany. Its substantial production is sold directly to two or three companies within West Germany

SOURCE: Charles River Associates, Processing Capacity for *Critical Materials,* OTA contract report, January 1984.

Table 5-16.—Chromium Ferroalloys and Metal: imports and Consumption (gross weight, short tons)

	Ferrochromium	Metal[a]
1971:		
Imports	85,187	NA
Consumption	253,193	NA
Imports as percent of consumption	34	—
1974:		
Imports	161,573	1,960
Consumption	472,379	5,479
Imports as percent of consumption	34	36
1980:		
Imports	297,218	4,075
Consumption	388,639	5,635
Imports as percent of consumption	76	72

[a] Metal import data include unwrought metal, waste, and scrap

NA—Not available.

SOURCE: U S. Department of the Interior, Bureau of Mines, *Minerals Yearbook,* VOl 1, 1971, 1974, and 1980.

other alloys is employed. In addition, Elkem Metals, which produces Chrome 98 at its plant in Marietta, OH, offers variable capacity because it uses its vacuum furnaces for other products, e.g., vanadium carbide and low-carbon ferrochromium. But briquetting equipment for preparing the furnace feed material limits production to 1,400 tonnes (1,300 tons) of chromium metal per year. A small investment in additional briquetting equipment could easily double output.

Western production of electrolytic chromium metal comes from two plants, one each in Japan and the United States. Toyo Soda has a capacity of 4,000 tonnes (3,600 tons) per year, and Elkem has a 2,800-tonne capacity (2,600 tons). Plans to expand capacity to 4,500 tonnes at Elkem were considered but shelved owing to lack of prospective markets.

The United States still has domestic capacity for all types of ferrochromium products, although "practical" (in operating condition) capacity no longer covers its needs. For instance, estimated practical capacity (1984-85) for high-carbon ferrochromium is placed at 130,000 tonnes (118,000 tons),[44] while 1982 consumption totaled 215,000 tons.[45] Imports are expected to continue to erode U.S. production capacity. Firms that appear to be able to remain viable—e.g., Globe Metallurgical Division of Interlake, Inc.—have small, flexible furnaces which can handle special orders and produce premium grades. In terms of chromium metal production, the United States has the ability to handle all stages of both the electrolytic and aluminothermic processes and produce a substantial portion of domestic needs.

Cobalt Production and Processing

State-controlled mining operations produce more than 90 percent of the world's cobalt supply. The industry is dominated by one such African producer, Zaire, which directly supplies nearly 40 percent of U.S. imports. Unlike the other first-tier strategic materials, the number of producer countries has grown in the past 20 years; and these four countries now hold 9 percent of overall output. In addition, a number of cobalt-containing ore deposits—including some in the United States—have been evaluated in the past decade, but all await improved prospects for primary ores and/or cobalt before any operations will be considered.

Cobalt minerals are oxides, sulfides, or arsenides, and they occur in a number of geological environments. The majority of the world's cobalt production comes from a particular geologic combination (stratabound copper deposits associated with sedimentary rock) that has only been found in Zambia and Zaire. Other geological types in which cobalt is located are laterite, hypogene, and hydrothermal deposits. Hypogene deposits are formed during the crystallization of molten rock in which minerals separate and accumulate. Hydrothermal deposits are formed when water containing metals circulates through rocks, solidifying along fractures to produce vein deposits. The principal product derived from cobalt-bearing laterites is nickel in combination with iron; from hypogenes, nickel, and/or copper.

Cobalt is only a secondary product of current mining operations; therefore, its mining and refining is tied to the primary metals nickel and copper, Thus, normal market fluctuations for cobalt do not usually directly influence decisions to alter production rates. Only two countries have had the capability to produce cobalt as a primary product: Zaire, partly because of its high cobalt content ores (0.35 percent); and Morocco, whose cobalt arsenide ores were mined until 1983. For other producers, increasing cobalt production in the absence of increased demand for copper or nickel means either bearing the cost of stockpiling copper or nickel or running a risk of depressing prices by creating an oversupply in those markets.

Although 12 countries reported mine production of cobalt in 1982, Zaire supplied 45 percent of the world's total output (table 5-17). Zambia contributed another 13 percent. These two African countries are the major sources of cobalt for the free world market, the principal consumers being the United States, Western Europe, and Asia. The United States is dependent on imports for all of its primary cobalt needs. (Eight percent of consumption in 1982 was provided by the recycling of purchased scrap.) The Eastern bloc's cobalt needs are supplied by the Soviet Union and Cuba. Little cobalt is consumed by producer countries, except the Soviet Union.

---

[44] Charles River Associates, op. cit., p. 58.

[45] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982,* vol. 1, p. **205.**

Table 5-17.—World Cobalt Reserves and Production by Country (million pounds of contained cobalt)

Producer country	Reserves	Average grade percent	Production[a] 1982	Percent of world production
Australia	50	0.10	4.8	9
Botswana	20	0.06	0.6	1
Canada	100	0.07	3.3	6
Finland	50	0.20	2.2	4
Morocco[b]	0	1.20	1.5	3
New Caledonia	500	0.05	1.1	2
Philippines	300	0.08	1.1	2
South Africa	40	NA	NA	—
Soviet Union	300	NA	5.2	9
Zaire	3,000	0.35	24.9	45
Zambia	800	0.25	7.2	13
Subtotal	5,160		51.9	94
Others	840		3.4	6
Total	6,000		55.3	100

[a] Mine output.
[b] Operations suspended in December 1982.
NA—Not available,

SOURCE: U.S. Department of the Interior, Bureau of Mines. Reserve base *Mineral Commodity Profile 1983: Cobalt*
Production: *Minerals Yearbook 1982, vol.* 1, p. *258*

Foreign Production of Cobalt

The cobalt industry is divided into two groups: vertically integrated firms, which mine ores and process them into cobalt products, and mine producers, which sell semiprocessed ores to refiners. Mining is singly controlled in each producer country, except in Canada, Australia, and South Africa. As table 5-18 shows, a tangle of multi-national firms produce cobalt. U.S. firms have interests in Australia (Freeport and, indirectly, Asarco), Botswana (Amax), Canada (Newmont Mines and Superior Oil), the Philippines (indirectly, Superior Oil, through Sherritt Gordon), and Zambia (Amax).

Cobalt flows worldwide in a number of forms until final products such as metal (electrolytic) cathodes and powder, cobalt salts, and oxides are produced for sale to industrial users. Even within integrated firms, intermediate products are often shipped from the mining country elsewhere for final processing. However, there is a growing trend toward complete processing in the country of origin.

In an emergency, one advantage of vertically integrated processing in the producing country is that final cobalt products—principally pure metal—can be air shipped at no great increase in cost. Intermediate products, on the other hand, have few metal units per pound, and shipping them other than by sea is costly. During the Shaba uprising in Zaire in 1978 and 1979, air transportation proved to be a successful export method.

Because of cobalt's varied and complex processing flows (see the following section on cobalt processing), mine production cannot be discussed independently from final processing. Cobalt production and import data often refer to both the mine producer and the downstream processing countries. When integrated mine producers and independent refiners are both considered, the world's sources of refined cobalt products appear to be diverse, although Zaire still dominates. As table 5-19 indicates, the flow of semiprocessed ores is toward the consuming nations. Zaire, Zambia, and Finland have integrated firms which can completely process their ores into cobalt cathode and powder forms. South Africa now exports both cobalt chemicals (sulfate) and metal powders. Some South African intermediates, however, are still shipped to England and Norway for processing. Canada's Inco now has the capability to produce metal from its ores but maintains the option to ship intermediates to

Table 5-18.—Cobalt Mining Industry by Country

		Ownership		
Country	Major firms	Sector	Major holders[a]	Primary national identity
Australia	Queensland Nickel Pty. Ltd	Private	Metals Exploration (50)	Local
		Private	Freeport[b] (50)	U.S.
	Western Mining Corp. Ltd.	Private	WM Corp. Holdings (100)	Local
	Agnew Mining Co. Pty. Ltd.	Private	Seltrust Mining (60)	Local
		Private	Mount Isa Mines[b] (40)	Local
Botswana	Botswana RST Ltd.	Private	Amax (30)	U.S.
		Private	AngloAmer (30)	South Africa/U. K.
		Private	various (40)	Local
	Operated by BCL Ltd.	Private	Botswana RST (85)	(see above)
		Government	(15)	Local
Canada	Inco Ltd.	Private	d	Canada
	Falconbridge Ltd.	Private	McIntyre Mines[e] (40)	Canada
Finland	Outokumpu Oy	Government	(81)	Local
		Private	(balance)	Local
Morocco[f]	Campagnie de Tifnout Tiranimine (CTT)	Private/ government	Omnium (81)	French/ Local
New Caledonia	Societe ie Nickel (SLN)	Private	Imetal (15)	French
		Government	SNEA[g] (15)	French
		Government	ERAP (70)	French
Philippines	Marinduque Mining and Industrial Corp.	Government	(87)	Local
		Private	Sheritt Gordon (10)	Canada
South Africa[h]	Rustenberg Platinum Mines Ltd.	Private	JCI (33)	Local
		Private	AngloAmer (24)	Local
		Private	Lydenburg (24)	Local
	Impala Platinum Holdings Ltd.	Private	Gencor (56)	Local
Zaire	Generale des Carrieres et des Mines (Gecamines)	Government	(loo)	Local
Zambia	Zambia Consolidated Copper Mines Ltd.	Government	ZIMCO (60)	Local
		Private	Zambia Copper Investment (27)[i]	South Africa/U. K.
		Private	RST International (7)	Local

[a] With approximate percentage of control, if available

[b] A wholly owned subsidiary of Freeport McMoran Inc (U.S)

[c] A subsidiary of MIM Holdings which is (49%) owned by Asarco Inc

[d] The largest single shareholder block of Inco stock is 4 Percent

[e] Falconbridge is 327 percent owned by Superior 011 through direct equity and its controlling Interest in MyIntyre

[f] Not in production since December 1982

[g] SNEA is 67 percent owned by ERAP-Entreprise de Recherches et d'Activites Petrolieres, giving ERAP about 80 percent control of SLN

[h] There are six finance houses (the "Groups") Which dominate the South African industry: The Anglo American Corp of S A Ltd (AngloAmer); Gold Fields Of S A Ltd, General Mining Union Corp Ltd (Gencor); Rand Mines/Barlow Rand, Johannesburg Consolidated Investment Co Ltd (JCI); and AngloTransvaal Consolidated Investment Co Ltd (AngloTC)

[i] Owned by Anglo American

SOURCES E&MJ 1983 *International Directory of Mining*, Bureau of Mines *Mineral Commodity Profile 1983: Cobalt;* Office of Technology Assessment

its plant in Wales, where cobalt salts are produced. Falconbridge exports processed ore from Canada to its plant in Norway for the production of cathodes.

Firms in Botswana, Australia, New Caledonia, and the Philippines mine and smelt their ores. This intermediate product (matte) is traded to refiners for final processing. Two Japanese firms refine intermediates from the Philippines and Australia. The resulting cobalt cathodes are either consumed in Japan or exported. Amax, the sole U.S. cobalt refiner, currently holds contracts to receive matte from one producer in Australia and from its own operations in Botswana, Output from the major Australian producer, Western Mining, is shipped to Sherritt Gordon's refinery in Canada for processing into cobalt powder. New Caledonia's small output is processed into cobalt salts by Metaux Speciaux in France.

Four of today's producer countries, shown in table 5-20, have initiated production since 1960, causing a redistribution of market shares despite the commanding hold on the market

Table 5-19.—World Refined Cobalt Production—1982, by Country (million pounds)

Country[a]	Recovered metal	Percent of total
CANADA	1,730	4
FINLAND	3,218	7
France	11,100	26
West Germany	880	2
Japan	4,282	10
Norway	2,184	5
SOVIET UNION	8,700	20
United Kingdom	1,600	4
United States	1,016	4
ZAIRE	13,200	30
ZAMBIA	5,392	12
ZIMBABWE	110	<1
Total	43,412	100

[a] Upper case indicates refiner is also an ore producer

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982,* vol 1, p 256.

that Zaire has maintained. Until the worldwide recession abates and steady economic growth is anticipated by the mining industry, the current producers of cobalt will remain the only sources.

There has been extensive activity since the late 1970s on cobalt-related projects around the world, including in the United States. A number of mining projects are being or have been evaluated, although none appear economic. Foreign projects (table 5-21) reportedly evaluated include Gag Island in Indonesia, Kilembe copper mine in Uganda (processing of copper-cobalt tailings), the Windy-Craggy deposit in Canada, Musongati in Burundi, Ramu River in Papua New Guinea (see the section on chromium in this chapter), and Goro in New Caledonia. Except for the Ramu River project, which depends on chromite and nickel, the economic viability of these projects will be determined by the market for nickel or copper. (U.S. projects are discussed in detail in the next section,)

Albania has contracted for the construction of a nickel and cobalt refinery, which will produce cobalt oxide from domestic nickeliferous[46] ores. (A West German government firm, Saltzgitter Industriebau A. G., and Inco of Canada are involved.) An unconventional source of cobalt is under investigation in Peru, involving concentration and refining of cobalt-bearing tailings from the Marcona Iron Mine.

These projects represent a potential 20 percent increase in supply for world markets under improved economic conditions. Bringing any of them into production, however, would require considerable capital and lead times of several years to develop the necessary infrastructure.

---

[46] Bearing or containing nickel.

Table 5-20.—Historical Production—Cobalt, 1960-80, by Country (thousand pounds, contained cobalt; percent of world total)

	1960		1965		1970		1975		1980	
Producer country	Production	Percent	Producer	Percent	Producer	Percent	Producer	Percent	Producer	Percent
Botswana	0	0	0	0	0	0	178	<1	498	1
Canada	3,330	10	3,648	10	4,562	9	2,986	5	3,534	5
Finland	0	0	3,292	9	2,800	5	3,090	5	2,282	3
Morocco	2,802	8	4,038	11	1,332	3	4,324	7	1,848	3
New Caledonia	0	0	0	0	0	0	4,528	7	400	1
Philippines	0	0	0	0	0	0	234	<1	2,934	4
South Africa	NA		NA		NA		NA		[a]	
Zaire	18,166	54	18,492	49	30,772	59	30,860	48	34,180	51
Zambia	4,070	12	3,404	9	5,290	10	5,252	8	9,700	14
Soviet Union	[b]		2,800	7	3,400	6	3,900	6	4,960	7
Subtotal	28,400	85	35,874	95	49,178	94	61,324	94	63,856	95
Other	5,000	15	1,760	5	3,400	6	3,600	6	3,620	5
Total	33,400	100	37,634	100	52,578	100	64,924	100	67,476	100

[a] Estimated 475,000 pounds in 1981

[b] Only Free World reported in 1960

NA—Data not available

SOURCE U S Department of the Interior, Bureau of Mines, *Minerals Yearbook*, 1961, 1966, 1971, and 1981

Table 5-21 .—Potential Foreign Cobalt Sources

Site	Estimated cobalt content, million pounds: Production per year	Deposit	Estimated leadtime to production
Gag Island, Indonesia	2.8	400	2 to 3 years
Kilembe, Uganda	NA	784	1 to 3 years
Windy-Craggy, Canada	NA	982	
Musongati, Burundi	NA	160	NA
Ramu River, New Guinea	5.9	NA	+5 years
Goro, New Caledonia	2.0	NA	3.5 to 5 years
Marcona Mine, Peru	4.0	NA	≈2 years
Albania refinery	NA	NA	≈1985

NA—Data not available.

SOURCE Office of Technology Assessment

Following is a brief discussion of each major cobalt mine producer's operations and the processing route of the ores. The industry experienced a cutback in mine production and delay in expansion plans because of the 1981-82 worldwide recession. In 1984-85 future prospects have been regarded cautiously.

Australia

Only intermediate cobalt products are produced in Australia. The major producer, Western Mining, is also the third largest nickel producer in the world. For cobalt recovery, the company processes nickel sulfide ores from deposits in western Australia into mixed nickel-cobalt sulfides, which are shipped to Sherritt Gordon in Canada for processing into cobalt powder. Queensland Nickel in northeastern Australia also produces a mixed nickel-cobalt sulfide, but its ores are nickel oxides from laterite deposits. The intermediate product is shipped to Nippon Mining's refinery in Japan under a life-of-mine contract. Agnew Mining's nickel sulfides are smelted by Western Mining in Australia and refined by Amax at Port Nickel in Louisiana. Although a minor world source of cobalt, Agnew is one of Amax's two current sources of cobalt intermediates. Internally, Australian producers rely on rail for transportation between mining, smelting, and exporting phases of production.

Botswana

The two mines in Botswana, Selebi and Pikwe, are operated by BCL Ltd. (15 percent government owned). The smelting furnace at the mining complex had a production peak of 47,000 tonnes of matte (nickel and copper at 38.5 percent each and cobalt at 0,56 percent) or, 479,000 pounds of contained cobalt in 1981. The matte is sent by railroad through South Africa to the port of East London or through Mozambique to Maputo for sea shipment to Amax's refinery in Port Nickel. The South African route is preferred because the loading facilities at East London are more efficient. Botswana RST has been reevaluating its copper-nickel sulfide ore deposits in recent years. Preliminary indications are that the reserves could be increased significantly, but an investment in extensive drilling is needed for confirmation.

Canada

Canada has two **integrated** mine producers, Falconbridge and Inco, and one independent refiner, Sherritt Gordon. Most of Canada's cobalt deposits are located in the Sudbury area of Ontario and are classified as nickel/copper sulfides. Falconbridge smelts its ores into a mixed metal matte containing nickel, copper, and cobalt (1 percent). This material is then shipped to Falconbridge's refinery in Kristianstad, Norway, where cobalt cathodes are produced. Inco has produced cobalt oxide at its own plants in Port Colborne and Thompson, Canada, Recently, an electrolytic plant with a design capacity of 900 tonnes (1.6 million pounds) of metal per year began operation at Port Colborne to complete domestic proc-

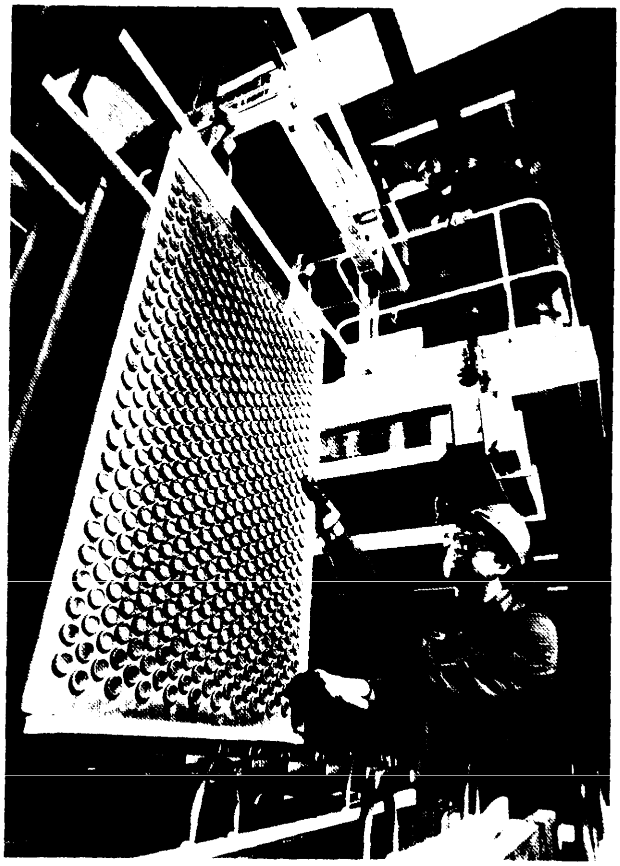


Photo credit: Inco, Ltd

Cobalt is recovered from nickel and copper ores in the Inco processing plant at Port Colborne, Ontario

essing of the ores. Cobalt oxide will still be produced at Thompson, with some being shipped to Inco's refinery in Wales for final processing. Inco and Falconbridge together normally have the capacity to mine ores containing 9 million pounds of cobalt per year. Inco's smelter has a maximum output capacity of 4 million pounds of cobalt per year. However, world market conditions have reduced actual output by half in the past few years. Sherritt Gordon stated in 1983 that if the price of cobalt rose to $10 per pound (signaling improved markets), the company would triple its output of cobalt powder.[47]

Finland

The integrated firm Outokumpu Oy, Finland's sole producer, derives cobalt from copper sulfide ores containing copper, zinc, and cobalt; the ores are from the firm's Keretti and Vuonos mines in eastern Finland. A cobalt concentrate is subsequently processed at the Kokkola refinery on the west coast. Products include both cobalt powder and salts. Outokumpo has been conducting exploration and process development work (a new concentration technique based on leaching technology) at the Talvivaara deposit near Sotkamo in order to improve the firm's reserve figures and develop a new source of cobalt, as well as nickel, zinc, and copper. Total resources have been estimated at 300 million tons of ore which, with a cobalt grade of 0.02 percent, represents 60,000 tons (120 million pounds) of cobalt. If the processing technique proves feasible, about 10 million tons of ore (containing 4 million pounds of cobalt) could be produced annually.

Morocco

Cobalt production in Morocco was discontinued in December 1982 because declining reserves and increased mining costs made the firm's cobalt production noncompetitive. A better worldwide economic climate could encourage broadening of the reserve base and reopening of the mines. Morocco's ores are cobalt-iron-nickel arsenides, and Morocco is the only world producer for which cobalt has been the primary product. The ores were processed in France by Metaux Speciaux, a subsidiary of Pechiney Ugine Kuhlmann, the state-owned metals group. The oxide and metal products were consumed internally. (Metaux Speciaux now receives cobalt intermediates from SLN in New Caledonia for processing into salts.) Amax considered using Moroccan ores and ores in the tailings at the Uganda Kilembe copper mine as a feed for its U.S. plant. Neither source presents any technical problems, but it is difficult and costly to transport the ores from either spot in northern Africa to the Botswana smelter for initial processing.

---

[47] *American Metal Market,* Oct. 27, 1983.

In 1982, the Trade and Development Program of the U.S. International Development Cooperation Agency completed a study of the prospects for Moroccan cobalt production.[48] The study reported that, although the reserves were approaching exhaustion, the potential for discovering new cobalt deposits in the Bou Azzer region (site of the closed mines) was very high, suggesting that extensive geological studies be undertaken.

New Caledonia

Only 8 percent of the cobalt in SLN's ores is recovered because most of its nickel oxide ores are smelted directly into ferronickel. (See discussion of cobalt losses due to ferronickel production in the following processing section.) The cobalt intermediates that are produced by SLN's smelter are processed in France by Metaux Speciaux. Cofremmi, S. A., a firm controlled by Amax, BRGM (France), and Patino N.V. (Netherlands), has studied the feasibility of mining the nickel laterite deposits containing cobalt at Goro, estimating a cobalt output of 1,000 tons (2 million pounds) per year. A deposit at Tiebaghi has been investigated by Amax. Both deposits could be exploited using existing technology, but eventual production from either source will depend on the nickel market.

The Philippines

Some *20* nickel laterite deposits, with varying cobalt content, have been identified in the Philippines, although only one is in production. Marinduque derives cobalt from a large deposit with 0.10 percent cobalt content at Surigao on Nonoc Island. A mixed nickel-copper sulfide is shipped to Japan for refining into cobalt cathodes by Sumitomo Metal Mining. Marinduque planned a cobalt refinery with a rated output of 1,200 tons (2.4 million pounds) per year, but current financial problems have prohibited any action. It is estimated that the plant would take about 18 months to complete.

South Africa

Cobalt from the Union of South Africa is produced from nickel products separated during platinum ore beneficiation. Data on actual cobalt production became available only recently. Production in 1981 has been estimated at 475,000 pounds of recovered cobalt. Two producers, Rustenburg and Impala, are now fully integrated within South Africa. Rustenburg processes nickel mattes into cobalt sulfate at a plant jointly owned with Johnson-Matthey. Impala's mattes are processed into cobalt powder at its refinery at Springs in the Transvaal Province, A third (minor) producer, Western Platinum Ltd., ships mattes to the Falconbridge plant in Norway for processing. (Falconbridge, a Canadian firm, is part owner of Western Platinum.)

Zaire

The copper oxide and mixed oxide-sulfide deposits of Zaire have one of the world's highest concentrations of cobalt (average 0.3 percent). Gecamines (the government mining firm) recovers cobalt after the last step of the copper ores processing. This makes cobalt production relatively inexpensive, but because the operations seek to maximize copper recovery, overall cobalt recovery from the mined ores is only in the 30-percent range. Mine-to-metal cobalt production is integrated at the mining area, Gecamines' two refineries produce cobalt metal cathodes.

Metallurgic Hoboken Overpelt in Belgium has an agreement with Zaire to process refined cobalt into cobalt chemicals and extra-fine powder. During the depressed markets of the past few years, Gecamines has stockpiled cobalt rather than substantially curtail its production rate. Estimates are that, by the end of 1982, Zaire and its sales agents were holding more than 20,000 tonnes (36 million pounds) of cobalt products off the world market. This amount exceeds Zaire's 1980 production rate of 17,090 short tons (34 million pounds),

Zaire was granted $360 million in loans by the International Monetary Fund in 1984 to help compensate for the decrease in export

---

[48] U.S. International Development Cooperation Agency, Trade and Development Program, *Morocco Cobalt Mission*, February 1982,

earnings due substantially to the depressed world markets for copper and cobalt. There have been attempts to open additional Zairian sources of cobalt by various consortiums of government and multinational private firms (e.g., Sodimiza and Societe Miniere de Tenke-Fungurume), but they have failed because of market conditions for both copper and cobalt.

After the Shaba crisis ended in 1979, Zaire continued to use air transportation for cobalt exports until the price of cobalt dropped dramatically. Land routes from Zaire include a river barge/rail combination west to the port of Matadi and rail routes via South Africa and Tanzania. Negotiations were underway in 1984 to allow Zaire the use of the Mozambique port of Beira.

Zambia

While Zambia produces from the same ore belt as Zaire, Zambia's ores are almost exclusively copper sulfides, and the concentration of both copper and cobalt (0.15 percent) is lower than in Zaire. The overall recovery rate for cobalt is about 25 percent. (The cobalt refinery yield is 75 percent, but only a third of the mined cobalt containing ores are processed for cobalt with the rest going to copper.) Sulfide ore processing requires smelting and separate streams for copper and cobalt rather than the sequential hydrometallurgical extraction process used in Zaire with oxide ores. The end product in Zambia is cobalt cathodes, half of which are of the high purity required for superalloy use.

The major transportation route from Zambia, especially for copper, is via the Tazara Railroad to the port of Dar es Salaam in Tanzania. The railroad was built in the 1970s, with assistance from the Chinese government, to reduce black southern Africa's dependence on rail routes through South Africa. It has been continually plagued with equipment and maintenance problems, reducing its reliability. China agreed to extend the grace period for repayment of the railway's debt, freeing up funds for repairs and for purchase of additional rolling stock. Several Western European nations have agreed to assist the rehabilitation effort. The port of Dar es Salaam tends to be a bottleneck causing extreme delays in shipments.

Potential Sources

The first of the following potential sources of cobalt is of particular interest because it is located close by in Peru and because little development would be required to produce cobalt. The time-consuming ground work has been completed for the second project, and it awaits economic viability.

Peru/Marcona Iron Mine

It has long been known that the iron sulfide (pyrite) tailings from operation of the Peru/Marcona iron mine contain cobalt. The Trade and Development Program (TDP) studied this project in 1982[49] at the request of Hierro-Peru, the Peruvian government iron mining concern, and estimated that at an iron mining rate of 7.2 million tons per year, 2,079 tons (4.2 million pounds) of cobalt could be recovered annually from the pyrite tailings. (In 1981, nearly 7.5 million tons of crude ore were mined, although the mine has an annual capacity of 15 million tons.) Additional cobalt is contained in the tailings generated over the lifetime of the mine's operation. The TDP report proposed that the cobalt ore be prepared for use in a U.S. refinery, such as the Amax refinery in Louisiana or one of Hall Chemical's plants. An evaluation was underway in 1984, funded by the TDP, to identify the required processing steps, the necessary infrastructure, and the capital requirements. This cobalt source might provide one of the quickest new supplies, given any disruption in the normal market, because the iron mining operation and most of the infrastructure required are already in place. Deepwater port loading facilities are available nearby.

---

[49] U.S. International Development Cooperation Agency, Trade and Development Program, *The Marcona Iron Mine: A Potential New Source of Cobalt in Peru,* November 1982.

Indonesia/Gag Island

After 10 years and a $50 million investment, further investigation on the nickel laterite project at Gag Island, Indonesia, was halted in 1981 by P.T. Pacific Nikkei Indonesia. The partnership of U.S. Steel, Amoco Minerals, and Ijmuiden Hoogovens BV of The Netherlands was subsequently liquidated. The reasons given for abandoning the project were the depressed state of the nickel and cobalt markets and the uncertainty of the future, along with interference by the Indonesian government, A production rate of 60,000 tons of nickel and 1,400 tons (2.8 million pounds) of cobalt for the first 10 years of operation had been projected,

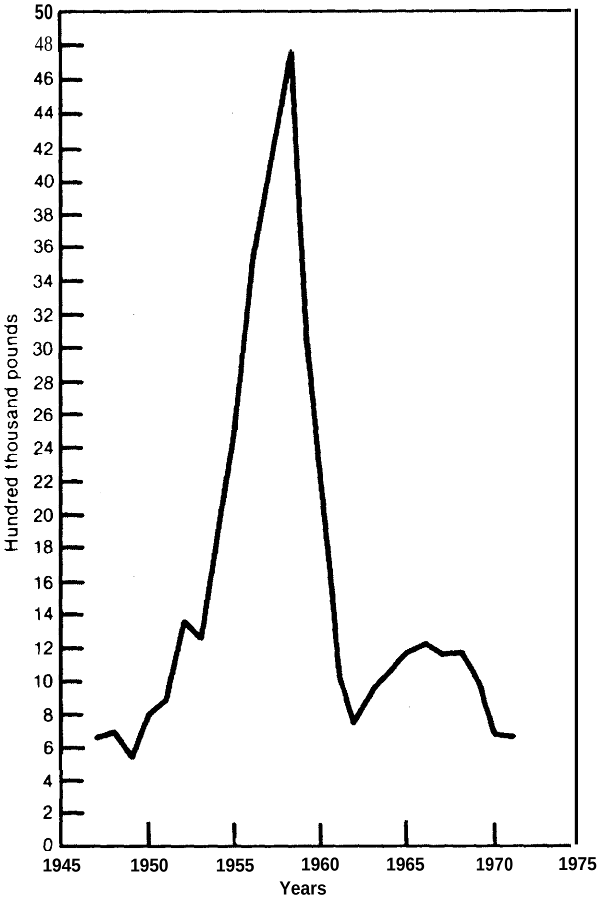
(See also the Ramu River, Papua New Guinea, project discussion in the chromium section.)

Domestic Production of Cobalt

Currently, cobalt is not produced from domestic mines, but this has not always been the case. U.S. mine production (fig. 5-3) reached a high point in 1958, when about 4.8 million pounds of contained cobalt were produced. (U.S. consumption of cobalt in 1958 was 7.5 million pounds.) In the 1948-1962 period, a total of approximately 14 million pounds were acquired by the government through stockpile purchases and Defense Production Act subsidies, Federal purchases included about 6 million pounds of cobalt from the Blackbird Mine in Idaho, and about 2.9 million pounds from mines in the Missouri Lead Belt (including the Madison Mine). There has been no production from these mines since the Federal purchase contracts expired more than two decades ago, During the period 1940-72, approximately 500,000 pounds of cobalt were produced each year from iron ore pyrite concentrates taken from Pennsylvania's Cornwall Mine.[50]

Since 1980, Federal subsidies for domestic cobalt production have again been proposed as an alternative to stockpiling, These proposals are discussed later in this section, and also in chapter 8.

Figure 5-3.—Total U.S. Cobalt Production, 1945-71
(cobalt content of mined ores)



SOURCE William S Kirk, Commodity Specialist, Bureau of Mines, Department of the Interior, 1984

Domestic deposits that may yield cobalt to meet national needs today are the Blackbird deposits, the Madison Mine of Missouri and associated cobalt in the Missouri Lead Belt, the Gasquet Mountain project in California, and in the Duluth Gabbro of Minnesota. Older, smaller mines primarily located in the Eastern United States, such as Pennsylvania's Cornwall Mine, are not considered potentially economic sources by the Bureau of Mines.

Fluctuating metal prices have made it difficult to assess domestic cobalt development projects, In 1981, spokesmen for the Blackbird, Madison, and Gasquet Mountain projects all

---

[50] The history of domestic cobalt production, through 1968, is discussed in James C. Burrows, *Cobalt: An industry Analysis,* " Charles River Associates Research Study (Lexington, MA: Heath Lexington Books, 1971], pp. 103-113 and 185-189.

stated that sustained market prices of from $20 to $25 per pound would be required to warrant production.[51] At that time, the market price for cobalt was $15 per pound, by 1983 it had dropped to $5 to $6 per pound, and in 1984 was being quoted at $10 to $12 per pound.

Although large deposits containing amounts of cobalt too small to be mined for cobalt alone occur throughout the world, the Madison and Blackbird deposits could—according to their proponents—support the mining of cobalt as a primary ore. Other domestic cobalt resources can be produced only as byproducts and would therefore be unlikely to respond solely to changes in the price of cobalt. The California-Oregon laterite deposits are primarily nickel, but the Gasquet Mountain project in northern California is dependent on nickel, chromium, and cobalt prices for success. The Missouri lead and zinc mines may have only a small relative incremental cost for producing small amounts of cobalt, but production at these mines is dependent on the base metals market. Moreover, cobalt recovery from these Missouri ores may require changes in lead and zinc processing practices and, in some cases, in end use standards. With present technologies, it is thought that increased cobalt recovery would result in higher iron concentration in recovered lead and zinc, which may not be satisfactory for consumers of lead-zinc products.[52]

The development of deposits in part of the Duluth Gabbro depends on copper and nickel markets. At copper and nickel prices at least double 1983 levels, these Minnesota deposits could become an attractive venture. Values of precious metals may also contribute to prospects for development of this area. However, the considerable excess production capacity of U.S. copper mines and of Canadian copper and nickel operations dampen prospects for production from these deposits.

Given the proper economic incentives (sustained, higher market prices for primary metals and/or Government subsidies), domestic sources (table 5-22) that have seen recent commercial activity could annually supply 7.7 million pounds of cobalt. Another 800,000 to 2 million pounds per year might be recovered from the Duluth copper-nickel sulfide deposits. (U.S. consumption of cobalt in 1982 totaled about 10 million pounds.) At current estimated resource levels, production from these deposits would range from 12 to 25 years.[53]

Blackbird Mine

The Blackbird Mine is located in the Salmon River Mountains of Lemhi County, ID. The Caldera Co. acquired claims to the Blackbird District in 1943 after investigations by the Bureau of Mines revealed the presence of commercially feasible deposits of cobalt. Production began in 1950 with subsidies under the DPA running from 1952 through 1959, when production ceased.[54]

Blackbird is now managed by Noranda Mining of Canada, which has proposed reopening the Blackbird Mine and concentrator to produce 1,200 tons of copper-cobalt ore daily.[55] A final environmental impact statement (EIS) was published in 1982. Permits currently allow production of 300 tons daily for a “pilot” operation. However, in 1981 Noranda began laying off employees, and when the final EIS was issued, only a few workers were still on site. The project is on hold awaiting improvement in cobalt demand and prices. The company has sealed off the mine at the 6,850-foot level, and the mine is filling with water.

Ore reserves at Blackbird are now given at 7.5 million tons of 0.72 percent cobalt (108 million pounds of contained cobalt) with 1.4 percent copper and 0.01 percent gold. The esti-

---

[51] Hearings before the U.S. Senate, Committee on Banking, Housing, and Urban Affairs, Oct. 26, 1981, p. 145, Noranda Mining, the Blackbird Mine owners, now believe that a sustained cobalt price of $16 per pound would make it feasible to bring the mine into production due to improved mine planning and the discovery of higher grade ores. The other mine owners have not revised their 1981 figures.

[52] Silverman, et al., op. cit.

[53] Production levels at Blackbird, Madison, and Gasquet Mountain were stated in testimony during U.S. Senate hearings before the Committee on Banking, Housing, and Urban Affairs on Oct. 26, 1981. They were also confirmed to OTA in telephone conversations with each mining firm in July 1984. Data for Duluth Gabbro is taken from the Minnesota study cited in note 67.

[54] Burrows, op. cit., p. 187.

[55] Silverman, et al., op. cit., p. 67.

Table 5.22.—Potential U.S. Cobalt Production

Resource/Mine	Estimated annual production capacity (million pounds of recovered cobalt)	Estimated mine life (years)	Production dependent on
Blackbird Mine Idaho	3.7	20	Cobalt price of about $16 per pound (1984)[a]
Madison Mine Missouri	2	20	Cobalt price of about $25 (1981)[a]
Missouri Lead Belt (tailings)	2	?	Cobalt price of about $20-25 (1984)[a]
Gasquet Mountain California	2	18	Cobalt price of about $20 (1981)[a] plus Nickel $2 to $3 per pound Chromite $40 per ton
Duluth Gabbro Minnesota	0.8-2	25	Copper, $1.50 per pound Nickel, $4.00 (1975 data converted to January 1983 dollars)

[a]Year of estimate

SOURCE Blackbird—Noranda Mining, July 1984
Madison—Anchutz Mining, July 1984
Missouri Lead Belt —Amax estimates, July 1984
Gasquet Mountain–California Nickel Corp , July 1984
Duluth Gabbro—State of Minnesota, *Regional Copper. Nickel Study*, 1979

mated cost of production has declined over the last few years with the discovery of higher grade reserves and improved mine planning, and the mine life has almost doubled to 20 years. An estimate provided to OTA by Noranda holds that about $16 per pound is the price of cobalt needed to promote the development of the project, should that occur, 3.7 million pounds of cobalt is expected to be recovered per year.[58]

The Blackbird ores contain high levels of arsenic, and past mining operations contaminated streams flowing into the Salmon River drainage, As a condition of reopening the project, Noranda agreed to install a water treatment facility and take other measures to improve and protect water quality. Noranda negotiated a settlement with the Environmental Protection Agency in July 1983 that allowed the company to close the water treatment plant, evidence of the declining commercial interest in this project. The cobalt concentrates from Blackbird also contain a level of selenium which may or may not be a problem in superalloy use. Noranda officials claim that effective techniques to reduce this element to a lower level, if necessary, are available. (The current maximum allowable limit for selenium in jet engine superalloy is 5 parts per million.)[57]

The proposed mining area is surrounded by private and public lands, approximately 6 miles from a wilderness area on National Forest land. Some of the mining claims (not connected with the Blackbird Mine, as proposed) extend into the wilderness area. However, the Act[58] creating the wilderness area made special provisions for exploration for cobalt. No exploration activities have yet been carried out in the special mineral management area, despite tentative approval granted Noranda by the U.S. Forest Service.

Large amounts of cobalt are contained in tailings from previous operations at Blackbird; however, Noranda does not count the tailings in its reserves, and at present is unlikely to exploit them for their mineral content. The firm would thereby avoid incurring responsibility for rectifying water pollution and waste problems caused by past imprudent handling of

---

[56] Richard Fiorini, Vice-President and General Manager, Noranda Mining Inc., persona] communication, July 1984.

[57] American Society for Metals, *Quality Assessment of National Defense Stockpile Cobalt Inventory*, prepared for the Federal Emergency Management Agency (Metals Park, OH, 1983), p. 26.

[58] Public Law 96-31 z., The Central Idaho Wilderness Act of 1980, authorized exploration for cobalt in special management zone in the River of No Return Wilderness area near Blackbird Mine,

these mine wastes. The State of Idaho filed a preliminary suit under the Resource Conservation and Reclamation Act against Noranda and previous owners for environmental damage.

Madison Mine and Missouri Lead Belt Deposits

Mines in the southeast Missouri lead district produced 5.2 million pounds of cobalt from 1844 to 1961. In 1979, Anschutz Mining acquired the inactive Madison Mine, located near Frederickstown in part of the old Missouri Lead Belt, an area where most of the lead and zinc mines have been depleted. The Madison Mine produced 2.8 million pounds of cobalt from 1954 to 1961, before it was closed. The mine also produced lead, copper, and nickel. The cobalt mineralization is reportedly high enough in one zone in the mine to support cobalt production as a primary ore.

If reopened, the mine could have an estimated annual production of 2 million pounds of cobalt. Recoverable geologic (as opposed to economic) cobalt reserves at the Madison Mine are given as 37 million pounds (in 5.6 million tons of ore and 3.4 million tons of existing tailings).[59] The depressed world price of cobalt and lack of Government action on proposed price supports under the Defense Production Act have led Anschutz to postpone opening the mine. In 1981, company officials said an estimated guaranteed price of about $25 per pound would be necessary to promote production from Madison.[60] Economic studies have not been revised to reflect any changes in mining costs since then.

Cobalt in the Madison Mine is a sulfide mineral. Anschutz Mining has reportedly found a previously unrecognized cobalt ore body that does not contain the lead and zinc customarily associated with cobalt deposits in the Missouri Lead Belt. This discovery could prove to be significant worldwide in identifying an additional geologic environment for cobalt occurrences.

An underground and surface mining operation has been proposed for the Madison Mine including a smelter to refine its own ores and process existing tailings from previous mining periods, as well as the tailings from other lead belt producers. Perhaps 300,000 to 400,000 pounds of cobalt is recoverable from these tailings given the current technologies used by the region's lead mines to produce lead and zinc from their ores.[61] Up to 1.5 million pounds might be available, given changes in lead and zinc recovery practices.

Another analysis[62] of extracting cobalt from the byproducts of lead-zinc mining in Missouri estimates that 2 million pounds could be produced per year, based on the recovery of 65 percent of the cobalt content in currently mined ores. Capital requirements would be in the range of $40 million to $65 million to install equipment to treat the raw materials (mill tailings, smelter slags, mattes, copper concentrates and copper-cobalt cakes), This is substantially less than would be required to finance a new mining venture and would likely yield an acceptable return if the price of cobalt were $20 to $25 and if raw materials from several firms operating in the Lead Belt were pooled to provide economies of scale. Successful implementation would also require work, in addition to that already done by the Bureau of Mines Rolla Research Center, on technologies to recover cobalt from mill tailings and blast furnace slag.

Gasquet Mountain Project

Cobalt resources are contained in nickel laterite deposits in northern California and Oregon.

California Nickel Corp., a wholly owned subsidiary of Ni-Cal Development Ltd. of Canada, has proposed development of the Gasquet Mountain mine on unpatented mining claims it controls in the Six Rivers National Forest in northern California. The mine, along with asso-

---

[59] John Spisak, Vice-President for Operations for Anchutz Mining, persona] communication, July 1984.

[60] U.S. Senate, Committee on Banking, Housing, and Urban Affairs, hearings, Oct. 26, 1981, p. 145.

[61] Silverman, et al., Op. cit., p. 111.

[62] This preliminary analysis was provided to OTA by Amax, which has extensive holdings in the Missouri Lead Belt from which it produces lead and zinc.

ciated milling and processing facilities, as proposed would annually produce 2 million pounds of cobalt (cathode), 19.4 million pounds of nickel (cathode), 50,000 tons of chromite concentrate (42 to 43 percent chromic oxide), and 100,000 tons of magnesium oxide, Mine life has been calculated at approximately 18 years .[63]

California Nickel has sought production subsidies from the government for the operation,[64] one of several factors that have made the proposal controversial. Viability of the project hinges on the economics of multiple (cobalt, nickel, chromium) metal production and processing, on successful mitigation of several adverse environmental impacts, and on demonstration that mine areas can be reclaimed, A draft EIS was published in March 1983, but the project appears to be in suspension,

Based on a Kaiser Engineers' mine feasibility study for the project, estimated total ore reserves at Gasquet Mountain are 23.6 million tons (16.0 million of which are proven reserves with grade of 0.75 percent nickel, 0.07 percent cobalt, and 2 percent chromium), Kaiser estimated annual ore production of 1.32 million tons would be required to generate 2 million pounds of cobalt per year.

Kaiser also examined several prospective processing techniques. It concluded that with the use of a high-pressure acid leach process (a well-established 20-year old hydrometallurgical technology) maximum extraction of both nickel and cobalt would occur. In addition, use of this process would make it possible to recover most of the chromite in the ores using existing gravity concentration methods and, "might yield another commercial product."[65]

The operation would be a surface mine operating at the crest of 2,000- to 3,000-foot mountains. The mineralization of the Gasquet deposit is shallow, down to about 25 feet; and mining would consist of scooping up the soil with backhaulers. Cost to build the project in 1982 was projected at $300 million.[66]

California Nickel has now split its operations into two separate units. One oversees the mining project itself and the other, Ni-Cal Technology Ltd., is pursuing the development and promotion of a modified acid leach processing technology that was intended for the Gasquet mine. Six patent applications have been filed so far, and Ni-Cal intends to build a pilot plant to test the process on ores from various sources. Marketing of the process is aimed at laterite mining operations in the Pacific rim area. No domestic prospects are in sight.

Duluth Gabbro

The Duluth Gabbro, in northeastern Minnesota, has been suggested as a potential source of cobalt, as well as PGMs. Cobalt production would only be as a byproduct, dependent on the production of copper and nickel. The area contains an estimated recoverable resource of 20 million tonnes of copper, 5 million tonnes of nickel, 80,000 to 90,000 tonnes of cobalt (145 million to 164 million pounds), and lesser amounts of titanium, platinum, gold, and silver.[67]

A Regional Copper-Nickel Study was released by the State of Minnesota in 1979.[68] The study, conducted from 1976 to 1979, assessed the technical aspects of the development of mining activities in the Duluth Gabbro and resultant environmental, economic, and social impacts. Mining schemes were developed with the goal of generating representative models, rather than for predicting or recommending the choices that might actually be made by a company developing a specific ore deposit. It was decided that technology and economic conditions required large-scale operations for Minnesota's low-grade resource to compete in late 1970s markets. Thus, the models provided for a minimum annual production of 100,000

---

[63] Documents provided to OTA by California-Nickel, March 1983.

[64] U.S. Senate, Committee on Banking, Housing, and Urban Affairs, hearings, Oct. 26, 1981, p. 185.

[65] Kaiser Engineers, *Interim Report for the Gasquet Mountain Project,* March 1982, p. 5-10.

[66] Ibid., p. 18.

[67] Minnesota Environmental Quality Board (State Planning Agency), *The Minnesota Regional Copper-Nickel Study, 1976-1979,* vol. I, Executive Summary, August 1979, p. 10,

[68] Ibid.

tonnes of metal (85 percent copper and 15 percent nickel). Three hypothetical mine-smelter complexes were considered, one each with an underground, open pit or combination underground/open pit mining operation. Assuming simultaneous development of these three models, an annual production of 254,000 tonnes (231,000 tons) of copper could be generated over a period of approximately 25 years.

A report prepared for OTA estimated potential overall cobalt recovery of 25 to 30 percent from Duluth ores, with significant amounts of the cobalt lost to mill tailings and during refining.[69] For every 100,000 tonnes of copper produced, associated cobalt recovery would be about 4100 to 450 tonnes or about 800,000 pounds.[70]

Operation of copper-nickel production at Duluth would be marginally economic at metal prices of $1.50 per pound for copper and $4 per pound for nickel, in January 1983 dollars.[71] (In *1983,* the U.S. producer delivered price for copper cathodes averaged 77 cents and the spot price for nickel averaged $2.20.)[72]

Other Domestic Cobalt Deposits

Pennsylvania's Cornwall Mine produced cobalt for many years, yielding 400,000 to 600,000 pounds annually as a byproduct of mining iron ore. From 1940 until operations ceased in 1972, the mine produced 100,000 tonnes (182 million pounds) of cobalt ore. The Gap Nickel Mine in Lancaster County, PA, has 1 million tons of remaining ore at grades of 0.1 to 0,3 percent cobalt. Although these small cobalt deposits are potential resources, there has been no thorough examination of the economic and technical viability of mining them. They have usually been omitted from Minerals Availability System Appraisal studies conducted by the U.S. Bureau of Mines because their probable cobalt yield is not considered significant.[73]

Proposed Federal Subsidies for Domestic Cobalt Production

As is discussed in chapter 8, proposed renewal of Federal support for domestic cobalt production has been the subject of considerable debate in Congress and the Administration. Most of this debate has focused on proposed Federal support for domestic cobalt production, under Title 111 of the Defense Production Act. (Title 111 authorizes purchase commitments, loans, and loan guarantees for materials, services, and facilities considered essential for defense needs.) president Reagan, in his April 1982 national materials plan submitted to Congress under the National Materials Policy, Research, and Development Act of 1980, indicated that analyses were ongoing to determine whether DPA incentives might be more cost effective than stockpile purchases in some circumstances.

The great fluctuation in cobalt prices since 1978 in fact has made it very difficult to make cost-benefit comparisons among stockpile/domestic production options, as was made clear in hearings held in early 1983 about an Administration proposal to provide federally guaranteed price supports for domestic cobalt production.[74] In August 1982, the Federal Emergency Management Agency (FEMA) issued a report comparing four alternative combinations of Title III subsidies and stockpile purchases for cobalt—ranging from exclusive reliance on government stockpile purchases on the world market to extensive reliance on a government-guaranteed minimum price to domestic cobalt producers—which might be used to realize the materials availability equivalent of the strategic stockpile goal of 85 million pounds of cobalt.[75]

---

[69] Silverman, et al., Op. cit., p. 181.

[70] *The Minnesota Regional Copper-Nickel Study,* Op. cit., p. 10.

[71] Silverman, et a]., op. cit., p. **182.** These data are based on conclusions from a 1975 study, *Mineral Beneficiation Studies and an Economic Evaluation of Minnesota Copper-Nickel Deposit From the Duluth Gabbro* by J.E. Lawver, et al., for the U.S. Bureau of Mines.

[72] U.S. Department of the Interior, Bureau of Mines, *Minerals and Materials; A Bimonthly Survey,* December 1983/January 1984, pp. 25 and 29.

[73] Silverman, et al., op. cit.

[74] U.S. Senate, committee on Banking, Housing, and Urban Affairs, Extension of the Defense Production Act, hearing on Mar. 21, 1983, 98th Cong., 1st sess., Senate Hearing 98-66 (Washington, DC: U.S. Government Printing Office, 1983).

[75] Federal Emergency Management Agency, *Alternative U.S. Policies for Reducing the Effects of a Cobalt Supply Disruption—Net Economic Benefits and Budgetary Costs,* August 1982, as reproduced in its entirety in ibid., pp. 15-100.

For each scenario, cobalt prices, budget expenditures, and overall economic costs were projected over a 10-year period (1981-90) under both a “no disruption” assumption and a peacetime disruption assumption affecting 50 percent of normal U.S. supplies. The disruption was assumed to occur in 1985. Each of these scenarios, which addressed the 1981-90 period, were intended to provide an equal degree of supply security. FEMA recommended, as the most cost-effective option, a so-called “hybrid” alternative entailing a 5-year program of government-stimulated production of 10 million pounds of cobalt annually from domestic mines, supplemented by stockpile purchases of 1,42 million pounds for 10 years. The domestic production would be stimulated through a federally guaranteed minimum price of cobalt of about $15 per pound.

When hearings were held on the FEMA proposal in March 1983, cobalt prices had fallen to about $6 per pound on world markets. The U.S. General Accounting Office (GAO), which testified on the FEMA report,[76] found that FEMA’s “stockpile only” analysis in a nondisruption scenario assumed cobalt prices would rise to over $36 per pound by 1990, more than double the price projections made by other government agencies. In its hybrid scenario, FEMA assumed that Federal price guarantees for domestic production would only be necessary for a 5-year period. This would only be the case if FEMA’s projected cobalt price is assumed to be accurate. GAO found that, at 1983 prices, buying cobalt on the world market for the stockpile would be far cheaper than subsidizing domestic production.

Another Defense Production Act issue that has received considerable attention concerns a Department of Defense (DOD) proposal for pilot plant production of domestic cobalt in order to evaluate the quality of this cobalt for defense applications, In 1983, the Air Force issued a draft Request For Proposal (RFP) to potential domestic producers concerning such a project. According to DOD, the draft RFP was issued for two reasons: 1) to secure “definitive data through legal contracting procedures for a cost/benefit analysis of domestic cobalt production”; and 2) “to *determine* if domestically produced cobalt will meet national security requirements.”[77] DOD maintains that the issuance of the draft RFP was simply to evaluate the costs and benefits of the proposal, in order to support activities of its DPA Title III steering committee, which has been set up to evaluate candidate DPA projects. However, the cobalt pilot plant became an issue in congressional debate about amendments to the Defense production Act in April 1984. (The DPA amendments are discussed in chapter 8.)

Domestic Mining and Processing Technology Prospects

Lateritic deposits containing cobalt are suited to open pit mining and to the continuous systems of excavators and conveyor belts that will gradually become more common in steep pits. Open pit mining in harder rock would be practicable in the copper-nickel-cobalt deposits of the Duluth Gabbro, with underground mining at depths involving open stoping and room-and-pillar methods. In the steeper hard-rock bodies of cobalt ore such as at Blackbird, cut-and-fill mining and the new ramp-in-stope system underground methods could be appropriate.

Process technology has been developed for recovering cobalt from the Blackbird and Madison deposits, and preliminary pilot-scale testing has been completed for both properties and byproduct cobalt production from Missouri’s lead mines. Commercial facilities have not been designed or tested, however. Ore processing systems could be designed for these deposits, plus Duluth Gabbro, that would allow shipment to the existing Amax Nickel refining plant at Port Nickel for final processing.

The Bureau of Mines has conducted research into reclaiming the cobalt from Missouri lead ores which is currently neglected (an estimated

---

[76] Statement of J, Dexter peach, Director, Resources Community and Economic Iii\’ision, U ,S. General Accounting Office, as reproduced in ibid., pp. 3-6.

[77] As discussed in U.S. Senate, Committee on Banking, HO Using, and Urban Affairs, hearing: Reextension of the Defense Production Act, Hearing on S. 1852, Sept. 15, 1983, Senate Hearing 98-400 (Washington, DC: U.S. Government Printing Office, 1983), p. 159.

2.5 million pounds of contained cobalt per year is lost) during lead, zinc, and copper processing.[78] In other research, the Bureau investigated the extraction of cobalt from the liquid which remains after dilute acid solutions have leached copper from its ore. One U.S. copper mine might be able to contribute 1.3 million pounds of cobalt per year through this process, which has not yet been economically evaluated.[79]

Research on Blackbird complex arsenical copper-cobalt ores is attempting to find the basis for less costly extraction technology than currently exists. Investigations have centered on methods for improving hydrometallurgical technology because severe sintering and atmospheric pollution problems occur with an alternative roasting procedure. Selective solvent extraction processes are being compared with conventional precipitation processes for removing iron and recovering cobalt, nickel, and copper from the resultant leach liquids.[80]

A comprehensive plan to recover all of the mineral values in Duluth Gabbro ores (nickel, copper, cobalt, silver, gold, and PGMs), rather than concentrate on the primary metals, has undergone investigation by the Bureau of Mines Twin Cities Research Center in Minnesota. The approach is a combined pyrometallurgical-hydrometallurgical process to recover a maximum amount of the byproduct metals without sacrificing energy or metallurgical efficiency.[81]

Laterite ores containing cobalt could benefit from a commercial hydrometallurgical process developed by Ni-Cal Technology Ltd. as a spin-off of the Gasquet Mountain project in northern California. After separating out chromite from the mined ores, a slurry of the residual nickel-cobalt-iron minerals is leached, producing separate nickel-cobalt sulfide and iron concentrates. Nickel and cobalt are then produced by standard selective precipitation and solvent extraction methods, and further refining is accomplished by electrowinning.

Domestic and Foreign Cobalt Processing

The primary industrial uses of cobalt are in superalloys, magnetic alloys, catalysts for the petroleum and chemical industries, and as a binder in tungsten carbide cutting tool materials. While catalyst producers use chemical forms of cobalt, superalloy and tungsten carbide makers use pure metal in cathode and extra-fine powder forms, respectively. Magnetic alloy production uses powder metallurgy techniques, and fabricators purchase either cathodes or powder forms.

Cobalt is produced from a variety of ores, and the processing, tailored for each deposit, depends on the type of ore in which the cobalt occurs, as figure 5-4 shows. Processes can be grouped into two general categories, pyrometallurgical and hydrometallurgical. The pyrometallurgical process is usually conducted in three stages. First, the minerals in the ore are concentrated. Second, a smelting or roasting process is used to produce a matte containing cobalt, with associated sulfur and the nickel and/or copper of the original ores. In the third step, the matte is treated chemically or electrolytically to separate the cobalt as metallic powder or cathodes, or as cobalt chemicals. In hydrometallurgical processes, the concentrated ore can be chemically processed without the intermediate smelting step but does require the application of heat and pressure.

Much of the cobalt content of mined ores is never recovered, owing to processing technologies and economics or to excessively low cobalt grades. Processes are such that a high recovery of the primary metal is often detrimental to the recovery of cobalt. In Zaire, for instance, the recovery of the cobalt content in the mined ores is only *30* percent, and in Zambia, *25* percent. (Cobalt is lost into tailings when the ores are initially concentrated and again when the concentrates are processed.) Yields of cobalt could be increased somewhat

---

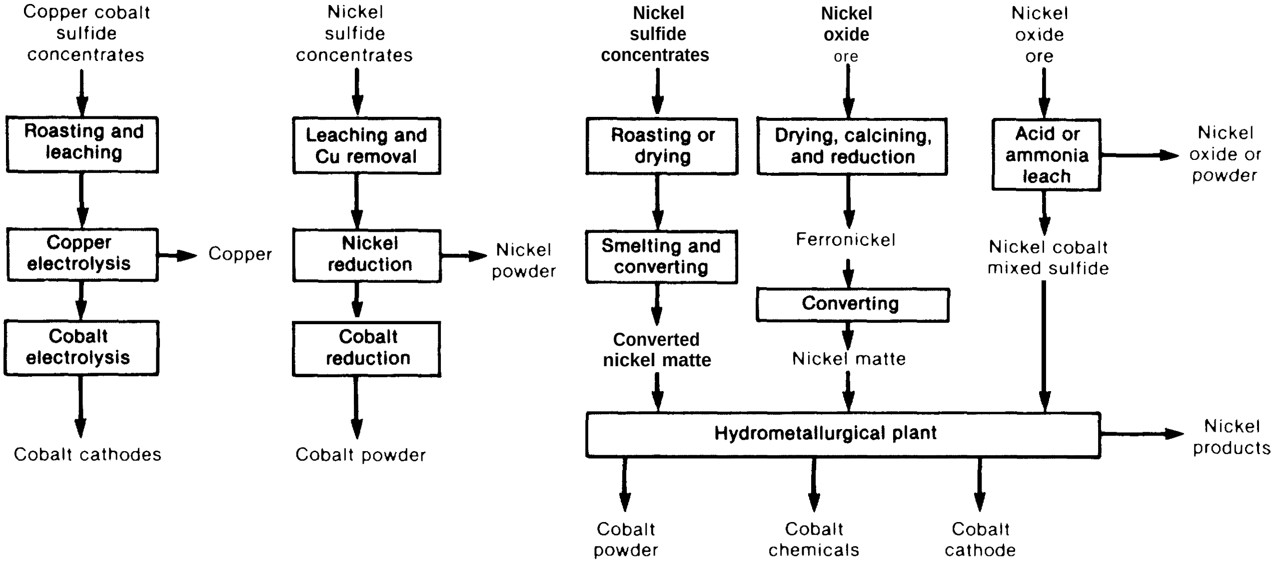
[78] U. S. Department of the Interior, Bureau of Mines, *Research 83*, p. 89.

[79] U. S. Department of the Interior, Bureau of Mines, *Mineral Industry Survey:* "Cobalt in February 1984."

[80] *Research 83,* op. cit., p. 91.

[81] National Materials Advisory Board, *A Review of the Minerals and Materials Research Programs of the Bureau of Mines,* p. 53; *Research 83,* op. cit., p. 83.

Figure 5-4.—Simplified Flowchart for the Production of Cobalt



SOURCE: Charles River Associates, January 1984, *Processing Capacity for Critical Materials*, contract report for OTA.

by improving the efficiency of producing cobalt from the concentrates,

Nickel laterite ores tend to have cobalt associated with them in very low (0.02 to 0,11 percent) grades. These ores can be leached to separate out both nickel and cobalt, The economics of nickel production, if energy sources are available and competitively priced, usually demand, however, that the nickel ores be smelted into ferronickel. The cobalt contained in the smelted ores is either lost into the ferronickel or the slag. New Caledonia, for instance, produces limited amounts of cobalt from nickel laterite deposits, because its main effort is concentrated on producing ferronickel. The cobalt that is produced is a byproduct of some ore diverted into nickel metal production. Substantially higher amounts of cobalt are produced by one nickel mining firm in Australia as a result of its ore-matte-nickel metal processing steps. Other copper and nickel producers totally neglect the cobalt units in their deposits. In this category are the Hanna Mining operation at Cerro Matosa in Colombia, the Larco operations in Greece, Bonao in the Dominican Republic (Falconbridge), and the now-mothballed Inco operation in Guatemala.

Ferronickel was originally developed by New Caledonia’s SLN and is used in lieu of nickel metal in the steel industry for the production of iron-nickel steels. Use of nickel metal is less energy-intensive than ferronickel, but ferronickel is not so much more expensive that steelmaker will alter their traditional methods. Nickel metal, however, must be used when the cobalt in ferronickel would be detrimental to the final product.

Domestic Processing Capacity

The United States has the operating capacity only to refine imported cathodes and process nickel-cobalt mattes or recycled materials into cobalt powder (table 5-23). In 1980, only one-tenth of the 10,825,000 pounds of cobalt metal consumed in the United States was produced domestically. The United States has no capacity to produce superalloy-grade cobalt, This material is all imported.

At its refinery in Louisiana, Amax Nickel produces cobalt powder, which is sold for applications other than superalloys. The plant, which mainly produces nickel, was originally designed with a 5 million to 6 million pound

Table 5-23.—U.S. Cobalt Processing Capacity

Product	Source material	Firm	Annual operating capacity
Superalloy grade			none
Powder	Imported smelted ores (matte)	Amax Nickel	1 million pounds Capable of production expansion to about 3 million pounds; can add electrolytic circuit to produce superalloy grade
Extra-fine powder	Cathodes (Zaire)	Carol met	2 million pounds
	Domestic scrap	GTE	32,000 pounds (pilot plant operation)
Salts (chemical) . . .	Recycled catalysts and scrap	Hall Chemical	1 million pounds Plus 3 million to 4 million pounds from projected plant; could add circuit to produce superalloy grade

SOURCE: Office of Technology Assessment.

U.S. Cobalt Consumption, 1982

End use	Thousand pounds contained cobalt
Superalloys.	3,319
Steel alloys.	326
Other alloys	2,829
Chemical	2,846
Other ... , ...	148
Total	9,468

SOURCE: U.S. Department of the Interior, Bureau of Mines. *Minerals Yearbook 1982*

annual output capacity for cobalt. Available feed and markets, however, have restricted the plant to a maximum of just over 1 million pounds. Estimates are that output could be raised to some 3 million pounds in a very short time, provided feed was available. In addition, all plans and design work have been completed for adding an electrowinning operation that would produce cobalt cathodes suitable for superalloy use. This plant modification would take approximately 2 years to complete. Feed for the plant is currently imported from Botswana and Australia in the form of mixed metal mattes. Other sources—e.g., Morocco, Uganda, and Peru—have been investigated and, while deemed technically possible, have been discarded as economically unfeasible. Amax's operation is a likely candidate to process and refine any domestic nickel-cobalt ores that might one day be produced.

At Carolmet, Inc., in North Carolina, an extra-fine powder for use in tungsten carbides is produced from cobalt cathodes imported from Zaire. The plant capacity is 1,000 tonnes (about 2 million pounds) annually. The other domestic source of extra-fine powder is the GTE Chemical and Metallurgical Division at Towanda, PA. Employing their own process, tungsten carbide scrap is used as the feed material, and a pilot plant now in operation has a capacity of 175 tonnes (32,000 pounds) annually. This process could also be used to purify substandard grades of cobalt and, if equipment were added to compact the powder produced, could possibly provide a source of cobalt for superalloy use.

Hall Chemical has plants in Ohio and Alabama to recycle catalysts and scrap metals, including cobalt, into chemical products for reuse. (See a discussion about the prospects for cobalt recycling in chapter 6.) A new plant has been planned by Hall that would more than triple its capacity, but the project has been halted by the recent recession, A large portion of this new capacity could be used exclusively for cobalt refining (from ore concentrates) with a lead time of 3 to 4 months. Installation of an electrolytic circuit to produce cobalt cathodes suitable for superalloy would require about 18 months.

Unlike the decline in domestic capacity for processing manganese and chromium, U.S. cobalt processing capacity has increased in the past 5 years with the addition of the two extra-fine powder production facilities mentioned above. Still, operational domestic capability remains at the last stages of processing only. Initiation of domestic ore production would require the development of smelting and refining facilities, as well. This could be accomplished by upgrading the standing plants in order for the United States to have the greatest flexibility and ability to use the cobalt produced in the most critical applications (e. g., superalloy).

Manganese Production and Processing

The bulk of the world's manganese ore is produced in a few countries where large, discrete deposits of high-grade ore are mined by multinational firms. These deposits offer the possibility for expansion on a large scale, but substantial mine expansion would have to be accompanied by expansion of processing and transportation facilities, The Western Hemisphere has two sources of manganese ores, Mexico and Brazil. One new deposit may come onto the world market soon—part of the Grande Carajas project in Brazil. How much this operation will provide in terms of net gain in the world's export supply of manganese is unknown owing to Brazil's growing domestic steel industry.

The largest occurrences of worldwide economic manganese deposits are sedimentary in origin, formed from either volcanic or weathering activity. Residual ores, which make up a small part of the economic base, are formed in a concentration process similar to that for laterite deposits. Manganese is also found in hypogene deposits and with metamorphic rocks, primary sedimentary ores that have been subjected to changes in mineralogy and texture due to pressure and/or heat. Manganese is mined as an oxide and/or carbonate mineral, and both minerals are often present to varying degrees in each deposit,

The bulk of the ore mined today, however, is an oxide mineral. Initial processing of these ores involves only sorting by size and concentrating to increase the manganese content of the ores to 40 and 48 percent. (U.S. industry standard is 48 percent for ferroalloy production), Manganese carbonate minerals, on the other hand, must be converted to an oxide by roasting. Currently, only Mexico mines carbonate minerals, but this mineral type may eventually become a more important source as the higher grades of oxide ores are exhausted.

Manganese ores are classified as metallurgical, chemical, or battery grades. For metallurgical grade,[82] the iron, silica and especially phosphorus content are important, In battery grades the manganese content is expressed in terms of manganese dioxide, and these ores typically contain from 70 to 85 percent MnO_2 (44 to 53 percent manganese).

The United States imports 99 percent of its consumption of manganese ore and metal. In 1980, manganese ore accounted for 41 percent of U.S. imports of manganese, but an ongoing trend in producer countries to integrate ferroalloy production with ore mining is decreasing the ratio of manganese ore to ferroalloys in U.S. imports and throughout world markets.

In 1982, manganese ore was produced in 26 countries. Of these, 8 accounted for 98 percent of total world production. As indicated in table 5-24, the Soviet Union and South Africa produced 64 percent, while five countries (Gabon, Australia, Brazil, India, and China) each made a substantial contribution of over a million

---

[82] About 90 percent of the world's manganese ores are destined for metallurgical uses,

Table 5-24.—World Manganese Ore Reserves and Production by Country (thousand tons)

Country producer	Reserves (recoverable metal content)	Product ion 1982 ore output	Estimated manganese content	Percent of world product ion
Australia	51,600	1,248	37-53	5
Brazil	20,900	1,433	38-50	6
China	15,000	1,760	20+	7
Gabon	110,000	1,667	50-53	7
India	21,500	1,596	10-54	6
Mexico	3,500	561	27+	2
South Africa	407,000	5,750	30-48	23
Soviet Union	365,000	10,140	30-33	41
Other	5,500	599		2
Total	1,000,000	24,754		100

SOURCE: U.S Department of the Interior, Bureau of Mines
Reserves—*Mineral Commodity Profile 1983" Manganese.*, p 8. table 3
Production–Minerals *Yearbook 1982,* vol 1, table 9, p. 587

short tons of ore. Mexico is the smallest producer of the eight at half a million short tons. Major exporters to market economy countries are South Africa, Gabon, India, Brazil, and Australia. India's exports are controlled by a government quota system and are destined primarily for Japan; the other four nations are the principal suppliers to the United States, Japan, and Western Europe.

Foreign Production of Manganese

In general, the manganese mining interests of each producer country are controlled by one or two firms, reflecting the concentrated nature of the deposits in these countries. Two private firms with primarily local, but also international, investors dominate South African production. Their deposits in South Africa occur in its northern Capetown Province in the Postmasburg and Kuruman (Kalahari) districts. The latter provides 75 percent of the total output.

The Soviet Union's government-controlled operations produce mainly from two areas in western Russia: the Nikopol Basin deposits, which contribute high-volume production; and those in the Tchiatura Basin, which provide the highest grade ores. Mexico and Gabon each have one privately operated firm in which the government holds a minority interest. Brazil's producing firms are a mixture of private and public sector interests. Brazil's manganese deposits in the Grande Carajas Development Project are being developed along with iron ore mines by Cia. Vale do Rio Doce (CVRD), a corporation jointly owned by the Brazilian government and local, private shareholders.

By contrast, manganese production in India and China is supplied by numerous small- or medium-sized operations scattered throughout each country. China's production is run by the national government, while India's ores are mined by a mixture of local private and state or national government firms.

U.S. firms participate in a number of foreign manganese mining operations (table 5-25). United States Steel has interests in Gabon's Comilog and South Africa's Associated Manganese; International Minerals & Chemical of New York has a minority interest in South Africa's Samancor. Bethlehem Steel owns part of Brazil's ICOMI and until the late 1970s was a partner in Mexico's Autlan. British investors are heavily involved with South African producers through traditional ties with the Anglo-American Corp., Ltd., Anglo Transvaal-Consolidated Co. Ltd., and General Mining Union Corp. Ltd (Gencor). These investment houses, or groups, hold interests in Samancor and Associated Manganese.

Historically, ores have been exported from producer countries after relatively minor beneficiation. The ore is ultimately moved to consumers by sea, which, along with transportation from a mining area to a shipping port, can account for a major portion of the cost of the product to consumers. Approximately two-

Table 5-25.—Manganese Mining Industry by Country

		Ownership		
Country	Major firms	Sector	Major holders[a]	Primary national identity
Australia	Groote Eylandt Mining Co.	Private	Broken Hill Prop. (100)	Local
Brazil	Industria e Comercio de Minerios S.A. (ICOMI)	Private	Bethlehem Steel (49)	Us.
		Private	CAEMI (51)	Local
	Urucum Mineracao S.A.	Private/ government	CVRD[b] (47)	Local
		Various	Local	
Gabon	Compagnie Minere de l'Ogooue S.A. **(Comilog)**	Government	BRGM (19)	French
		Government	(15)	Local
		Private	Imetal (16)	French
		Private	U.S. Steel (41)	Us.
Mexico	Cia. Minera Autlan S.A. de C.V.	Government	(34)	Local
		Private	Various	Local
South Africa[c]	SA Manganese Amcor Ltd. of S.A. (Samancor)	Private/ government	African Metals[d] (40)	Local
		Private	AngloAmer (32)	Local/U.K.
		Private	Gencor (7)	Local
		Private	Lavino[e] (10)	Us.
	Associated Manganese Mines of S.A.	Private	Assoc Ore & Metal[f] (38)	Local
			U.S. Steel (20)	Us.
			Fox Street (34)	U.K.

[a] With approximate percentage of control, if available.

[b] Cia. Vale do Rio Doce, which also controls the emerging production at Carajas in Brazil.

[c] There are six finance houses (the ', Groups'') which dominate the South African industry: The Anglo American Corp of S.A Ltd (AngloAmer); Gold Fields Of S.A Ltd , General Mining Union Corp Ltd (Gencor); Rand Mines/Barlow Rand; Johannesburg Consolidated Investment Co Ltd (JCI); and AngloTransvaal Consolidated Investment Co Ltd. (AngloTC)

[d] Owned by Iscor, a state-owned integrated steel firm, (49 75%) and Gencor (5025°/0)

[e] Wholly owned by International Minerals and Chemical (U.S).

[f] Owned by AngloTC and AngloAmer.

SOURCES E&MJ *1983 International Directory of Mining*, Bureau of Mines, *Mineral Commodity Profile 1983: Manganese;* Off Ice of Technology Assessment

thirds of the manganese ores traded on the free market are sold by contracts (generally of 1 year's duration) between producer and industrial user. Other forms of trade include captive sales within integrated firms (e. g., between Gabon and U.S. Steel) and spot market purchases when excess supplies are available.

World trade in manganese is now undergoing a shift from basic ores to the higher processed manganese ferroalloys. This new ferroalloy production capacity competes primarily with plants close to steelmaking centers in the United States, Western Europe, and Japan. As table 5-26 shows, however, not only the ore-producing countries have increased production of ferroalloys. Some other countries have increased or added local production to meet the domestic and export markets steel industry demand. While the major manganese ferroalloy producing countries in 1980 were the Soviet Union (23 percent of world's total), Japan (14 percent), South Africa (9 percent), and France (8 percent), the exporting countries were principally South Africa, France, and Norway. More recently, Brazil has increased its exports because its ferromanganese production capacity is far in excess of its domestic steel demand. South Africa remains the world's leading supplier of manganese ferroalloys, and Western Europe and the United States are the major importers. In 1982 the United States received 50 percent of its manganese ferroalloys from South Africa and 21 percent from France.

All of the major ore producers, with the exception of Comilog in Gabon, have the capability to produce manganese ferroalloys. Trade in manganese ferroalloys may not be replacing trade in ores as rapidly as ferrochromium is replacing chromite. Gabon is at the discussion stage regarding ferroalloy production, but any actual projects will depend on development of an energy source, Australia is restrained from increasing its ferroalloy capability by the lack of low-cost energy. Only in

Table 5-26.—Ferromanganese and Silicomanganese Production by Country (thousand short tonnes, gross weight)

Country[a]	1974	Percent of total	1980	Percent of total	Percent change 1974-80
Argentina	34	0.5	39	0.5	15
AUSTRALIA	69	1.1	124	1.7	80
Belgium	108	1.7	94	1.3	–13
BRAZIL	124	2.0	303	4.0	144
Canada	100	1.6	95	1.3	– 5
CHILE	12	0.2	6	0.1	–50
CHINA	NA		390	5.2	
France	587	9.4	551	7.3	– 6
Great Britain	91	1.5	57	0.8	–37
INDIA	163	2.6	193	2.6	18
ITALY	133	2.1	141	1.9	6
JAPAN	1,182	19.0	969	12.9	–18
North Korea	0		77	1.0	
SOUTH KOREA	0		60	0.8	
MEXICO	70	1.1	172	2.3	146
Norway	577	9.3	496	6.6	–14
Peru	0		1	0.0	
Poland	138	2.2	183	2.4	33
SOUTH AFRICA	400	6.4	650	8.6	63
Spain	211	3.4	239	3.2	13
SOVIET UNION	1,075	17.3	1,644	21.8	53
United States	740	11.9	377	5.0	–49
Venezuela	0		4	0.1	
West Germany	353	5.7	248	3.3	–30
YUGOSLAVIA	44	0.7	73	1.0	66
Zimbabwe	0		3	0.0	
Other[c]	13	0.2	334	4.4	2,469
Total	6,224	100.0	7,523	100.0	16

[a] Upper case indicates country was ore producer in both years, but did nOt necessarily cover its needs.
[b] Produced ore in 1974 only.
[c] In 1974 includes Thailand and Sweden; In 1980 includes BuLGARIA, Czechoslovakia, East Germany, and Portugal All Were ferroalloy producers in 1974 but amount of manganese ferroalloys unknown; thus, total shown for 1974 production is not accurate

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook.* 1976 and 1981

Tasmania, south of the Australian mainland, where hydropower is available, is it economic to produce ferroalloys. However, ore must be shipped approximately 3,000 miles from the north coast of Australia by sea, reducing some of the cost advantage of integrated ore and ferroalloy production. New manganese ferroalloy production is being added in Brazil and India. During recessionary periods this production appears on the export market instead of being consumed in domestic steel industries.

As indicated by table 5-27, there have been shifts over the last 20 years in the relative output of ore producer countries. Most notably, world production has been increasingly concentrated in the eight producer countries listed. From 79 percent in 1960, they now supply 97 percent of the world's total ore needs. The most recent producer to enter the world market was Australia's Groote Eylandt in 1966. There is one new manganese mining project now under development; Carajas in Brazil may add export production by 1986.

Between now and 2000, virtually all of the growth in total world output of manganese ore will come from the expansion of existing mines rather than the opening of new mines. A decrease or cessation of production from one source would force expansion of production from the remaining suppliers, Current world mining capacity is substantially greater than demand, as shown in table 5-28. In 1981 only 73 percent of existing capacity was used, That unused capacity was 1½ times South Africa's total output. Under such conditions, rapid expansion of production from existing mines is quite feasible. In times of tighter markets, there is potential for expansion of current mine ca-

Table 5-27.—Historical Manganese Ore Production, 1960-80, by Country
(thousand short tons, gross weight)’
(percent of world total)

	1960		1965		1970		1975		1980	
Producer country	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent	Tons	Percent
Australia	68	<1	112	1	828	4	1,714	6	2,226	8
Brazil	1,101	7	1,539	8	2,071	10	2,376	9	2,515	9
China	1,323	9	1,102	6	1,100	5	1,100	4	1,750	6
Gabon	0	0	1,411	7	1,602	8	2,444	9	2,366	8
India	1,321	9	1,815	9	1,820	9	1,688	6	1,814	6
Mexico	171	1	144	1	302	2	473	2	493	2
South Africa	1,316	9	1,738	9	2,954	15	6,359	23	6,278	22
Soviet Union	6,473	43	8,351	43	7,541	38	9,324	34	10,750	37
Subtotal	11,773	79	16,212	83	18,218	91	25,478	94	28,192	97
Other	3,216	21	3,345	17	1,866	9	1,598	6	869	3
Total	14,989	100	19,557	100	20,084	100	27,076	100	29,061	100

[a] Ores vary widely in contained manganese, see table 22

SOURCE U S Department of the Interior, Bureau of Mines, *Minerals Yearbooks,* 1961, 1966, 1971, and 1981

Table 5-28.—Manganese Mine Capacity and Usage in 1981, by Country
(thousand short tons, contained manganese)

Producer country	Estimated annual capacity	Percent in use	Estimated unused capacity
Australia	1,300	580/o	550
Brazil	1,350	76	320
China	550	96	22
Gabon	1,300	64	470
India	800	72	225
Mexico	300	81	60
South Africa	3,000	72	840
Soviet Union	3,800	80	760
Other	485	63	178
Total	12,885	73	3,610

SOURCE US Department of the Interior, Bureau of Mines, *Minerals Commodity Profile 1983 Manganese*

pacity, especially in South Africa, Gabon, and Australia. Given a year or more extra lead time, Brazil and Mexico could increase their production, as well.

Caracas in Brazil and a site at Tambao in Upper Volta are the only deposits of manganese ore that might alter future supply patterns. The Tambao deposit suffers from its location, far from existing transportation facilities. Activity there was halted at the end of the exploration phase. Although the Carajas project is proceeding, obtaining capital for development of such deposits is difficult because they must produce ore for markets that are already filled by suppliers with large reserves. Thus, the current ore producer countries will be the major producers of the future. Among these, the major exporters are expected to be South Africa, Gabon, and Australia, all of which have substantial resources in relationship to their own domestic needs.

In contrast, India’s ore production is increasingly tied to its expanding domestic steel production. India is also limited in the export market by the low grade of its manganese deposits and the inefficiency of its overall operations. Brazil’s future as a major supplier to the export market is uncertain, Facing the depletion of its most productive deposit in the 1990s, Brazil has instituted a policy of reserving much of its ore, including 50 percent of Carajas’ future production, for ferroalloy production and the domestic steel industry. If the Carajas deposit reaches its planned output of 1 million tons of ore per year and is the sole source of exports, this policy will result in an export level of about 50 percent less than current exports from Brazilian manganese mines.

The Soviet Union was once a major supplier of manganese ore to world markets, but since the 1970s, it has concentrated on trade within the Eastern bloc. Historically, this provided for self-sufficiency among this group. In the 1980s, however, some Eastern bloc countries (e.g., Romania, Czechoslovakia, and Poland) have begun satisfying a portion of their ore needs by importing from the same sources as the market economy countries. The Soviet Union negotiated with Gabon for supplies of ore in 1984 and has purchased from Gabon, India, and Australia in the recent past. The assumption in the West is that, since the ore production tonnages being reported from the Soviet Union are not declining, they are experiencing a depletion of higher grade material. China produces for internal consumption, and this policy is expected to continue as the country's domestic needs increase.

Following is a brief description of the operations of the producer countries of interest, with discussion of major factors that may affect future development and production of ore and ferroalloys.

Australia

Groote Eylandt Mining Co., a wholly owned subsidiary of the Broken Hill Proprietary Co, (BHP)—Australia's sole integrated steelmaker—produces from open pit mines located on an island 50 kilometers off the coast of the Northern Territory. Beneficiated ore is hauled 16 kilometers to Milner Bay for ocean shipping. Capacity has recently been increased to 2.6 million tons per year with the installation of a plant to upgrade ore fines (which were previously discarded). Further expansion plans to increase capacity to 3 million tons per year have been delayed because of unfavorable market conditions.

Barriers to expansion are the concentration plants and loading facilities at Milner Bay. Company officials have stated that, given an emergency, significant expansion in these areas would take an estimated 3 years to complete. With government financial assistance and guarantees of long-term markets, facilities could be in place in 2 years. Australia is currently heavily reliant on Japan as an export customer because of high shipping costs to other major consumers. Its one manganese ferroalloy plant is located in Tasmania and was originally constructed to supply BHP steelmaking needs. Recent expansion, however, has been based on the export market.

Brazil

There are two principal ore-producing areas in Brazil, one in the Federal Territory of Amapa and the other in the Matto Grosso state. The existing mines' location, remaining life, or ore quality limit their attractiveness. The Amapa deposits, owned by ICOMI, are located in northern Brazil, produce half of Brazil's output, and are operated mainly for exports because of the high cost of transporting the ores to the steelmaking center in southern Brazil. The steel plants are supported by the Matto Grosso operations of Urucum Mineraco S. A., and a small operation in Minas Gerais. ICOMI's reserves are expected to be depleted by the 1990s. Production by Urucum (about 100,000 tons of manganese ore in *1980)* is hampered by the quality (high alkali content) of the ores and accessibility of the deposits, which lie 2,000 kilometers from the nearest port. Future increases in production at Urucum could come from an underground deposit if manganese prices were to double.

The Grande Carajas Development Project, some 900 kilometers from the Atlantic coast in the state of Para, is a mineral development that includes iron ore, manganese, copper, nickel, gold, tin, and bauxite. The project is financed by national and international loans. Participants have included the EEC, Japan, West Germany, and the World Bank.

Three manganese deposits have been identified: Azul, Buritirama, and Serene. Development of the Azul deposits (with reportedly 16 million to 24 million tons of manganese)[83] is the second phase of the project. The initial phase has included the preparation of iron ore mines, along with the construction of the necessary infrastructure. A railroad to Sao Luiz on the coast and new ocean port facilities at Ponta da Madeira are expected to be completed in 1986, when manganese production of metallurgical grade ores will begin,

The deposit is currently being exploited for battery-grade ores which, because of their high value (grades up to 75 percent MnO_2), can be economically transported by truck to the coast for shipment, The metallurgical ores will be hauled from an open pit mine 20 kilometers to the railhead at the iron ore mine area. Processing will consist of washing and crushing, using existing facilities originally constructed as a pilot plant for the iron ores, It is expected that the output from the manganese mine will eventually total 1 million tonnes (900,000 tons) of about 48 percent manganese ores per year. With additional beneficiation equipment, the deposit could support up to 2 million tonnes per year.[84] This extension of facilities, however, must await favorable market conditions, An onsite ferroalloy plant was included in the original concept but lack of financing has shelved these plans.

U.S. Steel was involved in the discovery of the Carajas deposit, but its interest was bought out by CVRD in 1976. Utah International (previously owned by General Electric but in April 1984 transferred to Broken Hill Proprietary of Australia) holds the rights to the development of the Buritirama manganese deposits at Carajas; however, there are no development plans being considered for the near future.[85] The Sereno deposits are currently unexploited. Together, these deposits have considerably less identified reserves and resources than does Azul.

Brazil has five firms involved in producing various types of manganese ferroalloys for both domestic and export purposes.

Gabon

Market conditions now hold output from Gabon's Moanda mines well below the 1979 peak of 2,5 million tons. These mines are capable of supporting up to 4 million tons per year but shipments are limited to 3 million tons per year via the available transportation system.[86] This involves the use of a 76-kilometer aerial ropeway connection to the Congo's rail system, followed by a 560-kilometer rail trip to the port of Pointe Noire. An alternate route, the Trans-Gabon railway, has been under construction since 1974. Completion to the mine site near Franceville (500 more km) plus upgrading of the timber port at Owendo, Gabon, would make possible the shipping of the maximum of 4 million tons per year from Moanda, although current market conditions would not make increased shipments economically feasible, Development of ferromanganese facilities are under discussion, but no firm plans have yet been made.

Mexico

The Molango district deposits in Mexico are mined by the Cia. Minera Autlan S.A. de C.V. and represent significant reserves and resources which could support a substantial increase in production if the market and investment funds were available.[87] The deposits consist of two types, carbonates and oxides. The carbonate ores represent the bulk of the minerals present, and Autlan has reported measured reserves of 28.4 million tons of carbonate ore at 27.5 percent manganese (from a total estimated resource of 1.5 billion tons at 25 percent).

---

[83] Louis Fuchs of the CVRD office in New York, personal communication, December 1983. Total reserves were placed at 65 million tonnes of ore at about 48 percent manganese. Of this amount, 10 million tonnes consists of battery grade material at 74 to 75 percent MnO_2. The National Materials Advisory Board, in *Manganese Reserves and Resources of the World and Their Industrial Implications, 1981,* reported a crude ore resource of 65 million tonnes that would wash 44 million tonnes of product grading 46.5 percent manganese. Thomas Jones, commodity specialist at the Bureau of Mines, reports 45 million tonnes of ore at 40 percent manganese.

[84] Louis Fuchs, op. cit.

[85] Jean Goity, Public Relations, Utah International, San Francisco, personal communication, February 1984.

[86] Robert L'esperance, U.S. Steel Corp., Pittsburgh, PA, Personal communication, August 1983.

[87] NMAB 81, p. 39.

After mining and beneficiation, these carbonate ores are converted to nodules of manganese oxide (39 to 40 percent manganese) in a rotary kiln near the mines, One of the difficulties that Autlan manages to overcome is the rugged terrain of the Sierra Madre Oriental in which their mines (open pit and underground) are located. In these precipitous and densely vegetated mountains, elevations vary from 200 to 2,600 meters above sea level. The export ores (50 percent of Autlan's production) must be hauled 260 kilometers to Autlan's maritime terminal at Tampico on the Gulf Coast for shipment.

The quality of Autlan's ores has been questioned because of their high silica content and relatively low grades. The general commercial standard for ores used in ferroalloy production is 48 percent manganese. Although Autlan produces ferromanganese with its 40 percent ores, its customers blend the ores with higher grade ores in order to produce 78 percent ferromanganese, the U.S. industry standard for a high-carbon product. The high silica content makes the ores most suitable for the production of silicomanganese.

Several projects are currently being studied by Autlan to enable them to expand their production. Among them are the opening of a new open pit mine at Noapa, the installation of a second rotary kiln, and a new water supply system. Physically, the resources could support a doubling of production, but manganese prices and demand in the 1980s will not support such a change in policy. The Trade and Development Program in the U.S. International Development Cooperation Agency has been active in studying the manganese deposits in Mexico and in attempting to interest U.S. investors in joint ventures with Autlan to expand its production.[88]

South Africa

Associated Manganese and Samancor each own mines in both the Postmasburg and Kuruman (Kalahari) districts. The capacity of these mines has been estimated to be greater than 9 million tons of ore per year. Even at current operating rates, the reserves are sufficient to last hundreds of years, and South African production is capable of rapid expansion. Transportation, however, could be a limiting factor because ores must be shipped south from both mining districts by rail to either Port Elizabeth (950 km directly south) or to Saldanha Bay, north of Capetown (800 km southwest).

South Africa has four firms engaged in producing various manganese ferroalloys, plus two producing manganese metal. Ferroalloy production is integrated within mine producing firms, either directly or through "group" investment houses.

Potential Source

At Tambao, Upper Volta, a remote area 350 kilometers from a railhead, some 13 million tonnes (12 million tons) of 52 percent oxide ores have been identified. Extensive exploration work was done and feasibility studies were completed during the late 1970s while the project was being considered by a consortium consisting of a number of international firms including Union Carbide, The group subsequently fell apart owing to the divergent goals and conflicting interests of its members." It would take about 5 years to bring the area into production and provide the infrastructure needed to export the ores (the construction of a railroad and a port). Since Upper Volta is a landlocked country, arrangements would have to be made with the Ivory Coast for rail transiting and the development of port facilities.

Domestic Production of Manganese

Domestic manganese has made some contributions to U.S. needs, especially in wartime. During the latter part of the 19th century, the United States produced sufficient manganese from domestic deposits to meet its needs. With the growth of the U.S. steel industry since 1900,

---

[88] See U.S. International Development Cooperation Agency, Trade and Development Program, *The Molango Area (Mexico) Manganese Deposits of Compania Minera Autlan—The Largest Known Manganese Ore Reserve in North America,* June 1983.

[89] Benjamin Brittain, Union Carbide Corp., persona] communication, August 1983.

however, domestic manganese production has not been able to keep up with demand, Despite a variety of government incentive programs, domestic production was only 23 percent of consumption during World War I, 13 percent during World War II, and 8 percent during the Korean war. In 1944, manganese ores were produced in more than 20 States, but Montana, Nevada, New Mexico, Arizona, and Arkansas have provided the bulk of the historical production.

Today, aside from minor amounts, the prospects for production of manganese from U.S. deposits is highly unlikely except during a sustained cutoff of imported ores. And, unless world prices rose considerably during such a period, Federal Government production incentives would be required.

There has been no manganese *ore* (table 5-29) produced in the United States since 1970.[90] The last year of production of *ferruginous manganese* ores was 1981 and totaled 22,165 tons of contained manganese from Cuyuna North Range in Minnesota (20,712 tons) and from New Mexico (1,453 tons). The only domestic production in 1984 is of *maganiferous iron ores* from South Carolina which are used in pigments (total production in 1982 of this ore type contained 1,325 tons of manganese). Iron ores consumed in the United States in 1982 provided approximately one-third of the manganese used in domestic steelmaking. Since 30 percent of those iron ores were imported (mainly from Canada), domestic sources can be credited with 23 percent of that input.[91]

Table 5-29.—Definition of Manganese-Bearing Ores

Type	Description
Manganese ore	Ores containing more than 35 percent Mn
Ferruginous manganese ore	Ores containing from 10 to 35 percent Mn
Manganiferous iron ore	Ores containing from 5 to 10 percent Mn

SOURCE Use *of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese As An Alloying Element in Steels,* OTA contract report, 1983

Eight U.S. deposits of manganese were considered in a Bureau of Mines Minerals Availability System Appraisal[92] in 1982 and were termed "submarginally subeconomic." The report concluded that incentive prices ranging from $8 to almost $35 per long ton unit[93] of contained manganese would be required in order to encourage production from these deposits, as compared with the market value at that time of $1,70 per long ton unit.[94] Annual production from these sources would peak at 900,000 tonnes (818,000 tons) of recoverable manganese 6 years after simultaneous development began, declining thereafter (to 578,000 tons per year within 10 years, for instance) unless additional resources were located and/or technological improvements were made in mining or processing of the ores.[95] (U.S. apparent consumption of manganese was 1.25 million tons in 1979 and 672,000 tons in 1982.)

The more significant deposits among the identified domestic manganese resources are those of the Artillery Mountains, Arizona; Batesville, Arkansas; San Juan Mountains, Colorado; Aroostook County, Maine; and the Cuyuna Range in Montana. Collectively this group is estimated to contain over 70 million tons of manganese.[96] The average grade of manganese in U.S. deposits is generally less than 10 percent which compares unfavorably with the major world producers who extract manganese from deposits with grades of from 27 to 53 percent.

The National Materials Advisory Board in 1976 concluded that:

> The U.S. land-based manganese resources of significant size are very low in grade and should not be developed except in a dire emergency.[97]

---

[90] Thomas Jones, Jr., U.S. Department of the Interior, Bureau of Mines, *Mineral Commodities Profiles 1983: Manganese,* p. 10.

[91] See the discussion on manganese and steelmaking in ch. 6.

[92] Catherine C. Kilgore and Paul R. Thomas, U.S. Department of the interior, Bureau of Mines, *Manganese Availability—Domestic, A Minerals Availability System Appraisal,* Information Circular/1982 No. 8889.

[93] A long ton unit is 22.4 pounds of manganese and is the standard unit for quoting manganese ore prices.

[94] Another study has calculated a cost estimate for U.S. production at four times that of South African producers in 1980 dollars. See Processing *Capacity* for *Critical* Materials, op. cit.

[95] Kilgore, et al., op. Cit., p. 1.

[96] U.S, Bureau of Mines, *Mineral Commodity Profile 1983: Manganese,* p. 7.

[97] National Materials Advisory Board, *Manganese Recovery Technology,* NMAB-323 (Washington, DC: National Academy of Sciences, 1976), p. 1.

The NMAB study stated that, while there were no known deposits in the United States of manganese ores that could be exploited at current or even substantially higher prices, the best suited deposits for development in an emergency on a significant scale were those of the Cuyuna Range and in Aroostock County.[98] The Bureau of Mines' appraisal results concur. In its estimates of mining capacity, as summarized in table 5-30, these deposits could contribute the highest levels of production and be able to operate from 14 to 61 years.

In analyzing the impact of different variables (e.g., beneficiation and transportation costs, byproduct prices, State severance taxes), the Bureau of Mines determined that technologic improvements leading to a reduction in the cost of beneficiation methods would be the single most significant factor for improving the economic status of these deposits. Substantial increases in byproduct prices, for instance, would be necessary to significantly decrease the incentive price needed for domestic manganese. A 9-percent increase in iron ore prices would produce a 4-percent decrease in the manganese incentive price at Cuyuna Range, for instance. (Iron is also a byproduct of the Aroostoock area; silver at Hardsell in Arizona; and silver, lead, and zinc at Montana's Butte District.)[99]

Domestic Mining and Processing Technology Prospects

Manganese deposits in the United States are in a variety of environments ranging from rela-

Table 5-30. U.S. Manganese Resources and Potential Production

	Demonstrated resource			Estimated annual mine capacity		
Property name by State	Manganese grade (percent)	Ore (thousand tonnes)	Contained manganese (thousand tonnes)	Ore (thousand tonnes)	Contained manganese (thousand tonnes)	Estimated minelife (years)
Arizona:						
Hardshell Mine.	15.0	5,896	804	536	73	11
Maggie Mine (Artillery Peak)	8.8	8,441	671	328	26	26
Colorado:						
Sunnyside Mine	10.0	24,909	2,264	635	58	39
Maine—Aroostock County:						
Maple Mtn/Hovey Mtn . . .	8.9	260,000	20,965	4,263	344	61
North District	9.5	63,100	5,472	2,620	227	24
Minnesota:						
Cuyuna North Range (SW portion)	7.8	48,960	3,490	3,570	254	14
Montana:						
Butte District (Emma Mine).	18.0	1,232	202	400	65	3
Nevada:						
Three Kids Mine	13.2	7,230	868	1,050	126	7
Total		419,768	34,737	13,401	1,174	

SOURCES: Resources, ore grades, proposed ore mining capacity from U.S. Department of the Interior, Bureau of Mines, Manganese *Availability—Domestic*, IC8889/1982. Balance, calculated by OTA using that data

Apparent U.S. Manganese Consumption

Tons	Contained metal
1979 . . . .,. .	1,250,000
1982	672,000

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity* Summaries, 1984, p. 98.

---

[98] NMAB-323, p. 14 and p. 1.

[99] Kilgore, et al., op. cit., pp. 9-10.

tively soft deposits to steeply dipping veins in hard rock. Thus, standard mining methods would include both underground and open pit operations.

Solution mining of manganese ore has been proposed. Two variations are possible. In one the ore is mined, spread on the surface, and a solvent is applied. This "heap leaching" process produces a solution of manganese which can be collected. In another process, "in situ leaching, " a hard-rock ore body is blasted to induce permeability and the solvent is pumped into the fractured ore body, The leached solution is then pumped out of the mine, These solution mining techniques for manganese[100] were under evaluation by the Bureau of Mines for 2 years but the project was eliminated from the fiscal year 1984 budget, Preliminary economic analysis indicated that leached manganese could compete favorably with foreign manganese ores for chemical (battery) industry markets but not for the ferromanganese industry.[101] Conventionally mined metallurgical ores bound for ferromanganese production require little processing after mining; solution mined ores are uncompetitive. Another conclusion of the study was that solution mining applied to domestic manganese-silver ore bodies would permit the separation of these minerals not possible by other techniques. The private sector has expressed some interest in the process in order to obtain the silver values. Manganese could be a byproduct of any such operation. A pilot plant is apparently in operation in the Artillery Peak area of Arizona, funded by major mining companies, to test a heap leaching process on manganese ores,

Most of the U.S. manganese resources are not amenable to normal beneficiation methods of gravity and flotation alone owing to their low grades. Chemical and roasting processes (e.g., the ammonium carbamate leach and sulfur dioxide roast processes) have been developed for beneficiating domestic manganese. These processes have so far proved to be too costly for extended use. Grinding and fine-particle concentration processes might improve the economics.[102] A study to identify the three most promising processes for recovering manganese from low-grade domestic sources was underway by the Bureau of Mines in 1984.

Domestic and Foreign Manganese Processing

Manganese is used as a processing and alloying agent of steel and an alloying agent in nonferrous materials. Although manganese is used to some extent in the mineral form in which it occurs in the ore, for the most part it is useful only after several processing steps convert it to a metal or metal alloy. Steelmaking requires manganese ferroalloys with high-, medium-, or low-carbon content, and silicomanganese. Aluminum alloys are made with additions of pure metallic manganese. The compositions of these materials are shown in table 5-31. Figure 5-5 is a simplified flowchart for the production of these alloys showing the close relationship that exists between the processes for the various forms of ferroalloys.

The U.S. steelmaking industry has a standard of 78 percent manganese content for high-carbon ferromanganese, and this product is traditionally made from 48 percent manganese ores, It is technically possible to produce steel from a lower grade ferromanganese, and internationally this standard is not as rigorously applied. This is a possible area wherein diversity of supply of manganese could be broadened by turning to lower grade deposits such as those in Mexico if the need should arise.

Manganese Ferroalloys[103]

The major manganese commodity is high-carbon ferromanganese, used in the production of steel. It is now commonly produced in sub-

---

[100] See various Bureau of Mines papers including " Arizona's Artillery Peak Manganese Deposits and Their Potential for In Situ Leaching" (1981) by Peter G. Chamberlain; "Recovery of Silver From Manganese Ores" (1984) and "Recent Research on Leaching Manganese" (1983) by Peter G. Chamberlain, John E. Pahlman, and Charles A. Rhoades.

[101] U.S. Department of the Interior, Bureau of Mines, *Research 83*, op. cit., p. 5. Also National Materials Advisory Board, *A Review of the Minerals and Materials Research Programs of the Bureau of Mines*, *op.* cit., 1984.

[102] Silverman, et al., op. cit., p. 159.

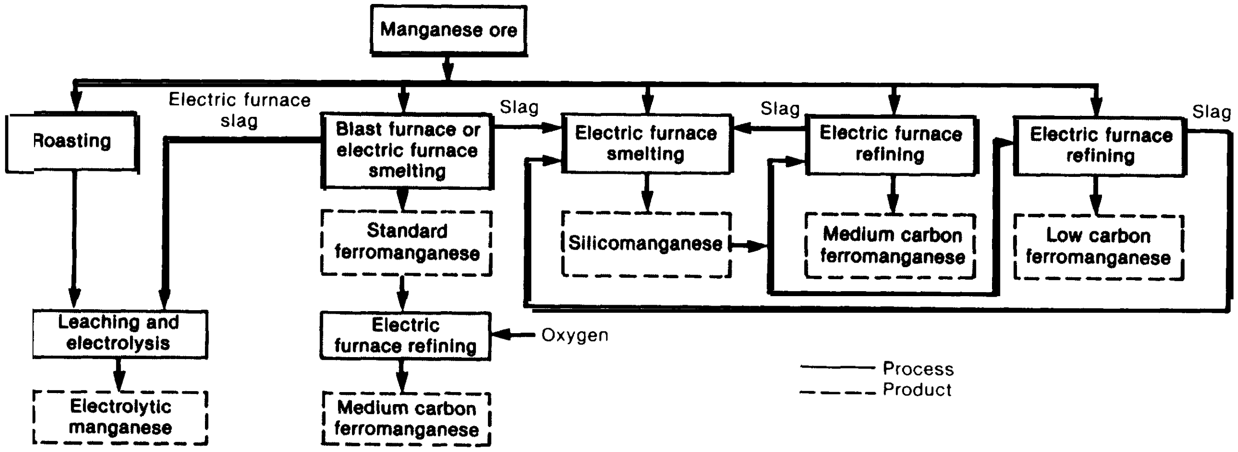
[103] This discussion of manganese ferroalloy processes is taken primarily from Charles River Associates, op. cit.

Table 5-31.—Composition of Manganese Alloys

	Manganese	Carbon	Silicon
Ferromanganese:			
High carbon	74-82	7.5	1.2
Medium carbon	80-85	1.5	1.2
Low carbon	80-90	0.7-0.75	1.2
Silicomanganese	65-68	1.5-3.0	12.5-21
Ferromanganese-silicon	63-66	.08	28-32
Manganese metal	99.5	.005	.001

SOURCE: U S Department of the Inter! or, Bureau of Mines, *Minerals Commodity* Profile *1983:* Manganese,

Figure 5-5.—Simplified Flowchart, Manganese Ore to Industry Use



SOURCE: Charles River Associates, *Processing Capacity for Critical Materials,* OTA contract study, January 1984,

merged arc electric furnaces, similar to those used for ferrochromium, rather than the original blast furnace method. (See the previous chromium processing section for a general discussion on ferroalloy production in submerged arc furnaces, the degree of convertibility between ferrochromium and ferromanganese furnaces, and the applicability of new technology to ferroalloy production.)

In the United States the blast furnace has been entirely supplanted by the electric furnace for the production of ferromanganese. The last ferromanganese blast furnace was shut down in 1969 by Bethlehem Steel after being damaged by the Johnstown, PA, flood. Limited blast furnace capacity still exists in Western Europe and South Africa, but all new furnace capacity worldwide is of the electric type.

Pig iron blast furnaces can be considered as alternative capacity for ferromanganese production. As the ferromanganese blast furnaces were generally adapted from old pig-iron furnaces, they are smaller than current pig-iron furnaces, and the hot blast temperatures are lower (about *1,0000* to *2,0000* F) than for modern iron furnaces. The main disadvantage of using the blast furnace for the production of ferromanganese is that the coke requirement is almost twice that for the electric furnace, since coke must be used both as a reducing agent and to supply the thermal energy for the reaction. Both furnace types require a blend of manganese ores and dolomite or limestone as a fluxing agent. Existing small, pig-iron blast furnaces could readily be converted to produce ferromanganese at minimal capital cost. Operating costs would be higher than for electric furnaces.

Silicomanganese is produced in an electric furnace similar to that used for ferromanganese production. The manganese content in the slag from a standard ferromanganese furnace operation normally ranges from 30 to 40 percent and is used as feed for the production of silicomanganese. Efficient production requires that both standard ferromanganese and silicomanganese furnaces be located in the same plant.

The silicomanganese furnace has a smaller crucible with smaller electrode diameter and closer electrode spacing than does a standard ferromanganese furnace. If a furnace designed for ferromanganese production has the capacity in its environmental control (gas-cleaning) system, it can be operated at higher power levels (to compensate for the charge property difference) to produce silicomanganese.

Medium- and low-carbon ferromanganese is produced by refining various high-carbon ferromanganese products in open arc furnaces. These furnaces are different from submerged arc furnaces in that the electrodes are not suspended deep within the charge.

Manganese Metal

Metallic manganese is commonly produced by an electrolytic process from an acidic solution of manganese ore. South Africa, Japan, and the United States are manganese metal producers.

Processing Distribution and Capacity

The worldwide distribution of processing capacity for ferromanganese, silicomanganese, and manganese metal is shown in table 5-32. Although having dramatically declined in capacity in the last decade, the United States still has the capability to produce all types of manganese ferroalloys and electrolytic manganese metal. Table 5-33 shows the growth of imports over the last decade that have eroded the U.S. industry, ferroalloys having made the greatest inroads.

Of the six firms in the United States still credited with the capacity to produce manganese ferroalloys (out of 10 in 1979), three have shut down their plants, and the others are operating at very low rates. A contributing factor to this demise—other than import penetration—was the steel industry depression during the early 1980s. Elkem Metals plant at Marietta, OH, for instance, in early 1984 had only 3 furnaces of an original 14 in operation; by mid-

Table 5-32.—Manganese Ferroalloys and Metal Production Capacity—1979
(tonnes, gross weight)

	Ferromanganese				
Country	High carbon	Medium carbon	Low carbon	Silico-manganese	Manganese metal
Argentina	40,000			2,000	
Australia	135,000				
Belgium	150,000	30,000		50,000	
Brazil	117,000	61,000	600	61,600	
Canada	90,000			50,000	
Chile	5,000			1,000	
France	580,000	50,000		60,000	
West Germany	298,000	35,000			
India	229,000	3,000		13,000	
Italy	130,000	15,000	5,000	4,000	
Japan	700,800	205,820		535,200	6,000
Mexico	135,000				
Norway	370,000	50,000	5,000	220,000	
Peru	3,600				
Portugal	150,000				
South Africa	493,000	10,000		122,000	35,000
Spain	60,000	35,000	10,000	45,000	
Taiwan	4,200			3,000	
Great Britain	80,000		300		
United States	453,000	36,000		125,000	11,000+
Yugoslavia	40,000			5.000	
Total	4,263,900	530,820	20.900	1,296.800	52,000

SOURCE Charles River Associates Processing *Capacity for Critical Materials*, OTA contract report, January 1984

Table 5-33.--Managanese Ferroalloys and Metal: U.S. Imports and Consumption (gross weight, short tons)

	Ferroalloys	Metal
1970:		
Imports	290,946	NA
Consumption	1,000,611	NA
Imports as percent of consumption	29	–
1974:		
Imports[a]	421,222	2,506
Consumption	1,115,395	34,748
Imports as percent of consumption	38	7
1980:		
Imports[b]	605,703	7,508
Consumption	789,076	25,092
Imports as percent of consumption	77	30

[a] Metal imports include unwrought metal, waste and scrap.
[b] Metals imports is unwrought metal only; waste and scrap total 407 tons

SOURCE: U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook,* vol. 1, 1970, 1974, and 19S0

1984 the picture was somewhat brighter owing to the steel industry revival. (Of the 14 furnaces some have been permanently decommissioned.) Elkem was awarded a contract by the General Services Administration (GSA) in the spring of 1984 to convert 48,476 tons of manganese ore in the national defense stockpile into ferromanganese.[104] This GSA plan to upgrade stockpiled ores was developed in late 1982 by the Reagan Administration to give financial relief to the domestic ferroalloy industry. The contract amount will, however, only provide about 6 months work for one Elkem furnace. (See the chromium processing section for details on a similar chromite conversion contract.)

Manganese metal, sufficient to cover domestic needs, can be produced in the United States, although the feedstock is imported manganese ores. In 1982 domestic production of manganese metal (18,600 tons) was greater than the consumption rate (17,100 tons),[105] while an additional 30 percent was imported. Due to general economic conditions, in 1983 two metal producing firms were operating at reduced levels of production and the third had shut down its facilities.

---

[104] "Macalloy Sets Reorganization," *American Metal Market,* Jan. 5, 1984, p. 1.

[105] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982,* vol. 1, pp. 579-580.

Platinum Group Metals Production and Processing

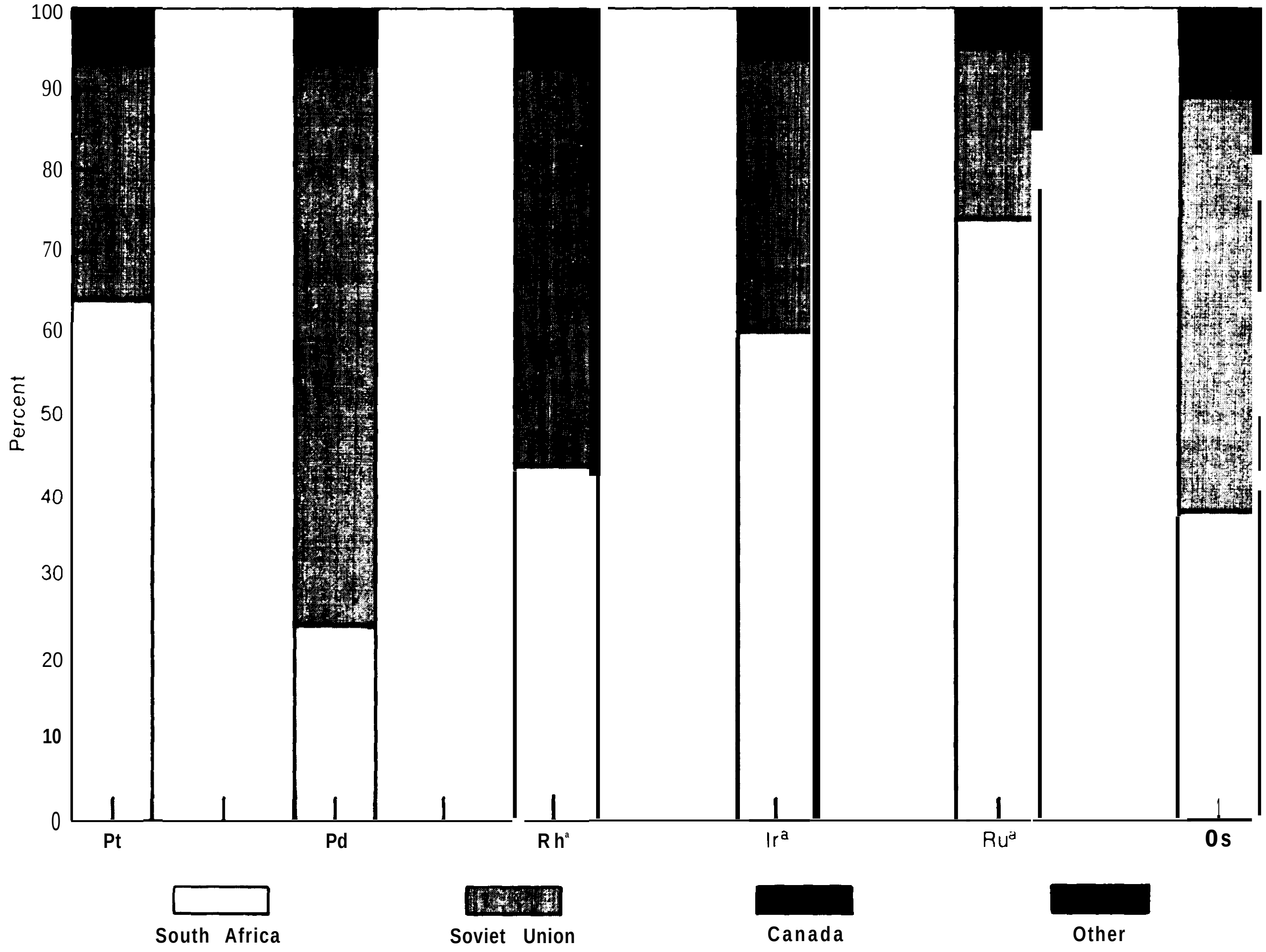
PGMs have always come from few locations. Colombian placer deposits were the original and only suppliers of PGMs until 1824, when Russian placer deposits were discovered. Production from Canadian nickel mines followed in 1919, and South African deposits were discovered in 1924. South Africa, the Soviet Union, and Canada are today the world's suppliers of these metals (see fig. 5-6).

The major deposits of this group of metals have been found in layered formations of igneous rocks among chromite, nickel, and copper, Only in South Africa and, it has been estimated, the United States (Stillwater, MT) can such vein deposits be mined primarily for their PGM content. Canada produces PGMs as a byproduct of nickel and copper production; the Soviet Union's production may be a coproduct rather than a byproduct. Chemical and physical weathering can separate platinum minerals from these primary ores, creating placer deposits in high enough concentrations to provide minable ore grades. Such a PGM deposit exists in Goodnews Bay, AK, but it has not been in production since 1975.

Each PGM deposit produces platinum and palladium and some of the other four metals (rhodium, ruthenium, iridium, and osmium) of the group. Among the similar sulfide deposits in the three producer countries, there are differences in the proportion of PGMs that each contributes to the market, as shown in table 5-34. Platinum and palladium are considered the most important metals of the group owing to their predominance and end uses in industry. While Canada produces roughly an equal

Figure 5-6.–Comparative PGM Production, 1981

By metal and country



[a]Less than 1 percent produced by other sources

SOURCE: Bureau of Mines, *Minerals Commodity Profile 1983: Platinum-Group Metals*, figures 1 through 6.

amount of platinum and palladium, the Soviet Union's output is principally palladium (67 percent), with platinum secondary (25 percent), In South Africa, platinum accounts for 61 percent of production, and palladium, 26 percent. For all three countries, the balance of output is in small amounts of the minor metals of the group. The proposed Stillwater mine is expected to produce almost 80 percent palladium, 20 percent platinum. Colombia has long been a relatively small producer from placer deposits. Its output is over 90 percent platinum, Very small amounts of the metals are produced by a number of other countries as byproducts from a variety of ores. The United States is included in this group with a contribution from copper mining and refining,

The world now depends on South Africa for two-thirds of its platinum and on the Soviet Union for two-thirds of its palladium. In 1982, 99 percent of the world's primary PGM supply was produced by five private firms and one government firm. Mines in South Africa and the Soviet Union provide 95 percent of the world's needs, while Canadian mines provide another 6 percent (table 5-35). Little change in this pattern is likely in the future. The most

Table 5-34.—Distribution of Platinum Group Metal Production by Metal and Country, 1981 (percentage)

Producer country	Platinum	Palladium	Rhodium	Iridium	Ruthenium	Osmium
Canada	6	6	8	6	5	10
South Africa	64	24	44	60	74	38
Soviet Union	29	69	49	34	21	51
Other	1	1	<1	<1	<1	<1
Total	100	100	100	100	100	100

SOURCE U S Department of the Interior, Bureau of Mines, Minerals Commodity *Profile 1983: Platinum-Group Metals*, figures 1 through 6.

Table 5-35.—Platinum Group Metals: World Reserves and production by Country (thousand troy ounces[a])

Producer country	Reserves 1981	Production 1982	Percent of world production
Australia		14.0	0.22
Canada	9,000	269.8	4.18
Colombia		12.0	0,19
Ethiopia		0.1	
Finland		3.6	0,06
South Africa	970,000	2,600.0	40.28
Soviet Union	200,000	3,500.0	54.23
United States	16,000	8.0	0.12
Yugoslavia		3.5	0.05
Other [b]		43.3	0.67
Total	1,200,000	6,454.3	100.00

[a] There are 1458 troy ounces per pound

[b] "Other production" reflects Japanese refining of ores originating in Australia, Canada, Indonesia, Papua New Guinea, and the Philippines

SOURCE: Reserve base—U S *Department of the* Interior, Bureau of Mines, Mineral Commodity Profile 1983 *Platinum-Group Metals*
Production—U S Department of the Interior, Bureau of Mines, *Minerals Yearbook 1982,* VOI 1

activity underway in investigating new, diversifying sources is in the United States with the effort to initiate mining from the deposits at Stillwater. For possible long-term applicability, the U.S. Geological Survey is conducting research on the platinum content of nickel laterite deposits in countries along the southwestern rim of the Pacific Ocean.

The principal importing nations are the United States and Japan, which together consume about two-thirds of the world's PGM production. Western Europe and the Soviet Union consume most of the remainder. The Soviet Union's position as the important palladium supplier to the West provides it with one of its valuable sources of foreign exchange, although gold sales are more important in this respect,

Foreign Production of Platinum Group Metals

Unlike many other mineral industries today, PGM production, excluding that of the Soviet Union, is entirely within the private sector, Ownership is a complex interconnection of multinational firms, as shown in table 5-36,

Rustenberg Platinum Mines and Impala Platinum Holdings control over 90 percent of South African production, Ownership of both firms is primarily local shareholders, through three investment houses. These "group" houses have connections with British industry that date back to colonial times. They also hold interests in American operations: Johnson Matthey—which jointly owns a South African refinery with Rustenberg (Matthey-Rustenberg

Table 5-36.—PGM Mining Industry by Country

Country	Major firms	Ownership: Sector	Major holders[a]	Primary national identity
Canada	Inco Ltd.	Private	[b]	Canada
	Falconbridge Ltd.	Private	McIntyre Mines[c] (40)	Canada
		Private	Newmont Mines[d] (40)	U.S.
South Africa[e]	Rustenberg Platinum Mines Ltd.	Private	JCI[f] (33)	Local
		Private	AngloAmer (24)	Local/U, K,
		Private	Ludenburg (24)	Local
	Impala Platinum Holdings Ltd.	Private	Gencor (56)	Local
	Western Platinum Ltd.	Private	Lonrho (51)	Local/U. K.
		Private	Falconbridge (25)	Canada/U.S.
		Private	Superior Oil (24)	U.S.
Soviet Union		Government	(100)	
United States[g]	Goodnews Bay	Private	Hansen Properties	Us.
	Stillwater Mining Co.	Private	Johns-Manville	Us.
		Private	Chevron Resources (Chevron USA)	Us.
		Private	Anaconda Minerals (Atlantic Richfield)	Us.

[a] With approximate percentage of control, if available

[b] The largest single shareholder block of Inco stock is 4 percent

[c] Falconbridge is 32.7 percent owned by Superior Oil through direct equity and its controlling interest in McIntyre

[d] Newmont Mining (22%) owned by Consolidated Gold Fields (UK), which is (29%) owned by Minerals & Resources Corp, which is (43%) owned by Anglo American

[e] There are six finance houses (the "Groups") which dominate the South African industry The Anglo American Corp of S A Ltd (AngloAmer); Gold Fields Of S A Ltd, General Mining Union Corp Ltd (Gencor); Rand Mines/Barlow Rand Johannesburg Consolidated investment Co Ltd (JCI); and AngloTransvaal Consolidated Investment Co Ltd (AngloTC)

[f] Johannesburg Consolidated Investment Co Ltd is (41) owned by the Anglo American

[g] Not in production, prospective only

SOURCES E&MJ *1983 International Directory of Mining*; Bureau of Mines, Mineral *Commodity* Profile *1983 Platinum-Group Metals* Office of Technology Assessment

Refiners)–and Engelhard Corp., both with refineries in England and the United States, are connected through Minerals & Resources Corp. to the Anglo American Corp. of South Africa, one of the group houses. The third South African producer firm, Western Platinum, is controlled by British, Canadian, and American interests,

Canada's two PGM-producing firms are primarily Canadian and American owned, Falconbridge, which is a part owner of Western Platinum in South Africa, owns a refinery in Norway. Inco operates refineries in Canada and the Mend Nickel Co. refinery in England.

While most of the mining firms are vertically integrated, from ore mining and processing through to metal production, processing has traditionally involved a physical, international flow of semiprocessed forms of the metals between mining countries and refiners in northern Europe. While Rustenberg now has the capability to process its ores completely within South Africa, some still follow the traditional path and are shipped as concentrates or in smelted form (matte) to England for refining. Western platinum ships mixed metal mattes to Norway, where nickel and cobalt are extracted. Final PGM units (as a "sludge") are returned to South Africa for final separation. Canada's Inco ships PGM sludge to its plant in England for refining. Falconbridge's semiprocessed ores go to Norway, with final recovery either in Norway or at the Engelhard refinery in Newark, NJ.

A consequence of this processing flow of PGMs is that essentially all the United States' primary PGM needs, even those obtainable from Canada, must ultimately be shipped from overseas. Both Ontario and Manitoba provinces in Canada have laws requiring all ores mined there to be fully processed in Canada, if possible. Inco and Falconbridge have so far been granted exemptions allowing them to export semiprocessed ores for refining, following a pattern set more than 50 years ago. Both expect to continue this system as long as it is economically feasible to use their northern European refineries. While semiprocessed ores are transported by surface, final metal forms are normally shipped by air, mitigating potential access problems (on the return journey) during crises.

Platinum group metals are investment as well as industrial commodities. Accordingly, three levels of trade exist: long-term contracts between producers and consumers, the dealer market for small and spot purchases, and investment and speculative buying of futures contracts on various metal exchanges, such as the New York Mercantile Exchange (platinum and palladium) and the Japanese Gold Exchange (platinum). At any one time, stocks of these metals are held by producers, refiners, investors, dealers, fabricators, and governments. The U.S. Bureau of Mines estimated that at the end of 1981 there were 900,000 troy ounces of PGMs (about a 4 to 5 months' supply) held by these groups in the United States alone.[106] The existence of widespread holdings of these stocks is one factor used to explain why the producer-set price recently gave way —after a 50-year dominance—to a market price for PGMs. In effect, the stocks held by a variety of groups serve as an intermediate supply, reducing producers' ability to set prices or control the flow of processed material.

Any near-term increase in demand is expected to come from current sources. South African producers, who tend to tailor production to their estimates of western consumption, have proven adept in drawing on their vast reserves to meet increased demand, In the 1970s, for example, South African firms greatly expanded production to meet demand created by requirements for automobile catalytic converters in the United States. They would likely respond similarly in the future, and their ample resources should allow them to do so.[107] Most of South Africa's production of PGMs is committed to major consumers—including the automobile industry (for catalytic converters)—through long-term (approximately lo-year) contracts. While information about contracts is not made public, Rustenberg reportedly supplies Toyota, Honda, and Ford; Impala is said to supply General Motors, Chrysler, and Nissan; and Western Platinum reportedly supplies Mitsubishi.[108]

While South Africa's portion of the world PGM market has steadily increased, Canada's production has not kept pace with growing demand. Since the 1960s, its share of the world market has decreased by 84 percent, while actual output has remained level.

The Soviet Union's production and marketing techniques cannot be determined accurately; most of its output is marketed through dealers rather than directly. Explanations for short-term changes in the amount of palladium made available for the market have ranged from pure political motivations to maximization of long-term commercial advantage. Over the past 20 years, the Soviets have managed to increase steadily the overall production of PGMs.

The following country-by-country overview of major producers discusses the current and projected status of PGM output.

Canada

Inco is the major PGM producer in Canada, with Falconbridge a distant second, Both derive PGMs as byproducts of nickel-copper sulfide deposits near Sudbury, Ontario. Inco also has lesser deposits at Thompson, Manitoba. PGM processing is tied to recovery of nickel, copper, and cobalt. Inco's ores are smelted at Copper Cliff, Ontario, with final recovery of PGMs at the firm's Mend Nickel Co. refinery at Acton, England. Falconbridge smelts ores in Sudbury; ships a nickel-copper matte to its plant in Norway for nickel, copper, and cobalt recovery; and refines the resulting PGM sludge in Norway or at the Engelhard refinery in Newark, NJ.

South Africa

In South Africa, PGMs are considered the primary product derived from sulfide depos-

---

[106] U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Profile* 1983: *Platinum-Group Metals,* p. 10.

[107] See for instance, the Bureau of Mines' *Platinum Availability—Market Economy Countries,* Information Circular No. 8897/1982.

[108] "Impala, GM Set Long-Term Pact Huddle," *American Metals Market,* June 2, 1983.

its. Rustenberg Platinum Mines produces more than 50 percent of South Africa's output, followed by Impala, with some 40 percent, The balance is produced by Western Platinum, which now has capacity to produce about 125,000 troy ounces of platinum per year. The Bushveld Complex in northeastern South Africa supports the entire PGM production. PGM deposits primarily occur in its Merensky Reef section—with concentrations ranging from 4 to 15 grams per tonne of ore or 4 to 15 parts per million (ppm). (Technically, 9 percent of South Africa's PGM reserves lie within the Bophuthatswana Homeland. Bophuthatswana actually produced over half of the PGMs credited to South Africa in 1982 as all of Impala's mining operations are within the homeland along with part of Rustenberg's.)

Two other sections of the Bushveld, the Upper Group (UG2) Chromium seam and the Platreef, have lower overall grades of PGMs but higher proportions of some of the lesser metals, such as rhodium and ruthenium. The Platreef is currently unmined. Western Platinum produces from some sections of the UG2. With the introduction of a new smelting process in 1984, PGMs can also be extracted from the chromite seams. The Bureau of Mines has stated[109] that commercial development of the UG2 and Platreef of the Bushveld Complex would more than double the amount of platinum available from South African deposits.

Rustenberg and Impala each have facilities in South Africa to process their ores completely to metal forms of separated PGMs. Rustenberg can also ship semiprocessed ores to the Johnson Matthey plant at Royston, England, for processing. Western Platinum ships all its production as mixed metal mattes to the Falconbridge (a part owner of Western) plant in Norway for separation of copper, nickel, and cobalt. A residual PGM sludge is returned to the Lonrho refinery at Brakpan in South Africa for final separation of PGMs. Western is currently considering development of its own matte treatment facility in South Africa, which—if established—would eliminate the time-consuming shipment of matte to Norway, cutting overall PGM processing time from about 6 to 2 months.

Gold Fields of South Africa Ltd. (partly owned by Consolidated Gold Fields of London, which is 30-percent owned by Anglo American) has been investigating a prospective new PGM mine on the Merensky Reef. The project was in the exploration phase in 1984. Potential PGM output is expected to total 386,000 troy ounces, including platinum (64 percent), palladium (27 percent), ruthenium (6 percent), and rhodium (3 percent). This would add about 5 percent to the world's output of PGMs (using 1980 as a base year).

Soviet Union

PGMs area coproduct or byproduct derived from nickel-copper sulfide deposits in Siberia (with PGM values as high as 10.4 grams per tonne of ore) and the Kola Peninsula. Limited amounts are also produced from placer deposits in the Ural Mountains. The mines at the Noril'sk mining combine in Siberia provide up to 90 percent of the total output. Ores, extracted under adverse conditions of an 8-month winter, are smelted and refined to metal within the Soviet Union. Expansion of capacity at Noril'sk, reportedly underway in the 1980s, could significantly increase Soviet production capabilities.

Potential Foreign Sources

The U.S. Geological Survey has a study underway to determine the PGM content of laterite formations in the Southwest Pacific (Indonesia, the Philippines, and New Caledonia). These mineralizations are found along with chromite. The separation techniques using plasma technologies that are being developed in South Africa for PGM/chromite deposits there could be applicable. The economic feasibility of mining PGM in these laterite formations may make it possible to extract the chromite content as a byproduct.

---

[109] T. F. Anstett, et a]., U. S. Department of the Interior, Bureau of Mines, *Platinum Availability—Market Economy Countries,* Information Circular No. 8897, 1982, p. 12.

Domestic Production of Platinum Group Metals

In contrast to the other first-tier materials, the United States is a producer, albeit minor, of PGMs (8,033 troy ounces in 1982 as a byproduct of copper mining and refining) and mining firms are actively pursuing the commercial possibilities of exploiting PGM deposits at Stillwater in Montana. These deposits could initially supply 14 percent of the US. palladium and 4 percent of platinum needs, or 9 percent of overall PGM needs (based on 1982 consumption data). Production from Stillwater is considered to be the only possible near-term, worldwide competition for existing PGM producers such as South Africa and the Soviet Union.

The Goodnews Bay Placer Mine in Alaska is a past producer of PGMs and was to resume operations in mid-1981 but did not. There are no immediate plans to do so. Other U.S. PGM resources exist in Alaska (Salt Chuck Mine and the Brady Glacier-Crillion-Le Pousse sulfide deposit) and Minnesota at the Duluth Gabbro. These latter properties have not been the subject of any recent commercial development interest. New U.S. mining activity in the development and expansion of gold and silver properties (the ore bodies of which often contain some PGMs) may result in small amounts of PGMs being recovered.

U.S. resources of PGM total 300 million troy ounces (less than 10 percent of world resources) and are concentrated in Montana, Alaska, and Minnesota.[110] An estimate of total possible U.S. production of PGMs from the most likely properties—Stillwater, Goodnews Bay, and the Duluth Gabbro—is shown in table 5-37.

Stillwater Complex, MT

PGM occurrences in the Stillwater Complex along the Beartooth Mountains in Montana have been commercially explored and evaluated over the past 15 years. The deposits are geologically similar to those in the Merensky Reef of South Africa and contain nickel, copper and chromite in addition to PGMs. Stillwater is being evaluated on the basis of extracting PGMs from sulfide ores as a primary product. The Complex is approximately 28 miles long and from 1 to 5 miles wide and is divided into distinctive mineralized zones with PGMs present at greater-than-normal concentrations in some bands. Typical PGM grades at Stillwater have been reported by the Bureau

---

[110] J. Roger Loebenstein, U.S. Department of the Interior, Bureau of Mines, *Mineral Commodity Profiles 1983: Platinum-Group Metals*, p. 3.

Table 5-37.—Potential U.S. PGM Production

Resource/mine	Estimated annual production capacity (troy ounces of contained metal)		Estimated minelife (years)	Production dependent on
Stillwater, Montana			10-25	Combined platinum-palladium price of about **$220** per troy ounce (1984)[a]
Initial:	Palladium	136,000		
	Platinum	38,000		
	Total	175,000		
Additional expansion:	Palladium	340,000		
	Platinum	97,000		
	Total.	437,000		
Goodnews Bay, Alaska			unknown	Platinum price of $600-700 per troy ounce (1984)
	Platinum	10,000		
Duluth Gabbro, Minnesota . . .			*25*	Copper, $1.50 per pound
	Palladium ., . .	30,800-92,400		Nickel, $4.00 (1975 data converted to January 1983 dollars
	Platinum	6,800-20,300		
	Total	37,600-112,700		

[a] Year of estimate.

SOURCE: Stillwater—Stillwater Mining, June 1984.
Goodnews Bay–Hanson Properties, July 1984.
Duluth Gabbro—Calculated by OTA using preliminary results of Bureau of Mines research on Duluth ores, State of Minnesota, Regional Copper-Nickel *Study*, 1979; Silverman, et al., OTA background study, 1983.

of Mines as 0.130 troy ounces of platinum and 0.509 troy ounces of palladium per ton of ore (5 ppm platinum, 17 ppm palladium). In comparison, grades of representative ore from the Merensky Reef are 0.154 troy ounces of platinum and 0.066, palladium per ton (5 ppm platinum, 2 ppm palladium).[111] The estimated PGM reserves of the entire complex have been reported at 7 million troy ounces.[112]

The most important PGM zone was discovered during exploration by the Johns Manville Sales Corp. in 1967 and sparked renewed commercial interest in this area once mined for its chromite content. The Johns Manville zone has an estimated 0.47 troy ounces of platinum and palladium per ton of ore with a palladium-to-platinum ratio of 3.5:1[113] (0.11 troy ounces of platinum and 0.36 troy ounces of palladium per ton of ore, or 4 ppm platinum and 12 ppm palladium).

Two sets of properties in the Stillwater Complex have been the object of extensive commercial exploration since 1979. The properties, since June 1983, have been held by a joint venture of Stillwater PGM Resources & Anaconda Minerals Co. under the name of Stillwater Mining Co. Stillwater PGM Resources is a partnership of Johns-Manville and Chevron Resources Co. (Chevron USA); Anaconda Minerals is a wholly owned subsidiary of Atlantic Richfield. Stillwater Mining Co. has selected a particular mineralized zone (the Minneapolis Adit) in one of the original Anaconda properties as the site for an 18-month exploration and evaluation effort. Core drillings, both from the surface and within the Adit, constitute a major portion of the evaluation project's data. This joint project may—or may not—result in eventual combined mine development and production activity.

The development phase would reportedly take 2 years to place into operation an underground, hard-rock mine producing 1,000 tons of ore per day. A milling plant, constructed at the mining site, would produce a concentrate from the mined ores by grinding and flotation processes. This product would be transported by surface to an existing smelter (e.g., Inco's in Canada) for refining. Estimated mine life for the project is 20 years.[114]

In mid-1984, the possibility of proceeding with mining development was considered "very price sensitive.’’[115] A weighted average price of $220 per troy ounce of PGMs is being used in Stillwater Mining's feasibility study calculations. (As a comparison, the June 1984 producer prices for PGMs were: platinum, $475 per troy ounce and palladium, $130 to $140.[116] At these prices and given the Stillwater palladium-to-platinum ratio of 3.5:1, a weighted average price of $206 to $214 is realized. Thus, the market prices did not quite meet the target price,] The drilling program and feasibility study is scheduled for a mining development "go/no go" decision by mid-1985.

Anaconda's Stillwater Project had originally proposed, for a 1982 draft EIS, a mining operation producing 350,000 tons of ore per year (1,000 tons daily for 350 days per year) over 25 years. Contained PGMs (at about 0.5 troy ounces per ton of ore) would be 500 troy ounces per day (or 175,000 troy ounces per year).[117] The Anaconda site (now the Stillwater Mining investigation) is smaller than the original Stillwater PGM Resources properties, whose reserves might be able to support a mining rate of 2,500 tons of ore per day,[118] or approximately 437,500 troy ounces per year of contained PGM values.

The Stillwater Complex is located in a rural, agricultural community, partly within the borders of two national forests. While development of mining at Stillwater would provide job opportunities and broaden the local tax base, local citizen groups have voiced concerns

---

[111] Ibid., p. 4.

[112] Anstett, et a]., op. cit., p. 7.

[113] *The Stillwater Citizen-Sun*, Apr. 26, 1984, sec. 2, p. 5.

[114] *The Stillwater Citizen-Sun,* p. 12.

[115] Les Darling, Environment] Coordinator and principal spokesperson, Stillwater Mining Co., personal communication, May 1984.

[116] "Closing Prices," *American Metal Market,* June 15, 1984, p. 31,

[117] Silverman, et al., op. cit., p. 104 (text of E] S).

[118] Silverman, et al., op. cit., p. 190. A Sept. 10, 1980, statement from the Manville group estimated a production rate of 1,000 to 3,000 tons of ore per day.

over population influx, overburdening of the public service system and environmental issues such as location of the mill and tailings pond, the wastewater's effect on the region's groundwater, and protection of air, water and wildlife. During any permitting process, Montana's Department of State Lands will coordinate the preparation of the necessary EIS; and the local government and the Montana Hard Rock Mining Impact Board will evaluate socioeconomic issues.

Goodnews Bay and Other Alaska Occurrences

The Goodnews Bay Placer Mine is a dredging operation located on the Salmon River near the Bering Sea coastline of Alaska. Production from Goodnews Bay totaled 641,000 troy ounces of PGMs (over 80 percent platinum) from 1934 until 1975, when production was halted.[119] Although new owners, Hanson Properties, announced intentions to resume operations in 1981, operational difficulties with dredging machinery, environmental issues, and overall, the costs of production have prevented them from doing so.[120]

While the major component of this placer deposit is platinum (reserves are estimated at 500,000 troy ounces of platinum),[121] other PGMs and precious metals are present. The approximate proportions of metals in the concentrate produced in the past were 82.31 percent platinum; 11.28, iridium; 2.5, osmium; 0.17, ruthenium; 1.29, rhodium; 0.38, palladium; and 2.24 percent gold.[122] The mine could possibly produce up to 10,000 troy ounces of platinum per year.[123] The high grade concentrate generated could be shipped directly to a U.S. refinery, such as Engelhard in Newark, NJ, for processing.

The Salt Chuck lode mine has been intermittently exploited for various PGMs since 1918 with the latest period of operation having been 1935 to 1941. Overall, 14,271 troy ounces of PGMs have been produced from this mine.

PGMs are known to exist in deposits in Glacier Bay National Park in the Crillion-La Perouse Complex. An unpublished U.S. Geological Survey report in 1980 indicated that platinum may be recovered as a byproduct from the Brady Glacier nickel-cooper ore body. The ore body, which extends under moving glacier ice, has not been extensively evaluated and could prove expensive to mine.[124] In addition, given its location, environmental concerns would weigh heavily on any mining prospects.

In general, there is potential for more lode and placer deposits in Alaska. The Alaska Field Operations Center of the Bureau of Mines has an ongoing program specifically directed toward improving the available information about occurrences of PGMs, as well as chromite and cobalt, in Alaska.

Duluth Gabbro, Minnesota

Copper and nickel sulfide deposits along the Duluth Gabbro in the Lake Superior region of northeastern Minnesota contain cobalt, PGMs and other precious metals that could be recovered as byproducts. Production of significant amounts of PGMs depends on copper and nickel mining on a large enough scale to make these low-grade resources competitive in global markets. Commercial production will not even be considered until the recovery of both primary metals markets occurs and existing worldwide nickel and copper mines have returned to full production. (For information on the economics of Duluth Gabbro and a Regional Cooper-Nickel study released in 1979 by the State of Minnesota, see the domestic cobalt section.)

---

[119] James C. Barker, et al., U.S. Department of the Interior, Bureau of Mines; *Critical and* Strategic Minerals in *Alaska: Cobalt,* the *Platinum-Group Metals and Chromite,* Information Circular No. 8869, 1981, p. 2.

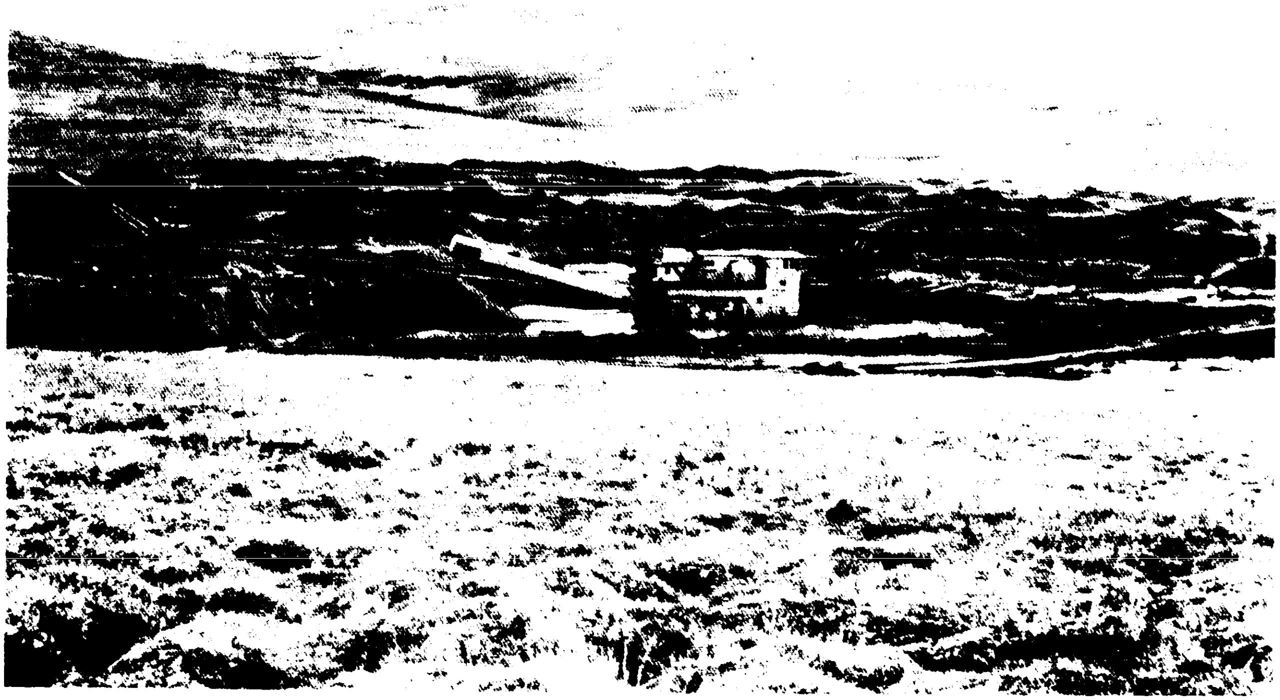
[120] Raymond Hanson, Hanson Properties, persona] communication, July 1984.

[121] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook* 1981, p. 668.

[122] These are the weighted mean percentages of the metals mined from Goodnews Bay from 1936 to 1970 as presented in the National Research Council, National Materials Advisory Board, *Supply and Use Patterns for the Platinum-Group Metals,* NMAB-359, *1980,* p. *17.*

[123] U.S. Department of the Interior, Bureau of Mines, *Minerals Yearbook, 1981,* vol. I, p. 668. Mr. Hanson inferred that this figure was high and commented that it was "what the oldtimers in Alaska claim, "

[124] *Critical and Strategic* Minerals in *Alaska,* op. cit., p. 3



G B

Industry interest in the area peaked between the late 1960s and 1970s. During that time, Amax Nickel acquired an option from Kennecott Copper and investigated the possibility of a combined surface and underground operation (Minnamax) and Inco considered opening an open pit mine (Ely Spruce). Inco's project was suspended in 1975, and Amax indefinitely postponed its project in 1981 owing to depressed metal prices. This property has now reverted back to Kennecott control. There has been no revival of commercial interest in the area.

These two holdings in the Duluth Gabbro contain demonstrated resources of less than 800,000 troy ounces of platinum.[125] PGM values of 0.00107 troy ounces of platinum and 0.00304 troy ounces of palladium per ton (0.036 ppm platinum, 1.03 ppm palladium) were estimated from an Inco sample by the Bureau of Mines.[126] The Minnesota Department of Natural Resources extrapolated this data to the rest of the area and estimated that about 18 million troy ounces of platinum resources existed in 4.4 billion tons of ore.[127]

The Bureau of Mines has recently conducted research on the processing of raw materials typical of Duluth Gabbro ores, and a report on the results is in preparation. Data from these studies indicate that, under optimum conditions, the recovery of platinum and palladium per ton of ore would be approximately 0.0005 troy ounce and 0.0022 troy ounce, respectively. This is equivalent to approximately 0.088 troy ounces of platinum and 0.40 troy ounces of palladium per ton of copper produced.[128] In the 1979 study by the State of Minnesota, the maximum possible annual output from Duluth was calculated at 231,000 tons of copper metal and, with one mine complex (rather than three) in operation, 77,000 tons of copper would be produced per year. This implies that between 30,800 and 92,400 troy ounces of palladium and between 6,800 and 20,300 troy ounces of platinum might be generated as byproducts from Duluth given the proper economic incentives for copper and nickel production.

Although the Duluth Gabbro lacked any commercial activity recently, this large resource of low-grade material will continue to be viewed as a potential source of metals. The proximity of potential mining areas to the Boundary Waters Canoe Area and Voyageurs National Park, as well as possible damage from sulfur emissions from a smelter operation processing Duluth Gabbro sulfide ores, will ensure an important role for environmental considerations in mine planning in the area.[129]

Domestic Mining and Processing Technology Prospects

PGM deposits which occur in hard-rock environments (Stillwater, for instance) are amenable to underground methods such as sublevel stoping and the newer vertical crater retreat system. Placer deposits are generally dredged unless, as maybe the case in some areas of the Goodnews Bay deposit in Alaska, the thickness of the overburden makes the technique uneconomic.

Domestic PGM deposits are not unique and, therefore, metallurgical processing technology is available. The high-grade platinum concentrates from Goodnews Bay can be sold directly to existing U.S. precious metal refineries for purification. Technology for the required smelting and refining of Stillwater's nickel-copper-PGM ores is well established. The most qualified North American smelter for the initial refining of its concentrates is the Inco plant at Copper Cliff, Ontario.

Included in current Bureau of Mines research is the evaluation of a method for processing of Stillwater ores. It involves flotation of the ores and subsequent smelting and leaching to recover the various metal values in the ores. The flotation concentrate results in 88 percent recovery of the PGM values and smelt-

---

[125] Anstett, et al., op. cit., p. 7.

[126] National Research Council, National Materials Advisory Board, *Supply and Use Patterns for the PlatinumGroup Metals, NMAB-359,* Washington, DC, 1980, p. 16.

[127] Ibid., p. 16.

[12] U.S. Department of the Interior, Bureau of Mines, letter to OTA, July 31, 1984.

[129] Silverman, et al., op. cit., p. 112.

ing to a sulfide matte retains 95 percent, for an overall recovery of 84 percent. This matte then requires a refining step to separate out PGMs and gold.[130] Duluth ores are also under investigation and are discussed in the preceding domestic cobalt section.

Processing of Platinum Group Metals

The major end uses of PGMs are as catalysts in the automotive, petrochemical, and chemical industries and as contacts in the electronics industry. These products are fabricated from chemical forms of PGMs, which are produced from metals, mainly platinum and palladium and, increasingly, rhodium.

PGMs follow the same processing path as cobalt because they originate in the same ores. PGMs are the last step in the long extraction process of these ores (fig. 5-7), and it can take up to 6 months to complete the cycle from mining of the ores to production of PGMs. The final residual from the sequential processing is a PGM concentrate, or "sludge," Separation of the precious metals from this concentrate is accomplished by various chemical methods, many of which are proprietary, A new extraction process developed by the South African National Institute of Metallurgy in 1975 can reduce the overall PGM processing time dramatically (to 20 days). Two South African refineries and one in England now use the institute's process.

PGMs are imported by the United States in forms such as unwrought and semimanufactured metal. Recycled catalysts from the petroleum and chemical industries are another source. The processing industry in the United States consists of refiners and fabricators. Large firms, such as Engelhard and Johnson Matthey, can handle the final PGM processing steps, while smaller firms only fabricate the end products. Engelhard's New Jersey refinery reportedly processes some of Falconbridge's (Canada) PGM sludge. The National Materials Advisory Board reported in 1980[131] that, as a whole, the U.S. PGM processing industry was healthy and aggressive and could readily meet the challenges of any increased demand.

---

[130] *Research83*, op. cit., p. 89.

[131] NMAB-359, op. cit.

Exploration

The development of the major known domestic resources of chromium, cobalt, manganese, and PGMs is technically feasible if political necessity dictates, However, with the exception of a PGM deposit, these domestic resources could be produced only at several times current world price.

Exploration for additional domestic deposits by private concerns will proceed only insofar as there are geologically favorable areas, perceived economic benefits to the explorer, and procedures that permit mining if a discovery is made. No group is actively exploring for first-tier strategic materials in the United States today, The benefits are not consistent with the costs and risks involved, especially when foreign countries can produce vast quantities of high-grade materials at costs well below that of any domestic producer.

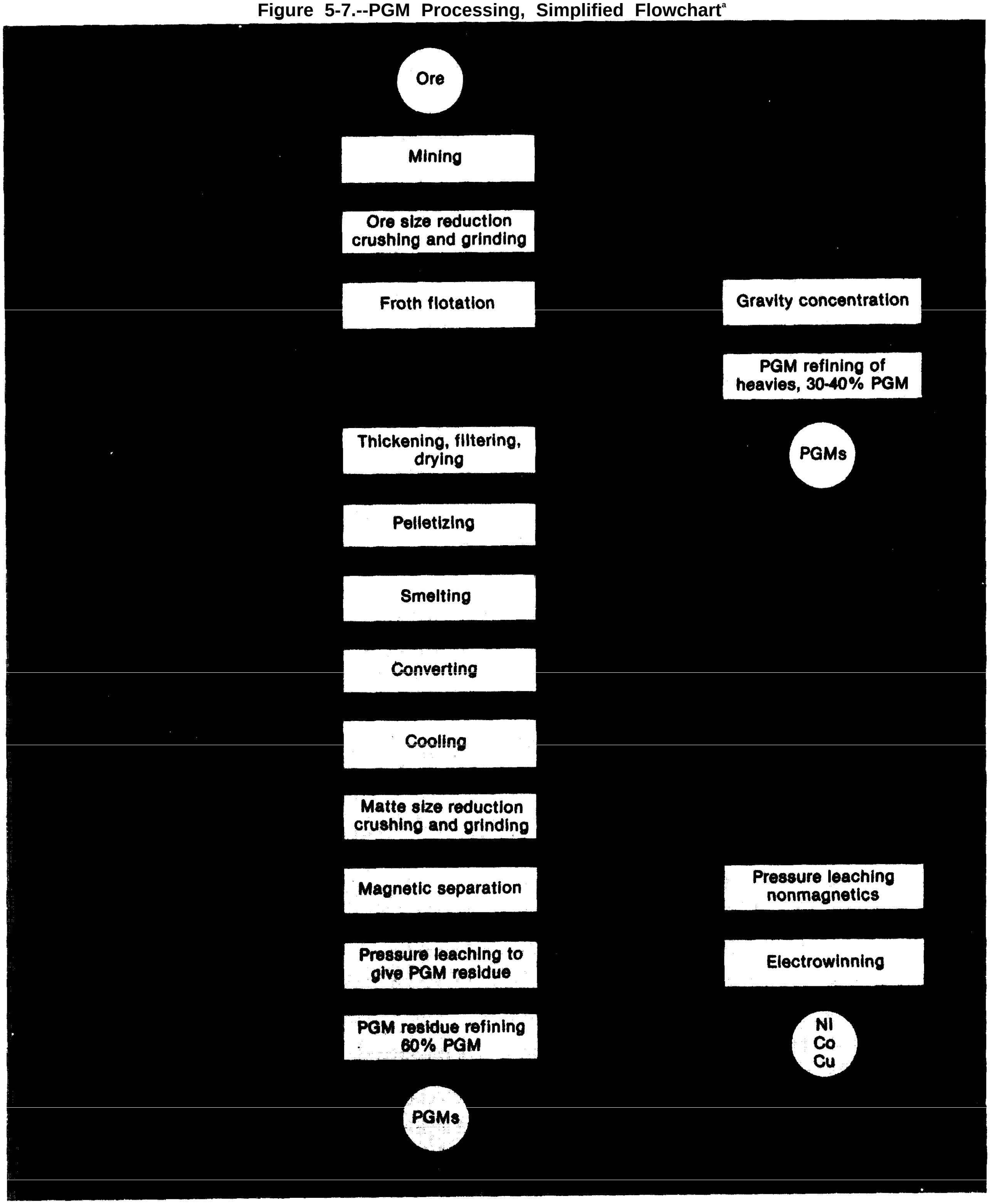
Land-Based Resources[132]

In North America, Precambrian rocks are considered the most geologically favorable areas for possible significant deposits of chromite and nickel-copper-cobalt sulfides with associated PGMs. Figure 5-8 shows the formation period (1 to 2.6 billion years ago) of certain world deposits of chromium, cobalt and PGMs. The formation of manganese deposits is not as exclusively timebound as the other

---

[132] This section is based primarily on Ben F. Dickerson III, and Carole A. O'Brien, *Exploration for Strategic Materials*, contractor study prepared for the Office of Technology Assessment, September 1983.

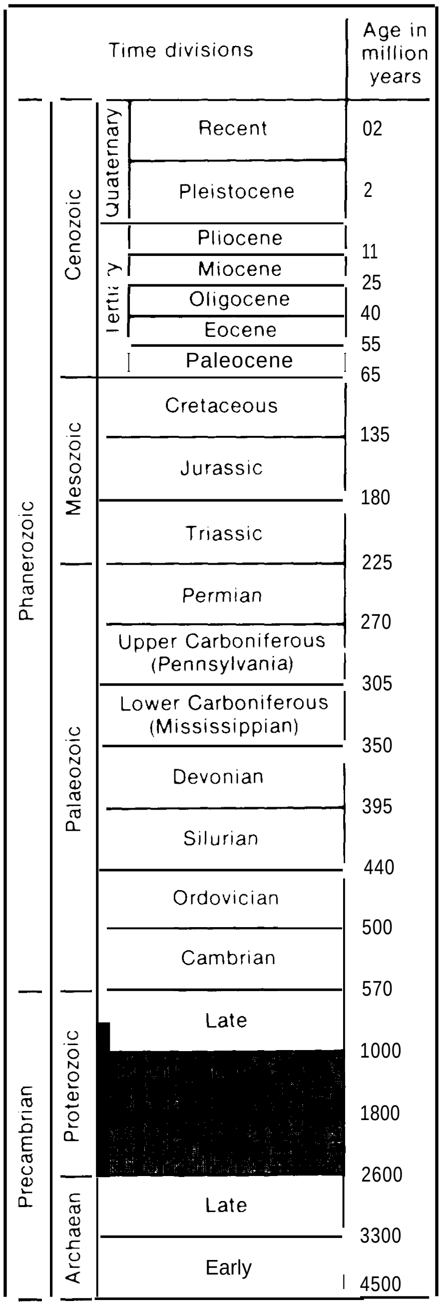
Figure 5-7.--PGM Processing, Simplified Flowchart[a]



[a] Typical South African process.

SOURCE: Department of the Interior, Bureau of Mines, *Platinum Availability—Market Economy Countries,* Information Circular #8897, 1982.

Figure 5-8.—Time Chart of Some First-Tier Strategic Material Deposits



Deposit	Location	Approx. Age (million yrs.)	Commodity
Katanga	**Zambia-Zaire**		Cobalt
Duluth Gabbro	**Minnesota**	1000-1800	Nickel-Cobalt
Sudbury	**Ontario**	1000-1500	Nickel-Copper. Platinum
Bushveld	**S. Africa**	**2000-2100**	Chromite-Platinum
Outokumpu	**Finland**	2000-2100	Copper-Nickel-Cobalt
Kemi	**Finland**	1800-2300	Chromite
Stillwater	**Montana**	2400-2500	Chromite-Platinum
Great Dyke	**Zimbabwe**	2600-2700	Chromite-Platinum
		2400-2500	

SOURCE. Ben F Dickerson III and Carole A O'Brien, *Exploration for* Strategic Materials, contractor study prepared for the Office of Technology Assessment, September 1983 strategic metals. In the United States the major exposure of Precambrian rocks (fig. 5-9) is in the Great Lakes region of Michigan, Minnesota, and Wisconsin, with smaller, scattered areas in many States, including Montana, Idaho, Colorado, Arizona, South Dakota, Wyoming, Texas, and Missouri.

The constraints on exploration imposed by the absence of extensive geological exposure cannot be ignored in assessing the Nation's strategic materials outlook. Currently unidentified geologic environments in the United States could possibly contain these metals, but the uncertainties involved in identifying such environments compound the already high risk of exploration of regions of known potential.

Metals experts interviewed by OTA generally agree that there is a very low probability that the United States contains significant, undiscovered economic deposits of chromite, cobalt, or PGMs. (Prospects for manganese are deemed somewhat better.) Undoubtedly, some geologists disagree with this majority opinion, asserting that increased geologic knowledge, better technology, and fresh exploration concepts can find new, economical deposits. Even if such deposits do exist, the apparent risk/reward ratio and the magnitude of identified foreign reserves preclude meaningful action under current conditions.

Experts were unanimous on one point: all believed their companies' management would reject any strategic metals exploration program, no matter how geologically well-conceived, now and in the near future.[133]

Until reliable long-term economic incentives [perception of profits commensurate with risks) are available, there will be no significant exploration for strategic materials in the United States. A recent estimate gave $290 million as the cost to find an ore deposit that would significantly affect the profits of a medium-sized corporation.[134] Any find would have to result in ores of higher than average grades and/or lower than average costs to mine, substantial and dependable markets, and an assumption of long-term stability in the domestic economy.

Exploration Technology Today and in the Future

The following briefly reviews present and potential near-term technological developments in land-based exploration for strategic materials. It is felt that the technology level that mineral geologists employ today is about 20 years behind the level used in oil and gas exploration. This may be a reflection of the value of national energy versus mineral needs. For instance, in 1977 fuel production in the United States was valued at $56.2 billion and metals production, a tenth of the fuels value at $5.2 billion.[135]

Most specialists think that a breakthrough in mineral exploration technology is unlikely in the next 10 years and that the exploration scene of the early 1990s will probably not be greatly different from that of today, except it will be more expensive. Current tools and techniques will be more precise and refined, owing largely to the application of mineral exploration advances, general scientific knowledge, and electronic technology. Lacking incentives to explore for strategic materials, there will be little attention to the development of specialized technology for that purpose; but any general improvements in exploration methodology or technology could be of use.

Chromite deposits, for instance, have generally been found by surface prospecting and drilling in and around identified outcrops (surface appearances). There are no unique problems in exploring for most types of cobalt deposits. Current geophysical methods can be used to detect the presence of copper, nickel and iron sulfide minerals, with which it is associated. Cobalt can be easily identified by relatively simple chemical analysis methods.

GENETIC THEORY

Increased interaction between industry and academia could lead to better application of new and developing concepts in genetic the-

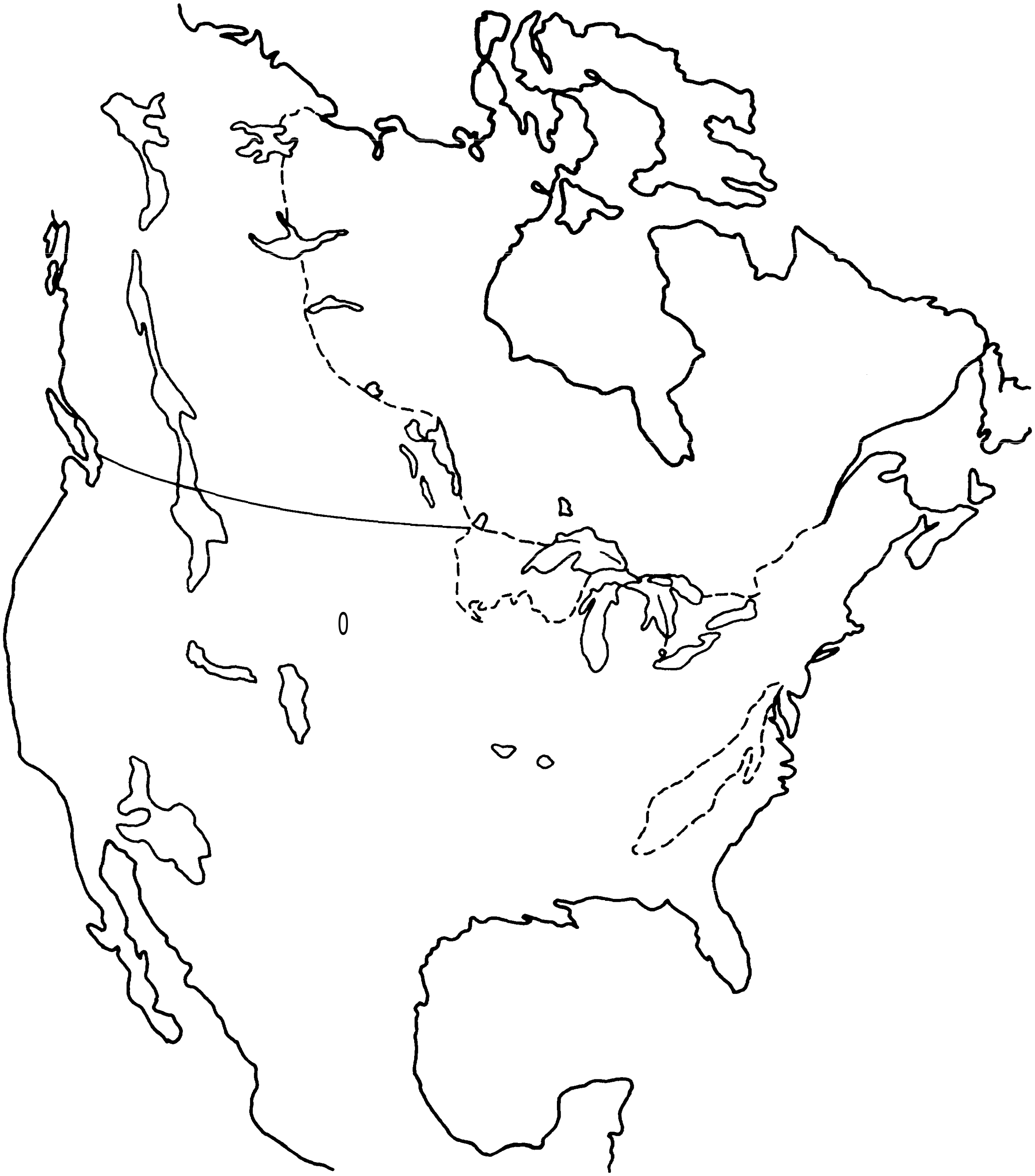
---

[133] Ibid., p. 11,

[134] Ibid., p. 18.

[135] *Statistical Abstract of the United States*, 1982-83 edition, table No. 1276, p. 715.

Figure 5-9.— Exposure of Precambrian Rock in North America



SOURCE Duncan R Derry, *A Concise World Atlas of Geology and Mineral Deposits,* 1980 ory. Most currently employed theories of ore genesis are derived from developments in the understanding of plate tectonics and continental drift.[136] These concepts are definitely useful in predicting areas favorable for certain types of mineral deposits and will probably continue to provide practical information.

Advances in this field are expected to call attention to some hitherto ignored, or currently unknown, geologic environments for some metals, particularly gold, silver, and perhaps some base and strategic metals. Explorationists do not feel, however, that any lo-year development of genetic theory will allow them to accurately fix the location and approximate quality of any type of mineral deposit. In fact, there is strong doubt that this could ever be done.

DATA INTERPRETATION

Data interpretation is the single, biggest problem facing exploration. A substantial improvement in this art might far outweigh potential technological improvements.

Both geophysics and geochemistry now can deliver vast amounts of data that no one completely understands. Fully integrating this information with data from other exploration techniques is very difficult. While a very few "seat-of-the-pants" ore finders may be able to do this intuitively, most explorationists are not so gifted. One geologist said, "Better instrumentation is like giving an encyclopedia to an illiterate—the pictures are neat, but it doesn't help him to read. "

GEOPHYSICS

Geophysical techniques for locating particular geological structures and compositions are one of the primary screening tools of mineral exploration. The process involves measurement of various physical fields in which variances in mineral content or physical condition will cause anomalies in the data produced.

Current techniques, however, particularly electromagnetic methods, are unable to distinguish between anomalies caused by various minerals such as pyrite, chalcopyrite, or graphite. This prevents the explorer from correctly identifying, or narrowing down sufficiently, the sought-after mineral environment.

Research programs of a few large exploring firms are aimed at developing instrumentation to discriminate between various minerals, particularly sulfides. Because the work is proprietary, very little information is publicly available, Geophysicists interviewed for this report said that such instrumentation would probably not be developed before the end of the century and, even then, may only compound current problems of interpreting findings.

Other than the major problem of data interpretation mentioned above, instrumentation:

- must be better able to screen out natural or human "background noise, " this improvement might increase the effective depth penetration, a current limitation of the geophysical techniques; and
- needs additional miniaturization and improvement for borehole use, also increasing depth penetration.

Geophysical techniques are expected to improve only slightly, as many methods are approaching absolute barriers imposed by physical laws. (In particular, the decline of signal strengths by the "inverse of the square of the distance" effect.) Miniaturization of geophysical instrumentation will be much more highly developed. The subsequent increased employment of down-the-hole geophysics will give, in effect, greater depth penetration in areas being explored and could cope with the physical law limits, However, this improvement will be of little use in the initial or reconnaissance stages of exploration.

Geosatellite imagery and other associated data will probably be employed cautiously, but more frequently, particularly if some of the uncertainties of spectral interpretation can be

---

[136] In 1912 a German, A. Wegener, suggested that about 200 million years ago the continents were packed together in one universal land mass called "Pangaea." Wegener called attention to the "jig-saw" piece matching effect of the South American and African continents; similarities in geology, plant and animal life; and in paleoclimates of various continents. This basic concept received little support until the mid 1950s.

eliminated and higher spectral resolution obtained, Unfortunately, many large, geologically favorable areas of the earth's crust are hidden beneath an alternate environment, preventing satellite identification despite improved technology.

There are no special geophysical problems related to strategic materials that preclude application of general improvements in exploration technology. For example, an effective borehole induced polarization (1P) transmitter and receiver would perhaps be effective in exploration for podiform chromite bodies, in areas where they are known to occur. Cobalt is associated with copper, nickel, and iron sulfides which have detectable electromagnetic signatures. Chromite and manganese oxide can be detected by using certain geophysical techniques as well. However, geophysical techniques have not been developed to identify economic concentrations of metals present in the earth's crust as carbonates and / or silicates (e. g., manganese carbonate deposits and nickel-cobalt silicate minerals in laterites). Limited success has been achieved in distinguishing carbonate and silicate minerals using satellite imagery but only when they appear on the surface. Manganese oxides, as well as sulfides, respond to 1P techniques but carbonates offer little, or no geophysical signature. Uncertainties abound, however. 1P effects are produced by graphite, magnetite, certain clays, and other minerals. In fact, many 1P anomalies have no ascertainable cause.

GEOCHEMISTRY

Geochemistry involves the analysis of soils, surface water, and organisms for abnormal concentrations of minerals. It is one of the basic tools of modern mineral exploration and is relatively rapid, cheap, and direct. But, faster, more accurate, more sensitive, and more specific analytical techniques are needed.

Current practice in sample preparation consists of crushing, grinding, pulverizing, and selecting a sample of appropriate size; each stage of this process offers opportunity for error. The ideal methodology would include automated sample preparation and on-the-spot whole-rock, accurate, multi-element analyses. An instrument for onsite analysis of drill-hole derived samples, at least semiquantitatively, is also needed. A technique that would not alter the physical characteristic of the sample is preferable.

Since strategic materials are not actively explored domestically, accurate multi-element analysis would be highly desirable, no matter what type of sample is being analyzed.[137] Potentially valuable deposits of one element have certainly been overlooked because analytical work was at the time concentrated on locating other elements. Even if no potentially economic element is present, there would be great geologic value in identifying and quantifying all of the trace elements associated with particular types of mineralized bodies. In time, the resulting patterns might offer definite clues to the presence or absence of economic mineralization.

Borehole and handheld instruments, employing X-ray fluorescence analysis methodology, have recently been developed. These are specific for such elements as silver, gold, molybdenum, and tin, But substantial improvements in **6** Compilation procedures for this "unwanted-at-the-time" information would need to be instituted, however, sensitivity and analysis reproducibility are needed. ICP (Inductively Coupled Plasma atomic emission spectrometry) is the latest technique and is claimed to be a multi-element analytical tool. There are, however, substantial problems with inter-element interference and element detection levels.

High-precision and sensitive analytical methods—including ICP, neutron activation, laser bombardment, irradiation by radioactive isotopes—have only limited use in geochemical work because of their high unit costs (more than $50 per sample) and certain physical limitations of the equipment.

The main advances in geochemical exploration are expected to occur in instrumentation

---

[137] Compilation procedures for this ''unwanted-at-the-time information would need to be instituted, however.

and in analytical techniques. Handheld and drill hole-adaptive, direct in situ analytical devices will be available in exploration for some elements, but probably only for PGMs among the strategic metals, since there is little economic interest in the others. Although semiautomated wet chemical analytical methods will be standard, and will increase reproducibility and sensitivity, more highly trained and more costly technicians and analysts will be required to perform the analyses,

Helicopter-borne spectral reflectance instrumentation, perhaps a spinoff of satellite research, may be used to screen vegetation geochemically in large forested areas. Practical instrumentation should be available that will directly measure gases emitted in decomposition of some economical minerals.

Chromite is a common accessory mineral in mafic/ultramafic rocks, but geochemical surveys have not been successful at identifying economic concentrations of chromite. Widespread high, but very variable, background concentrations of manganese in water, soils, and rocks make geochemical techniques very difficult to employ.

DRILLING TECHNOLOGY

Drilling is the ultimate test phase of all exploration, and its costs, direct and indirect, are one of the most significant limiting factors in minerals exploration today.[138] Improved technology which reduces these costs would allow testing of more targets, however they are identified and defined, and would help improve current ore discovery rates.

Techniques for mineral exploration include core and rotary drilling. Core drilling physically removes a cylindrical sample of rock while a rotary crushes and chips the rock so that only cuttings are removed by air or water,

Core drilling today is not greatly different from that of the 1860s, when it was first employed for coal exploration in Pennsylvania. Although overall technology has steadily improved, only two significant improvements in core drilling have been introduced in the past 30 years. The first was the introduction of wireline drilling (allowing the recovery of a sample core inside a drill stem); the second, the advent of long-wearing, impregnated diamond drill bits.

Rotary drilling techniques for metals have also generally stabilized. Sampling-related problems prevent rotary drilling from being employed to a much greater extent in minerals exploration.

There has been comparatively little direct research directed at improving mineral exploration drilling. The U.S. Bureau of Mines and a drill machine manufacturer and contract drilling company, E.J. Longyear, have jointly designed a method for replacing worn diamond bits without removing drill rods from bore holes, eliminating a costly and time-consuming operation. With the use of impregnated diamond bits, however, it has proven more cost effective to stay in the hole with these longer wearing bits than to purchase the relatively expensive equipment required to change the now partly obsolete surface set bits.

Most incremental improvements in drilling have been developed in oil exploration, Although helpful in strategic materials exploration, various factors—e.g., the size of target, rock types, dimensions of drill holes, and market size differences–prevent large-scale adaptation in mineral exploration. Substantial technical and cost benefits in mineral exploration drilling techniques may be possible only if a long-term, well-conceived, and adequately funded research program is undertaken.

Drilling techniques are not expected to be much different from those employed now. Most explorers foresee increased drilling costs and little change in drilling efficiency. If the rate of growth in average drilling depth is maintained, with its attendant increased costs per hole, it is probable that fewer holes will be drilled on any one target.

Research and Development

Mineral exploration technology and methodology have not been the subject of significant

---

[138] Dickerson, et a]., Op. Cit., p. 66.

research and development (R&D) attention for some time. Current metal market prices and other problems have led to reductions of previous, modest funding levels in the private sector.

A precise picture of mineral exploration related R&D, however, is difficult to develop. Most work is spread throughout academia (geology), the U.S. Geological Survey (geology, geophysics, and geochemistry), the Bureau of Mines (drilling, geophysics, and miscellaneous pursuits), and mining and oil companies (geology, geophysics, and geochemistry). Equipment manufacturers, with a few exceptions (mainly geophysical contractors), do very little R&D because their markets are so limited.

There appears to be no reliable figure available for the amount of direct exploration-related R&D expenditures for any specific period. (Guesses range from $10 million to $50 million per year by the private sector in North America.) The quantification problem is complicated by no agreed-upon definition of work that should be classified as mineral exploration R&D, especially within the Federal Government. Is a U.S. Geological Survey geologist studying the magnesium content of chromite engaged in mineral exploration research? Most practicing explorationists would say no, but an argument could be made otherwise. One thing is clear to explorationists: R&D in their field, no matter how defined, is, by comparison to most other technical fields, very poorly funded and directed.

Ocean-Based Resources

The floor of the ocean provides a favorable environment for the formation of expansive deposits of minerals containing manganese, iron, and other metals. Some of these deposits contain significant amounts of nickel, copper, or cobalt. As a result, they have gained some attention as possible alternative sources of metals to supplement or replace land-based sources of questioned reliability. The mineral resources of the deep seabed gained visibility during the 1970s when their status was added to many other subjects under consideration at the Third United Nations Conference on the Law of the Sea.

Three forms of the seabed manganese deposits are of interest from a strategic materials perspective: the manganese nodules and crusts located on the Blake Plateau off the coast of Florida, the manganese nodules of the east central Pacific Basin, and the cobalt-rich crusts located on the slopes of seamounts and islands in the Pacific. The status and outlook for exploitation of each of these types of deposits is summarized in table 5-38.

The Blake Plateau deposits contain approximately 15 percent manganese and 15 percent iron, but their content of more valuable metals is low. The water depth ranges between 300 and 1,000 meters, and they are located on the continental slope where they fall under the jurisdiction of the coastal state (in this case, jurisdiction is principally that of the United States, although some of the region is under Bahamian jurisdiction). In 1976, the National Materials Advisory Board evaluated these nodules as a potential domestic source of manganese. The nodules fared well against other domestic sources, but were still judged to be out of the realm of commercial exploitation since their production costs were high in comparison with the large land-based deposits now in production,

The Pacific manganese nodules differ from those of the Blake Plateau in several respects. They have attracted commercial interest because of their content of nickel, copper, and cobalt, which exceed that of many land-based deposits; they are located in water depths as much as 10 times that of the Blake Plateau; and they are located beyond the jurisdiction of any country, with their legal status clouded by the lack of widespread acceptance of any legal regime for exploitation.

Interest in the Pacific nodules began to increase before the technology for exploitation was developed and before the legal regime was developed. The value of the metals contained in the nodules was high in comparison to land-based ores, and the high value of contained metals grabbed attention before estimates of

Table 5-38.—Outlook for Development of Ocean-Based Resources of Strategic Metals

	Blake Plateau	Clarion-Clipperton Nodule Province	Cobalt bearing crusts
Depth	300-1,000 meters	4,000-6,000 meters	1,000-2,000 meters
Location	East coast of Florida, Georgia, South Carolina Bordered to east by Bahamian jurisdiction	Approximately 1,000 miles southeast of Hawaii. 2,000 miles southwest of California	Continental slopes of Hawaiian Islands, Line islands, and other Pacific seamounts
Metal content:			
Manganese	15.9 ± 7.1%	29.8 ± 20.6%	24.6 ± 4.0%
Iron	15.5 ± 12.5%	14.0 ± 4.8%	14.5 ± 2.5%
Nickel	0.59 ± 0.08%	1.5 ± 0.82%	0.49 ± 0.20%
Copper	0.14 ± 0.4%	1.2 ± 0.49%	0.065 ± 0.39%
Cobalt	0.41 ± 0.35%	0.35 ± 0.12%	0.79 ± 0.33%
Form	Nodules on surface of sediment	Nodules on surface of sediment	Crusts bonded to rock
Status of technology	Limited prototype mining tests completed in 1970	Some prototype mining and processing tests completed in 1980	Limited conceptual proposals for adaptation of nodule mining technology
Economic outlook.	Extremely low-grade manganese deposit is not competitive with land-based producers	Low nickel and copper prices make nodule mining subeconomic	Lack of technology, availability of land-based cobalt sources, and uncertain grade and quality of deposits makes economic outlook poor for commercial development
Legal regime	Under U.S. jurisdiction on the Outer Continental Shelf	Beyond U.S. jurisdiction: right to license development activities by U.S. citizens claimed by U.S. but challenged by supporters of the U.N. Convention on the Law of the Sea	Under U.S. jurisdiction on continental slope

SOURCE: Office of Technology Assessment

the costs of the mining and processing equipment were well developed. It is now apparent that capital and operating costs of deep ocean mining would be much higher that current costs of mining on land, and these high costs more than offset the higher value of the metals that the nodules contain.

There is little detailed information available about cobalt-bearing manganese crusts. These deposits are similar to the Pacific nodules, except that they are in the form of thin crusts bonded to the underlying rock on the slopes of seamounts such as the Hawaiian Islands. In some cases, the crusts have been found to be enriched with cobalt. In some samples, peak cobalt contents of more than 1 percent have been measured, but average cobalt levels have been less than 0.8 percent,

While interest in nodules has declined, the cobalt-bearing manganese crusts of the Pacific seamounts have gained increased attention. The high cobalt content of some of the crusts presents the same attraction that was once presented by Pacific nodules. The high value of the metal contained in the crusts, whether measured in price or strategic interest, overshadows the high cost of recovering the metals from their challenging environment and difficult mineral structure. Even though land-based deposits may have lower content of cobalt, nickel, or copper, they are more attractive to investors because the cost of recovering the metals is significantly lower. For manganese, the case for land-based production is even stronger since land ores are generally higher in manganese content, easier to mine, and more familiar to consumers in the metallurgical industries.

If so desired, the U.S. Government could assist private industry in overcoming the substantial barriers to exploitation of ocean-based resources of strategic materials and thereby encourage industry to commit the major sums needed to build and operate an ocean mine. Unless there is a major increase in prices for nickel, copper, and cobalt, the cost to the government of such assistance would be substantial. Furthermore, an ocean mine would not be secure against interruption; it would be vulnerable to physical interference at sea, and, without a widely accepted legal regime for exploitation of the minerals of the seabed, it could be the subject of international legal and political disputes.