# Open File Report 95-86



# Availability of Selected Strategic and Critical Minerals:
## Role of the Republic of South Africa

Minerals Availability Program



BUREAU OF MINES
UNITED STATES DEPARTMENT OF THE INTERIOR

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16. Abstract (Limit: 200 words)

Possible consequences of continuing internal political unrest and the imposition of foreign sanctions raise concerns about the traditional reliability of the Republic of South Africa as a major world supplier of important minerals. A recent Bureau of Mines' technical report (Open File Report 76-86) examined the impacts of temporary peacetime disruption scenarios for six key materials and mitigating options. Because of South Africa's dominant producer position for these minerals (except for cobalt), expansion of primary production capacity outside of South Africa is not a short term mitigative option. However, prospects of a longer term disruption would likely spur investment in capacity expansion in alternative Market Economy Country supply sources. This report identifies the resources, production costs, and burdens that would be placed on alternative MEC producers of chromium, cobalt, gold, manganese, and platinum-group minerals if South Africa's production were subject to a long term disruption. When long term supplies from South African deposits are discounted, more than a few years reserves were found only for cobalt and manganese. Even for these two minerals, higher sustained prices would be required to increase manganese production capacity and to support means of cobalt transportation not through South Africa.

17. Document Analysis a. Descriptors

| | | |
|---|---|---|
| South Africa | Resources/Reserve Base | Gold |
| Market Economy Countries | Production Costs | Manganese |
| Strategic and Critical Minerals | Chromium | Platinum-Group Metals |
| Minerals Availability | Cobalt | Geology |

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

| 18. Availability Statement | 19. Security Class (This Report) | 21. No. of Pages |
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# PREFACE

Internal political unrest as well as possible reactions to sanctions imposed by other countries have raised questions concerning the continued reliability of the Republic of South Africa as a major exporter of important minerals to the U.S., Japan, and the European Economic Community (EEC). A number of studies have resulted, including a report submitted to Congress by the Bureau of Mines analyzing the impacts resulting from various temporary peacetime mineral supply disruption scenarios, and the effectiveness of options available for mitigating those impacts. The study indicated that chromium and platinum-group metals pose more of a potential availability problem than do manganese, vanadium, or cobalt. Since the behavior of producers and consumers during a market disruption depends on their perception of its likely duration, severity, and recurrence, price increases could induce investment in new primary capacity outside South Africa that could have long term implications.

The Bureau of Mines assesses and classifies the primary mineral supply potential of Market Economy Countries (MEC) in terms of the relative size and estimated cost competitiveness of their minable resources. This report summarizes Bureau information on MEC resources (including production costs) of chromite, cobalt, gold, manganese and platinum group metals and, in-part, is a pre-release of summary data being prepared for publication on the long term availability of the nonfuel minerals studied by the Bureau's Minerals Availability program. The availability analyses have been modified to quantitatively differentiate the tonnage and cost potential of South African and alternative MEC primary suppliers. The types and effectiveness of long term mitigative measures, other than capacity addition, that would partially compensate for dramatically reduced primary production are not addressed.

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CHAPTER 1 INTRODUCTION

## BACKGROUND

South Africa is a principal source of several metals considered essential to the U.S. economy and security, and provides access to international markets via its transportation infrastructure for some neighboring countries which are also important mineral suppliers. The historic reliability of this region may be changing. A thorough understanding of the dominant producer position and extent of market economy country (MEC) dependence on these sources is fundamental to adjusting to a potential change in their reliability.

A recent U.S. Bureau of Mines' study, SOUTH AFRICA AND CRITICAL MATERIALS (1)*, focused on options for mitigating the impact of a temporary (3 years or less) disruption of South African supplies of six key minerals -- chromium, manganese, platinum-group metals (PGM's), cobalt, gold, and vanadium. Mitigating factors, such as existing stocks, excess or readily expanded mining and processing capacity outside South Africa, and technically and economically feasible substitution or conservation measures, including increased recycling of secondary materials, were evaluated. Chromium and PGM's were judged to present greater potential availability problems than manganese, vanadium, or cobalt. Extended price increases could induce investment over the long term in alternative sources. Potential longer term disruption of South Africa's mineral supplies increases the significance of alternative primary sources of certain minerals.

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*Underlined numbers in parentheses refer to items in the list of references at the end of each chapter.

The purpose of this report is to identify and compare the size and competitiveness of southern African and major alternative primary sources of chromium, cobalt, gold, manganese, and PGM's. Brief background information on the uses and importance, geological occurrence, and recent mine production of each mineral are followed by estimates of long run average production costs by region, and of aggregate availability. Evaluated resources of the five mineral commodities occur in 28 MEC's, including South Africa. Two availability curves are generated each for chromite, gold, and manganese at a 0-pct DCFROR. One depicts potential production from all MEC resources evaluated, and one depicts MEC resources less South Africa. (The vintage and scope of the resource data used in these studies are indicated for each mineral commodity.) Availability analyses provide insight into the burdens that would be placed on alternative primary suppliers by a long run disruption of South Africa's mineral production. Only minor amounts of cobalt are produced in South Africa -- a byproduct of PGM production -- most of it coming from Zaire and Zambia via South Africa's transportation infrastructure, as a byproduct of copper mining.

The rest of this introductory section provides a context for interpreting the commodity specific information in the body of this report by explaining the Bureau of Mines' Minerals Availability Program, mineral resource classification, and analytical approach.

## MINERALS AVAILABILITY PROGRAM

The Minerals Availability program (MAP) investigates the mineral supply potential of the United States and MEC's for minerals considered either essential or strategic to the U.S. economy and national security. Major activities include identification of important mines and mineral deposits, evaluation of their production costs, and assessments of physical, technologic, and economic factors that influence their production costs, hence minerals availability. Products range from data printouts of geological and engineering information to discounted cash flow analyses of individual mining operations and commodity availability curves. These outputs assist in assessing the minerals supply position of the United States, and in the formulation and evaluation of national policies that affect minerals such as provisions of the Trade Acts, Federal tax changes, and measures affecting the National Defense Stockpile. Engineering and economic analyses help set priorities for Federal programs in the development of new technologies to reduce costs, and minimize adverse environmental impacts and costs of mining and materials processing. The unique and key attributes of the program are its comprehensive resource, cost-engineering, and economic data for major international mines, deposits, and mineral processing facilities; data updating routines; and analytic systems enabling economic sensitivity analyses of the external variables that affect mineral production. Over 30 nonfuel minerals are presently included in the MAP. The resource potential of centrally planned economy countries (CPEC's) are not appraised by this method because of the general lack of individual deposit data.

The results of the MEC availability studies have been published, or are in final publication process, for all the covered minerals. This report updates availability information on five mineral commodities, previously published in Bureau of Mines Information Circulars (2, 3, 4, 5, and 6), for which South Africa or its neighboring countries are the important MEC producers. Updated summary availability information on all commodities evaluated will be published in 1987.

## MINERAL RESOURCE CLASSIFICATION

Mineral resources are characterized by the certainty of knowledge of the geology of the resource and by degree of economic viability. The Bureau of Mines assesses reserves and resources according to resource classification principles (7) agreed to by the Bureau of Mines and U.S. Geological Survey (USGS) to assure comparable and coordinated reporting of domestic and international resource information. Methods for estimating resources can be variable depending on the commodity, available information, and needs of the estimator, but the criteria and methodology must be specified.

Figure 1.1 conceptually illustrates the range and categorization of total resources according to level of geologic knowledge (horizontal axis) and estimated economic viability (vertical axis). Identified resources encompass a range of geologic confidence, measured through inferred--the level of assurance is determined by engineering measurement criteria. Demonstrated resources imply sufficient quantitative and qualitative resource assurance to design an extraction plan.

Reserve base is a more subjective category encompassing economic and subeconomic resources having, or presumed to have, technical and economic development potential in the foreseeable future. Reserve base estimates may be in terms of in situ material for an arbitrarily determined number of deposits or they may be in terms of recoverable ore (in situ material less mining and processing losses) determined on the basis of economic evaluation. Different reserve and resource estimating techniques and reporting requirements result in differing total estimates. The Bureau evaluates the economic viability of mineral resources and the USGS estimates geologic endowments. Throughout this report, resource and reserve base estimates representing recoverable quantities evaluated for significant properties are related to in situ materials reported by the Bureau of Mines and USGS.

Any assessment of economic resource potential is inevitably a point-in-time estimate, constrained by incomplete geological knowledge of resources and the necessity to make assumptions with respect to extraction technology and the interplay of political, economic, and institutional factors on minerals supply. Thus, while determination of tonnage and grade is a straight forward process of exploration, economic value can be estimated only by consideration of production costs and commodity prices which are variable over the life of the mine. Economic categorization is further complicated by the presence of co- and byproduct elements that enhance or detract from the value of the primary commodity. For some important minerals, e.g., cobalt, which is produced almost exclusively as a byproduct of copper and nickel mining, the availability of the byproduct commodity is determined by the production of the primary commodity. Thus, the challenge to resource classification is to consistently and comprehensively handle the significant deposit and commodity specific physical, technical, and economic variables that influence mineral commodity availability.

## AVAILABILITY ANALYSIS APPROACH

Identifying the relative economic viabilities of mines or producing regions requires going beyond geological estimates of resources to mining and processing cost analysis. Traditional aggregate estimates of commodity resources are usually limited to geological assessments of in situ resources and are characterized by subjective or arbitrary assumptions of current and future economic viability. Availability analysis involves developing costs in terms of a product for which a market price exists. This requires identifying specific mines and deposits, estimating the recoverable in situ material, and

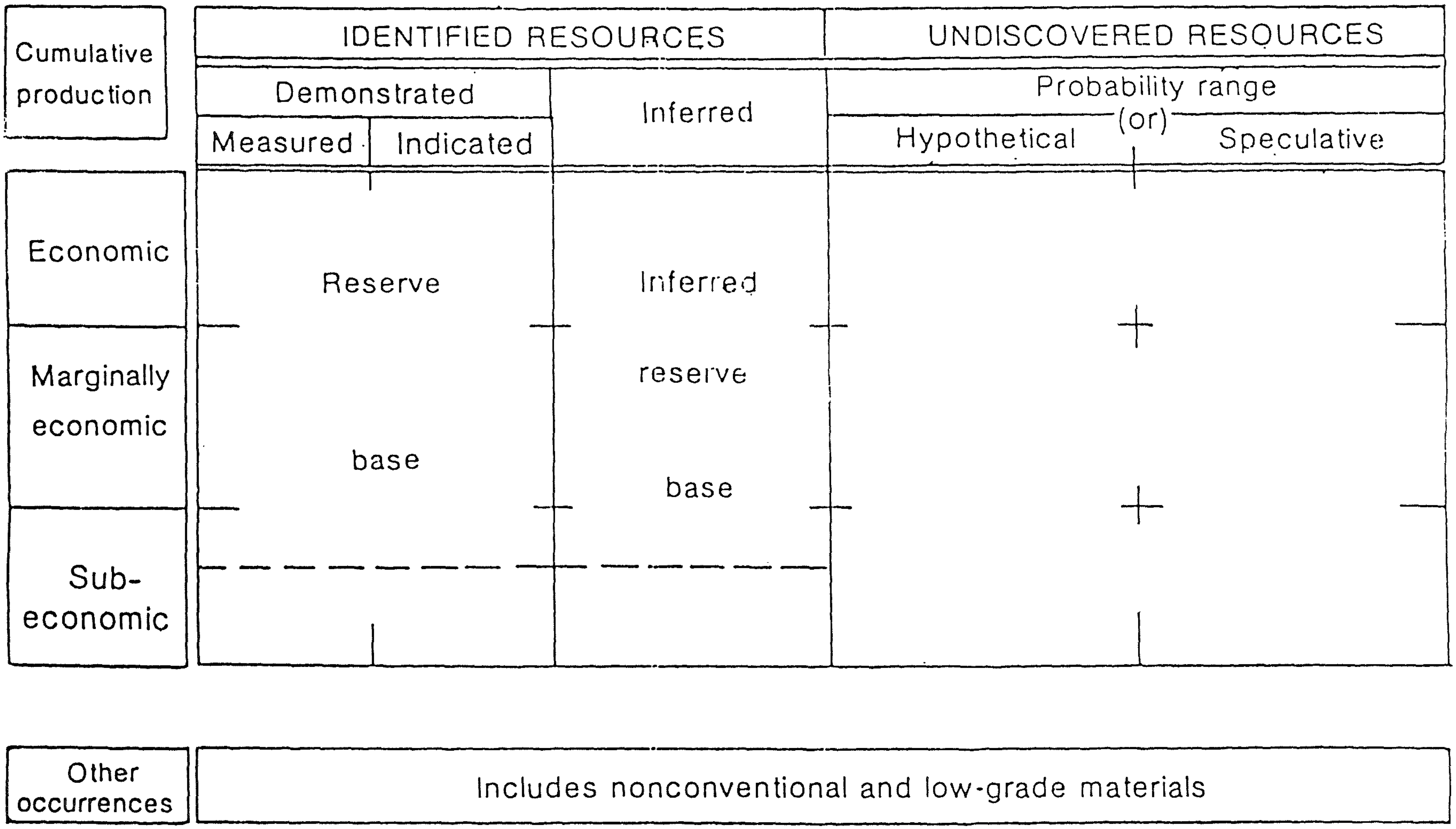


FIGURE 1.1 - MAJOR ELEMENTS OF MINERAL-RESOURCE CLASSIFICATION

determining the entire cost (mining, milling, smelting/refining, transportation) to produce a commodity which is traded on international markets. Once engineering and economic costs are developed, computer technology enables rapid updating and analysis of economic variables that collectively affect the relative costs of individual mineral deposits. Technical advance and new resources are addressed through deposit evaluation updating. Although political and institutional and macroeconomic factors may significantly modify the technical and economic availability of minerals, and can, when specified, be gauged by sensitivity analyses, they are not addressed here.

Known producing and developing mines are ranked by capacity and resources and are included in the availability studies in descending order of size to the point where their collective capacity represents 85 to 90 pct of MEC current production. Comparable undeveloped deposits are ranked and included similarly. However, comprehensive and uniform coverage across countries is constrained by budget, time, and data availability limitations. For example, MAP, resource estimates tend to be conservative where identified resources are sufficient to meet world demand into the indefinite future, governments tax reserve values, resource estimation is difficult because of the geology, or where most production comes from many small deposits rather than a few large ones.

The geographic distribution of mines and deposits included in the commodity availability studies are mainly a function of geologic endowment and information availability. Sufficient geological definition (including ore body dimensions, mineralogy, depth, attitude, host rock, etc.) is needed for the postulated resource at each property to estimate capital and operating costs. For the operating mines in the study, the costs include recovery of undepreciated original investment, capital reinvestment at intervals to replace equipment, mine and mill operating costs, transportation, and smelter and refinery costs. Undeveloped properties require pre-feasibility design of capacity parameters and infrastructure, and mine and mill capital and operating cost estimations. Total annual costs and revenues are estimated over the projected life of each mine via an economic time diagram to support financial analysis. Foreign production costs are adjusted to U.S. dollars using current exchange rates.

Economic analysis of the production costs, including a specified rate of return, and revenues are determined through discounted cash flow methods with credit for applicable depletion, depreciation, etc. Economic costs such as taxes and royalties are calculated against the estimated annualized yield. The result is a total production cost (mining through refining) averaged over the mine life for each mineral property evaluated. Availability curves rank and relate the average total production cost of each mine to the collective demonstrated resources.

## ADDITIONAL PRIMARY SOURCES

Reserve and resource inventorying, and rigorous availability appraisals developed by the process described above, provide a static estimate of mineral supply potential. Figure 1.2 depicts the dynamic nature of the economic and geologic resource categories in Figure 1.1. Geologic knowledge is expanded through exploration, the intensity of which is related to actual and expected mineral prices, and economic viability is cumulatively affected by improved recovery technology, changing factor and commodity prices, and even regulation.

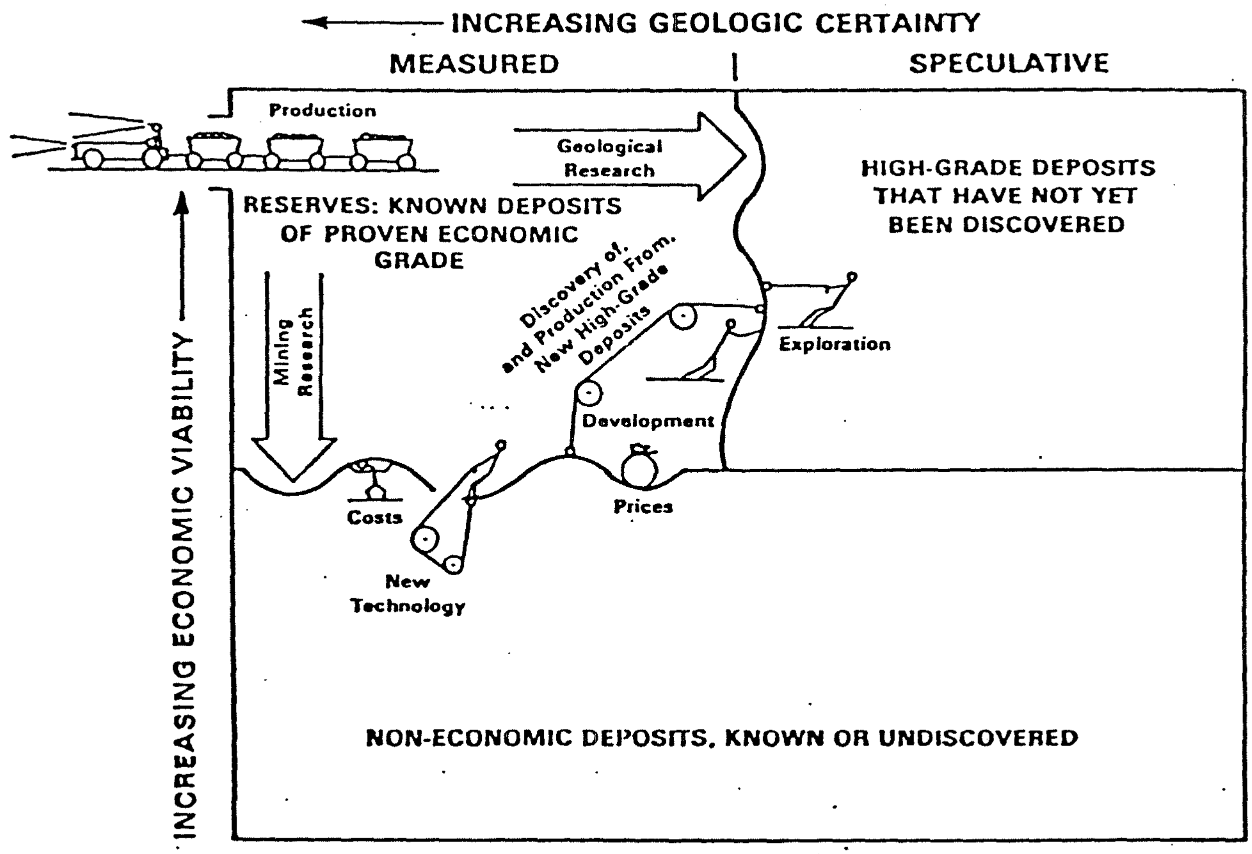


FIGURE 1.2 - MINERAL RESOURCE CLASSIFICATION DYNAMICS

The availability estimates reported in the following chapters were developed from site-specific resource data collected between 1979 and 1983, and updated to 1985 by decreasing reserves by capacity production over the interim. Cost estimates of the same vintage were updated to 1985 dollars using detailed indexes for various cost categories. To supplement the availability estimates derived from this vintage data, a descriptive section is provided of additional resources not included in the original availability studies of each mineral. Preliminary analysis indicates that MAP coverage of chromite and manganese in South Africa and cobalt in Zaire and Zambia is less complete (56, 54, and 41 pct, respectively, of reserves estimated in (8)) than in the MEC as a whole (75 pct, 87 pct and 70 pct). Only with gold does MAP cover a larger share (91 pct versus 80 pct)) of southern African than MEC reserves. Differences in PGM data definitions do not permit developing this comparison.

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# CHAPTER 2 CHROMIUM

## BACKGROUND

### Use and Importance

Chromite ore and concentrates and associated products of ferrochromium, chromium metal, chromium chemicals, refractory bricks, etc., are essential materials to the U.S. economy. Chromium is critical in metallurgical applications in that it imparts harden ability to alloy steel and resistance to oxidation and corrosion to stainless and heat resistant steels and alloys. There is no substitute for chromium in its major metallurgical use in stainless steel. Chromium, derived from chromite ore, is also used in the chemical and refractory industries. No significant chromite production has occurred in the U.S. since 1961, when the American Chrome Company fulfilled a nine-year government contract to produce a 850,000 mt (approximately) stockpile of chromite concentrate from the Stillwater Complex, Montana. Over the last five years, net chromium import reliance as a percent of apparent consumption has ranged from 90 pct in 1981 to 73 pct in 1985. The difference, 10 pct in 1981 and 27 pct in 1985, represents the recycling of purchased stainless steel scrap.

U.S. consumption of primary chromium in 1983 was estimated to be 229,000 metric tons (mt), equal to about 750,000 mt of chromite at the world's average grade. World consumption in 1983 was 2.5 million mt chromium or about 8.2 million mt chromite (1). Primary chemical applications are in the production of pigments, in metal plating and other metal treatment, in leather tanning, and as a catalyst. Refractory applications involve the use of chromite ores and concentrates in making basic refractory bricks of chromite-magnesia or magnesia-chromite refractory composition for use primarily in open-hearth furnaces. Also included in this refractory use category are foundry sands mainly produced in South Africa and Finland which are used for molds. Of the chromite consumed in the U.S., the metallurgical and chemical industries account for 86 pct and the refractory industry consumed 14 pct (2). These consumption percentages apply in general to other major MEC industrial nations.

Chromium is traded as chromite ore, and ferrochromium--an intermediate metallurgical product derived from ore by electric furnace smelting and used in quantity for steelmaking. Advances in ferrochromium production technology and changes in steelmaking technology have permitted the use of a wider variety of ores in metallurgical applications that have changed the traditional basis of classifying chromite ores by rigorous metallurgical, chemical, and refractory end use specifications. Now ores are more generally classified by the proportion of chromium to iron, magnesium, and aluminum in the ore mineral itself. Thus, high-chromium (to iron) ores are used mainly in metallurgical applications in the production of ferrochromium; high-iron chromite, formerly used mainly in the chemical industries, is now being used to produce low-chromium ferrochromium, and in refractories; and high-aluminum ores are used for refractory purposes. High-iron ores are also used in foundry sands. While greater than to 2:1 chromium-to-iron ratios are desirable for high-chromium ferrochromium, lower grade ferrochromium, "charge chrome," is being increasingly used in stainless steelmaking. Hence, some chemical-grade ores are now suitable for metallurgical purposes (2).

## Geology

Although the element chromium is found in a variety of minerals, all present commercial ore reserves and mineral resources of chromium are comprised of the mineral chromite (chromite henceforth means the marketable ore). Chromite quantities are expressed as gross weight mt with an associated chromic-oxide content (grade) expressed as percent $Cr_2O_3$. At present, marketable chromite products have $Cr_2O_3$ weight percentages ranging from the low 30's to the low 50's with the vast majority of producers in the 40-50 pct $Cr_2O_3$ range. These products are presently being produced from in situ ores grading from 20-50 pct $Cr_2O_3$. Natural characteristics such as the chromium-to-iron ratio (Cr:Fe), the chromite grain size and the $SiO_2$, $Al_2O_3$, MgO, and P contents are as important as the $Cr_2O_3$ content in determining the suitability of a chromite product for varying end uses.

Chromite mineralization occurs as massive or disseminated chromite grain accumulations in three broad types of structural or genetic deposit classifications. The three classes--stratiform, podiform, and eluvial-alluvial-lateritic deposits--are described in the following paragraphs.

Stratiform deposits are characterized by very large extents in two dimensions and small thicknesses (usually less than 3 m). In every major example of this type of chromite deposit, Bushveld Complex of South Africa, the Great Dyke of Zimbabwe, the Stillwater Complex in Montana, the Fiskenaesset Complex in Greenland, and the Bird River Sill in Manitoba, Canada the entire sequence contains more than one, and sometimes many different layers (or seams). Chromium-to-iron ratios are low in the vast majority of stratiform deposits--1.0 to 1.5 for the Greenland and Canadian deposits; 1.5 to 2.2 at the Stillwater Complex, Brazilian, some South African deposits; and

2.0 and above at the Great Dyke deposits in Zimbabwe.

Podiform deposits exhibit a variety of shapes such as pods, lenses and pipes, and even "U" shapes. In any particular area of podiform chromite deposits, the vast majority of the deposits are of small size (less than 100,000 mt). These deposits occur randomly in ultramafic rocks where their small size and conformity with the host rock make exploration and reserve extension difficult. The $Cr_2O_3$ typically ranges from 18-50 pct; the Cr:Fe ratio is typically greater then 2:1.

Eluvial-alluvial-lateritic chromite deposits are a genetic classification resulting from the weathering of ultramafic igneous intrusions. They are low-grade (less than about 15 pct $Cr_2O_3$ in situ) and consist of disseminated chromite grain accumulations either left in situ or transported from the original deposit. Examples of this chromite deposit classification include the eluvial deposits of Zimbabwe (which have seen production in the past), the Oregon beach sand deposits of the U.S.; numerous deposits in the Philippines; the Ramu River deposit in Papua New Guinea; laterites on the U.S. west coast (California and Oregon); and the Plum deposit located off-shore of New Caledonia.

## Production

Chromite is the primary chromium source material for all ferroalloy, metal, chemical, and refractory products that contain chromium. Hence, chromite is produced to many different specifications. Chromite is herein used to encompass the beneficiated, post-mill product of chromium ore, that is traded for its chromium content for the purpose of a general overview of chromium availability. In 1983, world chromite production was estimated at about 8.1 million mt, containing 2.45 million tons of chromium (1).

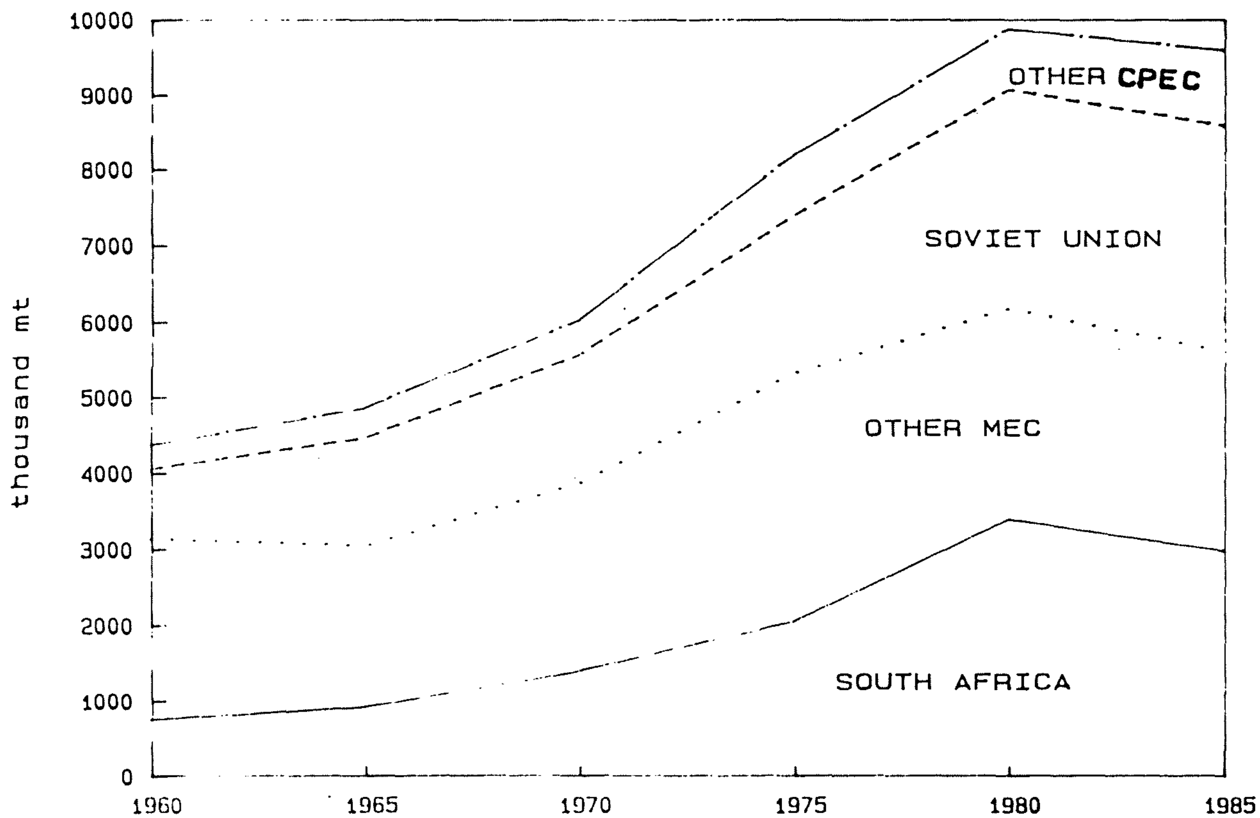


FIGURE 2.1 WORLD CHROMITE PRODUCTION 1960 - 1985

Figure 2.1 shows world production of marketable chromite products in 5-yr intervals from 1960 through 1985. Total world production of chromite has more than doubled over the last 26 years. The increase in annual world production has been shared almost equally between the MEC and CPEC. About 90 pct of the MEC increase over this period came from only 1 country--South Africa--which increased its annual production by 2.2 million mt and now accounts for 53 pct of MEC production and 31 pct of world production. Other MEC production increases since 1960 have occurred in India (+354,000 mtpy), Finland (+272,000 mtpy), Brazil (+266,000 mtpy) and Turkey (+154,000 mtpy of output). Significant decreases to annual output in major MEC producing countries since 1960 have occurred in the Philippines (-462,000 mtpy) and Zimbabwe (-185,000 mtpy).

The Soviet Union accounts for 75 percent of CPEC production and 31 percent of world production. Soviet chromite production is estimated to have increased by 2.0 million mtpy since 1960. Albania has become the third largest world chromite producer and now accounts for roughly 9 percent of world production. As a group, CPEC's account for about 40 percent of world production.

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*Shipping grade is defined as deposit quantity and grade normalized to 45 percent $Cr_2O_3$ for high-chromium and high-iron chromite and 35 percent $Cr_2O_3$ for high-alumina chromite. High-alumina chromite is defined as chromite containing more than 60 percent combined $Cr_2O_3$ and $Al_2O_3$.

The in situ numbers alone are normalized to allow for quantitative in situ cross-country resource comparisons. These resource data are not directly comparable with the evaluated in situ normalized chromite tonnages which represent actual resource quantities and grade.

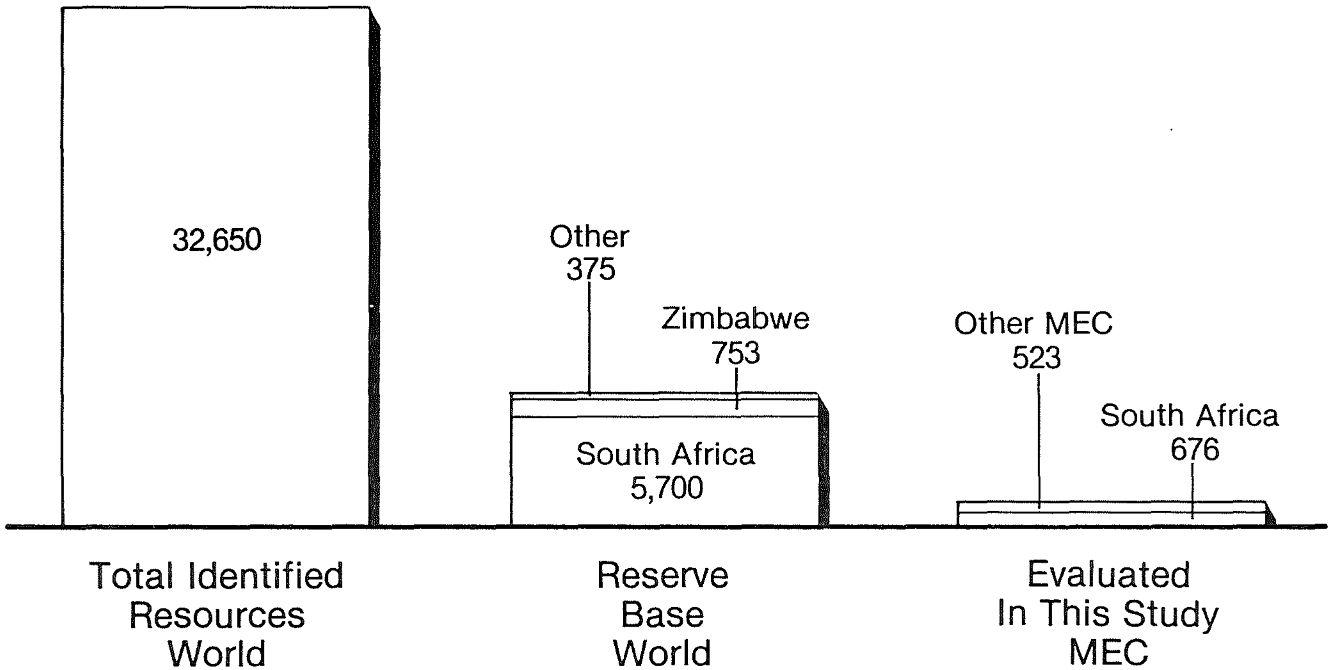



**Figure 2.2 World Chromite Resources (Million Metric Tons)**

EVALUATED RESOURCES

Figure 2.2 places the resources evaluated in the perspective of total identified resources. According to the Bureau, in 1986 (3) "world resources total about 36 billion mt of shipping grade* chromite, sufficient to meet conceivable world demand for centuries." The in situ reserve base values for chromite are shown as a the second stack in figure 2.2. Only two countries, South Africa and Zimbabwe account for 95 percent of the 6.8 billion mt reserve base, and the MEC's as a group represent over 97 percent. Resources in the United States are mostly in the Stillwater complex of Montana, black beach sands of Oregon, and numerous podiform some and laterite deposits in northern California and southern Oregon.

MEC chromite resources evaluated in this study total 1.2 billion mt in situ and, although they represent only a small portion of the MEC reserve base value, they still would support over 120 years of MEC chromite production at current levels. Table 2.1 lists the chromite mines and deposits evaluated in the availability study. In all of the nations where the majority of past production has come from podiform deposits (e.g. the Philippines, Turkey, Greece, Madagascar, Zimbabwe, the Soviet Union, and Albania) only a small percentage of the total number of deposits have provided the bulk of past production. In situ grades of the podiform deposits analyzed in this study range from 18 to 50 pct $Cr_2O_3$ and all have Cr:Fe ratios greater than 2.0 and are classified as high-chromium deposits. In situ $Cr_2O_3$ grades range from the high 20's to the high 40's for producing stratiform deposits evaluated, and from about 12 pct to 25 pct for the nonproducing stratiform deposits.

TABLE 2.1. -List of chromite operations included in the study[1]

| Name | Type of Occurrence | Status[2] |
|---|---|---|
| Brazil: | | |
| Pedrinhas (Campo Formoso) | Stratiform | P/S |
| Limoeira (Campo Formoso) | ....do.... | P/S |
| Finland: | | |
| Kemi | ....do.... | P/S |
| Greece: | | |
| Xerolivado | ....do.... | P/S |
| India: | | |
| Byrapur | ....do.... | P/S |
| Jambur-Tagadur | Stratiform | E |
| Cuttack District-low grade | Stratiform-podiform | E |
| Cuttack District-high grade | ....do.... | P/S |
| Keonjhar District-low grade | ....do.... | E |
| Keonjhar District-high grade | ....do.... | P/S |
| Madagascar: | | |
| Andriamena | ....do.... | P/S |
| Ranomena | ....do.... | P/S |
| New Caledonia: | | |
| Tiebaghi (Chromical) | Podiform | P/S |
| Philippines: | | |
| Masdang | ....do.... | P/S |
| Narra | ....do.... | P/S |
| Acoje (Santa Cruz) | ....do.... | P/S |
| Candelaria | ....do.... | P/S |
| Lagonoy | ....do.... | P/S |
| Llorente | Eluvial-alluvial | E |
| Bicobian | Lateritic-eluvial | E |
| Batang-Batang | Alluvial | P/S |
| Bacungan | Podiform-eluvial | P/S |
| Irahuan | Podiform-eluvial | P/S |
| Coto-Masinloc | Podiform | P/S |
| Kinmalgin | ....do.... | P/S |
| South Africa: | | |
| Zwartkop | Stratiform | P/S |
| Rustenberg | ....do.... | P/S |
| Ruighoek | ....do.... | P/S |
| Ntuane | ....do.... | P/S |
| Waterkloof | ....do.... | P/S |
| Millsell | ....do.... | P/S |

TABLE 2.1. -List of chromite operations included in the study[1]
Continued

| Name | Type of Occurrence | Status[2] |
|---|---|---|
| South Africa--Continued: | | |
| Kroondal | ....do.... | P/S |
| Bayer A.G. (Chrome Chemicals) | ....do.... | P/S |
| Henry Gould | ....do.... | P/S |
| Mooinooi | ....do.... | P/S |
| Jagdlust | ....do.... | P/S |
| Winterveld (TCL) - North Section | ....do.... | P/S |
| Groothoek | ....do.... | P/S |
| Dilokong | ....do.... | P/S |
| Montrose (Hendriksplaats) | ....do.... | P/S |
| Winterveld (TCL) - South Section | ....do.... | P/S |
| Lavino (Grootboom) | ....do.... | P/S |
| Grasvally | ....do.... | P/S |
| Marico (Nietverdiend) | ....do.... | P/S |
| Zeerust | ....do.... | P/S |
| Tweefontein | ....do.... | P/S |
| Chromebroone | ....do.... | P/S |
| Turkey: | | |
| Kefdag | Podiform | P/S |
| Soridag | Stratiform | P/S |
| Kavak | Podiform | P/S |
| Kopdag West-North Zone | ....do.... | P/S |
| Uckopru | ....do.... | P/S |
| Kandak | ....do.... | P/S |
| Zimbabwe: | | |
| Glenapp-Ivo | ....do.... | P/S |
| Impinge | ....do.... | P/S |
| Sutton-Rodcamp | ....do.... | P/S |
| Vanad | ....do.... | P/S |
| Caesar | ....do.... | P/S |
| Crown-Divide North | ....do.... | P/S |
| Glenapp-Hay-Noro | ....do.... | P/S |
| Umvukwes | ....do.... | P/S |
| Ore Recovery Tribute | ....do.... | P/S |
| Greenvale | ....do.... | P/S |
| Maryland | ....do.... | P/S |
| McGowan | ....do.... | P/S |
| Divide | ....do.... | P/S |
| Rutala | ....do.... | P/S |
| Umsweswe | ....do.... | P/S |
| Umsweswe-Bee | ....do.... | P/S |
| Windsor/York/York West | ....do.... | P/S |
| Bat Claims | ....do.... | P/S |
| Lalapanzi | ....do.... | P/S |
| Netherburn | ....do.... | P/S |
| York | ....do.... | P/S |

TABLE 2.1. -List of chromite operations included in the study[1]
Continued

| Name | Type of Occurrence | Status[2] |
|---|---|---|
| Zimbabwe - Continued: | | |
| Railway Block | Podiform | P/S |
| Selukwe Peak | ....do.... | P/S |
| Valley Chrome | ....do.... | P/S |
| Magazine Hill | ....do.... | P/S |
| Iron Sides | ....do.... | P/S |
| Iron Ton | ....do.... | P/S |
| Belingwe District | ....do.... | P/S |
| Impinge (Eluvial) | Eluvial | P/S |

[1]The term "operation" refers to either an individual mine or group of mines, or an area, section, or district, depending upon the criteria of each individual nation under study.

[2]The status is listed as either P/S or E. If listed as P/S, the operation is either a current or past producer. If listed as E, no production is known to have occurred as of January 1985.

## Mining

The vast majority of the South Africa and Zimbabwe resources are mined by underground methods. In general, the mining method in use on the Bushveld Complex, breast stoping, does not vary a great deal from operation to operation since the seams all dip gently (5-25 degrees) and have similar structural characteristics. The most significant difference affecting mine operating cost, is the thickness of the chromite seam. In the majority of South African operations, the seam thickness is 0.9 m or greater and usually represents 90 pct of stope height, which means that what little waste is produced can be backfilled in the mine. However, for some seams as thin as 0.4 m, fully half of the material blasted is waste that must be hoisted to the surface. This waste haulage and disposal can add as much as 60 pct to the mine operating cost on a crude ore basis. In Zimbabwe's Great Dyke, by comparison, the seams range in thickness from 0.1 to 0.3 m which means that up to 90 pct of the blasted material may be waste, with generally 40-50 pct of the waste having to be disposed of on the surface. Because of this, the cost to mine one ton of chromite from the stratiform deposits of the Great Dyke is roughly four times higher than mining the stratiform deposits of the Bushveld Complex in South Africa. Some Great Dyke deposits are mined by resuing, a high cost method that usually produces a direct shipping grade ore, and is particularly appropriate to very thin, high grade seams . Since the bulk of the known world resources are contained in South Africa and Zimbabwe, and since about 90 pct of Zimbabwe's chromite is contained in the Great Dyke, differences in seam thickness and its effect on mining costs are significant.

The underground mining of the podiform deposits in the Shurugwi and Belingwe districts of Zimbabwe, have involved many different mining methods over time. At Shurugwi, the prevalent present method is sublevel stoping which is estimated to have a weighted average mining cost of $34/mt of ore.

Other major podiform underground mining operations are two high-grade Philippines' producers, six major Turkish operations, as well as the mines in Greece and New Caledonia. Mining methods differ somewhat for all of these mines, but all of the large scale underground mines extracting ore from podiform deposits have extremely competitive mining costs.

Actual or proposed surface mining operations in this availability study include the majority of the resources and properties in India and the Philippines, as well as all of the properties in Brazil, Madagascar and Finland. Because of the wide range of surface mining operational aspects (e.g., waste to ore ratios, haulage distances and capacities), the surface mining category also shows a relatively wide range of economic viabilities.

## Processing

The complexity of chromite ore processing ranges from simple hand-sorting and screening operations to mills utilizing a combination of heavy media, gravity, magnetic, and high-tension electrostatic separation methods. The separation of lump material from fines and the upgrading of the $Cr_2O_3$ content are especially important at operations producing products for the metallurgical industry, while the elimination of excess iron is particularly important in processing low-grade ores, especially laterites. The lowering of the $SiO_2$ content is critical to chemical and refractory products.

The separation of lump ore from fines is accomplished either by sorting and screening or by heavy media separation. Magnetic separation is used at a limited number of properties to eliminate as much excess iron as possible. Nearly all of the analyzed operations require gravity separation methods to

TABLE 2.2. - Cost, Capacity, and Resources for selected MEC chromite mines and deposits (All costs are expressed in January 1985 U.S. dollars per metric ton of chromite on a weighted-average basis)

| Country | Demonstrated Resources($10^3$mt) in situ ore | Demonstrated Resources($10^3$mt) Recoverable chromite | Potential[1] Annual Chromite capacity ($10^3$) | Total Operating cost[2] | Production cost 0-pct[3] | Production cost, 15-pct[4] |
|---|---|---|---|---|---|---|
| South Africa | 675,786 | 466,631 | 5,300 | $50.00 | $57.00 | $62.00 |
| Zimbabwe: | | | | | | |
| Seam type | 174,422 | 114,617 | 470 | 184.00 | 202.00 | 220.00 |
| Podiform type | 14,357 | 11,730 | 520 | 111.00 | 114.00 | 139.00 |
| India:[5] | | | | | | |
| High grade | 13,225 | 9,904 | 220 | 53.00 | 57.00 | 63.00 |
| Low grade | 66,610 | 32,281 | 320 | 84.00 | 105.00 | 159.00 |
| Philippines:[6] | | | | | | |
| Low grade | 177,224 | 5,765 | 230 | 96.00 | 119.00 | 151.00 |
| High grade[7] | 18,559 | 7,640 | 810 | 41.00 | 53.00 | 65.00 |
| Turkey[8] | 8,300 | 5,846 | 420 | 51.00 | 64.00 | 69.00 |
| Others[9] | 49,838 | 25,209 | 960 | 25-84.00 | 27-131.00 | 27-176.00 |
| GRAND TOTAL | 1,198,000 | 680,000 | 9,200 | NM | NM | NM |

NM Not meaningful

[1] Potential average annual chromite product capacity that could be achieved in a three year period given that all properties were developed and/or operated according to the mining development plans incorporated into the analysis.

[2] Equal to the sum of mining, milling and transportation costs FOB the port of exportation.

[3] Equal to the sum of total operating costs, taxation and capital recovery determined at a 0-pct DCFROR.

[4] Equal to the sum of total operating costs, taxation generated at a 15-pct DCFROR, capital recovery plus a 15 pct return on unrecovered capital.

[5] Chromite resource separated into high and low grade for economic analysis. Low grade resource represents chromite in the Cuttack and Keonjhar Districts grading 30 pct $Cr_2O_3$ on average.

[6] Chromite resource separated into high and low grade for economic analysis. Low grade resource represents chromite in alluvial, eluvial and lateritic deposits with a weighted average grade of 2.0 pct $Cr_2O_3$.

[7] Does not include 21 non-refractory deposits containing about 1.8 million mt of in situ resource. Eighteen are very small (average 40,000 mt reserve); three are fairly large (average 360,000 mt). Does not include a further 12 refractory deposits containing about 1.1 million mt of in situ resource. Ten are very small (average 50,000 mt); two are fairly large (average 300,000 mt). Small size or lack of data precludes estimation of costs.

[8] Does not include the many small deposits and operations, representing 20 to 30 pct of Turkey's overall total production of chromite products, which are too small or sporadic to evaluate for costs.

[9] Others category includes Brazil, Finland, Madagascar, Greece, and New Caledonia.

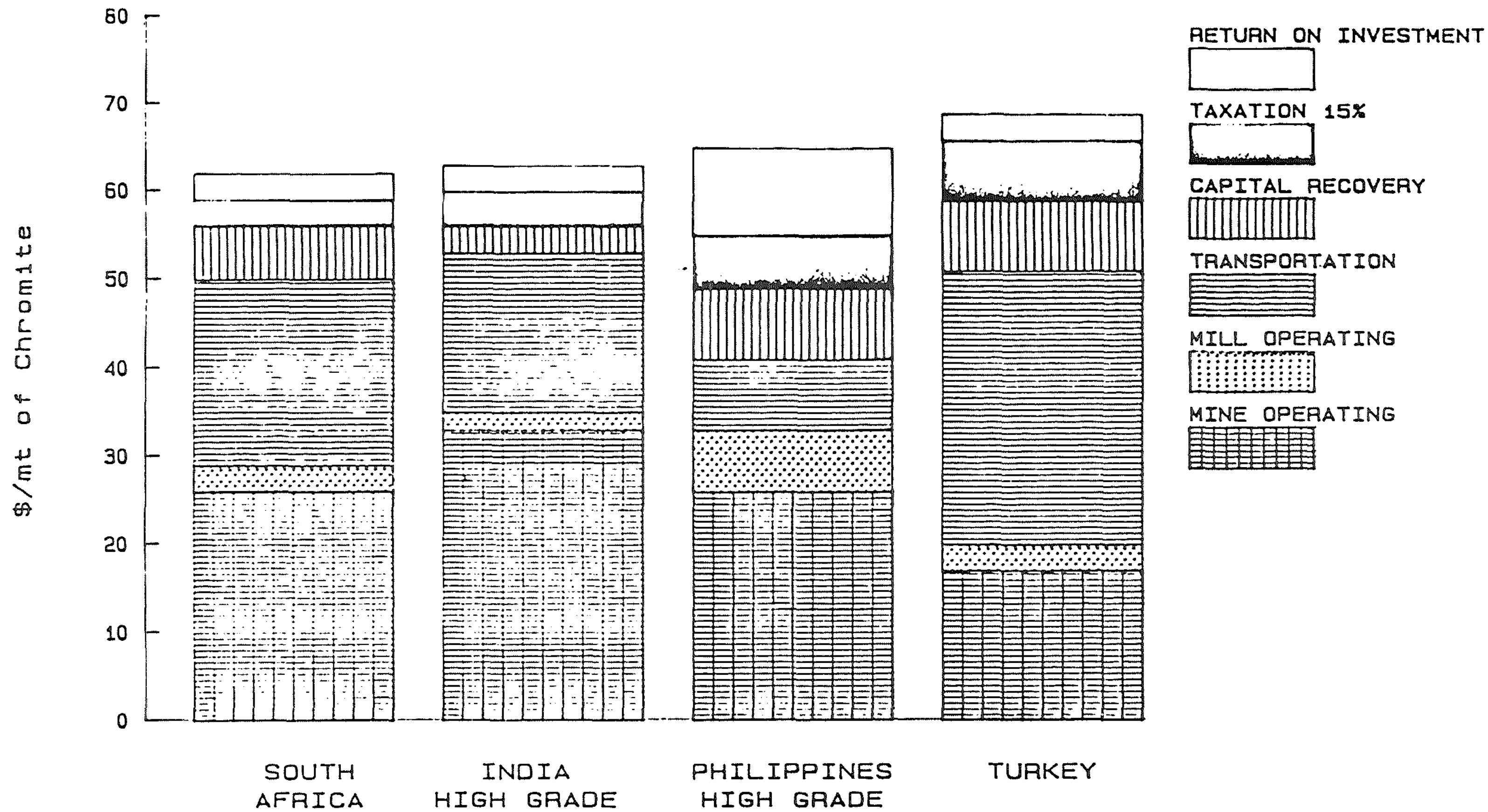



FIGURE 2.3 ESTIMATED AVERAGE PRODUCTION COSTS FOR SELECTED CHROMITE PRODUCING COUNTRIES

upgrade $Cr_2O_3$ content and/or lower the $SiO_2$ content, the only exception being some of the high-grade Great Dyke operations in Zimbabwe where only hand sorting and screening is needed to produce products sufficient for metallurgical uses.

## Production Costs

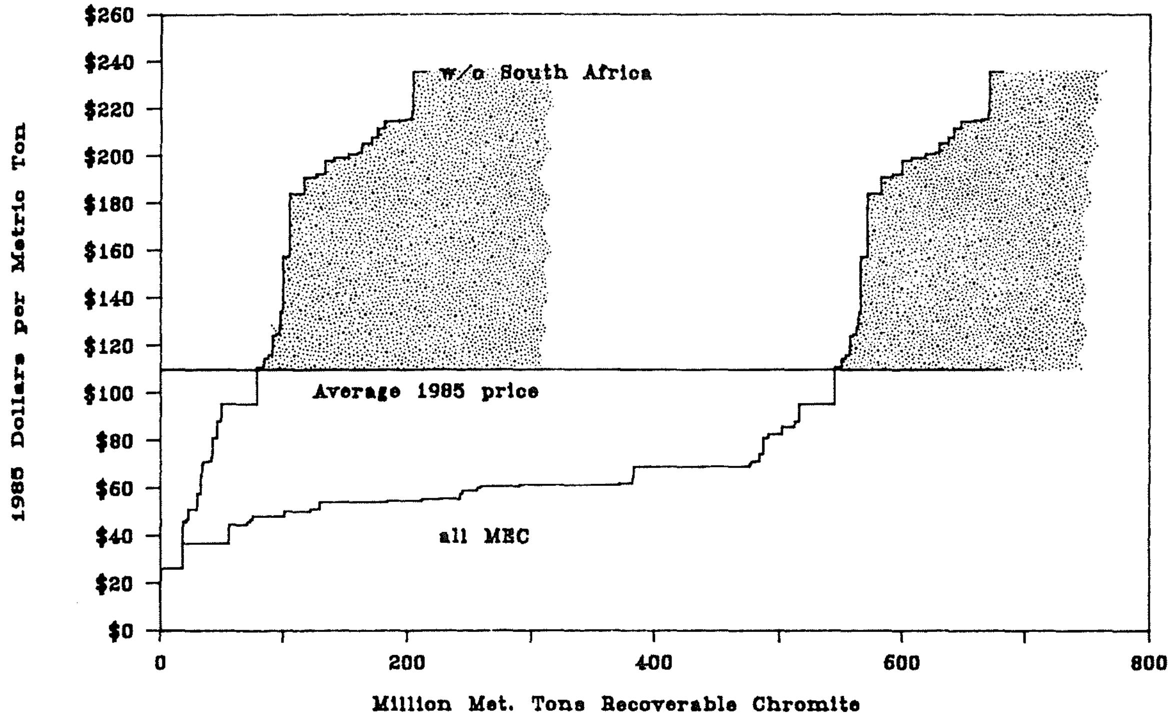
Table 2.2 lists costs, capacity and resources of chromite for the major producing countries. Figure 2.3 illustrates the relative size of the major cost components for four significant countries or resource types. From an economic standpoint, the beneficiation stage nearly always represents the smallest of the three major operating costs. The exception to this are the low-grade alluvial-eluvial-lateritic deposits of the Philippines. Because of their very low grades (weighted average of only 2.0 pct $Cr_2O_3$) the overall concentration ratio for these properties is 30 to 1. This level is very high relative to the other evaluated properties which have concentration ratios that are usually less than 2 to 1.

In general, prices have been sufficiently high ($40-$110/mt chromite) to render a great abundance of chromite economic. At $60/mt of chromite, for example, some 291 million mt (approximately 50 years of MEC production) is economically recoverable at a breakeven (0-pct DCFROR) level. At $90/mt, over 516 million mt of chromite is economically recoverable (76 pct of the total evaluated or about 90 years of MEC production). The only evaluated chromite resources that require in excess of $90/mt to cover total production costs are those of Zimbabwe, some of the low grade resources of the Philippines and India, a Greek chromite mine that serves as part of an integrated ferrochromium operation, and one operation in Brazil that is currently not producing. Chromite production in South Africa and Turkey is clearly economic as is production from the high grade podiform resources of the Philippines and from podiform and stratiform resources of India.

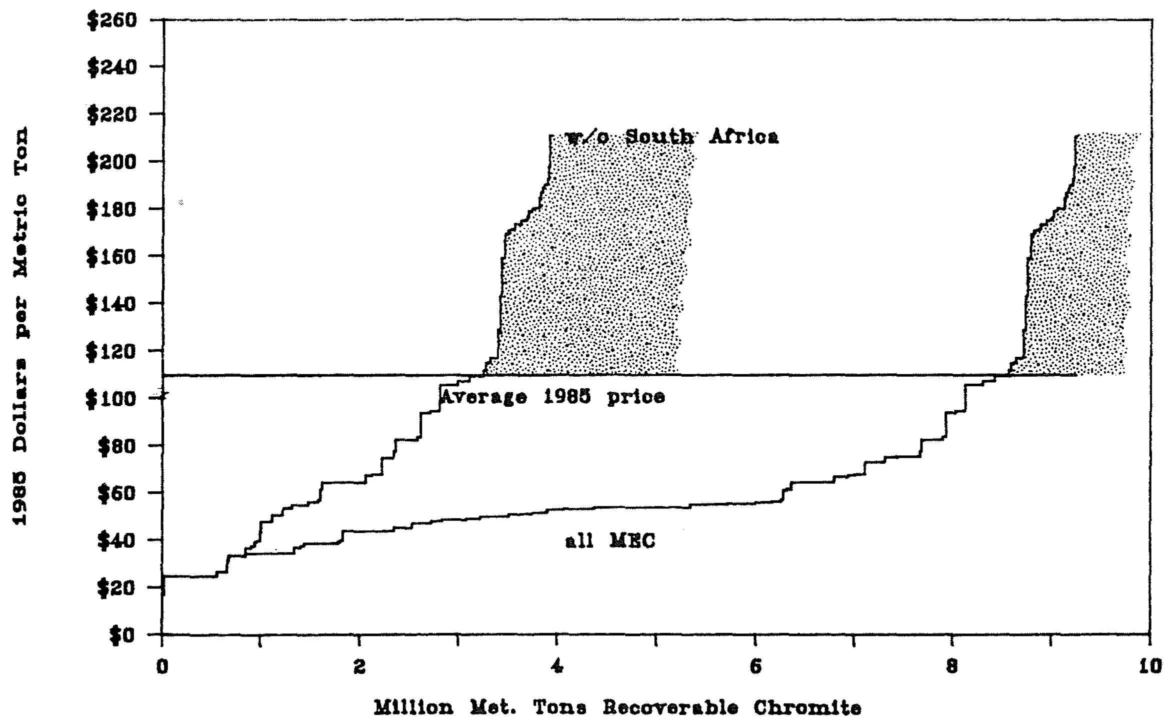
Zimbabwean production of chromite is uneconomic owing to both the high cost of mining the Great Dyke resources and the high cost of transporting chromite through Port Elizabeth in South Africa. This port has been handling 100 pct of Zimbabwe's chromium exports since mid-1984. Zimbabwe does not export any chromium in the form of chromite; instead the mining industry converts the chromite locally to high- and low-carbon ferrochromium and exports these products at competitive cost levels. Similarly, the low grade resources of the Philippines and India are not considered economic given that the sale of chromite products would have to cover the full cost of deposit exploitation. The low grade resources of India will likely be employed in the production of high carbon ferrochromium as this industry expands, but a great deal of uncertainty exists. As of 1985, a few of the low grade resources of the Philippines have had sporadic production; one was brought into production in 1982, and two are reported to be in development. Of these three properties, one is producing concentrates mostly for metallurgical use, one is planned to produce chemical grade concentrates and one is proposed to producepre-reduced pellets for sale to high-carbon ferrochromium producers. However, as a group producing chromite concentrates for export as a "stand alone" product, the chromite from these low grade resources is mostly uneconomic.

Within the "others" category, Finland is an economic producer of chromite. Brazil utilizes its chromite almost entirely for domestic production of ferrochromium. Madagascar and New Caledonia produce and export chromite primarily to Japan. Greece utilizes all of its domestic chromite production for domestic ferrochromium production; as a "stand alone" product, Greek chromite is uneconomic.

# Fig. 2.4.-Total Chromite Availability




# Fig. 2.5.-Chromite Production Capacity



## Availability

Chromite market prices vary from as low as $40/mt for South African high-iron chromite received on average during 1985 to a list price of $110/mt for Turkish high-chromium chromite (1). Individual product prices are as varied as chromite products themselves which are made to the specifications of the customer.

The 82 evaluated mines and deposits contain a total of 680 million mt of recoverable chromite. The step curves in figure 2.4 show the total availability of chromite, from the deposits evaluated, based on the long-run total cost (0-pct DCFROR) of each operation for all MEC's; and for MEC's excluding South Africa. The shaded area indicates that if all deposits were included, the total chromite availability would be larger than depicted by the step curve. Low cost sources are believed to be more fully covered than high cost sources.

Virtually all (91 pct) of the low cost (under $75/mt) material as well as about 70 pct of the total recoverable chromite in the evaluated deposits are eliminated when South African deposits are excluded. Much of the chromite outside South Africa (approximately 19 pct) is contained in deposits in Zimbabwe which is dependent upon access to South Africa'stransportation infrastructure to reach markets.

Annual production capacity of chromite from producing mines at each operation evaluated is illustrated in figure 2.5. The curves are based on average capacity for the producing mines at the estimated total operating cost level. Again, the shaded areas signify the conservative nature of these estimates. At $60/mt, about two-thirds of average annual chromite capacity covers these costs; excluding South Africa eliminates about 75 pct of this low cost annual capacity.

Installed capacity in 1985 was more than sufficient to fulfill all demand for chromite for all markets. This is particularly true of the chromite mines in South Africa which have large flexibility to expand capacity and production. If South Africa's 22 mines were fully developed and operated at capacity according to the development schedules of this evaluation, then an average of 5.3 million mt of chromite products could be produced annually, a level some 75 pct above 1985's actual production. This level of output could readily be met at a nonprohibitive cost given two years lead time. In South Africa, it is most likely that future chromite capacity increases will be associated with local ferrochromium production capacity given the continuing decline of ferrochromium capacity in other chromite importing countries, or from an increase in demand for chemical grade concentrates. In Zimbabwe, any expansion of chromite mining capacity would be driven by an increase in ferrochromium smelting capacity.

## RESOURCES NOT INCLUDED IN THE EVALUATION

Significant deposits not included on the availability curve are the Ramu River deposit in Papua New Guinea, the Plum deposit in New Caledonia, the Bird River deposit in Canada, and the Stillwater Complex in Montana. If developed, these deposits would add significantly to the availability of chromite outside of southern Africa. A recent study by the Bureau of Mines indicates the Stillwater Complex could supply 40-pct of the U.S. demand for high-carbon ferrochromium for the next 22 years (4). These deposits, however, all require higher prices to cover the total cost of development and operation, at least 3 years to develop, and perhaps most importantly, a market for their product. But with metallurgical consumption of chromite (in the form of ferrochromium production) continuing to shift to those countries that mine chromite, the availability of an export market for chromite producers is being reduced.

A large majority (approximately 80 pct or 4.6 billion mt) of the chromit reserve base value for South Africa reported by the Bureau of Mines is contained within the UG-2 reef. And, the UG-2 tailings contain between 30-32 pct $cr_2o_3$ with a chromium-to-iron ratio of between 1.2-1.3:1. The UG-2 is a potential source of chromium since the technology to extract the chromium from the tailings and produce ferrochromium has been demonstrated, but to date no chromium in any form has been produced on a commercial scale. Also, there is the uncertainty of a market for the resulting chromite or ferrochromium since the ferrochromium produced from this material would be lower in contained chromium than ferrochromium currently being marketed.

## CONCLUSIONS

World chromium resources are sufficient to satisfy consumption for the foreseeable future. Through its control of the world's largest resource, production capacity, and transportation infrastructure, South Africa controls access to 87 pct of the total available chromite products evaluated in this study. It is the largest MEC producer of chromite and has the greatest influence on setting the floor price of high-iron chromite for use in the metallurgical and chemical industries. If production of chromium (in any product form) from the UG-2 reef were to occur, the dominance of South Africa as a chromium producer would increase. Zimbabwe contains large chromite resources and possesses the ability to significantly expand chromite production capacity. It does not export chromite due primarily to the high cost of mining the Great Dyke deposits and the high cost of transporting chromite through South Africa, currently its only available outlet.

The United States does not produce chromite although it does possess subeconomic resources in the Stillwater complex, Montana and in numerous podiform deposits in California and Oregon. In addition, other chromite resources exist in Canada, New Caledonia, and Papua New Guinea but have not as yet been exploited. All MEC actual or potential chromite producers, in total, do not possess sufficient current production capacity nor a level of resources that are sufficient to replace the current dominance of South Africa as a supplier of chromite.

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# CHAPTER 3 COBALT

## BACKGROUND

### Uses and Importance

Cobalt is considered essential to the security of the United States because of its extensive use in defense related industries and because of U.S. reliance on imports to satisfy 100 pct of its needs for primary cobalt. Included among the physical properties which make cobalt essential to the manufacture of many defense related items are corrosion resistance, high-temperature strength, and high magnetic strength. It is also the best binder known in the manufacture of tungsten carbides. In recent years the U.S., with its consumption of 7,000-8,000 mt annually, has accounted for about one-third of apparent world cobalt consumption (1). Recycling usually supplies about 5 pct of U.S. cobalt needs. Nickel alloys and ceramics have substituted for cobalt in several applications during periods of high cobalt prices. As of September, 1985, the U.S. strategic stockpile contained 24,000 tons of cobalt.

Currently, there are no mines in the MEC's which produce cobalt as a primary commodity. All cobalt produced from mines is a byproduct of another commodity, principally copper or nickel, and to a lesser extent, PGM's. Therefore, cobalt availability is dependent on the production of other commodities, mostly copper.

### Geology

Cobalt most often occurs in economically recoverable quantities in three major types of ore deposits: (1) stratabound copper (Zaire and Zambia); (2) copper-, nickel-, and platinum-enriched magmatic deposits (Canada, South Africa, and the United States); and (3) nickel-cobalt laterites (The Philippines, Australia, New Caledonia, and the United States). Although cobalt is also recovered from other deposit types, more than 95 pct of MEC production originates from stratabound and magmatic deposits.

The Precambrian metasedimentary (stratabound) Copper Belts in Zaire and Zambia are the largest producing cobalt regions in the world. They are more than 500 km long and 30 km wide. Average copper grades generally vary from 1.8 to 5.0 pct, while cobalt grades range between 0.13 and 0.42 pct.

Important deposits of magmatic origin include the Sudbury and Thompson districts in Canada, the Merensky Reef of the Bushveld Complex in South Africa, and the Duluth Gabbro Complex in the U.S.

The Sudbury Complex, the largest nickel producing district in the world, also produces copper, cobalt, PGM's, and other precious metals. Cobalt grade generally ranges from 0.02 to 0.08 pct, averaging about 0.04 pct. The Thompson Nickel Belt in Manitoba contains several magmatic ore bodies which are currently being mined. Cobalt grades are generally lower than those at Sudbury, ranging between 0.02 and 0.06 pct. The Merensky Reef is mined primarily for PGM's, with cobalt and other metals recovered as byproducts. Cobalt grade is variable and comparatively low, about 3 parts per million. The Duluth Gabbro in Minnesota is one of the world's largest known basic igneous complexes and, although of low grade, is the largest known nickel-cobalt resource in the U.S. Cobalt grades are relatively low, ranging from 0.01 to 0.02 pct.

Nickeliferous laterites currently account for a minor percentage of world cobalt production, but have future potential. The deposits are formed by the weathering of ultrabasic bedrock, generally in equatorial regions. Laterite ores are essentially of two types, siliceous and limonitic. The limonitic ores are more amenable to cobalt recovery, usually by hydrometallurgical processes. Laterites are mined primarily for their nickel content, which generally exceeds 1.0 pct, while cobalt grades rarely exceed 0.2 pct. Seabed crusts and nodules, potentially important future sources of cobalt, have been discovered over large areas of the ocean floor. These deposits contain significant quantities of subeconomic cobalt, nickel, copper, manganese, and other metals. Crusts and nodules with cobalt grades as high as 2.0 pct have been collected. Average cobalt grades range between 0.27 and 0.63 pct.

## Production

In the last several years, efforts at cobalt price control by the two major producers (Zaire and Zambia) have been only periodically successful, despite low copper demand. Cobalt demand has been met and prices have remained stable because the copper mines have operated throughout the poor metal price environment and have controlled sales from stockpiles.

In the 10 years preceding 1977, an average of six million pounds per year of cobalt was sold from the National Defense Stockpile accounting for one-third of domestic apparent consumption for that period. Limited world production capacity combined with increased world cobalt demand and transportation difficulties in Zaire led that country in May 1978 to reduce the allocation of cobalt to its customers worldwide to 70 pct of what they had been receiving for the previous 16 months. This constituted a significant reduction in the world's supply of cobalt, because Zaire was, and is, by far the world's largest producer of cobalt. About two weeks later, Zaire's Shaba Province suffered from a short-lived invasion, resulting in a brief closing of its cobalt mining and refining operations. The impact on Zaire's production capacity was negligible, as it produced 28 pct more cobalt in 1978 than it did in 1977. However, the fear of a shortage had an impact on consumers causing producer prices to rise from $6.40 per pound in February 1977 to $25.00 per pound in February 1979. Cobalt prices have been unstable since then, and as of October, 1986 are about $6.00 per pound.

The recoverable cobalt contained in ore mined in 1985 was about 32,000 tons. Figure 3.1 illustrates cumulative historical cobalt mine production. Zaire alone accounted for over 50 pct of total world mine production and Zambia for about 12 pct. The USSR and Cuba produced approximately 4,145 mt or 11 pct of world mine production. The majority of the remaining portion of world mine production originated from Australia, Canada, Finland, and the Philippines. These four countries accounted for about 20 pct of the total.

In 1985, Zaire's cobalt metal production resulted from the processing of ores which yielded approximately 410,000 mt (6.5 pct of MEC production) of copper metal. An additional estimated 35,000 mt of copper was produced from mines in the country from which cobalt was not recovered. Although Zaire's cobalt refining capacity is approximately 17,000 mt of recoverable cobalt metal, the average production for the period 1982-1985 was less than 8,000 mt. Cobalt metal production peaked at 15,000 mt in 1980. During the period 1982-1985, copper production was nearly 95 pct of production capacity. The ratio of copper-cobalt recovery may vary on a year-to-year basis because of wide swings in cobalt grade and recoveries and a need to maintain a supply-demand balance for cobalt. Availability of this byproduct, therefore, is influenced more by these factors than on full capacity copper production.

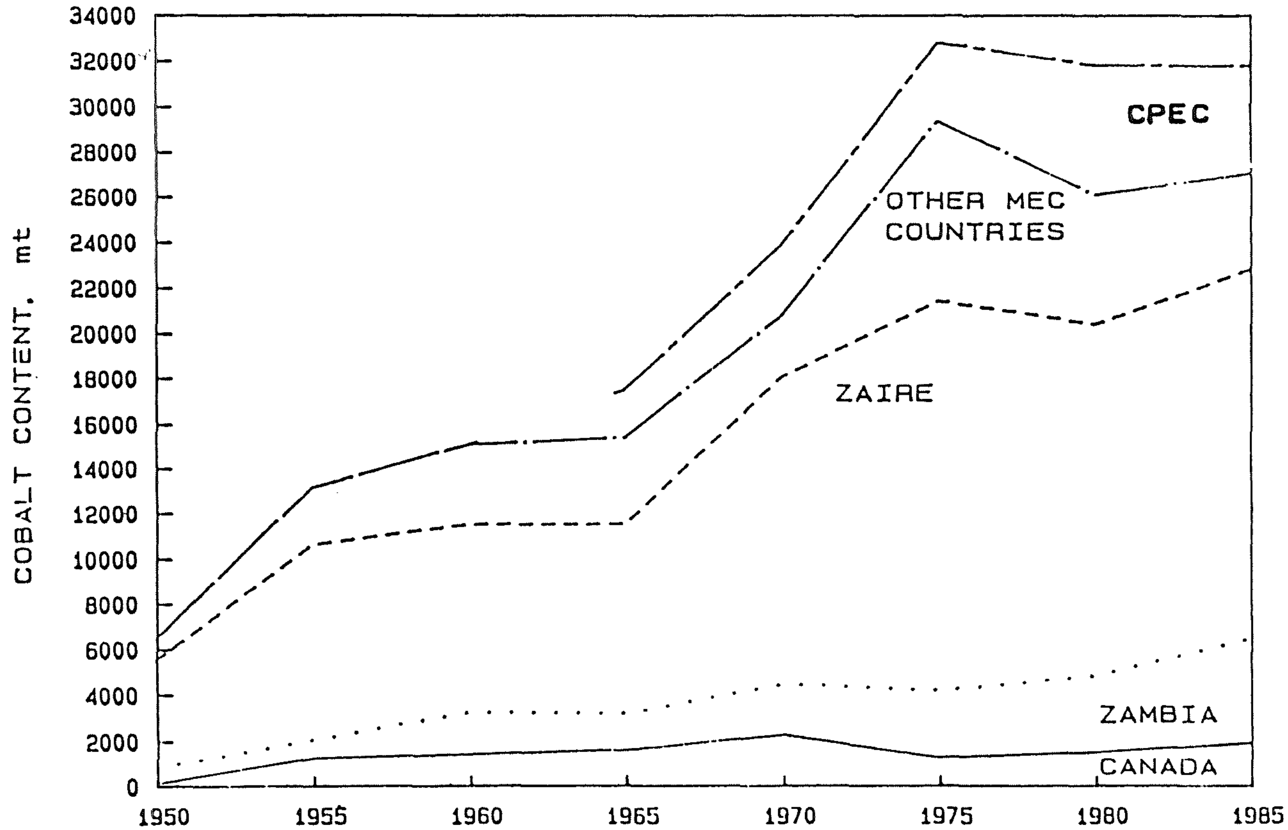


FIGURE 3.1 WORLD COBALT PRODCUTION 1950 - 1985

Zambia's production of copper and byproduct cobalt resembles that of copper operations in Zaire. Zambia's cobalt capacity is estimated at approximately 5,000 mt. However, production has only utilized about 65-70 pct of the capacity in recent years. Like Zaire, Zambia does not recover cobalt from some of its copper concentrates. In 1985, Zambian cobalt production reached 4,600 mt.

Canada is the largest producer of cobalt as a byproduct of nickel mining and the third largest cobalt producer among MEC's, mining approximately 3,000 mt of recoverable cobalt in 1985. Like Zaire's copper mines, the relationship between Canada's nickel and cobalt production varies. The most important variables include cobalt grades and recoveries. Overall cobalt recovery is estimated at nearly 45 pct but technical advances may increase production. At full nickel production, Canada has the potential capacity to produce about 3,000-4,000 mt of cobalt annually.

Australia's cobalt production is also primarily a byproduct of nickel, a large portion of which is from laterites. Peak production from Australian nickel sulfide and laterite operations was nearly 3,400 mt in 1977, but recent production averages about 1,200 mt (835 mt in 1985).

South Africa's cobalt production is low. Data on the cobalt content of ore mined is scarce. Current production is less than 550 mt of contained metal, entirely from PGM production.

The U.S.S.R. and Cuba's cobalt mine production amount is about 4,150 mt or about 11 pct of world production. Nearly all of this production is consumed in the Soviet Bloc.

From 1981 to 1984, the United States depended on Zaire for 40 pct of its imported cobalt requirements, Zambia and Canada for 12 pct each, Norway for 6 pct (most of which originated from Falconbridge's Canadian nickel matte, therefore, Canada's actual total share is about 18 pct) and other countries, including Australia and Botswana, for 30 pct combined (1). Much of the material from Botswana and Australia was refined at AMAX's Port Nickel Refinery in Louisiana. In 1985, AMAX closed their Port Nickel Refinery, which virtually eliminated all active domestic refining of primary cobalt. Existing cobalt production capacity by country is indicated in Table 3.1.

## EVALUATED RESOURCES

Figure 3.2 compares estimates of the cobalt reserve base and those demonstrated resources evaluated in this study. The Bureau of Mines reserve base estimate includes a larger area of the Duluth Gabbro Complex (which results in a larger U.S. resource estimate) and CPEC resources. The "other" category is larger in the reserve base because it includes more deposits than were evaluated. Other differences between the reserve base and resources used in this study result primarily from differences in grade and resource quantities. The tonnages used in this study are based on demonstrated resources in MEC's for which there was information that could be used to relate resource characteristics to appropriate mining and processing technologies and their associated costs. Table 3.2 lists properties included in the study.

### Mining

Cobalt is recovered as a byproduct of metals which are mined by both surface and underground methods. Most of the cobalt originating in Zaire and Zambia is mined by open pit methods. Waste to ore ratios are high, averaging

Table 3.1 --Cobalt Production Capacity
(Thousand Pounds)

| Country | Mine | Refinery |
|---|---|---|
| Market Economy Countries | | |
| Zaire | 37,000 | 37,000 |
| Zambia | 11,000 | 11,000 |
| Japan | 0 | 6,600 |
| Canada | 14,000 | 6,000 |
| Norway | 0 | 4,000 |
| Finland | 3,000 | 4,000 |
| France | 0 | 3,300 |
| South Africa, Republic of | 500 | 1,000 |
| Australia | 4,500 | 0 |
| Botswana | 700 | 0 |
| New Caledonia | 700 | 0 |
| Philippines | 2,800 | 0 |
| Zimbabwe | 200 | 0 |
| Centrally Planned Economy Countries: | | |
| U.S.S.R. | 6,000 | 10,000 |
| Cuba | 6,000 | 0 |
| Total: | 85,600 | 82,900 |

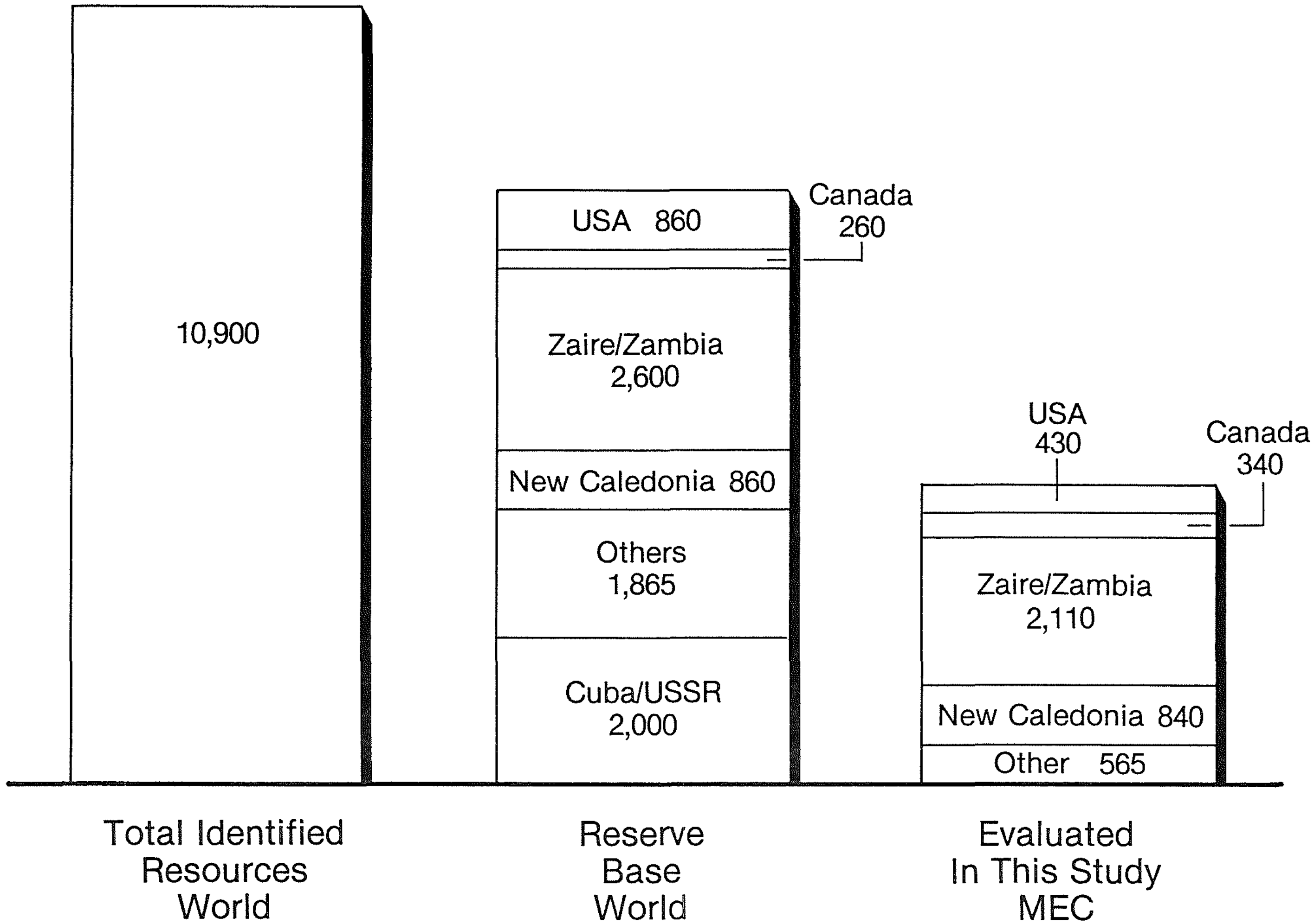


**Figure 3.2 World Cobalt Resources (Thousand Metric Tons Contained Cobalt)**

TABLE 3.2. -List of cobalt properties included in the study

| Country, state, and property name | Owner | Primary commodity | Status[1] | Type of operation[2] |
|---|---|---|---|---|
| Australia: | | | | |
| Agnew...................... | Agnew Mining Co. | Ni | P | U |
| Greenvale.................. | Metals Expl. Ltd. and Freeport | Ni | P | S |
| Kambalda................... | Western Mining Corp. | Ni | P | U |
| Mt. Keith.................. | Metals Exp/Freeport Exp/Aust C | Ni | N | S |
| Botswana: Selebi/Phikwe..... | BCL Ltd. | Ni | P | U |
| Brazil: | | | | |
| Niquelandia (CNT).......... | Companhia Niquel De Tocantins | Ni | P | S |
| Niquelandia (Codemin)...... | CODEMIN | Ni | N | S |
| Canada: | | | | |
| Manitoba: Inco Operations. | Inco | Ni | P | C |
| Ontario: | | | | |
| Falconbridge Operations.. | Falconbridge | Ni | P | U |
| Inco Operations.......... | Inco | Ni | P | C |
| Saskatchewan: Key Lake.. | Key Lake Mining Corporation | U | N | S |
| Finland: | | | | |
| Keretti Mine............... | Outokumpu Oy | Cu | P | U |
| Luikonlahti................ | Myllykoski Oy | Cu | P | U |
| Vuonos Mine................ | Outokumpu Oy | Cu | P | U |
| Guatemala: Eximbal.......... | Inco and Hanna | Ni | S | U |
| India: Sukinda.............. | Tata Iron and Steel | Ni | N | S |
| Indonesia: Gag Island....... | P.T. Pacific Nickel | Ni | N | S |
| New Caledonia: | | | | |
| Goro....................... | Inco | Ni | N | S |
| Ile Art.................... | Confremmi | Ni | N | S |
| Kouaoua.................... | Pentecost Nickel | Ni | P | S |
| Moneo...................... | OGMC Ballande | Ni | P | S |
| Nakety..................... | Societe Le Nickel | Ni | P | S |
| Nepoui..................... | Societe Le Nickel | Ni | P | S |
| Ouaco...................... | ..do............ | Ni | P | S |
| Ouinne..................... | Societe G. Montagnat | Ni | P | S |
| Poro....................... | Societe Le Nickel | Ni | P | S |
| Poum....................... | Cofremmi | Ni | N | S |
| Prony...................... | Penamex | Ni | N | S |
| Thio....................... | Societe Le Nickel | Ni | P | S |
| Tiebaghi................... | Cofremmi | Ni | N | S |

TABLE 3.2. -List of cobalt properties included in the study—Continued

| Country, state, and property name | Owner | Primary commodity | Status[1] | Type of operation[2] |
|---|---|---|---|---|
| Philippines: | | | | |
| Infanta .................... | Philippine Government | Ni | P | S |
| Nonoc Mine.................. | Marinduque Mining Corp. | Ni | P | S |
| Soriano .................... | Soriano Corp. | Ni | N | S |
| South Africa: | | | | |
| Der Brochen................. | Geduld proper./East Rand Cons. | PGM | N | U |
| Impala...................... | Platinum mines Union Corp. & Others | PGM | P | U |
| Rustenburg.................. | Rustenburg Platinum Ltd. | PGM | P | U |
| Western Platinum............ | Western Platinum Ltd. | PGM | P | U |
| Uganda: Kilembe............. | Uganda Government | Cu | N | U |
| United States: | | | | |
| Alaska: Yakobi Island..... | Inspiration Devel. Co. | Cu, Ni | N | U |
| California: | | | | |
| Pine Flat area........... | Hanna Mining Corp. | Ni | N | U |
| Gasquet.................. | California Nickel Corp. | Ni | N | S |
| Idaho: Blackbird.......... | Noranda | Co, Cu | N | U |
| Maine: Crawford Pond...... | Knox Mining Corp. | Ni | N | C |
| Minnesota: | | | | |
| Birch Lake............... | Inco/Hanna/Duval | Cu, Ni | N | C |
| Dunka River.............. | AMAX | Cu, Ni | N | U |
| Ely Spruce Mine.......... | Inco | Cu, Ni | N | S |
| Minnamax................. | AMAX | Cu, Ni | N | U |
| Partridge River.......... | United States Steel | Cu, Ni | N | S |
| Missouri: Madison......... | Anschutz Corp. | Co, Ni, Cu | N | U |
| Oregon: Red Flat.......... | Hanna Mining/Red Flats | Ni | N | S |
| Puerto Rico: Guanajibo.... | Puerto Rican Government | Ni | N | S |
| Zaire: | | | | |
| Dikuluwe/Mashamba.......... | Gecamines | Cu | P | S |
| Kakanda.................... | ..do..... | Cu | P | S |
| Kambove.................... | ..do..... | Cu | P | S |
| Kamoto UG Mine............. | ..do..... | Cu | P | U |
| Kov Open Pit............... | ..do..... | Cu | P | S |
| Tenke Fungurume............ | ..do..... | Cu | N | U |
| Zambia: | | | | |
| Baluba..................... | Zambian Consolidated Copper Mines (ZCCM) | Cu | P | U |
| Chibuluma.................. | ..do............................ | Cu | P | U |
| Nchanga Div................ | ..do............................ | Cu | P | U |
| Nkana Div.................. | ..do............................ | Cu | P | U |

TABLE 3.2. -List of cobalt properties included in the study—Continued

| Country, state, and property name | Owner | Primary commodity | Status[1] | Type of operation[2] |
|---|---|---|---|---|
| Zimbabwe: | | | | |
| Empress.................... | Rio Tinto Mining | Ni | N | U |
| Shangani.................. | Johannesburg | Ni | P | U |
| Trojan..................... | Trojan Nickel Mine Ltd. | Ni | P | U |

[1]P = producer; N = nonproducer; S = Standby.
[2]S = surface; U = underground; C,= combined surface and underground.

about 5:1. Ores in Zaire and Zambia consist of sulfide and oxide minerals. Since these sulfide and oxide ores require different processing methods, they are mined separately when possible.

Underground mines in Zaire and Zambia usually employ sublevel, open stoping. Australian and Canadian nickel ores are mined primarily by underground methods. Application of highly mechanized vertical crater retreat mining and other bulk mining methods are becoming increasingly important in an effort to reduce costs, especially in Canada.

Cobalt-bearing nickel laterites, such as those in New Caledonia and the Philippines, are mined by surface methods. Since laterites are generally of an unconsolidated nature, scrapers, shovels, and front-end loaders are used for mining and loading ore into trucks.

## Processing

Beneficiation techniques for the recovery of cobalt vary with ore characteristics. In Zaire and Zambia, revenues from copper are of greater importance than cobalt, therefore, efforts to maximize recovery of copper take priority over cobalt. The copper-cobalt mines in Zaire and Zambia require specialized beneficiation methods owing to the presence of oxide, and sulfide ores and occasionally dolomites ores. Ore, depending on its type, is directed to a specific concentrator designed to treat that specific ore chemistry. Cobalt feed grades may vary from 0.1 to 2.5 pct, but average 0.33 pct with an average mill recovery of approximately 35 pct. Recovery values are low because of variable cobalt grades and efforts to maximize copper recovery at the expense of cobalt.

Most cobalt in Zaire is processed through the DIMA-Kamoto concentrator (8 million mt/yr ore feed). This plant can produce a low-cobalt high copper concentrate of 0.5 pct cobalt and 60 pct copper or a high-cobalt, low copper concentrate grading 4-5 pct cobalt and 45 pct copper. Average overall concentrator recovery of cobalt can be as low as 18 pct. The average recovery, however, is approximately 35 pct. Most cobalt associated with oxide mineralization is not recovered.

The metals contained in the concentrates sent to the Luilu or Shituru plants are extracted and separated through leaching, precipitation, and electrolysis. The cobalt contained in concentrate shipped to the Lubumbashi smelter is not recovered, instead, it is incorporated in the smelter slag. As much as 10,000 mt/yr of cobalt ends up in the slag.

Nickel-cobalt sulfide ores, such as those at Inco's Sudbury operations in Canada, are directed to beneficiation plants where two concentrates, nickel and copper, are produced. Although there is some cobalt contained in the copper concentrates, it is not recovered. Nickel concentrate, from which cobalt is recovered, is sent to the Copper Cliff smelter-refinery complex. A resulting cobalt-nickel mixture is recovered from Inco's nickel refining circuit. The cobalt residues are sent to refineries for upgrading. Falconbridge's matte is sent to their Norwegian refinery for processing.

Historically, two problems have existed in processing of nickel laterites: (1) high energy consumption, and (2) inadequate recovery of metals, especially cobalt. Metals in laterite ores are recovered by pyrometallurgical and hydrometallurgical methods. The pyrometallurgical methods entail smelting the laterite to a matte followed by electrolytic separation to recover the cobalt, as is done with matte originating from sulfide ores. Relatively little cobalt is recovered from laterites using this process. The majority of cobalt from laterites is recovered by hydrometallurgical methods. These methods include variations on ammoniacal and sulfuric leach methods. The ammoniacal method was first applied to Cuban laterites during World War II, but low nickel recoveries, high energy costs, and low cobalt recoveries have rendered this process uneconomic. The sulfuric acid leach process is capable of higher recovery rates, about 90 pct for nickel and cobalt, and relatively low energy consumption. The resulting mixed sulfide concentrate is refined further to recover nickel and cobalt.

## Production Costs

Virtually all production costs for the recovery of cobalt from mining through refining, are secondary to those incurred for the primary commodity, copper or nickel. For this reason, it is difficult to acquire or estimate separate treatment costs for cobalt and to portray cobalt availability via an availability curve. However, estimated refinery operating costs to recover cobalt are between \$2-3 per lb. For these operations the production costs for copper and nickel are of the highest priority.

## Availability

In order to determine the availability of cobalt from MEC's, the Bureau evaluated demonstrated cobalt resources in selected copper mines in Zaire and Zambia and nickel mines in Australia, Canada, Finland, New Caledonia, the Philippines, the United States, and other countries. Actual cobalt grade, recovery data, and other pertinent information is difficult to acquire because of its byproduct relationship to the primary commodity. The availability of cobalt is limited by mining for the primary commodity, the plant's capacity and design, and the additional cost to recover the cobalt.

As listed in table 3.3, total potentially recoverable cobalt from the deposits evaluated is approximately 1.7 million mt. Copper properties comprise about 40 pct of the total while nickel or nickel-copper deposits make up about 55 pct. The remaining portion is in PGM and cobalt properties.

Cobalt Available from Copper

Virtually all of the cobalt recovered from copper ores, and at least 75 pct of the annual MEC cobalt mine production, originates from Zaire and Zambia. The Bureau evaluated ten copper mines and districts in these two countries; current cobalt production originates from seven of these operations. Two operations, Kakanda/Diselle and Kambove in Zaire, contain cobalt in the ore, but it is not systematically recovered. However, the Kambove mine tracks cobalt grades carefully and some concentrates are sent to the Shituru plant for recovery of the cobalt. There are no known plans to modify these operations for cobalt recovery. The remaining property, Tenke Fungurume in Zaire, is partially developed and may not begin production for several years. It is not known whether cobalt recovery is planned from this operation.

There is a total estimated recoverable cobalt resource of 637,000 mt in Zaire and approximately 73,000 mt in Zambia. About 87 pct (616,000 mt) of the total resource (710,000 mt) from these two countries, is in mines currently producing which, at a 0-pct DCFROR, have a weighted-average total production cost of about $0.55/lb copper. It is likely that there are additional costs to cover security, repayment of debt, plus other overhead, which can not be attributed to any one mining operation.

TABLE 3.3. —Summary of MEC demonstrated cobalt resources, January 1985[1]

| Region and country | Primary Commodity(ies) | Producing Mines Number | Producing Mines Recoverable Cobalt $10^3$mt | Nonproducing Deposits Number | Nonproducing Deposits Recoverable Cobalt $10^3$mt | Total Recoverable Cobalt $10^3$mt |
|---|---|---|---|---|---|---|
| Africa: | | | | | | |
| Botswana........ | Ni, Cu | 1 | 3 | 0 | 0 | 3 |
| South Africa[2]... | PGM | 3 | 14 | 1 | 2 | 16 |
| Zaire........... | Cu | 3 | 543 | 1 | 94 | 637 |
| Zambia.......... | Cu | 3 | 73 | 0 | 0 | 73 |
| Zimbabwe[3]....... | Ni, Cu | 2 | 1 | 1 | 1 | 2 |
| Southwest Pacific: | | | | | | |
| Australia....... | Ni | 2 | 13 | 1 | 15 | 28 |
| Indonesia....... | Ni | 0 | 0 | 1 | 27 | 27 |
| New Caledonia... | Ni | 7 | 5 | 6 | 505 | 510 |
| Philippines..... | Ni | 2 | 63 | 1 | 59 | 122 |
| Europe: Finland.. | Cu | 1 | 4 | 0 | 0 | 4 |
| India............. | Ni | 0 | 0 | 1 | 7 | 7 |
| South America: | | | | | | |
| Brazil.......... | Ni | 1 | 12 | 1 | 5 | 17 |
| Guatemala....... | Ni | 0 | 0 | 1 | 10 | 10 |
| North America: | | | | | | |
| Canada.......... | Ni, Cu | 16 | 50 | 9 | 16 | 66 |
| United States... | Cu, Ni, Co | 0 | 0 | 20 | 160 | 160 |
| Total............ | | 41 | 781 | 44 | 901 | 1,682 |

[1]Data for all countries, except Zaire and Zambia, is based on January 1981 resource data which was updated to January, 1985 by subtracting estimated production from operating mines.

[2]Since cobalt is a very minor revenue producer, South Africa was not economically evaluated as a cobalt resource.

[3]Additional recoverable very low grade cobalt resources are present in the Great Dyke PGM prospects, but are only available at very high cost.

The two countries have a combined estimated optimum annual capacity of nearly 22,000 mt of refined cobalt, which is about equivalent to the entire 1985 MEC cobalt metal production. Market conditions, however, generally dictate what portion of total capacity will be utilized. Annual production of cobalt from these two countries can vary widely on a year to year basis. This results from large variations in cobalt grade, despite relatively consistent copper grades, which hinders efficient recovery, technical problems associated with poorly maintained and antiquated equipment, and nonrecovery of cobalt when metal prices are low.

Zairian and Zambian mine production was evaluated at an average combined annual production level (1970-1980) of approximately 17,400 mt (13,000 in Zaire and 4,400 in Zambia) because the countries have not historically utilized their total production capacity. Based on the results of this study, all of this capacity is available at a total cost of production, including a 0-pct DCFROR, of about $0.55/lb copper (the average 1985 copper price was about $0.66/lb). Based on demonstrated resource estimates these countries could maintain production at this level through 1995.

## Cobalt Available From Nickel

Recoverable cobalt from evaluated nickel resources amounts to approximately 928,000 mt and is distributed as follows: New Caledonia 55 pct, Philippines 13 pct, Canada 7 pct and others 25 pct. Only about 16 pct is in deposits currently in production.

Approximately 66,000 mt of byproduct cobalt from 8.25 million mt of nickel is potentially available from the nickel mines and prospects evaluated in Canada. About 50,000 mt is potentially available from producers at a cost of less than $1.85/lb. nickel (at a 0-pct DCFROR). The published dealer cathode price was about $2.35/lb. in January 1985, but the metal could be bought for considerably less. Canada's Sudbury and Thompson Districts contain virtually all of the evaluated resource. Like the African copper mines, the ratio between Canada's nickel and cobalt production changes because of variable cobalt grades and associated recoveries.

The Philippines contain approximately 122,000 mt of recoverable cobalt, which is probably conservative. In 1985, about 900 mt of cobalt was produced from nickel laterite ore, although there is a capacity to produce in excess of 1,500 mt of cobalt in mixed sulfides and cobalt extracted from raw ore shipped to Japan. High grading and other temporary cost cutting measures allow nickel to be produced at prices close to the market price. However, suspension of activities may result if metal prices don't improve.

Australia's cobalt production is also as a byproduct of nickel mining. Approximately 28,000 mt of potentially recoverable cobalt is contained in the evaluated properties, about half of which is in producers. Two-thirds of the cobalt production originates from the Greenvale deposit. Although Australian sulfide operations are cost competitive with Inco's, the Greenvale laterite operation is higher cost. The weighted average total costs for producing Australian nickel properties is about equal to or slightly higher than $2.00/lb. nickel but less than the January 1985 published dealer cathode price.

Only 1 pct of the New Caledonia laterite resource is in producers and none of the evaluated resource is currently available at a total production cost of less than the January 1985 nickel price. New Caledonia does not have any nickel or cobalt refining facilities, instead, the cobalt is recovered at facilities in France. Less than 800 mt of cobalt per year originates from New Caledonian deposits and is not likely to increase in the near future. Most New Caledonian nickel ore is processed into ferronickel, from which cobalt is not recovered.

At the Madison Mine, in Missouri, cobalt is also associated with nickel and copper. This former producer contains an estimated 10,000 mt of potentially recoverable cobalt in ore and mill tailings. Approximately 30 pct of the Madison resource could be mined profitably at less than $10/lb. cobalt. The entire evaluated resource, however, would require a total production cost, including a 15-pct DCFROR, of over $20/lb. Mine feasibility plans called for an annual production of about 900 mt of refined cobalt along with byproduct nickel and copper.

The Blackbird deposit, in Idaho, contains high-grade cobalt (0.60 pct) with as much as 6 million mt of potential ore yielding approximately 25,000 mt of refined cobalt. This potential cobalt producer occurs in association with copper, but production is dependent on revenues from cobalt. Although a small portion of the resource may be currently profitable to mine, the entire resource could not be mined at a total production cost, including a 15-pct DCFROR for less than $20/lb. Average potential annual refined cobalt production is estimated at 1,500 mt and copper at 4,400 mt.

The Gasquet nickel-cobalt laterite project in California is also an important potential domestic cobalt producer. Approximately 15,000 mt of cobalt is contained in the laterite resource and is available at an average total cost of production, including a 15-pct DCFROR approaching $20/lb. of cobalt. The property has been partially developed, but no plans for production have been announced. Owing to low metal prices, it is doubtful that production will begin in the near future. Operating plans anticipated an annual refined cobalt capacity of about 1,000 mt and 8,600 mt of nickel, chromite concentrate, and magnesium oxide.

The largest U.S. cobalt resource is contained in the Duluth Gabbro Complex, a copper-nickel resource. Although the deposit may contain approximately 77,000 mt of recoverable cobalt, the resource is huge (over 3 billion mt) but of very low grade (about 0.01 pct). There are no known future development plans.

## Southern Africa Transportation Infrastructure

Although South Africa produces minor quantities of cobalt, it is potentially influential on the availability of cobalt by providing the most dependable transport for virtually all of Zaire's cobalt production and a significant quantity of Zambia's over its rail system and through its ports.

Three main routes are available for the export of Zaire's mineral products: 1) the Voie Nationale, which consists of rail, and barge transport to Matadi, Zaire's main seaport; 2) the southern route which connects Shaba province to South Africa's East London and Durban ports via the railways of Zaire, Zambia, Zimbabwe, Botswana and South Africa; and 3) the eastern route using Zaire's rail system, barge on Lake Tanganyika, and then over Tanzania's railways to the port of Dar es Salaam. Insurgent warfare over the last ten years in Angola has prevented transport to the Atlantic port of Benguela.

The Voie Nationale route is an inefficient system, plagued with equipment failure, low water levels and security problems. The Tanzanian route is also hampered by maintenance and logistical problems. Since 1978, South Africa has become the main means of transport of Zaire's cobalt.

## CONCLUSIONS

MEC cobalt availability is a function of copper and nickel production (capacity levels and variable ore grades), market demand, and political stability. These elements are critical because the United States is completely dependent on foreign sources to meet 100 pct of its needs for primary cobalt. Zaire, Zambia, and Canada are the main sources of cobalt having constituted 40, 16, and 13 pct, respectively, of U.S. imports from 1985 through 1986. Barring any major interruptions in supply, there is sufficient byproduct cobalt capacity from producing copper and nickel operations to meet current and projected levels of MEC cobalt demand for at least the next ten years.

Although there have been successful efforts in finding substitutes for cobalt superalloys and magnets, it is still an essential metal for military applications. Currently, there is a large amount of underutilized capacity in the cobalt recovery plants of Zaire and Zambia, as well as capacity underutilization of nickel operations in Canada. An increase in demand could be easily met by current producers. Since it is a minor byproduct of nickel, stepped-up Canadian production of cobalt may not occur in the event of a temporary interruption of supply from the African Nations.

The United States does have cobalt available from its own natural resources, but because of the high costs for development, the low grade-byproduct nature in most deposits, current low metal prices and under utilized capacity, no near term developments are expected. If development were initiated in the United States, the Madison, Blackbird, and Gasquet, deposits would most likely be developed first. There is about 50,000 mt of potentially recoverable cobalt in these three prospects. However, analysis indicates that cobalt prices of nearly $20/lb. would be required to encourage full-scale development and production at all three operations. If they were to be developed concurrently, and were based on currently available mining plans, there could be a combined annual production of about 3,500 mt of cobalt, equaling less than half of 1985 United States' apparent consumption.

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# CHAPTER 4 GOLD

## BACKGROUND

### Uses and Importance

Gold is a unique element in that it is, above all, an alternate store of wealth to fiat currencies, most notably the U.S. dollar. The U.S. dollar serves as the primary medium of exchange in international transactions and is the currency in which world gold prices are denominated. The great majority of gold is held either as an investment medium or as a form of insurance to hedge against uncertainty about the value of fiat currency or potential disaster. Gold is held in the form of jewelry, bars, medallions and coins.

Artistic and industrial applications together consumed about 3 million troy ounces (tr oz) in the U.S. and 33 million tr oz in the world in 1983 (1). Much of that metal will eventually be recycled. Only a small portion of the world's total gold production is consumed in artistic and industrial applications. The composition of gold consumption by country varies with the degree of industrial development. In the U.S. over the period 1973-1983, jewelry consumption accounted for 53 pct of total consumption, industrial applications primarily for electronics 32 pct, dentistry 10-15 pct and 1-6 pct into small bars, medallions etc. In other MEC's jewelry consumption is dominant and accounts for roughly three-fifths of total consumption. Industrial consumption for electronics accounts for only 8 pct on average in all MEC's.

### Geology

The world's primary gold deposits can be classified into four separate categories: placer deposits, lode deposits, "blanket" (or "reef-type") deposits, and disseminated deposits.

Placer deposits are surface deposits comprised of unconsolidated, loose materials, such as gravels and sands in which the gold particles occur as "free" particles ranging in size from coarse nuggets to grains to fine flakes. An important distinction is that a placer deposit represents material derived from the erosion and transport of the original country rock. Lode gold deposits, by contrast, consist of gold particles contained in the in situ, quartz veins or country rock. The "blanket" or "reef-type" deposits are deposits where the gold occurs in quartz conglomerates which have resulted from the consolidation of placer deposits.

The newest classification (recognized since the mid- to late-1960's) is the disseminated gold deposits of which the Carlin, Nevada deposit was the first example. These occurrences have been found in the southwestern United States (Nevada, Utah, New Mexico, and the southern portion of California) and in western Australia. In disseminated deposits the gold mineralization is fairly evenly distributed throughout the deposit rather than being concentrated in veins (as in lode deposits) or in "pay-streaks" (as in placer deposits).

Prior to the 1860's and 1870's, nearly all of the world's gold production came from the mining of placer deposits. Since that period, the "reef-type" deposits of the Witwatersrand Basin in South Africa have dominated, with the result that these deposits have been responsible for an estimated 40 pct of all of the world's gold production through the 1980. The disseminated deposits have seen production only since the 1967 start-up of the Carlin mine. However, these deposits presently constitute the vast majority of production in the state of Nevada and the state of Western Australia which are the largest gold producing regions in their respective nations.

## Production

Figure 4.1 shows gold production for South Africa, the U.S.S.R., and the rest of the world in 5-yr increments over the period 1950-85. Current world production is dominated by South Africa which produced a reported 21.6 million oz in 1985 (2). South Africa's production represented 57.8 pct of total MEC production and 45 pct of world production. The Soviet Union is the world's second largest producer with an estimated 1985 production level of 8.7 million oz which represented 18.0 pct of world production in that year. All other gold producing countries remaining are insignificant compared to South Africa and the Soviet Union.

In the aggregate, 1985 world production is approximately 0.7 million tr oz less than 1970. South Africa's 1985 production level represents a decline of 32.9 pct, or very close to 10 million oz of annual production, since 1970. This decline represents a lowering of the pay-limits (lowest economically minable grade) to which the companies must mine by South African law and a comparable increase in tonnage milled in reaction to the higher gold prices that resulted from demonetization. In fact, by 1975, grade and tonnage adjustments had been made such that the last 11 years have shown a steady level of production at between about 21 and 23 million oz per year.

By comparison, three major MEC producers (the United States, Canada, and Australia) had their lowest levels of annual production for the 1950-85 period occur during the years of 1979 and 1980. As of 1985, all 3 countries had dramatically reversed the 1970's production declines with the result that, in total, they are producing about 2.3 million more oz combined, on an annual basis, than in 1970. The U.S.S.R., the People's Republic of China, and Brazil have also increased their combined annual production levels by close to 5.5 million oz per year. Thus, these 6 countries have compensated for about 75 pct of South Africa's production decline since 1970.

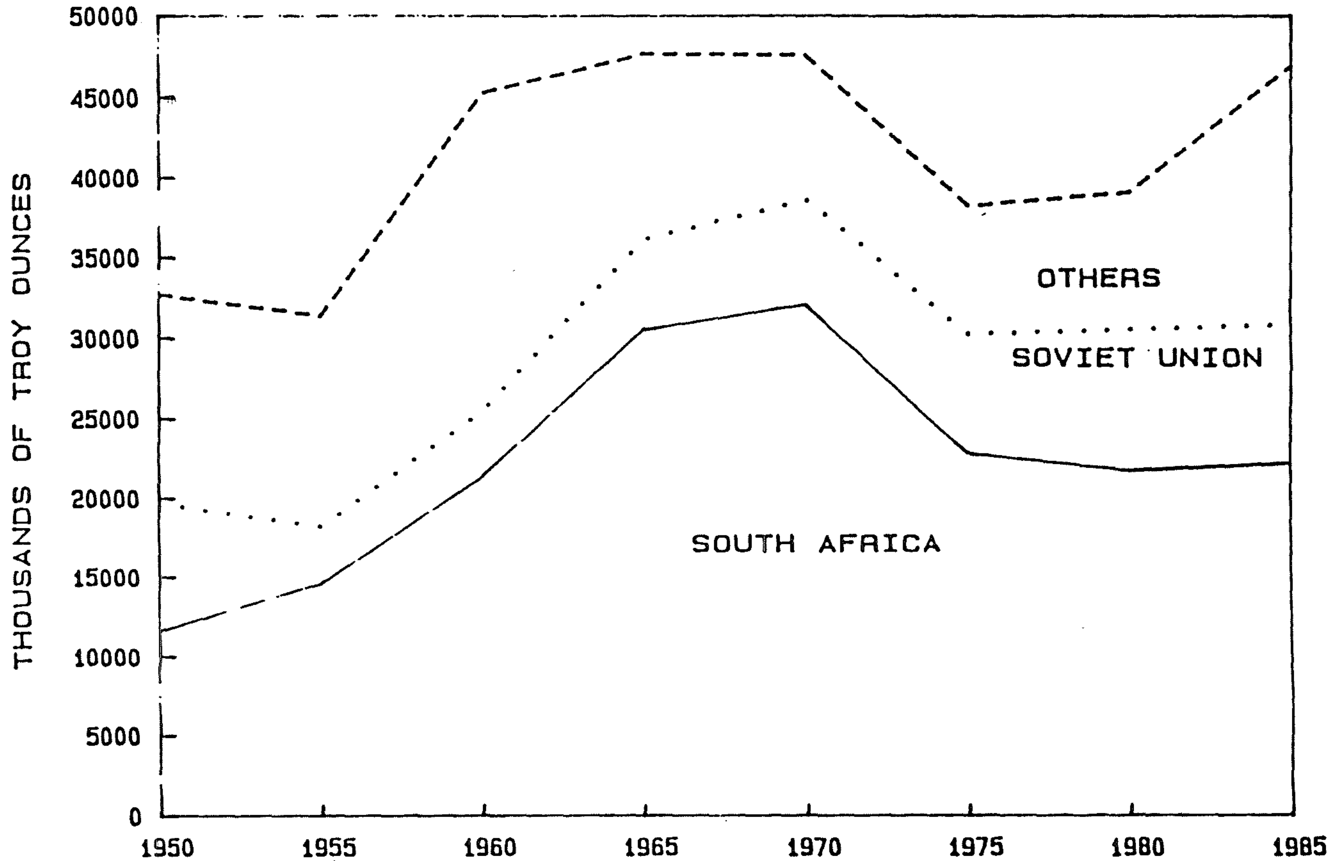



FIGURE 4.1 WORLD GOLD PRODUCTION 1950 - 1985

## EVALUATED RESOURCES

Figure 4.2 compares several different resource estimates. The U.S. Bureau of Mines estimated world in situ gold resources in the world to be 2.4 billion tr oz, 50 pct of which are in South Africa and the total world gold reserve base to be 1.45 billion tr oz of in situ gold (1,3). Of this total, 18 pct (0.26 billion tr oz) is estimated to be present in the CPEC's, and 1.19 billion tr oz is contained in MEC's (3). In comparison, the total gold estimated to be recoverable from the demonstrated resources of 110 evaluated MEC properties that were in production as of January 1985 amount to 0.792 billion tr oz, with South Africa accounting for 87.5 pct of the total and the United States, Canada, and Australia for 3.9, 4.4, and 0.7 pct, respectively. The evaluated properties are listed in table 4.1.

### Mining

Predominantly underground methods are used at 81 of the 110 operations evaluated providing 94 pct of the recoverable gold. Of the 29 surface mining operations, four are placer dredging operations, six are surface dump and tailings reprocessing operations in South Africa and 19 are conventional open-pit mines--15 of which are located in the United States.

Of the 37 underground producers in South Africa, 35 produce from Witwatersrand Basin paleoplacer gold deposits, and two produce from lode gold deposits in the archean "greenstone" gold district of the Eastern Transvaal. The Witwatersrand Basin gold mining operations are unique in comparison with other gold mining operations around the world. The mines are extremely large tonnage, multishaft operations that are highly labor intensive, yet have very high capital cost requirements. Some of the operations face technological hurdles related primarily to the requirement to mine from stopes ranging from only 0.9 to 2.3 m in height (an average of slightly over 1.4 m) at vertical depths of over 2 miles. The introduction of mechanization at several mines

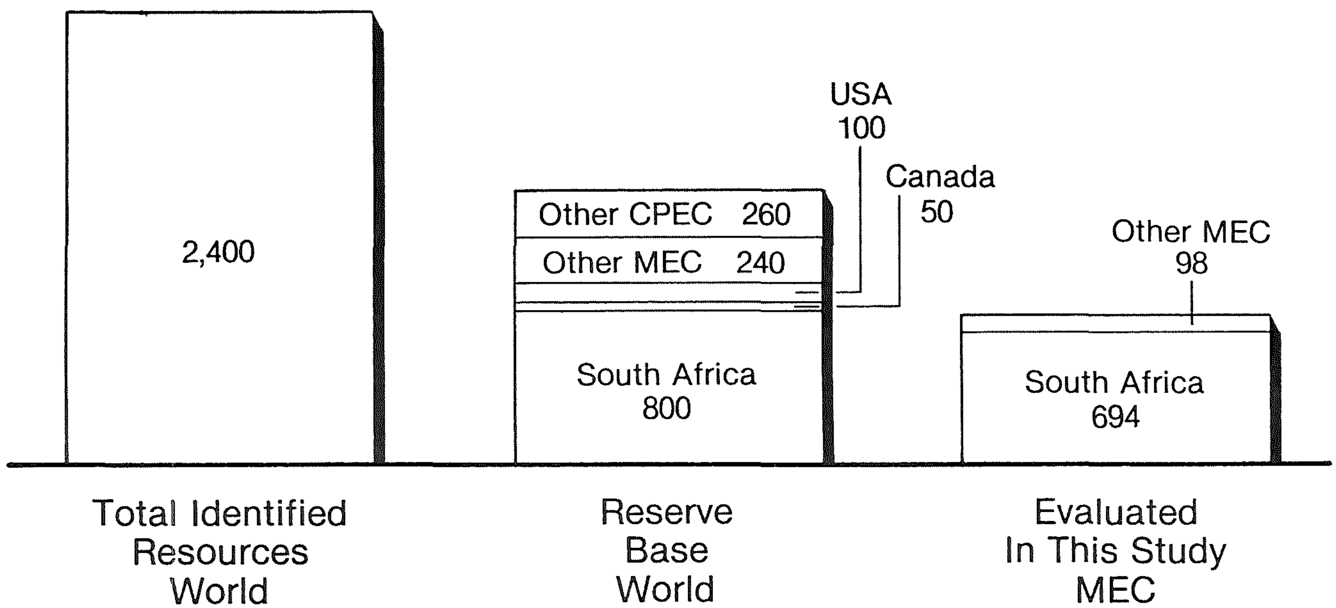



**Figure 4.2 World Gold Resources (Million Troy Ounces)**

TABLE 4.1.--List of evaluated MEC gold operations

| Country, state, nation and property name | Ownership | Mining[1] Method |
|---|---|---|
| Australia: | | |
| Central Norseman........... | Western Mining and General Pub. | C/U |
| Fimiston Leases............ | Kalgoorlie Mining Associates | U |
| Hill 50/Morning Star....... | Hill 50 & Western Mining | U |
| Mount Morgan Tailings...... | Peko Wallsend Ltd. | S/D |
| Mt. Charlotte.............. | Kalgoorlie Mining Associates | U |
| North Kalgurli............. | North Kalgurli Mines and Metals | U |
| Telfer..................... | Newmont Holdings & Dampier | S |
| Bolivia: | | |
| Teoponti................... | Compania Minera del Sur S.A. | S/D |
| Brazil: | | |
| Cerra Pelada............... | CVRD, Brazilian Government | S |
| Morro Velho................ | Bozzano/Simonsen/Anglo American | U |
| Canada: | | |
| Agnico-Eagle (Gold)........ | Agnico-Eagle mines Ltd. | U |
| Camflo/Malarctic Hygrade... | Camflo Mines Ltd. | U |
| Campbell Red Lake.......... | Campbell Red Lake/Dome Mines | U |
| Con-Rycon.................. | Cominco | U |
| Detour Lake................ | Various Owners | U |
| Dickenson.................. | Dickenson Mines Ltd. | U |
| Dome....................... | Dome Mines Ltd. | U |
| Giant Yellowknife.......... | Giant Yellowknife | U |
| Golden Giant (Hemlo)....... | Norado/Goliath/Golden Sceptre | U |
| Kerr Addison............... | Kerr Addison Mines Ltd. | U |
| Lac Minerals (Hemlo)....... | Lac Minerals | U |
| Ladner Creek............... | Carolin Mines/Aquarius Group | U |
| Lupin Project.............. | Echo Bay Mines Ltd. | U |
| Macassa (Willroy).......... | Willroy Mines Ltd. | U |
| Pamour Porcupine........... | Pamour Porcupine & Noranda | U |
| Sigma...................... | Sigma Mines/Dome Mines | U |
| Teck/Corona (Hemlo)........ | International Corona/Teck Corp. | U |
| Chile: EL Indio............ | St. Joe Minerals & Private | U |
| Columbia: | | |
| El Bagre................... | Mineros DE Antioquia | S/D |
| La Salada.................. | Sindico | U |
| Dominican: Pueblo Viejo..... | Rosario Dominicana S.A. | S |
| Ghana: | | |
| Ashanti.................... | Ghana Govt. & Lonrho | U |
| Prestea.................... | State Gold Mining Corp. | U |
| Tarlwa..................... | State Gold Mining Corp. | U |

TABLE 4.1.--List of evaluated MEC gold operations--Continued

| Country, state, nation and property name | Ownership | Mining[1] Method |
|---|---|---|
| Philippines: | | |
| Benguet (Gold)............. | Benguet Corp. | U |
| Masbate.................... | Atlas Consol.Mining & Dev. Corp. | S |
| Paracale................... | Philippine Eagle Mines Inc. | U |
| South Africa: | | |
| Beatrix.................... | Gencor | U |
| Blyvooruitzicht............ | Barlow Rand | U |
| Bracken.................... | Gencor | U |
| Buffelsfontein............. | General Mining Group | U |
| Consolidated Modderfontein. | Consolidated Modderfontein | U |
| Deelkraal.................. | Gold Fields | U |
| Doornfontein............... | Gold Fields | U |
| Dreifontein Consolidated... | Dreifontein Consolidated | U |
| Durban Roodepoort Deep..... | Barlow Rand | U |
| E.T. Consolidated.......... | Eastern Transvaal Consolidated | U |
| East Rand Proprietary...... | East Rand Proprietary Mines | U |
| Egoli Consolidated (East).. | Egoli Consolidated Mines | S |
| Egoli Consolidated (West).. | Egoli Consolidated Mines | S |
| Elandsrand................. | Anglo American | U |
| Ergo (East Rand Au & U Co). | Anglo American | S |
| Fairview (Barberton)....... | General Mining | U |
| Free State Geduld.......... | Anglo American | U |
| Grootvlei.................. | Gencor | U |
| Harmony.................... | Barlow Rand Group | U |
| Hartebeestfontein.......... | Anglo-Transvaal Consolidated | U |
| Joint Metallurgical........ | Various Mines | S |
| Kinross.................... | Gencor | U |
| Kloof...................... | Gold Fields | U |
| Leslie..................... | Gencor | U |
| Libanon.................... | Gold Fields | U |
| Loraine (Allanridge)....... | Anglo-Transvaal Group | U |
| President Brand............ | Anglo American | U |
| President Steyn/Video...... | Anglo American | U |
| Randfontein Estates........ | Johannesburg Consolidated | U |
| RMMM Slimes Project........ | Rand Mines | S |
| Simmer and Jack............ | Anglo American | C/U |
| St. Helena................. | Gencor | U |
| Stilfontein................ | Gencor | C/U |
| Unisel..................... | Union Corp. | U |
| Vaal Reefs................. | Vaal Reefs Exp. & M So. Vaal Holdings | U |
| Venterspost................ | Gold Fields | U |
| Village Main Reef.......... | Village Main Reef Gold Mining | S |
| West Rand Consolidated..... | Gencor | U |
| Western Areas.............. | Johannesburg Consolidated | U |
| Western Deep Levels........ | Western Deep Levels | U |

TABLE 4.1.--List of evaluated MEC gold operations--Continued

| Country, state, nation and property name | Ownership | Mining[1] Method |
|---|---|---|
| South Africa--Continued: | | |
| Western Holdings Complex... | Four Combined Owner/Operations | U |
| Winkelhaak................ | Gencor | U |
| Witwatersrand Nigel........ | African Exploration | U |
| Taiwan: Chin-Qua-Shih....... | Taiwan Metal Mining Corp. | U |
| United States: | | |
| California: | | |
| McLaughlin............... | Homestake Mining Co. | S |
| Yuba Placer.............. | Placer Service Co./Yuba Natural Resources Co. | S/D |
| Colorado: | | |
| Victor Project........... | Silver State Mining Corp. | S |
| Idaho: | | |
| West End/Garnet Creek.... | Superior Oil Co./TRV Minerals | S |
| Montana: | | |
| Golden Sunlight.......... | Placer Amex | S |
| Zortman-Landusky......... | Zortman-Pegasus Gold Ltd. | S |
| Nevada: | | |
| Alliator Ridge........... | Occidental Minerals/Amselco | S |
| Battle Mountain.......... | Duval Corporation | S |
| Borealis................. | Houston International Minerals | S |
| Carlin Operations........ | Newmont Mining Co. | S |
| Jerritt Canyon........... | Freeport Gold Co./FMC Gold Inc. | S |
| Pinson/Preble/Ogee....... | Lacana/Rayrock/Siscoe Metals | S |
| Round Mountain........... | Louisiana Land/Homestake/Case | S |
| Windfall................. | Western-Windfall Inc. | S |
| New Mexico: Ortiz......... | Gold Fields Mining Corp. | S |
| South Dakota: Homestake... | Homestake Mining Co. | U |
| Utah: Mercur.............. | Getty Mining Co./Gold Standard | S |
| Zimbabwe: | | |
| Arcturus.................. | Lonrho | U |
| Athens.................... | Lonrho | U |
| Blanket................... | Falconbridge Nickel | U |
| Dalny..................... | Falcon Mines Ltd. | U |
| How....................... | Lonrho | U |
| Mazoe..................... | Lonrho | U |
| Muriel.................... | Lonrho | U |
| Old West/Redwing.......... | Lonrho | U |
| Patchway/Brompton......... | Rio Tinto (Zimbabwe) | U |
| Renco..................... | Rio Tinto (Zimbabwe) | U |
| Shamva.................... | Lonrho | U |
| Venice.................... | Falcon Mines Ltd. | U |

[1]S = surface; S/D = surface dredge; U = Underground; C/U = Combined, primarily underground.

during 1986 will reportedly reduce labor requirements by as much as 50 pct of the 1985 levels.

In Canada, the 17 predominantly underground producers consist of 11 mines that have been in production since before 1975, and six that have commenced production since 1979. The six new operations include the three large Hemlo District operations that weren't technically in full production until sometime in 1986. The mining methods in use at the 17 operations show a wide variation from high-cost, cut-and-fill or narrow-vein shrinkage methods to low-cost, long-hole open stoping methods.

Most of the six Canadian operations that began production after 1979, or were in development as of 1985, either utilize, or plan to utilize, low-cost underground mining methods such as blasthole or long-hole open stoping. This partly reflects the increase in the price of gold, and, partly, a reflection of the discovery of a new type of ore body, the Hemlo type, which has very large thicknesses (for the gold grades obtained), that range from 3 to 30 m, and that can be mined utilizing low-cost, high-tonnage underground methods. Currently, the depth at which the 17 underground mines are operating does not, as of this date, appear to have a major influence on their overall cost of production.

## Beneficiation

The 43 South African properties operate a total of 79 individual mills, 19 of which were being utilized in the mid-1980's for $U_3O_8$ leaching and 60 for gold vat leaching with cyanide. As of 1983-84, six of these gold leaching mills were utilizing the relatively new carbon-in-pulp method for extracting gold from the cyanide leach solution and 54 were still using the older, more labor-intensive Merrill-Crowe (zinc dust precipitation) process. It is expected that in the future, all new gold leaching mills in South Africa will utilize the carbon-in-pulp method.

The 17 Canadian operations use 18 separate mills. All 18 of these mills utilize vat leaching with 14 utilizing the Merrill-Crowe method for gold extraction and four (including all three of the Hemlo District operations) using the carbon-in-pulp method. Only four of the 18 mills do not use pre-aeration or flotation methods prior to the cyanide leach stage and only five have jigs installed to extract free gold. There are no heap leaching operations represented by the 17 Canadian operations.

The seven Australian operations use six separate mills. Four of these mills are utilizing the Merrill-Crowe process for gold extraction and six are utilizing the carbon-in-pulp method. All five of the primary gold ore mills have a gravity separation circuit included to effect recovery of free gold. Of the nine ore types being beneficiated by the six mills, two are refractory ores (requiring roasting) and two require flotation and cyanide leaching of the concentrate. No heap leaching is done by these seven Australian operations.

The 17 U.S. producers include eight heap leaching operations, six vat leaching operations, two operations utilizing both heap leaching and vat leaching, and one dredging operation using conventional gravity methods for gold recovery. Both the heap and vat leach operations are characterized by a preponderance of carbon-in-pulp gold extraction circuits. For example, only three of the heap leaching operations and only two of the major circuits at the vat leaching operations utilize the old Merrill-Crowe gold extraction methods.

## Production Costs

Table 4.2 illustrates average production costs, capacity and recoverable gold for the four most important MEC gold producing countries. These four MEC countries, representing 61.7 pct of total 1985 world mine production and 80.5 pct of 1985 MEC mine production, are felt to be indicative of the basic

TABLE 4.2. - Cost, Capacity, and Resources for selected MEC gold mines and deposits
(All costs are expressed in January 1985 U.S. dollars per troy ounce of gold
on a weighted-average basis)

| Country | Demonstrated Resources: ore million mt | Demonstrated Resources: recoverable gold million tr oz | Average Annual gold production capacity ($10^3$ tr oz) | Total operating cost[1] | Production cost 0 pct[2] | Production cost 15 pct[3] |
|---|---|---|---|---|---|---|
| South Africa: | | | | | | |
| Underground mines | 2,879 | 680 | 20,984 | $148.27 | $204.26 | $235.45 |
| Surface mines | 2,008 | 14 | 306 | $159.77 | $226.11 | $290.86 |
| United States | 686 | 31 | 1,612 | $280.21 | $353.74 | $423.11 |
| Canada | 178 | 35.5 | 1,806 | $193.69 | $263.81 | $394.92 |
| Australia | 62 | 6 | 354 | $224.38 | $300.45 | $344.23 |
| Others | NM | 26 | 2,209 | NM | NM | NM |

NM not meaningful
[1] Equal to the sum of mining, milling and transportation costs FOB the port of exportation.
[2] Equal to the sum of total operating costs, taxation and capital recovery determined at a 0-pct DCFROR.
[3] Equal to the sum of total operating costs, taxation generated at a 15-pct DCFROR, capital recovery plus the per mt increase necessary to provide a 15-pct DCFROR.

technical, geologic and economic factors that govern the cost structure of the world gold mining industry. The production costs shown in table 4.2 are expressed in constant U.S. dollars at January 1985 exchange rates and are based on current extractive technology.

The changing value of the dollar relative to the currencies of other countries and the difference in rates of inflation quickly alter the absolute and relative values of the production cost estimates. To illustrate this effect, the January 1985 average total cost estimates for the 0-pct DCFROR level were compared with January 1984 estimates presented in IC 9070 (4). The January 1984 average total cost estimate for the South African underground mines was \$285/tr oz. By comparison, the January 1985 estimate is \$204/tr oz, a decline of 28.4 pct over the one year period. Similarly, Canada shows a 9.6 pct decline, Australia a 5.9 pct decline, and the U.S. weighted-average shows (by definition) no change. Essentially, all of these percentage changes reflect the degree to which the value of the U.S. dollar (in percentage terms) has increased or decreased in value relative to the currencies of these countries, after accounting for the differential in rates of inflation.

Figure 4.3 illustrates the relative size of the major components of these costs. As previous mining and beneficiation sections have indicated, cross comparisons of the individual cost structures for these major MEC gold producers are technically very difficult because of widely varying gold grades, ore types, size of operations, plus many other geologic, engineering and economic factors. The South African underground mines, which contain the vast majority of the evaluated recoverable gold summarized in table 4.2, have the lowest average total cost estimates at both the zero and 15-pct DCFROR levels. The South African underground mines on a weighted-average basis have three advantages: 1) the presence of a number of very large "supermines" with excellent scale economies, 2) the presence of a relatively low-cost labor

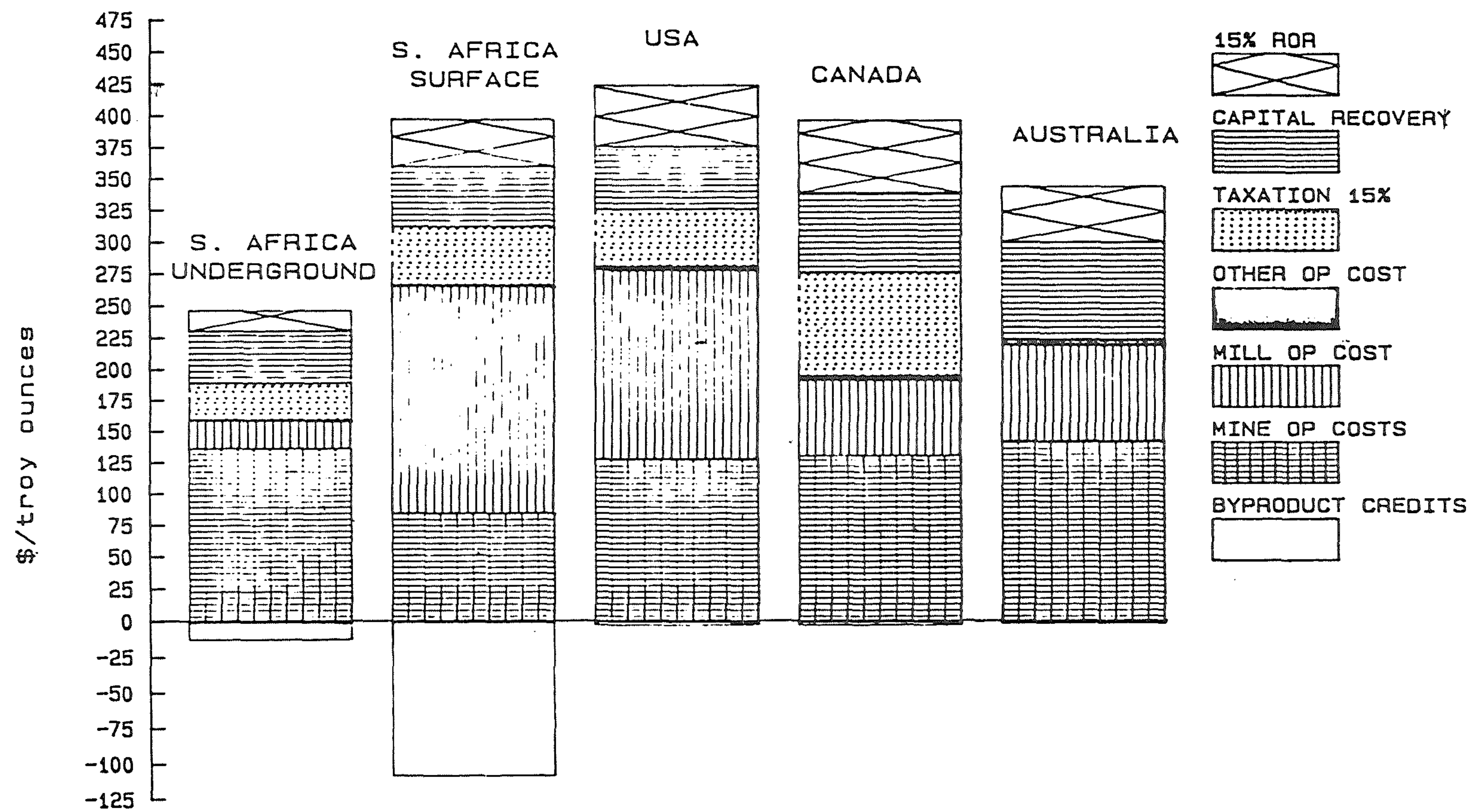



FIGURE 4.3 ESTIMATED AVERAGE PRODUCTION COSTS FOR SELECTED GOLD PRODUCING COUNTRIES

structure, especially in relation to the other three countries, and 3) relatively high average ore grades, at 9.6 g/mt in 1985. The total U.S. cost structure is the highest of the four countries owing primarily to the low average grade of the operations (2.0 grams/mt) and is the only one of the four countries with a mill operating cost estimate that is higher than the mine operating cost estimate. The predominance of lower-cost surface minable tonnage as well as low grades contributes to this anomalous circumstance.

Revenues from byproducts at primary gold mines are insignificant, overall, for the four countries. However, two of the surface waste reprocessors in South Africa do obtain significant byproduct revenue from the sale of recovered uranium (hence the high byproduct revenue estimate for these operations as a group) as do a few of the underground mines.

For all four countries, capital costs per oz of recoverable gold are similar, ranging from $41.22 to $76.07. As a percentage of total production cost, capital costs range from 14.1 to 25.3 pct. This similarity most likely reflects the fact that each operation adjusts to the particular ore and ore grade that constitutes their demonstrated resource. For example, the underground mines have much higher total capital cost requirements owing to the need for investment in expensive items such as deep shaft systems, but these costs are generally offset by higher grade ores.

## Availability

The step curve in figure 4.4 illustrates the total gold available from the deposits evaluated at the 0-pct DCFROR level, with and without South Africa. The shaded area indicates that total primary gold availability would be largher than depicted if all deposits and byproduct sources were included. At prices up to about $500/tr oz, 792.3 million tr oz of recoverable gold is available from all evaluated operations. South Africa accounts for 693 million tr oz, 87.5 pct of the total.

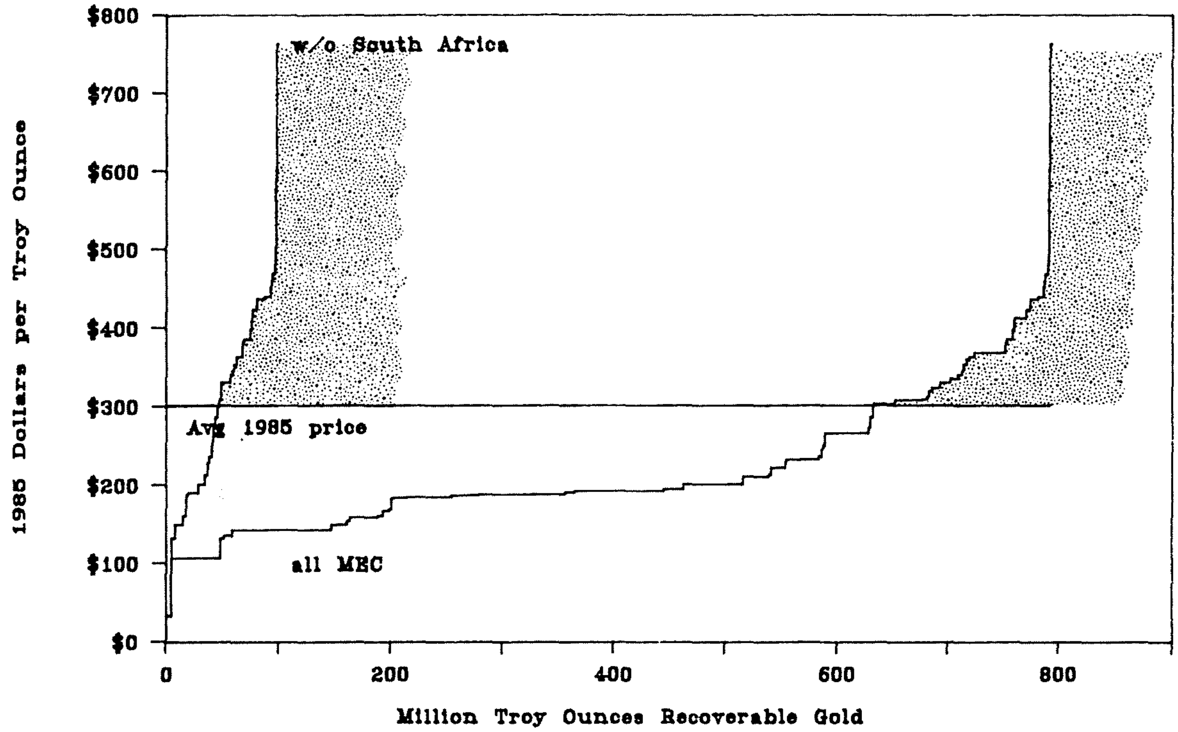
The January 1985 gold price was $302 per tr oz. At the 0-pct DCFROR level, 96 pct of total gold is available at a long run total cost of $400/tr oz or less and as the price line indicates 82 pct is available at $300/tr oz or less. If South African mines are excluded, total available gold decreases significantly to only 98.3 million tr oz, or about 2.5 times the amount of gold consumed in the MEC's during 1985 (5). At $300/tr oz, available gold is only 34.6 to 45.6 million tr oz., less than 1.5 years of total MEC production.

At the 15-pct DCFROR level (not shown), 90 pct of total gold is available at a cost of $400/tr oz or less (with South Africa accounting for 92 pct of this portion) and 72 pct of total gold is available at $300/tr oz or less (with South Africa accounting for 94 pct of this portion). In terms of total production cost and total resource inventory, South Africa dominates the gold mining industry of the MEC's. However, long-run gold prices exceeding $400/tr oz are required to ensure that all South Africa current producers will be able to cover their total production costs over the current estimate of mine life.

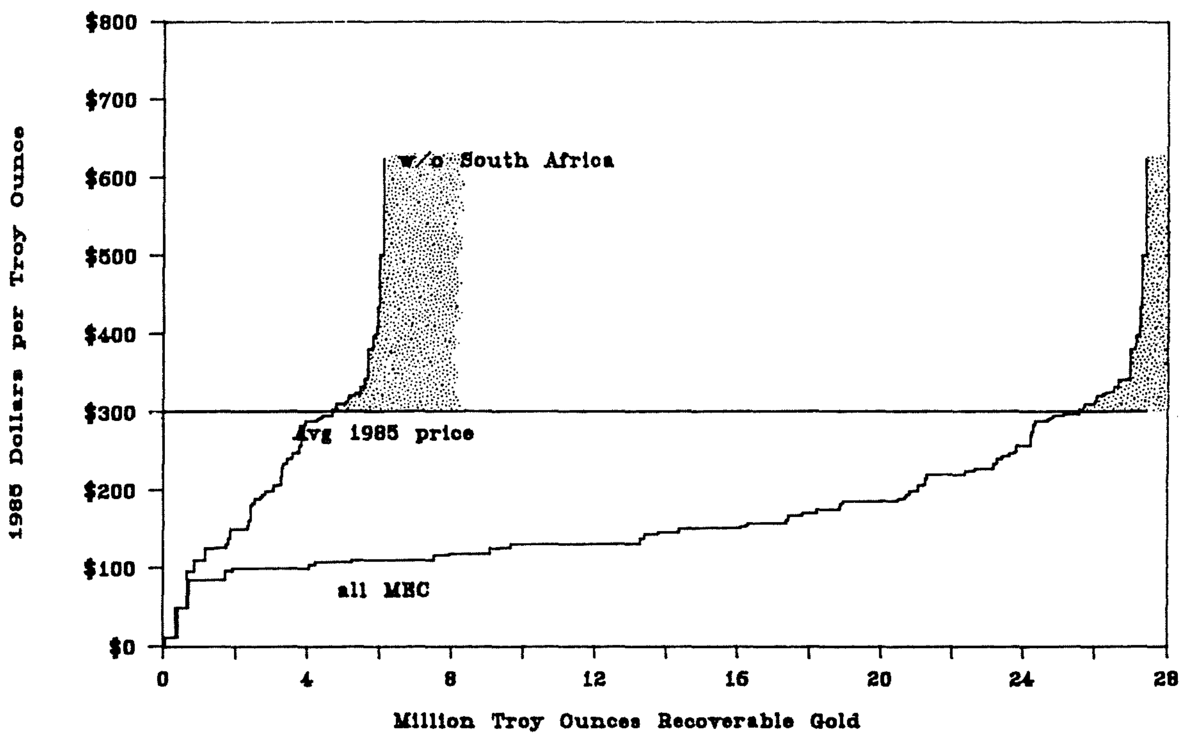
Annual output is also dominated by South Africa. Figure 4.5 shows potential MEC capacity production in 1985 from producing mines with and without South Africa. The curves show potential production available at a price level that covers net operating costs and the shaded areas again indicate that these are lower bound estimates. As shown, the 110 analyzed mines represent an estimated total capacity production level of some 26.3 million tr oz as of 1985. If South African mines are excluded, annual availability decreases significantly to 6.1 million tr oz of which 4.7 million tr oz is available at $300/tr oz. If the price of gold is held constant at the January 1985 level of $302/tr oz, approximately 93 pct of total production in that year could cover long-run average operating costs.

The 43 South African operations accounted for 22.1 million tr oz (84 pct) of the MEC total. During 1985, these operations provided the great majority

# Fig. 4.4.-Total Gold Availability




# Fig. 4.5.-Gold Production Capacity



of primary gold production and approximately 73 pct of total mine production of gold (including byproduct production) in the MEC. The availability curves shown include over 95 pct of total South African production capacity.

RESOURCES NOT INCLUDED IN THE EVALUATION

Relatively high gold prices have engendered a high level of gold exploration and development activity, especially in Australia, Canada, and the United States. Since 1982 at least 18 new Australian and 29 new U.S. mines or deposits of size comparable to some included are omitted from the January 1985 estimate. The large majority of these new 47 mines or deposits which were not included are, or will be, surface operations. An additional 100 or so new mines or explored deposits in MEC countries probably could have been added to the analysis had they been sufficiently explored to warrant classifying their resource tonnages at the demonstrated level. Thus, overall gold resource totals for a country can become quickly outdated in a period of expanded exploration and development activity.

The great majority of the new U.S. and Canadian mines are very small by comparison to the South African mines, although many of them are significant relative to the scale of evaluated producers in the U.S. and Australia. Total production and resources from these mines if added to the total or annual availability curves would probably not significantly alter the resource or cost picture. To put this in perspective, if South African output declined by 50 pct (roughly 11 million tr oz) it would require that, concurrently, sufficient resources in the U.S., Canada and Australia be discovered, developed and production maintained at a total annual production level that is double their current combined production. Furthermore, the factor of time must be considered; the development of a gold mine from deposit discovery to production can take roughly 2 to 10 yrs, depending upon a host of technical, financial, and legal factors (3). The probability of matching lost South

African production with additional new production from U.S., Canadian, and Australian sources is unlikely and would certainly require, among other factors, much higher long run prices than those prevalent recently.

CONCLUSIONS

South Africa contains the world's largest demonstrated resource of recoverable gold and should remain the world's largest gold producer through the remainder of this century (barring non-market problems). It is unlikely that other MEC mine producers of gold could replace the 50 pct of world mine production accounted for by South African mines at current or substantially increased gold price levels.

A large majority of the evaluated demonstrated resources are contained in operations that employ underground mining methods. The majority of the analyzed surface minable resource is contained in conventional surface mining operations in the United States and waste reprocessing operations in South Africa. Many new mines and explored deposits in the United States and Australia, which aren't analyzed, are or will be surface mining operations, but the long term availability of newly mined gold will continue to be dominated by underground operations.

The United States accounts for approximately 4 pct of the total recoverable gold and possesses a viable gold industry which continues to expand. The major long term issue for the U.S. is production maintenance through replacement of surface minable resources that have relatively short lives by comparison to underground producers in South Africa or Canada. Of the total recoverable gold evaluated in the U.S., approximately 75 pct is available from surface mines.

The changing value of the U.S. dollar relative to the currencies of other gold producing nations quickly and significantly alters the relative estimated costs of gold mining operations in different countries.

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# CHAPTER 5 MANGANESE

## BACKGROUND

### Uses and Importance

Manganese is a vital element in an industrial society, since it is virtually indispensible in enhancing strength, toughness, hardness, and harden ability in iron and steel. In nonferrous metallurgy, manganese is used as an alloying element in aluminum, magnesium, and copper. These metallurgical applications account for about 95 pct of total manganese consumption (1). At present, no satisfactory substitute exists to replace manganese in its alloying role. A large share of the remaining amount is used in the battery and chemical industries.

In 1985, the United States consumed an estimated 608,000 mt in Mn metal content (excluding ore containing less than 35 pct Mn) (2), all of which was imported. Recovery of manganese from secondary or scrap sources is insignificant. In 1983, the latest year for which estimates are available, the total manganese consumption in the world was approximately 8 million mt. Estimated manganese reserves are sufficient well into the next century, but manganese supply is of concern to MEC's because most significant manganese deposits are located in countries that are not major steel producers.

### Geology

Manganese deposits are classified into three geological types: hydrothermal, residual, and sedimentary (3). Hydrothermal manganese deposits are normally made up of carbonates and oxides of manganese minerals along with other hydrothermal minerals such as barite, fluorite, and sulphides. Examples of hydrothermal vein-type and replacement deposits include the rhodochrosite ore at Butte and Phillipsburg, MT.

Residual deposits are formed near the surface by weathering processes. Large deposits of economic significance include the Serra do Navio Deposits in Brazil, Moanda in Gabon, and several occurrences in Australia and India.

Sedimentary manganese deposits contain the largest portion of world economic manganese resources. These deposits are subdivided into several subclasses as shown below:

1. Volcanogenic deposits are those in which the manganese can be related directly or indirectly to volcanic sources. The Nsuta Mine in Ghana is in this class.

2. Nonvolcanogenic sedimentary deposits include those where the manganese is not related to any volcanic source. The more important manganese deposits of this type include Groote Eylandt in Australia, the Morro do Urucum area in Brazil, and the Maharashtra-Madhya Pradesh area in India.

3. Metasedimentary manganese deposits associated with iron formations are identified in Brazil and South Africa. The iron formation units are extensive and cover relatively great distances; however, the associated manganese beds within these formations vary in thickness and continuity.

4. Ocean floor nodules cover vast areas in the Pacific, Atlantic, and Indian Oceans. The nodules are found at all depths of the ocean, but higher grades are usually found within the deeper basins at great distances from land areas.

## Production

There is no standard definition and classification for manganese ores. Industry uses 48 pct manganese content as a standard for international trade pricing. The Bureau of Mines defines manganese ores as those ores containing 35 pct or more manganese. Manganiferous ores are defined as ores containing greater than 5 pct and less than 35 pct manganese. This term is subdivided into ferruginous manganese ore for those ores containing 10 to 35 pct manganese and manganiferous iron ores for those ores containing 5 to 10 pct manganese. In industry practice, the term manganiferous iron ores include ores grading as low as 2 pct manganese. The Bureau of Mines uses these terms in a broad and practical manner to avoid difficulties in classification purposes. Materials reported as ore may actually be in the form of concentrate, nodules, sinter or a synthetic manganese ore (3).

Total world production of manganese ore in 1985 was estimated at 23.4 million mt, of which 11.7 million mt (50 pct) was from MEC's (2). Figure 5.1 shows the trend of world manganese ore production in 5-year increments from 1950 to 1985, for the major producing countries and regions. (Note: Production for South Africa peaked in 1975 at 5.8 million mt, declined and rose almost to the same level in 1980.) The largest production in each year has been from the U.S.S.R. and China, of which approximately 85 pct is from the U.S.S.R. Currently, the largest MEC producing region is Africa, which produced an estimated 5.5 million mt of manganese ore in 1985 (2). The largest share (62 pct) of African production is from South Africa, which in 1985 produced 3.4 million mt of manganese ore. The other principal producer in Africa is Gabon which produced an estimated 2.1 million mt of manganese ore. The largest increase in manganese ore production among the MECs is from South Africa, where production rose from 791,000 mt in 1950 to a peak of 5.8 million mt in 1975.

## EVALUATED RESOURCES

This study evaluates costs to produce manganese concentrate delivered to the smelter, and all of the analysis is in terms of contained manganese in concentrate. Figure 5.2 places manganese resources evaluated for this study in the perspective of total resources as estimated by the National Materials Advisory Board (4) and reserve base estimates published by the Bureau (2). Total identified world resources of manganese ore were estimated by the

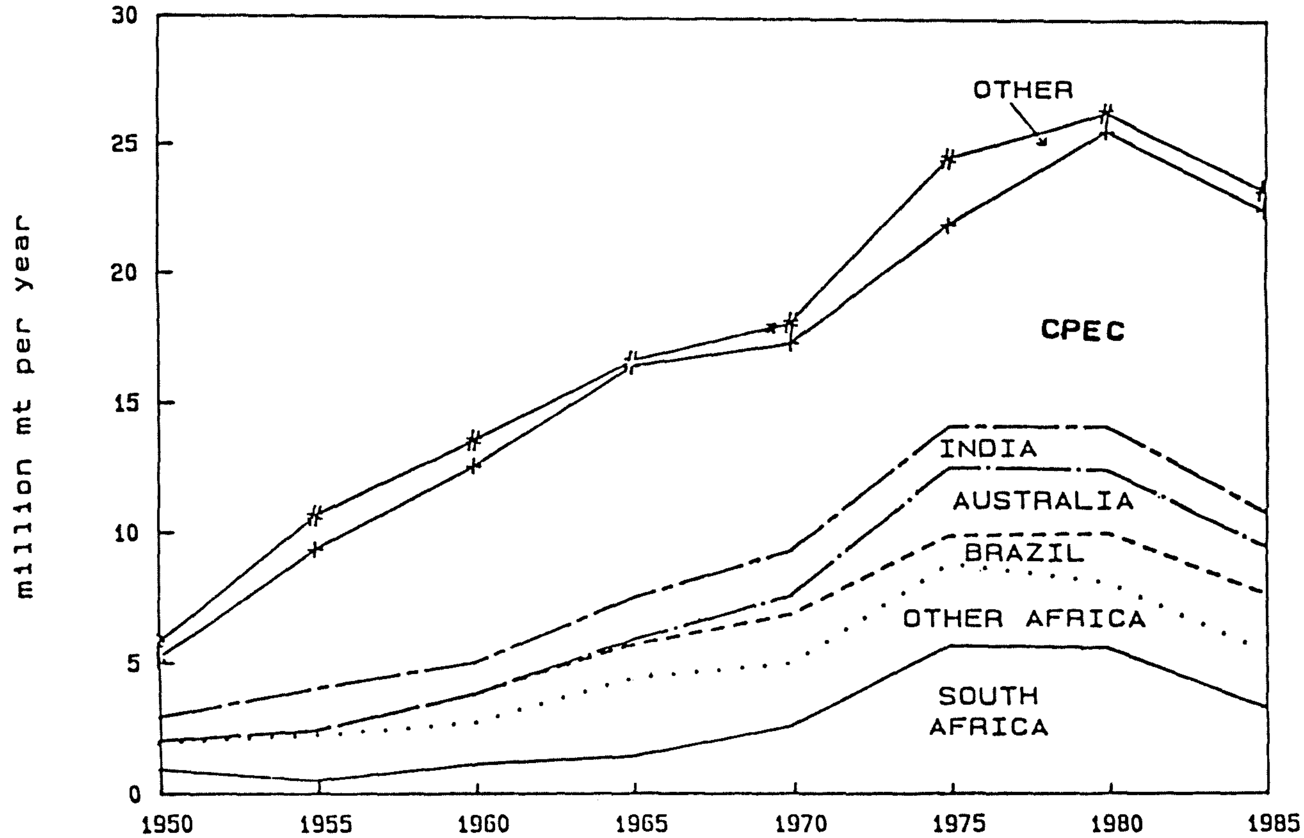



FIGURE 5.1 WORLD MANGANESE ORE PRODUCTION 1950 - 1985

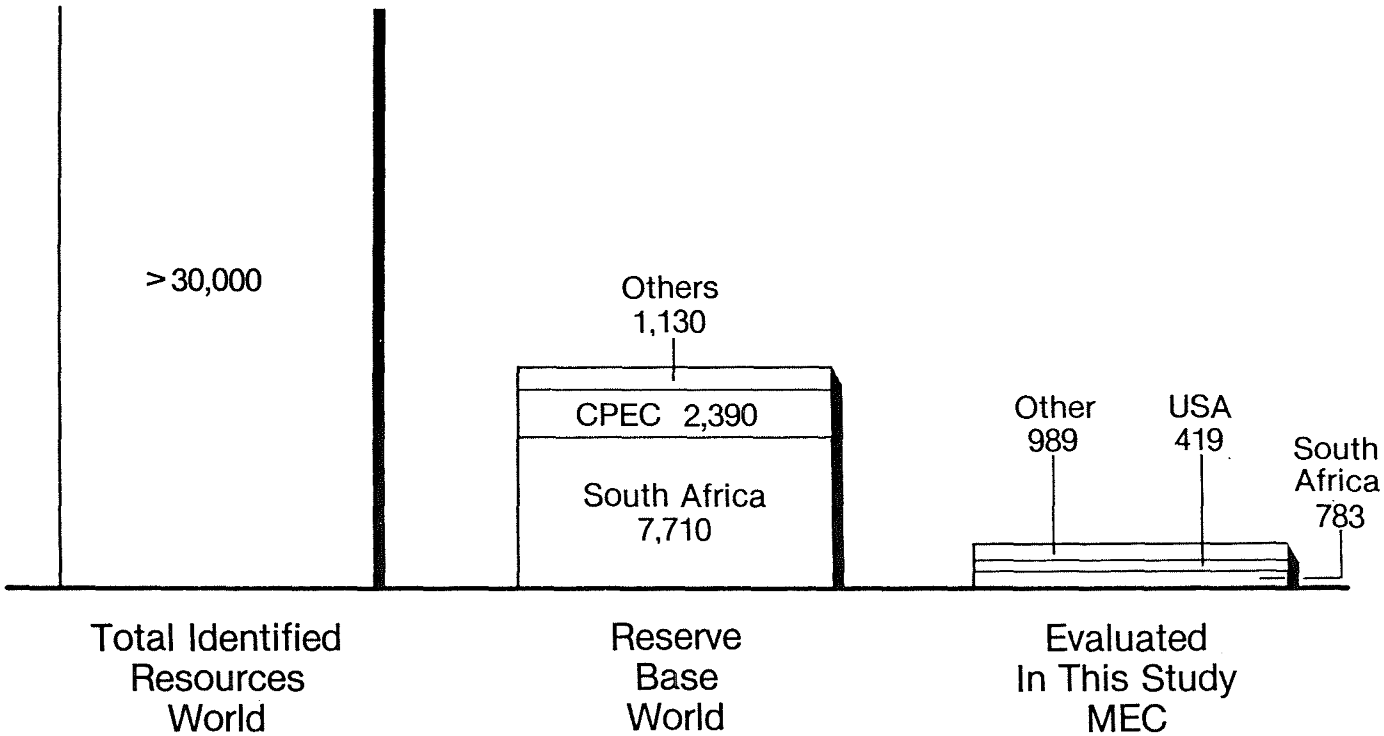



**Figure 5.2 World Manganese Ore Resources (Million Metric Tons)**

National Materials Advisory Board as being in excess of 30 billion st (4). World in situ reserve base tonnages estimated by the Bureau Mines total 11 billion mt of manganese ore, of which 8.5 billion mt are located in MEC's.

Total demonstrated resources evaluated for this study amount to 2,191 million mt of manganese ore. Resources classified at the inferred level encompass an additional 668 million mt of ore. Differences in the Bureau's reserve base figure for MEC's and the demonstrated resources tonnages in this report are attributable to the evaluation of only a portion of South Africa's reserve base for the availability analysis. For this report only those properties in South Africa were included for which sufficient information was available. Properties included in this report are listed in table 5.1.

## Mining

Manganese deposits are mined by open pit and underground methods. The physical character of the ore body influences the selection of the specific mining system for each deposit. The continuous character of the ore horizons in the major manganese resource areas permits highly mechanized operations in both open pit and underground mines. Room and pillar is the most widely used underground method.

Of the operating areas evaluated in this study, seven are being mined by open pit methods, six by underground methods, and two by combined open pit-underground mining methods. In terms of both production capacity and demonstrated resource, the open pit mines account for about 60 pct of the total quantities. Most mining operations are mechanized, except that operations are largely labor-intensive in India.

TABLE 5.1. - List of manganese properties included in this study

| Country and mine or deposit | Owner and/or operator | Deposit status[1] | Type of operation[2] | Avg feed grade pct Mn | Annual ore capacity 1,000 mt |
|---|---|---|---|---|---|
| Australia: | | | | | |
| Groote Eylandt | Broken Hills Proprietary Co. | P | OP | 44 | 5,000 |
| Brazil: | | | | | |
| Azul | Companhia Vale do Rio Doce (CVRD) | P | OP | | |
| Sereno | CVRD | E | OP | 34 | 1,500 |
| Buritirama | Prometal | E | OP | | |
| Santana | Companhia Paulista de Ferro Ligas | P | UG | 43 | 120 |
| Serra do Navio | Industria Commercio e e Minerios SA (ICOMI) | P | OP | 44 | 300 |
| Urucum | CVRD | P | UG | 46 | 400 |
| Gabon: Moanda | Cie Miniere de l'ogooue (Comilog) | P | OP | 44 | 4,000 |
| Ghana: Nsuta | Ghana National Manganese Corp. | P | OP | 31 | 450 |
| India: | | | | | |
| Maharastra-Madya-Pradesh Area (includes Balaghat, Kandri, Munsar, Tirodi, Ukwa) | Manganese ore India, Ltd. | P | OP/UG | 42 | 320 |
| Karnataka (Mysore) Bisgod | Mysore Minerals Ltd. | P | OP | 42 | 60 |
| Keonjhar District | Various owners | P | OP | 40 | 363 |
| Mexico: | | | | | |
| Tetzintla-Molango | Compania Minera Autlan | P | OP/UG | 27 | 800 |
| South Africa | | | | | |
| Black Rock area (includes Gloria, Nchwaning, Nchwaning West) | Associated Manganese Mines of S. Africa Ltd. (AMMOSAL) | P | UG | 40 | 2,700 |

TABLE 5.1. - List of manganese properties included in this study — Continued.

| Country and mine or deposit | Owner and/or operator | Deposit status[1] | Type of operation[2] | Avg feed grade pct Mn | Annual ore capacity 1,000 mt |
|---|---|---|---|---|---|
| South Africa—Continued: | | | | | |
| Mamatwan | S. African Manganese Amcor Ltd. (SAMANCOR) | P | OP | 35 | 2,500 |
| Middleplaats[4] | ..do.................. | P | UG | 36 | 1,100 |
| Wessels | ..do.................. | P | UG | 43 | 1,500 |
| Lohahtla[4] | ..do.................. | P | OP | 32 | 500 |
| United States | | | | | |
| Hardshell | 3 | E | UG | 15 | 536 |
| Maggie | Arizona Manganese Corp. | E | UG | 7.5 | 328 |
| Sunnyside | Standard Metals Inc. | E | UG | 10.0 | 635 |
| Maple Mountain Hovey Mountain | Various owners | E | OP | 8.9 | 426 |
| North Aroostock Dist. (Dudley and Gelot Hills) | Various owners | E | OP | 9.5 | 262 |
| Cuyuna Range (Southwest portion) | 3 | E | OP | 7.8 | 357 |
| Butte Dist. (Emma Mine) | The Anaconda | E | UG | 17.0 | 400 |
| Three Kids | Income Investment Inc. | E | OP | 13.2 | 1,050 |
| Upper Volta: | | | | | |
| Tambao | Societe Miniere de Tambao | E | OP | 54 | 500 |

[1]Status of deposit: P = Producers; E = Explored.
[2]Type of operation: UG = Underground; OP = Open pit.
[3]Property ownership unknown.
[4]Not operating in 1985.

## Processing

All manganese ores must be crushed and screened, and if the ore contains appreciable quantities of low-grade or barren clayey material, then washing is practiced. In general, crushing, screening, and washing may upgrade the product by only 1 to 3 pct manganese, though washing can improve the product more if there is a significant clayey material, such as in the Groote Eylandt Mine in Australia. In most cases, however, the fines removed by washing contain relatively high values of manganese (approximately 20 to 30 pct manganese), and thus the recovery of manganese is lowered. Recoveries estimated for the operations in this study range from about 60 to 75 pct. Long-term recoveries may be higher, however, because some of the material discarded at one time may be sold as low-grade blast furnace feed later, depending on demand.

Heavy-media separation can be used where there is a significant quantity of silica and alumina gangue in the ore and in some cases for upgrading chemical- and battery-grade ore. This process is currently in use at the Groote Eylandt Mine, the Molango-Tetzintla Mine in Mexico where silica gangue is encountered, and the Serra do Navio operations in Brazil in conjunction with reduction roasting and magnetic separation.

The nodulizing process is normally used in upgrading manganese carbonate ores. The process involves calcining the crushed ore in a rotary kiln to liberate carbon dioxide and to form nodules. Carbon dioxide is first liberated, then further heating softens the ore and forms nodules of about 25 mm in diameter, as at the Molango Mine in Mexico. A nodulizing plant was installed at the Nsuta Mine in Ghana to upgrade carbonate ores from 31 to 44 pct manganese (6). The advantage of this process is that the manganese content of the carbonate ore can be increased by 12 to 15 pct with little recovery losses.

In all processes, a certain amount of fines are produced which may or may not be further upgraded or shipped direct as sinter feed. All fines (generally minus 6 mm) must be sintered, and this is done at the smelter installation.

Smelting of manganese ore for the production of ferromanganese is carried out in either a blast furnace or a submerged arc electric furnace. Manganese recoveries to final products in the electric furnace are estimated to be 95 to 96 pct and in the blast furnace about 88 to 90 pct (1). If the slag in the electric furnace process were not used for silicomanganese production, electric furnace recoveries would be about the same as those for the blast furnace.

Blast furnace smelting can utilize iron blast furnaces converted to ferromanganese smelters. With the exception of the smelter at Boulogne, France, the primary purpose of the smelters is to supply the steel complex in which each is located. Excess production can be sold on the open market.

Electric furnaces can be used for producing all forms of manganese ferroalloy and other ferroalloys as well, whereas usually the blast furnace is only used to produce high-carbon ferromanganese. Recoveries in the electric furnace are higher when the slags, which may contain 30 to 35 pct manganese, are used to produce silicomanganese which may be used as is or can be used to produce medium- and low-carbon ferromanganese. The production of silicomanganese in the electric furnace process from these slags is mandatory, if the manganese in the slags is to be recovered. The slag is upgraded by the addition of manganese ore and resmelted to produce the silicomanganese.

Due to manganese oversupply in recent years, a number of smelters in the ore-importing countries have shut down. These smelters may remain closed even if demand improves because the ore-producing countries will attempt to expand their existing smelting facilities to meet new demand.

## Production Cost

Comparative costs, capacity, and resources of manganese ore and concentrates are listed on a regional basis in table 5.2. All costs are in terms of dollars per long ton unit (22.4 lbs.) of contained manganese in concentrate and therefore represent the effect of manganese grade on the cost elements. Transportation costs that are assigned to particular mines and deposits are based on assumed delivery patterns to areas of smelting.

Figure 5.3 illustrates the relative size of the major components of these costs in each region. For the producers, Asia incurs the highest mining cost; this is mostly due to inefficient and highly labor intensive mining among the Indian operations, while Latin America benefits from mechanized operations and cheap labor. Africa, because of its high mechanization, enjoys the cheapest milling cost compared to India where concentration process is limited to hand sorting. The transportation cost, because of the typically long distance to the smelters, are a uniformly large share of costs.

Among the nonproducers, the high operating costs reflect mainly U.S. ores which are low in grade. However, these deposits would recover some byproducts which would partially offset these higher costs. Large initial capital investment also makes for relatively high capital recovery costs for the nonproducers.

TABLE 5.2. - Cost, Capacity, and Resources for Selected MEC Manganese Mines and Deposits
(All costs are expressed in January 1985 U.S. dollars per long ton unit on a weight-averaged basis)

| Region | Demonstrated Resources Ore | Recoverable Mn million mt | Average Annual Capacity million mt Mn in Concentrate | Net operating cost[1] | Production cost, 0-pct[2] | Production cost, 15-pct[3] |
|---|---|---|---|---|---|---|
| Producers | | | | | | |
| Africa[4] | 1,191 | 323 | 3.85 | 1.01 | 1.03 | 1.07 |
| Latin America[5] | 112 | 30 | 0.62 | 1.15 | 1.20 | 1.30 |
| Asia[6] | 388 | 86 | 1.29 | 1.48 | 1.49 | 1.56 |
| Nonproducers[7] | 500 | 49.5 | 1.53 | 3.09[8] | 4.77 | 9.02 |

[1]Includes cost of mining, milling and transportation to smelters less any by product credits.
[2]Equal to the sum of net operating costs, taxation, and recovery of capital determined at 0 pct DCFROR.
[3]Equal to the sum of net operating costs, taxation generated at a 15-pct DCFROR, capital recovery plus the per ton increase necessary to provide a 15-pct DCFROR after taxation.
[4]Includes five mine areas in South Africa and one each in Ghana and Gabon.
[5]Includes three mine areas in Brazil and one in Mexico.
[6]Includes three mine areas in India and one in Australia (the properties in India are not economically comparable with the Australian property).
[7]Includes eight U.S. deposits and one each in Brazil and Upper Volta.
[8]Includes a $1.04 credit from byproduct revenues.

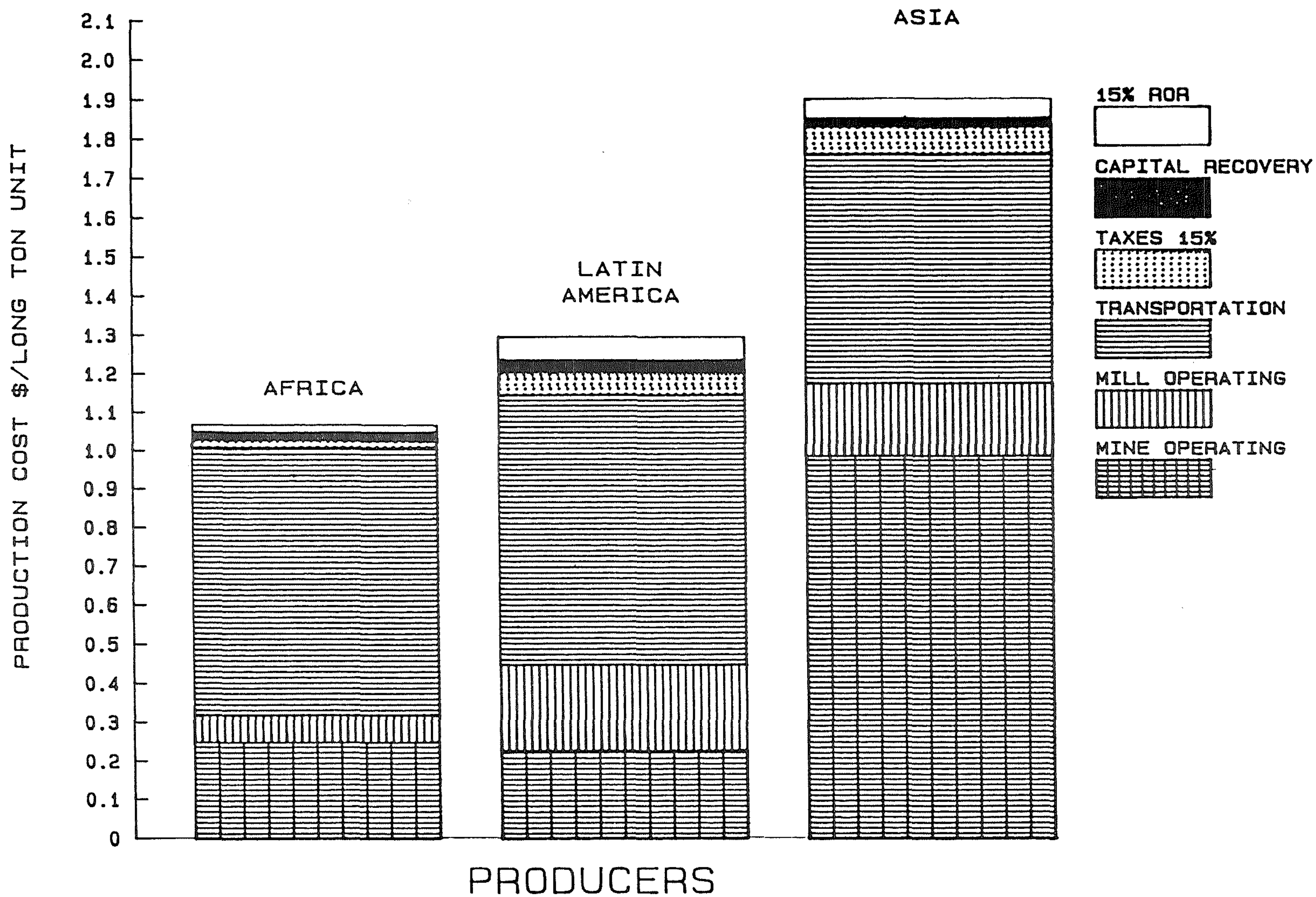



FIGURE 5.3 ESTIMATED AVERAGE PRODUCTION COSTS FOR MANGANCES MINES IN SELECTED COUNTRIES

Availability

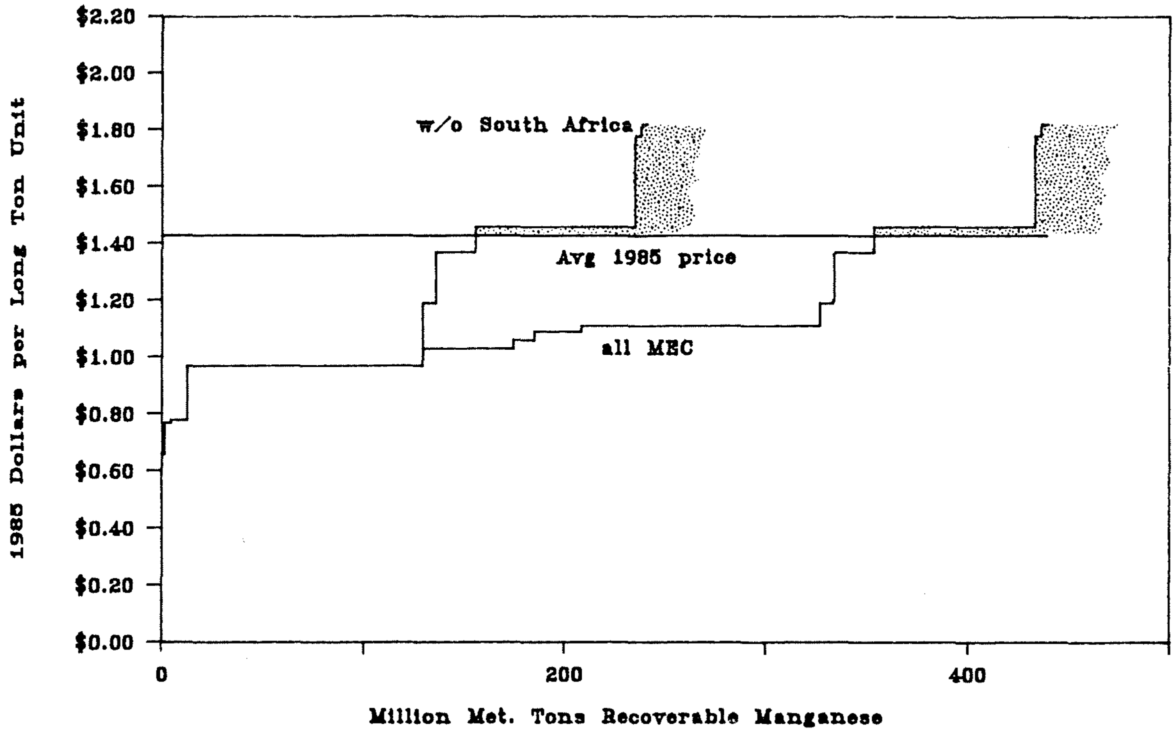
This study analyzed potential manganese production based upon the demonstrated resources of 31 manganese mines and deposits (combined in 25 mine areas) in 9 MEC's. Of these resources, an in situ amount of about 2.19 billion mt of ore was represented. This resource contains a recoverable amount of about 488 million mt Mn in concentrates, 90 pct from producing mines.

The potential total availability of manganese based on the long-run total cost (0-pct DCFROR) of each producing operation evaluated in the MEC with and without South Africa is illustrated in figure 5.4. The shaded areas indicate that additional, unevaluated sources of manganese exist. At up to $1.43/ltu (the approximate 1985 market price for manganese contained in concentrate), with a 0-pct DCFROR, the total MEC potential recoverable manganese from producers is about 353 million mt. At up to $1.85/ltu, total MEC potential recoverable manganese would be about 439 million mt from the producers. Comparable figures for the MEC without South Africa are 155 million mt at $1.43/ltu and 241 million mt at $1.85/ltu.

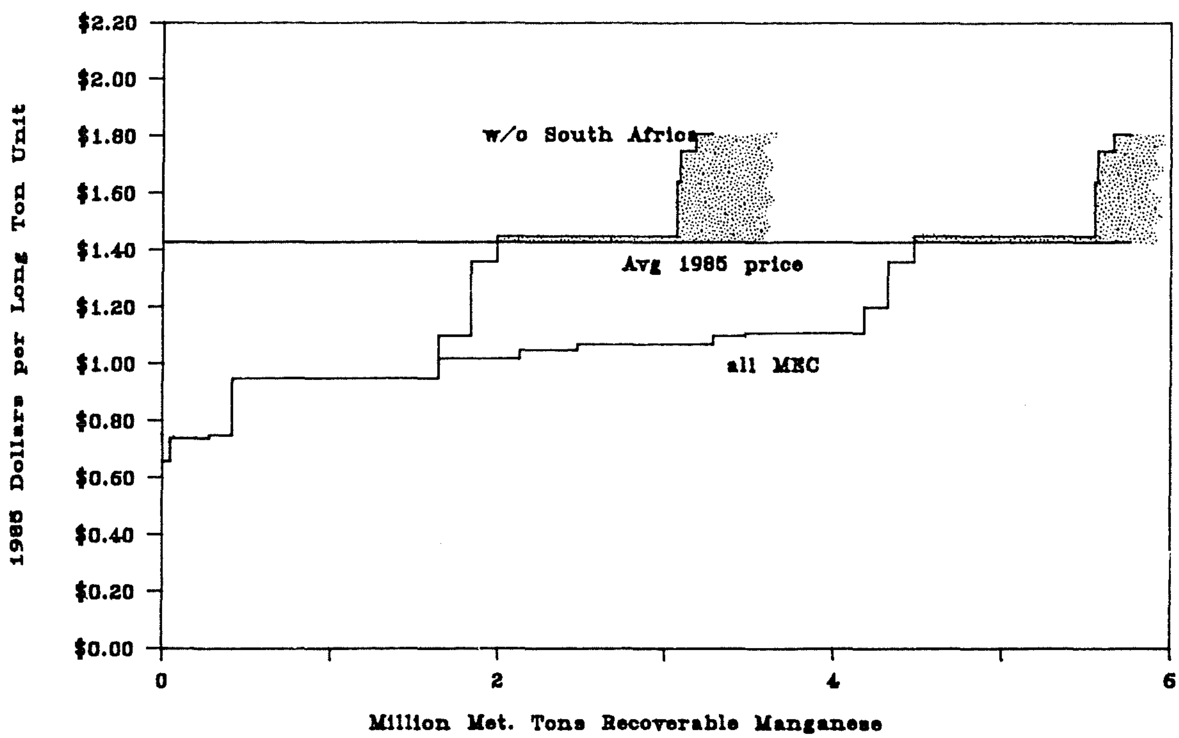
Not illustrated on the curve, the eight domestic and two foreign nonproducers evaluated have the potential to recover 18 million mt manganese in concentrate at costs less than $1.43/ltu. and a total of 26 million mt at costs less than $2.50/ltu. An additional 23 million mt of manganese in concentrate would have production costs exceeding $2.50/ltu. Most of this 23 million mt is in the United States.

Potential 1985 production of manganese from producing mines at each operation evaluated in the MEC and in the MEC excluding South Africa is illustrated in figure 5.5. The curves in each figure are based on the

## Fig. 5.4.-Total Manganese Availability




## Fig 5.5.-Manganese Production Capacity



estimated operating cost at the producing mines and shaded areas signify that these are conservative estimates of the actual capacity available. As shown, at a cost of $1.43/ltu, 4.5 million mt of Mn in concentrate could have been mined from the set of MEC producing mines. Estimated MEC production in 1985 of Mn in concentrate was approximately 5 million mt (2). At a total cost of $1.85/ltu, 5.9 million mt was available from these producers. Comparable figures for the MEC's without South Africa are 2.0 million mt at $1.43/ltu and 3.3 million mt at $1.85/ltu.

## RESOURCES NOT INCLUDED IN THE EVALUATION

At the time of this study no other deposits outside of South Africa could be identified which contained significant resources of Mn. Some 757 million mt of contained Mn at the demonstrated resource level in South Africa were not included in the availability analysis due to a lack of deposit specific information. Much of this South African material is believed to have a potential for contributing to future Mn availability.

## CONCLUSIONS

The demonstrated in situ resources of the 25 mine areas analyzed in this study amount to approximately 2.19 billion mt of manganese ore located in 9 MEC countries. Based on a 10-yr production average of about 13 million mt of manganese ore, the current demonstrated ore resource would last more than 168 yr. This resource is estimated to contain about 488 million mt of manganese in concentrate.

Over 88 pct of the total is contained in eight mining areas: Groote Eylandt, Australia; Amapa, Carajas, and Corumba areas, Brazil; Moanda, Gabon; and the Black Rock area, Middelplaats, Wessels, and Mamatwan, Republic of South Africa. Analysis indicates that about 45 pct of this material is available from sources outside South Africa at the real prices prevailing in 1985.

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# CHAPTER 6 PLATINUM-GROUP METALS

## BACKGROUND

### Uses and Importance

Platinum, palladium, iridium, osmium, rhodium, and ruthenium are the platinum-group metals (PGM) which commonly occur together in nature. Platinum always occurs in nature with one or more members of the PGM. Of the six metals, platinum and palladium have the greatest economic significance and are found in by far the largest quantities. For this reason, only platinum and associated palladium are evaluated in this chapter.

Platinum possesses a wide variety of physical and chemical properties that make it essential in many industrial applications, including auto emissions control, petroleum refining, and electronics. It is a strategic commodity for the United States due to heavy dependence upon imports from one major source -- South Africa.

The United States and Japan are the major platinum consumers. They accounted for 42 pct and 48 pct, respectively, of total 1985 MEC platinum consumption of 2.9 million tr oz. In 1985, total U.S. platinum consumption was 1.2 million tr oz with 66 pct for automotive catalytic converters, 10 pct for the electrical industry and 7 pct for the chemical industry. Total Japanese platinum consumption was 1.3 million tr oz. Jewelry accounted for 49 pct and the automotive and electrical industries ranked a distant second and third, respectively, at 13 pct and 12 pct of total Japanese platinum consumption.

### Geology

In order to estimate the platinum resources contained in PGM resources, the ratio of platinum to palladium must be determined. The ratio not only varies from one complex to the other, but is also variable within the same complex. For example, in the Bushveld Complex of South Africa, the Merensky Reef has a platinum to palladium ratio of 2.4 to 1. Below the Merensky Reef (running roughly parallel to it) lies the Upper Chromitite layer (commonly known as the UG-2), which has an average platinum to palladium ratio of 1.2 to 1 (1).

As in the Bushveld Complex in South Africa, the other major PGM deposits, such as the Stillwater Complex in the United States and the Noril'sk District in the U.S.S.R., are associated with mafic and ultramafic complexes. The Great Dyke of Zimbabwe includes four separate igneous complexes containing large quantities of platinum in association with palladium, nickel, and copper. Platinum metal is also recovered from alluvial deposits in present or ancient stream valleys, terraces, or beaches such as found in the Goodnews Bay mining district in the valley of the Salmon River in Alaska and with gold from placer deposits in Colombia

## Production

World annual production of PGM has increased from 0.6 million tr oz to 7.9 million tr oz between 1950 and 1985. South Africa and the U.S.S.R. are the two leading producers, having had almost equal shares since 1975, as illustrated in Figure 6.1.

The production of platinum is, however, dominated by South Africa because the platinum-palladium ratio in PGM's is about 2.5:1 in South Africa and only 0.4:1 in the Soviet Union. In 1985, world platinum production totalled 3.4 million tr oz; South Africa accounted for 67 pct or 2.26 million tr oz, and the U.S.S.R. produced 0.95 million tr oz or 28 pct of the total. Canada, which recovers platinum as a byproduct of nickel production from the Sudbury Complex in Ontario, ranked a distant third with 0.15 million tr oz of platinum or approximately 4 pct of total world platinum production. The United States

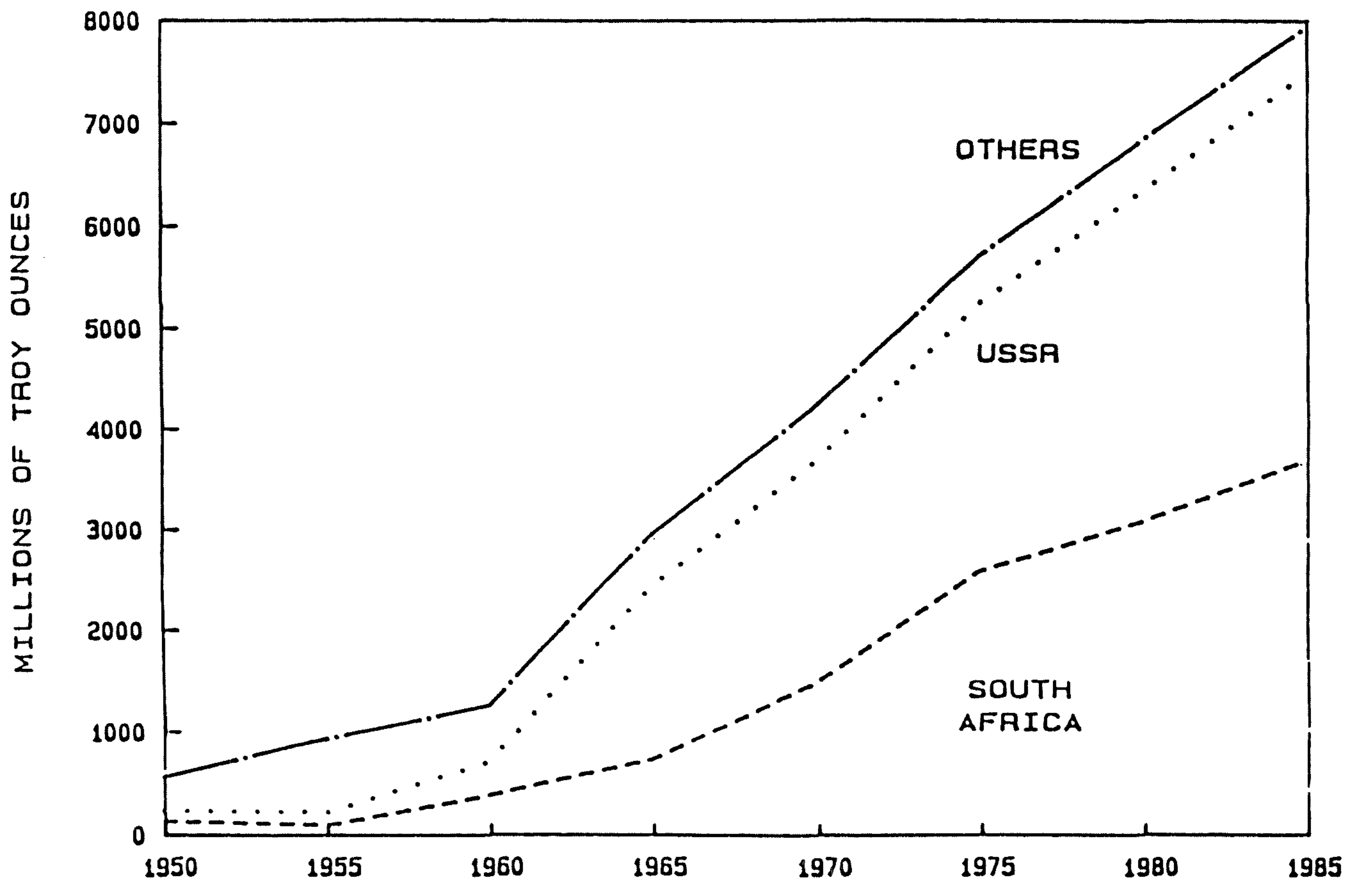


FIGURE 6.1 WORLD PGM PRODUCTION 1950 - 1985

produced only 1,000 tr oz of platinum as a byproduct from copper mines, but byproduct platinum recovery has decreased due to the poor copper market and the closing of copper mines in recent years. Platinum is also produced from deposits in Australia, Colombia, Ethiopia, Finland, Yugoslavia, and Zimbabwe in small amounts which together totalled 36,000 tr oz in 1985.

EVALUATED RESOURCES

The resources evaluated in this study are placed in perspective figure 6.2. As of 1985, the Bureau of Mines reports an in situ world reserve base value of 1,200 million tr oz of PGM that includes 970 million tr oz for South Africa (2). The estimate for South Africa includes the UG-2 calculated to a vertical depth of 600 meters. The estimate of South African PGM resources will be revised upward in 1987 to reflect deeper mining depths in both the Merensky Reef and UG-2.

Total PGM resources evaluated for this study are estimated at 235 million tr oz of contained PGM in 4 countries. South African deposits contain 229 million tr oz of PGM, including 143 million tr oz of contained platinum at three producing mines (Rustenburg, Impala, and Western platinum) and one nonproducing deposit, Der Brochen, in the Merensky Reef of the Bushveld complex.

Until Western platinum started to mine the UG-2 Reef in 1982, production came exclusively from the Merensky Reef. The UG-2 was opened up by a process developed by South Africa's National Institute of Metallurgy which solved the problem of removing chromite prior to smelting. Because resource estimates and associated costs for mining and processing the UG-2 are not yet available,

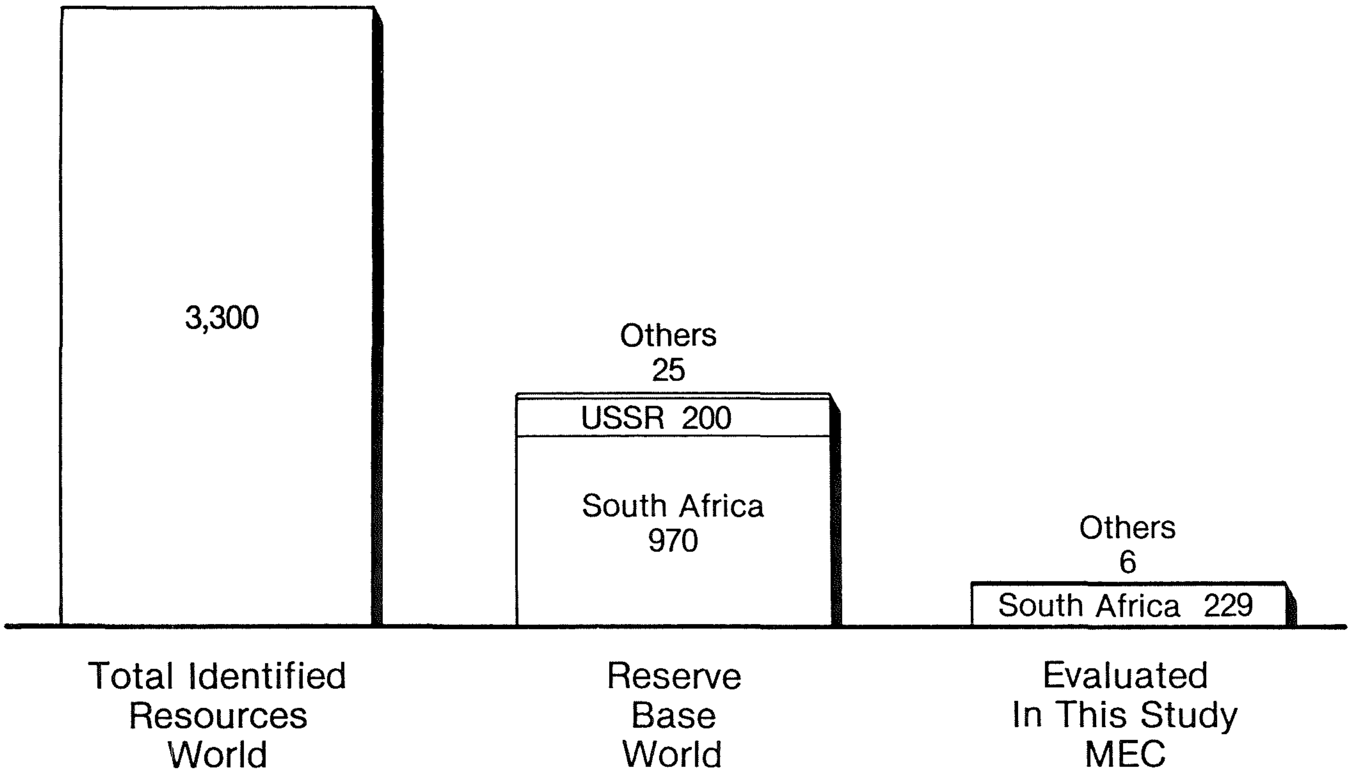


**Figure 6.2 World PGM Resources (Million Troy Ounces)**

resources from the UG-2 were not included in this study. Other sources not evaluated include the platinum recovered as a byproduct from nickel mines in the Sudbury Complex of Canada and the copper mines of Zimbabwe. Recovery of platinum from resources of the Great Dyke in Zimbabwe would be very costly compared with the present market price of platinum, and are therefore not evaluated in this chapter. Eighty-five million tr oz of platinum are potentially recoverable from Zimbabwe according to Bureau of Mines IC 8897.

## Mining

Nearly 95 pct of the platinum from MEC's is mined by underground mining methods, primarily longwall caving and shrinkage stoping. The remaining 5 pct is recovered by surface methods. The eight deposits evaluated in this study are listed in table 6.1 with specific data such as owner, status, mining and milling methods, and production capacity.

The large annual capacities at Rustenburg and Impala in South Africa are the result of combining workings at several locations. Rustenburg Platinum Holdings Ltd. operates four platinum mines at two separate areas. Three, the Amandelbult section near Chromite, the Rustenburg section at Bleskop, and the Union section at Swartkop are linked underground. The fourth, Atok platinum mines, is located in the Lydenburg area. The Impala operation includes four mines: North Bafokeng, South Bafokeng, North Wildebeestfontein, and South Wildebeestfontein. Western Platinum, Impala, and Rustenburg are currently recovering platinum from the UG-2 reef. About 40 pct of Western Platinum's total production is estimated to be from the UG-2 reef.

TABLE 6.1.—List of world platinum properties included in the study

| Country and deposit name | Owner | Status[1] | Mine method | Mill method | Average Annual mine capacity[2] 10³ mt ore |
|---|---|---|---|---|---|
| Canada: | | | | | |
| Lac Des Iles #1 | Boston Bay Mines | E | Open pit | Flotation | 820 |
| Colombia: | | | | | |
| Choco Pacifico | Mineros Del Choco | P | Dredging | Gravity | 12,000 |
| South Africa, Republic of: | | | | | |
| Rustenburg | Rustenburg Platinum Holdings Ltd. | P | Longwall caving | Flotation | 17,740 |
| Impala | Union Corp. and Others | P | ..do........... | Do. | 14,520 |
| Western Platinum | Western Platinum Ltd. | P | ..do........... | Do. | 2,210 |
| Der Brochen | Geduld Propr. East Rand Cons. | E | ..do........... | Do. | 1,440 |
| United States: | | | | | |
| Salmon River | R. A. Hanson Mining Co. | PP | Dredging | Gravity | 1,300 |
| Stillwater Platinum | Stillwater Mining Co. | D | Shrinkage/Cut and fill | Flotation | 159 |

[1]P - producer, PP - past producer, D - developing, E - explored. The status is of January 1985.
[2]Capacities are either actual or assumed.

Mining methods employed in South Africa are straight-forward due to the regularity of the mined units. Dredging operations for gold and platinum at Columbia's Choco Pacifico consist of standard bucket line dredges with a trommel-screen-jig circuit for metal recovery. Canada's Lac des Iles would employ open-pit methods. The Salmon River in Alaska utilizes dredging and the Stillwater deposit in Montana will be mined by shrinkage and/or cut-and-fill stoping methods.

## Processing

Except for the relatively insignificant production that results from placer mining, most platinum is beneficiated using flotation methods. In this process, ore is crushed, ground, and floated to recover the metallic minerals (high density PGM's are sent directly to the refinery). The resultant concentrate, which in some cases is pelletized, is then sent to an electric furnace where it is partially oxidized to a "green matte." The "green matte" is transferred to converters where, under an oxygen-rich atmosphere, it is melted and oxidized, resulting in a "white matte." The "white matte" is sent to a nickel-copper refinery, and the resulting sludge is sent to a precious metals refinery for further separation.

The precious-metal concentrates (sludge) from the nickel-copper refinery have a PGM content which normally ranges between 25 pct and 75 pct. The first stage of the refining process is the removal of the base metal content by roasting, followed by a pressure leaching process. Gold and silver are removed, then the individual PGM's are separated and refined by conventional selective precipitation methods. In the recently developed solvent extraction method, preleaching allows removal of base metals, and a single leaching with chlorine and hydrochloric acid dissolves the PGM's. In a series of continuous operations, metal recoveries from stripping solutions are accomplished by the precipitation of insoluble salts or complexes. The order of extraction of PGM's is palladium, platinum, osmium, ruthenium, iridium, and rhodium. This new solvent extraction method incurs lower capital and operating costs and improves processing time significantly. Osmium is recovered by distillation, not solvent extraction.

A new Solrex PGM refinery is being built by Johnson Mathey P.L.C. and Rustenburg Platinum and is expected to be completed in 1990. It is being modeled after the Royston, United Kingdom plant and will treat 100 pct of Rustenburg's primary PGM output (3).

## Production Costs

The average production costs for the three producing mines in South Africa and the two dredging operations, one each in Colombia and United States, are listed in table 6.2. Costs are in constant 1985 dollars and are based on current technology. Costs for operations in other countries are not shown in order to avoid disclosing confidential data. Platinum and palladium are essentially coproducts. As such, this study uses a methodology which fixes the relative prices of the coproducts at their January 1985 proportions ($274/tr oz platinum to $124/tr oz palladium) and solves for the joint revenue necessary to cover all costs.

Mining costs for underground operations in South Africa average $278/tr oz of refined platinum or $22/mt of ore versus an average of $336/tr oz of refined platinum or $0.39/mt of ore at the 2 dredging operations. The higher mining costs in terms of refined platinum in dredging operations are due to

TABLE 6.2. - Cost, Capacity, and Resources for Selected MEC Platinum Mines and Deposits

(All costs are expressed in January 1985 U.S. dollars per troy ounce of platinum on a weight-averaged basis)

| Region | Demonstrated Resources Ore million mt | Demonstrated Resources Recoverable PGM million tr oz | Average Annual Capacity PGM thousand tr oz | Net Operating cost[1] | Production cost, 0-pct[2] | Production cost, 15-pct[3] |
|---|---|---|---|---|---|---|
| South Africa[4] | 884 | 96.2 | 2,570 | 128 | 175 | 190 |
| Colombia and U.S.[5] | 141 | 0.165 | 17 | 150 | 257 | 346 |

[1]Includes cost of mining, milling, smelting, refining and transportation less byproduct credits for all commodities.

[2]Equal to the sum of net operating costs, taxation, and recovery of undepreciated capital investments in exploration, acquisition, development, mine and mill plant and equipment, and infrastructure as of January, 1985 and investments required over the life of the operation determined at a 0-pct DCFROR.

[3]Equal to the sum of net operating costs, taxation generated at a 15-pct DCFROR, capital recovery plus the per oz increase necessary to provide a 15-pct DCFROR after taxation.

[4]Three underground operations.

[5]Two dredging operations.

the extremely low platinum grades of placer deposits. Milling costs average $41/mt for South Africa and $174/mt for dredging operations based on recoverable platinum or $3.06 and $0.20/mt of ore.

Some of the production cost advantage of the South African operations is offset by the cost of their recovery of other members of PGM. These additional operating costs amount to $97/tr oz for smelting, refining and transportation costs for all commodities. The dredging operation in Colombia recovers gold and the U.S. recovers palladium; they incur an average $34/tr oz as other operating cost.

South Africa has been mining the Merensky Reef for a long time, and undepreciated capital investment costs per tr oz in the Merensky Reef operations are low. Capital costs for the dredging group are higher because of low grade ore requiring the handling of more material per oz recovered and because of investments associated with recently rebuilding the dredge at one of these deposits. Consequently, at the 15 pct DCFROR level the recovery of capital for the dredging operations is almost seven times that for the South African mines.

Availablilty

A total of 8 mines and deposits, containing 143 million tr oz of platinum were evaluated. Approximately 104 million tr oz of total recoverable platinum would be available at total production costs ranging from $150 to $610/ tr oz of platinum, including 15-pct DCFROR. Four producing mines, three in South Africa and one in Colombia, account for 96 million tr oz of recoverable platinum, 82 pct of which is from the Rustenburg Platinum operations. Annual production at full capacity from these four producing mines would provide about 89 pct of the 1985 MEC consumption.

Eighty-six pct of the total available platinum is economic at the January 1985 platinum spot price of $274/tr oz, all from producing mines. Platinum potentially available from nonproducing deposits would require a minimum platinum price of $375/tr oz. Total platinum availability from South Africa in this study is limited to evaluated resources in the Merensky Reef.

Potential annual platinum production from the producing mines of this study is expected to decline by 1995, owing to depletion of reserves at one mine. Hence, at a total production cost of $500 or below, 2.59 million tr oz was available in 1985, decreases significantly in 1993 to 1.49 million tr oz. In 1985, the capacity potential at a total cost of production of $200 per tr oz or less was estimated at 1.35 million tr oz of platinum from two producers which should remain in production through 1995. Maximum annual recoverable platinum of 2.7 million tr oz from all evaluated mines and deposits would be available at a total production cost of $610/tr oz of platinum. Additional production in 1985 was from the UG-2 reef and from byproduct platinum production at nickel and copper mines.

## RESOURCES NOT INCLUDED IN THE EVALUATION

In the Bushveld Complex of South Africa, the UG-2 reef lies below the Merensky Reef. Western Platinum Ltd has recovered platinum from UG-2 ore since 1982 by a flotation method and the presence of chromite in the flotation tailings is a significant potential asset. The tailings are stockpiled pending potential future use in ferrochromium production.

Until recently, UG-2 ore presented extraction problems due to the high content (30-32 pct) of chromic oxide. Metallurgical research at the South African Mineral Technology Institute (Mintek) has provided extensive information for the successful commercial exploitation of the UG-2 reef at the Western Platinum operation. Procedures were developed to reduce the chromic oxide content of the platiniferous concentrates to levels that were acceptable to a modified smelting technique (4). Western Platinum conducted an extensive testing program prior to installation of the new flotation plant in 1984. A new nickel-copper refinery, located near the PGM smelter was commissioned in 1985, and supplies feed for the PGM refinery at Brakpan, thus eliminating the shipping of nickel-copper matte to Norway and speeding up the recovery of PGM's.

Additional PGM resources with higher platinum and palladium ratios located in the UG-2 Reef could double South Africa's platinum resources. Rustenburg has been investigating the feasibility of exploiting UG-2 Reef platinum resources and production could begin in the near future. Gold Fields of South Africa has decided to start development work at its property adjacent to Rustenburg's operation at Amandelbult.

At the Western Platinum operation, the UG-2 ore has higher PGM grades, particularly rhodium, than Merensky ore and the lower nickel and copper contents of the UG-2 ore should result in a large reduction in smelting and refining costs. Additional platinum from the UG-2 Reef of Rustenburg Mines would be readily available with modification of current beneficiation facilities at the mine site. Mining the UG-2 Reef would utilize the existing shafts and infrastructures and continue development work to new levels at depth. The economics of the UG-2 material was not evaluated in this study due to the absence of data. However, Western Platinum has steadily increased production from the UG-2 Reef which indicates that the overall production cost is economic compared with the 1985 platinum spot price of $274/tr oz.

Although the UG-2 material is expected to allow the South African producers to maintain their dominance in the platinum market, new production from other sources is also expected. The Bureau of Mines has recently estimated demonstrated resources for the Stillwater Complex at 33 million mt, averaging 0.124 oz platinum and 0.437 oz palladium/mt (5). The Stillwater Mining Company plans to mine high grade zones (0.8 to 1 oz/mt PGM) at a rate of 610 mt/day starting in 1987 (6). Only a small port0on of the Stillwater Complex platinum horizon (30 miles along strike) has been explored in detail and evaluated for economics in this study, thus, significant additional resources could be developed to expand the current resource estimate. Platinum resources from the Great Dyke in Zimbabwe are currently not economic (at least four times the cost in South Africa) for development owing primarily to a low platinum grade. Byproduct PGM production in Canada, Australia, Ethiopia, and Yugoslavia also were not included in this evaluation.

## CONCLUSIONS

Major known platinum deposits located in four MEC's were chosen for detailed analysis. Three producing mines and one nonproducing deposit in South Africa account for 103 million tr oz or 99 pct of the total available. The remaining 1 pct includes two placer deposits with low platinum ore grades and one surface deposit and one underground deposit with small annual capacities. The South African producing mines, with the advantage of economies of scale, have a weighted-average total production cost of only \$175/tr oz at the 0-pct DCFROR level and \$190/tr oz including a 15-pct rate of return. These producing operations mining the Merensky Reef, accounted for 93 pct of the total potential platinum availability in this study.

Several factors could offset depletion of currently exploited platinum resources and even lead to an increase in platinum production. Commercial development of the UG-2 Reef of the Bushveld Complex could more than double the amount of platinum available from South Africa, probably with little if any increase in overall production costs. Improvements in technology could increase the amount of platinum available in producing or currently unexploitable deposits such as the resource in the Great Dyke in Zimbabwe. Expanding recycling efforts in recovery of platinum from automobile catalytic convertors could increase the amount of secondary platinum reused in the automotive industry. Loss of access to South African mine production would force adjustment largely in platinum demand and recycling since loss of this mine production cannot be compensated for by currently known resources or existing facilities in the MEC.

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# CHAPTER 7 SUMMARY

Salient results from the availability analyses in this study are reported and related to recent consumption and price levels in Table 7.1. When South African production is included, ample resources and primary production capacity were found to exist to support recent consumption levels of chromite, cobalt, gold, and manganese for many years at 1985 real price levels. Apparently economic platinum from new resources in South Africa could offset the approaching depletions of some of the resources evaluated. When South African deposits are excluded, more than a few years reserves were found only for cobalt and manganese. Even for these two minerals, higher sustained prices would be required to increase manganese production capacity and to support means of cobalt transport not through South Africa.

Other significant resources of all these minerals were not included in this evaluation, either because of insufficient information or because they have been delineated since the data for this analysis was collected. Only in the case of manganese are these potential additional reserves found solely in South Africa.

TABLE 7.1 - Summary Measures of Availability

| Category | Chromite: Million metric tons[4/] | Cobalt: Thousand metric tons | Gold: Million troy ounces | Manganese: Million metric tons | Platinum: Million troy ounces |
|---|---|---|---|---|---|
| Apparent Annual Consumption: | | | | | |
| United States | 0.75 | 7.2 | 3 | 0.6 | 0.8 |
| World | 8.2 | 21.4 | 33 | 8 | 2.5 |
| Share of Consumption from Primary Sources: | | | | | |
| United States | 77% | 95% | 55% | 100% | 85% |
| World | 83% | 96% | 83% | 100% | 90% |
| Average Price in 1985 | $42-<br>$110/mt | $11.50/lb | $318/oz | $1.43/ltu | $270/oz |
| Availability from Evaluated Resources[1/] at 1985 price level: | | | | | |
| all MEC | 550[2/] | 1,700 | 685 | 353 | 89 |
| w/o South Africa | 84[2/] | 1,700 | 48 | 155 | 1 |
| 1985 Capacity from Evaluated Deposits at 1985 price level[3/]: | | | | | |
| all MEC | 8.6 | 26 | 26 | 4.5 | 2.2 |
| w/o South Africa | 3.3 | 26 | 5.1 | 2 | 0.17 |
| Location of Potentially Significant Resources Not Evaluated | S. Africa, New Caledonia, U.S., Papua New Guinea, Zimbabwe | New Caledonia, U.S. | Australia, Canada, U.S. | South Africa | South Africa, U.S., Zimbabwe |

1/ Using 0-pct DCFROR cost.
2/ Using a single cutoff price of $110/mt.
3/ Using operating cost.
4/ Gross weight.

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The Bureau of Mines began design of the Minerals Availability System, cornerstone of the Minerals Availability Program (MAP), in 1971 to overcome traditional data problems that hindered economic analysis of minerals supply sources in real time. A capability now exists for detailed and comparable availability analysis for over 30 nonfuel minerals. Availability information and analysis are presented in Bureau publications and in special reports in support of policy issues. The MAP is implemented by approximately 100 personnel in four field offices and Washington, D.C.

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