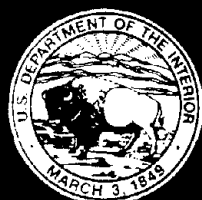


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BUREAU OF MINES
INFORMATION CIRCULAR/1993

Availability of Platinum and Platinum-Group Metals

By Catharine T. Fogg and Joseph L. Cornellisson



UNITED STATES DEPARTMENT OF THE INTERIOR

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PREFACE

The U.S. Bureau of Mines assesses the worldwide availability of nonfuel minerals. It identifies, collects, compiles, and evaluates information on active and developing mines, explored deposits, and mineral processing plants worldwide. Objectives are to classify domestic and foreign resources; to identify, by cost evaluation, resources that are reserves; and to prepare analyses of mineral availabilities.

This report is part of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources and the factors affecting availability. Questions about these reports should be addressed to Chief, Branch of Minerals Availability, U.S. Bureau of Mines, 810 7th St., NW, Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°	degree	lb	pound
°C	degree Celsius	m	meter
cm	centimeter	mg	milligram
cm ²	square centimeter	mm	millimeter
g	gram	Mm ³	million cubic meter
g/mt	gram per metric ton	Mmt	million metric ton
kg	kilogram	Mmtpy	million metric ton per year
km	kilometer	Moz	million troy ounce
km ²	square kilometer	mt	metric ton
kmt	thousand metric ton	mtpd	metric ton per day
kmtpm	thousand metric ton per month	mtpy	metric ton per year
kmtpy	thousand metric ton per year	oz	troy ounce
koz	thousand troy ounces	pct	percent
kW	kilowatt	yr	year

Note: Conversion factor—32.1057 troy ounces per kilogram

AVAILABILITY OF PLATINUM AND PLATINUM-GROUP METALS

By Catharine T. Fogg¹ and Joseph L. Cornellison¹

ABSTRACT

The U.S. Bureau of Mines investigated the availability of platinum, palladium, and rhodium from 16 deposits in four market economy countries (MEC's). Major recoverable products include 164 Moz of platinum, 80 Moz of palladium, 13 Moz of rhodium, 24 Moz of ruthenium, 4 Moz of Iridium, 2 Moz of Osmium, and 10 Moz of gold. The 12 deposits in the Republic of South Africa are estimated to account for 96.7 pct of total recoverable platinum. The base-case scenario estimates the long-term cost of production including recovery of capital, but provides no return on the investment or 0-pct discounted cash-flow rate of return (DCFROR). The total production costs in January 1990 U.S. dollars ranged from \$325/oz to \$1,288/oz of platinum compared to an average January 1990 price of \$492/oz. Approximately 83 pct of total recoverable platinum was economic at a cost level of \$450/oz or less. At the 15-pct DCFROR, only 26 pct of total recoverable platinum was economic.

For platinum-group metals (PGM), attention has been focused on the ratios of the three primary metals: platinum, palladium, and rhodium. Sensitivity analyses were performed to determine the impact long-term rhodium price increases could have on the total cost of production for platinum and palladium.

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INTRODUCTION

PGM are a family of six metals: platinum, palladium, iridium, rhodium, ruthenium, and osmium. These six have strong similarities with respect to various chemical and physical properties and are grouped together in the periodic table. All PGM are associated in geological occurrence, although there are variations in the relative abundance of each metal between various ore types. PGM are considered to be strategic materials in the United States because of their extensive uses in the petroleum, chemical, and electronic industries. This study of the world PGM industry is intended as an update of Bureau of Mines IC 8897, entitled "Platinum Availability—Market Economy Countries," (1),² published in 1982 and based on 1980 data. A complete reevaluation of resources, industry structure, and costs was prepared for this study.

Since the last report, much has happened in the PGM industry. The period 1982 to 1989 was characterized by development of new mines, expansion of existing mines, and construction of new smelters and refineries in South Africa; five new mines and one PGM refinery³ have opened. This industry expansion can be attributed to the desire of the South African producers to maintain

dominance in the market and to achieve a vertically integrated PGM industry. As of late 1989, there was some speculation by industry observers that the PGM industry may have overexpanded in anticipation of a large increase in platinum demand resulting from the passing of pollution control laws in Europe.

In the United States, the Comprehensive Apartheid Act of 1986 was passed, which imposed limited sanctions on South African products. The U.S. Congress exempted PGM from the South African economic sanctions. However, supply disruption as a result of political unrest in South Africa is possible and remains a very real threat to the stability of the market.

The Council of European Environment Ministers has passed emissions standards equivalent to the U.S. 1983 level for all cars sold in the European Community (EC). In the United States, stricter standards have been set for 1993 and would require increasing amounts of platinum, palladium, and rhodium used in three-way automobile catalysts. Rhodium prices have risen dramatically, averaging \$3,565/oz in 1990. The impact of rhodium price on platinum mines is studied in this report.

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COMMODITY OVERVIEW

This section addresses industrial demand and supply of platinum, palladium, and rhodium. Industrial stockpiles and substitution among precious metals are also discussed. The price relationships between platinum, palladium, and rhodium are addressed later in the "Commodity Pricing" section.

CONSUMPTION

PGM are utilized in a wide variety of applications. In many cases, there is limited or no substitutability for PGM by other metals or materials. In addition, new uses are continuously being developed for PGM. Rising consumption levels will have important applications for the future availability of PGM. Platinum, palladium, and rhodium consumption for the 1980's is summarized by region and

application in tables 1 through 3. Detailed discussions of demand by application are presented in appendix A.

Platinum, the most important metal in the group, is utilized in autocatalyst, jewelry, chemical, electrical, glass, petroleum, and dental applications. In addition, platinum investment demand has increased steadily in the last 6 yr. The Western World consumption of platinum increased from the 2.82 Moz in 1980 to 3.55 Moz in 1989, an increase of 26 pct for the decade as shown in figure 1. Historically, Japan, with consumption ranging between 0.94 Moz and 1.925 Moz, has been the overall major consumer of platinum, except in 1986 when the North American investment sector was unusually high. Jewelry accounted for approximately 60 pct of total Japanese platinum consumption. North America follows Japan with total platinum consumption ranging from 0.7 Moz to 1.275 Moz. The principal application was for autocatalysts, which increased from 45 pct of total North American consumption in 1980 to 69 pct in 1989. Western World consumption peaked at 3.78 Moz in 1988 with the autocatalyst and jewelry sectors accounting for 32 pct each.

²Italic numbers in parentheses refer to items in the list of references preceding appendixes at the end of this report.

³The Republic of South Africa now requires all PGM refining to be done within the country.

Table 1.—Platinum supply and demand trends

(Thousand troy ounces)

Region/application	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
PLATINUM SUPPLY										
Primary production:										
South Africa	2,320	1,800	1,960	2,070	2,280	2,340	2,350	2,520	2,580	2,590
Canada	130	130	120	80	150	150	150	140	145	150
Others	30	30	30	40	40	40	40	40	95	85
Total primary	2,480	1,960	2,110	2,190	2,470	2,530	2,540	2,700	2,820	2,825
Recycled autocatalysts: ¹										
North America	0	0	10	30	45	70	85	100	135	150
Japan	0	0	0	0	0	0	5	15	25	25
Rest of World ²	0	0	0	0	0	0	0	0	0	0
Total recycled	0	0	10	30	45	70	90	115	160	175
U.S.S.R. sales	340	370	380	290	250	230	290	400	440	550
Total platinum supply ..	2,820	2,330	2,500	2,510	2,765	2,830	2,920	3,215	3,420	3,550
PLATINUM DEMAND										
Japan:										
Autocatalysts	210	190	170	170	170	210	255	310	330	355
Chemical	10	10	10	10	15	15	15	15	15	15
Electrical	15	15	20	20	30	40	45	45	45	50
Glass	40	50	45	60	75	60	30	45	45	40
Investments:										
Small ³	0	0	0	5	15	35	35	60	115	35
Large ⁴	160	195	115	65	150	170	(125)	275	300	30
Jewelry	440	625	620	560	625	675	740	900	1,060	1,150
Petroleum	15	15	15	15	20	15	0	0	0	0
Other	50	50	55	45	40	30	20	15	15	15
Total Japan	940	1,150	1,050	950	1,140	1,250	1,015	1,665	1,925	1,690
North America:										
Autocatalysts	440	430	455	450	635	700	745	690	690	720
Chemical	115	50	80	100	100	75	65	55	55	55
Electrical	145	70	70	90	95	80	65	65	65	75
Glass	50	20	10	15	30	40	25	25	25	30
Investment	0	0	40	40	30	130	300	85	85	55
Jewelry	15	15	15	15	15	15	15	15	15	20
Petroleum	140	55	20	15	15	10	10	15	15	40
Other	75	60	20	25	35	30	50	50	50	50
Total North America	980	700	710	750	955	1,080	1,275	1,000	1,000	1,045
Rest of World: ²										
Autocatalysts	30	20	20	25	35	70	140	255	305	375
Chemical	135	190	170	135	145	135	115	125	90	90
Electrical	50	100	80	65	65	80	70	70	75	70
Glass	50	30	30	30	35	40	35	50	60	70
Investment	0	0	5	45	125	95	115	70	130	40
Jewelry	105	115	130	140	135	120	95	75	105	135
Petroleum ⁵	(25)	70	30	(10)	(20)	(10)	10	40	35	35
Other	65	55	95	80	60	40	60	55	55	50
Total Rest of World	410	580	560	510	580	570	640	740	855	865

See footnotes at end of table.

Table 1.—Platinum supply and demand trends—Continued

(Thousand troy ounces)

Region/application	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
PLATINUM DEMAND—Continued										
End-use platinum demand:										
Autocatalysts	580	640	645	645	840	980	1,140	1,255	1,325	1,450
Chemical	260	250	260	245	260	225	195	195	160	160
Electrical	210	185	170	175	190	200	180	180	185	195
Glass	140	100	85	105	140	140	90	120	130	140
Investment	160	195	160	155	320	430	325	490	630	160
Jewelry	560	755	765	715	775	810	850	990	1,180	1,305
Petroleum	130	140	65	20	15	15	20	55	50	75
Other	190	165	170	150	135	100	130	120	120	115
Total application demand	2,330	2,430	2,320	2,210	2,675	2,900	2,930	3,405	3,780	3,600
Sales to China/CPEC	30	30	30	20	30	30	40	30	40	40
Movement in stocks ⁶	460	(130)	150	280	60	(100)	(50)	(220)	(400)	(90)
Total platinum demand ..	2,820	2,330	2,500	2,510	2,765	2,830	2,920	3,215	3,420	3,550

¹Platinum recovered from catalytic converters removed from scrapped automobiles is allocated to the region where the vehicle is scrapped.

²Rest of World includes all territories except the U.S.S.R., other centrally planned economy countries (CPEC's), and China.

³Investments: Small" is the long-term holding of metal in the form of bars and coins weighing 10 oz. or less.

⁴Investments: Large" is the holding of metal in the form of 500g and 1kg bars in Japan.

⁵Platinum recovered as a result of closure of refining capacity.

⁶Movements in stocks reflect changes in stocks held by fabricators, dealers, banks, and individuals and does not include stocks held by primary refiners or final consumers.

NOTE.—Parentheses indicate negative numbers.

Source: Johnson Matthey (25, p. 22).

Table 2.—Palladium supply and demand trends

(Thousand troy ounces)

Supply/demand components	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
PALLADIUM SUPPLY										
Primary production:										
South Africa	870	910	820	790	980	1,010	1,040	1,090	1,105	1,135
Canada	170	160	160	110	190	190	190	190	170	205
Others	60	70	70	80	90	90	90	90	270	215
Total primary	1,100	1,140	1,050	980	1,260	1,290	1,320	1,370	1,545	1,555
Recycled autocatalysts: ¹										
Japan	0	0	0	0	0	5	10	10	15	15
North America	0	0	0	0	20	25	30	40	50	55
Rest of World ²	0	0	0	0	0	0	0	0	0	0
Total recycled	0	0	0	0	20	30	40	50	65	70
U.S.S.R. sales	1,240	1,430	1,550	1,560	1,700	1,440	1,600	1,790	1,770	1,650
Total palladium supply ..	2,340	2,570	2,600	2,540	2,980	2,760	2,960	3,210	3,380	3,275
PALLADIUM DEMAND										
End use by country/region:										
Japan:										
Autocatalysts	150	140	160	150	140	105	90	90	85	90
Dental	220	160	190	290	290	270	280	290	300	310
Electrical	160	360	390	650	680	600	750	920	1,020	980
Jewelry	40	60	60	50	60	60	70	80	105	110
Other	120	100	90	80	80	50	50	60	40	40
Total Japan	690	820	890	1,220	1,250	1,085	1,240	1,440	1,550	1,530
North America:										
Autocatalysts	150	130	130	150	200	215	160	160	155	160
Dental	200	210	260	280	330	340	375	390	390	395
Electrical	320	330	320	290	370	300	330	400	405	410
Jewelry	10	10	10	10	10	10	10	10	10	5
Other	160	140	140	100	100	100	120	115	110	135
Total North America ..	840	820	860	830	1,010	965	995	1,075	1,070	1,105
Rest of World: ²										
Autocatalysts	0	0	0	0	0	0	15	20	10	15
Dental	100	110	140	250	280	260	270	275	305	290
Electrical	110	110	130	150	180	200	240	255	280	265
Jewelry	130	140	150	140	140	140	90	75	65	65
Other	160	90	100	110	120	120	100	95	110	110
Total Rest of World ² ..	500	450	520	650	720	720	715	720	770	745
World Total:										
Autocatalysts	300	270	290	300	340	320	265	270	250	265
Dental	520	480	590	820	900	870	925	955	995	995
Electrical	590	800	840	1,090	1,230	1,100	1,320	1,575	1,705	1,655
Jewelry	180	210	220	200	210	210	170	165	180	180
Other	440	330	330	290	300	270	270	270	260	285
Total application demand	2,030	2,090	2,270	2,700	2,980	2,770	2,950	3,235	3,390	3,380
Movement in stocks ³	310	480	330	(160)	0	(10)	10	(25)	(10)	(105)
Total palladium demand	2,340	2,570	2,600	2,540	2,980	2,760	2,960	3,210	3,380	3,275

¹Palladium recovered from catalytic converters removed from scrapped automobiles is allocated to the region where the vehicle is scrapped.

²Rest of World includes all territories except the U.S.S.R., CPEC's, and China.

³Movements in stocks reflect changes in stocks held by fabricators, dealers, banks, and individuals and does not include stocks held by primary refiners or final consumers.

NOTE.—Parentheses indicate negative numbers.

Source: Johnson Matthey (25, p. 52).

Table 3.—Rhodium supply and demand trends

(Thousand troy ounces)

Supply/demand components	1985	1986	1987	1988	1989
RHODIUM SUPPLY					
Production: ¹					
South Africa	165	175	195	195	185
Canada	15	15	18	20	15
Total rhodium production	180	190	213	215	200
U.S.S.R. sales	45	85	100	100	130
Total rhodium supply	225	275	313	315	330
RHODIUM DEMAND					
By country/region:					
Western Europe	44	49	66	75	92
Japan	49	90	83	92	100
North America	134	111	127	110	106
Rest of World ²	17	18	20	27	32
Total geographical demand	244	268	296	304	330
Movement in stocks ³	(19)	7	17	11	0
Total rhodium demand	225	275	313	315	330
By application:					
Autocatalysts:					
Gross ⁴	135	188	226	232	268
Recovery ⁵	0	0	(3)	(7)	(8)
Chemical	45	22	21	32	32
Electrical	17	16	12	11	12
Glass	17	12	13	14	4
Other	30	30	27	22	22
Total application demand	244	268	296	304	330
Movement in stocks ³	(19)	7	17	11	0
Total rhodium demand	225	275	313	315	330

¹Includes recycled rhodium. Data on recycled rhodium included in rhodium demand by application.

²Rest of World includes all territories except the U.S.S.R., other CPEC's, and China.

³Movements in stocks reflect changes in stocks held by fabricators, dealers, banks, and individuals and does not include stocks held by primary refiners or final consumers.

⁴Gross autocatalysts demand is purchases of rhodium by the auto industry for manufacture of autocatalysts.

⁵Recovery amounts by region are unavailable but the majority of recovered rhodium is believed to originate in North America.

NOTE.—Parentheses indicate negative numbers.

Source: John Matthey (25, p. 60).

The largest consumption increases for the decade are automotive (autocatalysts) at 113 pct and jewelry at 133 pct. The usage in jewelry applications is almost exclusively in Japan. Platinum consumption in the last 5 yr has set the trend for the 1990's.

Palladium, the second most abundant metal in the group, is employed in electrical, dental, autocatalyst, jewelry, and other applications as indicated in table 2. The Western World consumption for palladium has increased 66 pct for the decade from 2.03 Moz in 1980 to 3.38 Moz in 1989 (fig. 2). The Western World consumption peaked at 3.39 Moz in 1988, with electrical and dental accounting for 52 pct and 30 pct, respectively. Historically, Japan has

been the major consumer of palladium, and Japanese electrical use has accounted for 40 to 46 pct of total Western World palladium consumption during the late 1980's.

Back in the mid-1970's, the major applications of rhodium were in chemical and petroleum refining catalysts, glass manufacture, and electrical applications with Western World consumption at 70 koz. Rhodium was first used in automotive (autocatalyst) applications beginning in 1981 (2). Automotive applications have since become the predominant use of rhodium. As a result, Western World consumption for rhodium has increased 35 pct, from 244 koz in 1985 to a high for the decade of 330 koz in 1989 as indicated in table 3. Autocatalyst demand

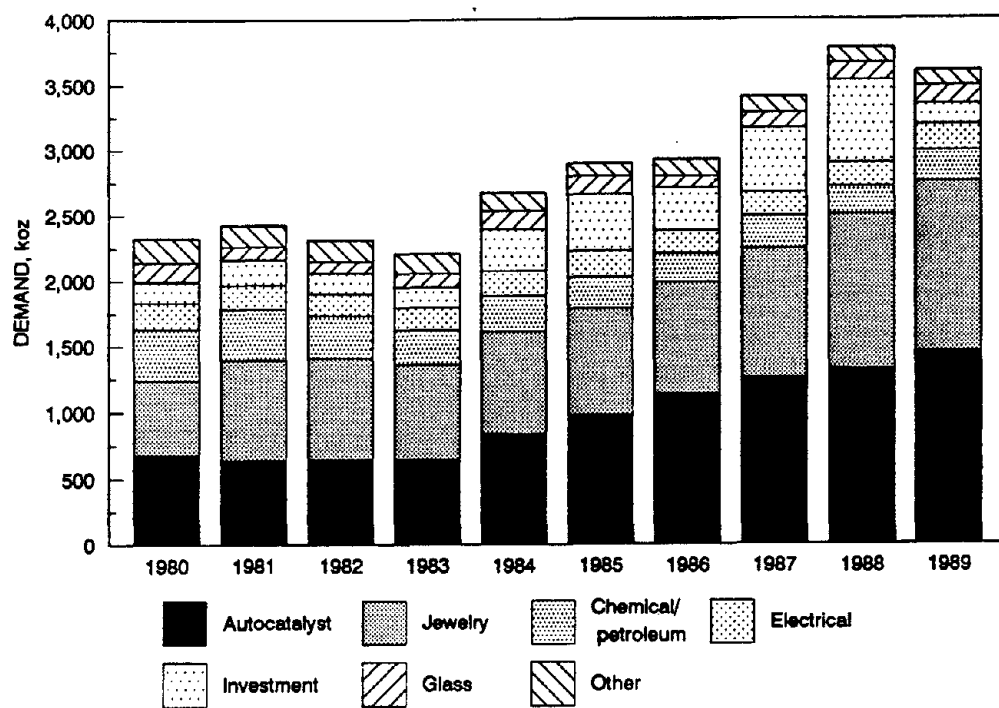


Figure 1.—World platinum demand.

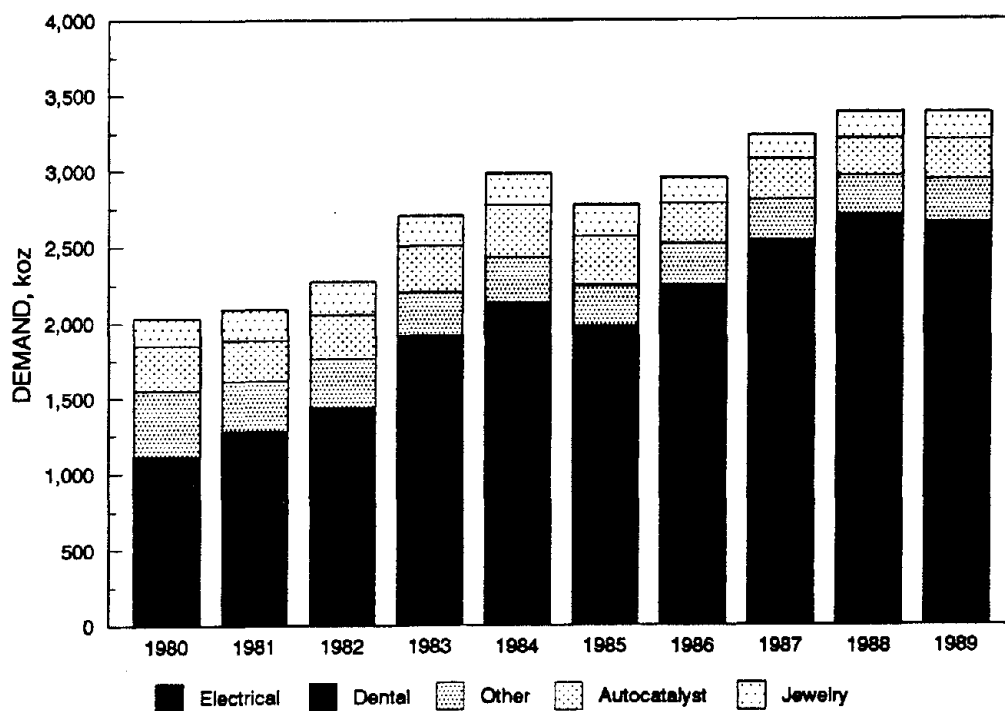


Figure 2.—World palladium demand.

accounted for 79 pct of Western World rhodium consumption in 1989. Historically, autocatalyst uses have accounted for 55 to 79 pct of total rhodium consumption. Consumption of rhodium in North America, Japan, and Western Europe was 106 koz, 100 koz, and 92 koz, respectively, in 1989.

PGM SUPPLY

Supply in this report includes primary production, byproduct platinum from nickel and copper mines, sales from the U.S.S.R., and PGM recovered from recycled autocatalysts. The trend of rapidly increasing platinum production in the 1970's resulted in a world supply of 2.82 Moz in 1980, which also corresponded with the peak historical price, more than \$850/oz platinum, in January 1980. Supply declined sharply to 2.33 Moz in 1981 and took the next 4 yr to recover back to the 1980 production level. In the past decade, total supply has increased 26 pct to 3.55 Moz in 1989. During the last 40 yr, South Africa has been the predominant producer, accounting for 77 to 81 pct of total world supply in the 1980's. As indicated in figure 3, South African supply has exceeded 2.5 Moz since 1987, and its position as the major producer is unlikely to be challenged in the foreseeable future.

During the 1980's, platinum production in North America from two Canadian nickel producers, one U.S. PGM mine, and as byproducts of U.S. copper refining averaged about 5 pct of total world supply. U.S.S.R. sales to the Western World ranged between 0.25 Moz and 0.55 Moz in the 1980's, peaking in 1989 with 15 pct of total world supply. Minor production of platinum also occurs as a byproduct of nickel and copper mining in Australia and Chile. These operations accounted for only 2 pct of total supply in 1989.

During the past decade, total palladium supply increased 42 pct from 2.3 Moz in 1980 to 3.3 Moz in 1989. In 1989, U.S.S.R. sales accounted for 50 pct, and South African producers contributed 35 pct (1.13 Moz) of the total palladium supply. Production in North America and other countries accounted for about 6 pct each. U.S.S.R. sales to the Western World ranged from 1.24 Moz in 1980 to 1.65 Moz in 1989, an increase of 33 pct.

Recently, rhodium supply data have been published by Johnson Matthey from 1985 to 1989. Total rhodium supply has increased 47 pct from 0.225 Moz in 1985 to 0.33 Moz in 1989 as shown in figure 4. In 1989, total world supply was distributed among South Africa (56 pct), U.S.S.R. sales (39 pct), and Canada (5 pct). For the foreseeable future, South Africa is likely to remain the dominant PGM supplier owing to the trend by the major producers to mine rhodium-rich ores of the Bushveld Intrusive Complex.

STOCKPILE

There is no documentation of platinum metal held in private stocks or in vaults in Zurich; however, one source estimates that at least half of the trading volume in physical platinum is channeled through Zurich (3). In the United States, PGM are held in both industrial stockpiles and in the National Defense Stockpile. Industrial stockpiles serve as inventory for manufacturers and consumers and as a hedge against price fluctuations. The National Defense Stockpile was designed to protect the United States against dependence upon unsure foreign sources of strategic and critical materials in times of national emergencies (4).

Industrial Stockpile

Yearend industrial stocks in the United States varied widely between 1985-89. According to Bureau of Mines statistics, total industrial stocks reached a record of 1,249 koz in 1986, with platinum stocks 15 pct higher and palladium stocks 20 pct higher than the 1985 stocks, as indicated in table 4 (5). In addition to the reported stocks, end users of PGM held sizable quantities of PGM that were not reported to the Bureau of Mines. This surge in 1986 yearend stocks was related to the Comprehensive Anti-Apartheid Act of 1986, which prohibited the imports of products produced, manufactured, marketed, or exported by South African parastatal⁴ organizations (6). Subsequently, certain strategic and critical minerals, including PGM, were exempted from the ban imposed by the Comprehensive Anti-Apartheid Act. In order to satisfy the prescribed conditions for the exemption, these materials had to be certified to the Congress that "the quantities essential to the economy or defense of the United States are unavailable from reliable and secure suppliers." It is assumed that the private sector acquired sizable stocks in 1986 to ensure a continuous supply of platinum. Stocks were also acquired because labor difficulties in South Africa had the potential for disrupting PGM production. This high level of stocks was depleted during 1988-89, and, by yearend 1989, stocks were relatively low.

In Japan, platinum jewelry accounted for 54 to 73 pct of the total platinum consumption in the 1980's. Stocks held by jewelry manufacturers are not readily available.

South African producers routinely stockpile PGM when prices are low. It is believed that the U.S.S.R. has historically stockpiled PGM and has exported PGM, through dealers, to Japan, the United States, and Europe in order

⁴A parastatal organization is defined as a corporation or partnership owned, controlled, or subsidized by the Government of South Africa.

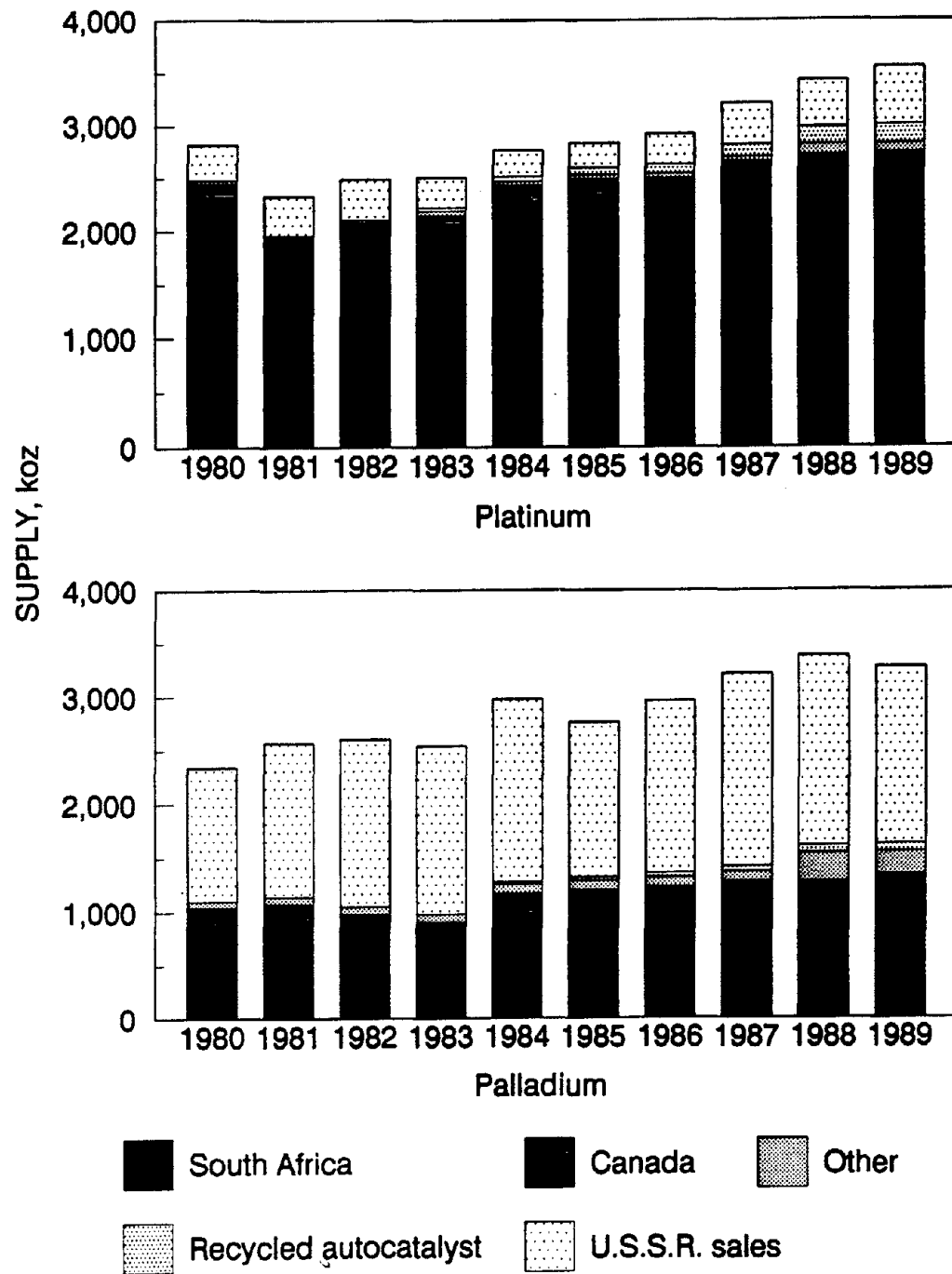


Figure 3.—Supply of platinum and palladium.

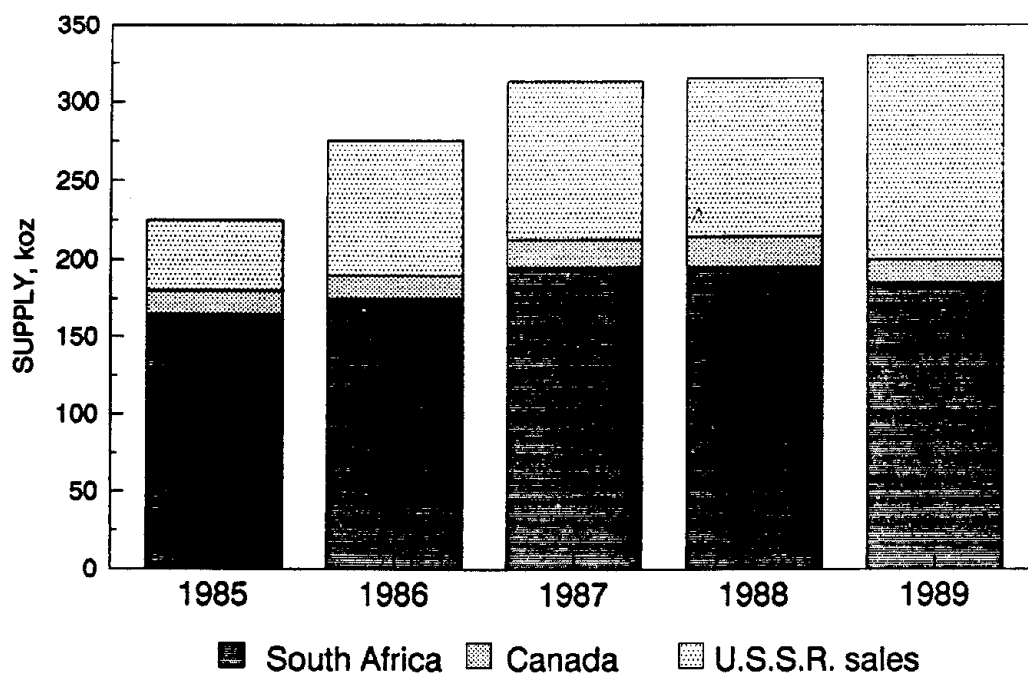


Figure 4.—Supply of rhodium.

to earn foreign exchange. The U.S.S.R. may soon sell directly to major consumers as its marketing network is developed. The amount of PGM stocks held by the U.S.S.R. is difficult to estimate. There has been widespread speculation about the source of recent sales, mine production, and stocks, and about the continuation of these relatively high sales levels.

Table 4.—Stocks of PGM held in the United States¹

(Thousand troy ounces)

PGM commodity	1985	1986	1987	1988	1989
Platinum	572	657	625	593	479
Palladium	455	545	528	477	488
Rhodium	47	47	32	37	35
Total PGM stocks ..	1,074	1,249	1,185	1,107	1,002

¹Refiners, importers, and dealers of PGM.

Source: Loebenstein (5).

National Defense Stockpile

Under the Strategic and Critical Materials Stockpiling Act of 1988, the President has designated the Department of Defense, Defense Logistics Agency, to manage the National Defense Stockpile. The Department of the Interior and the Department of Agriculture are responsible for research and development activities.

In 1989, the Department of Defense recommended reducing the stockpile goal for palladium from 93,300 kg to 66,873 kg and reducing the goal for iridium from 3,050 kg to 2,675 kg. Stockpile goals for rhodium and ruthenium were initiated at 933 kg and 2,022 kg, respectively. The goal for platinum was not changed. Table 5 (7) lists the amount of PGM for the old and new proposed stockpile goals, inventories as of September 1990.

Table 5.—U.S. PGM defense stockpile goals and inventory, September 30, 1990

(Kilograms)

PGM commodity	Old goal	New goal	Inventory
Platinum	40,745	40,745	13,673
Palladium	93,300	66,873	39,265
Iridium	3,050	2,675	920
Rhodium	Nap	933	0
Ruthenium	Nap	2,022	0

Nap Not applicable.

Stockpile policies for other countries are absent or may not be implemented because of lack of funding. In any case, stockpiling would only help when availability problems are of a limited duration.

AVAILABILITY OF PGM

This section addresses resources, cost and economic factors, and results of availability analysis. The method for estimating the total costs to produce platinum, palladium, rhodium, and gold in assigned price proportion ratios, along with byproduct credits from ruthenium, iridium, osmium, copper, nickel, and cobalt, is discussed under the "Commodity Pricing" and "Price Proportion" headings of this section. The study's methodologies for determining total costs using a DCFROR are presented in appendix B.

RESOURCES

PGM deposits occur in a variety of geologic environments. However, economically exploitable deposits occur in relatively few localities. The majority of PGM deposits are associated with magmatic intrusions of mafic and ultramafic rocks. Sutphin and Page (8) established three categories of geologic occurrences of PGM:

- Stratiform deposits in which PGM deposits occur as layered zones in large Precambrian complexes (Bushveld Intrusive Complex,⁵ South Africa; Great Dyke, Zimbabwe; and Stillwater Complex, United States).
- A unique intrusion of norite (Sudbury Irruptive Complex, Canada), believed to have been caused by a meteorite impact.
- Nickel- and copper-bearing dikes and sills, which are found in association with rift structures (Noril'sk-Talnakh District, U.S.S.R.).

Other deposits that contribute to the supply of PGM include placer deposits, nickel-sulfide deposits associated with komatitic extrusive rocks, sulfide deposits associated with zoned ultramafic to mafic intrusions, stratiform and podiform chromite deposits, porphyry copper deposits, shale-hosted base metal sulfide deposits, and miscellaneous hydrothermal deposits.

PGM resources are classified into three economic resource types for this study: primary PGM, byproducts of nickel and copper mining, and recycled (secondary) resources. Primary resources are recovered from mining operations that produce PGM as the primary products and are typically found in stratiform-type deposits. Byproduct PGM are typically produced from the Sudbury deposits and the Russian rift structure deposits that produce nickel and copper as the primary commodities. For these

operations, nickel and copper are the primary revenue-generating commodities; PGM production and revenues are secondary. PGM supplied from recycling efforts have historically not been considered as a traditional resource. However, the amount of PGM available from the recycling of autocatalysts first began to impact supplies in 1983 and has been steadily increasing. With the introduction of stricter emission standards in many countries, the use of PGM-containing autocatalysts is increasing. This will lead to an increasing supply of PGM (platinum, palladium, and rhodium) available from the recycling of autocatalysts in the future.

Primary PGM Resources

The world reserve base for PGM contains the in-place demonstrated (measured plus indicated) resource from which reserves are established and includes those resources that are currently economic or marginally economic.⁶ Figure 5 illustrates the Bureau of Mines estimate of the world reserve base that contains approximately 2,122 Moz or 66 kmt of PGM (9). For this report, 16 MEC deposits were evaluated for availability analysis: 12 in South Africa, 2 in the United States, and 1 each in Canada and Zimbabwe. Deposit information and production status are listed in table 6 and locations are shown in figure 6. Deposit descriptions of evaluated properties are discussed in appendix C.

South Africa

Currently, all of South Africa's production is derived from operations located on the western and eastern limbs of the Bushveld Intrusive Complex (BIC) as shown in figure 7. Approximately 88.3 pct of the world reserves are contained in the Merensky Reef,⁷ Upper Group 2 (UG2) Reef, and Platreef of the BIC. The active mining horizons are the Merensky Reef and the UG2 Reef, and exploration efforts have identified two areas on the Platreef for potential production.

Until recently, the Merensky Reef had been the sole source of ore. The reef averages about 1 m thick and is bounded by thin chromite seams. Platinum contributes between 54 and 61 pct of the total PGM plus gold grade, and the platinum-to-palladium ratio varies from 1.9 to 2.7. The in situ grade of PGM plus gold generally ranges between 6 to 8 g/mt (10). The reef also contains nickel and copper with grades of up to 0.26 pct and 0.13 pct, respectively.

⁵Also known as the Bushveld Complex, the Bushveld Igneous Complex, or the BIC.

⁶This does not, however, include PGM potentially available by recycling.

⁷The ore-bearing horizons are known as reefs in South Africa.

Table 6.—Salient PGM deposit information including in situ resources

Country	Deposit name	Type of deposit	Reef ¹	Owner and/or operator	Evaluated resource		
					Status ²	Type ³	(Mmt ore) ⁴
United States:							
Alaska	Salmon River ..	Placer	NAp	Hanson Properties	Dev	PL	92
Montana	Stillwater	Ultramafic intrusive.	JM	Stillwater Mining Co.	Prd	UG	12
Total United States							104
Canada	Lac des Iles ...	Layered volcanic	NAp	Madeleine Mines Ltd.	Dev	OP	6
South Africa	Atok Mine	Ultramafic intrusive.	MR	Lebowa Platinum Mines Ltd.	Prd	UG	86
	Crocodile River.	..do.	U2	Barplats Mines Ltd.	Prd	UG	89
	Eastern	..do.	MR	Eastern Platinum Ltd. ⁵	Prd	UG	57
	Karee	..do.	MU	Western Platinum Ltd. ⁵	Prd	UG	310
	Kennedy's Vale	..do.	U2	Barplat Investment Ltd.	Dev	UG	84
	Impala Platinum. ⁶	..do.	MU	Impala Platinum Holdings ..	Prd	UG	341
	Maandagshoek	..do.	MU	Lebowa Platinum Mines Ltd.	Dev	UG	67
	Lebowa	..do.	MU	Messina Ltd. ⁷	Dev	UG	60
	Northam	..do.	MR	Northam Platinum Ltd. ⁸	Dev	UG	60
	Potgietersrust ..	..do.	PR	Potgietersrust Pt Holding ⁹ ..	Dev	UG ¹⁰	56
	Rustenburg ¹¹ ..	..do.	MU	Rustenburg Platinum Holdings.	Prd	UG	721
	Western	..do.	MU	Western Platinum Ltd.	Prd	UG	219
Total South Africa							2,150
Zimbabwe	Hartley	..do.	NAp	Masasa Mines Ltd. ¹²	Dev	UG	63
Grand total ...							2,323

NAp Not applicable.

¹Reefs are abbreviated as follows:

JM J-M Reef, Stillwater Complex.

MR Merensky Reef, Bushveld Complex.

MU Combined Merensky and UG2 production, Bushveld Complex.

PR Platreef, Bushveld Complex.

U2 UG2 Reef, Bushveld Complex.

²Status of operation abbreviated as follows:

Dev Developing mine.

Exp Explored deposit.

Prd Producing mine.

³Type of operation abbreviated as follows:

OP Open pit.

PL Placer.

UG Underground.

⁴In situ tonnage.

⁵Lonrho PLC.

⁶Includes Bafokeng (North and South) and Wildebeestfontien (North and South) operations.

⁷Impala Platinum Holdings.

⁸Goldfields of South Africa Ltd.

⁹Joint venture between Lebowa and Rustenburg Platinum Holdings Ltd.

¹⁰Original plans called for an underground operation. This study evaluates this property as an underground operation. As of mid-1991, the mine development plan was changed to an open pit operation.

¹¹Includes the Amandelbult, Union, and Rustenburg sections.

¹²BHP-Utah International and Delta Gold Ltd. joint venture.

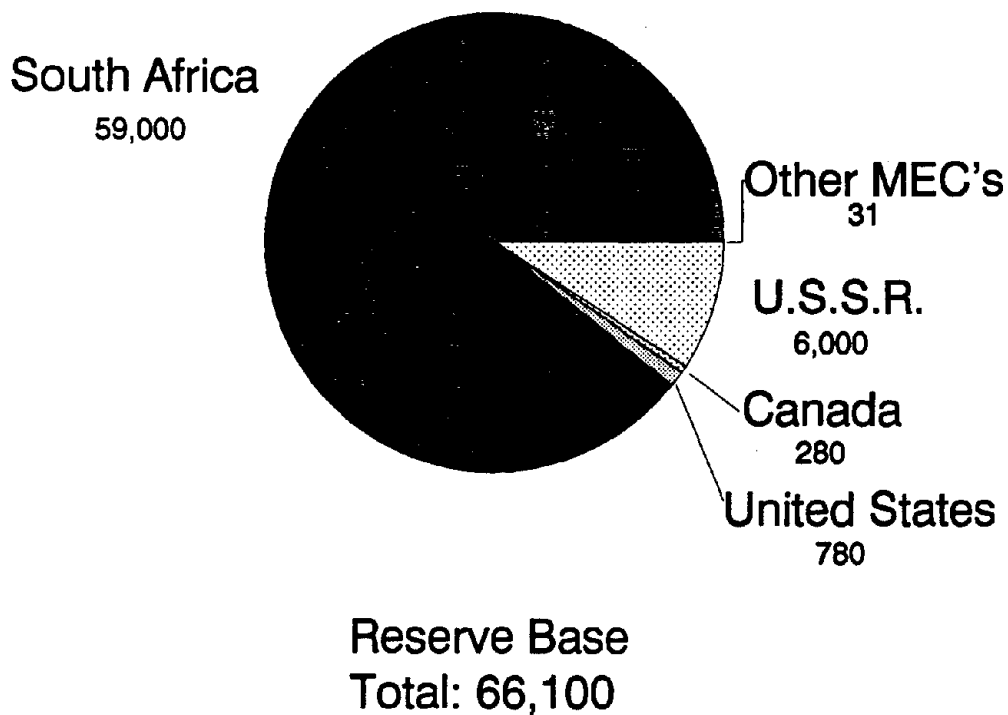


Figure 5.—World PGM reserve base (metric tons).

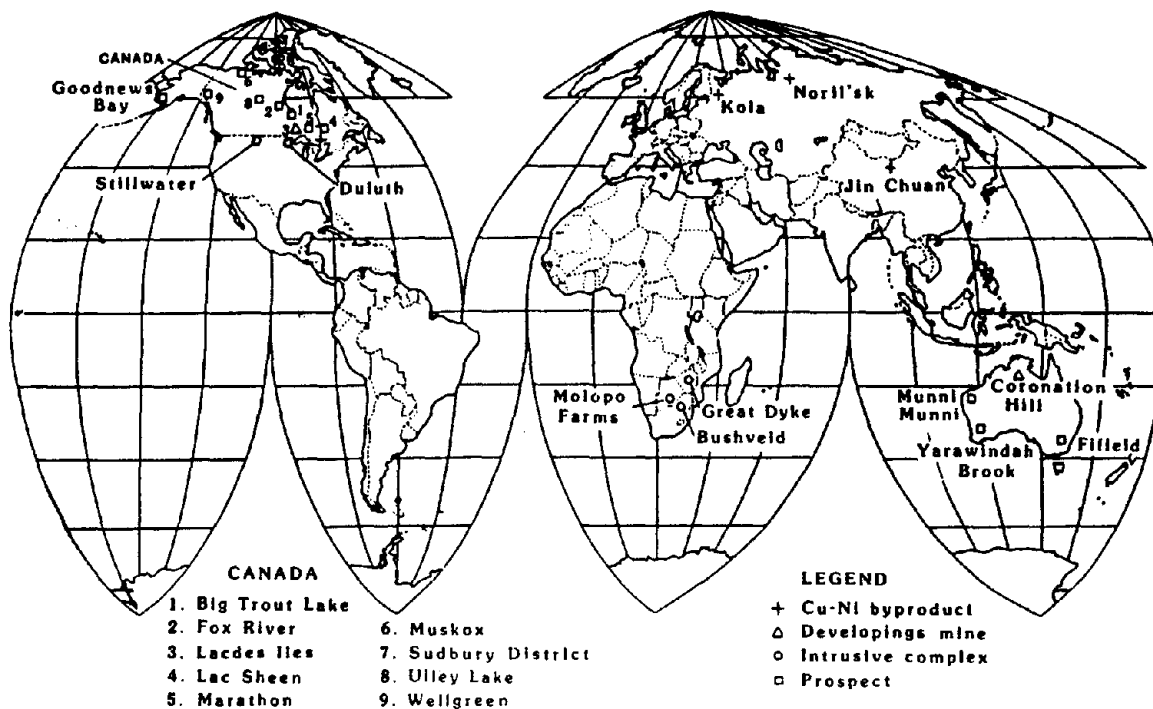


Figure 6.—PGM operations and prospects.

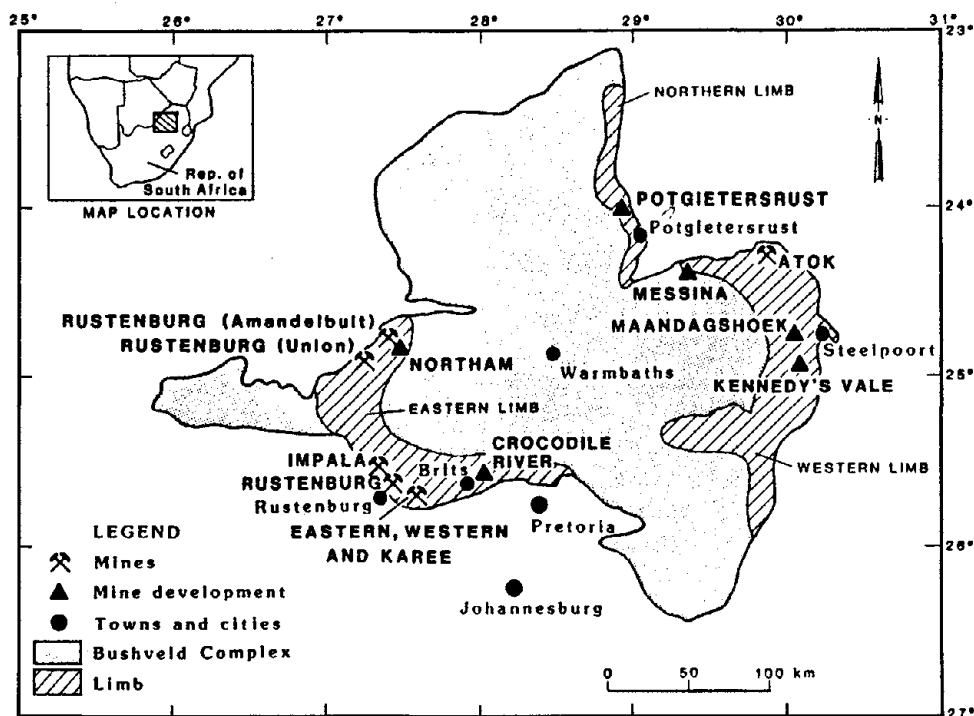


Figure 7.—PGM deposits in the Bushveld Complex.

The UG2 reef occurs some 25 to 400 m below the Merensky Reef. It is between 0.6 and 1.5 m thick and, with the exception of rhodium, has PGM grades typically lower than those found in the Merensky Reef. Platinum contributes between 39 and 54 pct of the total PGM plus gold grade and the platinum-to-palladium ratio varies from 1.2 to 2.6. The in situ PGM plus gold grade ranges from 5.9 to 7.7 g/mt (11). The upper limits for nickel and copper grades are 0.11 pct and 0.07 pct, respectively. UG2 reserves of PGM are estimated to be double those of the Merensky Reef.

The UG2 reef can also be classified as a chromite seam grading 25 to 35 pct Cr_2O_3 . The high-chromium and low copper-nickel content, which inhibits the recovery of PGM, required the development of a new beneficiation process. The high chromium content in the smelter feed can cause blockage in the furnace. A low copper-nickel content can result in a loss of PGM to the smelter slag. This new beneficiation process includes changes in the milling circuits to account for the different mineralogy of the UG2 ore and changes in the type of smelter used to smelt the UG2 concentrate. The milling process has to reduce the chromium content in the sulfide concentrate to 3.0 pct before smelting. An alternate method of processing UG2

ore is by blending Merensky and UG2 ore before milling. The blended ore (up to 20 pct UG2) can be beneficiated using conventional milling circuits and smelters (12).

The presence of chromite in the mill tailings may represent a potential asset. Lump chromium can be produced by initial screening, and chromite concentrates can be produced by upgrading the tailings with spirals. Pelletizing the concentrates and smelting would result in a 47- to 51-pct chromium high-carbon ferrochromium product. It is speculated that, by the year 2010, about half of South Africa's PGM production could be coming from UG2 material, with potentially 10 to 15 Mmtpy of chromite tailings being generated at this time (13). At present, the Crocodile River Mine is extracting ores solely from the UG2 Reef, and the Western, Rustenburg, and Impala operations have some production from the UG2.

The Platreef occurs in the northern area of the BIC and contains one of the first PGM deposits mined in South Africa. However, because of erratic ore grades in the Platreef, operations had ceased in the mid-1930's. The platinum-to-palladium ratio is 1.1, and the in situ grade ranges from 7 to 27 g/mt (14). Trial mining is presently being conducted in order to test the feasibility of establishing a new mine.

United States

Currently, the Stillwater Complex is the only location of primary PGM production in the United States. The Stillwater Complex is a 48- by 7.4-km mafic-to-ultramafic intrusion located in northern Montana (15) and is thought to be similar to the BIC. The producing horizon is the J-M Reef, with a platinum-to-palladium ratio of 1:3.4. The average in situ grade is estimated at 22.3 g/mt, and the indicated resources for the entire Stillwater Complex are estimated at 35 Moz of PGM (16). The Stillwater Mining Corporation's Stillwater Mine is currently the only producer. Exploration efforts are also being conducted by several other companies.

Alluvial deposits of platinum metals were previously recovered from the Goodnews Bay area (Salmon River) in Alaska. Production between 1927 and 1970 was estimated to be over 0.5 Moz. Potential resources for dredging operations at present are estimated at 30.85 Mm³ (17), but at high estimated production costs.

Canada

The majority of Canadian PGM production is a by-product of nickel mining, as discussed later. The only primary PGM operation, Lac Des Iles, is located 80 km north of Thunder Bay, Ontario. The operation is owned by Madeleine Mines and is currently undergoing development. The Lac Des Iles intrusive complex is composed of mafic and ultramafic rocks; the northern section is an ultramafic intrusion, and the southern section is composed of two mafic intrusions, the Eastern Gabbro and the Western Gabbro. The primary zone of mineralization, the Roby zone, is located at the contact of the two gabbros. Madeleine Mines has established a reserve of 20 Mt at 5.2 g/mt PGM and a platinum-to-palladium ratio of 1:7 (18). The mineralization is open at depth; the total reserve may be much higher.

Zimbabwe

The Great Dyke in Zimbabwe is believed to contain the largest PGM resource outside of South Africa. The platinum-to-palladium ratio averages 1.41:1, and the nickel and copper values are 0.2 pct and 0.15 pct, respectively (19). For this study, the proposed Hartley Project, which has a history of intermittent activity, was included in the availability analysis. Current investigations involve feasibility and financing studies.

Byproduct Resources

Byproduct PGM reserves from the nickel-copper resources of the U.S.S.R., Canada, and other MEC's total

207 Moz, with the U.S.S.R. accounting for 190 Moz in 1990 (20). Colombia, once the world's major source of platinum, now mines about one-half of 1 pct of the Western World's output from placer operations. PGM (primarily palladium) are also recovered as byproducts from the Jin Chuan nickel complex in Gansu Province, China. The PGM are consumed domestically, with no significant export. PGM are also known to occur in association with chromite deposits around the world, but their viability is not well known.

The nickel-copper mines in the U.S.S.R. are the largest source of palladium and the second largest source of platinum and rhodium in the world. PGM are recovered as byproducts of nickel-copper sulfide deposits in the Noril'sk-Talnakh area in the extreme northwest of Siberia and on the Kola Peninsula in the extreme northwest U.S.S.R., bordering on Norway. The U.S.S.R. does not release the amount of PGM produced; sales of PGM to the Western World are used in place of reliable production data. As shown in tables 1 through 3, annual sales of platinum, palladium, and rhodium to the Western World from 1980 through 1989 have ranged between 1.58 Moz and 2.33 Moz. Total U.S.S.R. platinum sales to the Western World reached a high of 550 koz in 1989, accounting for 16 pct of total world supply. Palladium sales were 1.65 Moz, or 51 pct of the world total; rhodium sales accounted for nearly 40 pct of the total estimated world supply of 330 koz.

The Noril'sk region contributes 90 pct of Soviet PGM output, and the ratio of platinum to palladium is between 1:2 and 1:5. The disseminated ore bodies average 0.1 to 0.3 pct copper, 0.1 to 0.3 pct nickel, and 3.4 g/mt PGM. High-grade veins occur with 3.4 pct combined nickel and copper with up to 10.4 g/mt PGM. The distribution of PGM has been estimated at 67 pct palladium, 25 pct platinum, 3 pct rhodium, 2 pct ruthenium, 2 pct iridium, and 1 pct osmium. The ore also contains recoverable quantities of selenium, tellurium, gold, silver, and uranium (21, 22). There are four underground mines. The largest mine, Oktyabr'skiy, started in 1980 and produces about half the output of ore in the Noril'sk-Talnakh area. Ores are processed at a smelter and refinery at Noril'sk at an estimated capacity of 80 kmtpy nickel metal. Part of the nickel-copper concentrate is transported by a 33-km pipeline to the second smelter at Nadezdha that has the capacity to treat 550 kmtpy nickel and 650 kmtpy copper concentrates. Electrolytic slimes from the Noril'sk complex are treated at the Krasnoyarsk refinery, yielding between 2.6 and 3.0 Moz PGM per year. The refinery is located 1,625 km south of Noril'sk near the trans-Siberian railway.

On the Kola Peninsula, the Pechenganikel Complex at Pechenga and the Severonikel Complex at Monchegorsk produce the remaining 10 pct of byproduct PGM from nickel and copper mining. The 80-kmtpy nickel smelter at

Monchegorsk processes concentrates from the Severonikel and Noril'sk complexes; PGM are also recovered from the refinery plant at Monchegorsk.

Byproduct PGM from Canadian nickel mines accounted for 205 koz palladium and 150 koz of platinum in 1989. Inco Ltd. recovers PGM as a byproduct of its nickel mining operation in the Sudbury District of Ontario. Very small amounts of PGM are also recovered from Inco's nickel operations at Thompson, Manitoba. In 1989, Inco's nine underground mines and one open pit operation in Sudbury accounted for 90 pct of PGM produced in Canada. The estimated content of Canadian PGM is palladium, 46 pct; platinum, 42 pct; rhodium, 4 pct; ruthenium, 3 pct; and combined osmium and iridium, 3 pct (23). The mining operations send their concentrates to the Copper Cliff complex, Ontario. From the Copper Cliff smelter and electrolytic nickel refinery, the PGM-bearing residues are shipped to Inco's platinum refinery at Acton, England. At yearend 1990, Inco's nickel-copper ore reserves in Canada totaled 369 Mmt containing 5.3 Mmt of nickel and 3.1 Mmt of copper (24). PGM content is estimated, based on the 1987-90 average production ratio of nickel to PGM, at 9.3 Moz.

Falconbridge Ltd. contributes the remaining 10 pct of Canadian byproduct PGM from five underground mines and one open pit in the Sudbury Basin. Ores are concentrated at the Strathcona mill, and the concentrates are transported to the Falconbridge smelter to produce nickel-copper matte that is shipped to Norway for refining and PGM recovery.

POTENTIAL RESOURCES

PGM mining is concentrated in very few locations throughout the world. Because of high metal price, perceived increases in demand, and the strategic nature of PGM, aggressive exploration programs⁸ have been launched in numerous places. Exploration has focused on areas of mafic/ultramafic intrusions (similar to the Bushveld), but other geologic terranes are also being explored. Exploration efforts are being conducted in Canada, Australia, Southern Africa, and the United States. PGM mineralization has been reported in Brazil, India, Greenland, and New Zealand (25, 26).

Three areas in Southern Africa are the focus of active exploration efforts. The Molopo Farms area, believed to be geologically similar to the Bushveld Complex, is located on the border of Botswana and South Africa. Low-grade

platinum mineralization has been detected. Several companies have active exploration and drilling programs in progress. The Chegutu Complex is part of the Great Dyke in Zimbabwe and is located south of the Hartley Complex. A multiyear drilling program is being conducted to evaluate the feasibility of establishing a platinum-nickel mine (27). The Platreef, immediately south of Potgietersrus Platinum Mines⁹ Platreef operation near Potgietersrus, is being evaluated by South Witwatersrand Exploration (SouthWits). Reserves are believed to be in excess of 25 Mmt with grades of 3.5 g/mt PGM and gold, 0.23 pct nickel, and 0.18 pct copper (28).

Australia shows only minor PGM production as a byproduct of the mining of nickel-copper deposits in Western Australia. There has been very minor past production from alluvial deposits in the Fifield region of New South Wales. The major advantage that Australia has is the varied geologic terranes. There are six different geologic settings where PGM mineralization has been found in Australia in 68 separate occurrences, of which four merit separate discussion (29).

The most unique deposit is the Coronation Hill deposit in Kakadu National Park, Northern Territories. From a geologic standpoint, the deposit is unique. It is a gold-PGM deposit that shows no mafic/ultramafic rock association, nor are there any possible mafic/ultramafic source rocks in the immediate area (30). It is believed to be of hydrothermal origin. Reported mineralization includes probable reserves of 3.41 Mmt containing 5.6 g/mt gold, 0.24 g/mt platinum, and 0.82 g/mt palladium, and possible reserves of 2.2 mt containing 6.8 g/mt gold, 0.31 g/mt platinum, and 0.95 g/mt palladium (31). However, political factors are controlling further development of the deposit. The deposit is located in a mineral-rich but environmentally sensitive area. The Government had originally set aside 2,250 km² for mining operations and had accepted a comprehensive environmental impact statement on the project. In October 1989, yielding to pressures from environmentalists, the Government reduced the area set aside for mining to 37 km² and required an additional environmental impact study that will take up to a year to complete. The status of the project, as of mid-1990, is uncertain.

Other prospects of note include the Yarawindah Brook, Munni Munni, and Fifield. Yarawindah Brook, north of Perth, is a layered mafic/ultramafic complex and contains anomalous values of platinum, palladium, and gold. The Munni Munni prospect is in a layered mafic/ultramafic complex similar to the Bushveld. The 1988 Hunter Resources Annual Report states that "potential" resources

⁸Assaying of PGM-bearing material is difficult and expensive. The detection limits are often in the parts per billion range. Instrumental-based techniques such as X-ray fluorescence (XRF) and inductively coupled plasma emission spectrometry (ICP) are replacing the traditional wet chemical methods. The new methods allow for more rapid and accurate analysis as well as a reduction in costs.

⁹Potgietersrus Platinum Mines is a 50:50 joint venture between Rustenburg Platinum Mines (RPM) and Lebowa Platinum Mines (LPM).

of 20 to 30 Mmt is inferred from drilling results with a grade of 2.9 g/mt combined platinum, palladium, and gold (32). Exploration work is continuing along with metallurgical testing of the material. The Fifield Area, located in central New South Wales, is a historic producer of platinum and gold from alluvial deposits. Several companies are currently exploring the associated intrusive complexes and have reported significant PGM values in drill-hole intersections.

Production of PGM in Canada is dominated by by-product production from copper-nickel mining, especially the Sudbury Intrusive Complex. The Sudbury Complex is believed to have been caused by a meteorite impact. The current theory is that the impact caused shock waves to penetrate to the mantle, which then caused melting and migration up the resulting fractures. Several intrusive events occurred that resulted in the formation of large nickel-copper sulfide deposits with minor PGM (33). No other PGM occurrences in Canada have approached the size of Sudbury.

Exploration for other PGM deposits in Canada is dominated by junior mining companies, often in partnership with the larger mining companies. Several deposits have received a great deal of interest. Aside from the developing Lac des Iles deposit, the Marathon deposit in Ontario Province has been explored intensely. The owner, Fleck Resources, is currently conducting pilot smelter trials. The deposit is believed to contain 37 Mmt of near surface reserves amenable to open pit mining (34). Crystal Lake, located south of Thunder Bay, is a low-grade copper-nickel deposit with minor PGM.

International Platinum Corporation is very active in PGM exploration in Canada. Their holdings include Muskox (Northwest Territories), Axegold (British Columbia), Wiley Lake (Saskatchewan), Reed Lake (Manitoba), Fox River (Manitoba), Superior (Ontario), Big Trout Lake (Ontario), and Lac Sheen (Quebec) (35). Of these, the Big Trout Lake prospect is the most promising. Big Trout Lake is a mafic/ultramafic intrusion and has reported grades of up to 5 g/mt of combined PGM. The final deposit of note in Canada is the Wellgreen copper-nickel-platinum-palladium prospect in the Yukon. The property had undergone preliminary development as a copper-nickel operation, including mine planning for an open pit mine and the construction of a mill. Current probable reserves are estimated at 42.4 Mmt grading 0.3 pct nickel, 0.35 pct copper, 0.5 g/mt platinum, and 0.3 g/mt palladium (36). The property is presently in a hold status while further exploration and environmental impact studies are conducted (37, 38).

The Duluth Gabbro is a large intrusive complex in northeast Minnesota. Intense exploration programs for large nickel-copper deposits were carried out in the 1970's. Several companies have reassayed the drill cores for PGM

and base metals with encouraging results. As a result, several areas are being reexamined for PGM mineralization, and drilling programs are currently being conducted. However, this area was not included in this analysis because no reliable resource, reserve tonnages, or grades were available at the time of the evaluation.

Nevada and Wyoming have historically produced small quantities of PGM from hydrothermal ore deposits. Both States are undergoing renewed exploration efforts. The Stillwater Complex is undergoing active exploration efforts by several companies. Drilling and surface sampling has confirmed the presence of PGM-rich sulfide layers at the Picket Pin property, 9 miles northwest of the Stillwater Mine (39). PGM mineralization associated with chromite veins is also being investigated at several locations (40).

RECYCLED RESOURCES

Rates of recycling vary, depending on the type of industry. The factor determining the rate of recycling is the degree of physical concentration that exists in the particular industrial segment.

The segment of the market with the greatest potential for increased recycling is the automotive market. The automotive sector (autocatalyst) is the largest consumer of platinum and rhodium and a significant consumer of palladium. As the auto fleet ages, a greater number of scrapped cars will contain potentially recoverable autocatalyst. Data on the amount of platinum from recycled autocatalysts was first reported in 1982 by Johnson Matthey¹⁰ in the amount of 10 koz, gradually increasing to an estimated 175 koz in 1989 as shown in table 1. Palladium from recycled autocatalyst was first reported in 1984 in the amount of 20 koz, gradually increasing to 70 koz in 1989 as shown in table 2. Rhodium from recycled autocatalyst was first reported in 1987 in the amount of 3 koz, increasing to 8 koz in 1989 as shown in table 3. Japan¹¹ is the only country, other than the United States, with any measurable amount of recycling, estimated at 25 koz of platinum and 15 koz of palladium in 1989. As European countries introduce emission control legislation, a supply of platinum, palladium, and rhodium from recycled sources will begin to appear in that region after 5 to 10 yr.

The number of autocatalysts available for recycling are dependent on a wide variety of factors. Roughly 10 million new cars and light trucks subject to emissions control are registered every year in the United States. The Motor Vehicles Manufacturers Association estimates the current life of an automobile at about 7 yr. Therefore, platinum-palladium catalysts, introduced in 1975, began arriving in

¹⁰The U.S. Bureau of Mines does not collect data on the quantity of PGM recovered from recycled autocatalysts.

¹¹The amounts reported by region are based on the region in which the vehicle was scrapped and not where the PGM are recovered from the autocatalyst.

quantity at scrapyards in 1982. Likewise, platinum-palladium-rhodium catalysts, the so-called three-way catalysts introduced in 1981, began arriving at scrapyards in quantity in 1988. Naturally, scrappage rates for the various models of cars will vary widely and thus affect the type of catalyst entering the recycle stream. Also, the Automotive Recyclers and Dismantlers Association estimates that only 70 pct of cars that are junked each year reach the automotive dismantlers, and a certain percentage of cars will not have the converters removed (41). Contrary to popular belief, the Environmental Protection Agency presently has no rules requiring the converter to be removed prior to shredding (42). This may change if rules covering the disposal of lead-contaminated products currently under consideration are introduced.

The potential amount of PGM available from reclaimed autocatalysts was once described as a "platinum mine on wheels." As in many mining ventures, this one too has failed to meet the early expectations. The efforts to recycle catalysts have been confronted with both technical and economic problems that are only gradually being overcome. Two general processing routes can be used to recover the PGM from the scrap autocatalysts: hydrometallurgical or pyrometallurgical. Each of the processing routes has inherent advantages and disadvantages and are discussed in detail in appendix D. All processes face several technical problems: (1) the possibly high lead content of the catalyst, (2) disposal of lead-bearing residue, (3) control of possibly hazardous reagents and disposal of possibly toxic effluent and residues, and (4) the need for high recovery rates to meet economic parameters (43).

The recycling of electrical and electronic scrap is done on both a toll and nontoll basis. When recycled on a toll basis, ownership of the scrap remains with the customer, and the refiner charges a toll or fee to the owner of the scrap for refining. In general, toll recycling is based on recycling of scrap material from the manufacturing process. When the scrap is actually sold to a refiner, it is referred to as nontoll scrap.

The recycling of petroleum catalysts is probably the most sophisticated of all the industries. The PGM-bearing catalysts represent a significant amount of capital investment to the petroleum companies, and they are regenerated on a toll basis. In some cases, the company that regenerates the catalyst will "loan" the petroleum refinery a supply of catalysts while theirs is undergoing regeneration. The only time that PGM will reenter the marketplace is when a refinery is closed.

Recycling in the chemical industries is dependent on the type of process and reactions involved. In the case of nitric acid production, roughly 90 pct of the PGM material is recycled. In most reactions utilizing catalysts, the catalysts are regenerated on a toll basis minus associated

processing losses estimated at 5 to 20 pct. In some reactions, such as the manufacture of silicones, there is no recycling because the catalyst is mixed with the other reactants and remains in the product.

Recycling in the glass industry is also done on a toll basis. The bushings used in fiberglass manufacture suffer minor operating losses because of the highly corrosive nature of the molten glass. The bushings are recycled and returned to the glass manufacturer. All the above-mentioned privately held recycled platinum is not considered as a potential supply source for this report.

COST AND ECONOMIC FACTORS

Mine and mill operating cost estimates are longrun averages for the purpose of availability analysis, include both variable (direct) and fixed (indirect) charges, and are based on complete extraction of the demonstrated resource for the specific property analyzed. A description of typical PGM operations is presented in appendix E. South African tax structure and inflation are economic factors to be examined. Price proportioning ratios between platinum and three commodities (palladium, rhodium, and gold) are presented in detail.

Mine Operating Costs

No meaningful information regarding costs is released by any of the PGM producers. For the purposes of estimating mining costs in South Africa, costs have been estimated from information on gold mining in South Africa and other cost data published by several South African investment companies. The physical mining methods for extracting PGM and gold are somewhat identical. Operational differences between gold and PGM operations include (1) smaller average stoping heights (0.8-1.7 m for platinum and 2.0 m for gold), (2) the higher density of platinumiferous Bushveld ores relative to Witwatersrand gold-bearing ores, (3) depth of operations, and (4) the higher geothermal gradient in the Bushveld with a requirement for refrigeration at shallower depths. Underground mining of both gold and PGM is labor intensive. The operating cost data for gold mines are published, therefore, one can establish approximate mining costs for PGM operations by examining similar-scale gold mines and adjusting the costs for depth and scale of operation.

The density, grade, and PGM ratio of the ore have various impacts when calculating the cost per ounce of refined metals (platinum, palladium, and rhodium). In South Africa, the shallow areas of Merensky Reef ore mined by Rustenburg, Impala, and Western have been depleted, and the deeper areas are more expensive to mine. Impala is presently mining at 1000-m vertical depth, and, since

1982, Western's operation has been decreasing the amount of Merensky ore mined in favor of shallower UG2 ore. New producers, Eastern, Atok, and Karee, have benefited during their startup periods from technical assistance and existing infrastructure of their parent companies. Consequently, their mining operating costs are similar to existing producers. In table 7, the mining operating costs for the producers average at \$202/oz of refined metals or \$25/mt of ore.

For nonproducers,¹² the Northam Mine has completed sinking its Number 2 shaft to a depth of 1,822 m below the surface and has taken the Number 1 shaft to 1,751 m on the way to its final depth of 2,097 m (44). Initial requirements for refrigeration resulted in the highest mine operating cost in South Africa. The proposed Platreef mine is conducive to modern shallow trackless mining techniques and would incur relatively low mining operating cost. Another disadvantage faced by the nonproducers is their size. Rustenburg Platinum Mines operates three mines and mills at 15 Mmtpy of ore, introducing economies of scale unavailable to the small nonproducing mines. The mining operating costs for nonproducers averaged \$250/oz of refined metals or \$33/mt ore.

The Stillwater, Montana (United States), and Hartley (Zimbabwe) underground operations are grouped as "Other countries" in table 7 to avoid disclosure of costs for these individual operations. The Stillwater Mining Co. is mining high-grade ore, and the plans for Hartley are to mine the shallow sections initially. Consequently, the average mining operating costs for these countries are significantly lower than the other groupings. High grading at Stillwater influenced the mine operating cost of \$75/oz refined metal, and the shallow depth at Hartley influenced the cost on a portion of ore basis at \$13/mt.

¹²Developing or proposed operations.

The proposed placer operation at Salmon River, Alaska (United States), and the open pit mine of Lac des Iles in Ontario, Canada, constitute the surface operations category. The Salmon River operation would recover dredging material with very low PGM grades resulting in high mining costs per ounce of refined metals. The transfer of such a large volume of material necessarily entails high mine operating costs on a per-ton-of-ore basis as well. The open pit operation at Lac des Iles in Canada could operate at one-eighth of the dredging costs; the surface mine operating cost in table 7 is heavily weighted by the very high cost of the Alaskan deposit. Mine operating costs accounted for an average of 65 pct of the total cost for producers and 74 pct for nonproducers, as indicated in table 7.

Mill Operating Costs

Mill operating costs for South African producers averaged \$29/oz of refined metals or \$4/mt of ore. For South African nonproducers, the average milling operating cost averaged \$46/oz of refined metals or \$6/mt of ore. The higher beneficiation cost for the nonproducers is due to smaller size operations and treatment of the UG2 ore and its associated high chromite content (up to 28 pct). For example, two of the nonproducers—Maandagshoek and Kennedy's Vale—are planning to mine UG2 ore only. Classification and regrinding of the cleaner tailings at these operations would reduce the chromite content to less than 3 pct in their mill concentrates, which is a requirement for UG2 concentrates for smelter feed. Consequently, these mines would incur a higher estimated milling cost than other mines treating only Merensky ore or a blended mixture of Merensky and UG2 ore. The average mill operating cost for the nonproducers was 59 pct higher than that for the producers.

Table 7.—Average PGM operating costs

Unit of measure	Mine type	Operation	Operating costs				
			Mine	Mill	Smelting	Refining	Total
\$/oz ¹	Underground ..	South African producers	202	29	25	25	281
	..do.	South African nonproducers ² ..	250	46	36	19	351
	..do.	Other countries ³	63	39	43	19	164
Do.	Surface	U.S. and Canada	165	33	53	29	280
\$/mt ore ⁴	Underground ..	South African producers	25	4	3	3	35
	..do.	South African nonproducers ² ..	33	6	4	3	46
	..do.	Other countries ³	2	11	7	8	28
Do.	Surface	U.S. and Canada	1	5	0.5	0.5	7

¹Weighted average based on the sum of recovered platinum, palladium, and rhodium.

²Included development of Potgietersrust as an underground operation. Plans as of mid-1991 call for this operation to be developed as an open pit.

³Includes Stillwater, United States, and Hartley, Zimbabwe.

⁴Weighted average based on ore mined.

The smelting category in table 7 includes costs for smelting copper and nickel, as well as transportation costs. The South African nonproducers usually send the mill concentrates to existing smelters and refineries in the first few years of production, and, therefore, a toll charge was included in the smelting operating costs. The smelting and refining costs account for 18 pct of the total costs for producers and 17 pct for nonproducers. It is noted that, as analyzed, the Salmon River operation would recover low-grade PGM by hydrometallurgical processes. The operation does not recover any base metals and thus had low smelting and refining cost on a basis of dollars per metric ton of ore; however, the low-grade material resulted in very high costs on a basis of dollars per troy ounce of refined metals.

Capital Costs

Capital costs are an important factor in any decision to develop a mining property. Capital expenditure on platinum mines in South Africa qualifies for a capital redemption allowance in tax calculations in the year in which it was incurred. In other words, capital expenditure is treated as a working cost. The South African Government also provides depreciation allowances for nonmining assets, such as a refinery, to encourage vertical integration of the mineral industry. The high price of platinum in recent years has encouraged capital investment to be financed internally by producers. Expansion by major producers to new, shallow areas in efforts to maintain or reduce unit operating costs has resulted in recent capital investments in equipment for trackless mining. Rustenburg has completed a PGM solvent extraction refinery at Bophuthatswana at an estimated cost of \$125 million (45). Impala has sunk new shafts in the last 2 yr to replace obsolete ones and has completed an extensive drilling program to increase ore reserves. Western Platinum Ltd. built a base metal refinery in 1986 with funding from Lonrho Ltd., intending to double Western's PGM capacity to 500 koz annually. A new 80 kmt per month concentrator for UG2 ore was commissioned in 1990 at Western Mine, and an identical plant is planned for Eastern Mine in the near future.

For South African nonproducers, estimated initial capital investment in mining equipment and plants range from \$53 million for shallow mines to \$118 million for deep mines. This range represents initial capital costs, exclusive of exploration, acquisition, and development costs. The mine capital costs averaged \$916/oz of recoverable platinum. The mill capital costs for the South African nonproducers varied from \$40 million to \$72 million with the mills treating UG2 or Platreef ores incurring higher costs than the mills treating Merensky only or Merensky-UG2

combination ore. On average, mill capital costs were \$893 per annual troy ounce of recoverable platinum. The greenfield operations such as Messina, Platreef, and Maandagshoek would require more infrastructure capital, ranging from \$16 million to \$23 million, for roads and housing for employees.

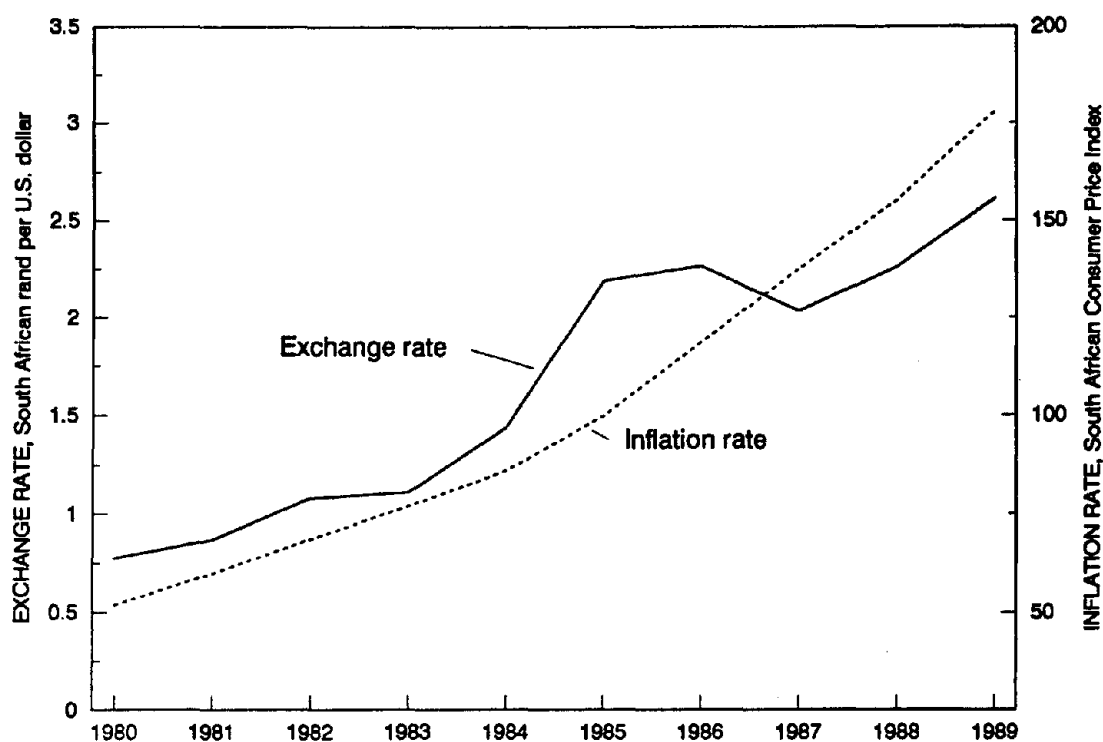
South African Economic Factors

In South Africa, the mining industry is allowed a redemption allowance for recovering capital costs, based on revenues from mining. Unused portions of the redemption allowance in any year are carried forward indefinitely to offset future income, but no carry back is allowed. This is a distinct difference to the multiyear depreciation method most countries use for capital recovery and is an advantage to the South African corporations. The South African mines are subject to central Government corporate income taxes. Income tax is 50 pct of taxable income plus a surcharge on taxable income of 15 pct. This combination results in an effective tax rate of 57.5 pct of taxable income. There is no depletion allowance or severance tax. Royalties are negotiated with the host tribes on long-term contracts; for this study, an average tribal royalty of 13 pct of taxable income was assumed.

Inflation is a major economic factor in South Africa, the Consumer Product Index (CPI) has increased almost 15 pct annually since 1981. Wage settlements by private sector unions during 1988 resulted in an average 20.7 pct increase in wages. Average minimum wages for laborers (88 pct unskilled workers in mining industry) in negotiated settlements rose 22.9 pct in 1988; the wages for skilled workers increased approximately 18 pct (46). As more black workers advance to become skilled workers, the labor portion of operating costs could increase accordingly.

The profitability of South African mines has been affected by the value of the South African rand relative to the U.S. dollar. PGM and base metals are sold to the world market in U.S. dollars, but the production costs are rand-based. The foreign exchange gain is transferred to the mines, resulting in higher profits. During the years 1984-89, the exchange rate changed by 82 pct (1.438 rands per U.S. dollar in 1984 to 2.616 rands per U.S. dollar in 1989) as shown in figure 8. This devaluation of currency in international monetary markets suggests that the change in inflation is being offset by a simultaneous currency devaluation. It is believed, however, this practice (whether intentional or inadvertent) cannot continue indefinitely, and eventually South African production costs must rise.

PGM production in South Africa is controlled by five holding company groups. These companies have control of the majority of the available mineral rights in the Bushveld Complex. The lack of available mineral rights



Source: International Monetary Fund, International Financial Statistics, 1990 Yearbook, Sec. on South Africa, 1991, pp. 643-645.

Figure 8.—South African and U.S. dollar exchange rate.

makes it extremely difficult for other companies to enter into PGM mining in South Africa. These companies have also invested heavily in developing specialized technology, especially in smelting and refining, for PGM processing. New entrants would also have to develop this technology at a significant capital expense.

The five holding company groups presently producing PGM include Johannesburg Consolidated Investment Trust Ltd. (JCI), General Mining Corporation of South Africa (Gencor), Barlow Rand, Gold Fields of South Africa (GFSA), and Lonrho. The relationship between the mining operations and the holding companies is shown in figure 9. The interrelationships between the companies enable them to share technology and capitalization requirements (through joint ventures), thereby erecting another barrier to entry.

PRICING AND PRICE PROPORTION ANALYSIS

A critical component of this availability analysis is the determination of the price of the commodities. Price determinations in the previous PGM availability study were accomplished by placing the predominant cost burden on

platinum as the primary commodity, with the remaining coproducts or byproducts providing offsetting revenues based on prevailing market prices. The revenue remaining after subtraction of byproduct revenues is used to determine the price needed to cover all costs at the specified DCFROR.

When a price determination analysis is performed for a property that produces the major PGM as coproducts, the total revenues (minus byproduct credits) are divided between the coproducts according to the market price ratio for each product. The underlying assumption is that the same relationship exists between market prices of the products and the share of production costs assigned to each of the products. For example, a property producing equal amounts of platinum (market price of \$500/oz), palladium (market price of \$125/oz), and rhodium (market price of \$1,200/oz) would have a factor of 1.0 (\$500 divided by \$500) assigned to platinum, a factor of 0.25 (\$125 divided by \$500) assigned to palladium, and a factor of 2.4 (\$1,200 divided by \$500) assigned to rhodium. This would result in revenues being split such that platinum revenues would be 27 pct (1.0 divided by 3.65), palladium revenues would be 7 pct (0.25 divided by 3.65), and

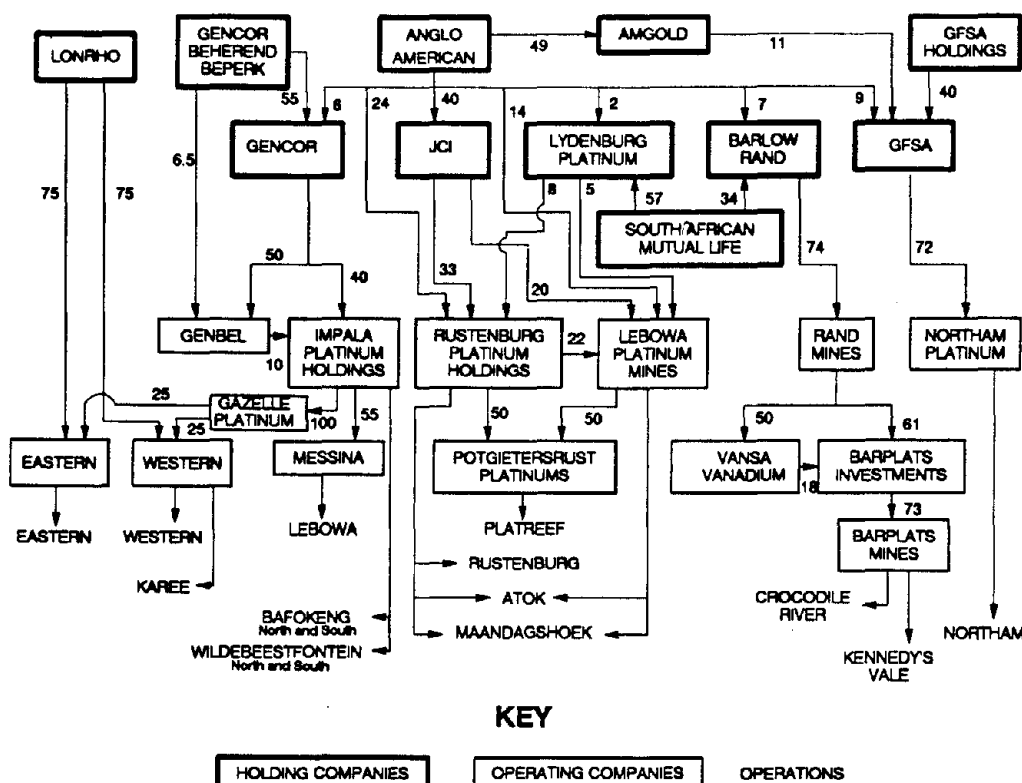


Figure 9.—Ownership network of South African PGM operations, April 1991.

rhodium revenues would be 66 pct (2.4 divided by 3.65) of the total available¹³ revenues.

For a property that produces unequal amounts of PGM, the available revenues would be adjusted by a factor based on the relative grades and recovered metal and the above-mentioned price ratios. For example, a property that produces 2.1 g/mt platinum, 3.6 g/mt palladium, and 0.24 g/mt rhodium would show 59 pct of the available revenues from platinum, 25 pct of the available revenues from palladium, and 16 pct of the available revenues from rhodium. The underlying price ratio of 1:0.25:2.4 is embedded in this revenue distribution.¹⁴

For this study, price proportions (or price ratios) are utilized for the major PGM: platinum, palladium, rhodium, and gold. Gold, while not a significant source of revenues for the operations, was included (1) under the assumption that gold and platinum prices react similarly to the same types of pricing pressures and (2) to provide a

basis of comparison between the gold price, a widely followed indicator in financial markets, and the platinum price. The minor PGM (osmium, iridium, and ruthenium) and nickel, copper, and cobalt were all considered to be byproducts. The market prices used in this analysis are presented in table 8. The 1989 price for nickel is somewhat above the prices of the previous years because of a variety of factors. Therefore, the byproduct revenues from nickel may not be representative of a long-term trend. Generally, this would only have a notable impact on the Merensky Reef-based mines; the nickel-poor UG2-based mines would only show a minor impact.

To determine the price proportion ratio, a review of pricing was made of the 1978-90 average monthly and average yearly prices for platinum, palladium, rhodium, and gold. In order to minimize effects of extreme price fluctuations, yearly averages were also examined. The average monthly prices¹⁵ from January 1978 through July

¹³Available revenues = total revenues minus byproduct revenues.

¹⁴This revenue distribution assumes 100-pct recovery and 100-pct payor. Depending on the relative recoveries and payor, this distribution would change.

¹⁵The prices presented and analyzed are based on the U.S. Bureau of Mines pricing data. The PGM are based on the low end of the New York dealer prices, and the gold price is based on the average Engelhard Industries daily quotation.

1990 are presented in figure 10. The price proportion factors of this study are based on the analysis of these price histories and are presented in table 9. As such, these factors reflect resource, economic, technologic, and market situations that existed during this time period. Over the short, medium, and long term, the relative proportions among the different products can be expected to change in response to changes in those situations.

Table 8.—Average 1989 prices for coproduct and byproduct commodities associated with PGM production

Commodity	Price	Unit
COPRODUCTS¹		
Platinum	\$507.00	oz.
Palladium	144.00	oz.
Rhodium	1,300.00	oz.
Gold	381.28	oz.
BYPRODUCTS		
Cobalt	8.65	lb.
Copper	1.07	lb.
Iridium	303.00	oz.
Nickel	7.06	lb.
Osmium	549.15	oz.
Ruthenium	62.00	oz.

¹For comparison only: Price was determined using price proportion methodology.

Source: U.S. Bureau of Mines Minerals Yearbook.

Table 9.—Price ratios used in analysis

Commodity	PGM price ratio (platinum price:other price) ¹
Platinum	1.00
Palladium	0.28
Rhodium	2.40
Gold	0.91

¹Platinum price = 1.

The gold, platinum, and palladium prices have generally followed similar trends: a peak price in 1979-80 followed by a 50-pct drop by 1982 and a moderate recovery of price in 1983-84 followed by another drop in early 1985. The gold price trended upward to almost \$500/oz by late 1987 and then gradually decreased to near \$350/oz in mid-1990. Platinum followed a similar trend, approaching \$600/oz several times before starting a downward trend in 1988. By mid-1990, the price had fallen to \$475/oz. Palladium experienced a similar trend of peaks in 1980 and 1984 and periods of relatively low prices in 1982 and 1985. By mid-1990, the price had fallen to \$116/oz.

The price fluctuations of platinum and gold have caused the gold/platinum monthly price ratio to fluctuate between

0.6 and 1.34 between 1978 and 1989 with an average of 0.91. The yearly ratio showed similar results; the range of fluctuations was much less. Generally, in expansionary economic conditions, the gold price is about 80 to 85 pct of the platinum price, while in recession the price ratio is about 1.0 (shows a slight advantage to gold). This may be caused by a combination of the heavy industrial use of platinum and the speculative nature¹⁶ of gold demand. This study used a price ratio of 0.91:1.0 (gold to platinum).

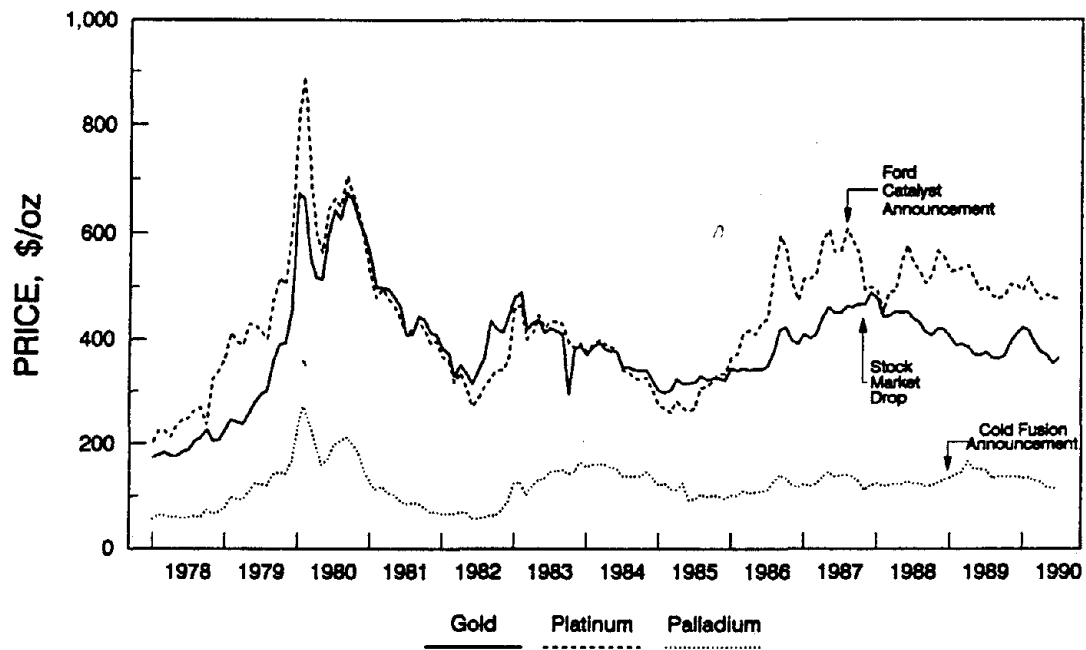
The monthly palladium ratio has ranged from 0.2 to 0.45. Generally, it has remained fairly constant, ranging between 0.2 to 0.35 and has averaged 0.28. This study utilized 0.28:1.0 for the price ratio for palladium to platinum.

The major exception to this overall precious-metals price trend has been the rhodium price. After the drop following the 1979-80 metal price peak, rhodium prices increased about 300 pct between 1981-86 as a result of the introduction of three-way catalytic converters (fig. 11). After 1986, rhodium prices obtained a degree of stability, ranging from \$1,100 to \$1,300/oz. The rhodium-to-platinum ratio also stabilized somewhat ranging from 2.0 to 3.7 with an average of 2.4. The study assumed a ratio of 2.4:1.0 for rhodium to platinum for all base-case analyses.

The rhodium price remained relatively stable, around \$1,250/oz, from 1987 until late 1989. In late 1989 and early 1990, reported problems at Rustenburg's new refinery sent the price to over \$2,000/oz. Buying by automobile manufacturers in response to proposed new U.S. emission control legislation and new European emission control legislation sent the spot price over \$7,000/oz in mid-1990. The dramatic price increase in early 1990 saw the rhodium-to-platinum ratio increase to more than 4.0 in the first quarter and jump to more than 10 by July 1990. The impact of higher rhodium prices on the availability of PGM is addressed in the sensitivity analyses included in later sections entitled "Impact of Rhodium Pricing" and "Rhodium as a Primary Revenue Source."

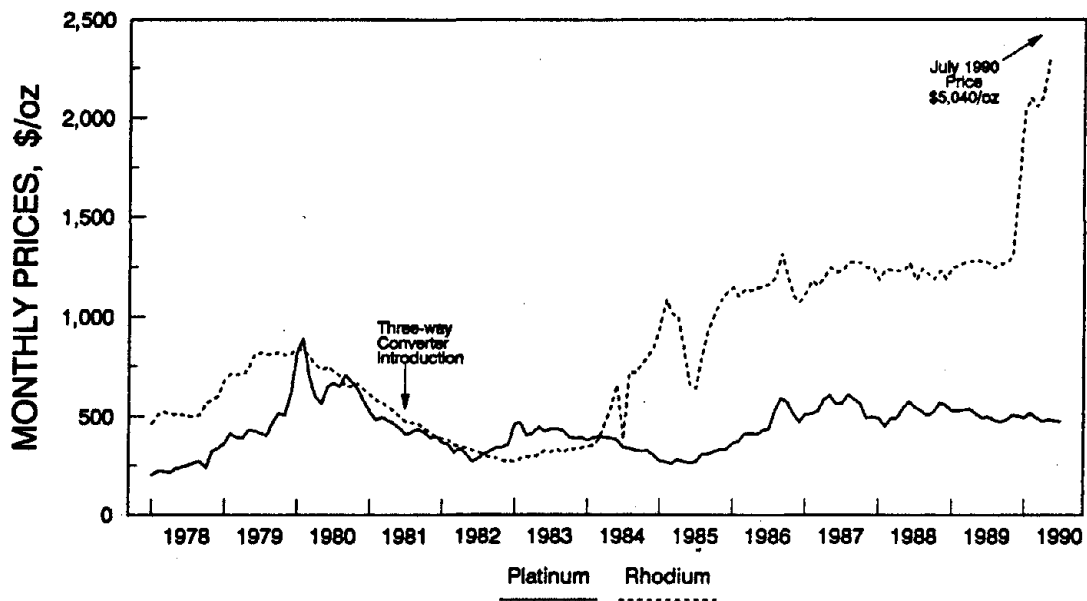
The minor PGM have shown some fluctuations during the last 10 yr. Iridium has generally followed the platinum price trend. With an extremely small market, osmium experienced a dramatic price increase in 1984-85 when only a small amount of metal was being refined. With the price increase, more metal entered the market. The price has since declined and stabilized. The ruthenium price has been exceptionally stable because of relatively small market demand, sufficient mine production, and adequate stocks.

¹⁶Gold has served historically as a "store of wealth." During a recessionary period, gold has historically been purchased to protect the purchaser against declines in purchasing power of currency.



Source: U.S. Bureau of Mines Minerals Yearbook.

Figure 10.—Relative monthly metal prices, 1978-90.



Source: U.S. Bureau of Mines Minerals Yearbook.

Figure 11.—Platinum and rhodium monthly prices, 1978-90.

AVAILABILITY ANALYSES

The availability of the PGM from primary PGM deposits presented in the base-case scenario estimates the longrun cost of production including recovery of capital at a 0-pct DCFROR in January 1990 U.S. dollars. Total production cost ranges and recoverable commodity quantities are presented in total availability curves and annual curves. Several scenarios analyzing the increasing importance of the rhodium availability are also presented. The relationship between rhodium grades in the ore and consumption patterns is presented. The influence of different rhodium grades and prices on the operations is analyzed by increasing the rhodium to platinum price ratio and by analyzing at what price rhodium would be the primary revenue generator.

Availability of PGM

Availability analyses were performed for 16 selected properties in 4 MEC's. Of the 12 South African deposits evaluated, the 7 producers had annual ore capacities ranging from 0.9 Mmtpy to 15 Mmtpy. At evaluated production rates, South African producers contribute 90 pct of the annual recoverable platinum of 3.85 Moz. The

remaining 10 pct would be recoverable from the five non-producers, which had annual capacities varying from 1.8 Mmtpy to 2.2 Mmtpy.

Evaluation methodologies are presented in detail in appendix B. The Supply Availability Model (SAM) was used to perform DCFROR analyses in order to determine the longrun prices of platinum, palladium, and rhodium, in price proportion, required for each operation to obtain a prespecified rate of return on its investment. This determined value is equivalent to an average total cost of production for the operation over its producing life. DCFROR analyses was performed at 0 and 15 pct.

Recoverable PGM from the 16 operations totaled 287.5 Moz as illustrated in figure 12. Total recoverable platinum from all operations was estimated at 164.3 Moz, representing approximately 50 yr of total world production at 1989 levels.

South Africa is the largest source of platinum production. The 12 South African properties represent 158.9 Moz (96.7 pct) of the 164.3 Moz total recoverable platinum analyzed as available from the 16 MEC properties.

The base-case scenario estimates the longrun cost of production including recovery of capital at a 0-pct DCFROR in January 1990 U.S. dollars. Total production

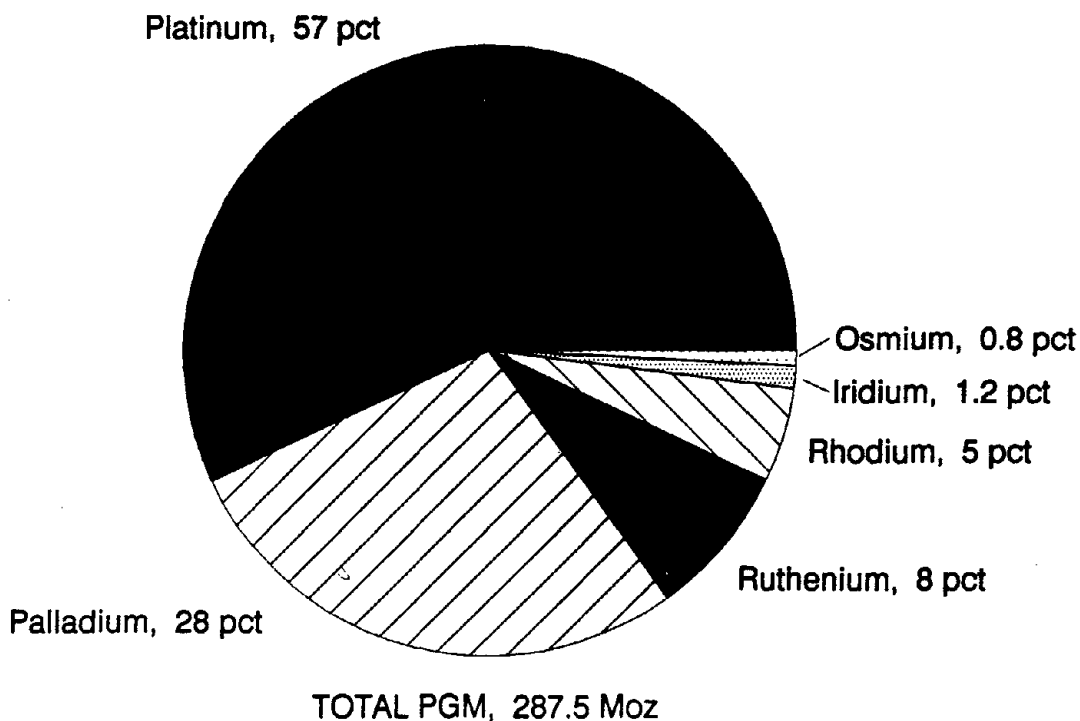


Figure 12.—Percentage distribution of evaluated PGM resources.

costs ranged from \$337/oz to \$1,288/oz platinum; the results are summarized in table 10 and illustrated in figure 13.

Table 10.—Total recoverable PGM at 0-pct DCFROR

Total cost range (\$/oz)	Number of operations	Total recoverable metal (koz)	Total recoverable metal (cumulative)	Share of availability (pct)
PLATINUM				
0-350	1	3,922	3,922	2.4
350-450	6	132,012	135,934	80.3
450-550	3	16,017	151,951	9.7
550-650	4	8,652	160,603	5.3
> 650	2	3,719	164,322	2.3
Total	16	164,322	NAP	100.0
PALLADIUM				
0-100	1	1,523	1,523	1.9
100-120	6	59,357	60,880	74.0
120-150	3	8,004	68,884	10.0
150-180	4	8,259	77,143	10.3
> 180	1	3,034	80,177	3.8
Total ¹	15	80,177	NAP	100.0
RHODIUM				
0-990	1	643	643	4.8
990-1,100	6	8,915	9,558	66.6
1,100-1,300	3	1,989	11,547	14.9
1,300-1,800	4	1,835	13,382	13.7
> 1,800	1	2	13,384	0.0
Total ¹	15	13,384	NAP	100.0

NAP Not applicable.

¹Only 15 operations recover palladium and rhodium.

Approximately 80 pct of total recoverable platinum was economic at cost levels of \$450/oz or less. The remaining 20 pct of recoverable platinum is contained in nine developing operations in deep reefs, shallow Platreef, and at surface deposits with low byproduct revenues.

The majority of recoverable platinum is contained within ore bodies mined by underground methods from the Bushveld Complex in the Republic of South Africa. This resource is predominantly rich in platinum and rhodium, two high-value commodities; consequently, the South African operations, mining reefs in the shallow and intermediate depth, have an economic advantage over operations in other parts of the world.

Table 11 summarizes the availability distribution of recoverable platinum at a 15-pct DCFROR. The 15-pct DCFROR production cost covers all costs and capital recovery as well as a 15-pct rate of return on invested capital. The total production costs ranged from \$421/oz to \$2,084/oz of platinum. Two South African producers

have total production costs estimated at the \$450/oz or less level, compared to seven operations (containing 82 pct of available platinum) under the 0-pct DCFROR base case. At total costs beyond the \$650/oz level, seven developing mines accounted for 12 pct of total recoverable platinum. Five of these operations would be mining at depth (more than 800 m) or in new areas without existing development work, and the other two properties have a low platinum grade. Figures 14 and 15 illustrate the palladium and rhodium availability at 0-pct and 15-pct DCFROR. Figure 16 represents proposed annual platinum production available for the year 1995 at total production costs below \$700/oz. According to minimum lead times assumed for development, 1995 would be the first year production would be ongoing at all 16 evaluated operations. Total recoverable platinum for 1995 (4.0 Moz) had production costs ranging from \$337/oz to \$1,287/oz of platinum. Interpreting the results of this curve, approximately 3.14 Moz of platinum would be potentially available in 1995 at or below total costs of \$438/oz. As stated previously, annual curves represent potential production levels and normally indicate maximum capacity levels rather than expected production rates.

Table 11.—Total recoverable PGM at 15-pct DCFROR

Total cost range (\$/oz)	Number of operations	Total recoverable metal (koz)	Total recoverable metal (cumulative)	Share of availability (pct)
PLATINUM				
0-350	0	0	0	0.0
350-450	2	42,375	42,375	25.8
450-550	3	85,747	128,122	52.2
550-650	4	16,017	144,139	9.7
> 650	7	20,183	164,322	12.3
Total	16	164,322	NAP	100.0
PALLADIUM				
0-100	0	0	0	0.0
100-120	2	17,490	17,490	21.8
120-150	1	27,457	44,947	34.2
150-180	6	13,959	58,906	17.4
> 180	6	21,271	80,177	25.5
Total ¹	15	80,177	NAP	100.0
RHODIUM				
0-990	0	0	0	0.0
990-1,100	3	6,771	6,771	50.6
1,100-1,300	1	43	6,814	0.3
1,300-1,800	0	4,096	10,910	30.6
> 1,800	11	2,474	13,384	18.5
Total ¹	15	13,384	NAP	100.0

NAP Not applicable.

¹Only 15 operations recover palladium and rhodium.

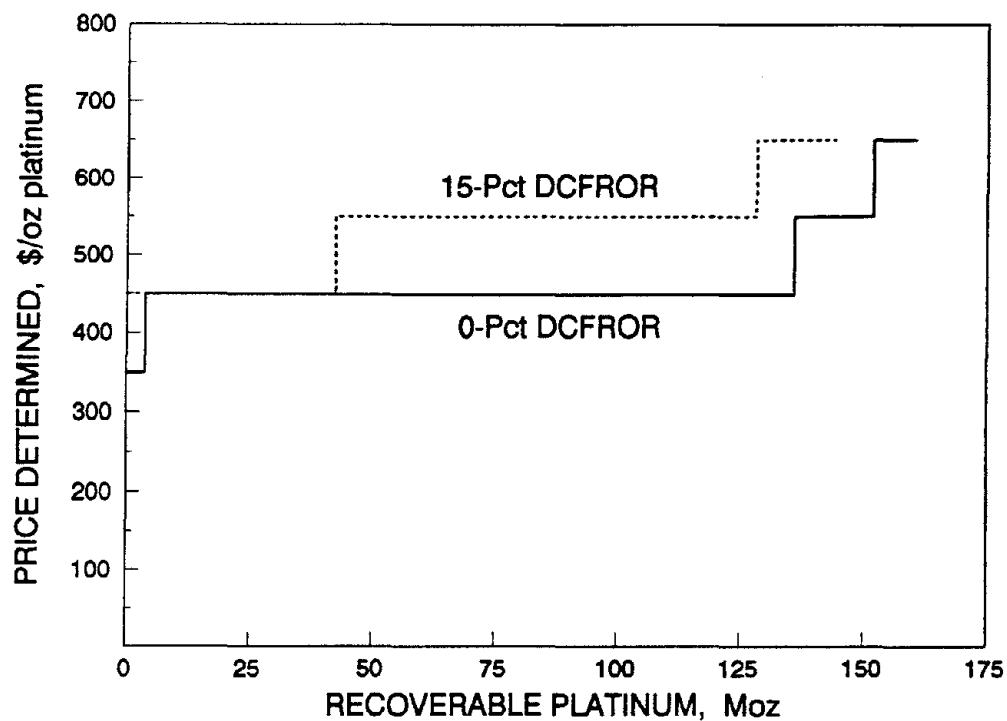


Figure 13.—Total recoverable platinum at 0- and 15-pct DCFROR less than \$650 cost.

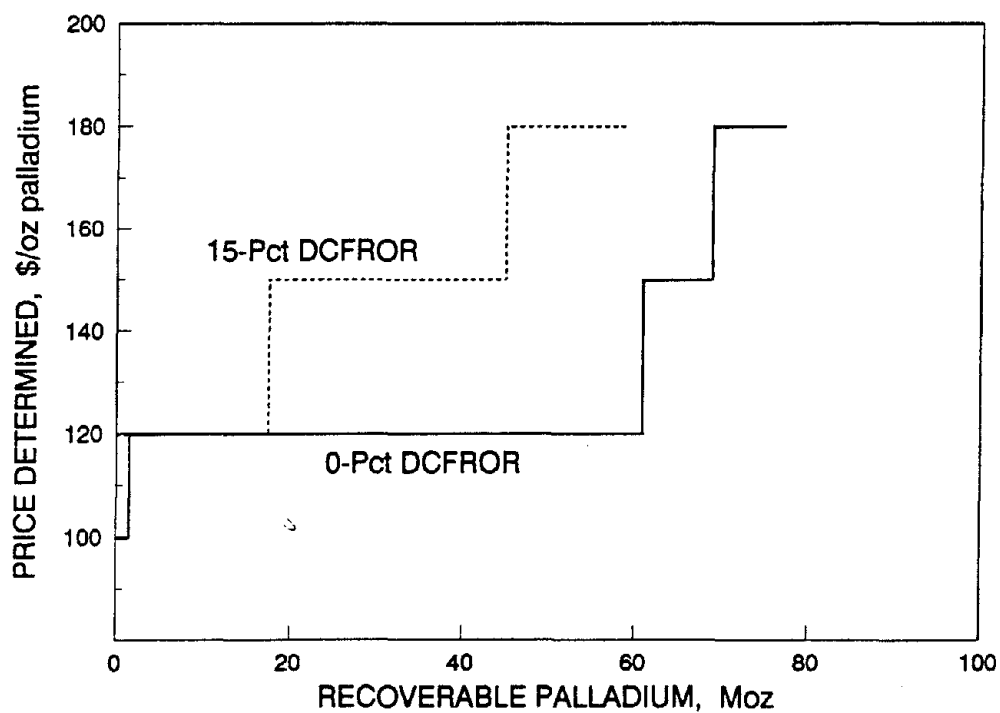


Figure 14.—Total recoverable palladium at 0- and 15-pct DCFROR less than \$180 cost.

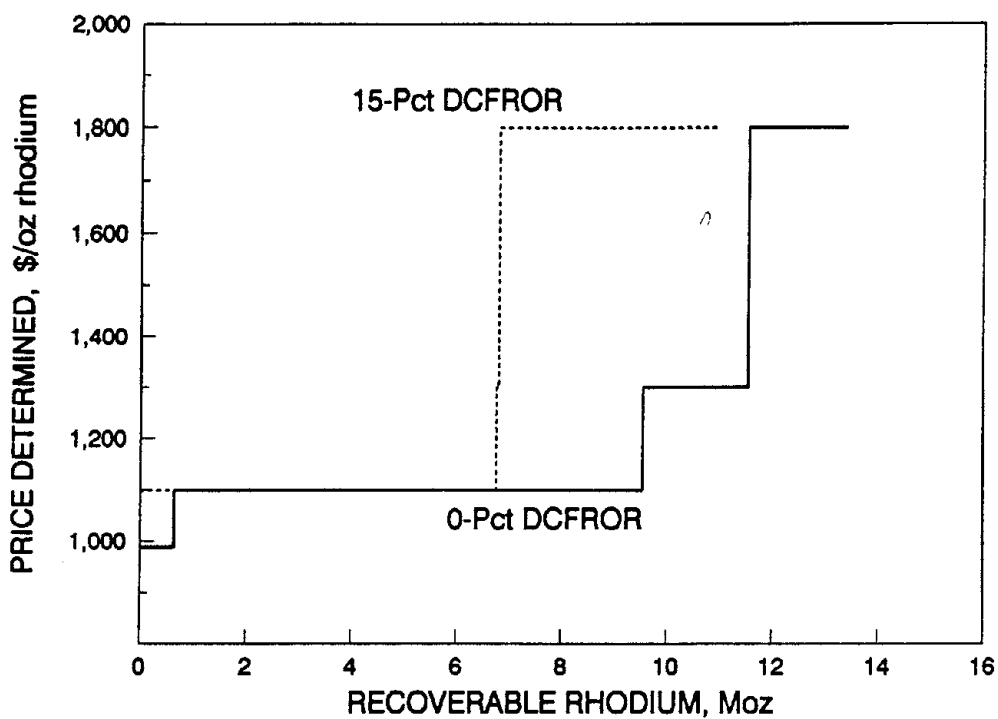


Figure 15.—Total recoverable rhodium at 0- and 15-pct DCFROR less than \$1,800 cost.

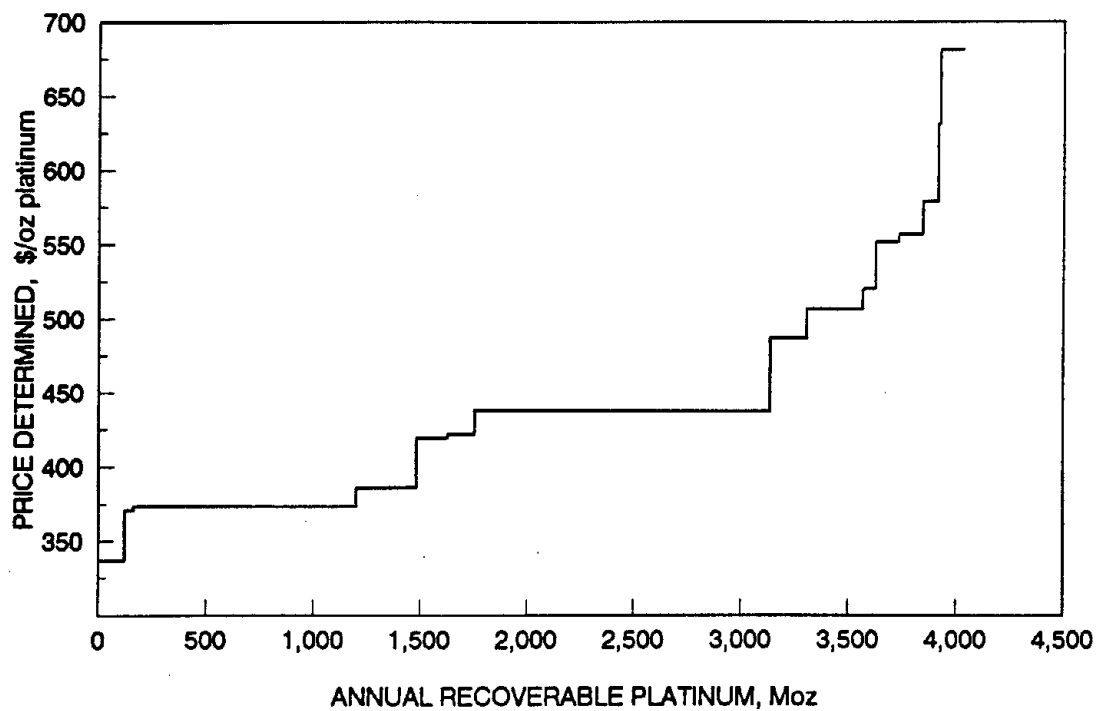


Figure 16.—1995 estimated recoverable platinum potentially available less than \$700/oz platinum.

Ratio of PGM in Ore Versus Consumption

The ratio of individual metal content of PGM contained in ore varies by deposit. This ratio can also be significantly different from the ratio of the metals in their major end uses. A mine cannot usually operate economically to produce one of the metals but is dependent on the revenues of all products. By emphasizing the production of one metal, a possible oversupply of other coproduct metals may result. This oversupply could cause a decline in the coproduct metal prices that, in turn, causes the overall gross value of the ore to decrease. Conversely, a moderate price decline in the coproduct metals may stimulate new applications and increased consumption for the coproduct metals.

For PGM, most of the attention has been focused on the ratios of the three primary metals (platinum, palladium, and rhodium) and whether or not they can be produced in relatively the same proportions as they are consumed. For example, the Merensky Reef platinum-to-palladium-to-rhodium ratio was 15:6.5:1, while, in 1989, the ratio of consumption was 11:10:1. With the introduction of rhodium-containing catalytic converters in 1981, the major concern was the availability of rhodium. Legislation lowering allowable emissions levels has generally caused the PGM loading of the catalytic converter to increase. The Clean Air Act of 1990 reduced allowable emissions levels, included stricter durability standards, and would require the amount¹⁷ of rhodium to double by 1993 (from 0.006 oz per catalyst to 0.012 oz per catalyst) and the amount of platinum to increase by 17 pct (from 0.06 oz to 0.07 oz) (47). Concurrently, the EC has phased in the

¹⁷The amount refers to average loadings of the auto fleet; loadings of each vehicle model may vary.

use of catalytic converters. As shown in table 12 and figure 17, the percentage of rhodium consumed for the new, post-1992 converters is significantly higher than the percentage found in typical ores.

The predominant source of production today, the Merensky ores, are relatively enriched in platinum while relatively deficient in rhodium. The only U.S. source of PGM, Stillwater in Montana, is predominantly a palladium producer, although it is somewhat enriched in rhodium.¹⁸ At present, the imbalance between the Merensky Reef (still the predominant MEC ore source) rhodium grade and the autocatalyst rhodium loading creates a potential rhodium supply imbalance.¹⁹ A higher production rate to supply more rhodium could possibly create an oversupply of platinum and a concurrent decline in the platinum price. As discussed previously, this could cause an overall drop in gross ore value. The marginal producers could then be forced to close, thereby further decreasing the supply of rhodium. However, with many of the South African mines shifting a portion of their production to the UG2 reef, the supply of rhodium may be adequate to meet future needs.

Impact of Rhodium Pricing

The impact the rhodium price has on total production costs at a 0-pct DCFROR is examined using three

¹⁸However, the operation is too small to make a significant impact on the U.S. demand for rhodium.

¹⁹Concurrent with a supply imbalance are drastic price swings. In late 1989, the U.S.S.R. announced that it would not be able to supply rhodium to the market. Also, problems with rhodium production at Rutenburg's new refinery were reported. The price went from approximately \$1,250/oz to over \$2,000/oz in a 3-month period. Proposed new emission control legislation and panic buying by automobile manufacturers sent the price to over \$7,000/oz in mid-1990. The monthly average price then settled in the \$4,000/oz to \$5,000/oz range by yearend.

Table 12.—Occurrence of PGM in major ore types and use in catalytic converters

(Percent of total PGM mineralization or application)

PGM	Ore types				Catalytic converters	
	Merensky	UG2	Platreef	Stillwater	Pre-1993	1993
Platinum	60.2	45.4	43.6	19.2	78.9	76.1
Palladium ¹	26.0	28.2	47.8	66.8	13.2	10.9
Rhodium	4.0	8.1	4.1	7.6	7.9	13.0
Ruthenium-Iridium-Osmium	9.8	18.3	4.5	6.4	—	—
Total	100.0	100.0	100.0	100.0	100.0	100.0

¹Palladium loading was assumed to remain constant between pre-1993 and 1993 converters.

NOTE.—Dashes indicate not applicable.

Source: Modified from table 2A in reference 47 and table 1.5 in Von Gruenewaldt, G., D. J. Hatton, and R. K. W. Merkleo. Platinum-Group Element Deposits Short Course Notes, Univ. of Pretoria, 1987, p. 1.14.

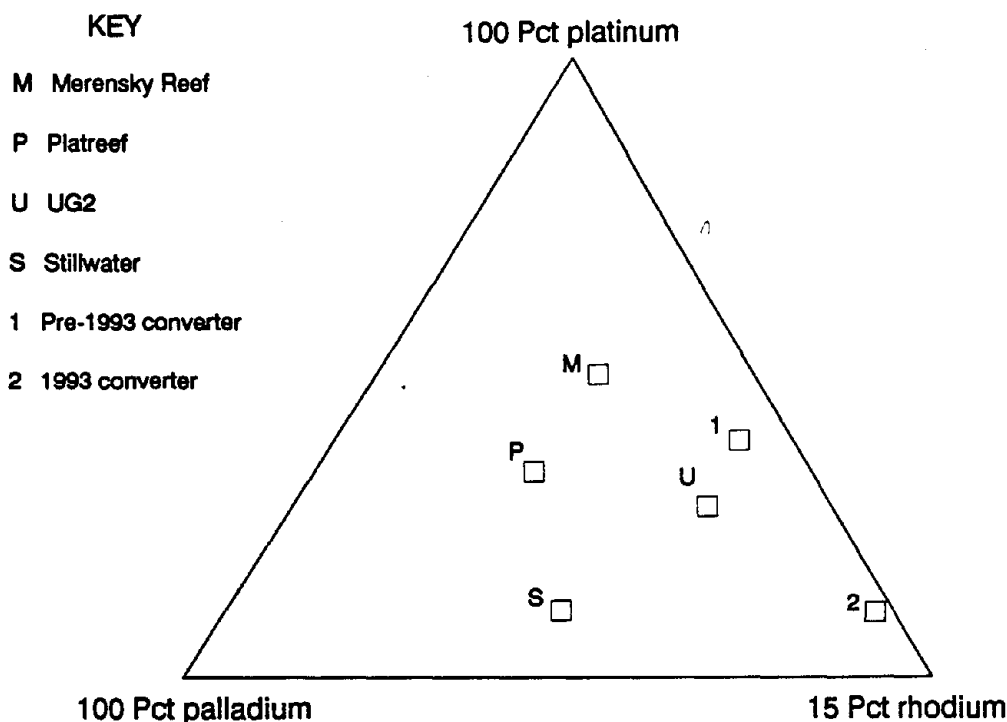


Figure 17.—Relative ore and use concentrations, platinum:palladium:rhodium.

platinum-to-rhodium price proportion ratios: 1:2.4, 1:4, and 1:9. Considering the small amount of rhodium present in the feed, the impact of the rhodium price is significant overall, particularly for operations with relatively higher concentrations of rhodium. The range of total production costs is lowered significantly at the higher platinum-to-rhodium ratios (table 13).

Table 13.—Price determination ranges at various platinum-to-rhodium price ratios at 0-pct DCFROR

Price ratio of platinum to rhodium	Platinum price range (\$/oz)	Rhodium price range (\$/oz)
1:2.4	337-1,287	781-1,635
1:4	282-1,255	1,154-2,326
1:9	181-1,156	1,627-3,826

The percentage of recoverable platinum available (table 14) at the \$350/oz or less cost level increased from 2 pct to 28 pct at the 1:4 ratio and to 48 pct at the 1:9 ratio. At the 1:9 ratio, virtually all platinum is recoverable below a total cost of \$450/oz platinum, compared to 82 pct for the base-case 1:2.4 ratio (fig. 18). Clearly, high rhodium prices can influence the average total cost

of production and affect the availability of PGM from marginal operations.

Table 14.—Share of total recoverable platinum at different cost ranges under various PGM price ratio scenarios

(Percent of total platinum recovered, unless otherwise noted)

Total cost range (\$/oz)	Price ratio of platinum to rhodium		
	1:2.4	1:4	1:9
0-350	2	28	48
350-450	80	58	52
450-550	10	11	0
> 550	8	2	0
Total	100	99	100

Rhodium as a Primary Revenue Source

During 1990, the market price for rhodium fluctuated between \$3,000/oz and \$7,000/oz, opening up the possibility of rhodium becoming the major revenue-generator of the PGM recovered at rhodium-rich operations. Four deposits were chosen to analyze the impact of rhodium

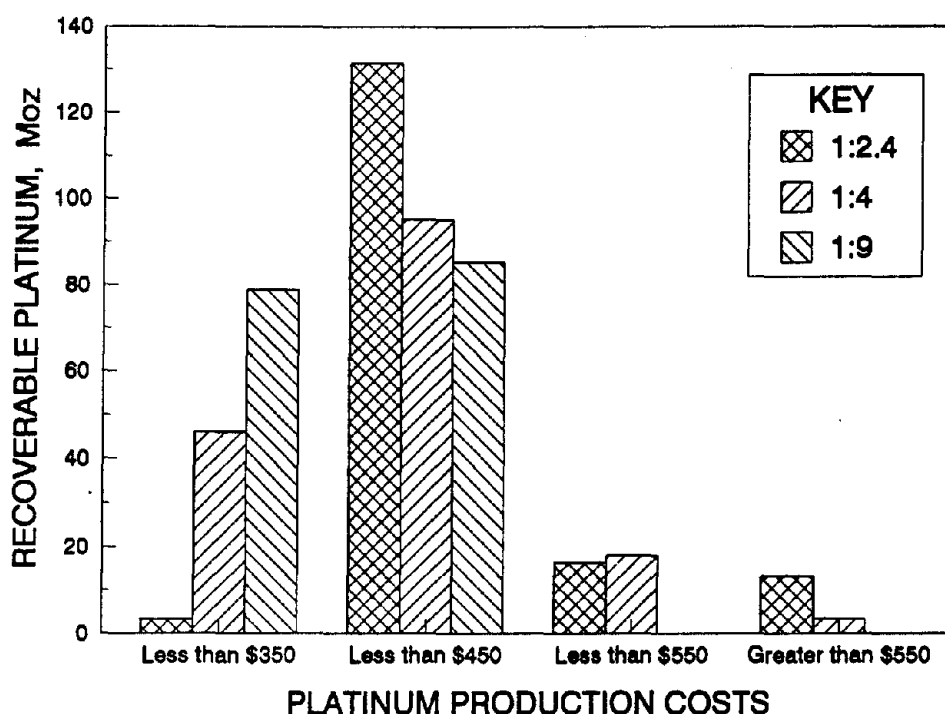


Figure 18.—Comparison of total recoverable platinum at three platinum-to-rhodium price ratios.

prices on PGM recoverability. The deposits represented the four major ore types in South Africa: the UG2 reef, combined UG2 and Merensky Reef, the Merensky Reef, and the Platreef.

Assuming platinum is the primary revenue-generator, an analysis was performed to estimate the rhodium price at which rhodium revenues would equal or exceed platinum revenues. Assuming a platinum price of \$459/oz, the platinum revenues for each type of ore deposit were calculated. The price calculated in order for rhodium to become the major revenue contributor (when compared

to \$459/oz platinum) was obtained by dividing the amount of rhodium recovered at each deposit into the platinum revenues from that deposit. The results ranged from \$2,370/oz in the rhodium-rich UG2 reef to \$9,045/oz for deposits in the rhodium-poor Platreef (refer to table 15). Although the rhodium grades are low for the Platreef, the high price was also influenced by toll refining charges for the proposed PGM production from this area. Proposed operations on the Platreef do not benefit from a vertically integrated refinery on-site. The actual impact of refining charges can be measured by the payfor

Table 15.—Comparison of rhodium prices needed to equal platinum revenues, by ore type

Ore type	Rhodium price (\$/oz)	Product recovered (koz)		Payfor ¹ (pct)		Revenues per PGM ² (billion \$)
		Rhodium	Platinum	Rhodium	Platinum	
UG2	2,370	1,278	6,516	75.9	76.9	2.3
Combined	3,580	1,760	13,858	77.5	76.8	2
Merensky	6,235	106	1,440	76	76	0.5
Platreef	9,045	223	3,125	54	76	1.1

¹Percentage of revenues returned to the mine following deduction of refining charges.

²Revenues based on 1990 average price of \$459/oz platinum and multiplied by the payfor percentage. Price for rhodium calculated from these revenues.

percentage shown on the table. This percentage represents the amount of revenues returned to the mine following refining and includes deductions based on typical smelter-refinery schedules and treatment charges.

With these rhodium prices, the price proportioning ratio of platinum-to-rhodium needed for rhodium as a primary revenue-generator for each type of ore can be easily estimated. For example, the ratio for the UG2 ore type was calculated for prices of \$459/oz platinum and \$2,370/oz rhodium; resulting in a platinum-to-rhodium ratio of 1:5.2. Employing this new platinum-to-rhodium ratio, base-case price determinations were performed with results of \$350/oz platinum and \$1,820/oz rhodium in the rhodium-rich UG2 reef. This can be compared to the base-case scenario with platinum-to-rhodium ratios of 1:2.4 and prices determined at \$490/oz platinum and \$1,170/oz rhodium. The estimated platinum-to-rhodium price ratios used for each deposit and resulting prices determined are given in table 16.

Table 16.—Platinum and rhodium prices determined, by ore type

Ore type	Price determined ¹ (\$/oz)		Ratio used platinum to rhodium
	Platinum	Rhodium	
RHODIUM AS PRIMARY ²			
UG2	350	1,820	1:5.2
UG2/Merensky	260	1,990	1:7.8
Merensky	350	4,770	1:13.6
Platreef	320	6,300	1:19.7
PLATINUM AS PRIMARY ³			
UG2	490	1,170	1:2.4
UG2/Merensky	390	930	1:2.4
Merensky	520	1,250	1:2.4
Platreef	560	1,340	1:2.4

¹Using price proportion methodology at a 0-pct DCFROR.

²Ratios determined for price proportions such that rhodium revenues exceed platinum revenues at \$459/oz platinum.

³Base-case scenario price determinations, with platinum as primary revenue-generator.

CONCLUSIONS

Resource availability and total production costs were determined for 16 deposits: 12 from South Africa, 2 from the United States, and 1 each from Canada and Zimbabwe. Evaluated resources totaled 2.2 billion mt of ore from eight currently producing operations and eight operations in various stages of development. Recoverable PGM from the 16 operations totaled 287.5 Moz, comprising 57 pct platinum, 28 pct palladium, 8 pct ruthenium, 5 pct rhodium, and 2 pct osmium and iridium. Platinum makes up the largest share of PGM production, and evaluated recoverable platinum from all operations was estimated at 164.3 Moz. This represents approximately 50 yr of total world production at 1989 levels.

The base-case scenario estimates the longrun cost of production including recovery of capital at a 0-pct DCFROR in January 1990 U.S. dollars to be in the range of \$337/oz to \$1,288/oz of platinum. Approximately 80 pct of total recoverable platinum was available at cost levels of \$450/oz or less. The remaining 20 pct of recoverable platinum is contained in nine developing operations in deep reefs, the shallow Platreef operation, and at surface deposits with low byproduct revenues. The majority of recoverable platinum is contained within ore bodies mined by underground methods from the Merensky Reef, UG2 Reef, and Platreef of the Bushveld Complex in the Republic of South Africa.

The total production costs at a 15-pct DCFROR, defined as the cost that covers all costs and capital recovery as well as a 15-pct rate of return on invested capital, ranged from \$421/oz to \$2,084/oz of platinum. Two South African producers have total production costs estimated at the \$450/oz or less level, as compared to seven operations (containing 82 pct of the available platinum evaluated) under the 0-pct DCFROR base case. An annual availability curve represents proposed annual platinum production available for the year 1995, the first year production would be ongoing at all 16 evaluated operations, thus indicating maximum capacity levels. Approximately 3.14 Moz of platinum would potentially be available at or below total costs of \$438/oz in 1995.

In the price proportioning method employed in this study, the total revenues (minus byproduct revenue) needed to attain a prespecified DCFROR at any property were allocated between the three major PGM (platinum, palladium, and rhodium) and gold, according to their price relationship (price ratio) in the market. Consequently, all four commodity prices are calculated from the total revenues (minus byproduct credits) and vary from deposit to deposit. The byproduct revenues allocated to minor PGM, copper, nickel, and cobalt recovered at any operation are established according to the 1989 market prices.

The impact the rhodium price had on total production costs at a 0-pct DCFROR was examined by changing

the price proportion ratio of platinum-to-rhodium from 1:2.4 in the base case to 1:4 and 1:9. The range of total production costs for the platinum in the base case (1:2.4) was \$337/oz to \$1,287/oz. The range of total production costs for platinum was lowered to \$282/oz to \$1,255/oz platinum for the 1:4 ratio, and \$181/oz to \$1,156/oz for the 1:9 ratio. The base-case rhodium total production cost range was \$781/oz to \$1,635/oz. At the 1:4 ratio, this range was increased to \$1,154/oz to \$2,326/oz and, for the 1:9 ratio, \$1,627/oz to \$3,826/oz. The percentage of

recoverable platinum available at the \$350/oz or less cost level increased from 2 pct to 28 pct at the 1:4 ratio and to 48 pct at the 1:9 ratio.

The platinum-to-rhodium price ratios of four typical South African ores (UG2, combined Merensky and UG2, Merensky, and Platreef) were calculated as 1:5.2, 1:7.8, 1:13.6, and 1:19.7, respectively. At relatively high rhodium prices (greater than \$5,000/oz), it appeared that most of the operations would derive the majority of their revenue from rhodium.

REFERENCES

1. Anstett, T. F., D. I. Bleiwas, and C. Sheng-Fogg. Platinum Availability—Market Economy Countries. BuMines IC 8897, 1982, 16 pp.
2. Johnson Matthey (London, England). Platinum 1985, p. 53.
3. Findlay, G. Trading in Platinum. Woodhead-Faulkner, 1988, 170 pp.
4. Davenport, J. C. Economic Sanctions Against South African and United States Platinum Supplies. Paper in Platinum Group Metals Seminar 1985, ed. by E. D. Zysk (Proc. Platinum Group Metals Seminar, 1985, Washington, DC). Int. Prec. Met. Inst., 1985, pp. 81-91.
5. Loebenstein, J. R. Platinum-Group Metals. Ch. in BuMines Minerals Yearbook 1989, v. 1, 11 pp.
6. Biviano, M., R. Gillette, and P. Smith. Estimated Direct Economic Impacts of a U.S. Import Embargo on Strategic and Critical Minerals Produced in South Africa. BuMines OFR 19-88, 1988, 49 pp.
7. U.S. Bureau of Mines. Platinum Group Metals in the First Quarter, 1989. Minerals Industry Surveys, June 9, 1989, p. 2.
8. Sutphin, D. M., and N. J. Page. International Strategic Minerals Inventory Summary Report—Platinum Group Metals. U.S. Geol. Surv. Circ. 930-E, 1986, 34 pp.
9. Loebenstein, J. R. Platinum-Group Metals. Sec. in BuMines Mineral Commodity Summaries 1990, pp. 126-127.
10. Edwards, D. The Bushveld. Luck of the Irish. S. Afr. Min., Gold, and Base Minerals, Aug. 1989, pp. 5-21.
11. ———. The Bushveld. Luck of the Irish. S. Afr. Min., Gold, and Base Minerals, Aug. 1989, pp. 5-21.
12. Liddell, K. S., L. B. McRae, and R. C. Dunne. Process Routes for the Beneficiation of Noble Metals From Merensky and UG-2 Ores. Pres. at Extraction Metallurgy '85, London, Sept. 9-12, 1985, 28 pages; available upon request from C. T. Fogg, BuMines, Denver, CO.
13. Officials of MINTEK. Personal communication, August 1988; available upon request from E. H. Boyle, Jr., BuMines, Denver, CO.
14. Edwards, D. The Bushveld—Luck of the Irish. S. Afr. Min., Coal, Gold and Base Metals, August 1990, pp. 5-21.
15. Postle, J. T., W. E. Roscoe, R. Y. Watanabe, and P. S. Martin. Review of Platinum Group Element Deposits in Ontario. Mineral Policy Background Paper No. 24. Ontario Ministry of Northern Development and Mines, 1986, 87 pp.
16. Buchanan, D. L. Platinum—Great Importance of Bushveld Complex and World Mining, v. 33, No. 9, Aug. 1988, pp. 56-59.
17. Page, N. J., and R. R. Carlson. Review of Platinum-Group Metal Geochemistry and the Major Occurrences in the World. U.S. Geol. Surv. OFR 80-90, 1980, 21 pp.
18. Wyllie, R. J. M. Platinum—Production, Projects, Prospects, Eng. and Min. J., Oct. 1987, pp. 26-34.
19. Von Gruenewaldt, G., C. J. Hatton, and R. K. W. Merkle. PGE Deposits in Other Large Layered Intrusions. Ch. in Platinum-Group Element Deposits Short Course Notes, University of Pretoria, 1987, pp. 6.1-6.14.
20. Loebenstein, J. R. Platinum-Group Metals. Sec. in BuMines Mineral Commodity Summaries 1990, pp. 126-127.
21. Buchanan, D. L. Platinum Group Element Exploration. Developments in Economic Geology No. 26, Elsevier Scientific Press, 1988, p. 96.
22. Hull and Co. Hull Report on Platinum Group Metals, 1986-2000. Mar. 1988, pp. 46-50.
23. Edwards, D. The Bushveld, Luck of the Irish. S. Afr. Min., Gold, and Base Minerals, Aug. 1989, pp. 5-21.
24. INCO Ltd. Annual Report 1990, p. 14-27.
25. Johnson Matthey (London, England). Platinum 1990, 64 pp.
26. Wyllie, R. J. M. Platinum—Production, Projects, Prospects. Eng. and Min. J., v. 188, No. 10, Oct. 1987, pp. 26-34.
27. Johnson Matthey (London, England). Platinum 1990, pp. 64.
28. Mining Journal. South Wits Progress at Platreef. V. 313, No. 8042, Oct. 20, 1989, p. 324.
29. Hoatson, D. M., and L. M. Glaser. Geology and Economics of Platinum-Group Metals in Australia. Resource Report 5. Australian Government Publishing Service, 1989, pp. 39-54.
30. ———. Geology and Economics of Platinum-Group Metals in Australia. Resource Report 5. Australian Government Publishing Service, 1989, pp. 48.
31. ———. Geology and Economics of Platinum-Group Metals in Australia. Resource Report 5. Australian Government Publishing Service, 1989, pp. 49.
32. Hunter Resources Ltd. (Australia). 1988 Annual Report, 30 pp.
33. Postle, J. T., W. E. Roscoe, R. Y. Watanabe, and P. S. Martin. Review of Platinum Group Element Deposits in Ontario. Mineral Policy Background Paper No. 24. Ontario Ministry of Northern Development and Mines, 1986, 87 pp.
34. Johnson Matthey (London, England). Platinum 1990, p. 18.
35. International Platinum Corp. (Canada). 1988 Annual Report, 32 pp.
36. Bokavay, G. Platinum Group Metals. Ch. in Canadian Minerals Yearbook 1989. Minerals Report No. 38. Can. Dep. of Energy, Mines and Resour., 1990, pp. 47.1-47.15.
37. Johnson Matthey (London, England). Platinum 1990, p. 18.
38. Porter, K. E. (U.S. Bureau of Mines). Private communication, June 1990; available upon request from J. Corneliussen, BuMines, Denver, CO.
39. International Platinum Corp. (Canada). 1988 Annual Report, 32 pp.
40. Engineering and Mining Journal. Boulder Gold NL Is Active at Stillwater. V. 191, No. 12, 1990, pp. 11, 39.

41. Hull and Co. Hull Report on Platinum Group Metals, 1989-2000. Mar. 1988, 436 pp.
42. Hoover, S. (U.S. Environmental Protection Agency). Private communication, June 14, 1990; available upon request from J. Cornelliison, BuMines, Denver, CO.
43. Hoffman, J. E. Recovery of Platinum Group Metals From Automotive Catalysts. Paper in Precious and Rare Metal Technologies, ed. by A. E. Torma and I. H. Gundiler (Proc. Process Metallurgy 5, Albuquerque, NM, Apr. 6-8, 1988). Elsevier, 1988, pp. 345-363.
44. Johnson Matthey (London, England). Platinum 1990, p. 17.
45. _____. Platinum 1989, 64 pp.
46. U.S. Bureau of International Labor Affairs (Dep. Labor). Foreign Labor Trends, South Africa, July 1987-Dec. 1988. FLT 89-21, 1989, 28 pp.
47. Humphries, M. Platinum Group Metals Use in the World Auto Industry: Effects of Tougher Tailpipe Emission Standards. CRS Report for Congress 90-219 ENR. 1990, p. 7.
48. Steel, M. C. F. Changing Patterns of Platinum Metals Use in Autocatalyst. SAE Tech. Paper Series No. 880127, 1988, 9 pp.
49. Florini, K. L., G. D. Krumbhaar, and E. K. Silbergeld. Legacy of Lead: America's Continuing Epidemic of Childhood Lead Poisoning. Environmental Defense Fund (Washington, DC), 1990, 46 pp.
50. Summers, J. C., J. J. White, and W. B. Williamson. Durability of Palladium Only Three-Way Automotive Emission Control Catalysts. SAE Tech. Paper Series No. 890794, 1989, 19 pp.
51. Wilkins, A. J. J., and N. A. Hannington. The Effect of Fuel and Oil Additives on Automobile Catalyst Performance. Platinum Met. Rev., v. 34, No. 1, 1990, pp. 16-24.
52. Hull and Co. Hull Report on Platinum Group Metals, 1986-2000. Mar. 1988, p. 106.
53. Hull and Co. Hull Report on Heterogenous Catalyst System, 1989-2000, Jan. 1990, 436 pp.
54. Monroe, D. M., and M. H. Krueger. The Effect of Pt and Rh Loading on the Performance of Three-Way Automotive Catalysts. SAE Tech. Paper Series No. 872130, 1987, 8 pp.
55. Hull and Co. Hull Report on Platinum Group Metals, 1986-2000. Mar. 1988, p. 107.
56. Steel, M. C. F. Changing Patterns of Platinum Metals Use in Autocatalyst. SAE Tech. Paper Series No. 880127, 1988, 9 pp.
57. Hull and Co. Hull Report on Heterogenous Catalyst System, 1989-2000. Jan. 1990, pp. 134-140.
58. Steel, M. C. F. Changing Patterns of Platinum Metals Use in Autocatalyst. SAE Tech. Paper Series No. 880127, 1988, 9 pp.
59. Hull and Co. Hull Report on Heterogenous Catalyst System, 1989-2000. Jan. 1990, 436 pp.
60. _____. Hull Report on Heterogenous Catalyst System, 1989-2000. Jan. 1990, 436 pp.
61. Engler, B. H., E. Koberstein, and H. Volker. Three-Way Catalysts Performance Using Minimized Rhodium Loadings. SAE Tech. Paper Series No. 872097, 1987, 7 pp.
62. Summers, J. C., W. B. Williamson, and M. G. Henk. Uses of Palladium in Automotive Emission Control Catalysts. SAE Tech. Paper Series No. 880281, 1988, 19 pp.
63. Summers, J. C., J. J. White, and W. B. Williamson. The Durability of Palladium Only Three-Way Automotive Emission Control Catalysts. SAE Tech. Paper Series No. 890794, 1989, 19 pp.
64. _____. The Durability of Palladium Only Three-Way Automotive Emission Control Catalyst. SAE Tech. Paper Series No. 890794, 1989, 19 pp.
65. Robbins, J. Converting the Public. Mater. Edge, No. 6, July-Aug. 1988, pp. 17-29.
66. Johnson Matthey (London, England). Platinum 1990, 64 pp.
67. Kreuzer, T. P. Catalytically Activated Diesel Traps. Paper in Platinum Group Metals Seminar 1985, ed. by E. D. Zysk (Proc. Platinum Group Metals Seminar 1985, Washington, DC). Int. Prec. Met. Inst., 1985, pp. 219-225.
68. Enga, B. E. Catalytic Filters Control Diesel Engine Exhaust. Platinum Met. Rev., v. 26, No. 2, 1982, pp. 50-57, 68.
69. Kreuzer, T. P. Catalytically Activated Diesel Traps. Paper in Platinum Group Metals Seminar 1985, ed. by E. D. Zysk (Proc. Platinum Group Metals Seminar 1985, Washington, DC). Int. Prec. Met. Inst., 1985, pp. 219-225.
70. Hull and Co. Report on Heterogenous Catalyst System, 1989-2000. Jan. 1990, 436 pp.
71. Harrison, B., A. F. Diwell, and M. Wyatt. Controlling Nitrogen Oxide Emissions From Industrial Sources. Platinum Met. Rev., v. 29, No. 2, 1985, pp. 50-56.
72. Budd, A. E. R. Injection Molding Fumes Purified. Platinum Met. Rev., v. 24, No. 1, 1980, 12 pp.
73. Hull and Co. Hull Report on Heterogenous Catalyst System, 1989-2000. Jan. 1990, 436 pp.
74. _____. Hull Report on Platinum Group Metals, 1986-2000. Mar. 1988, p. 304.
75. Johnson Matthey (London, England). Platinum 1989, 64 pp.
76. _____. Platinum 1989, 64 pp.
77. Hull and Co. Hull Report on Platinum Group Metals, 1986-2000. Mar. 1988, pp. 173-227.
78. _____. Hull Report on Heterogenous Catalyst System, 1989-2000. Jan. 1990, 436 pp.
79. _____. Hull Report on Platinum Group Metals, 1986-2000. Mar. 1988, p. 182.
80. Loebenstein, J. R. Platinum-Group Metals. Ch. in Mineral Facts and Problems, 1985 Edition. BuMines B 675, 1985, pp. 595-616.
81. Rosewicz, B., and Koenig, R. How Clean-Air Bill Will Force DuPont Into Costly Moves. Wall Street Journal (New York), May 25, 1990, p. A1.
82. Hull and Co. Hull Report on Platinum Group Metals, 1986-2000. Mar. 1988, pp. 132-133.
83. Holusha, J. Interest in Fuel Cells Rises Again. New York Times, July 26, 1989, pp. D-1.
84. Wright, M. K. Westinghouse Phosphoric Acid Fuel Cell Program With Emphasis on Platinum Requirements. Paper in Precious Metals 1986 (Proc. 10th Int. Prec. Met. Inst. Conf., Lake Tahoe, NV, June 9-12, 1986). Int. Prec. Met. Inst., 1986, pp. 341-346.
85. Davidoff, R. L. Supply Analysis Model. BuMines IC 8820, 1980, 45 pp.
86. Mining Journal. Lebowa Concludes Third Agreement. V. 313, No. 8045, Nov. 10, 1989, p. 395.
87. Johnson Matthey (London, England). Platinum 1990, 64 pp.
88. Lebowa Platinum Mines Ltd. Circular to Members of Lebowa Plats and Notice of General Meeting. June 10, 1988, 11 pp.
89. Mining Journal. Impala Gains in Interim. V. 314, No. 8057, Feb. 9, 1990, p. 115.
90. Ritchie, D. Platinum Mining—A New Arrow in the Quiver. Fergusson Bros., Hall, Stewart & Co. Inc. (South Africa), Dec. 1987, pp. 3.
91. Johnson Matthey (London, England). Platinum 1990, p. 15.
92. _____. Platinum 1990, p. 15.
93. _____. Platinum 1989, p. 19.
94. _____. Platinum 1989, p. 19.
95. Madeyski, M. Northam Platinum Limited. Met. and Mater., Fergusson Bros., Hall, Stewart & Co. Inc. (South Africa), July 1988, 15 pp.
96. Ritchie, D. Barplats Investments Limited. Met. and Mater., Fergusson Bros., Hall, Stewart & Co. Inc. (South Africa), Nov. 1987, 15 pp.
97. Johnson Matthey (London, England). Platinum 1985, p. 19.
98. Mining Magazine. Progress at Lac des Iles Pt-Pa Project. V. 157, No. 9, pp. 191.
99. Fechner, S. A. Bureau of Mines Mineral Investigation of the Goodnews Bay Mining District, Alaska. BuMines OFR 1-88, 1988, pp. 230.

100. North American Platinum Mining Journal (London). V. 312, No. 8001, Jan. 6, 1990, p. 3.
101. Walenga, K. Stillwater Expanding Mining, Seeking Permit for Smelter. Southwestern Pay Dirt. May 1989, p. 24A.
102. Mining Record. Stillwater Expansion. V. 101, No. 19, May 9, 1990, p. 1.
103. Johnson Matthey (London, England). Platinum 1990, 64 pp.
104. Hoffman, J. E. Recovery of Platinum Group Metals From Automotive Catalysts. Paper in Precious and Rare Metal Technologies, ed. by Torma, A. E., and I. H. Gundiler. Elsevier, 1989, pp. 345-363.
105. Hull and Co. Hull Report on Heterogenous Catalyst System, 1989-2000. Jan. 1990, 436 pp.
106. Russell, D. The Development and Exploitation of the UG2 Reef in the Bushveld Igneous Complex. Paper in Platinum Group Metals and the Quality of Life, ed. by A. A. Austin, C. M. Barnard, and G. E. Haslam (Proc. Seminar Int. Precious Met. Inst., Las Vegas, NV, Jan. 29-31, 1989). Int. Precious Met. Inst., 1989, pp. 119-130.

APPENDIX A.—PGM DEMAND AND USES

PGM are used in a wide variety of applications. Platinum, the most important metal in the group, is used in environmental applications (notably autocatalysts) as well as jewelry, chemical, electrical, glass, petroleum, and dental applications. In addition, platinum has generated significant interest in the investment sector in the last 6 yr. Palladium is used primarily in autocatalyst, dental, electrical, and jewelry applications. Rhodium, the highest value metal of the PGM, is used primarily in autocatalyst, chemical, electrical, and glass applications. The minor PGM, ruthenium, osmium, and iridium, are used primarily in the electrical, dental, and chemical industries.

The United States consumed more than 2.5 Moz of PGM in 1989 as shown in table A-1. The predominant uses were in autocatalyst and in electrical and dental/medical applications.

ENVIRONMENTAL APPLICATIONS

Environmental uses of PGM are some of the most critical applications of these metals and appear to have the greatest potential for expanded use. These applications fall into the following areas: autocatalyst use, diesel emissions control, and stationary emissions control.

Autocatalysts

The predominant use for PGM is for internal combustion engine emissions control. In the United States, legislated automotive emission control standards began in 1966 and were satisfied for nearly 10 yr by the use of engine modifications. By 1975, the new standards could only be achieved by the use of PGM catalytic converters.¹ Since that time, several revisions of the standards have increased the type and complexity of engine modifications² and the amounts and types of the catalysts used. Although extensive research has been conducted, no other catalysts have been able to achieve the same results as the PGM. The PGM three-way catalyst (TWC) is used to control the amount of carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxides (NO_x) produced from the internal combustion engine. The term "three-way" refers to the three

gas pollutants: CO, HC, and NO_x. The CO is converted to carbon dioxide, the HC is converted to water and carbon dioxide, and the NO_x are converted to nitrogen gas and carbon monoxide (48).³ The TWC can contain either a mixture of platinum, palladium, and rhodium or a mixture of platinum and rhodium. The use of unleaded gasoline⁴ (49) is required when used with autocatalysts that contain PGM. Both palladium and platinum are subject to deactivation (or poisoning) when used with leaded gasoline⁵ (50, 51). Platinum is much less susceptible than palladium to the detrimental effects of leaded gasoline residues. With the complete phaseout of leaded gasoline⁶ (e.g., no residues left in tanks, pipelines, etc.), the automotive industry may be able to increase the palladium loading in autocatalysts. Otherwise, the converter would not be able to meet required durability and emission requirements as set by Federal and State authorities.

The catalysts used prior to 1981 used a mixture of platinum and palladium. On average, each converter contained 0.036 oz platinum and 0.014 oz palladium. Beginning in 1981, the TWC, consisting of a mixture of platinum, palladium, and rhodium, was introduced. On average, each catalyst was believed to contain approximately 0.0836 oz platinum, 0.0107 oz palladium, and 0.0057 oz rhodium (52, 53). The catalytic converters used by General Motors from 1981 to 1985 contained from 0.05 to 0.1 oz of platinum, 0.02 oz of palladium, and 0.004 to 0.009 oz of rhodium. The typical loading was 0.05 oz platinum, 0.02 oz palladium, and 0.005 oz rhodium (54). Each catalyst manufacturer keeps confidential the exact mix of platinum, palladium, and rhodium; the type of washcoat; and the method used to apply the PGM.

A catalytic converter is composed of several different components: the PGM loading, the washcoat, the substrate, and the canister. The washcoat consists of an alumina coating to which the PGM salts are thermally bonded. The thermal stability of the alumina washcoat is critical in maintaining the life of the converter and the reactivity of the PGM. The substrate is the substance to which the washcoat and PGM are applied. The early converters consisted of ceramic pellets. For the most part,

¹The regulations do not specify the method the automotive manufacturer must use to meet the emission regulations. In most cases, the use of catalysts has proved the easiest method. Engine modifications were designed to improve fuel economy (also mandated) and to improve the operations of the catalysts. The choice of the catalyst is the responsibility of the manufacturer. However, the PGM have proved to be the only catalysts available that meet the emission regulations.

²Modifications include advanced carburetor systems, fuel injection systems, computer-controlled air-fuel mixtures, electronic controlled ignition, "lean burn" engine technology, etc.

³Italic numbers in parenthesis refer to items in the list of references proceeding appendix A.

⁴The mandatory use of unleaded gasoline has had a significant environmental side effect. The use of leaded gasoline caused elevated lead levels in both urban and suburban areas, especially near major roadways. With the phaseout of leaded gasoline, there has been a marked decrease in blood lead levels in the populations (53).

⁵Platinum and palladium are also susceptible to poisoning by phosphorus derived from motor oil (54, 55).

⁶Leaded gasoline residue also impacts the catalytic converter recycling industry as discussed in the recycling section.

pelletized catalysts have been replaced with monolith-type catalysts composed of cordierite (magnesium aluminum silicate). The interior structure of each monolith consists of square- or triangular-shaped cells arranged in a honey-comblike pattern. This provides a better gas/catalyst contact with a lower pressure drop than do the pellet-type

catalysts (55). The monolith-type catalysts have also shown better thermal stability and performance and are smaller than the pellet-type catalysts (56). The pelletized and monolith catalysts are believed to contain approximately the same amount of PGM. The canister enclosing the catalyst is commonly made of 409 stainless steel.

Table A-1.—Domestic PGM sales, 1989

Consuming industry ¹	Unit of measure ²	Platinum	Palladium	Iridium	Osmium	Rhodium	Ruthenium	Total
Automotive ³	Oz	603,597	157,088	0	0	63,723	0	824,408
Chemical	Oz	77,933	61,826	3,054	0	6,076	836	149,726
Dental-medical	Oz	20,319	270,837	3,376	1,833	32	482	296,880
Electrical	Oz	125,195	557,879	3,601	0	8,745	57,164	752,584
Glass	Oz	36,330	5,819	0	0	5,691	32	47,872
Jewelry	Oz	13,439	5,755	225	0	6,591	193	26,203
Petroleum	Oz	91,919	81,759	0	0	868	0	174,546
Miscellaneous	Oz	114,649	121,723	2,604	0	8,777	1,961	135,065
Total consumption	Oz	968,733	1,262,687	12,860	1,833	100,503	60,668	2,407,284
Average price	\$/oz	\$507	\$144	\$303	\$549	\$1,300	\$62	NAp
DISTRIBUTION BASED ON CONSUMPTION ⁴								
Automotive ³	Pct	62.3	12.4	0.0	0.0	63.4	0.0	34.2
Chemical	Pct	8.0	4.9	23.7	0.0	6.0	1.4	6.2
Dental-medical	Pct	2.1	21.4	26.3	100.0	0.0	0.8	12.3
Electrical	Pct	12.9	44.2	28.0	0.0	8.7	94.2	31.3
Glass	Pct	3.8	0.5	0.0	0.0	5.7	0.1	2.0
Jewelry	Pct	1.4	0.5	1.8	0.0	6.6	0.3	1.1
Petroleum	Pct	9.5	6.5	0.0	0.0	0.9	0.0	7.3
Miscellaneous	Pct	0.0	9.6	20.3	0.0	8.7	3.2	5.6
Total	Pct	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total value PGM sales	Thousand dollars	491,148	181,827	3,897	1,006	130,654	3,761	812,293
OF WHICH:								
Automotive ³	Thousand dollars	306,024	22,621	0	0	82,839	0	411,484
Chemical	..do.	39,512	8,903	925	0	7,899	52	57,292
Dental-medical	..do.	10,302	39,001	1,023	1,006	42	30	51,403
Electrical	..do.	63,474	80,335	1,091	0	11,368	3,544	159,812
Glass	..do.	18,419	838	0	0	7,398	2	26,657
Jewelry	..do.	6,814	829	68	0	8,568	12	16,291
Petroleum	..do.	46,603	11,773	0	0	1,128	0	59,505
Miscellaneous	..do.	0	17,528	789	0	11,410	122	29,849
DISTRIBUTION BASED ON VALUE ⁵								
Automotive ³	Pct	37.7	2.8	0.0	0.0	10.2	0.0	50.7
Chemical	Pct	4.9	1.1	0.1	0.0	1.0	0.0	7.1
Dental-medical	Pct	1.3	4.8	0.1	0.1	0.0	0.0	6.3
Electrical	Pct	7.8	9.9	0.1	0.0	1.4	0.4	19.7
Glass	Pct	2.3	0.1	0.0	0.0	0.9	0.0	3.3
Jewelry	Pct	0.8	0.1	0.0	0.0	1.1	0.0	2.0
Petroleum	Pct	5.7	1.4	0.0	0.0	0.1	0.0	7.3
Miscellaneous	Pct	0.0	2.2	0.1	0.0	1.4	0.0	3.7
Total	Pct	60.5	22.4	0.5	0.1	16.1	0.5	100.0

NAp Not applicable.

¹Investment demand is not included.

²Converted from kg using 32.1507 oz per kg.

³Platinum, palladium, and rhodium sales to the automotive industry are estimated based on U.S. light truck sales and U.S. automobile production.

⁴Amount of metal used in each application divided by total amount of each metal consumed.

⁵Dollar value for each metal and application divided by total value of all PGM sales.

Source: Loebeinstein, J. R. Platinum-Group Metals. Ch. in BuMinerals Minerals Yearbook, 1989, v. 1, pp. 789-799.

The use of emission regulations to control gasoline-powered internal combustion engines vary from country to country. They can also vary within a country as shown by the much stricter California State regulations in the United States. Some current worldwide regulations are shown in table A-2.

Table A-2.—Gasoline-powered passenger automobile emission control standards, 1990, maximum emissions¹

Country and specification	Effluent			Units
	CO	HC	NO _x	
United States	3.4	0.41	1.0	g/mile.
United States, California	3.4	0.25	0.4	g/mile.
Canada	3.4	0.41	1.0	g/mile.
Japan ² (10 mode)	2.1	0.25	0.3	g/km.
Japan (11 mode)	60.0	7.00	4.4	g/test.
European Community:				
>2 liters ³	25.0	3.00	3.5	g/test.
1.4-2.0l	30.0	4.00	(⁴)	g/test.
<1.4l	45.0	9.00	6.0	g/test.

¹Each country establishes its own test cycle. These cycles are a timed test that specify a hot or cold start and periods of acceleration, deceleration, and cruising.

²For practical purposes, these standards are considered equivalent to U.S. standards.

³Engine displacement.

⁴Total HC + NO_x must be less than 8.0 g/test.

Countries that do, or will, require a TWC and advanced engine fuel system design include the United States; Canada; Mexico; Austria; Finland; Norway; Sweden; Switzerland; the EC countries of the Republic of Germany, France, United Kingdom, Italy, Spain, Netherlands, Belgium, Denmark, Portugal, Ireland, Greece, and Luxembourg; Japan; Taiwan; Brazil; and Australia (57). Brazil will require TWC's by 1997. Australia requires only oxidation catalysts. Eastern European countries, the U.S.S.R., New Zealand, and South Africa currently require only engine modifications. Automotive emissions in the remainder of the world are essentially uncontrolled.

Changes in emission regulations in future years will impact the amount of PGM used in autocatalysts. The first major change will be the expansion of the regulations to include countries that do not currently require the use of catalysts to control emissions (in particular, for industrial plant emissions). It is evident that the growing environmental awareness in Eastern Europe will require stricter emission controls. The reunification of East and West Germany may serve to act as the prototype case for the imposition of strict emission controls into Eastern Europe. However, this will be dependent on the priorities each country's government sets on addressing the various pollution problems.

The second major change will be the increasing strictness of the regulations. Stricter controls may require the

use of increased PGM loadings in the catalytic converters. The increasing influence of the environmental community in Western Europe may require even more stringent emission controls than those now imposed⁷ (58). In the United States, California generally has much more stringent laws than the remainder of the United States. However, these regulations have been imposed across the United States after a 1- to 2-yr lag. It is also feasible that stricter standards will be instituted on certain high-pollution regions of the country such as the large northeastern urban areas.

Conversely, there is considerable debate over the effectiveness of further regulation. It is reported that current engine technology and catalytic converters remove as much as 96 pct of the total pollutant load (59). Any further improvements in technology would be very expensive and would show only marginal gains in pollution reduction. Emphasis may shift to alternate fuels, alternate power sources, strictly enforced mandatory vehicle testing, mandatory driving restrictions, and emphasis on mass transit. Some of the alternate fuels would also require the use of PGM-base catalysts. One of the more promising alternate power sources is the fuel cell that would also require PGM.

Much research has been done in reducing the cost of the PGM in catalytic converters by varying, reducing, or eliminating the type and quantity of PGM used in the converters. The controlling factor is the need to meet durability and emission requirements. This research has been concentrated in the areas of washcoat technology and elimination or reduction of the higher cost PGM. Research in washcoat technology has concentrated on improving the thermal stability of the washcoat, stabilizing the precious-metals dispersions, and reducing the interactions of the precious metals with the alumina contained in the washcoat. These effects are usually achieved by the addition of rare-earth additives, such as lanthanum and cerium, to the washcoat (60). Research in PGM loading has concentrated on reducing or eliminating the use of platinum and rhodium while increasing the use of palladium (61-63).

In December 1988, Ford Motor Co. disclosed the testing of a new type of emissions control device that does not use platinum. About 50,000 1989-model Ford Thunderbird and Mercury Cougar cars in California were fitted with the new converters. The announcement immediately depressed platinum prices on the futures market and bolstered the price of palladium, which some traders considered a possible substitute. The true significance of the announcement is in the flexibility it affords, both by

⁷There is considerable debate over the European test in that it is not representative of typical European driving conditions. It has been shown that a "clean car" is a major polluter at higher speeds. It is likely that the test will be modified in the near future (62).

allowing Ford to use a different mix of the three precious metals and by reducing the Nation's dependence on imports from South Africa. Cost reduction is another incentive to use palladium, which is about one-third of the platinum price. Palladium-only catalysts were compared to platinum and rhodium catalysts under a variety of operating conditions. Analysis of the results showed that the palladium catalyst was equivalent to the standard platinum plus rhodium catalyst, with the exception of a slight loss of control of nitrogen oxides. However, it must be noted that the palladium catalysts were loaded at 3.5 times the concentration of the platinum-containing catalyst (64). Therefore, the cost reduction objective of the palladium-only catalyst as a substitute was not clearly demonstrated. The flexibility of using palladium could take advantage of the abundant palladium resources of the U.S.S.R. and the Stillwater, United States, operation. With the implementation of converters for cars in EC, platinum applications for autocatalysts are likely to remain strong in the future (65).

Automotive use is the dominate consumer of PGM in the United States. Since 1980, the automotive industry has used an average of 60 pct of the platinum, 16 pct of the palladium, and almost 60 pct of the rhodium consumed in the United States. Table A-1 summarizes the amount consumed, the value, and percentage of use of PGM in the United States. In 1989, the value of PGM sales to the automotive industry was \$412 million, more than 47 pct of total PGM sales in the United States. On a worldwide basis, Johnson Matthey reported that the automotive industry used 1,450 Moz of platinum in 1989. However, the industry also returned 175 koz to the market for recycling (66). On a regional basis, North America roughly consumed 50 pct of the platinum used in catalysts, while the remainder was split roughly equally between Japan and the rest of the Western World. This split may shift in the near future toward Europe because of the introduction of strict emission controls. Worldwide palladium demand in 1989 in the automotive sector is estimated at 270 koz, with 75 koz returned to the market for recycling. North America is estimated to consume 61 pct, Japan consumes 34 pct, and the rest of the Western World is 5 pct. Again, this is expected to change with the introduction of pollution control regulations in Europe that require the use of autocatalysts.

Diesel Controls

Diesel engine combustion generates particulates⁸ in addition to hydrocarbons, carbon monoxide, and nitrogen

⁸Particulates, the sometime visible black smoke, are small soot particles composed primarily of carbon and a variety of solid and liquid hydrocarbons.

oxides (67). Particulate emission limits have been established for diesel-powered automobiles, light- and heavy-duty trucks, and buses. Two systems have been developed to eliminate particulates from the diesel exhaust-ceramic diesel traps and wire mesh filters (68, 69).

The systems work by filtering the particulates from the exhaust stream. The particulates may then be destroyed by burning (known as regenerating the filter). However, the temperature required (regeneration temperature) for the ignition of the trapped particulates is generally much higher than the normal operating temperature of the diesel engine. The regeneration can therefore be accomplished by increasing the operating temperature of the trap, reducing the temperature required for soot ignition, or a combination of both. The first method can be accomplished by increasing the engine operating temperature or utilizing a secondary heat source (i.e., electric heaters). Regeneration temperature can be reduced by the use of catalysts. The catalyst can promote the soot incineration, promote the conversion of exhaust gases, or a combination of both. PGM catalysts are used to reduce the regeneration temperature and to promote the conversion of other exhaust gases, in which the heat of reaction also promotes the regeneration.

A ceramic diesel trap (diesel particulate filter or DPF) is composed of a monolithic ceramic honeycomb that is porous and permeable to gases. The monolith is structured to trap the particulates on the cell walls. However, the collected particles would eventually plug the filter. The DPF must then be cleaned by burning off the trapped soot (known as regeneration), for which a PGM-containing catalyst is used.

The wire mesh filter trap consists of a mesh of stainless steel wire through which the exhaust gases pass. The wire acts as a substrate for an alumina-base washcoat that supports the PGM catalyst.

Stationary Sources

Growing environmental awareness of atmospheric pollution has lead to control of emissions from automobiles in many countries of the world. However, there are many stationary sources of atmospheric pollution such as electrical power station coal-fired boilers, industrial boilers, residential boilers, stationary engines, and residential fireplaces. Laws were enacted in most western countries to control sulfur dioxide (SO_x) emissions as a result of the concerns over acid rain. Similar concerns are being raised about NO_x. It is likely that mandated reductions on NO_x emissions will be enacted in the near future. PGM catalysts are adversely affected (poisoned) by emissions (primarily sulfur) associated with the combustion of fossil fuels utilized at these plants (70). However, if legislation requiring low sulfur fuels (resulting from further mandated requirements on SO_x reduction) is enacted, a large

market utilizing some type of PGM-base catalyst⁹ will likely develop (71).

Specialized PGM-base catalytic systems have been developed to control emissions of volatile organic compounds (VOC) or hydrocarbons used in various manufacturing processes (72, 73). A distinct advantage of catalytic oxidation is that the process temperatures are much lower than using flame incineration. Regulations to control this type of emissions have been enacted in high-pollution areas and will probably be enacted on a national level.

A final category of stationary emission control is the use of a platinum-base catalytic converter in woodburning stoves. The converter is used to reduce atmospheric pollution, improve burning efficiency, and reduce creosote accumulations (74). Local ordinances to control pollution may require the use of such devices.

At present, the markets for stationary control devices is fairly small. However, with increasing concern over emissions and the development of effective catalysts, the demand for PGM in this area has potential for rapid growth.

JEWELRY

Jewelry is the second largest application for platinum, with demand estimated at 1.3 Moz as indicated in table 1, an increase of 7 pct in 1988. Jewelry demand for the United States was 13 koz in 1989, which only accounted for 10.6 pct of total Western World platinum jewelry demand.

Japan accounted for 88 pct of total jewelry consumption at 1.1 Moz. Historical review of the development of the Japanese market would indicate that the jewelry demand has increased steadily every year since 1983. The Japanese people have demonstrated a cultural-based preference for white metal jewelry since the Edo period that began in 1603.

Platinum was introduced after the Meiji restoration in 1868, and the metal rapidly achieved a special position in the mind of the Japanese people that remains virtually unchanged over the years. During World War II, the use of platinum in jewelry in Japan occurred as a result of the nonavailability of gold (until 1973), as well as the success of promotional campaigns for diamond engagement rings set in platinum. Platinum combines high quality, prestige, and investment value to the Japanese people.

In addition to wedding and engagement rings, manufacturers were producing machine-made platinum chain in 1971, and that year platinum demand peaked at 1.06 Moz, a figure not equalled again until 1988. A slowing of

economic growth and a change in fashion left manufacturers overstocked in 1976, and demand declined, remaining on a plateau at about 840 koz for several years.

In 1984, the Platinum Guild in Tokyo began a product development program in association with jewelry manufacturers which has again broadened the appeal of platinum jewelry. The fastest growing product categories today are neck chains, pendants, and earrings; platinum jewelry is popular even without stones. The surge in 1987 is due to the strong Japanese currency against a weak U.S. dollar; platinum is relatively inexpensive in terms of the Japanese yen. During 1988, the manufacturers made determined efforts to design platinum into low-priced pieces to increase popularity among buyers of lower priced jewelry. One way of introducing platinum into this sector has been to combine it with gold. In 1988, approximately 45 pct of all jewelry pieces sold in Japan contained platinum. Although the proportions of gold and platinum in combination jewelry vary widely according to design, fashion, and price, the platinum component has grown in recent years.

In April 1989, tax changes in Japan removed the burden of a 15-pct commodity tax on all jewelry items retailing at more than 37,500 yen per piece. It is expected that younger, less affluent consumers will be able to afford platinum jewelry for the first time. The Japanese jewelry trade has a highly complex system of distribution, in which wholesalers play an important role. Wholesalers are, in some cases, refiners, manufacturers, or purchasers of metal and alloys for subcontract. The April 1989 tax changes also abolished the license required in order to become a retailer; therefore, small retailers and individuals may enter the jewelry trade in the coming years.

Innovative retailing techniques, similar to the gold jewelry trade in Hong Kong, are used in the marketing of platinum jewelry. Platinum items tend to be priced according to daily changes in the price of bullion, allowing the more price-conscious consumers to choose the moment for their purchase. Jewelry items are expressed as a fixed weight in grams, and the value can be easily determined by the customers themselves, using counter-top computers that are programmed with the latest bullion price. Both selling and buy-back prices in the "currency" are provided, illustrating the liquidity of the jewelry purchase.

The rest of the Western World, including Europe, has accounted for about 10 pct of the total jewelry demand every year. Platinum Guild International in Italy is strongly promoting the use of platinum to jewelry designers. A mass production method for hollow platinum chains will be utilized in the near future. Italy has a worldwide marketing network in the gold chain market; therefore, platinum chains may enjoy the same popularity when the Italian designers begin to use platinum.

⁹TWC's developed for mobile sources are not suitable for stationary sources because of the much higher oxygen levels in the flue gas.

INVESTMENT

Investment demand¹⁰ is relatively new to the platinum industry in the United States. From virtually no demand in 1980, the North American¹¹ demand rose to 30 koz in 1984, increased to 130 koz in 1985, and peaked at an unusually high 300 koz in 1986. This peak was the result of a 130-pct increase in the sales of small platinum bars and coins in the United States during a period of strong market growth. A return to previous levels occurred in 1987 and 1988 with a constant demand of 85 koz; demand dropped to an estimated 60 koz in 1989. The investment demand in 1986 accounted for 25 pct of total North American demand, while the 1989 investment demand accounted for only 7 pct.

Investment demand serves as a buffer between oversupply and undersupply. Four methods exist for investing in platinum and palladium: company stock, coins and medallions, bars, and futures. Investment via the purchase of jewelry was previously discussed in the Jewelry section of this appendix. There is no investment market for the minor PGM.

Investments in precious metals have been used as a store of value in uncertain times, as a hedge against inflation, or as a means to achieve capital gains. Gold and silver booms spurred the growth of the Western United States, and they continue to excite investor interest. Platinum, with a few minor exceptions, never was the cause of a large investment boom. Investing in PGM is relatively new to the general public. For many years, platinum was thought of as an industrial commodity; there was little public awareness and no practical means of investment for the majority of investors. New products, press attention, and aggressive marketing have led to a dramatic rise in the amount of investment.

Investment via purchase of common stock is one of the more traditional investment routes. The predominant mining stocks are South African corporations, which are traded on the Johannesburg or London exchanges. An American investor could face serious problems in logistics and currency fluctuations in a direct purchase of these stocks. To overcome the currency exchange problem, a financial instrument known as an American Depositary Receipt (ADR) was developed. An ADR is valued in American dollars and is sold on a per share basis, primarily traded over-the-counter (OTC). They are usually held by a bank that is acting as the company's representative and are relatively easy to trade. However, many investors will not trade in South African stocks because

of political considerations caused by the South African policy of apartheid. The only U.S.-based mining company currently involved in platinum mining, Stillwater Mining Company, is a jointly owned subsidiary of the Manville Corporation and Chevron Resources Corporation. Many companies in the United States, Canada, and Australia are currently involved in exploration for PGM. The larger companies' shares are usually traded on the major stock exchanges, while the smaller companies are traded on the OTC or so-called "penny stock" exchanges.

The easiest and most accessible method for investing in PGM is via the purchase of coins, medallions, or small bars. A bullion coin is considered legal tender by the country of issue; however, its face value is usually lower than the intrinsic value of the coin. Coins are commonly minted in one-, one-half-, one-quarter-, and one-tenth-troy-ounce sizes of 0.9995 fineness. The first contemporary platinum coin issued was the Noble, issued by the Isle of Man in 1983. Since that time, numerous coins have been issued, such as the Koala (Australia) and the Maple Leaf (Canada). A few palladium coins have also been issued, but they are not as popular as the platinum coins. Medallions vary from coins in that they are not considered legal tender. Several refiners have been successful in issuing 1-oz medallions.

Johnson Matthey has defined investing in bars as follows: Small bars are 10 oz and less, while large bars are 500 g and 1 kg. Small bars are marketed similar to coins and medallions, are issued by the major refiners, and are usually purchased by the smaller investor. The large bars are, by far, a Japanese phenomena. They are traded on a speculative basis and are purchased and sold depending, for the most part, on price fluctuations.

The trading of platinum and palladium futures contracts offers an alternate way to invest in precious-metals markets. The New York Mercantile Exchange (NYMEX) established a platinum futures contract in 1956 and a palladium futures contract in 1968. The platinum contract is based on a 50-oz lot, while the palladium contract is based on a 100-oz lot. Trading in both contracts has become extremely active during the past 10 yr as can be seen in figure A-1. The number of futures contracts traded is dependent upon currency fluctuations, investor fears, price speculation, political events, etc. The large number of platinum contracts traded in 1986 was in response to a rapid increase in the platinum price. The doubling in the number of palladium contracts traded in 1989 was in response to the announcement that a technique (dependent on palladium) for achieving cold fusion had been discovered.

The Tokyo Commodities Exchange (TOCOM) began trading 500 g platinum futures contracts in 1984. The fluctuations in the yen and Japanese stock market have caused a dramatic increase in the amount of trade on this exchange.

¹⁰U.S. investment demand data is not compiled by the U.S. Bureau of Mines. Demand numbers in this section are derived from Platinum 1990 (Johnson Matthey).

¹¹Johnson Matthey does not report a demand amount for just the U.S. but includes the amount in total North American demand.

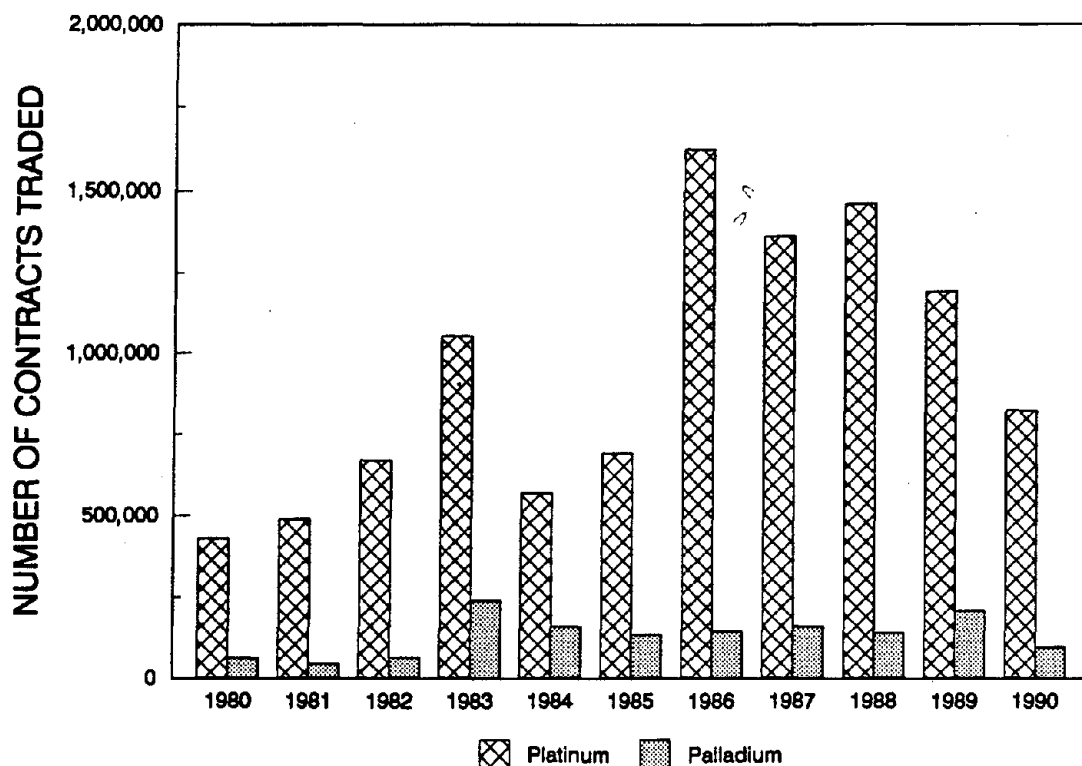


Figure A-1.—NYMEX yearly contract volumes.

Investment demand for platinum has gone from virtually nonexistent in the early 1980's to an important share of the market by the late 1980's (75). With the exception of the North American peak in 1986, Japan has accounted for the majority of worldwide investment demand. The remaining investment demand is usually split fairly equally between the United States and the rest of the Western World.

CHEMICAL

The PGM are used primarily for catalysts in the manufacture of chemicals. Minor uses are the manufacture of laboratory equipment and process equipment and controls for use in severe environments and production of miscellaneous compounds for use in electroplating. The predominant metal used is platinum, followed by palladium, ruthenium, rhodium, and iridium. Bureau of Mines statistics do not show any osmium use by the chemical industry. In 1989, chemical uses accounted for approximately 7 pct¹² of platinum demand, 5 pct of palladium demand, 24 pct of iridium demand, and 6 pct of rhodium

demand in the United States (table A-1). Based on average 1989 prices, more than \$57 million (6.6 pct of total sales) was spent by the chemical industry sector for PGM. It is important to note that this value is for new metal purchases only and does not include toll-refined metals.¹³ Based on the estimates by Johnson Matthey (76), approximately 30 to 40 pct of platinum demand for chemical applications is from the North American region, while 50 to 60 pct is for the "Rest of Western World." The Japanese demand is generally less than 10 pct.

The use of catalysts¹⁴ in the chemical industry can be divided into two categories, catalytic oxidation and organic

¹³A chemical producer will return spent catalysts for new catalysts. This amount of metal will not be reported in consumption numbers. New catalysts will only be purchased to replace process losses. Large demand for new catalysts will only occur during new plant construction or expansion that are dependent on worldwide economic trends. In times of rapid growth, demand will increase significantly; during times of economic contractions, large amounts of metal may enter the secondary market because of closure of excess capacity.

¹⁴Catalysts can be classified as heterogenous or homogenous. The heterogenous catalyst occurs in a different physical form than the other reactants; i.e., a solid catalyst reacting with a gas or liquid. The catalyst can be either self-supporting or used as a coating on a carrier matrix. The homogenous catalyst can be either a powder or liquid and is mixed directly with the other reactants.

¹²Percentages are exclusive of investment demand.

hydrogenation.¹⁵ Catalytic oxidation reactions are used in the production of nitric acid, hydrogen cyanide, hydrogen peroxide, and vinyl acetate (77, 78). Hydrogenation processes include the production of cyclohexane, ethylene and propylene, caprolactam, and aniline.

The most important oxidation reaction is the production of nitric acid from ammonia. Nitric acid is used in the production of ammonium nitrate fertilizer, explosives, and feedstocks for various plastics. The catalyst used is a wire gauze screen made from an alloy of 90 to 95 pct platinum and 5 to 10 pct palladium and/or rhodium (79). Palladium is becoming more popular because of the higher cost of rhodium. The catalyst used in the production of hydrogen cyanide (used in the production of various plastic feedstocks) is a wire gauze screen made from an alloy of 90 pct platinum and 10 pct ruthenium. The production of hydrogen peroxide is based on a palladium catalyst. The production of vinyl acetate (used in the production of various plastic feedstocks) is also based on a palladium catalyst.

Catalysts used in organic hydrogenation include supported and unsupported catalysts of copper, chromite, nickel, cobalt, platinum, and palladium. Some multistage processes require a different type of catalyst at each stage of the process. Cyclohexane, primarily used in the production of caprolactam, can be produced using a nickel catalyst or platinum catalyst. Caprolactam, used to produce specialty nylons and engineering plastics, is produced using a palladium catalyst. Ethylene and propylene are used as feedstocks for many other chemical products and are produced using a palladium catalyst (alternative catalysts of nickel-cobalt-molybdenum may be used). Aniline, a chemical feedstock, is produced in a two-stage process using a copper catalyst followed by a palladium catalyst. The manufacture of pharmaceutical and fine chemicals employs platinum, palladium, and ruthenium catalysts in various hydrogenation processes.

ELECTRICAL-ELECTRONIC

The PGM are used in electrical contacts, film circuits, capacitors, and thermocouples. The most predominant metal used is palladium, followed by platinum, ruthenium, rhodium, and iridium. In 1989, electrical applications accounted for 1.7 Moz or 49 pct of total Western World palladium consumption (refer back to table 2). Demand for platinum by the electrical industry was estimated at 195 koz or 5.5 pct of total Western World consumption. Approximately 51 pct (89 koz) of the ruthenium demand in the Western World was consumed by this

industry. Ruthenium is a key ingredient of resistor tracks in hybrid integrated circuits.

In the United States, electrical uses accounted for approximately 12 pct of platinum demand, 44 pct of palladium demand, 94 pct of ruthenium demand, 9 pct of rhodium demand, and 28 pct of iridium demand. Electrical and electronic applications for platinum are in two major categories: thin and thick film circuits and thermocouples and heating elements. Thin film technology involves the fabrication of circuits by vacuum deposition or sputtering. The silicide layer is formed in situ by sputtering a thin platinum layer onto the silicon surface followed by sintering at 650° C. These silicon chips are used in sensing, display, and integrated circuit technology. Thick films of platinum are used in gas sensing and monitoring equipment and to form contact surfaces on silicon and gallium arsenide wafers.

Thermocouples are the largest single use for platinum in the electrical application. The ability of platinum to resist oxidation attack at very high temperatures is crucial in high-temperature measuring systems and for furnace and heater windings. Platinum is frequently alloyed with rhodium at levels of 10 to 13 pct for temperatures up to 1,600° C. Increasing the rhodium content to 40 pct allows for higher operating levels, up to 1,850° C. Platinum and platinum-rhodium alloys are used as electrical resistance heating elements, with such applications as windings for muffler furnaces, sealing devices, hot wire ignition systems, nylon cutters, and even cigarette lighters.

The Western World electrical sector demand pattern for platinum has decreased from 240 koz in 1979 to 195 koz in 1989. Approximately 60 pct of total application is in the electronics sector. The decrease is a result of the development of new thin film sputtering technologies for the production of chips that required only a minute amount of platinum. In the United States, electrical sector consumption of PGM is related to general economic cycles. Consequently, electrical application bottomed out in 1987 at 58,500 oz but increased to 125,200 oz in 1989.

The expansion of the steel industry in Japan has resulted in a steady growth of platinum consumption in thermocouples; platinum demand of 15 koz in 1979 has expanded 200 pct to 45 koz in 1986 and has remained at this level for the last 4 yr. Demand for the rest of the Western World, including Europe, has varied between 50 koz and 100 koz in the past decade.

Palladium and palladium alloys are widely used in capacitors, electrical contacts, and connectors. Capacitor production represents the largest use for palladium. In ceramic capacitors, a metal layer is applied to an underlying ceramic base. The metal provides the necessary conductor effect, and the ceramic base provides the capacitor effect. Various processes are utilized to coat the metal onto the base, including a silk screen approach, in which

¹⁵Hydrogenation is a chemical reaction that adds molecular hydrogen to organic compounds. Hydrogenolysis is a similar chemical reaction that splits a molecule by combination with hydrogen.

metals are coated on in the form of inks, and electroplating. Coatings are usually applied in several layers on the ceramic base, and the devices are referred to as multi-layered ceramic capacitors (MLCC) in the electronics industry. The introduction of solid-state switching systems has reduced the demand for palladium relay switches used in telephone switching systems.

Gold, for many years, has been the dominant metal used for the electronic contacts in printed circuit boards. The use of palladium as a substitute for gold exhibits better compatibility with board materials and adhesives, better resistance to sliding wear from contact engagement and separation, and is about one-half the density of gold. The decline in relay switch usage is offset by the dramatic growth in the use of printed circuit boards in the electronics industry in recent years. The use of palladium in connectors, the interconnecting contacts to join circuit boards, has also grown substantially. It is expected that the growth trend in the electronics industry will account for an increasing share of the platinum and palladium demand in the future, with the more traditional uses becoming less important. In 1989, electrical application of palladium accounted for 1.7 Moz or 50 pct of total Western World palladium consumption. Japan is the major consumer at 980 koz and the United States is second at 558 koz.

In the electronics industry, palladium and palladium-base materials have substituted for gold in contacts for separable electronic connectors since 1984. Two major uses of palladium in electronics are in MLCC and in thick film hybrid integrated circuits (HIC). At present, most MLCC measure 2 mm by 1.5 mm or smaller. However, capacitors measuring 1.6 mm by 0.8 mm are expected to become the standard, and even smaller devices are in prospect to meet the trend to miniaturize consumer goods. Manufacturers have tried to substitute a portion of the palladium with silver or base metals in order to reduce costs. In the HIC, surface-mount printed circuit boards, which do not require printed palladium conductor tracks, are increasingly being preferred for the manufacture of video cameras, video recorders, and computers.

Platinum-cobalt magnets are used to power miniaturized instruments and are used in high-power electronic tubes in communication equipment. Platinum-containing electrodes are used in the control of algae and slime in industrial piping and other equipment.

GLASS

PGM are used in the glass industry in two major areas: manufacture of various specialty glasses and manufacture of glass fibers. Glass is produced at about 1,400° C under oxidizing conditions. The high-temperature stability of platinum and platinum-rhodium alloy and their resistance

to chemical attack are important factors in preventing the introduction of impurities into the glass melt. Platinum is usually purchased at 99.95 pct purity and rhodium at 99.8 pct or better. In the glass application, large initial amounts of PGM are needed for new manufacturing facilities, but only minimal quantities are subsequently needed to compensate for operating losses. Recycled PGM are usually toll refined.

Specialty glass manufacture uses platinum in melting tanks, stirrers, and crucibles for the manufacturing of optical glass, faceplates used in television sets, cathode ray tube display units, and various types of chemical laboratory ware for single crystal growth. For high-temperature strength, a platinum-rhodium alloy is used. Consumption for developed areas of Europe, Japan, and North America has remained the same during the past few years. Recent growth has been focused on the Far East and South America by establishing joint ventures to build new production plants for TV tube production for large-screen televisions.

A platinum-rhodium alloy is used in the bushings through which the molten glass fibers are drawn and other process areas including melting tanks, piping, and stirrers. The weight of each bushing is usually in the 2 kg to 10 kg range. In normal operation, bushing metal is lost because of evaporation and diffusion. Glass fibers are used mainly as reinforcing material in textiles and as insulating material in building construction and printed circuit boards. Production of glass-reinforced materials, including telegraph poles, various sporting goods, and automobiles, have increased demand for platinum in the glass industry.

In the manufacture of optical fibers, raw materials are first melted in a platinum crucible from which rods are drawn. The rods are then fed into a double crucible for fiber manufacture. Optical fibers resist moisture, prevent signal attenuation, and minimize radiation and scattering losses; therefore, optical fibers are most ideal for cable communication.

The Western World glass demand for platinum peaked in 1979 at 250 koz and has varied between 85 koz in 1982 and 140 koz in 1989 in 4-yr cycles. In 1989, Japan accounted for approximately 32 pct, and the United States accounted for 26 pct, of total Western World demand for glass applications. The expansion of the television glass in the developing countries and new applications for glass-reinforced materials resulted in the high overall demand in 1989.

PETROLEUM

The petroleum industry is dependent upon the operation of various PGM catalysts to improve the amount of gasoline (and high-octane blend stocks) produced. There are important regional differences in the refining industry,

based on the type of crude oil available to a given refinery and the mix of product wanted (gasoline versus fuel oil). Demand for the catalytic agents also changes with the amount of refining capacity (which is directly tied to the demand for motor gasoline). The trend toward using "heavier" crudes (resulting from the worldwide depletion of light sweet crudes) could potentially increase the demand for catalysts.

Within the petroleum refining industry, approximately 97 pct of the PGM in petroleum refining catalysts is recycled into new catalysts (80). Therefore, the demand for new catalysts is for replacing processing losses and for installing new units¹⁶ (81). Conversely, during closure of capacity, excess PGM may be placed back into the market, which happened in the mid-1980's (tables 1-3) in areas outside of the United States. U.S. demand for PGM catalysts rose from 60 koz in 1987 to 175 koz in 1989. Catalyst demand usually ranges from 2 pct to 8 pct of total U.S. demand. Value of sales to the petroleum industry rose from \$15 million in 1987 to \$60 million in 1989. On a worldwide basis, petroleum demand has generally accounted for less than 2 pct of worldwide demand.

The most important processes utilizing PGM catalysts are catalytic reforming, hydrocracking, and isomerization. The catalytic reforming process is the most important of these and uses the majority of the PGM.

Catalytic reforming is used to upgrade lower octane feedstocks to high-octane gasoline blend stocks. This process became more important with the widespread use of unleaded¹⁷ gasoline. With the introduction of environmental controls in the European market, the European refining industry may be required to modernize or retrofit much of its refining capacity in order to produce more unleaded gasoline. The type of catalyst used can either be a monometallic platinum catalyst or a bimetallic platinum-iridium or platinum-rhenium catalyst. The bimetallic catalyst offers a much longer service life. The United States is believed to use only bimetallic catalysts (82).

The hydrocracking process is used to increase the quantity of gasoline (relative to the amount of fuel oil) produced from each barrel of crude oil. This is especially

important with the current trend toward the "heavier" crude oil available for refining. It can also be used to seasonally adjust the amount of gasoline produced. A related process, hydrotreating, is used to process the feedstocks for catalytic cracking. The type of catalyst used in hydrocracking can either be a palladium-base catalyst or a nickel or nickel-tungsten catalyst.

Isomerization is used to produce octane-improving blend stocks for gasoline (usually isobutane) and to improve the antiknock characteristics of the lighter fractions of gasoline blend stocks. Isomerization is similar to hydrocracking in that either a platinum-base catalyst or a nickel-base catalyst can be used.

DENTAL AND MEDICAL

Dental and medical demand data is included in the "Others" category in tables 1, 2, and 3. In dental applications, a small amount of platinum is added to gold alloys as a hardening agent. Palladium alloys are gaining acceptance at the expense of gold alloys as the major component in braces, crowns, and other forms of tooth restoration because of their lower cost. Consequently, platinum consumption for dental applications in the United States is decreasing.

In medical applications, the anticancer drug Cisplatin, which contains ultrapure platinum, has been used for treatment of testicular and ovarian cancers. Research by the U.S. National Cancer Institute found complete remissions were achieved in 70 pct of patients suffering from testicular cancer who were treated with Cisplatin in conjunction with other cancer-fighting drugs. Cisplatin has deleterious side effects that prevent its acceptance as a common drug. The development of a second-generation drug of much lower toxicity, Carboplatin, has been licensed in the United Kingdom, Canada, and other European countries.

During the past decade, the U.S. platinum consumption level ranged between 15 koz and 26 koz, and the palladium consumption varied between 213 koz and 347 koz. In 1989, dental and medical applications composed less than 2 pct of the platinum and 21 pct of palladium consumption in the United States. The total Western World demand in dental and medical demand is not available.

MISCELLANEOUS

Platinum demand in fuel cells and environmental research programs is included in the miscellaneous category, which composed approximately 10 pct of total United States platinum demand in 1989.

Increasing concern with atmospheric pollution and the awareness of the environmental costs resulting from the use of fossil fuels have enhanced the developments in fuel cell technology. Fuel cells have a number of advantages to conventional power sources. They provide an efficient

¹⁶A provision of the Clean Air Act undergoing debate in Congress may require the production and sales of a "reformulated" gasoline in certain areas of the country. All gasolines have enough common properties to be sold as a common product, but they do have differences in composition that arise from the type of crude and refinery used to produce them. Requiring a reformulated or "one-formula" gasoline may make the refining process much more difficult. The petroleum industry has estimated up to one-third of the Nation's refineries may be closed, thereby returning a large amount of PGM back into the market. Refineries would have to be built or expanded to replace lost capacity, thereby requiring a large amount of PGM. The new process units needed may also require higher loadings of PGM-base catalysts.

¹⁷Tetraethyl lead, commonly known as TEL, was previously used to increase the octane of gasoline. This use has been, for the most part, eliminated by Environmental Protection Agency regulations.

power source, fuel cell electrodes are recyclable, they have the ability to use a variety of hydrogen-rich fuel sources, and fuel cells are environmentally clean.

The fuel cell was discovered in 1839 by Professor Sir William Grove while working at the London Institution. When carrying out experiments to dissociate water into its component hydrogen and oxygen gases by electrolyzing dilute sulfuric acid between platinum electrodes, he discovered that the process was reversible. The two gases readily combined to form water and in the process generated an electric current. In the 1950's and 1960's, the American space program used liquid hydrogen and oxygen, already carried on the spacecraft, to develop an on-board power source utilizing fuel cell technology.

The first commercially available fuel cell units are based on the use of phosphoric acid as an electrolyte and operate at 205° C. A subsidiary of United Technologies, International Fuel Cell Corporation, has received orders for 53 200-kW systems, each using a small but vital amount of platinum (83). A 200-kW generator could supply enough power to serve a 30-unit apartment building or small factory.

A number of different types of fuel cells are under development that utilize platinum electrodes. These

include the phosphoric acid fuel cell (PAFC) used for on-site generation of power for utilities, the alkaline fuel cell with potential aerospace and transport applications, the proton membrane (PEM) utilized for mobile power sources for aerospace and defense, and the direct methanol fuel cells for mobile power sources.

The average platinum loading for the electrodes varies from 0.25 mg/cm² to 4 mg/cm². The current cell performance is an average of 5 g of platinum per kW of generating capacity. This would equal approximately 1 kg of platinum for each 200-kW generator. Once installed, the platinum electrodes could be recycled, and therefore operating costs could be kept down.

The Westinghouse Company's industry projections estimate PAFC costs could be \$1,000/kW installed (84). However, other estimates suggest early fuel cells may cost as much as \$1,500 to \$2,000/kW. This points to the major hurdle facing fuel cell acceptance—high cost. In order for fuel cells to be a competitive alternative to fossil fuels, the cost of fuel cells needs to be between \$800 and \$1,000/kW. However, for remote areas and emergency power sources, this technology is feasible today even at the higher costs.

APPENDIX B.—METHODOLOGIES

The methodology of this updated study is different from the previous availability study (1) in three major aspects. Price proportion factors¹ were derived for platinum, palladium, rhodium, and gold to allow the results of the economic analyses to be on a common, market-oriented basis. Bureau of Mines personnel visited South Africa and Canada for data collection. Data and literature were obtained from the visits to mines, smelters, corporate and government offices, and from a variety of other sources.

The mine and mill operating costs estimates for this study have been based on complete extraction of the demonstrated resource for the specific property being analyzed. As such, this study's operating costs estimates should be viewed as the average longrun operating costs for extracting a specific resource tonnage. Therefore, they include both variable (direct) and fixed (indirect) charges. Variable (direct) operating costs include charges for materials, utilities, direct and maintenance labor, and payroll overhead. Fixed (indirect) operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research. Other costs in the analysis are fixed charges that mainly include local taxes, insurance, depreciation, and deferred expenses.

Capital expenditures were calculated for exploration, acquisition, development, mine plant and equipment, constructing and equipping the mill plant, and all necessary reinvestment. Capital expenditures for mining and processing facilities include the costs of mobile and stationary equipment, construction, engineering, facilities and utilities (infrastructure), and working capital. The facilities and utilities category includes the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance. For this study, working capital was estimated as 2 to 3 months of operating costs.

After capital and operating costs are determined, deposit data are entered into the Supply Availability Model (SAM)² (85). The Bureau developed the SAM methodology to perform discounted cash-flow rate of return (DCFRROR) analyses to determine the price of the primary commodity required for each operation to obtain a pre-specified rate of return on its investments. This determined value is equivalent to an average total cost of production (less all byproduct credits) for the operation over its producing life under the set of assumptions and

conditions established (e.g., mine plan, full capacity production, and a market for all output). The DCFRROR is most commonly defined as the rate of return that makes the present worth of cash-flow from an investment equal the present worth of all after-tax investments. For this study, both a 0-pct and 15-pct DCFRROR analysis were performed.

The Bureau's economic index system was used to update cost estimates from the original cost date (1987) to a common base date (January 1990 for this report). The index system includes updating factors for 12 separate components of mine cost (e.g., mining labor, mining equipment, diesel fuel) for foreign countries and 15 components for the United States. The index values for each component in each country take account of whether the expenditure is in local or foreign currency and what the traditional sources for needed imports are, such as machinery. A time series of exchange rates (also part of the index system) is used to translate the cost index values developed in local currencies into values expressed as U.S. dollars.

A separate tax records file, maintained for each state or nation, contains the relevant parameters under which the mining firm would operate. Tax parameters include structures and rates for corporate income taxes, property taxes, and any royalties, severance, or other taxes which pertain to PGM production. These tax parameters are applied to each mineral in the deposit under evaluation, with the implicit assumption that each deposit represents a separate corporate entity.

For purposes of the DCFRROR methodology, all capital investments incurred 15 yr before the initial year of the analysis are treated as fully depreciated costs. Capital investments incurred less than 15 yr before the initial year have the undepreciated balances carried forward to January 1990. All subsequent investments, reinvestments, operating, and transportation costs are expressed in January 1990 dollars. The exception to this depreciation schedule is South Africa where capital costs are expensed in the same year they are incurred.

Detailed cash-flow analyses are generated with the SAM system, and the results are presented in summary tables showing aggregated tonnages by increasing cost levels. Availability curves illustrating these results are presented in the text.

Certain assumptions are inherent in the availability analysis. First, all deposits produce at full operating capacity throughout the productive life of the deposit. Second, each operation is able to sell all of its output at the price equal to its average total production cost. Third, development of all nonproducing deposits follows proposed schedules published by companies available at the time of this analysis.

¹Price proportion factors are essentially ratios of the prices of various products to a preselected base product price. A complete discussion of price proportions used in this study are presented in the "Price Proportion" section in the body of the report.

²The Supply Availability Model was formerly titled the Supply Analysis Model.

APPENDIX C.—PROPERTY DESCRIPTIONS

REPUBLIC OF SOUTH AFRICA

Rustenburg Platinum Holdings

Rustenburg Platinum Mines Ltd. (RPM) was formed in 1931 with the assistance of technical, advisory, and secretarial services from Johannesburg Consolidated Investments (JCI). RPM acquired the assets of Union Platinum Mining Company Limited in 1949 and all the mineral rights of several small platinum companies during 1972. Union changed its name to Rustenburg Platinum Holdings Ltd. (RPH) and acquired Atok Platinum Mines (Pty.) Ltd. from Anglovaal in 1977. In 1981, RPH produced at full capacity of RPH of 1.3 Moz. The processing and refining of mine output is performed in South Africa¹ by the Matthey Rustenburg Refiners (MRR) Group. The holding company of the MRR Group is jointly owned by RPM and the Johnson Matthey Group. Johnson Matthey Public Ltd Co. (JM) is the sole marketing agent for the PGM products.

In this analysis, the Rustenburg operation includes three active operations: the Rustenburg section and the Amandelbult section producing from the Merensky Reef and the Union section producing from both the Merensky and UG2 Reefs. The Rustenburg section is located several kilometers east of the city of Rustenburg. The Union section is located 80 km north of Rustenburg, and the Amandelbult section is located 105 km north of Rustenburg. Only the Amandelbult section carries out mining entirely in South Africa; Union and Rustenburg sections mine more than 25 pct of their production within the Bophuthatswana homeland. Average annual combined capacity over the life of the three sections is estimated at 14.5 Mmt of ore.

The reserves currently being mined by RPM are all at depths of less than 1,000 m vertical depth. The Merensky Reef is known to exist at depths greater than 1,800 m below the surface; however, mining at that depth would involve costly refrigeration.² The new PGM refinery at Rustenburg was completed in 1990. The plant uses the modern solvent extraction process for recovery of PGM developed jointly by Rustenburg and Johnson Matthey and tested over a period of 12 yr in a pilot plant at Royston in England.

¹Refining had been performed previously in the United Kingdom before the construction of a new refinery in South Africa.

²The geothermal gradient of the Bushveld Complex is approximately 1° C per 26.5 m, compared to 1° C per 42 m on the Witwatersrand Gold fields.

Lebowa Platinum Mines

The eastern limb of the BIC is within the independent homeland of Lebowa and is located southeast of Pietersburg. Since the early 1920's, the deposits on the farms Maandagshoek and Driekop have been the scene of sporadic investigations and even small-scale mining. The UG2 Reef, which is the most important reef in this area, was sampled and mined on a limited scale, but problems with the metallurgy resulted in a loss of interest, especially once the Merensky Reef was exploited. In 1987, RPH entered into an agreement with the homeland of Lebowa and the Lebowa Development Corporation in which the RPH Atok subsidiary (Atok Mine, located 60 km southeast of Pietersburg) was transferred to the newly created Lebowa Platinum Mines (LPM). The agreement called for the expansion of the Atok Mine to 50 kmtpm of Merensky ore by 1989 and, if technically feasible, the establishment of a mine at Maandagshoek producing 50 kmtpm of UG2 ore. Maandagshoek is located 30 km southeast of Atok. The agreement further stated that, if the mine is expanded to 100 kmtpm within 5 yr, LPM would acquire exclusive rights to nearby, additional reserves. In March, 1988, a new agreement was made that the Atok Mine would be expanded to 70 kmtpm by August 1991, a 50-kmtpm or 100-kmtpm operation would be established at Maandagshoek and mined by RPH under a "tributing arrangement" by 1990, and LPM obtained 50-pct interest in the RPH platinum holdings on the Platreef. Furthermore, a 50-kmtpm mine will be established on the Platreef by 1993. A new agreement was reached in late 1989 that further modified the previous agreements. The decision to mine the Maandagshoek deposit was postponed because of high mining costs and the lack of favorable tax treatment between RPH and the Government of South Africa. However, production at Atok will be expanded to 100 kmtpm by August 1992, and a 200-kmtpm operation will be established at Platreef by 1994 upon favorable completion of trial mining operations in late 1990 (86).

Potgietersrus Platinum Mines

The RPH and LPM Platreef 50:50 joint venture is known as Potgietersrus Platinum Mines (PPM). The Platreef holdings of PPM cover an area some 25 km in length down to a vertical depth of 3 km near the town of Potgietersrus in the northern Transvaal. The proposed operation has an average grade of 8.7 g/mt PGM plus gold and an average nickel content of 0.37 pct. Reserves

are estimated at 17 Mmt to a vertical depth of 200 m. The average reef width is 3.7 m (the Merensky is typically not wider than 1.5 m). The platinum-to-palladium ratio is 1.1:1 (the Merensky Reef is 2.5:1) (87). The entire Platreef holdings of PPM contain an estimated 109 Mmt of reserves within 200 m of the surface at an average PGM plus gold grade of 5.6 g/mt and an average nickel content of 0.26 pct (88).

Impala Platinum Holdings

Impala Platinum Holdings (IPH) was formed in 1978 by the merger of Impala Platinum Ltd. and Bishopsgate. Impala Platinum Holdings' mines, concentrator, and smelter lie wholly within Bophuthatswana, near Rustenburg, where the mine offices and assay laboratories are situated. The nickel-copper refinery, PGM refinery, laboratories, and offices are all situated at Springs outside Johannesburg.

In 1988, legal proceedings were initiated by the Bafokeng Tribe in Bophuthatswana concerning royalties owed to the tribe from the existing operations. The Bafokeng tribe claimed the right to immediately terminate the mining leases that are due to expire in 2003. The dispute was settled in November 1989, in favor of the company (89). However, the dispute prevented Impala from negotiating extended mining rights in the area known as "The Deeps," which is down dip of current operations and will probably be an important source of Merensky ore in the future.

There are four active operations mining PGM from the Merensky Reef and to a lesser extent the UG2: Bafokeng North Mine, Bafokeng South Mine, Wildebeestfontein North Mine, and Wildebeestfontein South Mine. The 1989 production was estimated at 1.2 Moz of PGM with all mines operating at full capacity.

During 1987, Messina Platinum had identified both Merensky and UG2 reserves on the eastern limb of the Bushveld Complex, 45 km south of Pietersburg. The operation is unique from other Bushveld mines in that the ore body has a dip of 55° that gradually becomes vertical on the western portion of the ore body. The Merensky Reef ore contains 6.4 g/mt PGM, and the UG2 reef lies 100 m vertically below the Merensky Reef with an average grade of 6.2 g/mt PGM (90). At this time, Messina was a member of Sanlam, the parent company of Gencor who, in turn, owned Impala. During 1988, Impala began negotiations to buy a controlling interest in Messina from Sanlam. The deal was finalized in early 1990. During 1989, Messina sunk two ventilation shafts at its property to gain access to the UG2 and Merensky Reefs and to provide bulk ore samples. Messina's previous management had planned, after trial mining and metallurgical testing, to gradually increase production to 100 kmtpm of

UG2 ore and 60 kmtpm of Merensky ore. Impala is believed to be following a similar scheme (91).

The Karee Mine, between Brits and Rustenburg, was developed by Gazelle Platinum Ltd., which is a wholly owned subsidiary of Impala. In January 1990, Impala Platinum Holdings and Lonrho announced plans to merge Karee Mine with Lonrho's adjoining Western Platinum Mine. Impala will gain 25 pct of the equity voting rights in Lonrho's enlarged Western Platinum Ltd. and Eastern Platinum Ltd. Karee has reserves of 130 Mmt within the Merensky reef and 180 Mmt within the UG2. Production is planned to proceed at a rate of 100 koz of platinum in 1991 and thereafter to increase to full production at 300 koz/yr (92). The shallow reserves will enable low-cost mining to occur and short lead times to production. Four incline shafts have been initiated to exploit both UG2 and Merensky Reefs by trackless mining methods. The benefits of the merger include access to Karee's ore reserves from the Western shaft system, common use of established infrastructure, and unbroken access to both reefs for 26 km.

Lonrho South Africa

Lonrho PLC established Western Platinum Ltd. (Westplat) in 1966. The mining operation is located in the Western Limb of the Bushveld Igneous Complex, 30 km east of the town of Rustenburg. The mine is underlain by both the Merensky Reef and the UG2. The company commenced production in 1973, and, after a gradual build-up, platinum production reached 100 koz per annum by 1982. Production of UG2 ore only commenced in late 1982. Westplat increased its annual mine capacity to nearly 2.3 Mmt in 1987, producing nearly 302 koz of PGM and gold (93). It is believed that more than one-half of this figure was platinum.

Western Platinum was the first platinum producer to exploit both the Merensky and the UG2 Reef. The in situ grade in the UG2 within the Westplat lease area is apparently higher than that found in the Merensky Reef, in contrast to the situation at Rustenburg and Impala. In addition, the seam width of the UG2 Reef is wider than that of the Merensky, resulting in less dilution by waste during mining. The relative density of the ore is very much higher, resulting in improved tonnage-to-volume rates and lower mining costs. The much lower nickel and copper content of the ore results in a large reduction in smelting and refining costs.

The distribution of PGM differs in the Merensky and UG2 Reefs, where the percentage of rhodium in UG2 ore is nearly three times higher. UG2 ore, therefore, has a higher intrinsic value because of the much higher rhodium price. The higher rhodium grade encountered in the UG2 offsets the loss of revenue incurred by the

absence of base metal byproducts (copper and nickel) present in the Merensky ores.

Recent developments at Western include the increase of milling capacity to 270 kmtpm and the commissioning of the new UG2 concentrator. To gain access to the UG2 reserves, the Number 4 shaft was deepened to 1,000 m. Downstream processing improvements included the opening of a new smelter and increasing the capacity of the base metal refinery.

Eastern Platinum, a wholly owned subsidiary of Lonrho was incorporated in Bophuthatswana in August 1987. The company has approximately 10 km of strike on the UG2 Reef currently under development via three incline surface shafts. The UG2 concentrating plant was scheduled for commissioning in March 1990 and will be a virtual replica of the 80-kmtpm concentrator at Western Platinum. Mill concentrate will be toll-processed at Western's smelter and base metal and precious-metals refineries within South Africa. In the longer term, Eastern intends to double its production capacity, and, ultimately, it plans to construct a smelter and refinery within Bophuthatswana (94).

Although the grades of both the Merensky and UG2 Reefs improve at depth, the UG2 is richer, and the UG2 underlying the eastern portion of the lease areas has higher values than in the west. Lonrho's platinum interests are thus moving into richer ground as they expand.

As discussed in the Impala Platinum section of this report, the Western, Eastern, and Karee operations have been merged. Lonrho will manage the combined operations, but Impala does have equal representation on the boards of the two companies.

Gold Fields of South Africa

In 1981, Gold Fields of South Africa (GFSa) obtained a 10,000-hectare property southeast and downdip of RPM's Amandelbult Section. Drilling has indicated the Northam Platinum Mine has 163 Mmt of Merensky Reef reserves at a grade of 10.1 g/mt PGM plus gold and 319 Mt of UG2 reserves at a grade of 6.6 g/mt PGM plus gold to 2,700 m vertical depth (95). The high-temperature gradient of the Bushveld Complex will require expensive cooling of the mine workings. The mine will be developed by a twin-shaft system, and shaft sinking began in 1986. By the end of 1989, the Number 2 shaft (1,822 m depth) was completed, and the Number 1 shaft had been sunk to more than 1,700 m, on the way to a completed depth of 2,100 m. Production of Merensky Reef ore was slated to begin in July of 1991 at a rate of 50 kmtpm and is scheduled to increase to 150 kmtpm by 1994. A mill, smelter, and associated infrastructure are also under construction.

Rand Mines

Rand Mines, through its holding company, Barplats Investments, currently operates the Crocodile River Mine near Brits and is developing the Kennedy's Vale Mine north of Lydenburg. The Crocodile River mine began production in 1989 and is the first mine in South Africa to produce solely from the UG2 Reef. Development of the property, originally known as the Lefkoehrsos Platinum Mine, began in 1987. After serious cost overruns at the mine and refinery and difficulties in developing the mine, Barplats Investments gained control of Lefkoehrsos in 1988. The property was renamed Crocodile River and several changes were made in the mining plans. Production began in early 1989. The smelter matte is refined at the Barplats Refinery near Johannesburg. The mine is expected to produce 250 kmtpm by the end of 1992.

Concurrently, Rand Mines began developing the Rhodium Reefs property in 1986. With the acquisition of the Lefkoehrsos property, the Rhodium Reefs name was changed to Kennedy's Vale, and development was somewhat delayed. Drilling has shown the property contains 84 Mmt of UG2 reserves at grade of 6.3 g/mt PGM plus gold at 700- to 1,400-m vertical depth (96). This property, like Crocodile River, would concentrate mining in the UG2 Reef. The sinking of a 1,100-m twin-shaft system began in 1987. The proposed operation was to produce 180 kmtpm by 1993. However, the shaft system is equipped to extract ore at a rate of 270 kmtpm so production can be easily increased.

Summary

In summary, the Republic of South Africa has by far the largest reserves of PGM in the three reefs of the Bushveld Complex. Inferred resources for the Bushveld Complex, calculated to 1,200-m vertical depth, are estimated at 1,948 Moz of PGM (97). The Merensky Reef contains approximately 28 pct (547 Moz), and the UG2 Reef contains 53 pct (1,034 Moz), almost double that of the Merensky Reef. The Plat Reef composes 19 pct (363 Moz) of the total South African PGM resources.

CANADA—LAC DES ILES

Lac des Iles Mine is located approximately 80 km north of Thunder Bay, Ontario, in the southern part of the Lac des Iles Complex. Lac des Iles Mine, owned by Madeleine Mines, will start open pit production from the Roby Zone, an area that lies along the east gabbro-west gabbro contact. The Roby Zone is in excess of 600 m long, with a

maximum width of 115 m and is open at depth. The reported average grade of ore is 6.3 g/mt of PGM and 0.68 g/mt gold (98). Reserves analyzed for this study are mainly from the Roby Zone and have an estimated mine life of 9 yr for open pit operation. The crushing plant and mill at the company's former copper mine in Quebec have been dismantled and moved to the mine site, with an anticipated 1990 startup. Madeleine Mines has applied to the Ontario Government for permission to operate its mine. Drilling programs are planned to depths of up to 1,200 m in the Roby Zone and the lower grade Halo Zone west of the Roby Zone. Potential reserves for underground operation will depend on the result of this drilling program.

UNITED STATES OF AMERICA

The United States is a minor producer of primary platinum and palladium. This study includes two deposits: Salmon River, a past producer, and the Stillwater Mine, the only primary producer, with 1,000 mtpd capacity. In addition to these deposits, large areas of Alaska have been sampled in recent years, and exploration activities are ongoing in the Duluth Complex of Minnesota.

Salmon River

Goodnews Bay Mining Company produced platinum from two pay streaks³ occurring in placers located in the valley of the Salmon River, Alaska, from 1936 to 1976. During the 1980 season, operations again commenced on a limited basis, with the transfer of the property to Hanson Properties, Inc. Resources for this study are limited to two pay streaks: the valley floor pay streak located in the lower section of gravels along with the upper part of bedrock along the valley floor and the bench pay streak located directly east of the valley floor. The proposed mining plan will use a dredge after preproduction stripping using dragline and dozers. The Bureau of Mines has published an open file report (OFR 1-88) on the Goodnews Bay Mining District and has estimated the mean composition of recovered PGM in the following percentages: 83 to 86 pct platinum, 10 to 12 pct iridium, 1.32 pct rhodium, 2 pct osmium, and 0.4 pct palladium (99).

Stillwater Mine

Exploration for PGM in the Stillwater Complex was initiated by the Manville Corporation in 1967. The discovery of the 28-mile-long J-M Reef, the PGM-bearing zone, marked the first sign of commercial feasibility of mining operations. Chevron Resources earned 50 pct of

Stillwater PGM Resources, a joint venture with Manville Corp., by drilling and driving a decline in the Frog Pond area in 1979. Anaconda Minerals Corporation (AMC) completed 7,000 feet of adits, drifts, and crosscuts on the Minneapolis Adit between 1980 and 1983 and became an equal partner with Manville and Chevron in the Stillwater Mining Company (SMC) formed in 1983. In 1986, AMC sold its 33.3 pct share to Lac Minerals for \$15 million; Lac Minerals sold its interest back to the other two partners, Manville Corp. and Chevron Resources for \$40 million in 1989. Inferred resources at the Stillwater Complex are estimated at 35 Moz of PGM at an estimated grade of 22 g/mt; indicated resources are estimated at 7 Moz of PGM from 12.1 Mmt grading 3.9 g/mt platinum and 13.7 g/mt palladium (100).

The Stillwater Mining Company currently operates the Stillwater Mine near Nye, Montana, in the Beartooth Mountains. The Stillwater Mine began production in March 1987 and is the only mine producing platinum in the United States. The ore body is 8,800 m long and about 1,670 m deep. Resources estimated for this analysis predict a mine life of more than 30 yr. The company is developing ore reserves about 1 yr in advance of production, and reported annual ore production is estimated at 335 kmt or full capacity of 1,000 mtpd during 1990. The PGM grade was estimated at 22.2 g/mt, with platinum-to-palladium ratio of 1:3.4 (101). Manville Corp. and Chevron Resources are in the process of applying for a permit to expand production further (102). In 1990, a smelter to treat flotation concentrates from the mine was opened at Columbus, Montana, 78 km from the mine site. The smelter produces a converter matte that is presently air-freighted to the Metallurgie Hoboken-Overpelt refinery in Belgium for toll refining.

ZIMBABWE—THE GREAT DYKE

The Great Dyke is a stratiform, intrusive complex similar to the Bushveld Complex of South Africa. The complex runs generally north to south across Zimbabwe for approximately 500 km. There are presently two sulfide-rich areas of interest in the complex: the Hartley Complex and the Chegutu area. The Hartley Complex occurs about 60 km west of the town of Harare. A subsidiary of Delta Gold NL, an Australian Company, was granted an exclusive prospecting order for the area in 1987. This area had been extensively explored between 1968 and 1972 for nickel, copper, and PGM. However, all work was abandoned because of low metal prices. Delta reanalyzed the old data and subsequently initialized a limited drilling program. Promising results led them to commission a feasibility study in 1989. The results of this study led Delta to establish a partnership with BHP-Utah International in 1990. If appropriate financial and commercial

³A pay streak is the precious-metal-bearing layer in a placer deposit.

terms can be arranged, a 2 Mmtpy operation could be established by 1993 (103). South of the Hartley Complex, another region of the Great Dyke, known as Chegutu, is

being actively explored by a joint venture consisting of Plateau Mining, Rio Tinto, and Anglo American.

APPENDIX D.—AUTOCATALYST RECYCLING PROCESSES

In general, two processes are used to recover PGM, hydrometallurgical or pyrometallurgical. The hydrometallurgical process involves the dissolution of either the PGM or the substrate material. The dissolution of the PGM involves stripping the PGM-containing washcoat from the substrate with subsequent precipitation of the PGM or extraction from the stripping solution by solvent extraction. The other hydrometallurgical method involves dissolving the entire substrate with subsequent precipitation of the PGM. The second method is not suitable for cordierite (monolith) type substrates (104). The PGM-bearing concentrate is then sent to a precious-metals refiner.

The pyrometallurgical processes involve the smelting of the catalytic material. The first method involves the use of plasma fusion, in which the entire converter substrate material is melted. The PGM-bearing material is separated from the slag, the iron is leached out, and the subsequent PGM-rich concentrate is sent to a precious-metals refinery. The second pyrometallurgical method involves the use of base metal smelters (copper or nickel). In this method, the catalyst substrate is crushed, ground, and combined with the base metal concentrate. The concentrate is smelted, and the PGM combine into the resulting matte. The matte can then be processed by a precious-metals refinery. This method is used in Japan to treat imported catalytic converters. The third pyrometallurgical method involves using copper as a collector. The catalyst substrate is crushed and mixed with a fluxing agent and smelted with copper. As in the base smelter process, the copper forms a PGM-rich matte. The resulting matte is then treated to separate the copper and the PGM-bearing residue. The PGM-rich residue is then

sent to a precious-metals refinery. In the pyrometallurgical processes, the alumina-base (pellet type) converters require a few additional processing steps before smelting. However, the alumina is recovered as a byproduct.

The first major problem in recycling autocatalysts was obtaining a reliable supply. The U.S. automotive recycling industry consists of several tiers, each with varying degrees of capital and technical expertise required. The flow is dependent on whether pyrometallurgical or hydrometallurgical techniques are used to recover the PGM.

The industry has been described as a "reverse distribution network." Both recovery methods have in common the bottom tier of junkyards, muffler shops, and garages that obtain the used converters. The next tier up consists of local auto parts dealers that collect used parts from junkyards. Here the flow can begin to vary between the two methods. In the pyrometallurgical route, the dealer now sells the spent autocatalyst to a regional or national collector. The collector maintains an ongoing relationship with the larger consumers of spent catalyst. There are approximately 10 major specialized collectors (105). The collectors also decan¹ the catalyst. The collector then sells the spent catalyst to the smelter for recovery of the PGM. In the hydrometallurgical (hydromet) route, the dealer can sell his used autocatalysts to a local or regional hydromet processing plant or to a collector who, in turn, sells the autocatalyst to a hydromet plant. The hydromet plant can then sell the highly-enriched PGM concentrate it produces to a precious-metals refinery.

¹Decanning is the process of removing the substrate from the stainless steel canister.

APPENDIX E.—TYPICAL MINING AND PROCESSING TECHNOLOGIES

At present, nearly all PGM come from underground deposits mined by conventional but diverse methods. The majority of operations are located in the Bushveld Complex of South Africa. Many mining technologies have been developed or refined in the gold mining areas of South Africa and then transferred and adapted to the conditions of the Bushveld Complex. The thickness, dip, grade, and strike of the Merensky Reef is generally very regular and predictable. During mining operations on the Merensky Reef, access is gained from a series of inclined and vertical shafts. Longwall mining is the preferred method. A working face is developed at a 25° angle to the dip of the reef. Because of the narrow width of the reef, drilling is currently done manually. After blasting the ore, scrapers move the broken ore to transport strike gullies. Another scraper then moves the ore to ore passes that connect to haulage levels. The ore is loaded into cars drawn by battery-powered locomotives and then transferred to the shaft for hoisting to the surface. The reef is also interrupted by geologic features known as potholes. These circular depressions can range in size from a few meters in diameter to more than 500 m. The presence of deep potholes necessitates redevelopment, but shallow depressions are mined during normal stoping operations. The type of rock present is prone to fracturing, which can lead to bad ground conditions that require more expensive ground support measures. Extending the present shaft system to the UG2 Reef would be fairly simple.

Increasing mechanization is the trend in the PGM operations. Mechanization means fewer, more highly trained employees and is expected to reduce costs and produce significant improvements in productivity. This trend could enhance the advancement of black workers into higher skilled jobs with better wages. Despite the higher wages for black workers, mechanization would result in a smaller work force and reduce overall mining costs.

Much development work is now done with mobile, rubber-tired equipment such as load-haul-dump vehicles, drill rigs, and articulated dump trucks. Using this type of equipment, the mining operation is much more flexible. New innovations such as water-powered drills, mobile drilling rigs sized to fit the 1-m stope widths, and

continuous mining type systems are being developed in the gold mining areas and adapted to the PGM mines.

The treatment of Merensky Reef ore, where nickel and copper are subordinate in value to the PGM, is a complex metallurgical process. In a typical operation, the ore is first crushed and then milled to 50 pct minus 200 mesh. The economic minerals are concentrated in flotation circuits. Flotation involves roughing, scavenging, and cleaning to produce a concentrate of the 400- to 1,000-g/mt PGM at 85-pct recovery.

Smelting separates the oxide minerals (gangue) from the sulfides containing the noble metals. The concentrate is smelted in electric arc furnaces to a nickel-copper "green" matte. The green matte is then converted to a high-grade nickel-copper "white" matte containing about 1,500 to 2,000 g/mt PGM, 50 pct nickel, and 28 pct copper (106).

In the conversion process, oxygen is blown through the molten matte to oxidize the base metal sulfides in order to separate the base metals. The copper and nickel sulfides are oxidized to blister copper and metallic nickel. The preferred process for the nickel-copper refining is the Sherritt-Gordon process, which is a patented pressure leach process for treating converter matte to produce nickel, copper, and PGM in the residues. The anode slimes containing up to 75 pct PGM are sent to the PGM refinery. Historically, the extraction of the individual PGM from the concentrates is by analytical chemical methods based on selective precipitation. Platinum and palladium are the easiest of the metals to extract, requiring only a few weeks' time. Recovery is greater than 98 pct. Recovery of the other four metals is less efficient, purity is lower, and refinery residence time can extend up to 1 yr. About 75 pct of the PGM in South African ores is recovered.

New refining techniques such as solvent extraction and ion exchange have been independently developed by MINTEK, Inco, and Johnson Matthey. The new Rustenburg precious-metals refinery is the first large-scale commercial operation that utilizes the solvent extraction technology. The solvent extraction technology has significantly shortened the recovery times and reduced costs.