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A Platinum-Group Metals Consumption and Recycling Flow Model

By Robert C. Gabler, Jr.

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

kg	kilogram	$/kg	dollar per kilogram
pct	percent	$/lb	dollar per pound

A PLATINUM-GROUP METALS CONSUMPTION AND RECYCLING FLOW MODEL

By Robert C. Gabler, Jr.[1]

ABSTRACT

World resources of platinum-group metals appear ample for the foreseeable future; however, political and economic events in the last two decades have caused concern over the availability and reliability of an uninterrupted supply. Because of this concern, the U.S. Congress requested that the U.S. Bureau of Mines initiate a study of the flow of platinum-group metals in the economy that would delineate and quantify the production areas in which metal values are lost. As a result, the Bureau has developed a computerized commodity flow model for strategic and critical materials. Major attributes of this flow model are as follows: (1) it is generic and applicable to most commodities and (2) it can be updated as supply, demand, and/or production data change. The original model developed for cobalt, with slight modifications, was used to track the flow of platinum-group metals. This report follows the flow of platinum-group metals through their metallurgical, catalytic, and chemical applications and highlights areas in which significant losses occur because of downgrading, export, or disposal. The study indicates that materials containing about 63,426 kg of platinum-group metals were lost or could not be traced in 1989, representing about 63 pct of U.S. domestic consumption.

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INTRODUCTION

The platinum-group metals (PGM) are platinum, palladium, iridium, osmium, rhodium, and ruthenium. The PGM are indispensable elements in a variety of strategic and critical applications. PGM are used to produce catalysts for chemicals production, automobile emission control, and petroleum processing; dental and medical devices; electrical equipment; and other products in various noncritical industries. In many of their major uses, PGM have few effective and efficient substitutes. The United States currently is dependent on imports for 90 pct of its apparent consumption of PGM. The Republic of South Africa is the major producer of platinum, and the U.S.S.R. is the major producer of palladium. In the future, most new production of PGM is expected to come from the Republic of South Africa (*1*).[2]

Although world resources of PGM, as well as chromium, cobalt, and manganese, are ample for the foreseeable future, past political and economic events have raised concern about the uninterrupted availability and reliability of supplies of these strategic and critical materials. The risks of future disruptions of supply were considered high around the time of the 1978 Katangese rebellion (*2-3*). At that time the price of cobalt rose from $5/lb in 1977 to $23/lb in 1979. Although some of this price increase was due to sharply increased demand, significant concern was generated about future disruptions of supply of cobalt, and also chromium, manganese, and PGM. This concern led to studies on the strategic importance of a number of commodities, including PGM, and their availability and vulnerability to interrupted supplies (*3-11*). Most of these studies either are out of date and/or do not supply information on losses of the strategic and critical commodities due to waste disposal, downgrading, and/or export. The lack of knowledge on these unknown losses makes conservation difficult.

Industry officials in the production, manufacturing, and recycling of strategic and critical commodities are reluctant to discuss the quantities of scrap that go to disposal, downgrading, and export. This information is often considered to be proprietary in nature.

Even when data are available, there is confusion between disposition of materials and recycling. For example, in a survey of seven scrap recyclers in 1987 (*12*), the following estimates were obtained for disposition of scrap from the superalloy industry:

	Range, pct
Domestic recycling	60-100
Exports	60- 40
Of recycled scrap:	
Domestic remelting	75-100
Recycling to same superalloy	38- 90
Recycling to other high-value superalloy	5- 38
Downgrading	10- 25
Discarding	3- 5

These estimates are typical of the data on processing, manufacturing, disposal, downgrading, and recycling of strategic and critical materials. Therein lies the difficulty in determining the amounts of critical and strategic commodities that are discarded, downgraded, or exported, which is the reason for conducting this study.

In 1980, the U.S. Bureau of Mines reported the results of contracted studies by Inco Research and Development Center, Suffern, NY, and Arthur D. Little, Inc., Cambridge, MA, to assess the domestic availability of chromium in scrap and the amount that was recycled (*13-14*). These reports contain data up to 1976 and 1978, respectively; no updates of these studies were conducted following their publication. In 1983, the National Materials Advisory Board (NMAB) published a study of the flow of cobalt in all end uses, which discussed the amounts of downgraded scrap and waste produced by the cobalt industry (*3*). The report also discussed the need for improved recycling of cobalt-containing scrap.

In May 1985, the U.S. Congress, Office of Technology Assessment (OTA), produced a study entitled "Strategic Materials: Technologies To Reduce U.S. Import Vulnerability" (*15*). Included in the study were a set of recommendations to the Bureau to conduct a survey of recycling-related activities. OTA recommended a scrap recycling study to update the chromium scrap metal information contained in two Bureau publications (*13-14*), as well as to expand the scope of the previous studies to include information on scrap generated by cobalt, manganese, and the PGM industries, as well as the wastes generated by all the various industrial and Department of Defense users of these four commodities.

Acting on this recommendation, in 1987 the Bureau initiated a study of the four commodities. The main objective of this study is to produce a commodity-oriented structural model tracing flow, recycling, and final disposition of the four identified commodities, which can be updated in subsequent years. A second objective of the study is to provide, in an understandable manner, an overview of the

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

commodity flow that can be used by Congress and industry associations as a tool to help in the study of that commodity's vulnerability to political and availability factors outside the control of the United States. Another objective of the study is to highlight significant commodity loss areas where further research is required.

A hierarchical model for the commodity cobalt was developed (*16-17*). The model is generic, and it can be applied to other strategic and critical commodities. To meet the preceding objectives of this study, the model was applied to the PGM with slight modification.

DESCRIPTION OF THE FLOW MODEL

As stated in the introduction, the PGM model is based on the generic model developed for the commodity cobalt, with some minor modifications.

DEFINITIONS

Consumption

Apparent consumption.—Mine production + production from old scrap + (refined imports - refined exports) + (beginning inventories - ending inventories) (*1*). (Note that neither reported nor apparent consumption is actual consumption. However, apparent consumption is very close to actual consumption.)

Consumption.—Apparent consumption, except where it is listed as reported consumption.

Reported consumption.—Data reported to the Bureau in response to the Bureau's industry consumption survey questionnaires.

Scrap

Home scrap.—Scrap generated during processing that is internally recycled within the generating company and that can be considered as being endlessly recirculated. It is sometimes referred to as "run-around scrap." It is not counted as part of consumption (*9*).

Obsolete scrap.—Scrap generated by users and recyclers when used products are overhauled or when the product has reached the end of its productive life cycle (*9*).

Prompt scrap.—Also called prompt industrial scrap; consists of solids, turnings, grindings, sludges, and liquors generated during the manufacturing process when the primary product is fabricated into a finished product (*9*).

Run-around scrap.—Home scrap.

Toll-refined material.—Material owned by a first party that is refined by a second party for a toll or fee while remaining the property of the first party. The refined material is returned to the first party.

GENERAL CONFIGURATION

The PGM flow model is shown in figure 1. (Mathematical relationships in the PGM model are discussed in the appendix.) The supplies of PGM come from imports of refined metal, scrap, waste, crude material, and slimes; byproduct material; and domestically recycled material. In any given year, fractions of this material go to exports, stocks, domestic processing, and manufacturing. During processing, about 30 pct of input reports as home scrap and is internally recycled. About 0.5 pct of input reports to processing losses, some input is transferred to stocks (but not always), and most of the input reports to manufacturing (*4*). Note that home scrap is not counted, as it is endlessly recycled, and counting it would be double counting. However, it is part of the recycling of the commodity. The processed material then goes to product manufacturing along with the raw material that goes directly to manufacturing. During manufacturing, a small amount of PGM (about 0.3 pct) reports as waste (*4*). The remainder goes to final products. After a normal use life, each product that is not in a dissipative end use becomes obsolete scrap and waste. The estimated amount recycled, based on data reported to the Bureau, was 50,207 kg (*1*). Much of this material (46,253 kg) was secondary toll-refined PGM (*1*). There are no new data to show how much of this secondary toll-refined material reported to new PGM consumed in the various industries.

PROPERTIES OF THE FLOW MODEL

The flow model described in Bureau IC 9252 (*16*) is generic in nature and, thus, can be used for a wide variety of commodities with only minor modifications. The model is easy to update and is generally understood by the public,

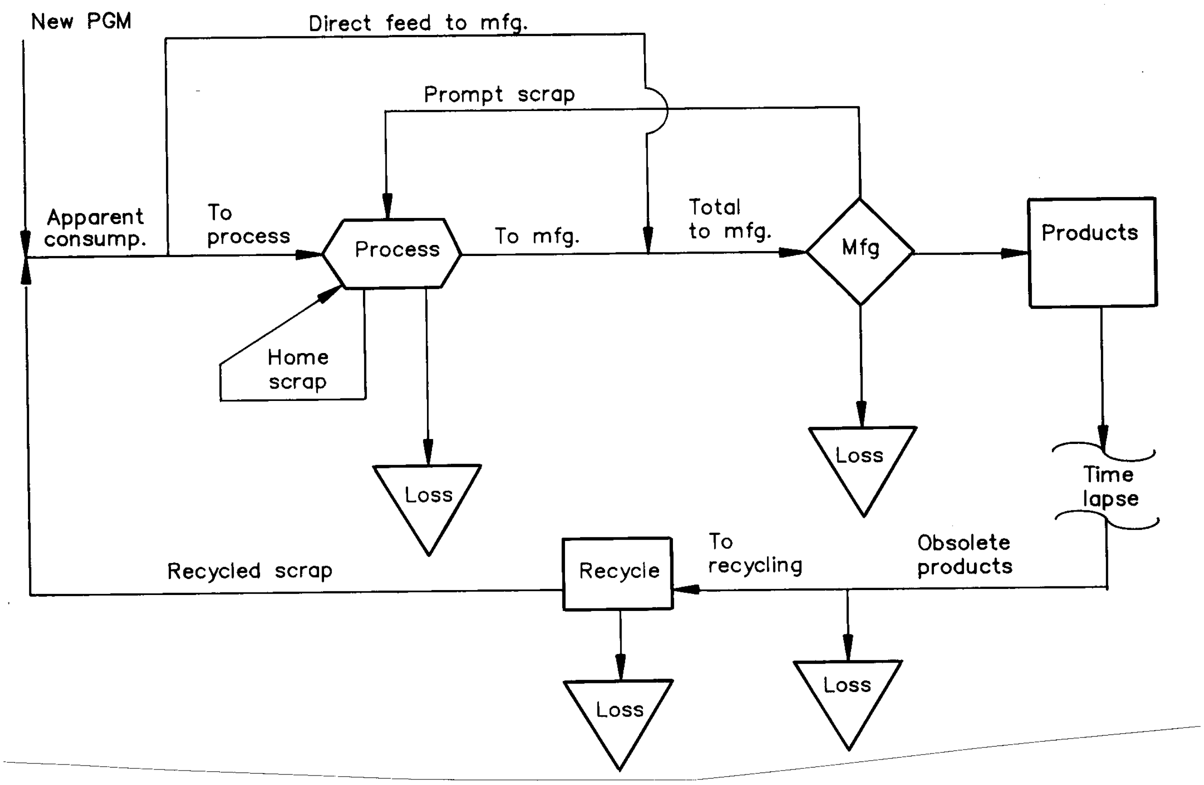

Figure 1.—Typical PGM industry flow model.

and it highlights areas where recycling research is needed. The model is hierarchical, with three levels: the entire PGM industry, the individual industry, and the individual plant. The data in this report cover the entire PGM industry and the individual industry.

ASSUMPTIONS IN THE MODEL

In the development of the model, a number of assumptions had to be made. These assumptions are as follows:

1. Where data were found, the percentages reporting in each category were used. Where no current data were available, data reported by NMAB were used and assumed to be still effective (*4*).
2. The use lives of various products vary over a wide range. While Kusler estimates a life span of 5 years for automotive catalytic converters (*20*), a recent publication estimates the current life span to be 10 years (*15*). Hennion estimates an average lifetime of 3 years for petroleum and chemical catalysts (*24*). No other lifetime estimates of PGM-containing products were found. Lifetimes of 10 years for electrical and electronic products, 5 years for glass industry devices, and 5 years for miscellaneous other products are assumed.
3. Lifetimes for most medical and dental products and for jewelry and decorative products are very long and most of these products are not recycled. The few orthodontic dental braces that are recycled are assumed to have a lifetime of 3 years, while the small amount of jewelry and decorative products recycled is estimated to have a 10-year lifetime.
4. Thus, it is assumed that obsolete scrap available for recycle in 1989 would come from the 1979 automotive, electrical and electronic, and jewelry and decorative products; the 1984 glass devices and miscellaneous other industries' products; and the 1986 chemical catalysts, petroleum catalysts, and dental and medical products.
5. Unless otherwise stated, all PGM quantities are kilograms of contained PGM. All values reported are the best estimates possible with currently available data.

PLATINUM-GROUP METALS INDUSTRY

The PGM industry has been described by a number of sources (*1*, *18-22*). PGM are used by seven major industries and a number of small miscellaneous industries (see table 1). In three of the major industries, PGM are either mostly or totally used as catalysts: the automotive, chemical, and petroleum industries. Together they accounted for 45 pct of the reported consumption of PGM in 1989. The other major industries are the medical and dental industry, the electrical and electronics industry, the glass industry, and the jewelry and decorative industry. Other miscellaneous small industries are listed together for simplicity. Typical examples of the miscellaneous small industries' end uses are metallurgical and laboratory crucibles and containers, high-intensity gamma-ray sources, magnets, and neutron absorbers.

Table 1.—Reported and apparent U.S. consumption of PGM in various industries for 1989, kilograms of contained PGM

Industry	Reported consumption		Apparent
	Amount, kg	Pct of total	consumption, kg
Automotive . . .	25,643	32.7	33,094
Electrical and electronics . .	23,408	29.8	30,210
Dental and medical	9,233	11.8	11,916
Petroleum . . .	5,429	6.9	7,007
Chemical	4,657	5.9	6,010
Glass	1,489	1.9	1,922
Jewelry and decorative . .	814	1.0	1,051
Miscellaneous other	7,766	9.9	10,023
Total	78,439	[1]100.0	101,233

[1]Numbers do not add to total shown because of independent rounding.

The high costs of PGM encourage the overall PGM industry to recycle a large amount of scrap and wastes. Chemical catalysts are about 85 pct recycled and petroleum catalysts are 97 pct recycled (*4*). The recycling of automobile catalysts is approaching the 40-pct range; however, only about 16 pct is recycled domestically (*1*). Most medical and dental products are nonrecyclable except for orthodontic braces (*4*). However, prompt scrap from the production of dental devices amounts to about 50 pct of the PGM used for these devices and this scrap is efficiently recycled (*4*). The recycling of PGM from electrical and electronic devices has increased (*23*). Most devices used in the glass industry are very efficiently recycled. The jewelry and decorative products manufacturers do an excellent job of recycling of prompt scrap from manufacturing. Most jewelry and decorative products are held and, thus, are not recycled. The recycling of PGM from miscellaneous end uses varies with the type of product.

AUTOMOTIVE INDUSTRY

The main use of PGM in this industry is for automobile and light truck exhaust catalytic converters for emission control. A small amount of PGM is used in such devices as contacts and oxygen sensors that control engine combustion. The flow of PGM in the automotive industry is shown in figure 2. Overall consumption of PGM in the automotive industry in 1989 was 33,094 kg.

Coombes estimates that 6,594 kg of PGM from scrap automobile catalytic converters was recycled in 1989 in North America (*25*). Loebenstein estimates that 80 pct of North American recycling of scrap automobile catalytic converters was performed in the United States.[3] The current report uses 5,275 kg (6,594 × 0.80) as the most reliable figure for 1989 U.S. PGM recycling in the automotive industry. This figure is confirmed as reasonable by a Mining Journal report (*26*). The Mining Journal data showed that an estimated 4,964 kg (15 pct of the U.S. automotive industry's 33,094 kg apparent consumption) came from recycled material.

Of the 33,094 kg of PGM consumed in the automotive industry in 1989, 3,048 kg went directly to manufacturing with no domestic processing. The remaining 30,046 kg was processed, leaving 144 kg in processing losses and 29,902 kg for manufacturing. In-house home scrap recycled is estimated to be 9,050 kg. This home scrap is not counted as material consumed because it is endlessly recycled and never leaves the plant. Total feed to manufacturing was 32,950 kg of PGM. Manufacturing produced products containing 32,673 kg of PGM and losses of 277 kg of contained PGM. The automotive industry estimates the life expectancy of automobiles and light trucks to be about 10 years. In 1979 the automotive industry consumed 35,732 kg of PGM, and that amount is potentially recyclable (*27*). Unknown and unrecovered losses of the 1979 obsolete converter scrap amounted to 29,871 kg of PGM. Much of this material may have been exported, but it cannot be followed with currently available data. The remaining 5,861 kg was recycled. Recycle processing losses are estimated at 10 pct, or 586 kg (*15*). The recovered 5,275 kg was recycled to the industry as part of its 1989 consumption. Thus, about 16 pct of available PGM was recycled.

The 29,871 kg of obsolete 1979 converter scrap lost is equal to 90 pct of the total apparent consumption of PGM by the automotive industry in 1989. This was the largest

[3]Information from J. Roger Loebenstein, PGM Specialist, Division of Mineral Commodities, Information and Analysis Directorate, U.S. Bureau of Mines.

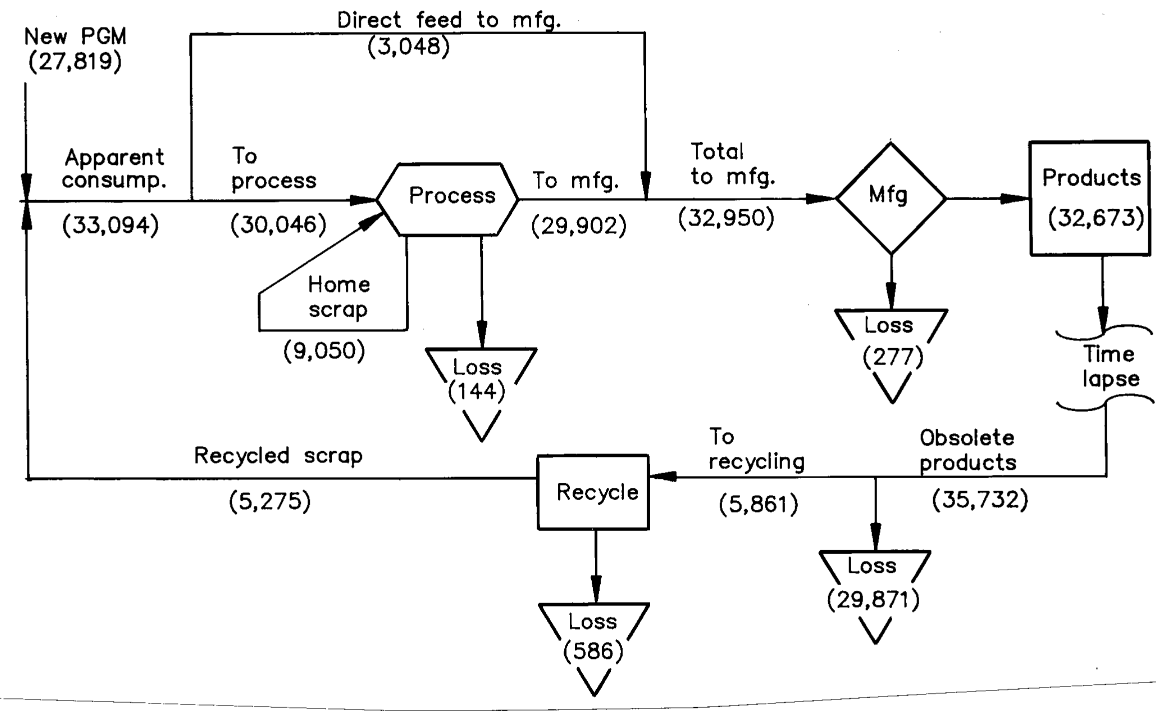

Figure 2.—Flow of PGM in automotive industry in 1989 (amounts in kilograms of contained PGM).

single loss area for PGM, amounting to more than 29 pct of PGM total apparent consumption in 1989. The Bureau is currently studying the recycling of this scrap.

ELECTRICAL AND ELECTRONICS INDUSTRY

In this industry, PGM are used in electrodes, thermocouples, contacts, conductors in printed circuits, high-temperature wires, resistors, capacitors, and various other devices. The flow of PGM in the electrical and electronics industry is shown in figure 3. The apparent consumption of PGM by the industry in 1989 was 30,210 kg: 4,480 kg of recycled obsolete scrap and 25,730 kg of virgin PGM. An estimated 2,783 kg went directly to manufacturing and 27,427 kg went to processing. In addition, 1,371 kg of prompt scrap went to processing. During processing, an estimated 30 pct (8,674 kg) was continuously recycled as home scrap and was not counted in the overall processing. Losses of PGM during processing were estimated to be 138 kg. The remaining 28,660 kg of processed PGM and the direct-to-manufacturing PGM of 2,783 kg went to product manufacturing. During manufacturing, an estimated 91 kg was lost as waste, 1,371 kg reported as prompt scrap, and 29,981 kg reported in final products. A lifetime of 10 years is expected for products from this industry. Thus, the 1979 apparent consumption of PGM of 19,478 kg was potentially available for recycle in 1989 (*27*). Of this amount, 14,500 kg reported as unknown and unrecovered losses of material. A total of 4,978 kg was processed for recycle with processing losses of 498 kg, leaving an estimated 4,480 kg for consumption in 1989. Electrical and electronic scrap losses in 1989 were a major loss area for PGM. Unknown and unrecovered losses amounted to 14.3 pct of total PGM apparent consumption in 1989. A recent publication shows that an increasing amount of this scrap is being recycled (*23*). Technology previously developed by the Bureau for recovering precious metals from obsolete electronic scrap has helped increase the recovery of PGM scrap (*23*).

DENTAL AND MEDICAL INDUSTRY

Most PGM consumed in this industry (an estimated 80 pct) goes to dental uses. In the field of dentistry, PGM are used in crowns, bridges, restorations, and orthodontic braces. In the medical field, some PGM are

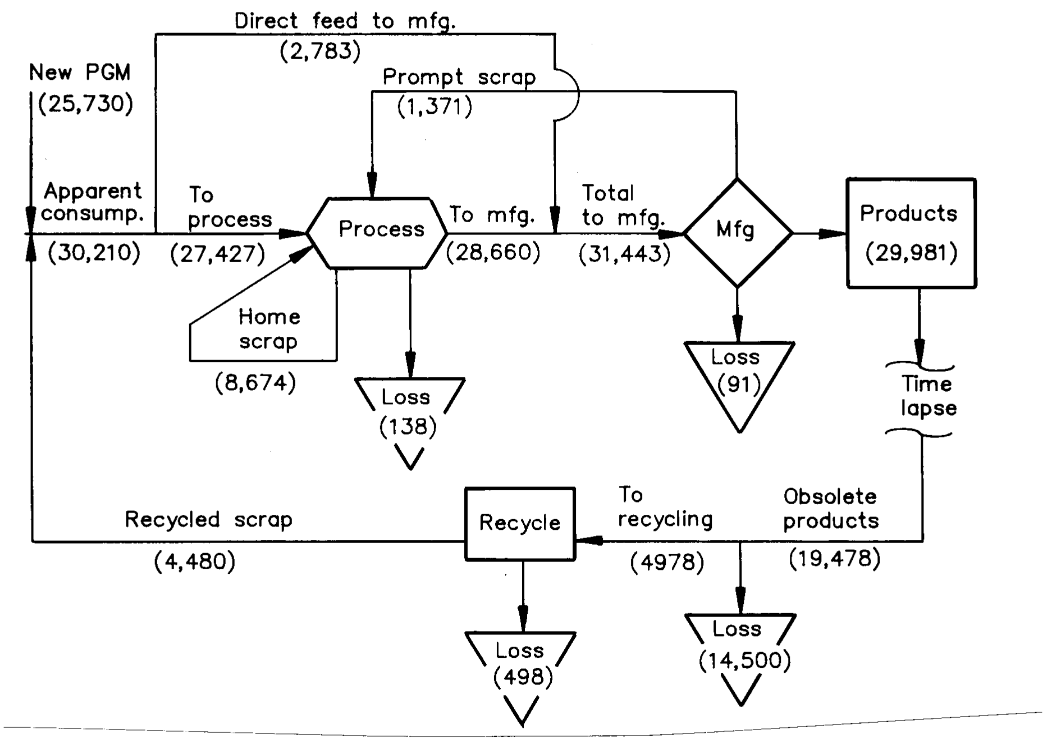

Figure 3.—Flow of PGM in electrical and electronics industry in 1989 (amounts in kilograms of contained PGM).

used in prostheses and anticancer chemotherapy pharmaceuticals. Figure 4 shows the flow of PGM in the dental and medical industry. Apparent consumption of PGM by this industry was estimated at 11,916 kg in 1989. Of this amount, 11,903 kg was estimated to be new PGM, and about 13 kg was from recycled obsolete dental scrap. Almost all of this obsolete dental scrap was from orthodontic braces. Approximately 1,098 kg was estimated to go directly to manufacturing, and 10,818 kg went first to processing. In addition, about 4,327 kg of recycled prompt scrap from manufacturing also went to processing. During processing, about 73 kg was lost as waste. An additional 4,562 kg reported as home scrap that was internally recycled. The remaining 15,072 kg of PGM from processing and the 1,098 kg of PGM that reported directly went to manufacturing. During manufacturing, an estimated 4,327 kg of PGM reported as prompt scrap, 47 kg as manufacturing losses, and 11,796 kg as final products.

Because of the nature of the final products in this industry, only a very small amount of PGM from orthodontic braces is recovered. All other products, by their nature, are not available for recycling. An estimated 15,302 kg was consumed in 1986 and was potentially available for recycling in 1989 (*28*). However, because of the dissipative and permanent end uses of the products, only an estimated 15 kg (or 0.1 pct) in orthodontic braces was available for recycle, leaving 15,287 kg in unknown, unrecovered, and dissipative losses. Assuming a recycle processing loss of 10 pct or 2 kg, only 13 kg was estimated to be recycled.

PETROLEUM INDUSTRY

PGM are used extensively as catalysts in the petroleum industry to produce motor fuels from crude petroleum during refining. This industry consumed 7,007 kg of PGM in 1989; the flow of PGM is shown in figure 5. Of this, 2,786 kg was virgin PGM and the remainder, 4,221 kg, was from recycled obsolete scrap. About 645 kg reported directly to manufacturing and 6,362 kg reported to processing. During processing, an estimated 31 kg reported as losses. Approximately 1,916 kg was internally recycled

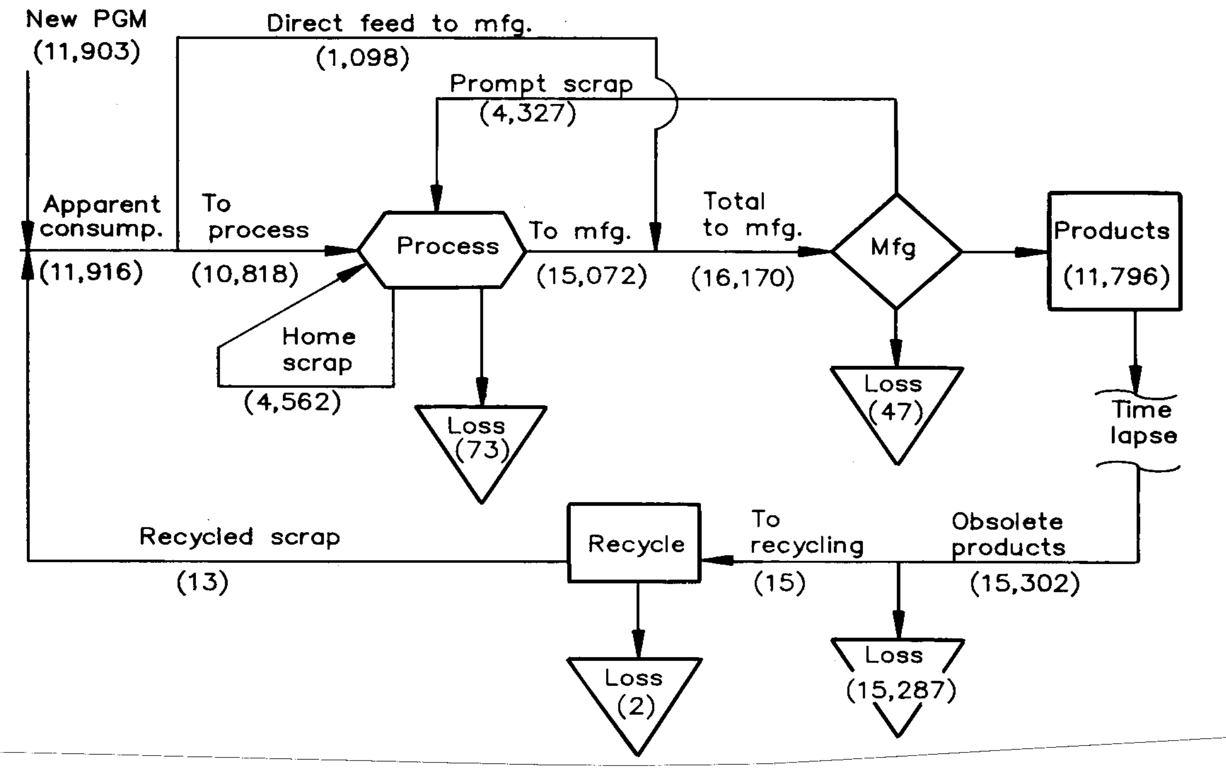

Figure 4.—Flow of PGM in dental and medical industry in 1989 (amounts in kilograms of contained PGM).

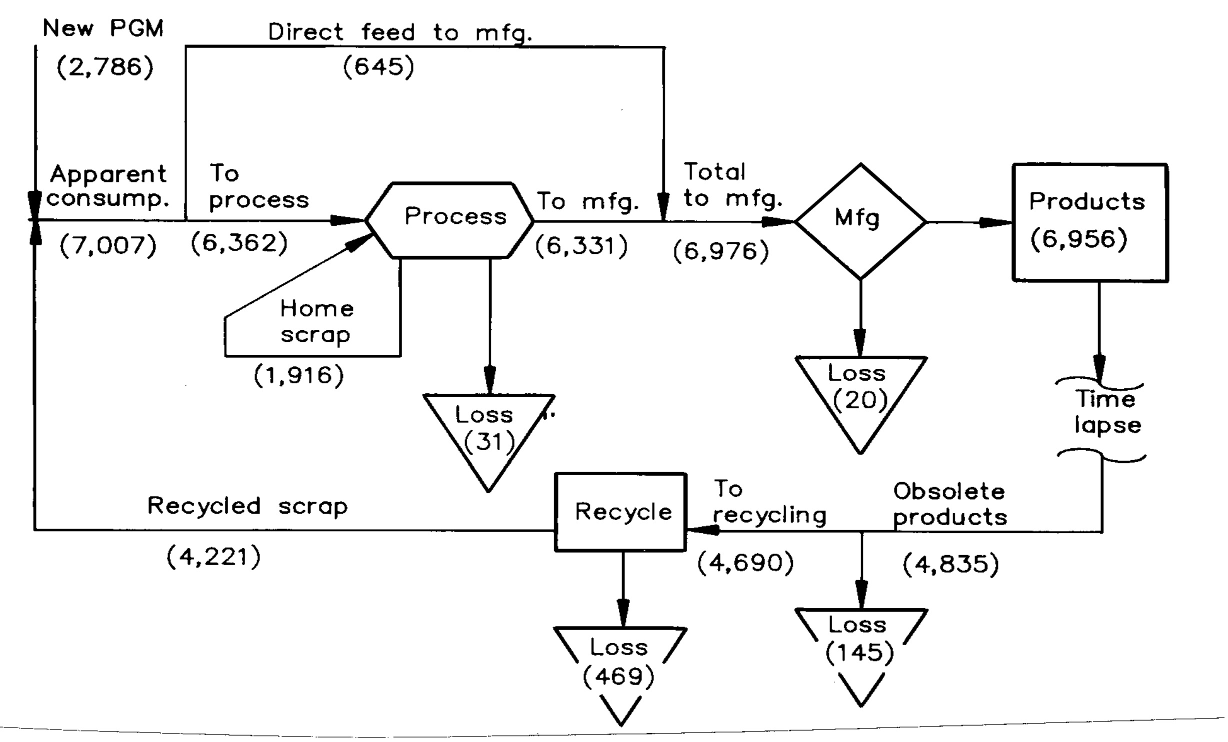

Figure 5.—Flow of PGM in petroleum industry in 1989 (amounts in kilograms of contained PGM).

home scrap. About 6,331 kg of processed PGM reported to manufacturing along with the amount that reported directly to manufacturing. During manufacturing, about 20 kg reported as losses and 6,956 kg was contained in finished catalysts. The catalysts can be regenerated two to three times, but ultimately become obsolete scrap after about a 3-year lifetime. Catalysts in this industry show a 3-pct loss during use and are typically 97 pct available for recycle. About 4,835 kg was potentially recyclable from the amount consumed in 1986 (*28*). An estimated 3 pct, or 145 kg, was lost in use. During recycle processing of the remainder, about 469 kg was lost, with an estimated 4,221 kg recycled in 1989.

CHEMICAL INDUSTRY

PGM in the chemical industry are predominantly used as catalysts for a variety of chemical processes. For example, PGM catalysts are used in nitric acid (NHO_3) production, hydrogen cyanide (HCN) production, and in the removal of O_2 from H_2. In 1989, the industry's apparent consumption was 6,010 kg of PGM. Almost all this material came from the recycle of obsolete scrap. The flow of PGM in the chemical industry is shown in figure 6. Of the 6,010 kg consumed, 554 kg went directly to manufacturing and 5,456 kg went to processing. During processing, 26 kg reported as waste and 5,430 kg reported to manufacturing. About 1,643 kg was continuously recycled home scrap. Manufacturing losses were 17 kg, and 5,967 kg reported in products. From 1986 products, about 8,089 kg was potentially recyclable (*28*). A loss of 15 pct during use and recycling was reported by NMAB (*4*). Thus, about 1,213 kg was lost and 6,876 kg was recycled. Because apparent consumption in 1989 was only 6,010 kg, approximately 866 kg went as obsolete scrap feed to other PGM industries or was stockpiled.

GLASS INDUSTRY

Some typical uses of PGM in the glass industry are as tanks, dies, bushings, and valves for fiberglass production; crucibles for melting optical salt crystals; and heater windings for glass, ceramic, and ferrite research. The glass industry's apparent consumption of PGM was 1,922 kg in 1989; the flow of PGM in this industry is shown in figure 7. About 1,301 kg was new PGM and 621 kg was recycled obsolete PGM scrap. Processing took 1,745 kg, with the remaining 177 kg reporting directly to manufacturing. An additional 87 kg of prompt scrap was fed to processing. During processing, losses amounted to 8 kg, 1,824 kg went to manufacturing, and about 551 kg reported as home scrap. During manufacturing, 6 kg was lost, 87 kg was prompt scrap, and 1,908 kg reported to products.

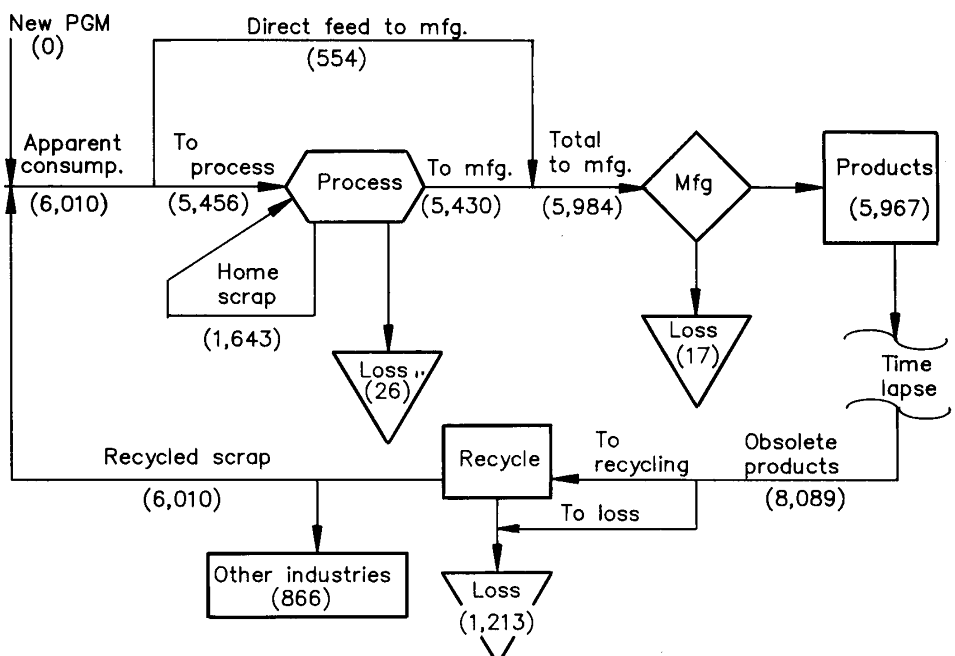

Figure 6.—Flow of PGM in chemical industry in 1989 (amounts in kilograms of contained PGM).

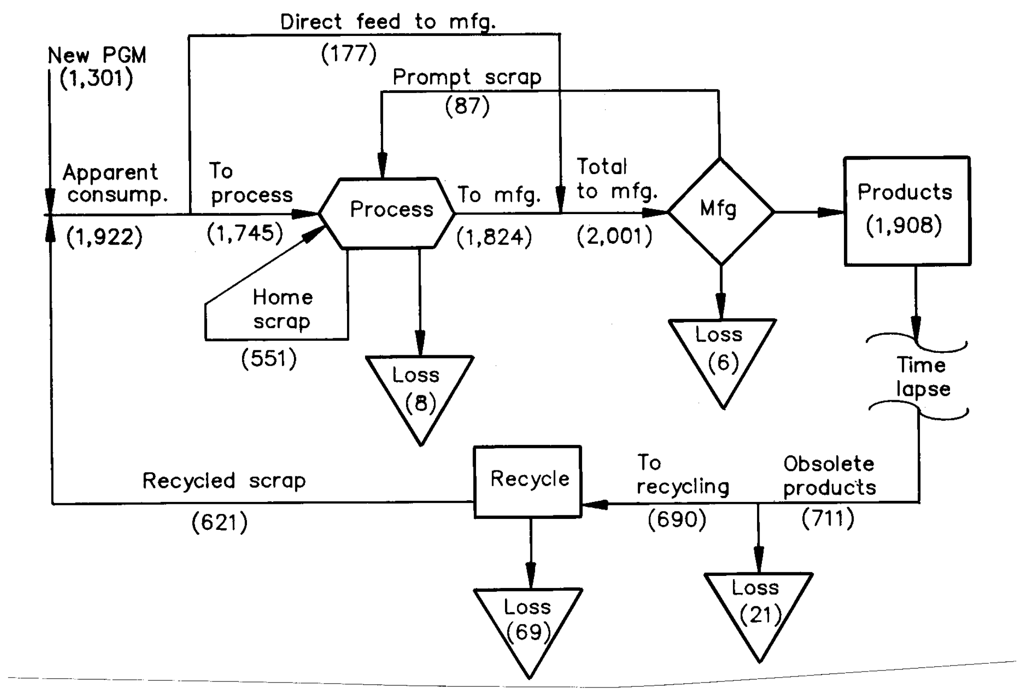

Figure 7.—Flow of PGM in glass industry in 1989 (amounts in kilograms of contained PGM).

From 1984 apparent consumption of PGM, about 711 kg was potentially recyclable (*29*). Approximately 21 kg was lost in unknown and unrecovered material. During recycle processing, about 69 kg was lost and 621 kg was recycled.

JEWELRY AND DECORATIVE INDUSTRY

In this industry PGM are used as strengtheners in alloys and as settings for gemstones. Some are also used for decorative coatings on a variety of products. Flow of PGM in this industry is shown in figure 8. The jewelry and decorative industry's apparent consumption of PGM was 1,051 kg: 1,021 kg of new PGM and 30 kg of recycled obsolete scrap. About 97 kg reported directly to manufacturing and 954 kg reported to processing. Forty-eight kilograms of prompt scrap also reported to processing. During processing, about 5 kg was lost as unrecovered waste, 302 kg was continuously recycled home scrap, and 997 kg went to manufacturing. Of the total 1,094 kg that went to manufacturing, about 3 kg was lost as waste, 48 kg was manufacturing prompt scrap recycled to processing, and 1,043 kg reported in products. From 1979 consumption, about 1,674 kg was potentially recyclable (*27*). However, because of the nature of jewelry and decorative products, only a small amount was available for recycle. Thus, an estimated 1,641 kg was lost, held, or hoarded, and only 33 kg was available for recycling. About 3 kg was lost in recycling and 30 kg was recycled to new products in 1989.

MISCELLANEOUS OTHER INDUSTRIES

These industries by themselves are small consumers of PGM, but as a group they consumed about 10 pct of total PGM apparent consumption in 1989. Typical examples of uses of PGM in these industries are for fuel cell electrodes, crucibles for molten lead and bismuth, containers for high-temperature materials, neutron absorbers, intense gamma-ray sources, magnets, laboratory ware, and reflectors for ultraviolet and infrared radiation. The flow of PGM for this industry group is shown in figure 9. In 1989, apparent consumption was 10,023 kg: 5,905 kg of new PGM and 4,118 kg of recycled obsolete scrap. About 923 kg reported directly to manufacturing and 9,100 kg reported to processing. About 455 kg of prompt scrap also reported to processing. During processing, 2,878 kg was continuously recycled home scrap and 46 kg was lost as waste. The remaining 9,509 kg reported to manufacturing.

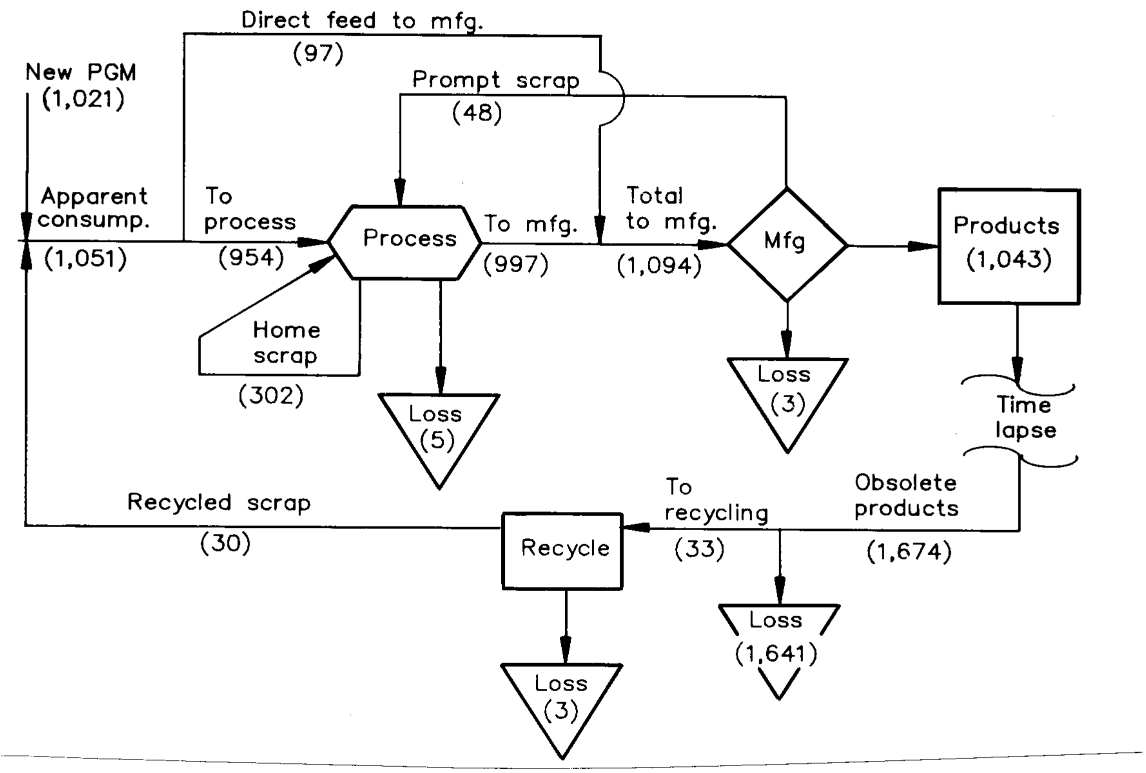

Figure 8.—Flow of PGM in jewelry and decorative industry in 1989 (amounts in kilograms of contained PGM).

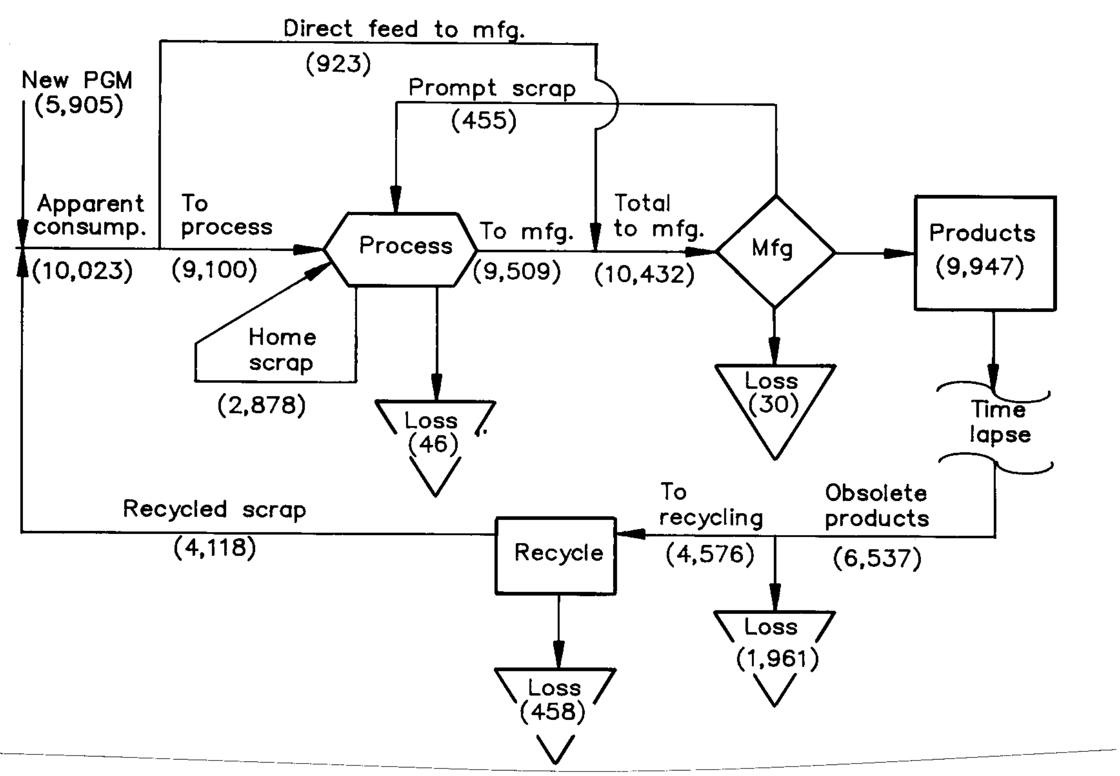

Figure 9.—Flow of PGM in miscellaneous other industries in 1989 (amounts in kilograms of contained PGM).

During manufacturing, 455 kg was recycled to processing as prompt scrap, 30 kg was manufacturing loss, and 9,947 kg reported as products.

Assuming an average 5-year lifetime, 6,537 kg was available in 1989 as potentially recyclable obsolete scrap from 1984 apparent consumption (*29*). About 1,961 kg went to unknown and unrecovered losses. During recycle processing, 458 kg was lost as unrecovered waste and 4,118 kg was recycled for 1989 consumption.

OVERALL PLATINUM-GROUP METALS INDUSTRY

In 1989, input to apparent consumption included imports of 111,107 kg of PGM: 6,280 kg of PGM from domestic mining and byproduct production, 2,972 kg of PGM from industry stocks (35,515 kg end of 1988 minus 32,543 kg end of 1989), and 3,954 kg from secondary non-toll-refined PGM. Of this, 23,082 kg of PGM was exported and 101,233 kg reported to U.S. apparent consumption (see figure 10). Figure 11 shows the overall view of the combined PGM-consuming industries. In 1989, these industries had an apparent consumption of 101,233 kg of PGM: 25,634 kg of recycled obsolete scrap and 75,599 kg of new PGM. About 9,325 kg reported directly to manufacturing. The feed to processing included 91,908 kg of new and recycled obsolete PGM scrap and 6,288 kg of prompt scrap. Processing output reported as 471 kg to miscellaneous losses and 97,725 kg to manufacturing feed. During processing, 29,576 kg of home scrap was generated and recycled internally. Manufacturing feed included 9,325 kg of direct PGM feed and 97,725 kg of processed PGM. Manufacturing output was reported as 6,288 kg to prompt scrap, 491 kg to manufacturing losses, and 100,271 kg to products.

From 1979 apparent PGM consumption in the automotive, electrical and electronics, and jewelry and decorative products industries; 1984 apparent PGM consumption in the glass and miscellaneous other industries; and 1986 apparent PGM consumption in the dental and medical, chemical, and petroleum industries, a total of 92,358 kg of PGM was potentially recyclable in 1989 (see table 2). About 63,426 kg of PGM was unavailable for recycle because of dissipative, unknown, and unrecovered losses to the U.S. economy. Some of this material is probably exported scrap and waste. Of the 28,932 kg processed for recycle, about 3,298 kg reported as recycle losses and about 25,634 kg was effectively recycled.

Table 2.—Lifetimes of products from industries that use PGM and estimated amounts of PGM potentially available for recycle

Industry	Product lifetime, years	Year of production	Potentially recyclable, kg[1]
Automotive	10	1979	35,732
Electrical and electronics	10	1979	19,478
Dental and medical	3	1986	15,302
Petroleum	3	1986	4,835
Chemical	3	1986	8,089
Glass	5	1984	711
Jewelry and decorative	10	1979	1,674
Miscellaneous other	5	1984	6,537
Total			92,358

[1]References 27-29.

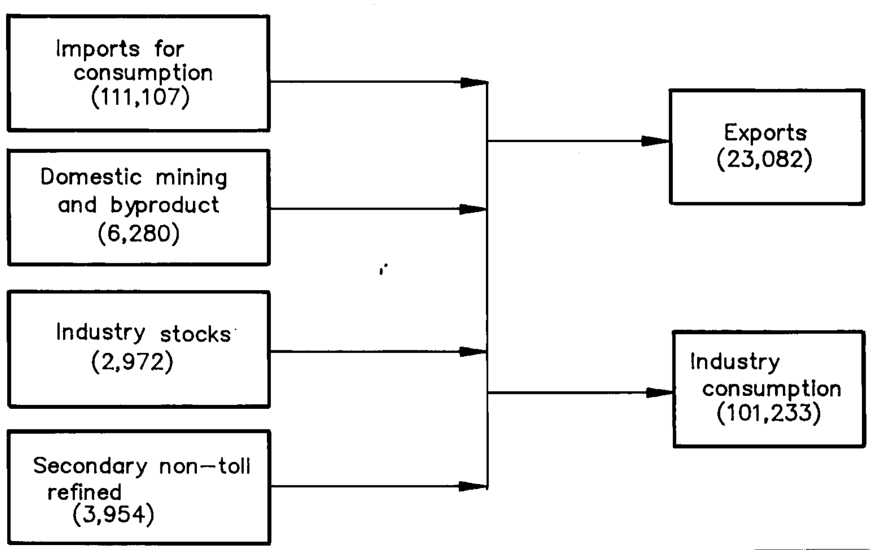

Figure 10.—Raw material flow in PGM industry in 1989 (amounts in kilograms of contained PGM). (Numbers do not total because of independent rounding.)

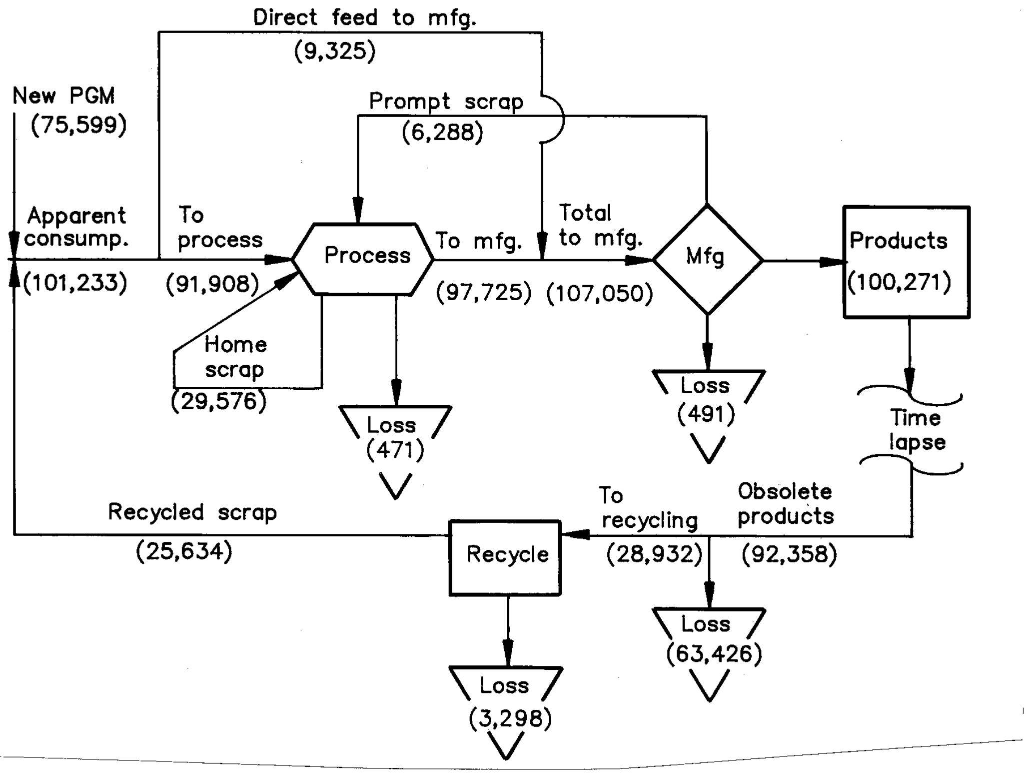

Figure 11.—Overall PGM flow in 1989 (amounts in kilograms of contained PGM).

Significant and total losses from the PGM industry are shown in table 3. The three major loss areas were unknown and unrecovered obsolete scrap from the automotive industry (29,871 kg), unknown and unrecovered obsolete scrap from the electrical and electronics industry (14,500 kg), and dissipative and unrecovered obsolete scrap from the dental and medical industries (15,287 kg). The combined losses totaled about 59 pct of the 1989 apparent consumption of PGM.

Table 3.—Estimated losses of PGM in 1989, kilograms and percentage of apparent consumption

Industry[1]	Type of loss[2]	Amount, kg	Pct of 1989 total apparent consumption
Automotive	Unknown and unrecovered	29,871	29.5
Dental and medical	Dissipative and unrecovered	15,287	15.1
Electrical and electronics	Unknown and unrecovered	14,500	14.3
Miscellaneous other	Dissipative, unknown and unrecovered	1,961	1.9
Jewelry and decorative	Unknown and unrecovered	1,641	1.6
Chemical	Use, unknown, unrecovered, and recycling	1,213	1.2
All industries	All other losses[3]	3,213	3.2
Total		67,688	66.9

[1]Petroleum and glass industry losses are included in figures for "All industries."

[2]Losses of obsolete scrap products, except as noted.

[3]Losses from manufacturing, processing, and recycling for all industries, except those listed above.

Current technology for recovery of PGM from obsolete automotive catalytic converters has reduced losses during recycling to about 10 pct (*30*). Preliminary Bureau research has increased recycling yields to the 98- to 99-pct range on new catalytic converters with a sodium cyanide (NaCN) leach process (*31*). The major loss area was in unrecovered or exported catalytic converters. The recycling industry is driven by economics. Cunningham estimated that about 30 pct of automobile catalyst PGM would be recycled at a PGM price of $6,430/kg, and 60 to 65 pct of automobile catalyst PGM would be recycled at a PGM price of $25,721/kg (*32*). The 1989 recycling rate was about 16 pct, with a PGM price of about $12,860/kg, considerably below Cunningham's prediction. Processing economics for removal and recovery of obsolete catalytic converters, decanning of the catalyst and support, and recovery of the PGM evidently will have to improve before recycling will begin in the United States to recover the majority of PGM in obsolete catalytic converters. In 1988 Hoffmann reported that, as technology for stratified or lean combustion engines matures, the use of catalytic converters for automobile emission control may decrease or end (*30*). Thus, processes requiring significant capital investment with long payback times are, at best, risky investments. Hoffman also stated that processing in an existing copper or nickel smelter might be the best means of recycling the PGM in automobile catalysts because "during smelting the PGM report virtually completely in the copper or nickel matte" (*30*). The PGM could then be recovered during refining.

The unknown and unrecovered losses of PGM in electrical and electronic products are the third highest loss area for PGM. In these end uses the PGM are widely dispersed in small concentrations or amounts in a wide variety of devices. The Bureau conducted research on the recovery of precious metals from electronic scrap that was reported in 1980 (*33-34*), 1983 (*35-36*), and 1986 (*37*). At the present time this technology is not being used to any great extent. It appears that new research will be needed to provide better, more efficient, more economical processes to recover PGM from electrical and electronic scrap. The major factor affecting recovery of PGM from this industry's obsolete products is probably their wide dispersal at very low concentrations in obsolete scrap.

PGM losses in the dental and medical industry are due to the dissipative and permanent nature of their final products. PGM in these fields are predominantly used in dental and medical prostheses. Among these devices are dental caps, crowns, and bridges. Some PGM are used in orthodontic braces. These are recycled, but only amount to a small portion of PGM used in this field. All other dental prostheses are essentially permanent implants. Some medical prostheses also contain PGM, but, again, these are permanent implants. The other uses of PGM in the medical field are as anticancer chemotherapy pharmaceuticals. As such, they are used in dissipative end uses and are not recovered. As far as can be found, there was only the small amount of recycle of orthodontic braces in this industry, and no studies of the recovery of PGM from prostheses are being carried out or contemplated.

The next highest loss area was in the miscellaneous other industries' uses. Many of the end uses had dissipative, unknown, or unrecovered products for a variety of reasons, and about 1,961 kg of PGM was lost in these end uses. About 1,641 kg of PGM was lost in unknown and unrecovered PGM from the jewelry and decorative industry. Most of this consumption resulted in products that were held or hoarded and, thus, not recycled. In the chemical industry, the dissipative, unknown, unrecovered and recycling losses amounted to 1,213 kg of PGM. As much as 15 pct of chemical catalysts were lost in use (*4*). This amount of PGM probably reported as very minor contamination of the final chemical products produced by using these catalysts, along with some small regeneration losses during the catalysts' use lives.

Below this level, all other PGM losses from all industries represented only about 3 pct of total PGM apparent consumption in 1989.

SUMMARY

A commodity flow model was developed for the industries that consume PGM. Based on available data, the model follows PGM through its processing, manufacturing, and recycling operations showing estimated values for material lost through these operations. The model was developed using certain estimates and assumptions and the best data available at this time. The model can be easily updated as new data become available. The multiplication factors will all change with time. New factors can replace older ones as data are acquired.

An industry flowchart was presented for each of the industries that consume PGM. The overall flow of the PGM commodity was also presented. The apparent consumption of PGM in 1989 was 101,233 kg. The estimated amounts consumed by the various industries were shown in table 1. The largest amounts consumed were in the automotive industry, in which PGM were used mainly as catalysts for emission control; the electrical and electronics industry, in which PGM were used in contacts and various electronic devices; and the dental and medical industry, in which PGM were consumed as prostheses and in chemotherapy pharmaceuticals. Other uses of PGM were as petroleum and chemical catalysts; spinnerettes, crucibles, and bushings in the glass industry; in jewelry and other decorative items; and in various other small industries.

Based on the estimated lifetimes of the various products and the estimated amounts consumed in 1979 (10 years), 1984 (5 years), and 1986 (3 years), there were potentially recyclable products containing 92,358 kg of PGM in 1989 (see table 2). From literature data, an estimated 25,634 kg that can be traced was recycled in 1989 for consumption. Loebenstein shows a total of 50,207 kg of secondary PGM, 3,954 kg as non-toll refined and 46,253 kg as toll refined (*1*). The difference between the reported 50,207 kg refined-recycled from secondary sources and the 25,634 kg estimated recycled from literature data is probably part of the estimated new PGM used in the various industries. There is currently no means of tracing the source from which this additional 24,573 kg of recycled PGM comes.

CONCLUSIONS

A PGM flow model has been developed. The mathematical relationships in the model are discussed in the appendix. The model estimates the distribution of 101,233 kg of PGM consumed in the eight PGM industries. The best available data show that an estimated 962 kg of PGM was lost during processing and manufacturing operations, 6,288 kg of PGM in efficiently recycled prompt scrap was produced during manufacturing, and 29,576 kg of efficiently recycled home scrap was generated during processing. Of the material potentially available for recycling estimated with current available data, the disposition of only about 28,932 kg to recycling can be followed. The remaining 63,426 kg of PGM as unknown, unrecovered, use-life, or dissipative losses cannot be traced with current data. There is a need to obtain data that trace where this material goes. Thus, it is recommended that the Bureau make changes in its data-gathering survey sheets to obtain the required information on a continuing basis. This would provide a continuously up-to-date flow model that could be supplied to those requiring the information to develop national policy regarding PGM.

REFERENCES

1. Loebenstein, J. R. Platinum-Group Metals. BuMines Minerals Yearbook 1989, v. 1, 11 pp. (preprint).

2. U.S. Congress, Office of Technology Assessment. Effects of the Katangese Rebellion on the World Cobalt Market. 1982, 74 pp.; NTIS PB 86-154085.

3. National Materials Advisory Board—National Research Council. Cobalt Conservation Through Technological Alternatives (BuMines contract J0113103). Nat. Acad. Press, Publ. NMAB-406, 1983, 204 pp.

4. ____. Supply and Use Patterns for the Platinum-Group Metals (U.S. Gen. Serv. Administr., U.S. Dep. Commerce, and BuMines contract GS-00-DS-(P)-94008). Nat. Acad. Press, Publ. NMAB-359, 1980, 197 pp.

5. Petersen, G. R., D. I. Bleiwas, and P. R. Thomas. Cobalt Availability—Domestic. A Minerals Availability System Appraisal. BuMines IC 8848, 1981, 31 pp.

6. Mishra, C. P., C. D. Sheng-Fogg, R. G. Christiansen, J. F. Lemons, Jr., and D. L. DeGiacomo. Cobalt Availability—Market Economy Countries. A Minerals Availability Program Appraisal. BuMines IC 9012, 1985, 33 pp.

7. U.S. Department of Commerce. Critical Materials Requirements of the U.S. Steel Industry. U.S. GPO, 1983, 259 pp.

8. National Materials Advisory Board—National Research Council. Basic and Strategic Metals Industries: Threats and Opportunities. Nat. Acad. Press, Publ. NMAB-425, 1985, 151 pp.

9. Kilgore, C. C., and P. R. Thomas. Manganese Availability—Domestic. A Minerals Availability System Appraisal. BuMines IC 8889, 1982, 14 pp.

10. Anstett, T. F., D. I. Bleiwas, and C. Sheng-Fogg. Platinum Availability—Market Economy Countries. A Minerals Availability System Appraisal. BuMines IC 8897, 1982, 16 pp.

11. U.S. Bureau of Mines. An Appraisal of Minerals Availability for 34 Commodities. BuMines B 692, 1987, 300 pp.

12. Papp, J. F. Letter Report (U.S. Air Force Mil. Interdep. Purchase Request FY615-87-05292), July 29, 1987, 19 pp. Available from R. C. Gabler, Jr., BuMines, Albany, OR.

13. Kusik, C. L., H. V. Makar, and M. R. Mounier. Availability of Critical Scrap Metals Containing Chromium in the United States. Wrought Stainless Steels and Heat-Resisting Alloys. BuMines IC 8822, 1980, 51 pp.

14. Curwick, L. R., W. A. Petersen, and H. V. Makar. Availability of Critical Scrap Metals Containing Chromium in the United States. Superalloys and Cast Heat- and Corrosion-Resistant Alloys. BuMines IC 8821, 1980, 51 pp.

15. U.S. Congress, Office of Technology Assessment. Strategic Materials: Technologies To Reduce U.S. Import Vulnerability. OTA-ITE-248, 1985, 409 pp.

16. Gabler, R. C., Jr., and W. D. Riley. A Cobalt Commodity Recycling Flow Model. BuMines IC 9252, 1990, 16 pp.

17. Gabler, R. C., Jr. A Cobalt Commodity Recycling Flow Model. Paper in Proceedings of the Second International Symposium on Recycling of Metals and Engineered Materials, ed. by L. H. L. van Linden, D. L. Stewart, Jr., and Y. Sahai. Metall. Soc. AIME, 1990, pp. 119-136.

18. Worff, H. H., Jr. United States Reliance on Import of Minerals and Metals: A Case Study. M.A. Thesis, Univ. TX, Austin, TX, 1978, 134 pp.

19. U.S. Congress, Office of Technology Assessment. Strategic and Critical Mineral Position of the United States With Respect to Chromium, Nickel, Cobalt, Manganese, and Platinum. OTA Working Pap., 1983, 467 pp.

20. Kusler, D. J. Demand for Platinum To Reduce Pollution From Automobile Exhausts. BuMines IC 8565, 1973, 32 pp.

21. U.S. Bureau of Mines. South Africa and Critical Materials. BuMines OFR 76-86, 1986, 86 pp.; NTIS PB 86-236601.

22. Robertson, A. R. Precious Metals and Their Uses. Ch. in Metals Handbook, v. 2. ASM, 10th ed., 1990, pp. 688-695.

23. Riley, W. D., C. B. Daellenbach, and R. C. Gabler, Jr. Recycling of Electronic Scrap. Ch. in Metals Handbook, v. 2. ASM, 10th ed., 1990, pp. 1228-1232.

24. Hennion, F. J. Availability of Precious Metals From Spent Catalysts. Ch. in Platinum-Group Metals—An In-Depth View of the Industry, ed. by D. E. Lundy and E. D. Zysk. Int. Precious Met. Inst., 1983, pp. 61-81.

25. Coombes, J. S. Platinum 1990. Johnson-Matthey PLC, 1990, 64 pp.

26. Mining Journal. Platinum Pauses for Breath. V. 314, No. 8071, 1990, pp. 406-407.

27. Moore, C. M. Platinum-Group Metals. Ch. in BuMines Minerals Yearbook 1980, v. 1, pp. 629-650.

28. Loebenstein, J. R. Platinum-Group Metals. Ch. in BuMines Minerals Yearbook 1987, v. 1, pp. 741-753.

29. ____. Platinum-Group Metals. Ch. in BuMines Minerals Yearbook 1986, v. 1, pp. 741-753.

30. Hoffmann, J. E. Recovering Platinum-Group Metals From Auto Catalysts. J. Met., v. 40, No. 6, 1988, pp. 40-44.

31. Atkinson, G. B., D. P. Desmond, R. J. Kuczynski, and L. A. Walters. Recovery of PGM From Virgin Automotive Catalysts by Cyanide Leaching. Paper in Platinum-Group Metals and the Quality of Life, ed. by A. Austin, C. M. Barnard, and G. E. Haslam. Int. Precious Met. Inst., 1989, pp. 109-115.

32. Cunningham, C. E. Pre-Recovery-System and Recovery-System Losses of Platinum-Group Metals Contained in Automotive Catalytic Converters. A-1 Specialized Services and Supplies, Inc., Edison, NJ, 1984, 20 pp.

33. Dunning, B. W., Jr., and F. Ambrose. Characterization of Pre-1957 Avionic Scrap for Resource Recovery. BuMines RI 8499, 1980, 20 pp.

34. Ambrose, F., and B. W. Dunning, Jr. Precious Metal Recovery From Electronic Scrap. Paper in Proceedings of the Seventh Mineral Waste Utilization Symposium. IIT Res. Inst., 1980, pp. 184-197.

35. Dunning, B. W., Jr., F. Ambrose, and H. V. Makar. Distribution and Analyses of Gold and Silver in Mechanically Processed Mixed Electronic Scrap. BuMines RI 8788, 1983, 17 pp.

36. Hilliard, H. E., and B. W. Dunning, Jr. Recovery of Platinum-Group Metals and Gold From Electronic Scrap. Ch. in Platinum-Group Metals—An In-Depth View of the Industry, ed. by D. E. Lundy and E. D. Zysk. Int. Precious Met. Inst., 1983, pp. 129-142.

37. Dunning, B. W., Jr. Precious Metals Recovery From Electronic Scrap and Solder Used in Electronics Manufacture. BuMines IC 9059, 1986, pp. 44-56.

APPENDIX

This section discusses the assumptions and mathematics used in developing the PGM commodity flow model. The assumptions for the overall PGM data are as follows:

1. The difference between reported consumption and apparent consumption is proportionally divided among the components of "U.S. consumption of PGM in various industries" (see table 1 in main text). The apparent consumption values were calculated as follows:

$$IAC = IRC \times TAC/TRC, \qquad (A\text{-}1)$$

where IAC = 1989 apparent consumption of PGM by the industry,

IRC = 1989 reported consumption of PGM by the industry,

TAC = 1989 total apparent consumption of PGM,

and TRC = 1989 total reported consumption of PGM.

The data under "apparent consumption" were used in the flow model.

2. Where more recent data were found, the percentage reporting in each category was used. Where no current data were available, the data reported by NMAB were used and assumed to be still valid until new data are available (*4*).[1]

3. The use lives of various industry products vary over a wide range. While Kusler (*20*) estimated a life span of 5 years for automotive catalytic converters in 1973, a 1985 document indicates a current life expectancy of 10 years (*15*). Hennion estimates an average life of 3 years for petroleum and chemical catalysts (*24*). No other lifetime estimates of PGM-containing products were found. A lifetime of 10 years for electrical and electronic products, 5 years for glass devices, and 5 years for miscellaneous other products are assumed.

4. Lifetimes for medical and dental products and for jewelry and decorative products are mostly very long and there is little recycling of many of the products. For those few dental devices that are recycled, i.e., orthodontic braces, a lifetime of 3 years is assumed. For the few jewelry and decorative products recycled, a lifetime of 10 years is assumed.

[1]Italic numbers in parentheses refer to items in the list of references preceding this appendix.

5. Thus, it was assumed that potentially recyclable obsolete items from the 1979 automotive, electrical and electronics, and jewelry and decorative industries would be recycled in 1989. The 1984 glass and miscellaneous other industries' obsolete products would be recycled in 1989. The 1986 dental and medical, petroleum, and chemical industries' obsolete products and devices would be recycled in 1989.

AUTOMOTIVE INDUSTRY

As stated above, potentially recyclable PGM-bearing materials from this industry's 1979 obsolete products would be available for recycle in 1989. The obsolete scrap estimated to be recycled was determined using data from "Platinum 1990" (*25*) as follows:

Summing up the North American recovery of platinum and palladium from scrap as reported in "Platinum 1990,"

$$NA = NAPt + NAPd, \qquad (A\text{-}2)$$

where NA = sum of platinum and palladium recovered in North America in 1989 from automobile emission control catalysts,

NAPt = platinum recovered in North America in 1989 from automobile emission control catalysts,

and NAPd = palladium recovered in North America in 1989 from automobile emission control catalysts.

Summing up the recovery of platinum and palladium in Japan reported in "Platinum 1990" (*25*),

then $$JPN = JPt + JPd, \qquad (A\text{-}3)$$

where JPN = platinum and palladium recovered in Japan in 1989 from automobile emission control catalysts,

JPt = platinum recovered in Japan in 1989 from automobile emission control catalysts,

and JPd = palladium recovered in Japan in 1989 from automobile emission control catalysts.

Japan and North America were the only areas in the world where PGM were recovered from obsolete scrap automobile emission control catalysts in 1989;

thus, $$WOR = NA + JPN, \tag{A-4}$$

where WOR = world recovery of platinum and palladium in 1989 from automobile emission control catalysts.

Only world recovery of rhodium is reported in "Platinum 1990" (*25*). Assuming that the ratio of North American platinum and palladium recovery to world platinum and palladium recovery is valid for rhodium,

then $$NARh = WRh \times NA/WOR, \tag{A-5}$$

where NARh = North American recovery of rhodium in 1989 from automobile emission control catalysts,

and WRh = world recovery of rhodium in 1989 from automobile emission control catalysts.

Assuming that 80 pct of PGM recovered in North America is PGM recovered in the United States,[2]

then $$USR = (NA + NARh) \times 0.80, \tag{A-6}$$

where USR = PGM recovered in the United States in 1989 from obsolete automobile emission control catalysts produced in 1979,

and 0.80 = fraction of PGM recovered in North America in 1989 from obsolete automobile emission control catalysts that is PGM recovered in the United States.[3]

Johns states that about 10 pct is lost during recycling (*15*).

Then $$A = USR \times C/D, \tag{A-7}$$

where A = obsolete scrap recovered for recycling,

C = 1.00 (fraction available for recycling),

and D = 0.90 (fraction recycled).

Then $$E = USR \times F/D, \tag{A-8}$$

where E = recycling losses,

and F = 0.10 (fraction lost in recycling).

The remainder of the material potentially available for recycle from obsolete automotive scrap is determined as follows:

$$G = H \times I/J, \tag{A-9}$$

where G = amount of potentially available automotive scrap for recycling in 1989,

H = 1979 reported consumption of PGM by the automotive industry (*27*),

I = 1979 total apparent consumption of PGM (*27*),

and J = 1979 total reported consumption of PGM (*27*).

Then $$K = G - A, \tag{A-10}$$

where K = unknown and unrecovered losses of PGM during life cycle of 1979 products potentially available for recycle.

Then $$L = M - USR, \tag{A-11}$$

where L = new PGM input to the automotive industry in 1989,

and M = 1989 apparent consumption of PGM in the automotive industry (see table 1).

Then $$N = M \times 0.09211, \tag{A-12}$$

where N = raw material feed that reported directly to manufacturing,

and 0.09211 = fraction of raw material feed that reported directly to manufacturing (*4*).

Then $$O = M - N, \tag{A-13}$$

where O = total outside feed to processing.

Then $$P = O \times 0.3012, \tag{A-14}$$

[2]Information from J. R. Loebenstein, PGM Specialist, Division of Mineral Commodities, Information and Analysis Directorate, U.S. Bureau of Mines.

[3]See appendix footnote 2.

where P = home scrap generated during processing,

and 0.3012 = fraction of total outside feed to processing that reported to home scrap (*4*).

Then $$Q = O \times 0.0048, \quad \text{(A-15)}$$

where Q = processing losses,

and 0.0048 = fraction of total outside feed to processing that reported to losses (*4*).

Then $$R = O - Q, \quad \text{(A-16)}$$

where R = processing feed to manufacturing.

Then $$S = R + N, \quad \text{(A-17)}$$

where S = total feed to manufacturing.

Then $$T = S \times 0.0084, \quad \text{(A-18)}$$

where T = manufacturing losses,

and 0.0084 = fraction of total feed to manufacturing that reported to manufacturing losses (*4*).

Then $$U = S - T, \quad \text{(A-19)}$$

where U = PGM contained in automotive products produced in 1989.

ELECTRICAL AND ELECTRONICS INDUSTRY

This industry is characterized by recycling about 23 pct of its own obsolete parts (*15*). The amount recycled is calculated as follows:

$$V = W \times Y/Z, \quad \text{(A-20)}$$

where V = 1979 apparent consumption of PGM by the electrical and electronics industry,

W = 1979 reported consumption of PGM by the electrical and electronics industry (*27*),

Y = 1979 total apparent consumption of PGM (*27*),

and Z = 1979 total reported consumption of PGM (*27*).

Then $$AA = V \times 0.23, \quad \text{(A-21)}$$

where AA = amount recycled in 1989,

and 0.23 = fraction of 1979 obsolete scrap recycled in 1989 (*15*).

Recycling losses are estimated at 10 pct (*15*); thus, "AA" equals 90 pct of the amount fed to recycling.

Then $$BB = V \times CC/DD, \quad \text{(A-22)}$$

where BB = obsolete scrap recovered for recycling,

CC = 1.00 (total amount),

and DD = 0.90 (fraction fed to recycling).

Then $$EE = BB \times 0.10, \quad \text{(A-23)}$$

where EE = recycling losses,

and 0.10 = fraction lost in recycling (*15*).

Then $$FF = V - BB, \quad \text{(A-24)}$$

where FF = unknown and unrecovered losses.

The 1989 apparent consumption of PGM by the electrical and electronics industry was 30,210 kg (see table 1).

Then $$GG = HH - AA, \quad \text{(A-25)}$$

where GG = new PGM consumed in 1989,

and HH = 1989 apparent consumption of PGM by the electrical and electronics industry (*1*).

Then $$II = HH \times 0.09211, \quad \text{(A-26)}$$

where II = raw material that reported directly to manufacturing,

and 0.09211 = fraction of apparent consumption that reported directly to manufacturing (*4*).

Then $$JJ = HH - II, \quad \text{(A-27)}$$

where JJ = raw material feed to processing.

Assuming that prompt scrap equals 5 pct of raw material feed to processing,

then $$KK = JJ \times 0.05, \quad \text{(A-28)}$$

where KK = prompt scrap generated in manufacturing and returned as feed to processing,

and 0.05 = fraction of raw material reporting to processing that was recycled as prompt scrap.

Then $$LL = KK + II, \quad \text{(A-29)}$$

where LL = total outside feed to processing.

Then $$MM = LL \times 0.3012, \quad \text{(A-30)}$$

where MM = home scrap generated during processing,

and 0.3012 = fraction of total outside feed to processing that reported to home scrap (*4*).

Then $$NN = LL \times 0.0048, \quad \text{(A-31)}$$

where NN = processing losses,

and 0.0048 = fraction of total outside feed to processing that reported to processing losses (*4*).

Then $$OO = LL - NN, \quad \text{(A-32)}$$

where OO = processing feed to manufacturing.

Then $$PP = OO + II, \quad \text{(A-33)}$$

where PP = total feed to manufacturing.

Then $$QQ = PP \times 0.0029, \quad \text{(A-34)}$$

where QQ = manufacturing losses,

and 0.0029 = fraction of total feed to manufacturing that reported to manufacturing losses (*4*).

Then $$RR = PP - QQ - KK, \quad \text{(A-35)}$$

where RR = PGM contained in electrical and electronic products produced in 1989.

DENTAL AND MEDICAL INDUSTRY

Very little obsolete scrap is ever recycled except for small amounts in orthodontic prostheses, because most end uses are dissipative (cancer drugs) or permanent implants. Recovery of obsolete prostheses is not a socially acceptable practice. Assuming that only a small amount is recycled (0.1 pct) from orthodontic braces and a lifetime of 3 years, the amount is calculated as follows:

$$SS = TT \times UU/VV, \quad \text{(A-36)}$$

where SS = 1986 apparent consumption of PGM by the dental and medical industry,

TT = 1986 reported consumption of PGM by the dental and medical industry (*29*),

UU = 1986 total apparent consumption of PGM (*29*),

and VV = 1986 total reported consumption of PGM (*29*).

The dissipated, unknown, and unrecovered obsolete PGM dental and medical scrap is calculated as follows:

$$WW = SS \times 0.999, \quad \text{(A-37)}$$

where WW = dissipative, unknown, and unrecovered losses from obsolete scrap,

and 0.999 = fraction of potentially available scrap not recovered for recycling.

Then $$YY = SS - WW, \quad \text{(A-38)}$$

where YY = obsolete scrap recovered for recycling.

Then $$ZZ = YY \times 0.10, \quad \text{(A-39)}$$

where ZZ = recycling losses,

and 0.10 = fraction lost in recycling (*15*).

Then $$AB = YY - ZZ, \quad \text{(A-40)}$$

where AB = amount of obsolete scrap recycled to 1989 consumption.

Then, in 1989 consumption and production, the use pattern is as follows:

$$AC = AD - AB, \quad \text{(A-41)}$$

where AC = new PGM consumed in 1989,

and AD = 1989 apparent consumption of PGM by the dental and medical industry (see table 1).

Then $$AE = AD \times 0.09211, \quad \text{(A-42)}$$

where AE = raw material that reported directly to manufacturing,

and 0.09211 = fraction of apparent consumption that reported directly to manufacturing (*4*).

Then $$AF = AD - AE, \quad \text{(A-43)}$$

where AF = raw material feed to processing.

Dental castings are about two times installed weight or 50 pct prompt scrap (*4*). Assuming dental is 80 pct of dental and medical processing material,

then $$AG = AF \times AH \times AI, \quad \text{(A-44)}$$

where AG = prompt scrap generated in manufacturing and returned as feed to processing,

AH = 0.80 or fraction of raw material feed to processing that becomes dental products,

and AI = 0.50 or fraction of raw material reporting to processing that was recycled as prompt scrap.

Then $$AJ = AI + AF, \quad \text{(A-45)}$$

where AJ = total outside feed to processing.

Then $$AK = AJ \times 0.3012, \quad \text{(A-46)}$$

where AK = home scrap generated during processing,

and 0.3012 = fraction of total outside feed to processing that reported to home scrap (*4*).

Then $$AL = AJ \times 0.0048, \quad \text{(A-47)}$$

where AL = processing losses,

and 0.0048 = fraction of total outside feed to processing that reported to processing losses (*4*).

Then $$AM = AJ - AL, \quad \text{(A-48)}$$

where AM = processing feed to manufacturing.

Then $$AN = AM + AE, \quad \text{(A-49)}$$

where AN = total feed to manufacturing.

Then $$AO = AN \times 0.0029, \quad \text{(A-50)}$$

where AO = manufacturing losses,

and 0.0029 = fraction of total feed to manufacturing that reported to manufacturing losses (*4*).

Then $$AP = AN - AO, \quad \text{(A-51)}$$

where AP = PGM contained in dental and medical products produced in 1989.

PETROLEUM INDUSTRY

Petroleum catalysts last about 3 years. Recycle in this industry is very efficient with about a 3-pct loss in use (*4*). Assuming that the catalysts have this 3-year life span before recycling, that the obsolete scrap came from 1986 apparent consumption for petroleum catalysts, and that apparent consumption is divided proportionally to reported consumption,

then $$AQ = AR \times AS/AT, \quad \text{(A-52)}$$

where AQ = 1986 apparent consumption of PGM by the petroleum industry,

AR = 1986 reported consumption of PGM by the petroleum industry (*28*),

AS = 1986 total apparent consumption of PGM (*28*),

and AT = 1986 total reported consumption of PGM (*28*).

Then $$AU = AQ \times 0.03, \quad \text{(A-53)}$$

where AU = loss in use of PGM in petroleum catalysts produced in 1986,

and 0.03 = fraction of 1984 apparent consumption that reported to 1984 products loss in use.

Then $$AV = AQ - AU, \qquad \text{(A-54)}$$

where AV = obsolete scrap recovered for recycling.

Then $$AW = AV \times 0.10, \qquad \text{(A-55)}$$

where AW = recycling losses,

and 0.10 = fraction lost in recycling (*15*).

Then $$AX = AV - AW, \qquad \text{(A-56)}$$

where AX = amount of obsolete scrap recycled to 1989 consumption.

Then $$AZ = BA - AX, \qquad \text{(A-57)}$$

where AZ = new PGM consumed in 1989,

and BA = 1989 apparent consumption of PGM by the petroleum industry (see table 1).

Then $$BBB = BA \times 0.09211, \qquad \text{(A-58)}$$

where BBB = raw material that reported directly to manufacturing,

and 0.09211 = fraction of apparent consumption that reported directly to manufacturing (*4*).

Then $$BC = BA - BBB, \qquad \text{(A-59)}$$

where BC = total outside feed to processing.

Then $$BD = BC \times 0.3012, \qquad \text{(A-60)}$$

where BD = home scrap generated during processing,

and 0.3012 = fraction of total outside feed to processing that reported to home scrap (*4*).

Then $$BE = BC \times 0.0048, \qquad \text{(A-61)}$$

where BE = processing losses,

and 0.0048 = fraction of total outside feed to processing that reported to processing losses (*4*).

Then $$BF = BC - BE, \qquad \text{(A-62)}$$

where BF = processing feed to manufacturing.

Then $$BG = BF + BBB, \qquad \text{(A-63)}$$

where BG = total feed to manufacturing.

Then $$BH = BG \times 0.0029, \qquad \text{(A-64)}$$

where BH = manufacturing losses,

and 0.0029 = fraction of total feed to manufacturing that reported to manufacturing losses (*4*).

Then $$BI = BG - BH, \qquad \text{(A-65)}$$

where BI = PGM contained in catalysts in the petroleum industry in 1989.

CHEMICAL INDUSTRY

Chemical catalysts last about 3 years and account for the vast majority of PGM consumed by the chemical industry. Thus, it is assumed that all chemical industry consumption of PGM is in chemical catalysts. Obsolete catalyst scrap for recycle would have been generated from products manufactured in 1986.

Then $$BJ = BK \times BL/BM, \qquad \text{(A-66)}$$

where BJ = 1986 apparent consumption of PGM by the chemical industry,

BK = 1986 reported consumption of PGM by the chemical industry (*28*),

BL = 1986 total apparent consumption of PGM (*28*),

and BM = 1986 total reported consumption of PGM (*28*).

NMAB stated that 85 pct of chemical catalysts are recycled (*4*).

Then $$BN = BJ \times 0.85, \qquad \text{(A-67)}$$

where BN = amount recycled in 1989,

and 0.85 = fraction of 1979 obsolete scrap recycled in 1989 (*4*).

Then $$BO = BJ - BN, \qquad \text{(A-68)}$$

where BO = use and recycling losses.

The amount recycled exceeded the 1989 chemical industry apparent consumption in 1989.

Then $$BP = BN - BQ, \qquad \text{(A-69)}$$

where BP = amount of recycled materials that was consumed by another industry as new PGM or was added to industry stocks,

and BQ = 1989 apparent consumption of PGM by the chemical industry (see table 1).

Then $$BR = BQ \times 0.09211, \qquad \text{(A-70)}$$

where BR = raw material that reported directly to manufacturing,

and 0.09211 = fraction of apparent consumption that reported directly to manufacturing (*4*).

Then $$BS = BQ - BR, \qquad \text{(A-71)}$$

where BS = total outside feed to processing.

Then $$BT = BS \times 0.3012, \qquad \text{(A-72)}$$

where BT = home scrap generated during processing,

and 0.3012 = fraction of total outside feed to processing that reported to home scrap (*4*).

Then $$BU = BS \times 0.0048, \qquad \text{(A-73)}$$

where BU = processing losses,

and 0.0048 = fraction of total outside feed to processing that reported to processing losses (*4*).

Then $$BV = BS - BU, \qquad \text{(A-74)}$$

where BV = processing feed to manufacturing.

Then $$BW = BV + BR, \qquad \text{(A-75)}$$

where BW = total feed to manufacturing.

Then $$BX = BW \times 0.0029, \qquad \text{(A-76)}$$

where BX = manufacturing losses,

and 0.0029 = fraction of total feed to manufacturing that reported to manufacturing losses (*4*).

Then $$BY = BW - BX, \qquad \text{(A-77)}$$

where BY = PGM contained in chemical products produced in 1989.

GLASS INDUSTRY

The glass industry has about a 3-pct loss in use of its consumed PGM (*4*). Devices are estimated to have lifetimes of about 5 years.

Then $$BZ = CA \times CB/CD, \qquad \text{(A-78)}$$

where BZ = 1984 apparent consumption of PGM by the glass industry,

CA = 1984 reported consumption of PGM by the glass industry (*29*),

CB = 1984 total apparent consumption of PGM (*29*),

and CD = 1984 total reported consumption of PGM (*29*).

Then $$CE = CA \times 0.03, \qquad \text{(A-79)}$$

where CE = loss in use of PGM in glass products produced in 1984,

and 0.03 = fraction of 1984 apparent consumption that reported to 1984 products loss in use (*4*).

Then $$CF = CA - CE, \qquad \text{(A-80)}$$

where CF = obsolete scrap recovered for recycling.

Then $$CG = CF \times 0.10, \qquad \text{(A-81)}$$

where CG = recycling losses,

and 0.10 = fraction lost in recycling (*15*).

Then $$CH = CF - CG, \quad (A\text{-}82)$$

where CH = amount of obsolete scrap that was recycled to 1989 consumption.

Then $$CI = CJ - CH, \quad (A\text{-}83)$$

where CI = new PGM consumed in 1989,

and CJ = 1989 apparent consumption of PGM by the glass industry (see table 1).

Then $$CK = CJ \times 0.09211, \quad (A\text{-}84)$$

where CK = raw material that reported directly to manufacturing,

and 0.09211 = fraction of apparent consumption that reported directly to manufacturing (*4*).

Then $$CL = CJ - CK, \quad (A\text{-}85)$$

where CL = raw material feed to processing.

It is assumed that about 5 pct of raw material consumed in processing becomes manufacturing prompt scrap.

Then $$CM = CL \times 0.05, \quad (A\text{-}86)$$

where CM = prompt scrap generated in manufacturing and returned as feed to processing,

and 0.05 = fraction of raw material reporting to processing that is recycled as prompt scrap.

Then $$CN = CL + CM, \quad (A\text{-}87)$$

where CN = total outside feed to processing.

Then $$CO = CN \times 0.3012, \quad (A\text{-}88)$$

where CO = home scrap generated during processing,

and 0.3012 = fraction of total outside feed to processing that reported to home scrap (*4*).

Then $$CP = CN \times 0.0048, \quad (A\text{-}89)$$

where CP = processing losses,

and 0.0048 = fraction of total outside feed to processing that reported to processing losses (*4*).

Then $$CQ = CN - CP, \quad (A\text{-}90)$$

where CQ = processing feed to manufacturing.

Then $$CR = CQ + CK, \quad (A\text{-}91)$$

where CR = total feed to manufacturing.

Then $$CS = CR \times 0.0029, \quad (A\text{-}92)$$

where CS = manufacturing losses,

and 0.0029 = fraction of total feed to manufacturing that reported to manufacturing losses (*4*).

Then $$CT = CR - CS - CM, \quad (A\text{-}93)$$

where CT = PGM contained in glass products produced in 1989.

JEWELRY AND DECORATIVE INDUSTRY

Most products in this end use are either held or hoarded and, thus, are not available for recycling. Any potentially recycled obsolete products would have been manufactured in 1979, assuming a 10-year use life.

Then $$CU = CV \times CW/CX, \quad (A\text{-}94)$$

where CU = 1979 apparent consumption of PGM by the jewelry and decorative products industry,

CV = 1979 reported consumption of PGM by the jewelry and decorative products industry (*27*),

CW = 1979 total apparent consumption of PGM (*27*),

and CX = 1979 total reported consumption of PGM (*27*).

Assuming only a 2-pct availability for recycling,

then $$CY = CU \times 0.98, \quad (A\text{-}95)$$

where CY = unknown, unrecovered, holding, and hoarding losses from obsolete scrap, and 0.98 = fraction of potentially available scrap not recovered for recycling.

Then $$CZ = CU - CY, \quad (A\text{-}96)$$

where CZ = obsolete scrap recovered for recycling.

Then $$DA = CZ \times 0.10, \quad (A\text{-}97)$$

where DA = recycling losses,

and 0.10 = fraction lost in recycling (*15*).

Then $$DB = CZ - DA, \quad (A\text{-}98)$$

where DB = amount of obsolete scrap that was recycled to 1989 consumption.

Then $$DC = DE - DB, \quad (A\text{-}99)$$

where DC = new PGM consumed in 1989,

and DE = 1989 apparent consumption of PGM by the jewelry and decorative industry (see table 1).

Then $$DF = DE \times 0.09211, \quad (A\text{-}100)$$

where DF = raw material that reported directly to manufacturing,

and 0.09211 = fraction of apparent consumption that reported directly to manufacturing (*4*).

Then $$DG = DE - DF, \quad (A\text{-}101)$$

where DG = raw material feed to processing.

It is assumed that about 5 pct of raw material feed to processing is generated as prompt scrap during manufacturing.

Then $$DH = DG \times 0.05, \quad (A\text{-}102)$$

where DH = prompt scrap generated in manufacturing and returned as feed to processing,

and 0.05 = fraction of raw material reporting to processing that is recycled as prompt scrap.

Then $$DI = DH + DG, \quad (A\text{-}103)$$

where DI = total outside feed to processing.

Then $$DJ = DI \times 0.3012, \quad (A\text{-}104)$$

where DJ = home scrap generated during processing,

and 0.3012 = fraction of total outside feed to processing that reported to home scrap (*4*).

Then $$DK = DI \times 0.0048, \quad (A\text{-}105)$$

where DK = processing losses,

and 0.0048 = fraction of total outside feed to processing that reported to processing losses (*4*).

Then $$DL = DI - DK, \quad (A\text{-}106)$$

where DL = processing feed to manufacturing.

Then $$DM = DL + DF, \quad (A\text{-}107)$$

where DM = total feed to manufacturing.

Then $$DN = DM \times 0.0029, \quad (A\text{-}108)$$

where DN = manufacturing losses,

and 0.0029 = fraction of total feed to manufacturing that reported to manufacturing losses (*4*).

Then $$DO = DM - DH - DN, \quad (A\text{-}109)$$

where DO = PGM contained in jewelry and decorative products produced in 1989.

MISCELLANEOUS OTHER INDUSTRIES

This industry area includes many small industries that consume PGM and are not large enough to be considered singly. It is assumed that these products have a 5-year use life and, thus, 1989 obsolete scrap from these industries would have come from 1984 products.

Then $$DP = DQ \times DR/DS, \quad (A\text{-}110)$$

where DP = 1984 apparent consumption of PGM by miscellaneous other industries,

DQ = 1984 reported consumption of PGM by miscellaneous other industries (*29*),

DR = 1984 total apparent consumption of PGM (*29*),

and DS = 1984 total reported consumption of PGM (*29*).

Assuming 30 pct of obsolete 1985 products are lost through dissipative, unknown, and unrecovered losses,

then $$DT = DP \times 0.30, \quad \text{(A-111)}$$

where DT = dissipative, unknown, and unrecovered losses from obsolete scrap,

and 0.30 = fraction of potentially available scrap not recovered for recycling.

Then $$DU = DP - DT, \quad \text{(A-112)}$$

where DU = obsolete scrap recovered for recycling.

Then $$DV = DU \times 0.10, \quad \text{(A-113)}$$

where DV = recycling losses,

and 0.10 = fraction lost in recycling (*15*).

Then $$DW = DU - DV, \quad \text{(A-114)}$$

where DW = amount of obsolete scrap that was recycled to 1989 consumption.

Then $$DX = DY - DW, \quad \text{(A-115)}$$

where DX = new PGM consumed in 1989,

and DY = 1989 apparent consumption of PGM by miscellaneous other industries (see table 1).

Then $$DZ = DY \times 0.09211, \quad \text{(A-116)}$$

where DZ = raw material that reported directly to manufacturing,

and 0.09211 = fraction of apparent consumption that reported directly to manufacturing (*4*).

Then $$EA = DY - DZ, \quad \text{(A-117)}$$

where EA = raw material feed to processing.

Assuming a 5-pct fraction of raw material feed to processing reported as prompt scrap during manufacturing,

then $$EB = EA \times 0.05, \quad \text{(A-118)}$$

where EB = prompt scrap generated in manufacturing and returned as feed to processing,

and 0.05 = fraction of raw material reporting to processing that was recycled as prompt scrap.

Then $$EC = EB + EA, \quad \text{(A-119)}$$

where EC = total outside feed to processing.

Then $$ED = EC \times 0.3012, \quad \text{(A-120)}$$

where ED = home scrap generated during processing,

and 0.3012 = fraction of total outside feed to processing that reported to home scrap (*4*).

Then $$EF = EC \times 0.0048, \quad \text{(A-121)}$$

where EF = processing losses,

and 0.0048 = fraction of total outside feed to processing that reported to processing losses (*4*).

Then $$EG = EC - EF, \quad \text{(A-122)}$$

where EG = processing feed to manufacturing.

Then $$EH = EG + DZ, \quad \text{(A-123)}$$

where EH = total feed to manufacturing.

Then $$EI = EH \times 0.0029, \quad \text{(A-124)}$$

where EI = manufacturing losses,

and 0.0029 = fraction of total feed to manufacturing that reported to manufacturing losses (*4*).

Then $$EJ = EH - EI - EB, \quad \text{(A-125)}$$

where EJ = PGM contained in miscellaneous other products in 1989.

OVERALL FLOW

The data shown in figure 11 in the main text for the overall PGM commodity flow have been estimated by summing the various fractions from each of the eight PGM-consuming industries in 1989.