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Platinum Recycling in the United States in 1998

By Henry E. Hilliard

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FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

A handwritten signature in black ink, appearing to read 'C. Groat', with a long horizontal flourish extending to the right.

Charles G. Groat
Director

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1. Salient statistics for U.S. platinum scrap in 1998 B3

CONVERSION FACTORS

Most measurements in this report are in metric units, but a few terms are in customary units. Conversion factors are provided below.

Multiply	By	To obtain
<i>Length</i>		
kilometer (km)	0.6214	mile
inch (in.)	25.4	millimeter
<i>Volume</i>		
cubic foot (ft ³)	0.02832	cubic meter
<i>Mass</i>		
microgram (μg)	0.0000003527	ounce avoirdupois
gram (g)	0.03527	ounce avoirdupois
kilogram (kg)	2.205	pound avoirdupois
kilogram (kg)	32.1507	troy ounce
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
troy ounce (troy oz)	31.10	gram
<i>Pressure</i>		
kilopascal (kPa)	0.1450	pound force per square inch
kilopascal (kPa)	0.009869	1 atmosphere
<i>Other</i>		
gram per metric ton (g/t)	0.0292	troy ounce per short ton

For temperature conversions from degrees Celsius (°C) to degrees Fahrenheit (°F), use the following:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

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By Henry E. Hilliard

ABSTRACT

In the United States, catalytic converters are the major source of secondary platinum for recycling; about 25,500 kilograms of platinum-group metals from automobile catalysts was available for recycling in 1998. Other sources of platinum scrap include reforming and chemical-process catalysts. The glass industry is a small but significant source of platinum scrap. In 1998, an estimated 7,690 kilograms of platinum was recycled in the United States. The U.S. recycling efficiency for old scrap was calculated to have been 76 percent in 1998; the recycling rate was estimated at 16 percent.

INTRODUCTION

World resources of platinum appear ample for the foreseeable future. Political and economic events in the past decade, however, have raised concerns about the availability and reliability of the supply of platinum and other metals in this group. This report discusses the 1998 flow of platinum in the United States from mining, through metallurgical and chemical applications, to recycling (fig. 1, table 1). Factors influencing the rate and availability of material for recycling are described, especially areas where significant losses occurred.

Platinum-bearing scrap is a heterogeneous material that may also contain one or more of the other platinum-group metals. This report deals primarily with platinum, which was the most valuable and abundant platinum-group metal (PGM) found in scrap materials at the time of this study. The annual recycling rate for platinum, which represents the fraction of the metal's apparent supply that is scrap, was estimated at 16 percent in 1998. The balance of apparent supply was primary platinum (see appendix). This study also indicates that materials containing about 8,500 kilograms (kg) of platinum were unrecovered in 1998, representing about 14 percent of U.S. apparent consumption.

Six elements of group VIII in the periodic table of the elements have been collectively designated the platinum-group metals; they are palladium (Pd), platinum (Pt), iridium (Ir), osmium (Os), rhodium (Rh), and ruthenium (Ru). Sometimes called noble metals because of their resistance to

oxidation, these precious metals are found in the Earth's crust in very low concentrations. PGM's are conveniently separated into two subgroups; the light PGM's (those of lower atomic weight) are Ru, Rh, and Pd, and the heavy PGM's are Os, Ir, and Pt.

The PGM's are strongly siderophilic and chalcophilic; that is, they occur predominantly as pure metals and alloys and, to a much lesser extent, combined with sulfur, tellurium, and arsenic. They occur in rock-forming silicates in small to negligible amounts. For the most part, PGM's are concentrated in the early stages of magmatic differentiation and, consequently, are most abundant in magmatic mafic and ultramafic bodies and associated ore deposits. Under certain conditions, as yet imperfectly known, the PGM's are carried through the differentiation process because of their lack of affinity for the silicate minerals and are then concentrated in the products of late hydrothermal solutions (Wright and Fleischer, 1965, p. A2).

Despite their limited availability, these metals and chemical compounds containing them are extremely useful as catalysts in the automobile, chemical, and petroleum industries, as conductors in the electrical and electronic industries, in extrusion devices, in dental and medical prostheses, and in jewelry. Also, the glass industry takes advantage of platinum's high melting point, its noncontaminating behavior, and its chemical inertness and resistance to corrosion in the manufacture of high-quality optical and special glasses.

Platinum is primarily an industrial metal. There are, however, small quantities in the possession of speculators and investors. In 1998, there was strong demand for the platinum American Eagle coin, launched by the U.S. Mint in 1997. Domestic and foreign sales of this coin totaled 5,443 kg in 1998 (U.S. Mint, 1999, p. 7-13). Although Eagle coin sales were concentrated in the United States, the coin also found a market in Japan. Demand in Japan was mainly for smaller coins, weighing 0.10 or 0.25 troy ounce (troy oz), many of which were incorporated into watches and other items of jewelry. There are no reliable statistics available about the quantity of platinum held by speculators and investors. Probably stocks are held in banks and private holdings. This material, held for speculation and profitmaking, is

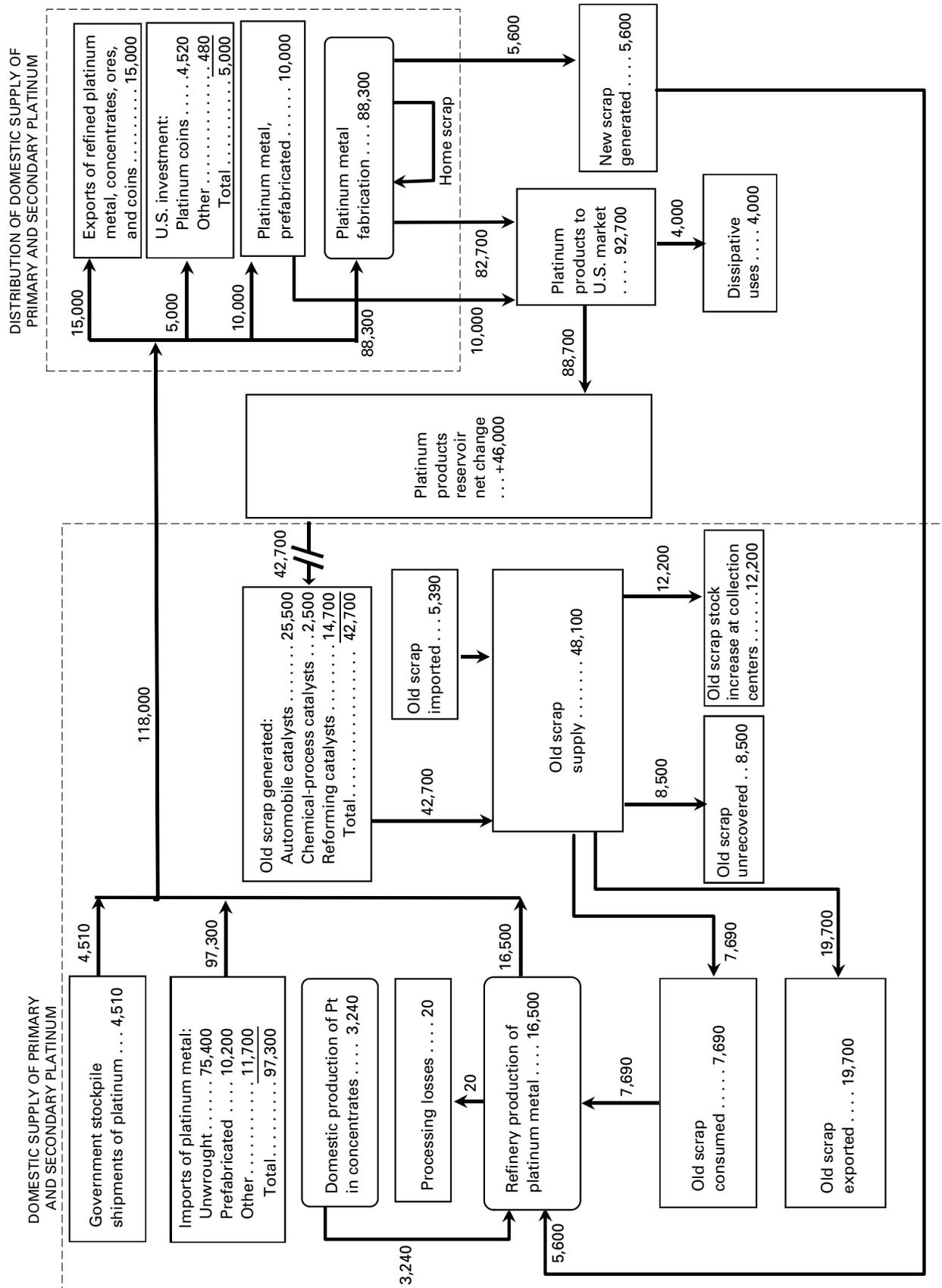


Figure 1. U.S. platinum materials flow in 1998. Values are in kilograms of contained platinum, and totals have been rounded to three significant figures. Sources of data are described in the section titled "Sources of Platinum Scrap."

put on the market infrequently, depending upon price and price outlook. The material is usually of high purity and is not likely to be found in the recycling circuit, except as home scrap during its manufacture.

SOURCES OF PGM ORE

Canada, South Africa, Russia, and the United States account for nearly all of the world’s primary production of PGM ore. The relative amounts of the individual elements in ores vary from deposit to deposit and from country to country. The ratio of platinum to palladium in ores can vary from 3:1 in the Bushveld Complex in South Africa to 1:3.5 in the Noril’sk deposit in Russia and 1:3 in the J-M Reef of the Stillwater Complex in the United States and the Sudbury Complex in Canada (Conradie, 1997).

CANADA

Small amounts of silver, gold, and PGM’s are present in most sulfide deposits of nickel. In Canada, PGM’s are mainly a byproduct of copper-nickel production. Most of the nickel ores are located in the Sudbury Complex in Ontario. The complex is a large stratiform, oval intrusion with dimensions along the axes of 50 and 23 kilometers (km). The copper-nickel deposits of the Sudbury area are peripherally located around the structure of an elliptical basin-shaped stratiform complex referred to as the Nickel Irruptive or the Sudbury Basin. The Nickel Irruptive consists of an outer part of noritic rocks and an inner part of granophyre (micropegmatite) (Cabri and Laflamme, 1976, p. 1159). The concentration of PGM’s averages about 0.9 to 1.0 gram per metric ton (g/t), with about 40 percent Pd, 40 percent Pt, and 20 percent Ir, Os, Rh, and Ru. Canada also produces nickel-copper ores with byproduct PGM’s from the entire spectrum of ultramafic and mafic complexes that occur in Manitoba, Ontario, and Quebec (Allen, 1960, p. 1–26; Page and others, 1973; Sutphin and Page, 1986, p. 2–7).

SOUTH AFRICA

South Africa is the world’s largest source of platinum. South Africa’s PGM output is derived mostly from the Bushveld Complex, with only a small amount coming from the Evander Gold Field and the Phalaborwa Complex. Currently, 10 mines are producing platinum in the Bushveld Complex (South Africa Department of Minerals and Energy, Minerals Bureau, 1997, p. 34–40). Of these, nine exploit the Merensky Reef and UG2 Chromite Layer, and one, Potgietersrust Platinum Ltd., the only open-cast operation, exploits the Platreef on the northern limb of the complex. Eight of the mines are located on the western limb of the Bushveld Complex; Atok Mine, of Lebowa Platinum Mines Ltd., is currently the only producer on the eastern limb. Beneficiation of PGM ore through milling, flotation, and smelting (to form a matte containing PGM’s, gold, silver, and the base metals cobalt, copper, and nickel) is

Table 1. Salient statistics for U.S. platinum scrap in 1998. [Values in kilograms of contained platinum, unless otherwise specified]

Old scrap:	
Generated ¹	42,700
Consumed ²	7,690
Value of old scrap consumed	\$117 million
Recycling efficiency ³	76 percent
Supply ⁴	48,100
Unrecovered ⁵	8,500
New scrap consumed ⁶	5,600
New-to-old-scrap ratio ⁷	42:58
Recycling rate ⁸	16 percent
U.S. net exports of scrap ⁹	14,310
Value of U.S. net exports of scrap	\$200 million

¹Platinum content of products theoretically becoming obsolete in the United States in 1998. Net U.S. imports of semifinished products containing platinum in 1998 are included. Dissipative uses are excluded.

²Platinum content of products that were recycled in 1998.

³(Old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

⁴Old scrap generated plus old scrap imported plus old scrap stock decrease.

⁵Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

⁶Including prompt industrial scrap but excluding home scrap.

⁷Ratio of quantities consumed, in percent.

⁸Fraction of the metal apparent supply that is scrap, on an annual basis.

⁹Trade in scrap is assumed to be principally in old scrap. Net exports are exports of old scrap minus imports of old scrap.

undertaken at the various mines. Further refining of the matte, including extraction of the base metals and recovery of the precious metals, takes place at refineries near Rustenburg, Brakpan, and Springs. Some matte is sent to refineries outside the country for toll refining. In 1998, South Africa produced about 117,000 kg of platinum and 57,300 kg of palladium (Hilliard, 2000b, p. 58.7).

RUSSIA

Probably more than 97 percent of Russia’s mine output of PGM’s is a byproduct of nickel-copper mining. The nickel-mining complex at Noril’sk, in northwestern Siberia, accounts for about 95 percent of total Russian production, and the mines at Pechenga on the Arctic coast account for most of the remainder. Modes of occurrence and composition of PGM’s in different types of ores vary significantly at Noril’sk. In disseminated ores, the main PGM minerals are represented by isoferroplatinum and cooperite, whereas in massive ores, very diverse palladium intermetallic compounds and tetraferroplatinum occur (Genkin and Evstigneeva, 1986, p. 1204). PGM’s are refined at the metallurgical complex in Krasnoyarsk, East Siberia. In 1998, Russia produced about 17,000 kg of platinum and 47,000 kg of palladium (Hilliard, 2000b, p. 58.7).

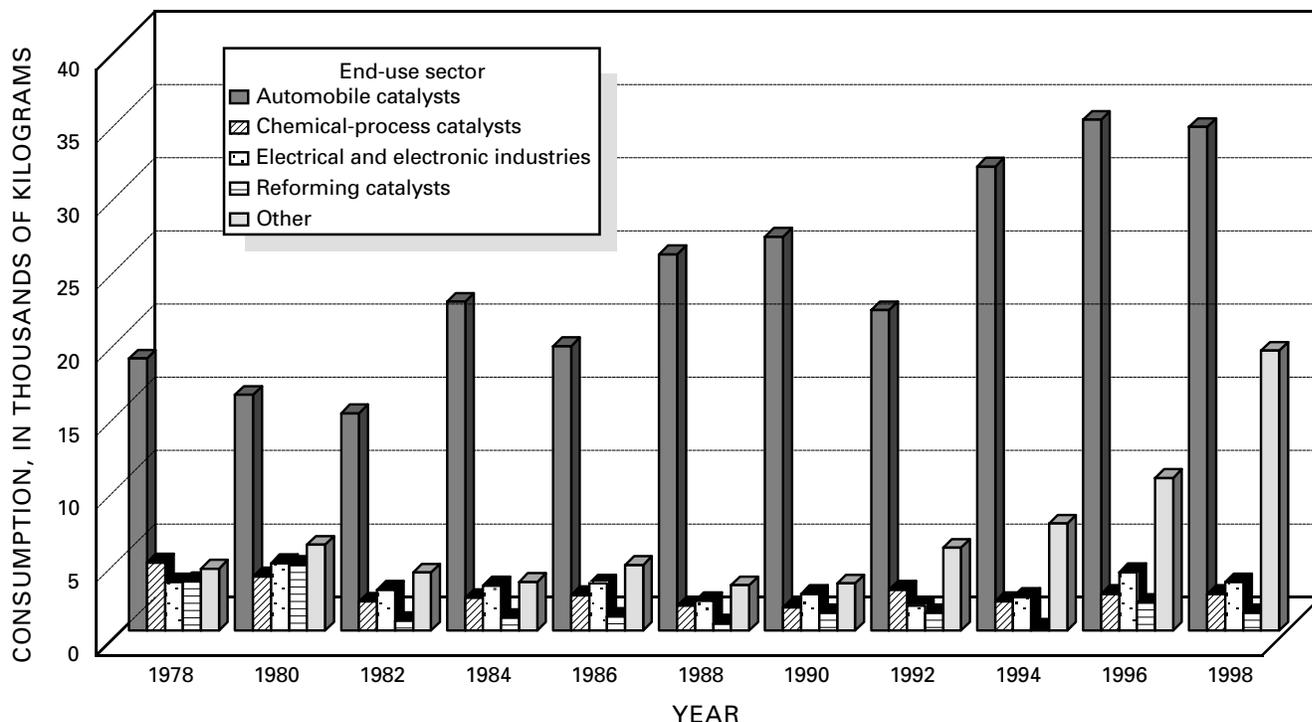


Figure 2. U.S. platinum consumption by end-use sector from 1978 to 1998.

UNITED STATES

The Stillwater Mine near Nye, Mont., is the only primary PGM producer in the United States. The Stillwater Complex is an elongated assemblage of intrusive rocks that occurs in Sweetwater County, Mont., and extends into Park and Stillwater Counties. In its annual report, the Stillwater Mining Company reported its 1998 production as 10,575 kg of palladium and 3,235 kg of platinum (Stillwater Mining Company, 1999). In 1998, the company mined 653,184 metric tons (t) of ore. In conjunction with the operation of the mine, the average throughput at the mill facility was 1,196 metric tons per operating day (t/d) with a recovery rate of 91 percent. The mill head grade was 23.7 grams (g) of combined palladium and platinum per metric ton of ore.

The Stillwater Mining Company operates a smelter and base-metals refinery (BMR) at the company's metallurgical complex in Columbus, Mont. At the smelter, concentrate is treated to produce matte containing approximately 22.3 kg of palladium and platinum per metric ton. The matte is subsequently sent to the BMR, which produces a filter cake that is about 60 percent palladium and platinum. The filter cake is sent to metal refiners in New Jersey, California, and Germany, where it is converted into palladium and platinum sponge for sale to end users.

In 1998, the Stillwater Mining Company restarted its program to process spent automobile catalysts for the recovery of PGM's. In 1998, approximately 139 t was processed in the BMR at a rate of 1 t/d. The usual procedure was to blend spent catalysts with concentrate from the mill (Stillwater Mining Company, 1999).

SOURCES OF PLATINUM SCRAP

Typical sources of platinum for secondary refining include spent automobile, reforming, and chemical-process catalysts; electronic scrap; jewelry; and used equipment from the glass industry (fig. 2). Spent automobile catalysts have emerged as the major source of secondary platinum, palladium, and rhodium. In the United States, about 25,500 kg of PGM's from automobile catalysts was available for recycling in 1998 (see p. B5).

OLD SCRAP GENERATED

Old scrap generated is defined as the platinum content of products theoretically becoming obsolete in the United States in 1998. Total platinum old scrap generated in 1998 in the United States from automobile catalysts, reforming catalysts, and chemical-process catalysts was estimated as 42,700 kg (table 1). Old scrap consumed, defined as the platinum content of products recycled, was estimated at about 18 percent of old scrap generated or 7,690 kg.

AUTOMOBILE CATALYSTS

Spent automobile catalysts have emerged as the major source of secondary platinum, palladium, and rhodium. The amount of platinum that is recovered from automobile catalytic converters depends upon the following factors: (1) the average loading of platinum in the converters, which will not be a constant, (2) the probability that vehicles from each of the previous model years will be taken out of service in the year under consideration, (3) the percentage of the vehicles that are taken out of service in that year and are scrapped,

and (4) the percentage of platinum that is recoverable from a used converter. The first of these factors can only be estimated, but industry-based statistics are available for the second factor. A value for the third factor depends upon the returns expected in the scrap market. Annual figures for automobiles scrapped are influenced by the strength or weakness of the scrap metal market. Thus, vehicles retired in years when the price of scrap is depressed may not reach the scrap yard until there is sufficient economic incentive. In the long run, however, it is likely that most vehicles withdrawn from service end up as scrap. As for the fourth factor, research has shown that the high recovery rates typical of PGM recycling in the chemical, petroleum, and electronic industries can also be achieved with automobile catalysts (Dhara, 1983).

Beginning with the 1974 model year, new automobiles sold in the United States have been equipped with catalytic converters that chemically convert polluting substances in automobile exhaust to nontoxic materials. Automobile catalysts were developed to remove carbon monoxide (CO), hydrocarbons (HC), and the oxides of nitrogen (NO_x) that cause air pollution from vehicle exhausts. Small amounts of platinum, either alone or combined with other PGM's, were used to oxidize and reduce the exhaust gases, thereby significantly lowering harmful emission levels.

The first catalytic converters used a monolithic system that incorporated palladium and platinum as the active constituents to oxidize the CO and HC. NO_x was controlled by modifications to the engine. In addition to monoliths, highly porous pelleted materials were also used. All converters now use monolithic supports because of the monolith's high geometrical surface area and low pressure drop during operation.

Since the introduction of the basic catalytic converter in 1974, the technology has advanced in response to tightening air-quality-control regulations; for example, the three-way oxidation-reduction converter (TWC) was developed. In the TWC system, all three pollutants—CO, HC, and NO_x —are converted in one reactor using a platinum-rhodium catalyst coated on a ceramic monolith. Thus, a reducing-type catalyst, based on rhodium for the reduction of NO_x , is combined with a conventional oxidation catalyst to provide three-way emission control of the pollutants. In TWC's, the platinum-to-rhodium ratio is generally about 10:1. The amount of PGM's used in the manufacture of these devices is more than the total amount consumed in all other U.S. uses combined (Roskill Information Services Ltd., 1991, p. 99).

At the beginning of the 1980's, General Motors suggested that a typical TWC might contain 1.555 g Pt, 0.622 g Pd, and 0.156 g Rh (Roskill Information Services Ltd., 1991, p. 100). The oxidizing units of early TWC's are thought to have contained platinum and palladium in the ratio of 2:1. The palladium content subsequently has risen considerably. Newer TWC's may contain about 1.8 kg (58 troy oz) PGM's per cubic meter of monolith. A catalytic converter measuring 10 centimeters (cm) in diameter by 15 cm in length would contain 2.3 g (0.074 troy oz) PGM's. A typical mean level of 1.5 g (0.048 troy oz) was suggested.

In 1998, about 200 million automobiles were in circulation in the United States, and about 17 million automobiles were scrapped. If each catalytic converter in the scrapped automobiles contained an average of 1.5 g of platinum, then about 25,500 kg of platinum was available for recycling from this source. Of the 17 million scrapped automobiles, about 12 million were recycled through shredders (Fenton, 1999, p. NN1). If it is assumed that the catalytic converters were collected from the automobiles prior to shredding, then 18,000 kg of platinum was available for recycling.

REFORMING CATALYSTS

Heterogeneous catalysts containing platinum are widely used in the petroleum-refining industry for a variety of hydrocarbon conversion processes, including reforming. The products made by these processes, such as motor fuels and aromatic hydrocarbons, are of great economic value to the United States. For example, increasing the aromatic hydrocarbon content of gasoline raises the octane rating and lessens knocking.

Catalysts in this service can be deactivated by several different mechanisms, but deactivation is primarily the result of deposition of carbonaceous materials onto the catalyst surface during hydrocarbon processing at elevated temperature. This deposit, known as coke, results in substantial deterioration in catalyst performance (Fung, 1993, p. 91–96). The catalyst activity, or its ability to convert reactants, is adversely affected by this coke deposition, and the catalyst is referred to as "spent."

The original performance of the fresh catalyst can be restored by proper regeneration to remove this coke (Kim and others, 1992, p. 39–46). Regeneration allows continued use of the same catalyst for many years. The actual loss of platinum during use by the petroleum industry is very small, and this efficient metal recovery contributes greatly to the economics of platinum use. There is a limit, however, to the number of times that a catalyst can be regenerated, and eventually the catalyst must be replaced. Many reforming and selective hydrogenation catalysts are regenerated two or more times. As a general rule, after a catalyst can no longer be regenerated to at least 75 percent of its original activity, it is reclaimed or discarded (Chang, 1998).

When the catalysts are removed from service, they are sent to a toll refiner for recovery of the metal values, which are returned to the owner. About 70 percent of the replacement market is for the bimetallic form commonly consisting of 0.3 percent platinum and 0.3 percent rhenium. Monometallic catalysts average 0.4 percent platinum (Burke, 1979). It is estimated that the amount of platinum used in catalytic reforming in 1998 was over 40,200 kg and was increasing by about 6,200 kg each year. Because PGM's are valuable, great care is exercised in monitoring all streams entering and leaving catalyst manufacturing sites to ensure that no significant amounts of material are lost. Yearly overall materials recovery rates of about 99.8 percent are attainable.

CHEMICAL-PROCESS CATALYSTS

A typical use of a PGM catalyst in a chemical process is the production of nitric acid. During the manufacture of nitric acid by the oxidation of ammonia, platinum-rhodium and platinum-palladium-rhodium alloy gauzes are used as catalysts. Traditionally, the process is carried out at temperatures of 750°C to 950°C and at pressures of 101.3 to 1,013 kilopascals. The amount of platinum lost from catalyst gauzes during nitric acid production depends upon the properties of the catalyst alloys, the operating conditions (temperature and pressure), and the technical control. The rate of platinum loss from a binary gauze consisting of 90 percent platinum and 10 percent rhodium varies from 0.05 g of platinum per metric ton of nitric acid produced in plants operated at atmospheric pressure (101.3 kilopascals) to 0.45 g of platinum for each metric ton of nitric acid produced in some high-pressure plants (Platinum Metals Review, 1999). In 1998, the United States produced 9.3 million metric tons of nitric acid (Chemical & Engineering News, 1999). With that rate of nitric acid production, about 2,300 kg of platinum is estimated to have been consumed in this process. Not all of this material was allowed to escape into the atmosphere. Various filters and "gettering" devices allowed recovery of perhaps half of the lost metal. Of the platinum that escaped, most was probably trapped in absorption towers and ended up in the nitric acid.

About 200 kg of platinum was consumed in other industrial or commercial catalytic applications.

NEW SCRAP

New scrap is defined as scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semi-finished articles that must be reworked. Typical sources of platinum new scrap are used equipment from the glass industry, jewelry, and electronic scrap (fig. 2). Platinum and platinum-rhodium alloys are basic to the glass industry and are used in a variety of glass-handling and -forming equipment. Platinum is used in these applications because of its high melting point, high-temperature strength, low oxidation rate, and noncontaminating behavior. Pure platinum is used to make stirrers and tanks and crucibles for melting glasses. Alloys of 90 percent platinum and 10 percent rhodium are used for the bushings and baskets needed in the production of glass fibers. This use represents a large application for platinum-rhodium alloys. Similarly, alloys of platinum and 10 to 40 percent rhodium are used for crucible liners, structures conveying molten glass, fiber-optics-forming devices, laser-glass melters, and stirrers for glass homogenization. Very low metal losses are experienced in these uses. Worn parts are recycled on a toll basis, and the recovered metals are returned to the industry for fabrication into new parts.

The platinum used in jewelry is theoretically available as an aboveground resource, but there is very little recycling,

apart from machining chips and grindings resulting from jewelry fabrication. The machining chips and grindings are efficiently recycled.

Precious metals in the electrical and electronic industries are dispersed in the assemblies, and until recently, little effort was made to recycle discarded scrap. Electronic scrap may contain recoverable amounts of gold, palladium, and silver but only trace levels of platinum (Hilliard and Dunning, 1983). The amount of platinum in electronic scrap may change dramatically as hard disk drives from computers manufactured after 1996 are scrapped. The first hard disk drives used 50 disks, each measuring 61 cm in diameter, to store just 5 megabytes of data. A typical modern personal computer can store 15 megabytes on a hard disk drive containing two or three disks that are only 9 cm in diameter. This efficiency was achieved by incorporating a platinum-cobalt magnetic layer on the surface of the disk to improve storage capacity. About 50 percent of the hard drives manufactured in 1998 used platinum, and it was estimated that in 2000 more than 90 percent of the hard drives used magnetic thin films containing platinum (Johnson Matthey, 1999, p. 26). It will be several years, however, before these hard drives begin appearing in scrap streams for recycling.

Almost all new PGM scrap generated is consumed. As shown in table 1, new scrap consumed in 1998 was estimated to have a platinum content of 5,600 kg, and the new-to-old-scrap ratio was 42:58.

HOME SCRAP

In every company that manufactures semifinished and final PGM products, virtually all of the scrap generated is reprocessed for precious-metals recovery. Casting scrap, such as croppings of castings, is recovered simply by adding it to melt charges. This scrap is not counted as material consumed because it is endlessly recycled and never leaves the plant. Grindings, ingot scalping, and machining chips, which are processed through toll refining, are not home scrap.

DISPOSITION OF PLATINUM SCRAP

SCRAP CONSUMPTION

Recovery of PGM's from spent automobile catalysts is growing in the United States, where a network of recycling facilities is being put in place. This growth is due to the higher PGM loadings in automobile catalysts in recent years. Nevertheless, the amount of PGM's recovered from catalysts remained only a fraction of the total amount consumed. In 1998, more than 6,000 kg of PGM's was recovered from spent automobile catalysts and other sources in the United States (Hilliard, 2000a). This represented about 8 percent of U.S. apparent consumption in 1998. More than 19,000 kg of platinum in spent automobile catalysts and other scrap materials was exported to other countries (fig. 1) where the metal values were recovered and the recovered platinum sold back to the United States.

UNRECOVERED OLD SCRAP

Only about 64 percent of the catalytic converters scrapped in the United States are being collected (Dhara, 1983). Of these scrapped converters, less than 30 percent are being processed domestically for recovery of PGM content; about 30 percent are shipped to collection centers to await more favorable economic conditions before processing; 20 percent are unrecovered. The remaining catalytic converters (20 percent) are exported to Japan and Europe for processing.

OLD SCRAP RECYCLING EFFICIENCY

Old scrap recycling efficiency shows the relation between old scrap materials recovered and reused and old scrap that is available to be recovered and reused. By definition, this relation is (the amount of old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any decrease in old scrap stocks or minus any increase in old scrap stocks). Platinum-bearing scrap materials consist mostly of spent catalysts from the automobile, chemical, and petroleum industries. In 1998, the chemical and petroleum industries recycled spent catalysts with recovery rates above 98 percent. Overall recycling efficiency for platinum was lower because of the many automobile catalysts that were not being recycled in 1998. Uncertainty in the exact value for recycling efficiency is increased because of lack of data on stocks of platinum-bearing material, but old scrap recycling efficiency is estimated at 76 percent.

INFRASTRUCTURE OF PLATINUM SCRAP SCRAP COLLECTION SYSTEMS

Anyone who owns a car manufactured in the United States after January 1, 1974, also owns a certain amount of automobile catalyst. Although spent automobile catalysts are readily available, collecting the material systematically is a complicated task. Because the catalysts are unevenly distributed, it is assumed that 20 to 40 percent of the total available catalysts will be either uncollected or unaccounted for (Dhara, 1983, p. 86). The flow of the material is unpredictable, as many factors, such as PGM prices, govern the collection effort.

The low PGM content in automobile catalysts and the nature of the monoliths used as support have required the development of specialized recovery techniques, as well as the establishment of an infrastructure of collection centers. These factors have slowed the development of an automobile catalyst recycling industry.

TRADE

In 1998, the United States imported 103,000 kg of pre-fabricated platinum, unwrought platinum, platinum scrap, and other platinum materials. The value of these imports was \$603 million. South Africa (69 percent), the United Kingdom (12 percent), and Germany (4 percent) were the major foreign sources of imports. The United States exported

14,300 kg of refined platinum and 20,447 kg of platinum in scrap, ores, and concentrates. The value of these exports was \$240 million (Hilliard, 2000b, p. 58.6). These quantities differ from those given in figure 1 because the U.S. Census Bureau reports some imports and exports as gross weight and estimates were made for the platinum content of these materials for inclusion in figure 1.

In the first half of 1998, delayed shipments from Russia caused platinum prices to rise by more than \$60 to reach a peak of \$434 per troy oz on April 14. Prices began to fall soon afterward, following news that Russian export quotas had been approved. Platinum prices declined sharply from May through October 1998 because of the economic crisis in Asia and renewed financial and political uncertainty in Russia. As a result, the price of platinum sank to a 5-year low of \$337 per troy oz in October. In 1998, the average annual price was \$372.50 per troy oz (Hilliard, 2000b, p. 58.3).

PROCESSING OF PLATINUM SCRAP

Automobile and catalyst-canister manufacturers arrange to recover in-house stainless steel and PGM-bearing scrap materials. Once a canister containing PGM's is mounted on a car that is sold, however, it is not regarded as an item for recovery by the manufacturers. Initially, each canister contains about 1.5 to 3 g of PGM's; 1 to 3 micrograms of PGM's are emitted per 1.6 kilometers from the exhaust systems of automobiles equipped with the canisters. For the present, the economic conditions of salvage through automobile scrap yards limit the amount of PGM's recovered from this source. Several processes are available for recovering platinum from spent automotive industry catalysts:

- Selective dissolution of the PGM's from ceramic support in aqua regia. Soluble chloro-complexes of platinum, palladium, and rhodium are formed, and reduction of these compounds yields crude PGM's for further refining.
- Dissolution of the catalyst support in sulfuric acid, in which PGM's are insoluble. This technique is widely used for the treatment of reforming and isomerization catalysts in which γ -alumina is the substrate but is not suitable for dissolution of the cordierite honeycomb substrates used in many automotive catalysts.
- A gas-phase volatilization in which the PGM's are selectively chlorinated to produce volatile compounds that are condensed in a cooler zone.
- Blending of the catalyst with PGM concentrate to be refined by the same process as PGM ore (Dhara, 1983, p. 89).

In the United States, A-1 Specialized Services & Supplies, Inc., Croydon, Pa., and Multimetco, Inc., Anniston, Ala., are among the leading buyers and processors of scrap catalytic converter canisters. These companies have a network of collection points across the country and pay between \$3.00 and \$17.00 per canister (International Precious Metals Institute, 2000).

OUTLOOK

The amount of platinum recovered from scrapped automobile catalysts continues to climb slowly and is expected to increase significantly in the long term because of increased demand for catalytic converters and platinum jewelry in Japan and China. Catalytic converters are the major source of platinum and other PGM's for recycling. The outer shell of the converter is recycled for its stainless steel content, and the substrate is shipped to extractors to recover platinum, palladium, and rhodium. The U.S. price of steel scrap, a key ingredient of the steelmaking process, continues to be depressed, primarily because of the import of new foreign steel (Fenton, 2000, p. 40.1). With lower steel scrap prices there is less incentive to dismantle cars as dismantlers cut back in hope of a price rebound, resulting in fewer salvage catalytic converters coming to collection centers. In many instances, the converters that find their way to collection centers are exported to countries with lower labor cost—recycling catalytic converters is a labor-intensive task—allowing for the economic recovery of the PGM's. The relatively low value of the metal content (about \$19.00 in each converter), the low concentration of PGM's (less than 0.1 weight percent), and the difficult logistics of returning the material to a central recycling location are reasons why recycling of PGM catalysts is not yet economically viable in the United States. Consequently, it is doubtful that there will be a significant increase in the reclamation of metals from automobile emissions control catalysts in the immediate future.

Significant changes are on the horizon. The U.S. automobile industry has begun to enter the automobile recycling business, which could lead to an improved infrastructure of collection centers. Pending regulations will deter catalysts from entering landfills and will redirect spent catalyst traffic from disposal to regenerating and reclamation plants. Although the number of cars being scrapped in the United States is fairly constant, new sources of material, especially from Mexico, where new air-quality regulations are being considered, could increase significantly the number of catalytic converters available. Beginning in 2001, automobile manufacturers will shift to a more palladium-intensive catalyst. It will be 5 to 6 years, however, before any change is seen in the relative amounts of various PGM's available for recycling.

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APPENDIX—DEFINITIONS

γ -alumina. An activated form of alumina, made from Bayer α -trihydrate, widely used in adsorption and catalysis, where its large surface area, pore structure, and surface chemistry play an essential role.

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

aqua regia. Royal water, usually a solution of 1 part nitric acid and 3 parts hydrochloric acid used to dissolve platinum and other precious metals.

catalyst. A substance that changes the rate of a chemical reaction but is itself not permanently changed in chemical form.

chalcophilic. Having an affinity for sulfur.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizer, making it exceptionally difficult and costly to recycle.

heterogeneous catalysts. Catalysts in which phase boundaries exist between the catalysts and the reacting substances, such as a solid catalyst in a gas or liquid phase reaction.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

metal values. The amount of a specified precious metal or nonferrous scrap recovered by a refiner plus the cash value of other desirable metals recovered minus a penalty for undesired metals recovered.

monolith. [*monos*, one + *lithos*, stone] A single ceramic block coated with catalytic materials.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed in percent of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from

industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizer, are not included.

old scrap generated. Metal content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as (consumption of old scrap (COS) plus exports of old scrap (OSE)) divided by (old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{OSE}}{\text{OSG} + \text{OSI} + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

price. Based on unit value of platinum in materials.

primary platinum. Platinum derived from ore.

recycling. Reclamation of a metal in useable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the metal apparent supply that is scrap on an annual basis. It is defined as (consumption of old scrap (COS) plus consumption of new scrap (CNS)) divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{\text{COS} + \text{CNS}}{\text{AS}} \times 100$$

reforming. A petroleum-refining process that uses a platinum catalyst to convert aliphatic hydrocarbons to aromatic hydrocarbons. Increasing the aromatic hydrocarbon content of gasoline raises the octane and lessens knocking

secondary platinum. Platinum derived from or contained in scrap.

siderophilic. Having an affinity for iron.

toll refining. Custom refining of metal scrap or residue (feedstock) for which the refiner is paid an agreed fee (toll) for the recovery of specified precious metals or nonferrous scrap. The refined product is returned to the owner of the feedstock.