Conservation of Strategic Materials

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Introduction

Past experience has shown conservation to be an important response to shortages of materials, and strategic materials are no exception. In all of the post-World War II supply disturbances discussed in this report, industry responded with increased recycling and, in some instances, adopted new practices which used materials more efficiently, Conservation also can be an ongoing strategy to reduce industry dependency on insecure sources of supply, In this chapter, several different conservation techniques that can conserve strategic materials are discussed, Included are recycling, product life extension, trimming of alloy additions to the low side of acceptable ranges, and improved processing techniques, Substitute materials and use of surface modification technologies can also conserve strategic materials; these are addressed in chapter 7.

Recycling

Recycling differs from other conservation techniques in that it directly adds to material supplies. Sources of recycled metals include scrap material generated by the primary producer, which is called "home" or "revert" scrap, and secondary (or purchased) scrap, Secondary scrap generated by manufacturers and fabricators is called "prompt industrial scrap," while scrap that comes from products that have been used and discarded is called "obsolete scrap. " Another secondary source is process waste that can be reclaimed from metal processing plants.

Purchased scrap (comprised mostly of prompt and obsolete scrap) accounted for 8 percent of domestic cobalt consumption, 15 percent of platinum consumption, and 12 percent of chromium demand in 1982.[1] Actual levels of recy-

cling are significantly higher owing to internal recycling by industry, toll refining arrangements, and incomplete reporting to the Bureau of Mines. In addition, a substantial amount of manganese is recycled from ferrous scrap, and this may grow in the future.

Home scrap, which includes trimmings and ends from castings and overflows from ingots, is generally recycled with great efficiency. Since it is clean and its composition is known, it can simply be returned to the melt for reprocessing.

Recycling of prompt scrap is less uniform than home scrap. In large manufacturing operations, where substantial amounts of scrap are generated, efforts to separate scrap by type, to keep it free from contaminants, and to maintain collection and marketing operations are often justified by the market value of the scrap. In smaller operations, or in processes where oils or cutting fluids contaminate the scrap, materials may be discarded as waste. Even when recycling offers economic advantages, firms may not want to divert their resources to the establishment of a new set of internal procedures for segregation and collection of scrap.

Collection of obsolete scrap presents even greater problems. This scrap may be disseminated across wide areas and mixed with a variety of other materials, Impurities from metallurgical contaminants must be eliminated to make the scrap reusable. Owing to the expense of collecting, identifying, and separating this scrap, a substantial amount of metal is lost. Even when quantities of known materials are collected, limitations set by the processing technology may result in the scrap being downgraded to a less demanding application. For example, superalloy scrap may be downgraded to make stainless steel in which the cobalt content serves no purpose, and is essentially lost.

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[1] U, S. Department of Interior, Bureau of Mines, *Mineral Commodity Summaries 1983* (Washington, DC: U.S. Government Printing Office, 1982), pp. 32, 36, and 116.

Significant quantities of strategic materials are lost in process wastes, because the costs of treatment or handling for recovery exceeds the value of the contained metals, Technological development, combined with imposition of high costs on the disposal of wastes containing hazardous materials, have given impetus to research on processing of such waste to ease disposal problems and, where possible, to obtain saleable products from the processing.

Advanced Processing and Fabrication Technologies

Industry constantly searches for new processing and manufacturing technologies that can increase production, decrease costs, save energy and materials, or improve performance. Adoption of new technologies sometimes conserves strategic materials. The rapid phase-in of the argon-oxygen-decarburization (AOD) process for making stainless steel during the 1970s is a dramatic case in point. The AOD process led to major improvements in chromium utilization in making stainless steel, including the ability to use more high-carbon ferrochromium (which is cheaper, and requires less energy to make than low-carbon ferrochrome) as a raw material, and enhanced chromium recovery from scrap ferrochromium charges. Nearly all stainless steel producers now use the AOD process, so that further improvements in chromium utilization arising from the process are likely to be modest.

Although it is rare for a new technology to be adopted as pervasively and quickly as the AOD process, ongoing industrial trends in metals processing and fabrication may lead to appreciable savings in some strategic materials on a per-part or per-unit basis in the years to come. For the most part, industry investment in advanced processing and fabrication technologies is driven by concerns about product performance, reducing costs, and minimizing reject parts. Material conservation is not often a primary reason why industry adopts advanced processing technologies, but it is often an important side benefit.

The need for U.S. steelmaker to remain competitive with foreign producers, for example, is leading to the replacement of older, less efficient facilities with new processes which are more cost effective and produce higher quality steel.[2] Furthermore, major savings in manganese can be achieved as steelmaker upgrade basic steelmaking processes. As newer technologies and processes are introduced, important reductions in the amount of manganese needed to process each ton of steel can be expected. The pace of this phase-in will depend on industry resources committed to upgrading of domestic steelmaking capabilities.

Materials conservation is also a side benefit of advanced processing technologies that are increasingly used in producing and fabricating aerospace parts made from superalloys. Often referred to as "near-net-shape" processes, these casting and powder metallurgy techniques are used primarily to reduce costs of machining and to improve control over manufacturing reliability. Because less metal is removed during processing, product yields are improved significantly.

Conservation Through Part Life Extension and Design

Life extension approaches to material conservation are of primary relevance to very high-value parts. The overall value of a turbine blade installed in a jet engine, for example, may be 500 times the raw material value. Technologies and maintenance strategies that extend the usable life of a part, therefore, can result in substantial savings in replacement part costs and materials over time.

Some life extension strategies are integrally related to advances in nondestructive evaluation or testing (NDE or NDT) of products. On the inspection line of manufacturing facilities, NDE can be used to identify flawed products

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'The need for technological adjustments by the U.S. steel industry is discussed in the OTA assessment, Technology and Steel Industry Competitiveness, OTA-M-122, June 1980.

which can be immediately set aside for reworking or recycling.

NDE has also been used on the production line to monitor machine tool conditions in order to avoid breakage or other damage. For example, tungsten carbide drill bits have often been retired prematurely because of concern about breakage. A process developed by the National Bureau of Standards for continuous monitoring of the drill bit allows selective retirement of a bit when failure is detected to be imminent, rather than relying on a statistical average or waiting until the bit actually breaks, In addition, since cobalt is used to bind the tungsten carbide, strategic material use may be reduced.

NDE's potential role in monitoring of in-service parts is expected to grow in the years to come as confidence in the reliability of inspection devices increases. Formal retirement for cause maintenance programs are being evaluated by the Department of Defense and may be implemented in the late 1980s.

It is also possible to conserve strategic materials in the design of products, This sometimes happens inadvertently. For example, U.S. automakers, in their effort to downsize cars, have substantially reduced chromium use in cars even though strategic materials conservation was not a primary objective. Design strategies specifically intended to minimize strategic materials use (e.g., industry's effort to conserve cobalt in the late 1970s) are probably rare. However, in many noncritical applications, designers have a wide range of materials that could be used. Actual choice of a material may be governed not only by cost and performance factors, but also by the designers' experience and esthetic considerations. In theory, as computer-aided design technologies and computer-aided selection of materials advance, designers may become more aware of alternative materials that use less strategic materials.

Design of products so that they can be easily recycled is another frequently proposed conservation technique. However, the trend in some industries is toward use of more complex materials and products that pose greater difficulties for recycling.

Interrelationships of Conservation Approaches

As discussed in subsequent sections of this chapter, the prospects for conserving strategic materials in many applications are quite good. However, the extent to which any given approach will be adopted by industry will depend on how well it fits into the overall corporate strategies of many different firms. Generally speaking, strategic materials conservation per se is seldom a primary motive in industry decisions—although it is sometimes an ancillary benefit.

In the future, industry concerns about competitiveness, improving product performance, and cutting production costs will lead to adoption of new technologies, some of which may lead to conservation of strategic materials. It is difficult, however, to predict overall impacts of conservation on U.S. import reliance: these new technologies will interact in complex ways—sometimes simultaneously in a given application, For example, increased use of materials-efficient fabrication processes in the aerospace industry will reduce the amount of home and prompt superalloy scrap that would otherwise be available for recycling, The overall effect of this on strategic materials use, however, is likely to be positive, since some fabrication scrap is difficult to recycle. Life extension techniques would reduce demand for replacement parts containing strategic materials, but would also reduce the quantity of obsolete scrap available for recycling.

Case Studies of Strategic Materials Conservation Opportunities

Conservation of some strategic materials increased during the late 1970s and early 1980s, encouraged in part by higher costs for raw materials and energy, Government waste disposal requirements, and industry investment in new materials-efficient technology. However, major opportunities to conserve strategic materials are still evident. These vary by material and application:

1. Despite advances in manufacturing technologies, total cobalt losses in **1980** in unrecovered or downgraded scrap, or in processing wastes, amounted to 7.7 million pounds—nearly half of the estimated 16.5 million pounds of cobalt actually consumed domestically that years By far, the largest opportunity for increased cobalt recycling lies in the increased recovery of obsolete scrap. Of the 6.3 million pounds of cobalt in products estimated to have become obsolete in 1980, nearly three-fourths (about 4.6 million pounds) was unrecovered or downgraded. Potential sources for improved recovery include superalloy from obsolete jet engine parts and cobalt-bearing catalysts. Other cobalt recycling opportunities include reduction of downgrading of obsolete scrap and improved recovery of processing waste, which together entail cobalt losses of 3.1 million pounds.

2. The steel industry is the country's dominant user of manganese, consuming nearly **90** percent of total U.S. requirements. Manganese consumption is dependent not only on the amount of steel produced, but also on how efficiently manganese is used in steel production. Significant future reductions in the amount of manganese needed per ton of steel are expected: greater attention to trimming is expected to reduce the average amount of manganese in steel by 12 percent, from 13.8 to 12.2 pounds per ton by 2000. This, together with adoption of improved steelmaking technologies, such as external desulfurization, contin-

uous casting, and ladle and secondary refining techniques are likely to decrease the amount of manganese required to produce a ton of steel from *35.6* to *24.8* pounds by the year *2000.* The consumption of imported manganese ore and ferromanganese is estimated to decline from **17.8** pound per ton of steel to 9.5 pound per ton, a reduction of over 45 percent. Most of these technologies will be implemented for product quality and cost competitiveness reasons.

3. Widespread adoption of the AOD process by stainless steelmaker led to industrywide improvements in chromium use that are not likely to be repeated soon. However, chromium conservation opportunities, including increased recycling, and reduced overspecification of materials, could lead to major savings. In the 1977-81 period, an average of 64,000 tons of chromium contained in purchased stainless steel scrap was recycled each year.[4] By contrast, an estimated *62,000* tons of chromium contained in obsolete stainless steel scrap went unrecovered or was downgraded in 1977 (the last year for which detailed estimates have been made). The largest single opportunity for enhanced recovery of obsolete scrap is in automotive recycling, where most chromium-bearing scrap is downgraded. Chromium recovery from industrial processing wastes is increasing, owing to adoption of collection procedures and commercial reprocessing systems,

4. The high price of platinum group metals (PGMs) encourages highly efficient use of these materials. Recycling probably accounts for over *40* percent of U.S. PGM consumption when internal (toll refining) recycling by industry is taken into account. The key opportunity for increased recycling over the next 10 to 15 years will be recovery of PGMs from automotive catalytic converters which could add up to *500,000* troy ounces annually to U.S. PGM

[3]National Materials Advisory Board, *Cobalt Conservation Through Technological* Alternatives, publication NMAB-406 (Washington, DC: National Academy Press, 1983), fig. 3 (p. 23) and table 11 (p. 24).

[4]U. S. Department of Commerce, Critical Materials Requirements *of* the U.S. *Steel* Industry (Washington, DC: U.S. Government Printing Office, 1983), p. 62,

supplies by 1995. Obsolete electronic scrap is also a promising source for secondary recovery of PGMs, even though such scrap is disseminated widely throughout electronic equipment which, in turn, is spread all across the country, making collection and separation of metals expensive. The Department of Defense, which is a large generator of electronic scrap, and the Bureau of Mines, have cooperated in developing improved means for processing this scrap.

In the pages that follow, prospects for strategic materials conservation in certain specific applications are discussed.

Superalloy

Superalloy constitute the largest single category of cobalt use. They are also the principal users of high-purity chromium metal and major users of low-carbon ferrochrome. Typical cobalt-base superalloy contain up to 65 percent cobalt- and nickel-base, alloys may contain up to 20 percent cobalt. Chromium content ranges between 10 and 25 percent.

Since 1978, when disturbances in Zaire led to widespread concern about cobalt supplies, manufacturers of aircraft jet engines and engine components and several Federal agencies have placed increased emphasis on reducing the need for cobalt in jet engines. One approach, covered in detail in chapter 7, is the development and use of substitute alloys that contain less cobalt. Other approaches emphasize conservation, through recycling of superalloy scrap, use of near-net-shape manufacturing processes to reduce fabrication scrap, and extension of the useful life of components. As industry adopts these techniques, the need for cobalt, and for other strategic metals, such as chromium, nickel, and tantalum, will be reduced on a per part basis.

Substantial amounts of cobalt, chromium, and other strategic metals used in the production and fabrication of superalloys do not end up in the final part. Table 6-1, adapted from a 1983 National Materials Advisory Board (NMAB) report on cobalt conservation oppor-

Table 6-1 .–Cobalt Consumption in Superalloys, 1980

	Wrought	Cast	Total
Input:			
Primary cobalt . . . . ,	3.47	1.73	5.20
Prompt scrap.	0.26	1.50	1.76
Obsolete scrap ., ...	0,87	0.32	1.19
Total production . .	4.60	3.55	8.15
output:			
Final parts ., ...	2.34	1.24	3.58
Total lost ., ...	2.00	0.82	2.82
(Waste)	0.21	0.28	0.49)
(Downgraded)	1.79	0.54	2.33)
Prompt scrap.	0.26	1.50	1.76

SOURCE Adapted from National Materials Advisory Board, *Cobalt* Conservation *Through* Technological Alternatives, National Academy of Sciences, 1983, pp. 147, 148

tunities,[5] estimates sources and end results of the cobalt used in the production of superalloy in 1980, the most recent year for which detailed information is available. Several important points can be drawn from the table:

- Of nearly 8.2 million pounds of cobalt used in superalloys in 1980, only 3.6 million pounds, less than 45 percent, were contained in final parts.
- Almost 55 percent of the consumption of primary metal was lost through downgrading or waste in the production of superalloy parts in 1980.
- Almost 44 percent of the initial amount of wrought alloys were lost or downgraded; for cast alloys the fraction is lower, about 23 percent.
- The use of obsolete superalloy scrap was quite low, accounting for less than 15 percent of the total cobalt used in processing superalloys. NMAB also estimated that only half of the cobalt in superalloy scrap that became obsolete in 1980 was recovered for recycling by the superalloy industry (1.19 million out of 2.4 million pounds),

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[5]*Cobalt* Conservation Through Technological *Alternatives,* op. cit. Some uncertainty surrounds the estimates shown in table 6-1, owing to the inadequacy of the available data on scrap use and new cobalt requirements of the superalloy industry. As a result, various assumptions had to be employed by NMAB to approximate conditions in 1980. While NMAB believed its cobalt material flow model to be "reasonable approximation of reality, ' it noted that further work would be needed to confirm or reject its assumptions (pp. 25-26).

These statistics suggest the tremendous potential of conservation techniques to reduce requirements for primary cobalt. In 1980, 2,8 million pounds of cobalt were lost through downgrading and to waste in fabrication of superalloy parts. In the future, much more of this material may be recoverable as superalloy recycling technologies advance. Alternatively, the amount of material lost could also be reduced through the increased use of near-net-shape manufacturing processes, particularly with respect to the wrought alloys.

Obsolete scrap is a large potential source of cobalt. Most of the 3.58 million pounds of cobalt used in finished superalloy parts in 1980 will eventually be available for recycling, but much of this material may be downgraded unless jet engine manufacturers are confident that scrap can be safely recycled for jet engines, The raw materials for superalloys, whether it is cobalt, nickel, chromium, or ferrochromium, must be of the highest purity in order to avoid faults in the final part that could cause it to fail, Thus, manufacturers of aircraft engines often prohibit use of obsolete scrap unless certified processes for collecting and processing the scrap have been approved, Rates of obsolete scrap generation in the future may be affected by techniques that extend the service life of parts.

Near-Net-Shape Processes

The use of high-temperature alloys in a jet engine is very inefficient in terms of the amount of material consumed to produce a finished part. Ratios of *8* to 1 for input material to final part (also referred to as the "buy-to-fry" ratio) are common, and ratios of 20 to 1 are not unheard of. This ratio can be significantly reduced by near-net-shape processes.[6] Three general types of near-net-shape processes are in use at this time: precision casting, advanced forging, and powder processing.

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[6] These processes are discussed in detail in New Metals Processing Technologies, a report prepared for OTA by Charles River Associates, Inc.

PRECISION CASTING

Casting, the solidification of molten metal in molds, is a near-net-shape process that has been used for jet engine components since the birth of the industry. Casting is very efficient in its use of material. Although it is necessary to use gates and risers to control the flow of metal into the mold, resulting in as little as *40* percent of the metal actually ending in the final casting, large castings are very near to their final shape (only *5* to 10 percent of the material needs to be removed during the final machining and finishing operations). Further, most of the scrap generated in casting is "immediate revert"—that is, it can be recycled without further processing. Since it is recycled in the same shop in which it is generated, segregation and identification are simple matters. Therefore, most material poured from the melting furnace is eventually used.

Recent trends in casting technology have resulted in precision castings of up to *500* pounds (typically 10-pound units were produced in the past). This results in two advantages. First, a larger portion of the engine can be produced by the material-efficient casting method, and second, the elimination of numerous steps of component assembly reduce the cost of assembling the engine.

New casting technologies have also resulted in improved material properties. Through the use of directional solidification, components, principally blades and vanes, can be cast so that grain boundaries are very long and are aligned with the axis of the component. It is also possible to cast components as a single crystal, eliminating grain boundaries altogether, This allows the elimination of elements that are often added to strengthen grain boundaries, such as zirconium and hafnium.

ADVANCED FORGING METHODS

Closed die forging is used extensively to fabricate gas turbine components ranging from small turbine buckets to large fan blades and very large disks. In this process, the starting stock is heated to various temperatures depending on the alloy being forged and is placed be-

tween two dies that are forced together, enclosing the stock and deforming it to the shape of the die. Usually the starting stock is wrought—i.e., it consists of a bar or billet that has been hot-worked from an ingot. The hot working ensures that the original casting achieves full density and chemical homogeneity.

The major disadvantage of this process, as conventionally practiced, is that a large amount of the material must be removed to reach final shape. It is common for the final part to contain only one-tenth of the original materials. This large material loss due to forging maybe considerably reduced through the use of two advanced technologies.

Isothermal Forging.—Isothermal forging is distinguished from conventional forging operations in that the temperature of the forging die is the same as the piece being worked, approximately 1,7500 to 1,9500 F. Through reduction of heat loss from stock to die, the plastic deformation of metal is significantly improved. The operation is conducted in an inert gas atmosphere. Parts can be processed to close to the final specifications, although the shape must be configured to allow nondestructive inspection, usually by acoustic methods (hence the term "sonic shape" for the form as it leaves the die). Further machining is required to reduce the shape to its final dimensions. Pratt & Whitney Aircraft has patented and licensed a variation of the isothermal forging process which it claims can reduce the input material by 50 percent, thereby making a large reduction in the "buy-to-fly" ratio. Isothermal forging is now routinely used for the forging of turbine disks. .

Near-Isothermal Forging.—Also referred to as "hot-die forging, " near-isothermal forging differs from isothermal forging in that the die is not heated to the temperature of the stock, but to *1500* to *3000* F below the stock temperature. The operation is conducted in air and can be adapted to conventional presses, making it more widely available at a lower cost than isothermal forging. Although the improvements are not as great as those for isothermal forging, this process does reduce the amount of input material required by conventional closed die forging,

POWDER PROCESSING

A third process for the manufacture of superalloy components is based on the processing of ultrafine powder into billets or parts. The powder may be of a single composition or a mixture of materials. By the latter method, oxide dispersion-strengthened alloys, such as MA-754, are produced.

Powder metallurgy is attractive, not just because it can produce new materials, but because it can produce substantial reductions in the amount of scrap generated during forming operations. Powder "pre-forms" are produced by techniques similar to casting processes. The pre-forms are then compressed at high temperatures and pressures to eliminate voids and inclusions. The components are then ready for inspection and final machining.

The combination of powder pre-forms and hot isothermal forging has allowed the development and use of some of the most advanced nickel-based alloys in turbine disks, including IN-100, MERL-76, and Rene-95, none of which could be reliably formed into components by conventional means.

The advantages of powder metallurgy are not limited to conservation of strategic metals in the more exotic applications such as jet engine components. Gears and camshafts, parts which normally require considerable machining, can be manufactured to near-net shape by powder pre-forms, thereby reducing scrap production and machining, The need for resulfurized steel in these applications, normally used for its improved machining characteristics, can be eliminated as well, reducing the requirements for manganese in this type of steel.

Recycling

Until cobalt supplies were seen as threatened by the 1978 Katangese rebellion in Zaire, recycling in the superalloy industry was largely limited to home scrap. Prompt industrial scrap and obsolete scrap were either downgraded for

stainless steel production or exported out of the country. As prices rose and supplies became uncertain, the importance of recycling of super-alloy scrap became apparent. Alloy producers, parts fabricators, and turbine manufacturers began to segregate fabrication (prompt indus-trial] scrap by alloy type so that it could be remelted and reused. Some turbine manufac-turers modified earlier specifications to allow greater use of prompt industrial scrap and even some obsolete scrap, provided that the source and type of the scrap was known. The exact amount of the savings provided by recycling during the period of high cobalt prices ($25 per pound at their producer price high point in 1979-80) is not known, but domestic consump-tion of primary cobalt in superalloy was prob-ably 10 to 25 percent less than might otherwise have been the case.[7]

Identification and separation of scrap is time consuming and expensive. With 1983-84 cobalt prices ranging from $6 to $12 per pound, it is not clear whether the gains made in the late 1970s will continue. Some firms have contin-ued their recycling programs, particularly for prompt scrap, by encouraging suppliers and customers to separate scrap by alloy type. Spe-cialized scrap processing firms now have great-er experience with this kind of recycling, which may encourage jet engine manufacturers to up-date specifications to allow greater use of scrap in the production of superalloys. Once such specifications are established, recycling of superalloy scrap can be increased quickly in response to increased metal prices or supply uncertainties.

PROCESSING OF SUPERALLOY SCRAP

Commercially used technologies for recy-cling superalloy scrap are based on the same processes used in the original production and refining of the alloy, including vacuum induc-tion melting and vacuum arc remelting, but strict attention is paid to segregation of scrap by type.

For production of superalloys, uncontami-nated home scrap of known composition can be and is reverted directly to the charge. Ad-ditional processing sometimes involving sev-eral steps may be needed if prompt industrial scrap or obsolete scrap is to be recycled.

Vacuum and air furnace technologies needed to remelt high-quality superalloy scrap into usable master alloys are already in place in the United States. In-house scrap is now carefully separated and routinely added to the alloy melt by many producers of superalloys, and a spe-cialized industry has developed to produce master alloys from fabrication scrap. Some firms report that they now recover virtually all in-house scrap. Obsolete scrap is also recycled to some extent, although generally not for the most demanding application—rotating parts of jet engines. As is discussed in box 6-A, instru-ments able to identify complex alloys and con-taminants are now being marketed and may alleviate some technical problems associated with scrap sorting. According to recycling in-dustry sources, several million pounds of high-temperature alloy scrap have been shipped from scrap processors to melters in the last 10 years.[8]

Air-melting processes, involving electric fur-nace melting of the scrap charge and subse-quent refining in an argon-oxygen-decarburi-zation vessel, can produce alloys from scrap that are suitable for many noncritical superal-loy and super stainless steel applications, but are not appropriate in critical applications such as gas turbines used in aviation. Nickel and co-balt recovery is high, but readily oxidizable al-loys are lost in the slag. Air melting of scrap can also be used to produce master melt alloys suitable for further processing through vacuum melting into superalloys.[9]

Vacuum melting processes are used to pro-duce superalloy suitable for the most demand-ing applications or superalloys containing highly reactive elements. Only the highest qual-

[7]As discussed in Charles River Associates, Inc., *Effects of the 1978 Katangese Rebellion on the World Cobalt Market*, contract report prepared for OTA, December 1982, pp. 1-6.

[8]Information provided by the National Association of Recy-cling Industries.

[9]J. J. deBarbadillo, "Nickel-Base Superalloy: Physical Metal-lurgy of Recycling, " Metallurgical Transactions A., vol. 14A, March 1983, p. 332.

Box 8-A.-Scrap Sorting and Identification Instruments

Recycling of complex materials requires detailed knowledge of scrap constituents. Nickel- or cobalt-based superalloy scrap may contain 8 or even 10 separate alloying elements, as well as potentially troublesome tramp elements and contaminants that need to be removed during processing. Concerns about scrap quality are not limited to superalloys: in stainless steel production, for example, presence of phosphorus in scrap needs close monitoring, due to its adverse effect on working, forming, and ductility of stainless steel. Very small amounts of titanium in scrap charges are believed to be harmful in tool steels and high strength steels. Failure to correctly identify and sort scrap is a major reason for the extensive downgrading of superalloy and stainless steel scrap that is still prevalent.

Certification requirements placed on scrap processors by their customers have become increasingly stringent. In some premium uses, scrap processors may have to identify scrap constituents to an accuracy of a few parts per million. Under these circumstances, conventional scrap sorting techniques—entailing visual inspection, magnetic separation, or spark testing—are not sufficient in themselves.

Growth in recycling of superalloy and specialty materials during the last decade has led to increased use of mobile and inexpensive ($4,000 to $50,000) sorting instruments. These devices were not developed primarily for use in scrap processing, but most can be used by unskilled operators (or in some cases trained technicians) to identify complex scrap components more accurately.[16] Some of these (e.g., chemical spot testing) are used to confirm the presence of alloys after preliminary hand sorting is carried out. These techniques are qualitative or semiquantitative in nature. More complex readings can be obtained through X-ray spectrometers, thermoelectric instruments and eddy current devices—all of which

are now available as portable units which can be used in scrap yards.[17]

A recent recycling advance has been linkage of scrap identification devices to user friendly computers, which provide workers with step-by-step procedures for classifying scraps. Commercially available programs specifically geared to the needs of small firms in the recycling industry have been marketed for several years. One such program, used in conjunction with a portable X-ray spectrometer device, reportedly allows rapid identification of up to 16 elements in a sample.[18] Initial analysis can be completed in 10 to 50 seconds; a more complete quantitative analysis requires several minutes, if needed. If properly programmed, the computer will identify the trade name of the alloy or materials which the scrap most closely approximates. This is especially useful in obsolete scrap identification, where the origin of the materials may not be known.

Identification devices are increasingly used by the scrap industry–with the encouragement of the National Association of Recycling Industries, the Institute of Scrap Iron and Steel, and the Bureau of Mines. Most of these instruments were designed for laboratory or scientific use, not the difficult operating environment of the scrap yard. Portable devices have the ability to test a large number of samples rapidly on site, but are not capable of such detailed analysis as laboratory or stationary instruments. As instrument manufacturers become more aware of the scrap industry, instruments specifically designed for scrap industry use may be developed.

Likely trends in materials processing suggest that scrap classification techniques will need continuing refinement. Use of more complex alloys, and parts made from multiple alloys will increase recycling difficulties.

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[16]Xavier Spiegel and E. Horowitz, Instruments for the Sorting and Identification of Scrap Metal, Sponsored by the Institute of Scrap Iron and Steel (Baltimore, MD: The Johns Hopkins University Center for Materials Research, Oct. 15, 1981), p. 1.

[17]Newell, R. E. Brown, D. M. Soboroff, and H. V. Makar, A Review of Methods for Identifying Scmp Metals, Bureau of Mines Information Circular 8902 (Washington, DC: U.S. Government Printing Office, 1982).

[18]As discussed in: "Philips PB9500 X-Ray Spectrometer Speeds Recycling of Critical Materials," Norelco Reporter, vol. 28, No.1, May 1981, pp. 40-42.

The Bureau of Mines is identifying alloys for which current identification and sorting methods are not adequate, as a preliminary step towards development of new methods.[19] Another area of government R&D (undertaken by both the Bureau of Mines and the National Bureau of Standards) is instrumented spark testing techniques, which could reduce subjectivity in spark analysis by workers,

Ultimately, effective recycling requires well-developed linkages among processors, melt shops, fabricators, and manufacturers. Dur-

ing the last decade, many firms in the super-alloy industry established recycling programs, entailing close coordination of requirements along the entire chain of the industry. A properly controlled program to ensure scrap integrity entails accurate separation and identification of scrap, and adequate measures to reduce risk of contamination.[20]

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[19]U.S. Department of the Interior, Bureau of Mines, *Avondale Research Center Research Program Fiscal Year 1983,* (n.p., n.d.)

[20]A detailed discussion of superalloy scrap processing requirements can be found in R. S. Cremisio and L. *M.* Wasserman, "Superalloy Scrap Processing and Trace Element Consideration," Vacuum *Metallurgy: Proceedings of the* 1977 Vacuum *Metallurgy Conference,* R. S. Krutenat (ad.) (Princeton, NJ: Science Press, 1977), pp. 353-3S8.

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of known composition and history can be vacuum melted without extensive preprocessing,

In the long term, the potential for recycling will depend more heavily on obsolete scrap as the use of near-net-shape technologies increases. Where traditional machining of superalloy parts can typically require up to 10 times as much material as contained in the final part, new processes can reduce this figure to as low as 2 or 3 to 1. This reduces the amount of prompt scrap generated and thus increases the importance of obsolete scrap.

The technical feasibility of using obsolete superalloy scrap to produce investment cast jet engine turbine blades has been demonstrated by Certified Alloy Products. The company reportedly has produced a master alloy from used superalloy turbine blades.[10] The process entails oxygen lancing in an electric arc furnace, followed by refining in a vacuum induction furnace. Testing of blades made from the recycled alloy showed comparable quality to turbine blades manufactured from virgin materials. The firm developed the process in the aftermath of the 1978 cobalt price spike and has subsequently discontinued its use.[11] Al-

ity of scrap is suitable for vacuum melting. Such scraps are certified by alloy content and must be free of contaminants and tramp elements. With careful separation and identification, some in-house scrap and fabrication scrap

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[10]This process is described in Michael J. Woulds, "Recycling of Engine Serviced Superalloy s," *Superalloys* 1980: Proceedings *of* the Fourth International Symposium on *Superalloys,* John K. Tien, et al. (eds.) [Metals Park, OH: American Society for Metals, 1980), pp. 31-41.

[11]Private communication between personnel of Certified Alloy Products and OTA staff in May 1983.

though such techniques may enhance the potential for reuse of obsolete superalloy scrap, further work to establish process reproducibility and results may be needed.

Both vacuum and air melting furnace technologies continue to evolve. New processes, such as Electron-Beam Refining, Vacuum Arc Double Electrode Remelting (VADER), and Plasma Arc processes may have considerable relevance to superalloy recycling. Some of these technologies are in the early stages of use in the United States.

Several laboratory-scale processes have been developed which separate superalloy scrap into its constituent metals, but none have been commercialized. Such techniques overcome most concerns about contaminants. In a laboratory project sponsored by the U.S. Bureau of Mines, Inco developed a process that utilized a combination of hydro- and pyre-metallurgical processes to recover 93 percent of the chromium, 99 percent of the nickel, 96 percent of the cobalt, and 92 percent of the molybdenum from clean, solid superalloy scrap.[12] Other Bureau of Mines research projects on superalloy scrap are underway. In one experiment, the superalloy scrap is melted with aluminum or zinc to form an intermetallic compound which can be crushed into small particles. The particles are then dissolved by acid; the resulting solution would then be treated hydrometallurgically to recover the metals. The process is thought to be especially promising as a means for recycling mixed combinations of bulk superalloy scrap which have not been sorted.[13]

GTE Sylvania Corp. has a commercial facility for recovering high-purity cobalt from secondary sources that include some types of superalloy scrap, including grindings. GTE's

proprietary manufacturing process uses chemical means to recover highly purified cobalt powder that is now used in cemented carbide products. The firm is considering a larger scale recovery process which would produce compacted briquettes of cobalt that maybe suitable for superalloy production.[14]

Commercialization of advanced superalloy reclamation processes by industry is impeded by the currently low price of cobalt. Plans to undertake a pilot plant to test the Inco/Bureau of Mines laboratory process discussed above were discontinued when cobalt prices fell in the early 1980s. Feasibility studies showed that the pilot plant process, and a small-scale commercial facility would have been profitable at 1980 metal prices, but would operate at a deficit at cobalt prices in the 1981-84 period. Estimated costs of a pilot plant project able to handle 100 pounds of scrap feed per hour were estimated to be about $5 million in 1980 dollars, assuming no donation of equipment by industry. Operating costs for such a facility would be in the neighborhood of $2 million for an 18-month period.[15]

RETIREMENT FOR CAUSE AND PRODUCT LIFE EXTENSION PROGRAMS

currently, critical components of jet engines, such as turbine disks, are retired from service on a predetermined schedule, based on the number of hours a part has been in operation—not on the basis of actual detection of flaws or defects in the part, This has been necessary because of difficulties in detecting the early stages of flaws that could lead to a disastrous failure of a part. While the current retirement procedures minimize risk of failure, most parts are removed from service long before actual flaws occur.

Turbine disks used in the F-100 jet engine, for example, are only kept in service for the number of hours in which there is a statistical probability of a fatigue crack developing in one out of a thousand disks. As a result, 999 parts can be expected to be removed from service

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[12]J. J. de Barbadillo, J. K. Pargetter, and H. V. Makar, Process *for* Recoloring Chromium and *Other Metals* From *Superalloy* Scrap, U.S. Department of the Interior, Bureau of Mines Report of Investigation 8570 (Washington, DC: U.S. Government Printing Office, 1981),

[13]Jerald R. Pederson, compiler, Bureau *of Mines Research 1983* (Washington, DC: U.S. Government Printing Office, n.d.), p. 103: and G. B. Atkinson, Increasing *the Leaching Rate of Bulk Superalloy* Scrap by *Melting With* Aluminum, U.S. Department of the 1 nterior, Bureau of Mines Report of Investigations 8833 (Washington, DC: U.S. Government Printing Office, 1983).

141 nformation provided by GTE Products Corp.
15Information provided by the U.S. Bureau Of Mines.

prematurely for every single part that is defective. Subsequent testing has shown that the useful life of many of these retired parts could be 10 times longer than the disk in which the initial crack occurs.[21]

With the substantial technical advances that have been made in NDE in recent years, it may soon be possible to evaluate individual parts from operating jet engines at prescribed intervals in order to determine whether the initial stages of a flaw have appeared. Parts which have such flaws could then be retired for cause (RFC); those without flaws could be kept in service.

Such a strategy underlies the Air Force's Wright-Patterson Aeronautical Laboratory evaluation of methodologies for a maintenance program based on retirement for cause. If implemented, the program will permit parts from some jet engines to be used until there is actual evidence of an incipient flaw. An actual decision about implementing the program will probably not be made until after 1985. However, early indications are that the program has the potential to reduce spare-part requirements, and therefore to conserve strategic materials.

The initial Air Force evaluation centers on the F-100 jet engine. If initiated in 1985, the program's savings in spare parts over the 15-year average engine service life left in the F-100 fleet could be $249 million. By 2000, a 70 percent material savings from requirements for reduced spare parts would also be achieved, according to the Air Force.

A related Air Force initiative is aimed at "stockpiling" retired jet engine parts until they can be returned to service rather than simply disposing of them as scrap, as is ordinarily done.[22] Many of these parts have been retired simply because they have reached the end of the predetermined service life discussed above, and could be returned to service if retirement-for-cause (RFC) methodologies are implemented.

These parts are also being used as test specimens for the evaluation of RFC methodologies. Other parts in these "holding accounts" may be capable of rejuvenation through current and prospective technologies discussed in the previous section.

It is possible to extend the lifetime of components of the jet engine if flaws and defects can be caught at an early time. Researchers in West Germany, for example, have reported that if an engine is dismantled at three-quarters of its normal life and the turbine blades are subjected to hot isostatic pressing to eliminate incipient cracks, the overall life of the blades will extend to 50 percent beyond their normal life in service, as illustrated in figure 6-1.

Hot isostatic pressing (HIP) has also been shown to extend the service life of vanes and blades if it is used as a post-casting treatment to eliminate all porosity remaining in the material after casting. The post-casting HIP treatment has been shown to increase the average stress-rupture life by 100 percent and the fatigue life by 800 percent in two nickel-base alloys, B-1900 and IN-792, both modified by the addition of hafnium.

Figure 6-1.—Service Life Time of Turbine Blades
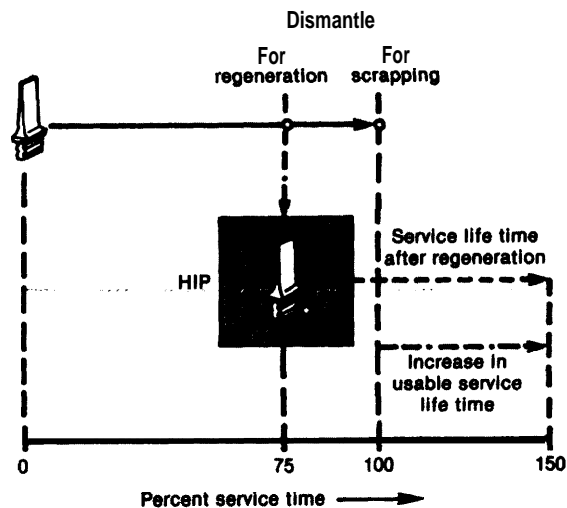
SOURCE" H. Huff, R. Grater, and R Fröhling, "Measures for Materials Conservation in Aero-Engine Construct ion," paper delivered to the NATO Advisory Group for Aerospace Research and Development Conference, Vimeiro, Portugal, October 1983

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[21]J. A. Harris, et al., Concept Definition: Retirement *for* Cause *of F100* Rotor Components. Technical Report AFWALTR804118 prepared for U.S. Air Force Materials Laboratory at Wright-Patterson Air Force Base by Pratt & Whitney Aircraft Group (Washington, DC: U.S. Government Printng Office, 1981).

[22]Information provided by the U.S. Air Force.

A quite different approach toward material conservation is to design parts for the life of the aircraft. Such approaches may require more strategic materials to be used in the initial part, but because these parts have a longer life expectancy, the end result may be to conserve materials. Such strategies are being evaluated through the engine structural integrity program of the Air Force.

OUTLOOK FOR CONSERVATION OF STRATEGIC MATERIALS IN SUPERALLOYS

All of the factors discussed above—materials-efficient processing, recycling, and life extension—will play a role in determining conservation levels achievable in superalloy production and parts manufacturing. More efficient processing and fabrication could reduce input raw materials needed for each jet engine by 10 percent by 1990 and 25 percent in the early years of the next century, compared to current levels. This is a judgmental estimate, which assumes that many currently used technologies (which are less efficient in conserving materials) will continue to be used throughout much of the period. Advanced technologies are likely to be introduced primarily when new alloys and successive generations of jet engines are brought into production, typically at 5- to 10-year intervals.

As fabrication becomes more efficient, home and prompt scrap—now preferred for recycling—will comprise a less important portion of the materials available for recycling. If processing problems are overcome, obsolete scrap will probably ascend in importance, although to what extent is difficult to foresee. Part life extension technologies and RFC maintenance philosophies could extend the material life cycle, thus temporarily reducing obsolete scrap production levels, even if advanced recycling technologies are implemented.

Development of new alloys and manufacturing techniques by superalloy producers and jet engine makers can have unpredictable effects on recycling. Increased use of powder metallurgy, coatings, multiple alloy components, and phase-in of advanced ceramics and composites may make the job of recycling more difficult.

For example, coated or clad superalloys may reduce the value of some superalloy scrap owing to added costs of identifying and recovering the surface layer. continuing evolution in scrap processing technologies to keep pace with rapid changes by producers and component manufacturers will be required if the promise of recycling is to be realized.

Conservation of Manganese in the Steel Industry[23]

Nearly 90 percent of the manganese consumed in the United States is used in the production of steel, either as an alloying element or as a processing agent.[24] Consumption of manganese in this industry is dependent not only on the level of steel production, but also on the mix of steel grades produced and processing technologies used. This section discusses the function of manganese in both steel and steelmaking, and assesses the effects of product and processing trends on the pattern of manganese use in the steel industry.

Manganese as an Alloying Element in Steel

Manganese is second only to carbon in importance as an alloying element in steel. Through its influence on steel chemistry and microstructure, manganese influences an assortment of physical and mechanical properties. As discussed in box 6-B, manganese provides sulfur control, enhances hardenability, wear resistance, and solid solution strengthening, and retards recrystallization. The amount of manganese used as an alloying element depends on the specific property requirements of the particular steel product. Some grades make greater use of it than do others.

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[23]Much of the analysis in this section was based on G. R. St. Pierre, et al., Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alloying Element in Steels, OTA contractor report, February 1983.

[24]Based on data from Minerals Yearbook Volume I (Washington, DC: U.S. Bureau of Mines, Department of the Interior, 1980, 1981, 1982). Includes manganese consumed in ores with greater than 5 percent Mn, ferroalloys, and metal, but not the manganese contained in most iron ores

Box 6-B.—The Role of Manganese as an Alloying Element[25]

Sulfur Control.--In nearly all grades of steel, sulfur is an unwelcome impurity. It is a tramp element that is picked up from the coking coal, fuel oils, and ferrous scrap used in the production of iron and steel. Iron and sulfur form compounds (FeS) at the grain boundaries within steel, causing a detrimental condition known as "hot shortness." Problems arise because FeS has very little structural integrity, being either liquid or extremely plastic at the temperatures encountered during many finishing (hot working) operations. The presence of this strengthless phase as a film along the network of grain boundaries severely weakens steel at high temperatures and causes cracking during fabricating operations, Furthermore, in ferritic grades, FeS causes problems with low-temperature mechanical properties. To minimize these effects, the sulfur content is typically held below 0.05 percent by weight. Manganese is added to react with the remaining sulfur, which would otherwise combine with iron. The globular MnS precipitates formed upon the addition of manganese are solid at typical hot working temperatures and are structurally amenable to hot forming operations. Although it is not a remedy for all sulfur-related problems, manganese generally improves both the high- and low-temperature properties of steel.

Hardenability.--Heat treatment is the most potent method for optimizing the strength and ductility of steel. The cooling rate required to form a given martensite profile during the heat treatment quench is a very important parameter, known as "hardenability," of steel. Additions of the common alloying elements, namely molybdenum, manganese, chromium, silicon, and nickel, facilitate the formation of martensite, thereby reducing the cooling rate requirement and increasing the hardenability of steel. Manganese is a very cost-effective hardenability agent and consequently is one of the most vital alloying elements for influencing the response of steel to heat treatment.

An allied effect of some alloying elements concerns their influence on the shape and distribution of iron carbides in steel. Weld embrittlement can occur if the iron carbides form a continuous film at the grain boundaries during the thermal excursion. Manganese tends to enhance weldability of steel by inhibiting the development of such film.

Wear Resistance.--Manganese, like nickel, lowers the austenite-to-ferrite transformation temperature of steel and is termed an austenite stabilizer. High-carbon steels that remain austenitic at room temperature can be produced by adding manganese to levels greater than 10 percent by weight. Austenitic steels as a class are attractive because their strength increases markedly as they are deformed and they have excellent resistance to fracturing under impact conditions, two properties important for wear resistance. The austenitic manganese grades, called Hadfield steels, display good abrasion and impact resistance and serve in construction, mining, quarrying, oil-well drilling, steelmaking, cement and clay manufacturing, railroading, dredging, and lumbering applications. Other austenitic grades (containing 15 to 25 percent manganese) have been developed for their nonmagnetic properties and high toughness. These high-manganese austenitic steels are suitable for structural uses in strong magnetic fields and at cryogenic temperatures and may replace the stainless steels commonly used in these applications.

Solid Solution Strengthening.--Steel generally becomes stronger when an alloying element is dissolved in the iron phases. This effect is known as "solid solution strengthening." It is a very important means of strengthening ferritic steels, which cannot be strengthened by heat treatment. Alloying elements vary markedly in their potency as solid solution strengtheners. In ferritic steels the order of decreasing effectiveness appears to be: silicon, manganese, nickel, molybdenum, vanadium, tungsten, and chromium. While silicon is highest on this list, it is not used extensively because of an accompanying loss of ductility. Thus, manganese has great utility as a solid solution strengthener.

Recrystallization.–When steel is deformed or heavily worked, its microstructure is altered in a way that is detrimental to the properties of steel. To alleviate problems, steel in this condition is usually annealed, whereupon the microstructure is recrystallized. Manganese slows the rate of recrystallization considerably. This is not a desirable effect and can have negative impacts on the productivity of various steel-treating processes, such as continuous annealing operations.

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[25]The terms ferrite, austenite, and martensite that appear throughout this discussion refer to the various microstructural phases of steel.

MAJOR CLASSES OF STEEL

Steel is produced in a myriad of compositions, and the relative popularity of each grade changes as consumer demands shift. Trends in manganese use vary among the four broad categories of steel: carbon, full alloy, high-strength low-alloy (HSLA), and stainless. All four classes contain manganese, but in differing proportions.

The most widely used systems for designating steels in terms of their chemical compositions are those of the American Iron and Steel Institute (AISI) and the Society of Automotive Engineers (SAE). These cataloging systems are very similar and are carefully coordinated by the two groups. In addition to the common grades listed by these organizations, steelmaker produce proprietary grades, but the manganese contents of these are comparable. The chemical specifications for a particular grade of steel vary slightly according to the product nature. Specifically, the ranges in plates are a little wider than those for bars, simply because compositional variations due to segregation are greater in the large rectangular ingots used in plate production than in the smaller ingots used for bars.

Carbon steel.—The main constituents of carbon steels are iron, carbon, and manganese, with manganese present up to a maximum of 1,65 percent. The majority of carbon steels have manganese specifications whose midpoints fall in the range 0.40 to 0.85 percent. The average manganese content of the entire carbon steel category is estimated to be about 0.65 percent, or 13. o pounds per ton of steel.

Manganese is used in carbon steels primarily for its sulfur control and solid solution-strengthening characteristics. It also improves the heat treating characteristics (hardenability) of these grades, though this is not a major consideration for many uses of carbon steel.

Two types of carbon steel have especially high manganese and sulfur contents in order to improve machinability, These resulfurized and resulfurized-rephosphorized grades typically contain 0.7 to 1.65 percent manganese and find service in applications, such as gears and cams, where considerable machining is needed. The large number of manganese sulfide particles in these steels improve surface finish, enhance metal removal rates, and increase the tool life by facilitating the chip formation process.

Full Alloy Steel.—Alloy steels usually contain more manganese and silicon than do carbon steels and, in addition, may contain other elements such as chromium and molybdenum. The extra alloying additions enhance mechanical properties, fabrication characteristics, or other attributes of the steel. In the more common alloy steel grades, manganese is added primarily for hardenability and less importantly for sulfur control. The average manganese content of alloy steels is estimated to be 0.75 percent, or 15. o pounds per ton of steel.

There are experimental alloy steels which have not yet been assigned regular AISI-SAE designations. In general, these experimental grades have higher manganese specifications than the standard grades. This suggests that manganese is becoming more popular as an alloying element and that the average manganese content of alloy steels should be expected to increase.

Although most alloy steels contain under 2 percent manganese, several grades containing 10 to 14 percent manganese are used. These are the Hadfield grades, which have excellent abrasion and impact resistance and are used in construction, mining, and other high-wear applications. There are also alloy steels with manganese contents as high as 25 percent that have been developed for use in strong magnetic fields and at cryogenic temperatures.

HSLA Steel.—HSLA steels have been developed as a compromise, having the convenient fabrication characteristics and low cost of carbon steels and the high strengths of heat-treated alloy steels. HSLA steels are generally used in applications such as energy production and automobiles, where savings in weight can be made as a result of their greater strength and atmospheric corrosion resistance and where better durability is desired.

HSLA's derive their superior properties from a variety of alloying elements in relatively low concentrations of 0.2 to 1.6 percent, coupled with controlled rolling and heat treatments. Common alloy additions include manganese, nickel, chromium, columbium, molybdenum, titanium, and vanadium. In comparison with the majority of carbon and alloy steels, the HSLA steels contain greater manganese contents. The limits in the 14 alloys designated by the SAE range from 1 to 1.65 percent manganese, with an average of about 1.1 percent, or an average of 22.0 pounds per ton of steel.

Stainless Steal .—Stainless steels are ferrous alloys that are rich in chromium and sometimes nickel. They are used in a variety of applications requiring good corrosion and oxidation resistance, as well as good strength. Compositional specifications for stainless steels usually do not prescribe minimum manganese levels, only maximum concentrations. Stainless alloy 304, which constitutes roughly 42 percent of the stainless steel produced in the United States, has a manganese specification of 2.0 percent maximum. On the average, stainless steels contain 1.7 percent manganese, or 34.0 pounds per ton of steel.

Several stainless steels, however, contain far more manganese than the average. In part, these alloys reflect the fact that an increase in manganese levels permits a reduction in nickel content. Tenelon steel, containing 14.6 to 16.5 percent manganese, was developed by U.S. Steel Corp. following concern over nickel shortages that occurred during World War II and the Korean conflict.

TRENDS IN THE STEEL PRODUCT MIX AND MANGANESE USE

The average amount of manganese consumed strictly for alloying purposes is being influenced by two major trends. The first is a changing product mix. Steel consumers are using increasingly greater proportions of full alloy, stainless, and HSLA steels, which usually contain more manganese than do carbon steels. Figure 6-2 shows the historical product shares for each of the major steel classes. The classes containing the most manganese, namely, full alloy, HSLA, and stainless steels, are expected to increase their portions of the market. By 2000, the product shares for the various products are expected to be approximately: carbon 80 percent; full alloy 9 percent; HSLA 9 percent; and stainless 2 percent.

The second contrasting trend is the decreasing manganese composition of carbon steels. This is a result of improvements in the steelmaking process, namely, better sulfur removal techniques and more reliable composition control, This effort is driven by economic pressures to conserve raw materials and increase product fabricability. New technologies allow steelmaker to retain the same quality product with less manganese. They can now afford to reduce manganese content to save on raw materials costs and to avoid some of the more unpleasant attributes of manganese, such as the recrystallization problem alluded to in box 6-B. Two manganese reduction techniques are likely to be administered: trimming to the lower end of the specified manganese range for each of the grades and reduction of minimum manganese compositions because less is needed for sulfur control.

Trimming.—Most manganese specifications for steels are listed as ranges. To be on the safe side, steelmaker generally aim for the midpoints of these ranges. Trimming involves aiming for the lower end of the specified range. Improved ladle practice is the key to effective trimming. Better manganese composition control is attainable with improved melt protection, alloy additions packaging, and sensing, analytical, and control instrumentation. Trimming practices could be implemented very quickly in an emergency, especially if operators become better aware of the statistical nature of quality control. The manganese content of steel could be reduced by as much as 0,05 to 0.10 percent with the use of trimming.[26]

Reduction in Specified Manganese Range.—Sulfur specifications of most steels, except for the resulfurized grades, are usually about 0.05 percent maximum. In practice, steels are produced with average sulfur contents of about

[26]John R. Stubbles, "Conservation Could Cut Steelmaking Requirements," American Metal Market, Oct. 20, 1983.

Figure 6-2. —Historical Market Shares for Major Classes of Steel
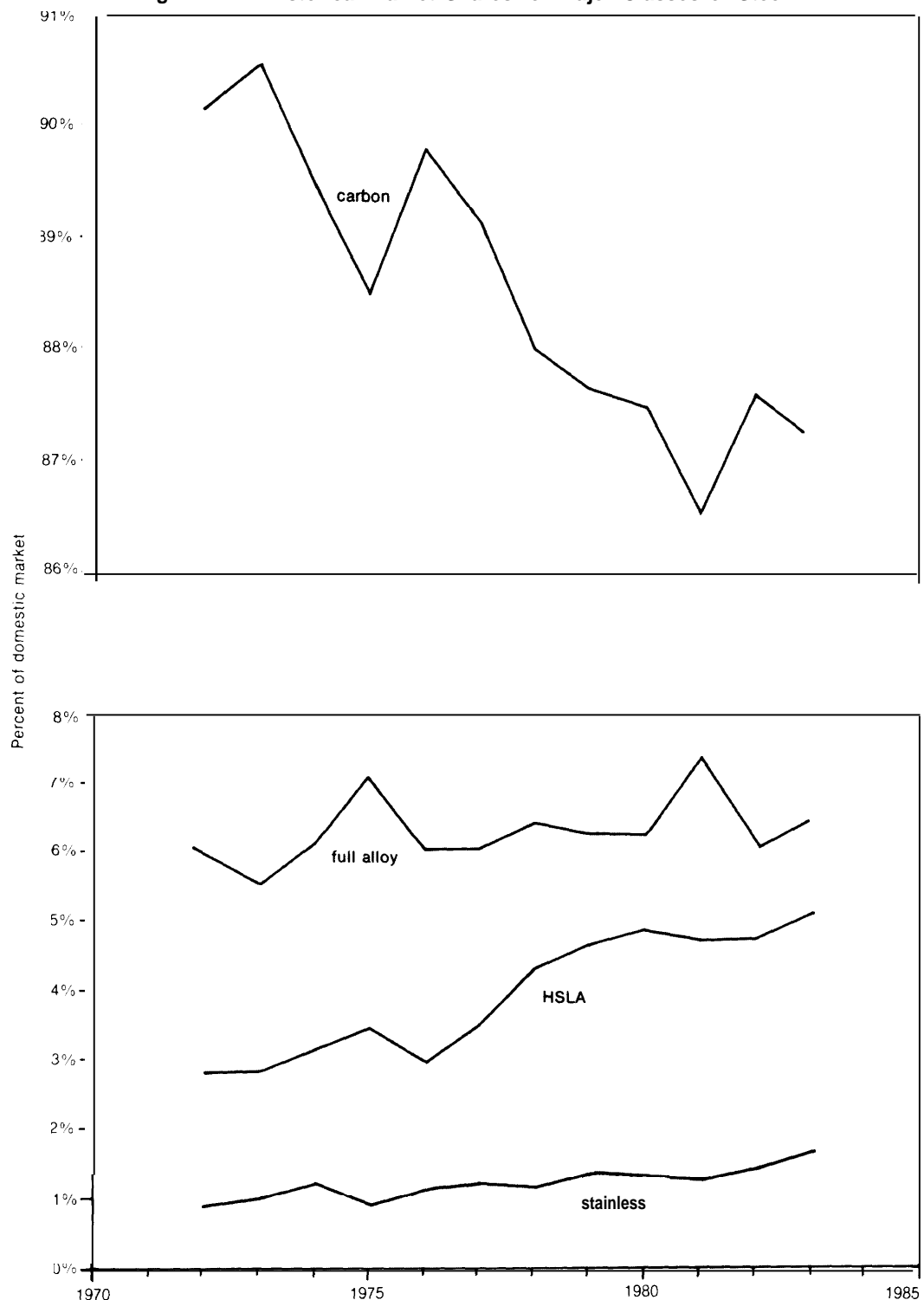
SOURCE Office of Technology Assessment, based on shipments data from the American Iron and Steel Institute, Washington DC

0.025 percent. Manganese specifications could be reduced to reflect this lower sulfur level.

Technologies such as external desulfurization of blast furnace iron and ladle metallurgy techniques allow steelmaker to reduce the sulfur content of the finished product further still. External desulfurization involves injecting calcium carbide or magnesium metal into the hot metal prior to its introduction to the basic oxygen steelmaking units. Lime is sometimes injected as an auxiliary agent with these desulfurization materials. Implementation of this technique will become almost universal in the domestic industry by 1990. This will reduce the need for desulfurizing during the steelmaking stage and lead to much lower residual sulfur levels in new steel and, eventually, in recycled scrap. Furthermore, ladle injections of desulfurizing agents such as lime, calcium, or rare earths just prior to primary casting reduces the sulfur content below 0.01 percent, and often below 0.005 percent. Ladle metallurgy technologies may not be installed primarily for sulfur reasons, but once they are in place they will no doubt be used to reduce sulfur levels in addition to providing the other benefits.

By 2000, the average sulfur content of steel may be as low as 0.01 or 0,02 percent. This means that less manganese is required in the finished product solely for sulfur control purposes. Even though proportionally higher manganese-to-sulfur ratios are required at lower levels of sulfur, a net reduction in the actual amount of manganese needed is realized by reducing the sulfur content. The manganese content of each grade of steel could probably be reduced by 0.2 percent with the widespread implementation of external desulfurization and ladle technologies. For carbon steels, this represents a 30-percent reduction in the manganese content.

SUMMARY OF TRENDS IN THE MANGANESE COMPOSITION OF STEELS

The effects of the product mix and manganese composition trends on the average manganese content of steel is illustrated by table 6-2. Note that even though the high-manganese alloy products become more pervasive, the average manganese composition is likely to drop from 0.69 to 0.61 percent. That is a reduction of 1,6 pounds (from 13,8 to 12.2 pounds) of manganese for each ton of steel.

Manganese in the Steelmaking Process

On an industry average, almost three times more manganese is added to steel during its processing than ends up in the finished product. When the 11 percent of the manganese additions that comes from in-house recycling is discounted, the overall manganese recovery rate comes to about 39 percent. This section outlines the major trends in steelmaking practice that affect the efficiency of manganese use in the production process.

Table 6-2.—Manganese Content for Major Grade of Steel

	Current (1982)		Forecasted	2000[a]
	Market share	Manganese content	Market share	Manganese content
Carbon[b]	87.6	0.65	80	0.5
Full alloy	6.1	0.75	9	0.8
HSLA	4.8	1.1	9	1.2
Stainless	1.5	1.7	2	1.7
Total	100.0	0.69	100	0.61

[a]Drastic changes in the balance of economic activity could shift the market shares in 2000 to: 90 percent carbon, 9 PerCent combined full alloy and HSLA, and 1 percent stainless In the low case; or 70 percent carbon, 27 percent combined full alloy and HSLA, and 3 percent stainless in the high case An average manganese content of O 67 percent (high case) might arise from a shift in favor of alloy steels caused by a severe reduction in new construction and manufacture of machinery, vehicles, and containers with a relative gain in the construction of new chemical, petrochemical, coal conversion, and powerplants. Similarly, a substantial shift in favor of carbon steels caused by extremely high demand for new buildings, highways, vehicles, and primary machinery might result in a manganese content of 0,56 percent (low case)

[b]Trimming, together with reductions in the specified manganese range, could cut the manganese content of carbon steels by 0.25 to 0.30 percent. A conservative reduction of O 15 percent is shown here to account for less than full implementation of these practices.

SOURCE: Office of Technology Assessment based on data from the American Iron and Steel Institute, Washington, DC, and G R St Pierre, et al , *Use of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an Alleying Element in Steels*, OTA contractor report, February 1983

PATTERNS OF MANGANESE USE IN STEELMAKING

Figure 6-3 shows the conventional steelmaking sequence, from raw materials preparation to casting and finishing. Manganese enters the process flowstream from five distinct sources: iron ore, fines and waste materials, manganese ore, iron and steel scrap, and ferromanganese.

On an industry average, iron ore and fines and waste materials contribute approximately **36** percent of the manganese (disregarding that present in ferrous home scrap] ultimately added to the process stream. Iron ores contain approximately **0.16** percent manganese.[27] Although this is a small concentration (and has been declining in recent years), large quantities of iron ore are added to the blast furnace. Fines and waste materials generated by the steel production process contain large amounts of manganese. Though currently there are no satisfactory methods for extracting manganese from the iron and steelmaking slags, dusts, sludges, scales, and other wastes, some plants operate sinter strands to recycle some of these materials, The ore sinter (consisting of partially fused limestone, fine iron ore particles, and steelmaking dust and other waste products) produced in sinter strands can be charged (added) to blast furnaces for hot metal production. Steelmaking slags and dusts consume a large proportion (approximately **42** percent) of the manganese added to the process stream. Slags from both electric and basic oxygen steelmaking furnaces can be charged into blast furnaces, however, basic oxygen furnace (BOF) slags are more commonly recycled in this manner. This is because of the proximity of BOFs to blast furnaces—BOFs are always part of integrated steelmaking facilities, while electric arc furnaces (EAF) are not, According to a **1976** NMAB study, about **40** percent of the BOF slag (containing on average **4.5** percent manganese) produced is recycled to the blast furnace: the rest is discarded. [28] No blast furnace slag is

recycled in this manner, but it does find other commercial uses in the brick, aggregate, glass, and bedding industries. There are no reliable data on the overall extent to which manganese is recovered from steelmaking waste materials, but most likely less than 20 percent of the manganese contained in iron and steel industry waste materials is currently recovered for reuse.

Manganese ore charged to the blast furnace accounts for 5 percent (industry average) of the total input of manganese to the processing stream. Charging this ore is a relatively inexpensive way of increasing manganese concentrations to levels beneficial for the processing characteristics of ironmaking and steelmaking.

Iron and steel scrap is charged to the steelmaking furnaces and, to a lesser extent; the blast furnace. The manganese content of home scrap depends on the stage in the steelmaking process at which it is generated. That created at the steelmaking stage contains roughly **0.2** percent manganese, while that coming from casting and finishing reflects the manganese specifications of the product mix of the particular mill in question. Manganese contributions in purchased scrap depend on the trends in the manganese content of steel products, discussed in the preceding section.

Ferromanganese is added to the process stream during the ladle refining stage. Approximately 45 percent (industry average) of the total manganese input is added as ferromanganese. This manganese is not intended to be sacrificed for the sake of processing improvements. Coming late in the steelmaking process, it is intended to bring the level of manganese in the steel up to final product specifications.

Much of the manganese contributed by these five sources does not make it into the finished product, but ends up instead in steel scrap and processing waste products. The percentage that does end up in the finished product is a function of the manganese recovery factors for the various process stages. These recovery factors are dependent on process yield rates and manganese migration characteristics. Poor yield rates result in both large quantities of

[27]According t. the American Iron Ore Association (Cleveland, OH), in 1982, 7(I percent of U.S. iron ore consumption was from U.S. sources, while 20 percent was from Canadian sources, On average, the U.S. ores contained 0.12 percent manganese and the Canadian ores contained 0.31 percent manganese.

[28]National Materials Advisory Board, *Manganese Recovery Technology*, publication NMAB-323 (Washington, DC: National Academy Press, 1976].

Figure 6-3.— Flow Diagram Showing the Principal Process Steps Involved in Converting Raw Materials Into the Major Steel Product Forms, Excluding Coated Products

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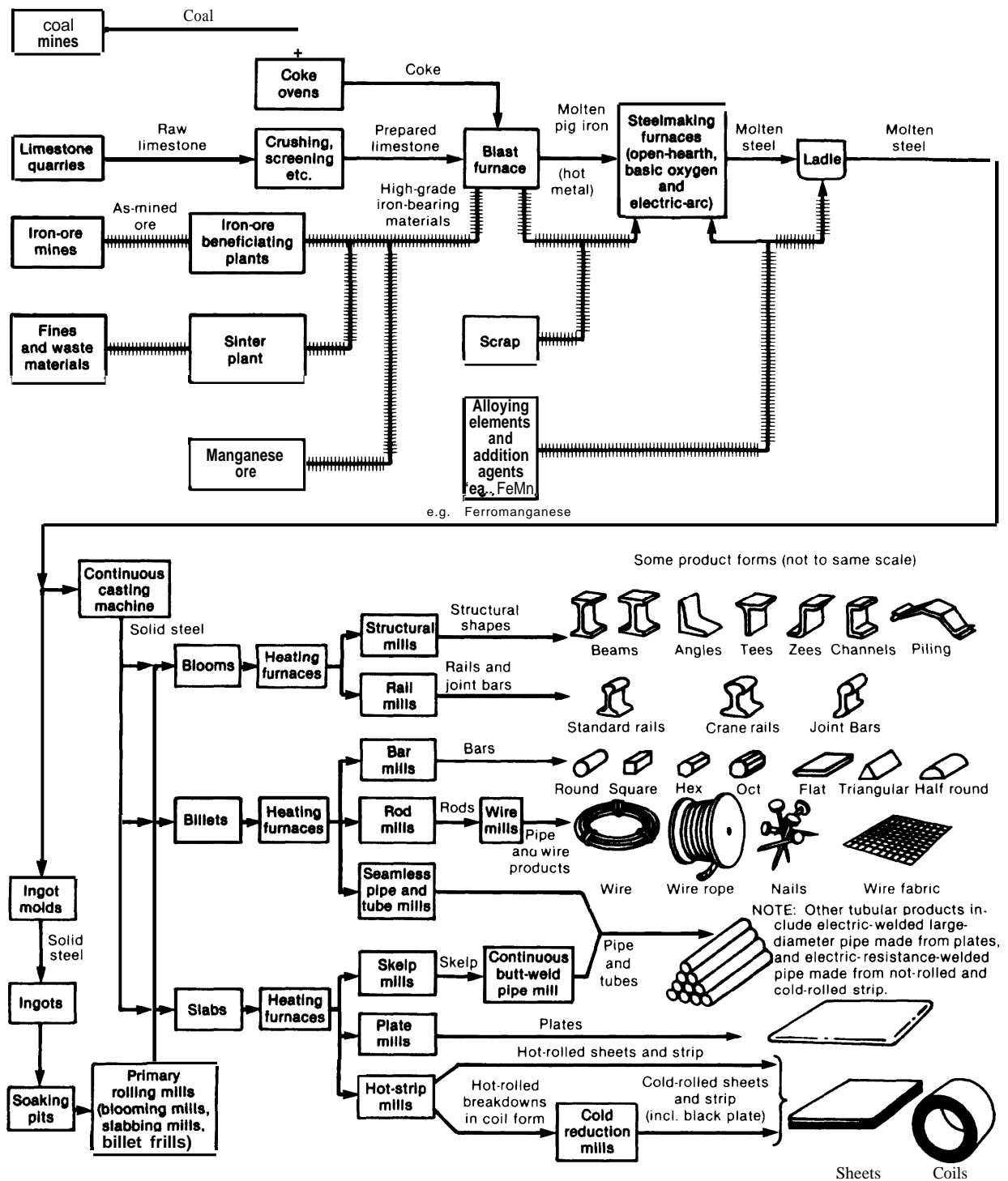
SOURCE *The Making, Shaping, and Treating of Steel,* the United States Steel Corp., Pittsburgh, PA, 1971, adapted by the Office of Technology Assessment to show manganese flows.

wastes that cannot be recycled, and sizable amounts of home scrap from which additional wastes are produced during recycling. Manganese losses are exacerbated because waste materials such as slags and dusts commonly contain manganese in concentrations greater than those in the steel, Manganese, as well as many other alloying elements, often migrates to the process wastes. Sometimes this segregation of elements between the steel and the wastes is intentional, as during the steelmaking stage when manganese is used to react with dissolved oxygen and carry it into the slag.[29] In a sense, these are "sacrificial losses. " In other instances the segregation is an unwanted consequence of the process chemistry, Regardless of the intent, this manganese migration

causes the recovery factors to be lower than the yield rates.

TRENDS IN STEELMAKING TECHNOLOGY

Figure **6-4** shows the current pattern of manganese use in the production of one ton of steel product. Of the total manganese consumed in the steelmaking process, 39 percent is embodied in the finished steel product, and 61 percent is lost in slags, dusts, and wastes. Note that 13 percent of the manganese inputs are recycled as home scrap, generated principally during the casting and finishing steps, The flows in the figure are industry averages and do not reflect operations in any particular steel plant, They are aggregates based on the current mix of equipment and operating characteristics for the industry. Shifts in this mix of steelmaking technologies are expected to change the manganese flow pattern.

Ironmaking.—From 50 to 80 percent of the manganese charged to blast furnaces is retained in the molten pig iron, Typically, the average recovery rate is 75 percent. The remainder is lost to blast furnace slag, which is not recycled or processed for its manganese content. Although construction and operation of direct reduction ironmaking plants will con-

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[29]Oxygen dissolved in molten steel reacts with carbon to Produce gaseous carbon monoxide, which, when trapped during ingot solidification, causes defects known as blowholes. This problem can be avoided by reducing the oxygen content of the steel with the addition of elements that react with the oxygen and carry it off to the slag. Manganese, aluminum, and silicon are the most important of the deoxidizing agents. Though a weak deoxidizer by itself, manganese enhances the deoxidizing capacity of silicon. Moreover, the presence of manganese oxide in the slag helps to develop proper slag characteristics, in part through more rapid dissolution of lime, If the manganese content of the steelmaking charge is too low, additional slag fluxes containing fluorspar, which is considerably more expensive than ferromanganese, must be used.
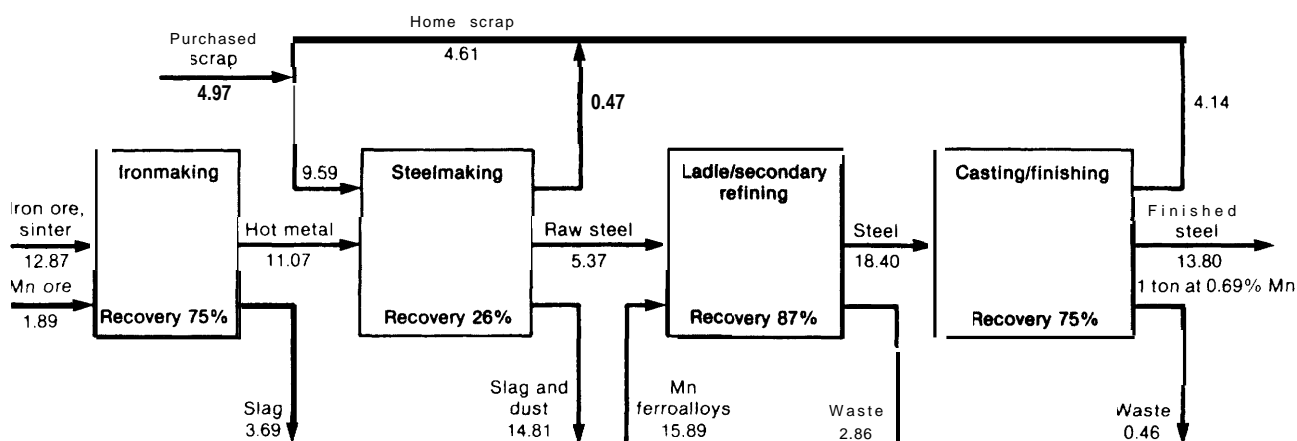

Figure 6-4.—Current Pattern of Manganese Use in Steelmaking (pounds of manganese of finished steel)

'Recovery with respect to ferromanganese additions is assumed to be 82 percent, while complete recovery of Mn is assumed for raw steel

SOURCE Office of Technology Assessment; and G R, St Pierre, et al , Use of *Manganese in Steelmaking and Steel Products and Trends in the Use of* Manganese as an *Alloying Element in Steels*, OTA contractor report, February 1983.

tinue, particularly in certain parts of the world, e.g., the Middle East, Mexico, South America, and Soviet Union, where natural gas is abundant, the principal source of domestic crude iron will continue to be the blast furnace,

Over the next few years, the trend to shut down the oldest and least efficient blast furnaces and to upgrade the better furnaces will continue. Furnaces are upgraded in a number of ways; including modifications of the charging systems and relining configurations, adoption of improved hot blast, additive, pressurization, and tapping procedures, and installation of better instrumentation and control equipment. All of these developments taken together will increase the operating performance of blast furnaces but are unlikely to have a major effect on manganese use.

Manganese retention in the blast furnace can be expected to decrease somewhat from its current value of 75 percent because of the use of more acidic slags allowed by external desulfurization, However, this should be offset by the opportunity to include more manganese-bearing steelmaking slag (primarily for its iron, lime, and flux content, but also for manganese) in the blast furnace charge.

Steelmaking.—Currently, manganese recovery in BOF steelmaking ranges from 20 to 50 percent, depending on the final carbon content and temperature of the melt (manganese recovery improves with increases in both), Recovery in electric steelmaking is substantially greater, The proportion of steel produced in EAFs is increasing relative to BOFs. The current ratio of EAF steel to BOF steel, roughly 30:70, is expected to increase to 40:60 by 2000. This not only improves the average manganese recovery rate, but also increases the average ferrous scrap charge rate. Scrap is typically 100 percent of the charge to EAFs while only 30 percent to BOFs. Thus, greater use of EAFs increases the recycling of manganese,

Operating practices for both EAFs and BOFs are changing. The basic oxygen processes are undergoing dramatic changes with the incorporation of bottom blowing and inert gas mixing techniques, Manganese recovery will prob-

ably increase to the range of 40 to 60 percent over the next few years as a result of these and other changes, such as separate desiliconization and better control of the charge and slag. Manganese recovery in EAFs is expected to improve somewhat over the next few years from better charge materials, reduced oxidation during high-speed meltdown, improved end-point control, and greater use of secondary and ladle refining.

Based on current operating practices and mix of BOF and EAF steelmaking, the average manganese recovery of the steelmaking stage is estimated to be 26 percent. The increasing use of EAF steelmaking and improvements in operating characteristics are expected to improve this average recovery rate to 42 percent by 2000.

Ladle and Secondary Refining.—The role of ladle and secondary refining has grown rapidly during the past few years, In stainless steel production, adoption of AOD processing, which is a secondary refining process, is almost universal. For low-alloy and carbon grades, deoxidation and desulfurization procedures have been greatly improved with the increased use of argon shrouding of steel surfaces and pouring streams. In addition to the trimming benefits mentioned in the previous section, these processes capture the manganese content of ferroalloy additions to a much higher degree and reduce reoxidation loss during subsequent pouring. These improvements are expected to raise the recovery of manganese from the ferroalloys from 82 to 90 percent which raises the overall manganese recovery rate of the process from 87 to 95 percent.

Casting and Finishing .—The benefits of continuous casting have been fully established. Continuous casting leads to overall cost savings as well as improved product quality (cleanliness, homogeneity), reduction of energy requirements and decreased metal loss (scaling) during ingot reheating. In addition, it gives greater yields of steel products from raw molten steel.[30]

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[30] The i,,,t. to-slab yield of conventional ingot casting operations varies greatly according to the nature of the products. Owing to large shrinkage cavities, the yields for killed grades

Continuous casting of steel is one of a variety of
improved steelmaking technologies
that conserve manganese

From the manganese standpoint, increased
yield means that less home scrap must be recy-
cled through processes where there are ir-
recoverable losses. In 1982, about 29 percent
of domestic steel was continuously cast. This
rose to about 36 percent in the first half of 1984,
and is likely to increase to 70 percent by 2000.
Manganese losses are not a major problem at
the casting stage because there is very little
migration of manganese to the waste products.

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can be quite poor, even as low as 70 percent. The yields for
rimmed products are substantially better. On an industrywide
basis, the average yield of ingot casting operations is estimated
to be approximately 87 percent. Continuous casting, the more
modern and more desirable process, has a yield of approximately
96 percent.

Direct rolling of hot slabs and billets from
continuous casters has been demonstrated in
several plants throughout the world. By elimi-
nating the cooling and reheating steps, this
technology offers potential for further improve-
ments in metal recovery as well as energy
savings.

Based on the trends toward greater use of
continuous casting and direct rolling, the yield
rate during casting and finishing operations is
expected to increase from its 1982 value of 75
to 85 percent by 2000.

Summary of the Effects of Processing Trends

The current and expected yield rates and
manganese recovery factors for each stage of
the steelmaking process are shown in table 6-
3. These embody the shifts in technology dis-
cussed above. The overall manganese recov-
ery rate increases from 39 to 49 percent.

Outlook for Manganese Use in the Steel Industry

The expected impacts of steel product and
processing trends on the manganese use pat-
tern in 2000 are outlined in table 6-4. High and
low cases are included in the table to illustrate
the effects of different product mixes and var-
ious schedules of investment in new equipment.

A 12-percent net reduction in the average
manganese content of steel (from 13.8 to 12.2
pounds per ton) is expected to accompany the
contrasting shifts towards the greater use of
high-manganese products and the increased at-
tention to trimming. Trends in steelmaking
technology are expected to cut average man-
ganese consumption losses from 21.8 to 12,6
pounds per ton of steel, a reduction of 42 per-
cent. In addition, these technology changes in-
crease the role of purchased ferrous scrap
(available domestically) as a source of man-
ganese.

Most importantly, these product and proc-
ess trends decrease the per-ton-of-steel require-
ment for manganese in the form of ferroalloys
and manganese ore by 47 percent, from 17.8
to about 9.5 pounds. Depending on the prod-
uct mix and the rate of adoption of the proc-
ess improvements, the requirement could be

Table 6-3.—Parameters Affecting Manganese Retention in the Steelmaking Process

	Current (1982)		Expected 2000	
	Yield rate (percent)[a]	Manganese recovery factor (percent)[b]	Yield rate (percent)[a]	Manganese recovery factor (percent)[b]
Ironmaking (blast furnace)	100	75	100	75
Steelmaking (BOF and EAF).	85	26	90	42
Ladle and secondary refining[c].	100	87	100	95
Casting and finishing	75	75	85	85

[a]Yield rate = (lbs of iron in primary output product) ÷ (lbs of iron in input materials),
[b]Recovery factor = (lbs of manganese in primary output product) ÷ (lbs of manganese in input materials).
[c]Recovery factors for ladle and secondary refining are based on 100 percent recovery of manganese in molten steel combined with 82 percent (current) and 90 percent (2000) recovery of the manganese in ferroalloy additions.

SOURCE: Office of Technology Assessment; and G R. St Pierre, et al , *Use of Manganese in Sfee/making and Steel Products and Trends in the Use of Manganese as an A//eying Element in Steels,* OTA contractor report, February 1983

Table 6-4.—Current and Projected Manganese Consumption in U.S. Steel Production
(all figures in pounds of manganese per ton of steel product, except where noted)

	Current (1982)	Projected, Year-2000		
		Expected	Low	High
Total manganese use (excluding home scrap)	35.6	24.8	20.6	30.4
outputs:				
Retained in steel products	13.8	12.2	11.2	13.4
Losses (slag, dust, waste)	21.8	12,6	9.4	17,0
Inputs:				
Manganese ore.	1.9	1.2	1.0	1.5
Manganese ferroalloys	15.9	8.3	5.5	12.2
Iron ore and sinter.	12.9	8.5	7.1	10.1
Purchased ferrous scrap.	5.0	6.8	6.9	6.6
Overall manganese recovery rate				
(ignoring home scrap) (percent).	39	49	54	44
Assumptions:				
Manganese content of steel (percent)	0.69	0.61	0.56	0.67
Percentage of molten steel produced in				
EAF processes (percent)	28	43	48	38
Manganese recovery rates and yield rates:				
Ironmaking:				
Recovery (percent)	75	75	75	75
Yield (percent)	100	100	100	100
Steelmaking:				
Recovery (percent)	26	42	50	34
Yield (percent)	85	90	93	87
Ladle and secondary refining:				
Recovery (percent)	87	95	98	90
Yield (percent)	100	100	100	100
Casting and finishing:				
Recovery (percent)	75	85	90	80
Yield (percent)	75	85	90	80

SOURCE: Office of Technology Assessment: and G R. St. Pierre, et al., Use *of Manganese in Steelmaking and Steel Products and Trends in the Use of Manganese as an A//eying Element in Steels,* OTA contractor report, February 1983

as low as 6.5 pounds per ton or as high as 13.7 pounds per ton.

Automotive Catalysts

Since 1975, the catalytic converter (now used on most cars to control air pollution) has become the single largest use for PGM in the United States, accounting for over 30 percent of all PGM consumption. Platinum, palladium, and, since 1981, rhodium are the active ingredients used in converters to control hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emission levels. In addition, about 10,000 tons of chromium are used annually in the stainless steel shell of the catalytic

converter—about 1.5 percent of U.S. chromium consumption, and 3 percent of chromium consumption in stainless and alloy steels.

As a result of nearly a decade of using catalytic converters, a very large "above-the-ground mine" of PGM has accumulated in the Nation's automotive fleet-some portion of which can be retrieved each year through collection and recycling of converters from scrapped cars. As the fleet of converter-equipped cars ages, the inventory of PGM available from scrapped cars will grow very rapidly through the 1980s and into the 1990s. If effective retrieval and recycling of catalytic converters from these scrapped cars occurs, U.S. PGM imports can be reduced appreciably below what they would be otherwise,

The current level of PGM recovery from catalytic converters is low, in part because converter-equipped cars are only now appearing at scrapyards in large numbers. This may change in the near future: the average life of a car is about 9 to 10 years, so post-1975 model cars (the first year in which production model cars were equipped with a converter on a na-

tionwide basis) will comprise an increasing proportion of scrapped vehicles.

Figure 6-5, based on projections prepared for OTA by Sierra Research and Energy and Environmental Analysis, Inc., compares the maximum theoretical potential for catalyst recycling from scrapped cars with projected PGM demand for new vehicles through 1995.[31] As shown, the theoretical potential for recycling will grow from about 115,000 troy ounces in 1983 to over 800,000 troy ounces in 1995. Assuming a 50 to 60 percent recovery rate, catalytic converter recycling could add 400,000 to 500,000 troy ounces annually to domestic PGM supplies by the mid-1990s. This compares with new vehicle demand of 770,000 troy ounces in 1983, which is projected to grow to 1.4 million troy ounces in 1995. Less economic incentive exists to recycle chromium values from the stainless steel shell of catalytic converters.

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[31]Sierra Research and Energy and Environment Analysis, Inc., Critical Metal Consumption in Automotive Catalysts, Trends and Alternatives, report prepared for OTA, December 1983, Much of the analysis and data in this section are derived from this report.

Figure 6-5.— PGM Demand by Vehicle Category
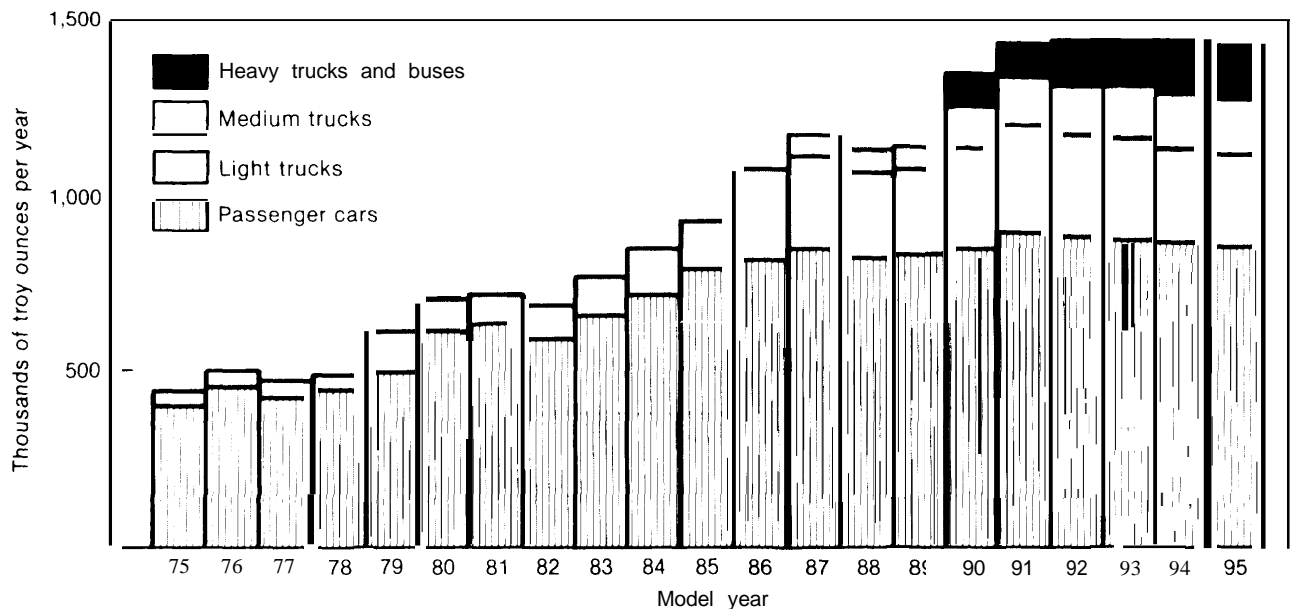
SOURCE: Sierra Research

However, if the above recovery rates are assumed, 5,000 to 6,000 tons of chromium could be provided annually.

It should be noted that considerable uncertainty surrounds the projections in figure 6-5—especially those related to PGM requirements for new vehicles. The projections for new vehicle PGM requirements are for the total U.S. market for vehicles, without assumption about prospective import levels. The projected demand is based on medium growth assumptions about vehicle sales. The projections also reflect anticipated new emission control standards expected to be applied to vehicles in the 1985-90 period. Changes in the timing and nature of these standards would change the projections. Readers are referred to chapter 3 for further discussion of the projected growth in PGM use for vehicle emission control.

Somewhat less uncertainty surrounds the projections of PGM potentially available for recycling through 1995. Cars already on the road will constitute the great majority of vehicles scrapped during the projection period. Actual recycling levels will be considerably lower than the theoretical potential, due to losses of PGM while cars are in service, and at each of the several steps entailed in recycling. Estimates of PGM losses from catalytic converters while cars are in service range from under to well over 10 percent, and this is not reflected in figure 6-5. According to the Automotive Dismantles and Recyclers Association (ADRA), only 70 to 80 percent of the 10 million cars that are "detitled" in a normal scrappage year (1979 was the last such year) actually reach dismantling yards where the converter can be removed for recycling. Moreover, not all dismantles remove the converter from the car before it is compacted into a bale or shredded. Some PGM shipped to a refiner (perhaps 10 percent) is lost in refining. Hence potential addition of PGM to U.S. supplies from catalytic converter recycling probably will only be 50 to 60 percent of the levels shown in figure 6-5, Actual levels or recycling will depend on economic incentives and the effectiveness of the collection networks that are established.

Structure of the Recycling Industry

Among the types of firms that have an interest in the growing market in PGM recycling are primary and secondary PGM producers, manufacturers of emission control devices, scrap processors and dealers, automotive dismantles, muffler shops, collectors and distributors of used automotive parts, and decanners—a new specialized business that has arisen around the catalytic converter. There are no major technological barriers to recycling of either PGM or chromium values from catalytic converters, and the number of firms involved in catalyst collection networks is expected to increase gradually as the market continues to grow. In addition, the industry appears capable of responding quickly to price increases, so that recycling could be greatly expanded if there were a supply disruption.

The industrial refining capacity needed to recycle PGM from automotive catalysts taken from scrapped cars is already in place. Major domestic PGM refining facilities operated by Gemini Industries and Johnson Matthey are available for converter recycling. These facilities are able to recover PGM values both from new catalysts rejected by automakers and from scrapped converters. Domestic scrap processors are also able to recycle the stainless steel shell of the catalytic converter as a scrap feed. Steps entailed in recycling spent catalysts are described in box 6-C.

Institutional factors could impede recycling levels, however. Three categories of catalytic converters are potential sources of PGM for recycling: unused catalysts that fail to meet product specifications, rejected and damaged catalysts from operational vehicles, and spent catalysts from scrapped vehicles. Of these, the last category represents the largest future supply of PGM, but also presents the greatest collection difficulties. Reasons for this include fluctuating PGM prices, the fragmentation of the automotive dismantling industry, and a lack of effective linkages between refiners and dismantles.

The availability of automobile catalysts for recycling is affected by several factors. Some

Box 6-C.—How Catalytic Converters Are Recycled

With the advent of the catalytic converter, a new industry has evolved to recover PGM values from scrapped automobile catalysts. From a technical standpoint, there are few barriers to refining PGM from spent catalysts. In the mid- and late **1970s,** facilities were set up to recycle unused catalysts that failed to meet product specifications. This gave refiners the experience needed to take advantage of the far greater amount of PGM that can be recovered from scrapped cars. However, the business of organizing effective collection systems has proven surprisingly complex.

Part of the reason for this is that catalytic converters are not uniform products whose value can be easily identified. In 1982 model cars, for example, there is a 10-to-l range in PGM content among different converter models—().33 troy ounces on heavily loaded converters down to 0.03 troy ounces on lightly loaded converters. (This wide range in catalyst loadings is probably not a measure of the efficiency of the converter in reducing emissions; instead the heavily loaded catalysts are probably installed in car models with engines that produce higher than average emission levels prior to catalytic treatment.) Many of the converters, especially on older model cars, have catalyst pellets (some of which maybe lost in the course of vehicle operation), while others are monolithic, with the catalyst deposited on a secure substrate. Chromium content in the stainless steel shell of converters also varies from 1.5 to 3 pounds. Finally, early model converters contained just platinum and palladium, but more recent "three-way converters" contain rhodium as well.

Before lots of spent catalysts actually arrive at a refiner for reprocessing, several separate firms— including automotive dismantles, collectors, decanners, and scrap processors—can be involved. Some of these firms specialize in collection of certain types of converters and do not purchase other types. Some work under an arrangement with refiners. Others are independent.

Preliminary sorting is done by the automotive dismantle after the converter is removed from the car by torching or cutting or, in the case of larger shredding operations, popped off with a forklift. Some converter containers contain little or no catalyst. Spent catalysts commonly contain at least some lead, which is particularly undesirable to refiners, and moisture, which can also affect chemical analyses and reprocess smelting. If the scrapped converter is sold to a collector, it may be visually inspected by the collector for catalyst content. However, the dismantle may choose not to sell the converter to a collector and may instead stockpile it, waiting for a price increase, or keep it for sale to retail customers.

The decanner (who maybe the collector or the the auto dismantle) removes the catalyst substrate from the stainless steel container. After it has been removed, the catalyst is placed in drums to prevent further moisture accumulation, and is sold to a refiner. The stainless steel shell of the converter may be sold to a scrap processor, some of whom also may serve as collectors or decanners.

Both the quality and quantity of the catalyst play major roles in determining the price paid to decanners by refiners. Some require a minimum shipment of 3,000 pounds of catalyst substrate. Bonuses may be paid for shipments that exceed average PGM content, while penalties may be charged for below-average shipments. A partial payment for the catalyst maybe paid upon receipt, with the balance reserved until actual assay, often 6 to 10 weeks later.

Once the spent catalysts are accepted by the refinery, several commercialized processes can be used to recover the PGM. Two major domestic refiners—Gemini and Johnson Matthey--use proprietary hydrometallurgical processes to separate the substrate from the PGM through an acid or alkaline leach. Final removal of the PGM from the resulting leach liquor or sludge is complex, involving as many **as 18 separate** steps, but can recover more than 90 percent or more of the PGM. Scrapped catalysts can also be run through copper or nickel pyrometallurgical refining circuits to recover about **90** percent of the PGM. This approach was taken by Inco, a large Canadian nickel and copper producer, in 1980 and 1981, when PGM prices were high, but has been subsequently discontinued.

In addition to recycling PGM, interest is growing in the possibility of "regenerating" spent catalysts. This would involve leaching out lead and other impurities and washing additional PGMs as required, while keeping the substrate and shell intact.

cars are simply abandoned; some are taken directly to a scrap processor for baling or shredding, where the value of the PGM (and chromium in the converter shell) is lost; others are exported. As a result, about 20 to 30 percent of all cars are never taken to a dismantle.

Even those cars that reach dismantling yards will not necessarily have their converter removed. According to the ADRA, the majority of automotive dismantling firms have less than 10 employees. With a 1983-84 scrap price of only about $5 to $7 per converter, not all dismantles feel it is worth their employees' time to remove the converters, while others maybe stockpiling the catalysts until prices rise. A 1982 survey of some ADRA members and some unaffiliated dismantles by Arthur D. Little, Inc., found that 12 percent of those firms responding to the survey leave the majority of converters on the car.[32] However, ADRA members and other respondents may not be representative of the industry as a whole. Small firms that lack the resources to participate in the trade association may be more likely to leave converters on cars.

Providing refineries with a steady supply of scrapped converters has also been a problem. The auto dismantling industry is highly decentralized, having 11,000 separate firms, according to ADRA, while only a few large firms are involved in refining the catalyst. As more actors have become involved, intermediary firms specializing in collection and decanning have arisen either independently or in affiliation with refiners. Because refiners are trying to assemble economic volumes for recovery, a premium is paid for larger volumes of material. When a sufficient number of converters has been collected by a dismantle they are sold to collectors and/or decanners. Usually a minimum of 50 to 100 converters is required to deal with a large collector.

Collectors accumulate small lots of whole converters within a particular region and sell larger lots at higher prices to decanners. Some collectors are also decanners. Often, collectors have regular truck routes to purchase converters from dismantles and, in some cases, from shredding yards.

Decanners purchase large lots of whole converters, and separate the catalyst's substrate from the housing or shell, usually by shearing the canister in half. The pellets and honeycombs are packed separately in 55 gallon drums. Owing to the low nickel content and accumulated impurities, the 409 stainless steel used in the converter shell has a low market value ($1 10 per ton in late 1983). Nevertheless, the shell represents an additional source of value to the decanner.

The quality of catalyst material sold to refiners, as well as the volume, plays a major role in determining the price paid to decanners. Decanners are cautioned not to include contaminated units. Pure white catalyst substrates indicate burnout and loss of the PGM coating, Catalysts coated with lead and oil are also undesirable in the refining process.

Auto dismantles would prefer to have more than one purchaser (collector or core buyer) for used converters to ensure the best price and most reliable pickup, while refiners prefer to purchase large quantities of catalysts from one collector. During periods of low platinum prices, both dismantles and collectors may stockpile catalysts, waiting for prices to rise. In the long term, many of the problems apparent in the early stages of the industry's evolution may be overcome, due to the increased numbers of scrapped cars equipped with converters available for recycling and possible increases in PGM prices.

USED AND RECONDITIONED CATALYTIC CONVERTERS

A recent development in the automotive dismantling industry has been the emergence of a market for secondhand catalytic converters bought as replacement parts. The exact magnitude of this market is not known, but a recent survey in California found that about 80,000 secondhand converters were used annually in the State.[33] Most of these secondhand

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[32] Automotive Dismantlers and Recyclers Association, *Profile: Automotive Dismantling Industry*, published in cooperation with Arthur D. Little, Inc. (Washington, DC: Automotive Dismantles and Recyclers Association, 1983), p. 12,

[33] Mobile Source Control Division, Used Catalytic Converter Survey (El Monte, CA: State of California Air Resources Board, July 1983), memo.

converters were obtained from parts distributors who purchased them from auto salvage dealers at a somewhat higher price (averaging $7 per unit) than is typically paid by refiners. Auto dismantles also sell converters directly to retail customers as used parts, often at a price of **$45 to $70**.

The apparently growing market for secondhand converters concerns some refiners since it adds an additional layer of competition in their efforts to secure a supply of catalysts for recycling. The competition is great because this market is an important source of income to dismantles, who typically obtain three-fourths of their income from sales of used parts, while scrap sales form only a small part of their business.

An emerging issue associated with the apparently growing market for secondhand catalytic converters concerns possible reuse of defective catalysts in cars. While secondhand converters are substantially cheaper to the motorist than new replacement converters, which range in price from **$170 to $320**, many secondhand converters are defective, and will therefore adversely affect air quality if they are installed in cars.

It is not possible to determine whether a used converter is operating properly without emissions inspection and testing. A gradual deterioration in catalyst efficiency occurs over time, and most automakers guarantee the converter for only 50,000 miles. In addition, leaded gas, which destroys the emissions control capability and the platinum metal values in the catalysts, is often used in converter-equipped cars and trucks. Occasionally this happens inadvertently, if fuel supplies in a filling station become contaminated or are switched. More often, motorists deliberately and illegally misfuel because of lower price and perceived improved performance of leaded gasoline.

Currently, overall procedures for testing and certifying secondhand catalytic converters are not in place. Although the U.S. Environmental Protection Agency has issued voluntary aftermarket part self-certification regulations, these relate primarily to new replacement convert-

ers. However, methods to test used catalytic converters are under development by a major muffler firm, using the voluntary self-certification regulations. The entire issue associated with use of secondhand converters is highly complex, and is likely to be an increasingly important concern in both emission control programs and recycling efforts in the years to come.

ALTERNATIVES TO PGM USE IN THE CATALYTIC CONVERTER

At present, PGM use in the catalytic converter is the most effective means for meeting emissions control standards under the Federal Clean Air Act. Near-term (before 1995) alternatives to PGM use in the catalytic converter are not promising, Most currently developed alternatives would entail major loss of fuel economy and/or a need to relax automotive emissions standards. These problems could be overcome, given several years lead time, but there is no persuasive reason at this time for auto makers to pursue these alternatives.

Increased use of diesel engines could also reduce the need for PGM catalysts. However, while diesels do not currently require converters to reduce carbon monoxide and hydrocarbons, they do produce substantial amounts of particulate. A more stringent particulate national emission standard for diesel-fired light-duty vehicles (cars and light trucks) is expected to take effect in 1987. Some manufacturers are expected to employ a platinum-catalyzed trap oxidizer to meet the standard. The other most likely alternative–a trapping system which uses onboard dispersing of fuel additives—would not entail PGM use. A particulate emissions standard for heavy duty vehicles, if adopted as expected in 1990, most likely will require PGM catalyzed trap oxidizers, because additives are unlikely to prove practical over the long lifetime of these engines. (In the projections shown in figure 6-5, it was assumed that half of the light duty diesel vehicles will use a PGM particulate trap when the standards take effect—1986 in California and 1987 nationwide—but that all California light trucks and diesels would use particulate traps to meet the more stringent State standard expected in 1989.

It was also assumed that all heavy duty diesel engines will require PGM particulate traps to meet the anticipated 1990 national standard.)

Even in the longer term (beyond 1995), PGM use for emission control is likely to continue, although use of substitute materials, more efficient loading of PGM, and basic changes in the overall design of automobiles, might reduce per vehicle requirements. At present, the major auto makers foresee no major change in total loadings of PGMs used in converters, although ratios of platinum, palladium, and rhodium may change, Alternative base metal catalysts are not likely to substitute for PGM catalysts, unless breakthroughs overcome major technical problems that make them less effective in emissions control.

Downsizing of engines to meet federally mandated fuel efficiency standards, coupled with improved catalyst formulations, may reduce the amount of PGM needed to treat emissions effectively. With long-term increases in gasoline prices, downsizing may occur regardless of whether Federal standards are extended beyond 1987. Alternative trends in downsizing to the year 2000 are discussed in detail in the 1982 OTA assessment, Increased Automobile Fuel Efficiency and Synthetic Fuels.[34]

Considerable speculation exists about possible future use of alternative automotive engines that are radically different from those used today, such as the automotive gas turbine (AGT) and stirling engines. These engines would have very low emissions levels, thus reducing emission treatment needs. As is discussed in chapter 7, technical problems (including development of reliable ceramic parts) make it unlikely that the AGT will be widely used until after the year 2000, if then. Alternative fuels, such as methanol, are also under consideration as a principal fuel for some automobiles, Emissions from cars retrofitted to burn methanol do not meet current standards without catalytic treatment. Moreover, emission tests on methanol-burning cars show rela-

tively higher levels of aldehyde emissions than for gasoline-powered cars. Aldehyde emissions can be reduced by catalytic after treatment. Aldehydes are not covered in current emission standards, so new standards could be required if methanol is widely used.

STRATEGIES FOR EMISSION CONTROL IN A SUPPLY DISRUPTION

PGM recovered from catalytic converters can be reprocessed into virtually any form needed by industry. In a major supply disruption, automotive catalyst production could be temporarily curtailed, thus permitting PGM that is recovered from scrapped catalytic converters to be diverted to more critical economic and military uses. PGM use in catalytic converters is critical to controlling air pollution, but is not otherwise a critical component of the U.S. economy. In a national emergency, a temporary discontinuance of PGM use in the manufacture of new catalytic converters, together with intensified recycling of PGM from scrapped cars, would insulate the most critical economic uses from the effects of a supply disruption.

As a result, U.S. ability to contend with a supply cut-off has theoretically improved, owing to reliance on PGMs for emission control, even though PGM imports have increased because of it. Use of such an emergency strategy, however, would have major impacts on the emissions control program established under the Federal Clean Air Act.

Alternative strategies for auto makers and Government officials for dealing with a near-term curtailment of PGM supplies were addressed in the report prepared for OTA by Sierra Research and Energy and Environmental Analysis, Inc. This analysis demonstrates that practical alternatives to the catalytic converter are not currently available that could meet both current emissions and fuel economy standards. In a near-term supply disruption in which no PGM was available for emissions control, auto makers would probably have little alternative except to build cars without catalytic converters—although this could be accompanied with a requirement for retrofit when the shortage ended.

[34]*Increased* Automobile Fuel Efficiency and Synthetic Fuels (Washington, DC: U.S. Congress, Office of Technology Assessment, September 1982), p. 17.

In a supply disruption lasting 1 to 3 years, recalibration of new vehicles for lower emissions without catalyst use would be feasible. This could entail programming of fuel metering systems for leaner operation to reduce hydrocarbon and carbon monoxide emissions. In addition, retarding spark advance to further reduce HC and NO_x emissions could be undertaken. These changes would not entail substantial design changes or development costs. Although some fuel economy penalties would be incurred, average new car emission levels approximately equal to 1977-79 standards could be achieved in this way. Since computer controlled systems are now used in many new vehicles, retrofitting after the disruption would be comparatively simple, entailing replacement of a computer chip or (more likely) the entire electronic control unit of the vehicle.

With an intensive program of research and development (R&D), according to the analysis, alternative emission control systems that do not use PGM but would approach current emissions and fuel economy standards could probably be developed. However, this would require at least 5 years and is unlikely to be undertaken by auto makers simply out of concern about future supply disruptions.

Development of such technology could be necessary in the event of a "worst case" supply disruption of several years' duration in which national emergency requirements could not be satisfied from recycled PGM alone. Under such dire circumstances, pressures would mount to recover PGM from operating vehicles.

The total current in-service vehicle fleet contains roughly twice as much PGM as was consumed for all uses domestically in 1982, This will more than double by 1995—to a total of 9 million troy ounces of PGM, some portion of which could be recovered in a dire emergency through Government programs aimed at removing some catalytic converters from the in-service automotive fleet.

Ultimately, both the objectives of national preparedness in the event of a supply emergency and national air quality objectives could best be served if contingency planning were undertaken to determine under what circumstances, and in what way, allocation of PGM would occur in a supply emergency. Such planning could also be used to identify emission control strategies available to auto makers in the event that supplies of PGM are not available for manufacture of catalytic converters,

Other Conservation Opportunities

Petroleum and Chemical Catalysts

Both PGMs and cobalt are extensively used in the petroleum and chemical industries as catalysts. PGM use in these catalysts is already highly efficient so that only limited improvements in current patterns of use can be made in the foreseeable future. The PGM contained in industrial catalysts is generally retained in ownership by the user firm and is refined or regenerated on a toll basis by a specialized recycling firm. This system is highly efficient: Of the 235,000 troy ounces of new PGMs that were purchased for petroleum and chemical industry catalyst applications in 1982, only about 10 percent was to make up metal losses during processing and toll refining; the rest was to meet new production needs. The only catalysts that are not now recycled contain less than 0.05 percent PGMs. Recovery of PGM values from these catalysts is technically feasible, but the refining costs (including transportation costs to and from the refinery) exceed the contained metal value.

In the case of cobalt-containing catalysts, however, major opportunities exist to increase recycling levels, particularly in the case of the cobalt contained in spent petroleum refining catalysts. Although some other metals are now reclaimed from these spent catalysts, cobalt values are not.

Overall national trends in cobalt catalyst use (exclusive of paint dryers) were extensively analyzed for OTA by the Inco Research & Development Center, Inc.,[35] and are summarized

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[35]F. J. Hennion, J. J. deBarbadillo, J. H. Weber, and G. Alex Mills, Use of *Critical* Materials in Catalysts *for the* Petroleum and Chemical Industries, *Cobolt* and Platinum Group *Metals* (prepared for OTA by Inco Research & Development Center, Inc.]. Much of the information in this section is derived from this report.

in table 6-5. This information, obtained from estimates provided by industrial sources in late 1983, is believed to be the most up-to-date and detailed information about these trends that is publicly available.

As shown in table 6–5, three major processes dominate cobalt catalyst consumption: petroleum hydroprocessing, used to remove contaminants from sour and heavy crude oil; alcohol production through hydroformulation; and production of terepthalic acids and derivatives, used to produce polyester fibers and films. Cobalt is also used in catalysts to produce synthetic fibers, solvents, pharmaceuticals, and industrial chemicals.

Significant recycling of the cobalt used in chemical catalysts is occurring. According to Inco, about 1.5 million pounds of cobalt were consumed in both chemical and petroleum catalysts in 1982. Of this, 1.1 million pounds—about 72 percent—was contributed through recycling. Fresh cobalt needed to makeup the difference was only about 426,000 pounds. This is less than some other estimates which may underestimate the extent of recycling by the chemical industry.

However, cobalt from spent petroleum hydroprocessing catalysts is not now recycled. Since none is recovered, all of the cobalt consumed in hydroprocessing was fresh cobalt. Inco estimated that about 270,000 pounds of cobalt was consumed in hydroprocessing in 1982. This is less than some estimates for prior years, due to lower refinery utilization. The

Inco estimate is consistent with a National Materials Advisory Board finding that between 200,000 to 300,000 pounds of cobalt were consumed in this use in 1982.

Expanded use of hydroprocessing catalysts in the petroleum industry is likely in the years to come. However, growth in demand will probably be less than was anticipated in the mid and late 1970s, when refineries were rapidly installing hydroprocessing capacity to process heavy source crude oils obtained from non-OPEC sources. The combined effects of energy conservation and the 1981-82 recession have resulted in scaling back projected requirements. While hydroprocessing capacity can be expected to grow appreciably from the depressed 1982 levels, "fresh" cobalt requirements will not necessarily increase proportionately. According to the National Materials Advisory Board, future cobalt make up requirements could be in the range of 200,000 to 400,000 pounds a year, assuming that effective recycling takes place. Substitution of nickel-molybdenum catalysts could reduce future requirements by another 100,000 pounds a year, according to NMAB.[36]

In current practice, hydroprocessing catalysts may be regenerated one or more times in the course of their life cycle (2 to 3 years). At some point, however, the catalyst becomes so contaminated that subsequent regeneration is impossible. These spent (unregenerated) catalysts may be stored temporarily on site by refiners, landfilled, or sent to a processor for recovery of non-cobalt metal values or for export, The typical spent catalyst will contain about 8 percent molybdenum, 1.5 percent cobalt, 0.5 to 1.5 percent nickel, 1 to 6 percent vanadium, 10 to 15 percent carbon, 10 percent sulfur, 0,2 percent phosphorus, and the balance, alumina.

During the late 1970s, when molybdenum and cobalt prices were very high, considerable effort was made to recover metal values from these spent catalysts. However, most of these efforts were discontinued as prices fell. By

Table 6-5.—Cobalt **Consumption and Recycling in Catalysts, 1982**

Process	Cobalt consumption (thousand pounds)	Percent recycled	New cobalt for makeup (thousand pounds)
Hydroprocessing . .	270	0	270
Hydroformulation . .	700	90	70
Terephthalic acid	500	90	50
Organic acid	35	0	35
Alkyl amines	30	95	1.5
Total	1,535	72	426.5

SOURCE" F. J Hennion, J.J. de Barbadillo, J. H. Weber, and G. Alex Mills, Use of *Critical Metals* in Catalysts *for the* Petroleum *and Chemical Industries (Cobalt and Platinum Group Metals),* 1983. Report prepared for OTA by the Inco Research & Development Center, Inc., December 1983.

[36]*Cobalt Conservation Through Technological Alternatives,* op. cit., p. 119.

1982, Gulf Chemical & Metallurgical Co., of Freeport, TX, was believed to be the only domestic firm recovering metal values from spent hydroprocessing catalysts. Gulf C&M, which has been in the catalyst recycling business for over two decades, uses a combination of pyro- and hydro-metallurgical techniques to recover molybdenum and vanadium values from the spent catalysts but does not currently recover cobalt, nickel, or other metals.

From years of reprocessing, some 100,000 tons of processing residues are reported to have accumulated at the Gulf C&M facility, As much as 7 million to 8 million pounds of cobalt and nickel may be present in this residue, some portion of which could be recovered with adoption of adequate reprocessing technology. The company has reportedly developed a pilot-scale process to recover nickel, cobalt, and alumina values from this residue, but economic recovery of these metal values at current prices is not feasible. Because Gulf C&M reprocesses spent catalysts from both foreign and domestic sources, more cobalt residues are accumulated at the facility each year than are generated from domestic hydroprocessing activities alone.

At least two other domestic firms–Hall Chemical of Wickliffe, OH, and CRI Metals of Baltimore, MD—have announced plans to construct facilities to reclaim cobalt and other metals from spent hydroprocessing catalysts. Hall Chemical, which currently produces 1 million pounds of cobalt salts annually, is constructing a facility (at Arab, AL) said to be able to reclaim individual components of spent cata-

Photo credit: Gulf Chemical & Metallurgical Co.

Molybdenum and vanadium are recovered from petroleum refinery catalysts at this plant in Texas. Several million pounds of potentially recoverable nickel and cobalt are left in the waste and slag that is stored in containment ponds surrounding the plant

lysts, including cobalt, nickel, molybdenum, vanadium, sulfur, and alumina. Hall intends to purchase spent catalysts from generators around the world.

CRI Metals, a unit of Catalyst Recovery Inc., has announced plans to establish a hydroprocessing catalyst reclamation facility in the South. The CRI process has been evaluated through pilot plant trials, but CRI has yet to commence construction, owing to depressed metal prices. Like the Hall process, the CRI plan is to recover several contained metals— cobalt, nickel, vanadium and alumina—from the spent catalysts for reuse by the catalyst industry. CRI apparently plans the recycling venture to complement its current catalyst regeneration activities.

Although the industrial capability to reclaim cobalt from spent catalysts may soon be in place, prospects for improved recovery will depend on an increase in cobalt prices. Sizable quantities of spent catalysts may continue to be landfilled, with cobalt values effectively lost in the interim. From the refinery's point of view the fastest method of disposal of spent catalysts is preferred. At current prices, this often means paying the freight to ship spent catalysts to reprocessors, storing the catalyst at a temporary site off the premises, or landfilling. While the technology exists to reclaim landfills, the high cost of such activities means that recovery of cobalt values from landfills is unlikely.

An important issue associated with both recycling or landfilling of spent hydroprocessing catalysts concerns hazardous waste disposal requirements. Although spent hydroprocessing catalysts are not a listed hazardous waste, some spent catalysts may contain trace amounts of lead, arsenic, and other compounds that are toxic. For hazardous wastes, refiners must decide within 90 days about whether the waste is to be landfilled in an approved site or recycled. With current depressed metal prices, there is little economic incentive to recycle these spent catalysts, so that many refiners may choose to landfill them.

Stainless Steel and Steel Process Wastes

Chromium used in stainless steelmaking is obtained from ferrochromium and from scrap. The scrap charge includes home scrap gathered within the plant during various stages of the steelmaking process, prompt scrap obtained from mills and fabricators, and obsolete scrap from postconsumer products and salvage. With the exception of steelmaking wastes, home scrap is generally recycled with a high degree of efficiency. Stainless steel producers routinely recycle most of the solid scrap generated in making stainless steel and in forming primary products, such as sheets, bars, and wires. An estimated 35 to 45 percent of stainless steel production is derived from such home scrap, but since the home scrap cycle is within the mill, it is not considered to be a secondary supply source.

Owing to adoption of the AOD process, which cut losses of chromium to slag by more than half, purchased scrap is an increasingly important source of chromium in stainless steel products. Prompt industrial scrap and obsolete scrap together form the purchased component of scrap supplies. An estimated one-fourth of the chromium needed to make stainless steel and heat-resisting steels in the 1977-81 period came from purchased scrap.[37] Chromium is present in other alloy steels and in cast iron scrap, but in low concentrations that do not favor recycling for chromium content. These materials are usually recycled for their iron content, and the value of the alloying metals is lost (this practice is referred to as "downgrading").

More chromium may be lost each year to downgrading or to failure to recover obsolete products than is recovered from purchased scrap. According to estimates prepared for the Bureau of Mines,[38] about 135,000 tons of stain-

[37]U.S. Department of Commerce, Critical Materials Requirement *of* the U.S. *Steel* Industry (Washington, DC: U.S. Government Printing Office, 1983), p. 32.
[38]Charles L. Kusik, et a]., Availability *of Critical Scrap Metals* Containing Chromium in the United States: Wrought Stainless *Steel* and Heat Resisting Alloys, U.S. Department of the Interior, Bureau of Mines Information Circular **8822** (Washington, DC: U.S. Government Printing Office, 1980).

less steel scrap containing about 24,000 tons of chromium were included in the carbon steel scrap used in nonstainless steelmaking in 1977. Another 38,000 tons of chromium was lost in obsolete scrap that was not recovered. (The range of uncertainty of these estimates is high owing to a variety of factors, including imprecise export and import data and long lifetimes of stainless steel products,) Of course, not all of the stainless steel that was downgraded could have been recovered, since it may have been present only in small amounts or have been inseparable from other materials, but the volume of downgraded scrap makes it clear that there are major opportunities to increase the recovery of chromium from scrap.

Large quantities of scrap are generated when stainless steel is made into fabricated products, but most firms collect and separate the better quality scrap for sale either to scrap collectors or to primary producers for recycling. The comparatively low value of chromium in prompt industrial scrap may slow the return of some scrap for recycling and lead to some downgrading. The nickel-chromium stainless steels (AISI 300 series) are usually recycled because of the high value of nickel and other alloying agents, Recycling of the 400 series scrap, which has 12 to 30 percent chromium but little nickel or other alloying agents, is affected by the relatively low value of chromium.

Recovery of obsolete stainless steel scrap is impeded by dispersed location, the uncertain quality of materials in the scrap, and the long lifetime (5 to 25 years or more) of stainless products. Only a small proportion of stainless steel used in appliances, cutlery, and other consumer items is ever likely to be recovered from scrap, although some may end up in municipal solid waste collection systems from which metals recovery is possible. Fuller recovery of stainless steel scrap from used automobiles, machinery, and other industrial applications takes place, but seldom in excess of 60 percent.

Automobiles provide the single greatest opportunity for reduced downgrading of obsolete chromium scrap. About one-third of the obsolete stainless steel recycled in 1977 came from

scrapped automobiles, but this amounted to only about 30 to 40 percent of the potential quantities of chromium that could have been recovered from scrapped cars, Baling, which is used for 10 to 20 percent of scrapped cars, prevents recovery of most stainless steel except easy-to-remove items, such as hubcaps, Shredding of vehicles permits better recovery since nonmagnetic stainless steel can be separated from the carbon steel scrap and sold separately, However, magnetic stainless steel, including the steel used for converter shells, is not easily separated. This downgrading of stainless steel is not likely to be overcome because of the low value of the chromium and the high cost of identifying and separating it from other steels.

Prospects for improved recovery of chromium from scrapped automobiles will be closely tied to efforts to recycle PGMs in catalytic converters, since the converter shells are made of stainless steel, The average 1976 U.S.-built car (now approaching obsolescence) contained about 4.8 pounds of chromium, of which 2.6 pounds was contained in the shell of the catalytic converter. Since 1975, chromium used in catalytic converters has averaged about 10,000 tons per year. Assuming that 70 percent of the cars that annually become obsolete reach dismantling yards, 7,000 tons of chromium could theoretically be recovered from converter shells alone. Since additional losses are likely, recovery of 5,000 to 6,000 tons per year is probably the maximum practical level of recycling. Most cars now manufactured have monolithic-type converters (containing about 1.5 pounds of chromium), so that per vehicle chromium recovery rates in the mid-1990s will decline compared to today. At the same time, the number of cars scrapped each year may grow, hence, the overall amount of chromium that is potentially available for recycling will increase.

The value of chromium in the converter is low, however, and the recovery of the shell for recycling will depend largely on the value of the PGMs contained in the catalyst itself. Most dismantlers–even those who remove the converter to collect PGM catalysts—do not segre-

gate the shell for recycling as stainless steel scrap. Instead, the shell is shredded or baled with the rest of the car.

While small in relation to overall chromium demand, appreciable quantities of chromium as well as other critical metals are also lost in flue dusts, slags, sludges, and other steelmaking and chemical wastes each year. These wastes are not suitable for direct recycling because of contaminants such as lead or zinc, but the chromium and other metals from some of these wastes are increasingly recovered through special processing,

According to Bureau of Mines researchers, about 17,400 tons of chromium were contained in metallurgical wastes generated in 1974 (the most recent year which comprehensive data were collected).[39] Until recently, these low-grade wastes were almost entirely unrecovered. However, some firms are now commercially recovering chromium containing wastes, and several steel producers have established their own in-house waste recovery programs. A partial impetus for this has been environmental regulations restricting the disposal of solid wastes.

Since 1978, Inmetco, a subsidiary of Inco, has been recovering chromium and nickel from low-grade steelmaking wastes. This facility has the capacity to process 47,000 tons of waste per year to produce 25,000 tons of pig metal containing 4,500 tons of chromium and 2,000 tons of nickel. The pig metal, which is 18 percent chromium and 8 percent nickel, is suitable for use in AISI-type 304 stainless steel or, if it contains molybdenum, AISI 316. Inmetco currently processes about 75 to 80 percent of the flue dust, mill scale, and grinding swarf of U.S. stainless steelmaker. The company estimates that 3,100 tons of chromium was contained in wastes entering their plant in 1982, of which 2,800 tons were recovered. The Inmetco facility also has the capacity to recover chromium

red

and other materials from catalysts, superalloys, and other products. An Inmetco subsidiary, Pittsburgh Pacific Processing Corp., reprocesses oil-contaminated scrap.

Economic processes for recovery of chromium and other metals from specialty steelmaking slags have yet to be developed, Estimates made in the 1970s of nationwide losses of chromium to slag in stainless steelmaking vary widely—from 3,000 to 30,000 tons per year. The lower figure is from the previously cited 1974 estimate of total chromium losses in metallurgical wastes, and appears to be quite low. The latter figure, based on 1965-75 data, is from a study by the National Materials Advisory Board, which also projected that losses would be reduced to about 10,000 to 15,000

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[39]W. M, Dressel, L. C. George, and M. M. Fine, "Chromium and Nickel Wastes: A Survey and Approval of Recycling Technologies, " Proceedings *of the Fifth* Mineral Waste Symposium, Eugene Aleskin (cd.), cosponsored by the U.S. Bureau of Mines and the I IT Research Institute (Chicago, IL: I IT Research Institute, 1976), p. 269.

tons per year as stainless steelmaker switch entirely to the AOD process,

Revised estimates do not appear to have been made since the NMAB study, which was published in 1978, but the AOD process is now used almost universally. Nonetheless, the losses remain appreciable. Chromium content in steelmaking slags analyzed by the Bureau of Mines Rolla (MO) Research Center range between 1 and 12 percent, with most samples in the range of 6 to 7 percent. Experiments being conducted at the Center are aimed at upgrading chromium and nickel from crushed and ground slag. Concentrations of more than 20 percent chromium have been achieved. Future research will assess ways to recycle the concentrates in steelmaking furnaces.[40]

Over 3,000 tons of chromium were also lost annually in processing wastes from the chemical industry, metal plating and etching shops, and leather tanning firms, according to the 1974 data mentioned previously. Recovery of the chromium in such wastes is expensive, and until recently wastes were generally disposed of in municipal wastewater systems or landfilled without significant preprocessing. Environmental requirements under Subtitle C of the Resource Conservation and Recovery Act (RCRA) and the Federal Clean Water Act have resulted in the need to process such wastes prior to disposal. As a result, the opportunity to recover chromium from the waste has arisen.

Many metal finishing wastes are classified as hazardous wastes by the Environmental Protection Agency and are subject to the disposal requirements of RCRA. Pollutants, including chromium, must be reduced to acceptable levels before disposal in Subtitle C landfills. Disposal fees at landfills may run on the order of $25 to $50 per drum, which does not include costs of transportation and preprocessing.[41] Recovery of metal values may be incorporated

into waste processing, and the value of the metals can then help reduce the cost of disposal.

Several processes have been developed or are under development by public agencies and industry to recover or recycle metals from processing wastes. Corning Glass reportedly has developed a closed-loop process which permits reuse of chromic acid etching solutions, thus reducing the amount of waste and reducing the need for new chromium-bearing chemicals. Another process to recover chromic acid etching solutions, developed by the Bureau of Mines, has been demonstrated to be economically competitive with the purchase of new acid, when savings of disposal costs are included in the analysis. This process, which extends the useful life of the acid a hundred fold, results in major materials savings and also permits the recovery of other metals, such as copper, which can be sold.[42]

Electronic Scrap

The key constraint in recycling of PGMs from electronic scrap is the very small amount of metal used in each unit. The two largest consumers of PGMs in the electrical and electronic sector are the telecommunications industry, which uses them in electromechanical contacts, and the ceramic capacitor industry. In telephone relays, palladium and platinum are found in the contact points, which are brazed to base-metal alloy arms. In a single hand-dismantled relay module taken from a large unit, the Bureau of Mines found 18 large and 36 small PGM contacts, weighing a little more than 0.06 of 1 percent of the weight of the whole module.[43] The National Association of Recycling Industries estimates that 1,000 tons of telephone relay scrap are generated each year. However, this scrap contains only a minute proportion of PGMs.

[40]As discussed in Bureau of Mines Research 83, op. cit., p. 104.
[41]U.S. Environmental protection Agency, Environ mental Pollution Control Alternatives: Sludge Handling, Dewatering and Disposal Alternatives for the Metal Finishing Industry (Washington, DC: U.S. Government Printing Office, 1982), p. 1, EPA 62515-82-018.

[42]Deborah A. Spotts, Economic Evaluation of a Method to Regenerate Waste Chromic Acid-Sulfuric Acid Etchants, U.S. Department of Interior, Bureau of Mines Information Circular 8931 (Washington, DC: U.S. Government Printing Office, 1983].
[43]Fred Ambrose and B. W. Dumay, Jr,, ''Mechanical processing of Electronic Scrap to Recover Precious Metal Bearing Concentrations, '' paper presented at the International Precious Metals Institute Conference, Vicksburg, VA, May 1983.

Another potential barrier to recycling of PGMs from electronic scrap is the fact that palladium (which, with an average 1982 dealer price of $100 per troy ounce is much lower in price than platinum or gold) predominates in this sector. Palladium is used in ceramic capacitors and is increasingly substituted for gold in low-voltage, low-current electrical contacts, such as telephone relay contacts. Higher reliability electronics, including those for military use, require greater amounts of platinum and gold in contacts, capacitors, and other electronic components.

Despite these potential barriers, there is a growing electronic scrap recycling industry in the United States. An industry observer[44] estimates that 102,000 troy ounces of platinum, or more than the total yearly platinum purchases by the industry, were recovered from electronic scrap in 1982. The growth in recycling of this type of scrap is reflected in the location of the secondary precious metals industry. Twenty years ago, most precious metals refiners and semi-refiners were clustered around the jewelry industry on the east coast. Today, many semi-refiners and refiners are located in California's "Silicon Valley," Texas, and other areas where the electronics industry has developed.

As in other sectors, PGM recovery is greatest from manufacturing scrap. Large refiners such as Johnson Matthey deal in both primary metals and scrap, supplying the electronic component industry with palladium metal, powders, and pastes, and recycling the metal from their reject components. In addition, some large electronics companies have set up their own in-house recycling processes to recapture the precious metals from both their manufacturing scrap and obsolete scrap. However, the percentage of PGMs recycled from obsolete electronic scrap is generally lower. Because of the high labor costs involved in manually processing electronic scrap prior to final refining, some electronics firms and scrap dealers find that foreign dealers offer the best

[44]Mark Stringfellow, "Platinum: Its Present and Future, " paper presented to the National Association of Recycling Industries, Dec. 15, 1982.

price for their scrap. Material is shipped both to Europe, where such firms as SGM in Belgium have a long history of expertise and sophisticated technology for precious metal refining, and to Taiwan and other Asian countries, where lack of raw materials and low labor costs make low-grade scrap more attractive.

Industry assessments of the quantity of electronic scrap exported by the United States vary. Total sales of PGMs to the electrical and electronic sector were 438,000 troy ounces in 1982. By comparison, exports of all types of PGM-bearing scrap that year were 388,437 troy ounces.[45]

Future trends in domestic recovery of PGMs from electronics are difficult to predict. Over the next decade, the scrap market is expected to increase as technological advances make equipment obsolete. Computer manufacturers, concerned about possible resale of their obsolete components, may crush the parts and sell them for recycling. However, whether the platinum group metals found in this scrap are recovered for U.S. consumption depends on a variety of factors. While some of the materials may be exported for overseas refining, this may be done on a toll-refined basis. For example,

[45]U.S. Department of Interior, Bureau of Mines, Mineral *Industry Surveys,* Platinum Quarterly, June 7, 1983, table 5.

Photo credit' GTE Corp

Precious metal scrap produced during the manufacture of electronic components is segregated to enhance recycling of gold, silver, and platinum group metals

a recently opened Engelhard plant in Cinderford, England, will refine metal from scrapped components and circuitry from U.S. sources on a toll basis, providing an equivalent amount of PGMs to those sources from Engelhard's U.S. refineries.[46] In addition, a number of European firms, such as De Gussa, a German firm, have begun to operate PGM recycling plants in the United States. It is too early to tell whether these trends will have a major impact on the amount of scrap that is exported.

As in other platinum-consuming industries, the long-term potential for recycling of strategic materials from electronics will depend on the quantities of materials used in production, The rapid evolution of the electronics industry has led to continual improvements in efficiency of use of the precious metals. For example, palladium-silver alloys are increasingly replacing pure palladium in electrical contacts, dampening both palladium use and potential future levels of palladium recycling. In addition, composites show promise for replacing contacts made entirely of PGMs.[47] A fiber composite made of a copper matrix with embedded palladium fibers and an overall palladium content of 30 percent has the same electrical and thermal conductivity as a palladium-copper alloy having a composition of 60 to 85 percent palladium. One of the greatest impacts on PGM use will come from the Bell System's present conversion to solid-state switching, thus reducing electromechanical switching and platinum and palladium demand.

Despite these trends in increased efficiency of use, opposing trends are causing overall demand for PGMs in electrical and electronic equipment to increase. Because of its low cost, palladium is increasingly being substituted for gold in electrical contacts and printed circuits, and new types of components, such as ceramic capacitors, are making use of PGMs. In addition, ruthenium, which is already used in the large quantities of reed switches used in electronics, is finding new applications in the in-

dustry. Overall, it appears that consumption of palladium and ruthenium will increase, and that there will be large quantities of these materials available for recycling beyond 1990.

Technologies for recycling PGMs from electronic scrap require further development. While several hydrometallurgical and pyrometallurgical processes are available for final refining of PGMs, preprocessing technology is not yet adequate. Currently, there are numerous steps in the refining process, often carried out by different companies, with each step adding to recycling costs. The initial manual disassembly of the most valuable components from the aluminum and copper frames (e.g., snipping off contacts with wire cutters) may be done either by the electronics company or by a specialized preprocessing firm. These firms sell some components for reuse and others for scrap to both domestic and foreign businesses.

Semi-refiners of electronic scrap collect circuit board scrap after initial disassembly and process it further. This may involve simply stripping off the plastics with chemicals, followed by shredding and chopping the components, or more complex steps such as ball mill crushing and pulverizing of capacitors, which leave a "sweep" or pulp containing precious metals. Other firms combine these processing steps with smelting out the PGMs as crude bullion, which may be either sold to electronic component manufacturers or shipped to refiners. Final refining to high specifications is generally done by one of a handful of specialized refiners using pyrometallurgical techniques.

Using obsolete electronic scrap provided by the Defense Property Disposal Service, the Bureau of Mines has developed a process for mechanically upgrading electronic scrap, The process is made up of a series of unit operations using technology already widely available in the recycling industry. These operations include shredding, eddy current separation, and high-tension separation. The process can break down mixed scrap into an iron-base fraction, an aluminum base fraction, a wire fraction, and a high and a low precious metal concen-

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[46]Judith Crown, ''Engelhard Revamping Precious Scrap Setups, '' American *Metals* Market, July 8, 1983, p. 1.
[47]Stockel, "composites for Electrical Contact Applications, '' *Zeitschrift fuer Werkstoffechnik*, July 1979.

trate, greatly reducing the amount of material that must be processed for precious metal recovery and also reducing shipping and toll refining costs.

The Bureau of Mines process could reduce costs of refining electronic scrap by replacing costly, slow, and unpredictable hand stripping with reliable automated techniques. While it can be used on mixed scrap, it is most effective when incoming scrap is first separated into lots. For example, connector assembly plating, printed circuit cards, wiring, and other components high in precious metals should still be manually separated from their outer box covers. While all segments of the precious metals recycling industry have expressed interest in the process, economic factors may prevent widespread adoption of fully automated processing. Some in the recycling industry view the high capital costs of the equipment and the high energy costs of operating it as formidable barriers to profitable domestic processing of low-grade mixed scrap.

Cemented Carbides

About 8 percent of the cobalt consumed domestically each year is used as a binder in cemented carbides, which are used in cutting tools or other high-wear applications. Most scrap produced during fabrication of cemented carbides is now recovered, and in the last few years, producers of cemented carbides have begun to recycle substantial quantities of obsolete cemented carbide scrap. This improved recovery became pronounced in the late 1970s but the improvement was less a function of industry response to the cobalt price increase than of the ongoing adoption of technological advances by tungsten carbide producers.

According to the NMAB, up to 0.5 million pounds of cobalt from obsolete products are now recovered by tungsten carbide producers each year. In early 1984, installed capacity to reprocess such scrap is estimated to be 36 percent of domestic consumption. Obstacles to increased recycling of obsolete carbide scrap include widespread geographic diffusion of products and difficulties in recovering worn or broken parts,

Tungsten carbide scraps constitute a major proportion of current tungsten recycling. GTE Corp., the largest domestic producer of tungsten, established a patented process in the early 1970s for recycling tungsten scraps and in 1978, a proprietary process for producing extra-fine, highly purified cobalt powder from recycled scrap on a toll and nontoll basis. With sintering, the powder can be turned into a metallurgical cobalt material suitable for use in superalloy, GTE has also established a pilot plant project to reclaim cobalt from superalloy scrap. The recycled cobalt is equivalent to highly refined cobalt produced from virgin ores. Although the cobalt is produced as powder for cemented carbide use, it may be suitable for superalloy if compacted and pelletized.[48]

Other cemented carbide producers, such as Teledyne, employ a zinc process to recover both cobalt and tungsten carbide as powders from tungsten carbide scrap. The process was developed by a British firm in 1946 and furthered by the U.S. Bureau of Mines,

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[48]Information provided to OTA by GTE, Aug. 10, 1983.

Prospects for Conservation of Strategic Materials

Table 6-6 summarizes key opportunities for increased recycling of chromium, cobalt, and PGMs. Data limitations prevent close estimation of prospective recovery opportunities in many applications, but it is clear that very large quantities of materials are involved. Under tight supply conditions, appreciable increases in recycling can be anticipated as scrap collectors, processors, and consumers respond to increased prices of primary metals.

Table 6-6.—Selected Opportunities for Increased Recycling of Chromium, Cobalt, and Platinum Group Metals

Current level of recycling	Key recovery opportunities	Barriers to increased recycling		
		Technical	Economic	Institutional
Superalloy (Co, Cr): An estimated 2.8 million lbs of cobalt-bearing superalloy processing scrap was lost or downgraded in 1980; 1.2 million lbs of cobalt in obsolete scrap was not recovered. However, these figures are **based** on 1976 scrap use rates.	Increased recovery of obsolete scrap, reduced downgrading of high-quality industrial scrap and recovery of wastes, using advanced recycling technologies.	Concern about contaminants limits recycling in superalloy production to high-quality scrap and processes that have been certified. Experimental processes to reclaim elements separately have not been commercialized.	Current prices encourage downgrading of superalloy scrap for use in stainless steel or nickel alloy production in which the cobalt is not needed. Certifying recycled materials for superalloy use is expensive and time-consuming.	Not significant once manufacturing specifications for use of recycled materials have been established; however, this can take several years.
Petroleum hydroprocessing catalysts (Co): No cobalt recovery at this-time; 270,000 lbs of cobalt was not recovered from spent catalysts in 1982.	Cobalt consumption in catalysts is expected to grow to 675,000 lbs in 1990, 900/. of which could be recovered.	Not significant; various proprietary processes are purported to recover Cr, Co, Ni, Mo, Va, and other metals for catalytic or chemical purposes.	Current prices may discourage recovery of cobalt in preference for molybdenum. However, at least two firms have proprietary processes for recovery of all elements in catalysts.	Landfilling of spent catalysts by refineries prevents possible future recovery of some catalysts.
	Accumulated spent catalyst residues may include 8 million lbs of cobalt and nickel.	Some technical problems; pilot-scale recovery process is under investigation by a private firm.	Reprocessing of residue is not profitable at current prices.	Not significant; residues are stored on site of major processor.
Cemented carbides (Co): 10 to 30°/0 of cobalt used in domestic cemented carbide shipments came from recycling.	Obsolete scrap (a high proportion of industrial scrap is already recovered.)	Not significant: several firms use a Bureau of Mines process to recover cobalt binders. One firm produces highly refined, pure cobalt powders from scrap that could potentially be used in" other premium uses.	Recovery of obsolete scrap from dispersed uses may not be economic at current prices.	Lack of effective scrap collection programs by industrial users. Practical limits for postconsumer recovery vary by industry. However, some users (such as the oil industry) return 80% of their scrap for recycling; the coal mining industry, by contrast, only returns 150/0 (out of a practical limit of 500/0).

Table 6.6.–Selected Opportunities for Increased Recycling of Chromium, Cobalt, and Platinum Group Metals (Continued)

Current level of recycling	Key recovery opportunities	Barriers to increased recycling		
		Technical	Economic	Institutional
Stainless steal (Cr): Home scrap is efficiently recovered; purchased scrap for stainless steel accounted for about 20°/0 of total demand for Cr in 1983.	Improved recovery, reduced downgrading of obsolete scrap, especially automotive catalytic converters.	Not significant, but current industrial practices encourage downgrading.	Comparatively low price of chromium and labor costs associated with removal of stainless steel components from automotive and other obsolete scrap encourages downgrading.	Recovery of obsolete consumer products containing stainless steel catalytic converter shells is a primary candidate for recovery, but will depend on effective linkage of PGM and Cr recovery efforts.
	Increased recycling of industrial processing wastes (slags, flue dust, low-quality fabrication scrap, etc.)	Recovery of chromium from some wastes (e.g., slags) is technically difficult.	Resource recovery from industrial wastes may not be economic: however. commercial recovery of low-grade flue dusts, grindings, turnings, borings is now being undertaken commercially.	Environment and solid waste disposal requirements are providing increased impetus to recovery where economic.
Catalytic converters (PGM, Cr): Up to 30°/0 of scrapped converters may now be recovered for recycling.	Retrieval of PGM from scrapped automobiles, muffler shops, etc. Maximum theoretical PGM recovery will grow to 800,000 troy oz by 1995. Maximum practical recovery rate will probably be about 500,000 troy oz.	Several companies have proprietary processes to recycle catalysts.	Dependent on PGM prices, but appears favorable.	Some dismantles do not remove catalytic converter from cars prior to scrapping. Collection networks have not been established in many areas. Dismantles want more for the catalysts than reclaimers are willing to pay.
Electronic scrap (PGM): **High for industrial** scrap, low for obsolete scrap.	Obsolete scrap.	Lack of technology for preprocessing of scrap to a form usable by a refinery.	Depends on PGM prices; hand labor disassembly encourages export of scrap.	Collection of obsolete scrap from consumer electronics (i.e., households) is unlikely without incentives. Value of scrap is not widely recognized; monitoring of trends is inadequate.

SOURCE: Office of Technology Assessment.

Evidence from past "crises' '-most notably the Canadian nickel strike of 1969 and the cobalt price spike in 1978—suggests that U.S. industry can quickly increase recycling when concerns about supplies are paramount or when prices rise rapidly. In 1969, nickel scrap purchases exceeded 1968 levels by over 60 percent despite the fact that the Canadian strike did not occur until mid-1969. Nickel scrap as a proportion of domestic consumption expanded rapidly over the following 3 years—accounting for 22 percent of domestic supplies in 1972 as compared to 8 percent in 1968, (The current level is about 23 percent,) Cobalt scrap purchases doubled in 1978 and remained at or above 1 million pounds per year through 1981, a growth from 4 percent of domestic consumption to 8 percent.

It is more difficult to quantify savings of strategic materials likely to arise from adoption of new manufacturing and processing technologies by U.S. industry, but they are also large—particularly in the cases of manganese used in steelmaking and strategic materials used in superalloy. Upgrading of basic steelmaking processes could lead to important reductions in the amount of manganese needed to produce each ton of steel (see table 6-6). Use of advanced manufacturing technologies by the aerospace industry will reduce chromium, cobalt, and other strategic material input requirements for superalloys on a perpart basis. Part life extension programs could also conserve materials over the long run. As discussed in chapter 7, increased use of coatings and other surface treatment technologies and use of advanced ceramic and composite materials also could reduce per part strategic material requirements, especially in the long term.

Recycling Technology

With some notable exceptions, there appear to be few significant technological barriers to increased recycling of strategic materials. High-quality scrap generated in the production and manufacture of products is recognized to be a valuable source of raw materials by industry and is usually effectively recovered and reused. Ongoing industrial trends, including establishment of specialized scrap processing firms and improved industrial waste treatment processes, have expanded the range of waste materials considered suitable for recycling, so that continued incremental improvement in recycling is likely in the coming decade. Difficulties in identifying and sorting complex scrap containing several materials have recently been eased by the commercial availability of portable and relatively inexpensive instruments suitable for use in scrapyards, as discussed in box 6-A.

In the area of superalloy recycling, considerable technological advances have been made over the last decade. However, additional innovations may be needed if full use of obsolete scrap and other less preferred scrap is to occur. In the most demanding applications, even small trace amounts of impurities may be unacceptable. Because of concern that contaminants acquired from scrap material could result in failure of superalloy parts, use of superalloy scrap in jet engines has been limited to scrap of the highest quality—generally, home and prompt industrial scrap, although limited use has been made of obsolete scrap obtained from commercial aircraft, where parts can be identified by alloy type. Much of the remaining scrap is downgraded to use in stainless steel, where it is used for its nickel and chromium content. When this occurs, cobalt is lost, and the previously high-quality chromium used in superalloys becomes a replacement for chromium usually supplied from high-carbon ferrochrome or stainless steel scrap.

Nontechnical Impediments

In most applications, institutional and economic constraints on recycling are more formidable than the technical constraints. Fluctuating commodity prices, costs associated with segregation and processing of scrap, transportation costs, and industry structure all affect the ability of recycled materials to compete with primary metals.

ECONOMICS OF RECYCLING AND CONSERVATION

The economic incentive for recycling high-priced materials, such as PGMs, is very high.

However, other strategic metals are less expensive and often account for only a very small proportion of the scrap. For many applications, raw materials comprise only a small fraction of the total value of the product. A 6,000-pound jet engine, for example, may cost $3.5 million, while the value of the materials it contains is only $60,000. Even though an alloy may contain metals that are relatively rare and high priced, the cost of separation of the alloy into its constituents may be so high that it discourages any attempt to recover the metals; so, the alloy is downgraded to recover its nickel and chromium content.

Recycling opportunities will change along with changes in manufacturing processes and product designs. More efficient manufacturing processes will require less raw material, so there will be less prompt industrial scrap available for recycling, New product designs that use combinations of materials to achieve desirable properties will present difficult and expensive problems for the separation of materials for recycling. Often, products can be designed for ease of recycling, but since raw material costs are generally a small component of overall cost, this is seldom done,

Materials conservation is an important side benefit of the advanced manufacturing technologies widely used by the aerospace industry. These technologies may gradually filter down to other industrial users. Diffusion of computer-aided design and nondestructive evaluation techniques may be impeded to some extent by lack of experience of engineers, designers, and others with these new approaches. This is not a major problem in the aerospace industry or in other critical uses, however.

INFRASTRUCTURE

The complex structure of recycling industries, often entailing primary metals processors, collectors and dealers, scrap processors, and parts manufacturers, can inhibit initiation of recycling programs, even when the programs may be economically advantageous. Generally, the secondary metals industry comprises a large number of small firms that respond to prices offered by the primary metals

industry, This system works well for materials for which there is a relatively constant demand for a standard product. Although recycling firms can respond rapidly to changes in materials demand due to shortages of primary materials, exacting standards for superalloy and other premium materials can only be met through the use of sophisticated equipment and experienced personnel who are familiar with the needs of consumers. This can delay recycling response time in a shortage situation,

Recycling and Conservation Data Base

Accurate information is needed to have a realistic picture of the potential for recycling to reduce U.S. materials import vulnerability. The existing data are weak, with many uncertainties about their accuracy. Key areas where improvements can be made are: upgrading of annual information about scrap purchases by consuming industries, development and use of materials flow models on a periodic basis, and improved tracking of the ultimate disposition of obsolete scrap and industrial wastes that contain appreciable amounts of strategic materials,

The U.S. Bureau of Mines prepares annual estimates of scrap purchases by domestic industry. In most instances, these estimates are based on voluntary reporting by private firms. Not all firms are canvassed, and of those that are, not all respond. Consumers of more than one strategic material may be surveyed about only one material. Although adjustments can be made to compensate for incomplete reporting, the resulting estimates are subject to considerable uncertainty. In the course of this study, OTA found evidence that substantially more recycling may be taking place than is currently reported in Bureau of Mines' data.[49]

Scrap purchases alone provide only a limited picture of recycling trends, Substantial recycling occurs internally and through toll refining arrangements that do not involve purchases,

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[49]Other reports have reached a similar conclusion. See, for example, the NMAB report, Cobalt Conservation Through Technological Alternatives, op. cit., p. 25.

Also, scrap purchases provide no insight into the ultimate fate of scrap that is not recovered. Periodically, Federal agencies such as the Bureau of Mines and the NMAB have published detailed and relatively comprehensive materials flow models for individual metals. These models have appreciably increased understanding of overall recycling trends, but they have been prepared infrequently and there has been little or no consistency in procedures used in developing the models.

A notable impediment—from the perspective of identifying possible responses to disruptions in materials supply—is the absence of information about accumulations of unrecovered obsolete scrap containing strategic materials. Only a portion of the scrap that becomes obsolete each year is recycled domestically. Some

is exported, while the rest is unaccounted for in national statistics. Much of this lost material may now be effectively unrecoverable owing to disposal in landfills, dissipative corrosion, contamination, or abandonment in unknown locations. Some, however, may be retrievable from industrial disposal sites, commercial scrap yards, and military storage depots for use during supply disruptions. Extensive efforts have been made over the years to estimate the accumulated "inventory" of potentially recoverable ferrous scrap, but a similar effort to monitor the disposition of strategic materials in obsolete superalloy parts, catalysts, and other applications has not been made. As a result, plausible estimates of the above-ground mine of strategic materials recoverable in an emergency are not available.