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By Kim B. Shedd

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

g/mt	gram per metric ton	mt/yr	metric ton per year
mt	metric ton	%	percent

THE MATERIALS FLOW OF COBALT IN THE UNITED STATES

By Kim B. Shedd[1]

ABSTRACT

An initial evaluation of the flow of cobalt-containing materials in the United States was prepared. The following aspects of materials flow were included: cobalt released as a result of mining and processing other metals and minerals; scrap generation and subsequent recycling or cobalt recovery; and cobalt losses resulting from the generation of wastes, dissipative uses, and disposal of used products. Where possible, estimates were made to quantify the amount of cobalt lost from the materials flow.

More than 2,000 metric tons (mt) of cobalt are released annually from mining and mineral processing in the United States, including 480 mt of cobalt in coal produced in the United States. Metallurgical industries examined in this study have well-established recycling or cobalt recovery practices. The petroleum industry recycles spent catalysts, and some chemical catalysts are also recycled.

Losses generated during cobalt chemical and powder processing were estimated at 50 mt to 80 mt of cobalt annually. Losses from alloy processing and the manufacture of parts and products were estimated to be 360 mt. These industrial losses are greatly outweighed by an estimated 2,780 mt of cobalt consumed in the United States each year to make products that will ultimately be disposed.

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INTRODUCTION

The U.S. Bureau of Mines has initiated a series of studies on the flow of materials resulting from the production and use of various commodities. The purpose of this study was to prepare an initial evaluation of the flow of cobalt-containing materials in the United States. Aspects of materials flow considered for the study included cobalt released during the mining and processing of other metals and minerals; scrap generation and subsequent recycling or cobalt recovery; and cobalt losses resulting from the generation of wastes, dissipative uses, and disposal of used products. Where possible, estimates were made to quantify the amount of cobalt lost from the materials flow.

Estimates of cobalt consumed by various industries were made from data published in the Bureau's Minerals Yearbook (*1*).[2] In most cases, consumption in the present study represents an average of 2 to 3 years of data ending in 1989. The Bureau's consumption data represent the amounts of cobalt reported by U.S. industries to make superalloys, magnetic alloys, cemented carbides, catalysts, paint driers, etc. The Bureau does not collect data on how these products are used or whether they are used in the United States or exported.

Because of trade flows between the United States and other parts of the world, identification of the actual amounts of cobalt in final products used in this country is much more difficult. The cobalt content of imports and exports of consumer products is not available. If a significant portion of cobalt-containing products is exported, then downstream distribution of those materials in the United States will be overestimated. Conversely, if significant amounts of cobalt-containing products are imported into the United States, then the distribution of cobalt in those products will be underestimated. An example of the latter case is cobalt in magnets. The estimate for cobalt lost through disposal of magnets in used products given later in this report is based only on the cobalt content of magnetic alloys produced in the United States. A realistic estimate of cobalt in magnets produced elsewhere and imported into this country both separately and in products was not feasible.

Many of the estimates for scrap recycling and losses were based on information in two earlier studies, one by the National Research Council's National Materials Advisory Board in 1983 (*2*), and one by Inco Research and Development under contract for the U.S. Bureau of Mines in 1980 (*3*). Supplemental references were used where available. The Bureau of Mines' Albany Research Center has also done research on materials flows and recently published a report on cobalt (*4*). As in the current study, the Albany study relied heavily on reference 2. The authors generated estimates for quantities of cobalt used, recycled, or lost during U.S. production of cobalt-containing products in 1987. The approach of the current study was slightly different from that of the Albany study. The emphasis of the current study was on the total flow of cobalt-containing materials in the United States. In addition to cobalt flows during processing and manufacturing, the current study also addressed cobalt losses during mining and mineral processing, from the burning of fossil fuels, from dissipation during use, and from disposal after use.

It was not always possible to determine the final distribution of cobalt-containing materials. Wastes can be downgraded,[3] stockpiled, exported, or discarded. Some reports do not distinguish between downgraded cobalt and environmental losses, because for the purpose of their studies both represent a loss of usable cobalt. Therefore, a portion of the cobalt listed as "losses" in this study may have been incorporated into other materials flows via downgrading, or it may no longer be present in the United States, because it was exported.

The author recognizes that technological changes, such as changes in recycling practices and cobalt uses, since the cited references were written may have caused changes in the materials flow. However, it is hoped that the results of the current study will give an estimate of the relative magnitudes of cobalt lost from various sectors of the U.S. cobalt flow and will provide a starting point for further studies on this subject.

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

[3]A glossary of terms is included at the end of this report.

THE ANNUAL GLOBAL COBALT CYCLE

The flow of cobalt through the global environment was characterized by Donaldson, et al. (*5-6*). An adaptation of Donaldson's "cobalt cycle" is presented as figure 1. Donaldson estimated that on a global scale, 50,000 mt of cobalt enter the environment each year. Most of this cobalt is released through the natural processes of rock weathering (20%) and biological extraction (60%). Biological extraction refers to the biochemical processes in which cobalt is extracted from rocks and soils by bacteria and other microorganisms. An important example is the conversion of inorganic cobalt to cobalamins—vitamin B_{12} coenzymes. These processes occur in various environments including the rumen fluids of ruminant animals, soils, nodules of leguminous plants, dairy products, marine sediments, and seawater (*7*).

The remaining 20% of global cobalt release is attributed to industrial emissions. One-half of the industrial emissions is thought to originate from the burning of fossil fuels, primarily coal. The other one-half of industrial emissions is released during the annual production and use of 25,000 mt of cobalt. Six percent of the global cobalt releases result from its use as a metal and 4% result from chemical and other uses.

Donaldson attributed only minimal releases to worldwide mining and refining of cobalt. Because cobalt is produced as a byproduct, and recovery of nickel, copper, or platinum is the principal concern, cobalt recovery rates would not be expected to be as high as recovery rates for the principal metals. In cobalt-producing operations, cobalt recoveries from milling ores to concentrates range from less than 10% when little effort is made to recover the cobalt, to greater than 80% when cobalt recovery is emphasized (*8*). Therefore, 20% to 90% of the cobalt originally present in the ore is lost to the tailings during beneficiation. Following beneficiation, further losses occur when concentrates are processed to recover the metals. As one example, cobalt losses to the slag phase are high when nickel sulfide concentrates are smelted to form matte (*9*). Compilation of overall recovery rates for each cobalt-producing operation to estimate an average worldwide rate is beyond the scope of the present study. If the overall worldwide cobalt recovery from ore to refined metal is roughly estimated as 50%, then the amount of cobalt lost during its production would equal the amount produced. Therefore, on a global basis, 25,000 mt of cobalt would be lost each year from the production of 25,000 mt of metal.

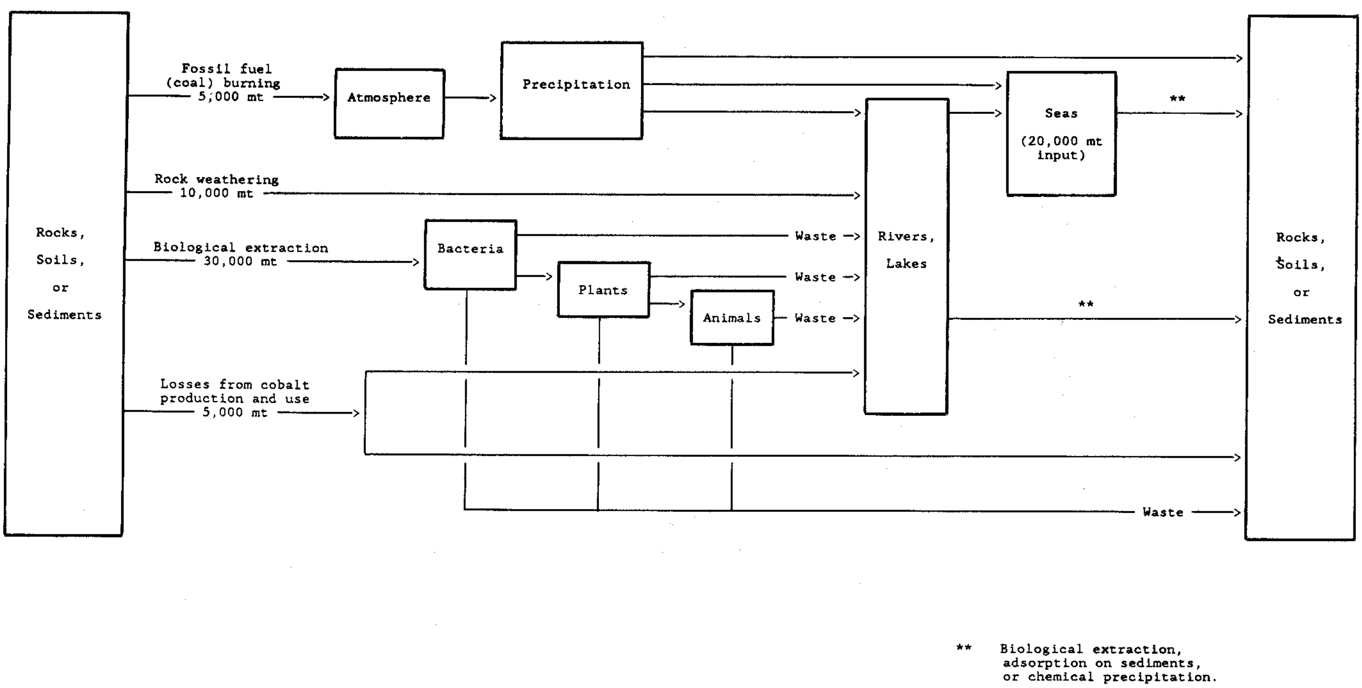

Figure 1.—The annual global cobalt cycle. Adapted from references (*5*) and (*6*).

Adding this estimated loss from cobalt production to Donaldson's estimates for global releases increases the total global release of cobalt to 75,000 mt/yr. In addition, the ratio of natural emissions versus industrial emissions changes from Donaldson's estimate of 80% natural/20% industrial to roughly equal amounts released from natural processes and industrial processes. The breakdown of individual components would then be as follows: 40% from biological extraction, 13% from weathering, 7% from fossil fuels, 4% from metal use, 3% from chemical and other use, and 33% from ore and metal production (table 1).

Additional cobalt would be lost from mining and refining operations where cobalt is present, but is not produced as a primary product or byproduct. Examples of cobalt released in the United States during the production of other metals are discussed in the following section.

Table 1.—Global sources of cobalt to the environment (metric tons cobalt per year)

Source	Amount
Natural emissions:	
Biological extraction	30,000
Weathering of rocks and soils	10,000
Volcanic emissions	small
Industrial emissions:	
Fossil fuels	5,000
Metal use	3,000
Chemical and other use	2,000
Ore and metal production	25,000
Total	75,000

Source: References (5) and (6), except for "ore and metal production," this study.

ANNUAL U.S. COBALT MATERIALS FLOW

The present-day flow of cobalt-containing materials in the United States can be divided into four general industry/consumer stages: mining and refining operations/fossil fuels, chemical and powder processing, fabricate/manufacture, and use. The general flow of cobalt materials is shown in figure 2, from raw materials to products,

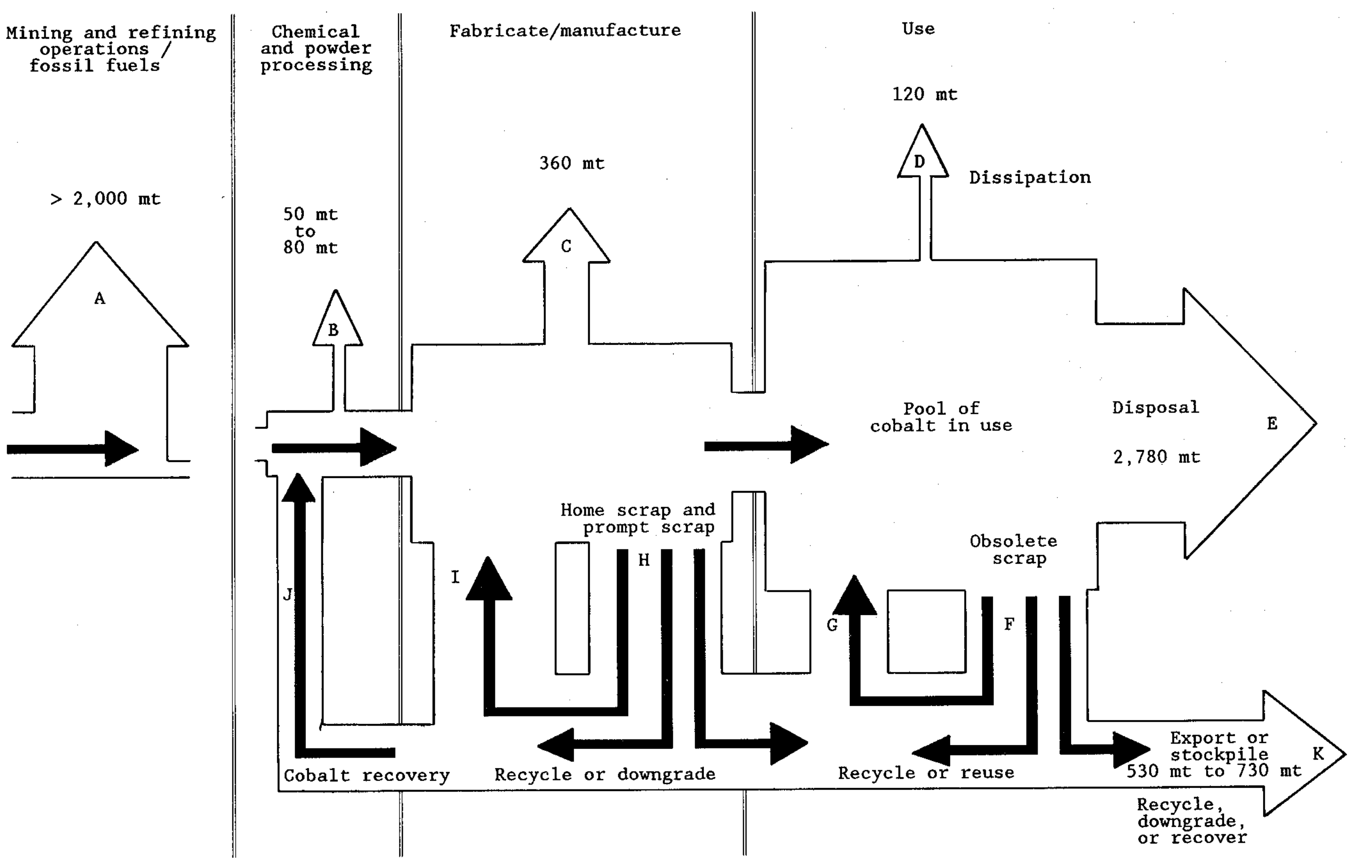

Figure 2.—Current annual U.S. cobalt materials flow.

left to right. Flows of cobalt recovery and recycling were identified, and depicted as black right-to-left arrows at the bases of the industry/consumer stages. Losses of cobalt from each stage were identified, and are represented by white up-arrows. Two white arrows at the "end" of the cobalt materials flow diagram represent additional ways that cobalt leaves the U.S. cobalt materials flow. The relative sizes of the boxes at each industry/consumer stage and the relative sizes of the white arrows are intended to represent relative quantities of materials. Descriptions of losses and recycling flows are presented in table 2.

Table 2.—Cobalt losses and recycling flows in the United States

Designation on figure 2	Description
A	Cobalt released during mining and refining and from burning fossil fuels.
B	Cobalt lost during chemical and powder processing.
C	Cobalt lost during alloy production and/or product manufacture.
D	Dissipative cobalt losses during use.
E	Cobalt lost from the disposal of products following use.
F	Cobalt-containing products leaving the flow following use.
G	Recycled products reentering the flow without reprocessing.
H	Home scrap and prompt scrap leaving the flow.
I	Scrap reentering the flow during alloy production or product manufacture.
J	Scrap reentering the flow during chemical and powder processing.
K	Loss to the U.S. flow via export or stockpile of materials or products.

MINING AND REFINING OPERATIONS/ FOSSIL FUELS

The United States is not considered a cobalt producer. The last significant byproduct cobalt mine production ceased at the end of 1971, and the one U.S. cobalt refinery stopped processing imported nickel-cobalt matte in late 1985. However, small amounts of cobalt are sometimes associated with other ores and metals being produced in the United States such as lead, copper, gold, zinc, ferronickel, iron ore, and coal. Most of the cobalt in these ores is separated from the primary minerals or metals during beneficiation or metallurgical processing. When ore containing cobalt is treated, the cobalt reports to mill tailings; smelter slags, mattes, drosses, or flue dusts; residues or other products of metallurgical processing. These materials are sometimes stockpiled. Unless recovered in other countries from exported materials, this cobalt does not reenter the U.S. cobalt flow. In some cases, cobalt is not separated from the primary product during processing and remains in the final product. Coal and ferronickel are two products that can contain varying amounts of cobalt. Cobalt in U.S. coal is discussed below. Cobalt in ferronickel (generally less than 1%) would report to steel and possibly also to wastes associated with steel manufacture. Three examples of cobalt flows associated with current U.S. metal and mineral production are presented below.

Missouri Lead Ores

In 1988, 86% of U.S. primary lead production was from the Missouri Lead Belt. Based on an estimated 0.015 weight percent cobalt in these ores (*10*), and an annual mine production of 5.4 million mt of ore (*11*), over 800 mt of cobalt was mined, but not recovered, in 1988. Roughly one-half of this cobalt reported to mill tailings. The remainder was distributed among various concentrates, and ultimately reported to mattes, residues, and other materials generated from lead, zinc, and copper operations (fig. 3). The mattes, residues, etc., are discarded, stockpiled, or exported (*12*). If stockpiled, they are temporarily out of the U.S. flow. If exported, they have left the U.S. flow. Therefore, the estimates reported in figure 3 should be considered potential losses whose final placement (in the United States or elsewhere) is not known.

Copper Leach Solutions

Cobalt is associated with some of the copper ores in Arizona, New Mexico, and Utah (*13*). In processing these ores, most of the cobalt accumulates in flotation mill tailings and/or in spent copper leach solutions produced from heap-leaching dumps of low-grade ores. No estimates of cobalt in copper mill tailings are currently available. The spent copper leach solutions have been investigated as a potential source of cobalt. U.S. Bureau of Mines researchers estimate that spent leach solutions from five domestic sources could produce more than 900 mt of cobalt each year (*14*).

Coal

Trace amounts of cobalt are also present in fossil fuels such as coal and oil. As discussed previously, an estimated 7% to 10% of cobalt emissions into the global environment are from the burning of fossil fuels. U.S. coals are estimated to contain an average cobalt content of 0.6 g/mt (*15*). The cobalt is associated with sulfide minerals present in the coal. Based on 0.6 g/mt of cobalt in coal, the 800 million mt of coal consumed in the United States in 1989 (*16*) could have contained 480 mt of cobalt. In order to meet emission standards, coal powerplants either use

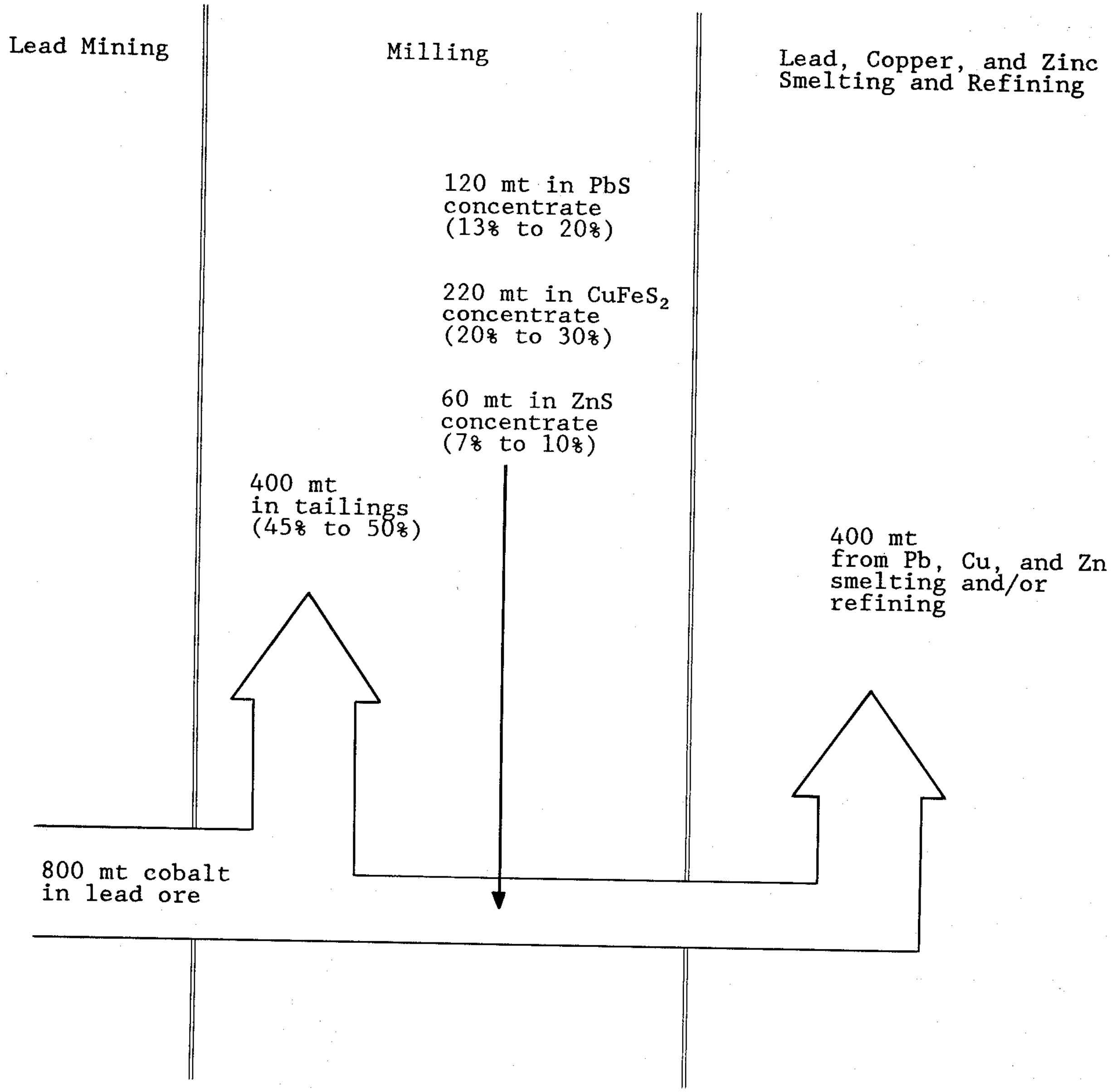

Figure 3.—Cobalt released annually from Missouri lead ores. Adapted from reference (*10*).

processed coal or clean their emissions with scrubbers. Therefore, cobalt in some coals would be removed during coal processing, and cobalt in other coals would most likely report to the fly ash produced during combustion and be captured by antipollution devices.

For this study, losses associated with coal production and use are included with losses from metal mining and refining operations. Based only on these three examples, a minimum of 2,000 mt of cobalt is released each year from these sources (A on figure 2).

CHEMICAL AND POWDER PROCESSING

Chemical and powder processing industries manufacture cobalt chemicals and/or powders from imported cobalt metal and/or cobalt-containing scrap. Examples of scrap feed materials include cemented carbide scrap and catalyst residues. At this stage in the cobalt materials flow, when scrap is the feed material, cobalt is recovered—separated from other metals present in the scrap and residues. For example, cobalt in cemented carbide scrap can be separated from tungsten carbide and reprocessed to make pure cobalt metal powder. The products from these industries—cobalt chemicals and powders—are consumed to make products in the fabricate/manufacture stage, used directly in the use stage, or exported (fig. 2).

Chemical and powder processing are assumed to be fairly efficient and to have low losses. Cobalt yields of 98% for powder processing and 97% for chemical processing have been reported (*17*). Based on a rough estimate of 2,600 mt of U.S. chemical and powder production, losses would be only 50 mt/yr to 80 mt/yr (B on figure 2).

FABRICATE/MANUFACTURE

This stage of the cobalt flow diagram represents many individual industries that consume cobalt to manufacture a wide variety of products. Examples of products include jet engine parts, magnets, cemented carbide tool inserts, catalysts for petroleum refining, paints, and porcelain enamel products. Raw materials used in this part of the cobalt industry include imported cobalt (metal, powder, and chemicals), cobalt from U.S. chemical and powder processors, and cobalt-containing scrap.

Recycled scrap can constitute a significant portion of the raw materials for some industries (I on figure 2). In the case of superalloy processing, this scrap can originate from various stages of the cobalt flow diagram. Scrap originating from the fabricate/manufacture stage (H on figure 2) can either be home scrap or prompt scrap. Scrap can also originate from the use stage (F on figure 2) as used jet engine parts (obsolete scrap).

Products from the fabricate/manufacture stage are either used in the United States or exported. Losses from this stage are labeled C on figure 2. The 360 mt of cobalt lost from this stage is the sum of estimated losses from individual industries discussed later in this report.

USE

This stage of the cobalt flow represents cobalt-containing products that are still being used, regardless of the year in which they were manufactured. It can be viewed as a pool of use where newly manufactured products join products still in service. The length of time a product remains in the "use pool" varies depending on the product, and can change over time with changes in technology or conditions of use.

In addition to U.S. products, imports of cobalt-containing products also enter the "use pool." Cobalt-containing materials or products leave the use pool in four ways: dissipation, disposal, recycling or cobalt recovery, and exporting or stockpiling. Dissipation is defined as losses occurring during use or as a result of use (D on figure 2). Attrition of cemented carbides during machining operations, mining, or drilling, and the dispersal of cobalt agricultural supplements from the soil to plants to animals are examples of dissipation. For the purpose of this study, paint is not counted as a dissipative use, although some losses in paint could be considered as such. An estimated 120 mt of cobalt are lost each year in the United States from dissipation.

The second way cobalt can leave the use pool is by disposal (E on figure 2). Disposal is the conveyance of cobalt-bearing items or materials to landfills. These cobalt-containing products are removed from the materials flow without recovering the cobalt or recycling the product. In some products, recycling or cobalt recovery might be possible, if collection, recycling technology, and economics were amenable. For instance, cobalt-containing magnets could be recycled if they were collected from obsolete equipment, sorted by alloy type, and returned to magnet alloy melters. In other products, recycling or recovery of cobalt is nearly impossible. The main reason for this is the extremely low cobalt content in these products. Many cobalt chemical applications, such as paint and rubber additives, are essentially nonrecyclable. A sum of the estimates for individual industries discussed later in this report gives a total of 2,780 mt of cobalt consumed each year in the United States to make products that will ultimately be disposed.

The third route to leaving the use pool is through recycling or cobalt recovery. In some cases, materials are recycled without reprocessing and return almost immediately to the "use pool" (flow labeled F to G on figure 2). For example, homogeneous catalysts used in some chemical processes are separated from the product and then reused on-site. A small fraction of magnets from consumer products may be reused without remelting. In most cases, however, cobalt-containing products are recycled at an earlier stage in the materials flow. For example, used jet engine parts are cleaned up by scrap processors and returned to alloy melters (I on figure 2). Most used magnets would also be recycled by remelting at the alloy processing stage. Cobalt recovery from obsolete products is done by chemical and powder processors (J, see also "Chemical and Powder Processing" above).

The final way cobalt can leave the U.S. use pool is by exporting or stockpiling. Cobalt-containing exports range from materials such as scrap metal and processing residues to finished products, such as alloys or consumer goods. Stockpiled materials represent cobalt temporarily removed from the U.S. flow. These materials may be later reintroduced to the flow via recycling or metal recovery, or leave the flow via disposal or export. K on figure 2 represents cobalt contained in exported scrap and exported or stockpiled residues. Estimation of the cobalt contained in exported finished products was not practically feasible.

ANNUAL COBALT FLOWS IN INDIVIDUAL CONSUMING INDUSTRIES

SUPERALLOYS

The largest use of cobalt is in superalloys, which are alloys designed to resist stress and corrosion at high temperatures. The main use for superalloys is in aircraft turbine engine parts, but they are also used in other applications, such as turbines in electric powerplants, helicopter rotors, and prosthetic implants. The superalloy industry involves many stages, beginning with the initial melting of raw materials, through various fabrication stages, ending with machining or other processing to make a final part. Superalloys can be categorized as three main types depending on the primary fabrication method used in their production: wrought superalloys, cast superalloys, and superalloys made by powder metallurgy. The material flows and resultant losses in these three ways of making superalloys differ. Estimates for materials flows in the production of wrought and cast superalloys follow. Insufficient data were available to estimate materials flows in the production of superalloys by powder metallurgical techniques.

Large volumes of scrap are generated in the production of wrought and cast superalloys. In 1980 (*18*), only 27% of the raw materials melted to produce wrought superalloys was contained in the finished products. The remaining 73% ended up as waste or scrap. In the production of cast superalloys, 32% of the raw materials was contained in finished products and 68% ended up as waste or scrap.

The superalloy industry recycles a high percentage of the scrap it generates. The melts for wrought alloys were estimated to contain 47% home scrap, 13% purchased scrap (3% prompt scrap and 10% obsolete scrap), and 40% primary metal (*19*). This agrees with more current estimates by a wrought alloy producer (*20*). Melts for cast alloys were estimated to be composed of 8% home scrap, 47% purchased scrap (39% prompt scrap and 8% obsolete scrap), and 45% primary metal.

The quality of the scrap produced at various stages in the superalloy industry will influence the ability to recycle it. Uncontaminated well-identified solids and processed turnings are most likely to be recycled. Other types of scrap, such as dusts, furnace scale, sludges, and slags, tend to be composed of more than one alloy type and can be contaminated or highly oxidized, thus complicating recycling efforts. In the case of materials like melt-shop smoke, metal prices determine whether the material is recycled or landfilled (*21*).

Some cobalt-containing scrap is not recycled to the superalloy industry, but is instead downgraded to other alloys such as steels. These alloys reenter the use pool, although their cobalt content is greatly diminished. Superalloy scrap is also exported, or can be processed to recover individual elements such as cobalt and nickel. A diagram showing the flow of scrap materials in the superalloy industry is shown in figure 4.

The annual cobalt materials flow diagram for the superalloy industry is shown in figure 5. This diagram represents a combination of the wrought and cast superalloy industries based on a ratio 2:1 for the amount of primary cobalt in wrought versus cast superalloys (*22*). The raw materials input to alloy processing includes primary cobalt, purchased scrap (prompt and obsolete), and home scrap. Industry averages for the percent of each raw material were provided (*3*), and are shown in table 3 and figure 5. The amount of primary cobalt plus purchased scrap was estimated to be 2,850 mt from an average consumption of cobalt in superalloys (*1*). The total cobalt input to superalloy processing was estimated to be 4,385 mt, based on the assumption that the primary cobalt and purchased scrap represented 65% of the total. Additional estimates for the quantities of materials recycled, lost, downgraded, and exported were similarly derived from published percentages (*2-3*).

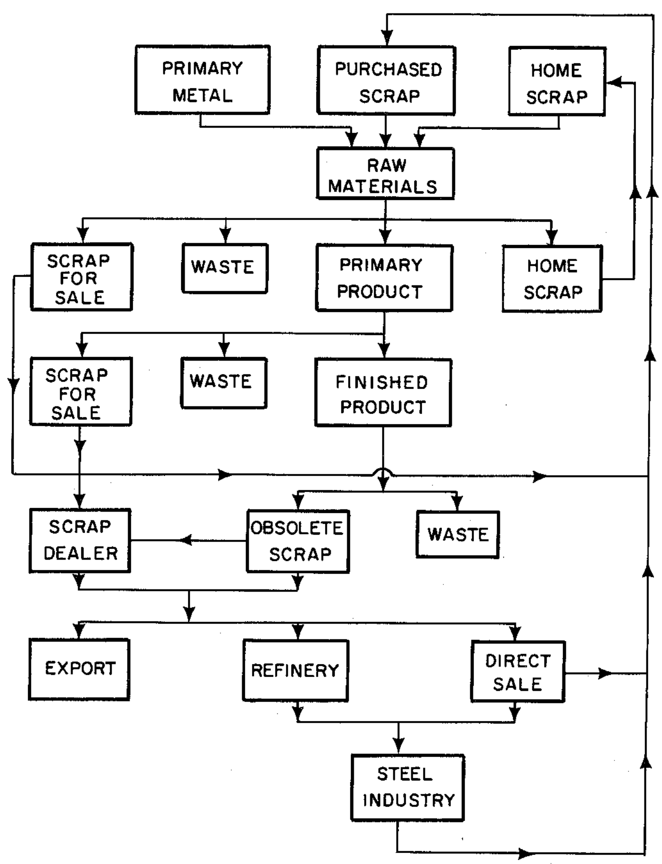

Figure 4.—Flow of scrap materials in the superalloy industry. Source: Reference (*3*).

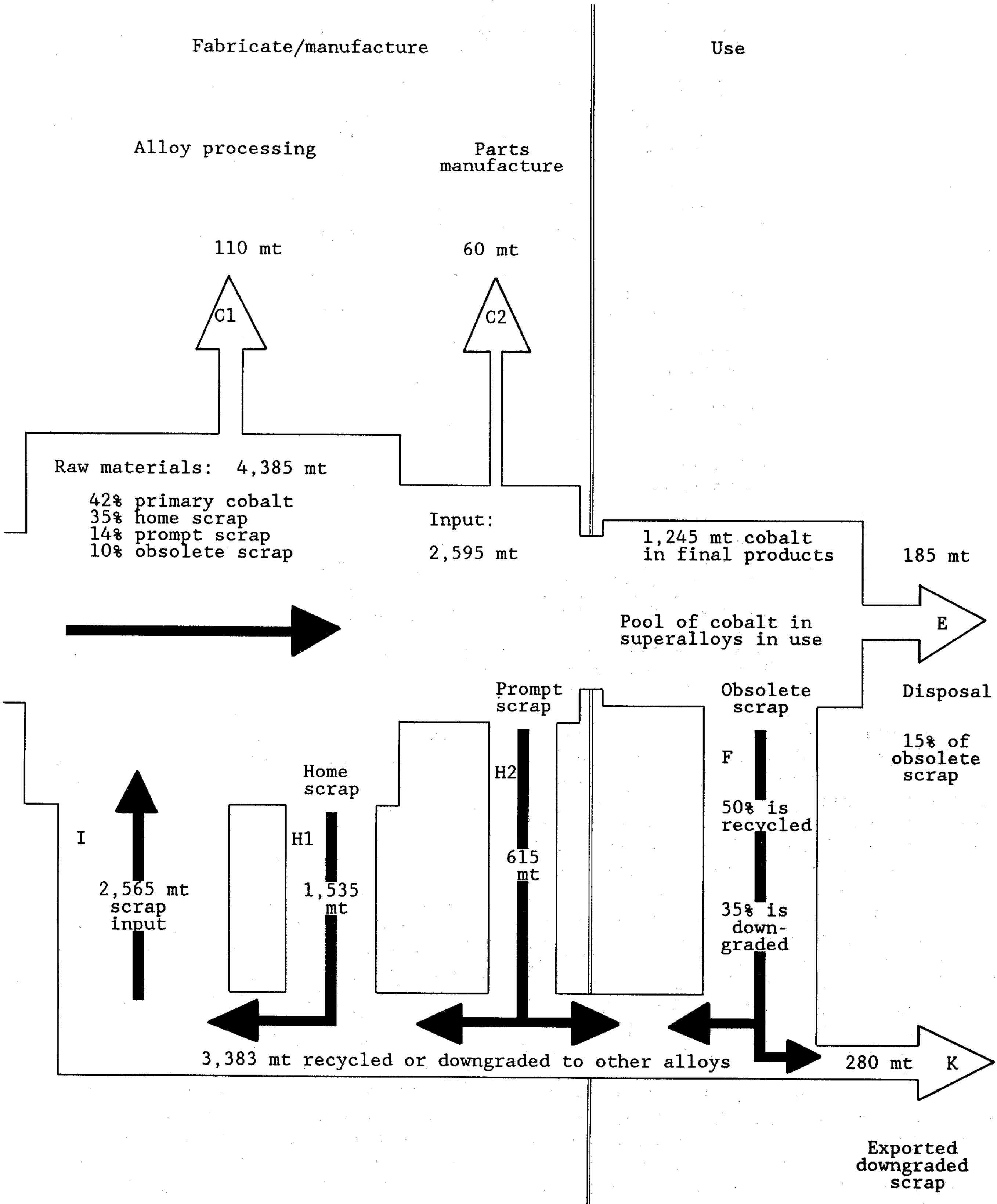

Figure 5.—Annual cobalt flow in the superalloy industry (wrought and cast superalloys).

Table 3.—Annual flow of cobalt materials in the superalloy industry[1]

	Percent[2]	Quantity, (metric tons)	
Superalloy processing:			
Raw materials input:			
Primary metal	42	1,820	} 2,850
Purchased scrap:			
Prompt	14	615	
Obsolete	10	415	
Home scrap	35	1,535	
Total	100	4,385	
Waste	[3]2-3	-110	
Downgraded scrap	[3]3	-145	
Home scrap generated	[3]35	-1,535	
Parts manufacture:			
Input materials		2,595	
Waste	[4]2-3	-60	
Prompt scrap generated	[3]14	-615	
Downgraded scrap	[4]26	-675	
Final products:			
Contained cobalt	[3]29	1,245	
Totals:			
Waste	[3]4	170	
Downgraded scrap	[3]19	820	
Exported downgraded scrap	[5]34	280	

[1]Data may not add to totals shown because of independent rounding.
[2]From reference (2) or (3).
[3]Percent of raw materials input to superalloy processing.
[4]Percent of input materials to parts of manufacture.
[5]Percent of downgraded scrap.

An estimated 2% to 3% of the total 4,385 mt of cobalt melted is lost as wastes during alloy processing, and 2% to 3% of the 2,595 mt of cobalt input to parts manufacture is lost as wastes, resulting in a total loss of 4% of the initial raw materials melted. Nineteen percent of initial raw materials is downgraded, representing a loss of usable cobalt, but not an environmental loss. Thirty-four percent of the downgraded scrap was thought to have been exported. In terms of obsolete scrap, in the early 1980's, only one-half of the obsolete scrap generated in a given year was thought to have been recycled to superalloys, 35% was downgraded to steels, and 15% was lost, presumably through disposal (*23*). If this disposal rate has not improved, as much as 185 mt of the cobalt used each year to produce superalloy parts would eventually be disposed of following use.

The estimates in table 3 and figure 5 do not take into account technological changes that may have occurred since the early 1980's. For instance, the relative amounts of primary cobalt in wrought and cast superalloys have changed, and the fraction of superalloys produced by powder metallurgy was not taken into account. In addition, the influence of the price of cobalt on scrap recycling was not taken into consideration. However, the average percent of scrap in the raw materials melt was not expected to increase without a major breakthrough in alloy melting or refining technology (*24*).

MAGNETS

Magnetic alloys are another important use for cobalt. Various permanent and soft magnetic alloys contain cobalt, but the largest use is in Alnico permanent magnets. In 1983, an estimated 90% of the cobalt consumed in magnetic alloys was used to make Alnico and iron-chromium-cobalt alloys (*25*). However, the iron-chromium-cobalt alloys represented only a very small portion of this cobalt use. The remaining 10% of the cobalt used in magnets went to the production of samarium-cobalt magnets.

Most Alnico magnets are formed by casting, although some are made by powder metallurgical techniques. Iron-chromium-cobalt alloys are either cast to size or cast to an ingot that is then rolled and/or drawn to its final shape or to a form that can be cut. Samarium-cobalt magnets are usually formed by powder metallurgical processes.

Most of the home scrap generated in the production of cast and wrought magnets is recycled. Minor losses might occur during reprocessing of grinding sludges, and some manufacturing scrap may be downgraded. Sludges produced from manufacturing samarium-cobalt magnets by powder metallurgical techniques are either lost or reprocessed to recover the samarium or both the samarium and cobalt.

In 1989, roughly 860 mt of cobalt was used in the United States to produce magnetic alloys. Estimates for cobalt lost through wastes and downgrading during alloy processing and magnet manufacture were made based on estimates for wrought and cast magnet production (*2*). Industry averages of 4% waste and 4% downgraded scrap during alloy processing and 3% waste from magnet manufacture were used to develop figure 6. These estimates do not take into account technological changes that have occurred since the early 1980's. For instance, in 1987 as much as 20% of all cobalt used in magnet manufacture would have been processed by powder metallurgical techniques, based on the relative amounts of cobalt consumed to make samarium-cobalt and Alnico magnets (*26*). Other areas for further study include changes in the relative proportions of cast and wrought magnet production, changes in the recycling rates of magnet scrap, and uses of other cobalt-containing scrap as feed for magnet manufacture.

In any case, losses from manufacturing are thought to be greatly outweighed by losses from disposal of magnet-containing products. It is estimated that only a small portion of cobalt-containing magnets are recycled after use. Two examples are magnets recovered prior to the disposal of leased equipment, such as telephones or computer disk drives, and large magnets identified and recovered by specialty scrap dealers. Most of these magnets would be remelted and reenter the cobalt flow at the alloy processing stage (I on figure 6). A small fraction might be reused without remelting (flow F to G on figure 6).

The 765 mt loss attributed to disposal on figure 6 assumes that all used magnets are disposed. Further research is necessary to refine this estimate. As mentioned above, some cobalt-containing magnets are recycled following use. In addition, other cobalt-containing magnets would be downgraded if not removed prior to the recycling of products such as automobiles. As with other cobalt uses, data on the cobalt content of imported and exported magnets are not available. Therefore, the amount of cobalt in magnets disposed of in the United States may be greater or less than 765 mt, depending on the net trade flow. Cobalt imported and exported in magnets, either alone or in products such as electrical equipment, could be significant, but would be very difficult to quantify.

CEMENTED CARBIDES

Cemented carbides are wear-resistant materials used for a wide range of industrial applications including metal-cutting, metal-working, mining, and oil and gas well drilling. An estimated 550 mt of cobalt metal powder is used each year to make cemented carbides. Powder processing on figure 7 represents the industries that make pure cobalt powder from metal or scrap. Losses during powder processing are discussed in the "Chemical and Powder Processing" section of this report.

In the fabricate/manufacture stage cobalt and tungsten carbide powders are blended together and sintered to produce cemented carbide parts. Reject parts and scrap are segregated and recycled. Losses are thought to be negligible at this stage (*27*).

Cemented carbides are designed for wear-resistance, so dissipative losses from attrition during use are expected to be low. An estimated 70% of cemented carbide is used to make cutting tool inserts. These inserts lose their cutting edge after less than 1% of their mass has been used (*28*). The remaining 30% of cemented carbides are used in mining and wear-resistant applications, which may suffer losses up to 30% during use. Based on this information, overall cobalt losses due to attrition are estimated to be no more than 50 mt/yr.

The greatest losses from cemented carbides are likely to be from the proportion of obsolete scrap that is not recycled. These losses were estimated from information on recycling in the cemented carbide industry. An estimated 30% to 40% of the cobalt consumed to produce cemented carbides originates from cemented carbide scrap (*29*), and most of this scrap is obsolete scrap from consumers (*30*). The ability to recycle used cemented carbides varies depending on the consuming industry. Estimates of recycling limits for cemented carbides from various industries, as identified in the early 1980's, are presented in table 4.

Table 4.—Estimated recycling limits for cemented carbide scrap (percent)

Application	Theoretical maximum	Probable practical limit	Practical limit in the early 1980's
Cutting tool inserts	95	60	40
Brazed tools	75	40	15
Oil drilling	90	85	80
Coal mining	65	50	15
Mining	85	85	65
Wear parts	90	85	80

Source: Reference (2).

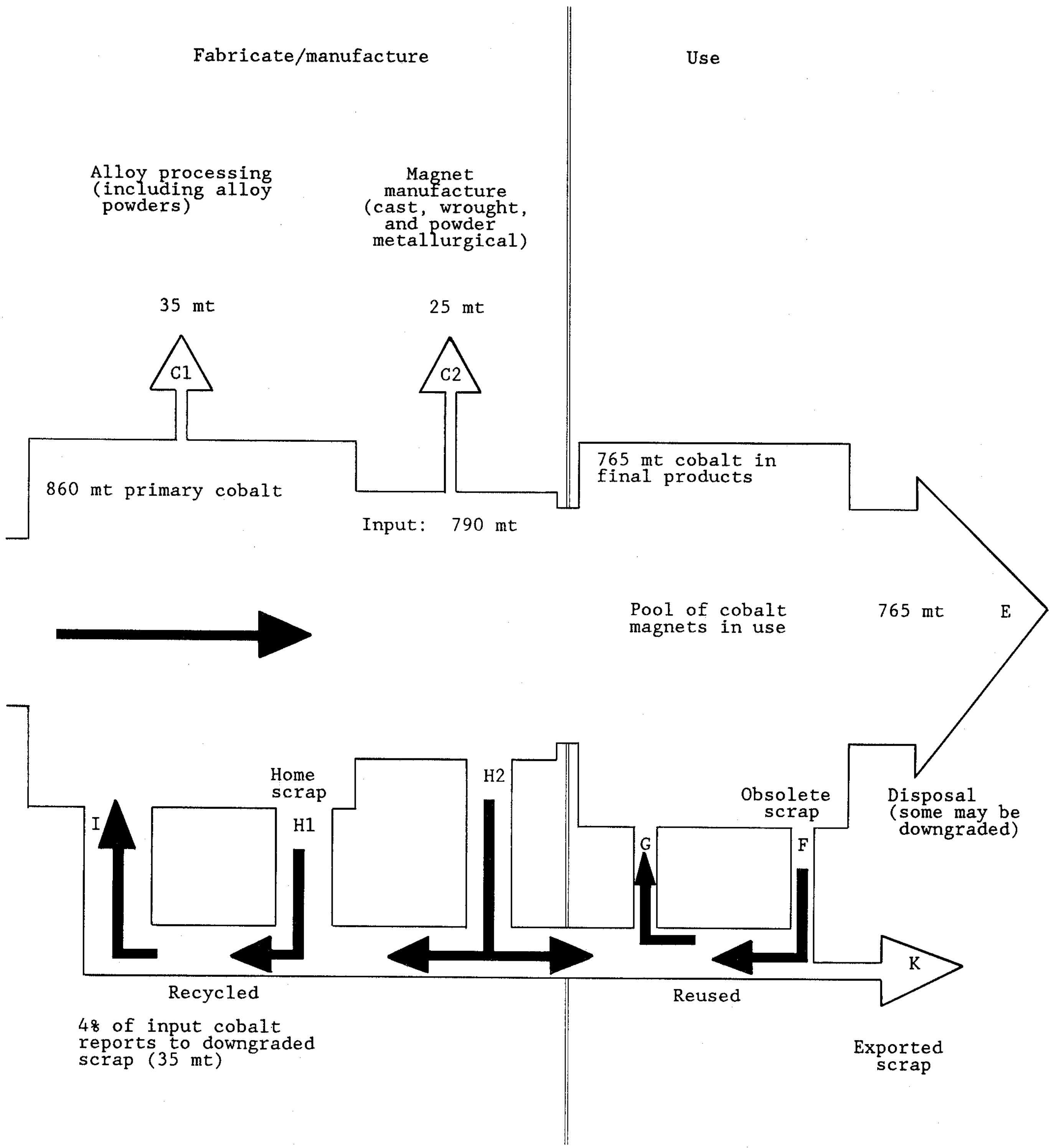

Figure 6.—Annual cobalt flow in the magnet industry.

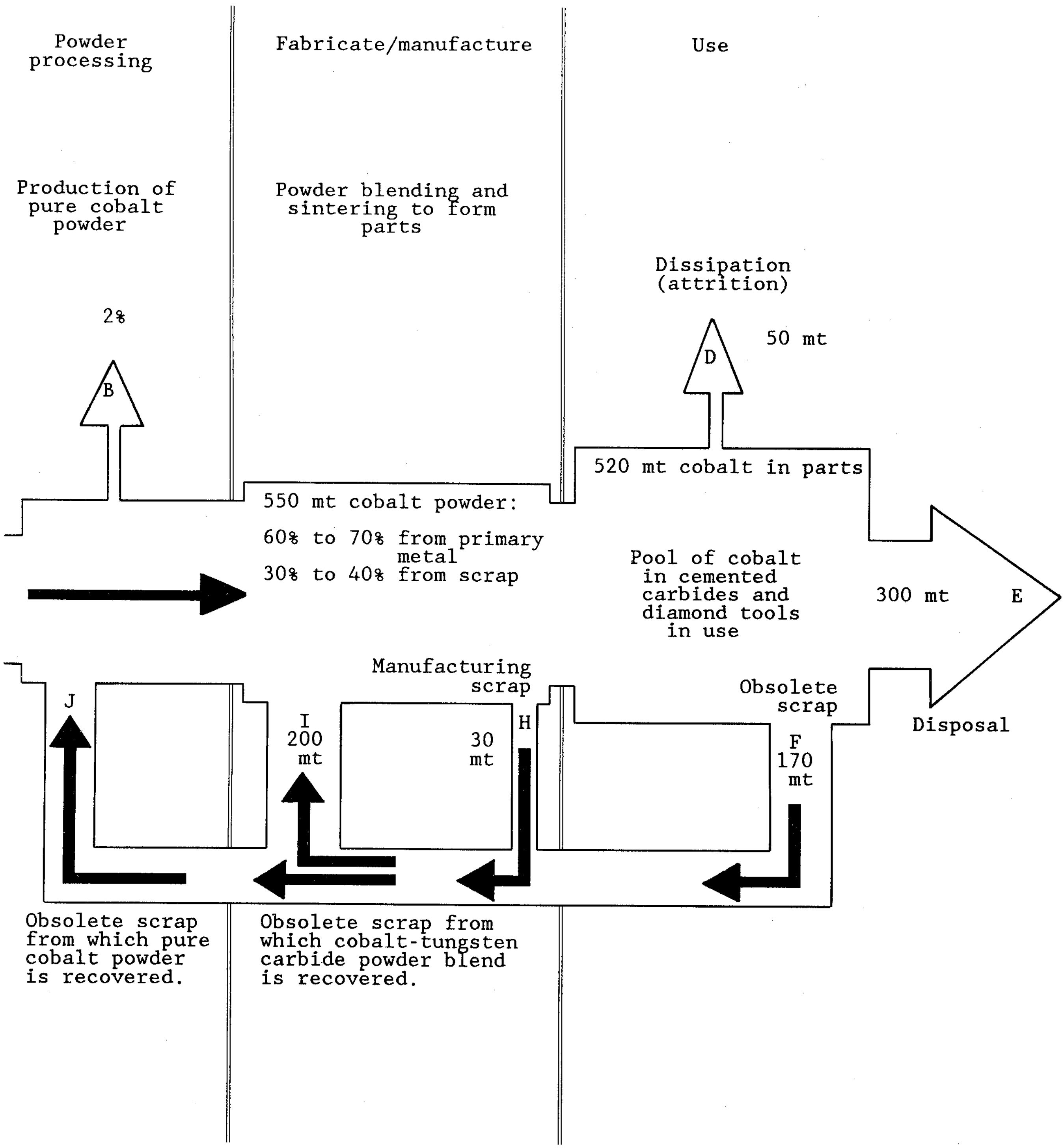

Figure 7.—Annual cobalt flow in the cemented carbide industry.

Recycling occurs at various stages in the cemented carbide industry. In addition to the recycling of obsolete scrap already discussed, almost all "manufacturing scrap" is recycled (*31*). Home scrap represents approximately 5% of the raw materials consumed to make cemented carbides (*32*).

Cemented carbide scrap can be broken down for recycling by various processes. Reclaimed powders from some processes can be reused directly to make new cemented carbide parts in the fabricate/manufacture stage (I on figure 7). The "zinc process," as modified by the Bureau of Mines, is one of the most important direct methods for recycling cemented carbides. U.S. annual capacity for recycling by the zinc process is 2,200 mt of cemented carbide (*33*) (roughly 220 mt of cobalt). In the late 1980's, U.S. annual secondary production using the zinc process was estimated at 600 mt of blended powder (*34*). This would have contained roughly 60 mt of cobalt.

A second recycling option is the use of chemical processes that break down cemented carbides to yield pure cobalt powder and tungsten carbide, tungsten, or ammonium paratungstate. A high percentage of cemented carbide scrap is recycled using chemical methods (*35*). This scrap would reenter the cobalt flow at J in the powder processing stage or I in the fabricate/manufacture stage (fig. 7). A third recycling option is to crush and grade used cemented carbides, then use the resulting material for grits, or braze it onto metals for use as an abrasive for grinding, or use it as hardfacing on construction and earthmoving machinery. Cemented carbide scrap, in the form of tungsten carbide tool inserts, has also been used by the superalloy industry as a source of tungsten (*36*). Some cemented carbide scrap could also be downgraded, when parts are not removed from scrap that is recycled to the steel industry.

As was done for other industries in this study, the net imports and exports of cemented carbides were assumed to be zero. Based on an average of 550 mt of cobalt consumed to produce cemented carbides, about 200 mt would have been from recycled cemented carbide scrap (170 mt from obsolete scrap plus 30 mt from manufacturing scrap). Of the 520 mt of cobalt in cemented carbide products, 50 mt could have been lost during use, 170 mt would be recycled, and the remaining 300 mt could have been lost by disposal. However, this estimate of discarded scrap is probably a maximum, because it does not take into account scrap consumed by superalloy melters for its tungsten values, scrap downgraded to steel, or scrap crushed to be used as abrasives or hardfacing.

MISCELLANEOUS METALLIC USES

Roughly 600 mt to 700 mt of cobalt are used each year in other metallic uses. Information on the tonnage consumed in each end use is not available. However, high-speed tool steels and hardfacing alloys use a large portion of this cobalt.

Approximately 200 mt of cobalt are consumed in tool steels. Sixteen percent of the primary cobalt melted is lost as waste from semifinished steel production and 2% of the input cobalt to tool manufacture is lost as waste during that stage (*37*). This would leave approximately 165 mt of cobalt in the final products. If 70% of the obsolete tool steel scrap is recycled or downgraded (*38*), the remaining 30% or 50 mt would be lost by disposal. Increases in production by powder metallurgical techniques and other technological changes since the early 1980's may have reduced the amount of waste generated. In addition, the amount of cobalt lost by disposal of obsolete products assumes no losses due to exports and no gains due to imports of these products.

As much as 200 mt of primary cobalt and cobalt in purchased scrap is used in the production of hardfacing alloy rods and powders (*39*). In addition to primary cobalt and purchased scrap, 8% of the raw materials originates from home scrap. During alloy processing, 6% of the raw materials melted is lost as waste, 8% becomes home scrap, and 8% is downgraded (*40*). During parts manufacture, an additional 3% of the initial raw materials is lost as waste and 29% becomes prompt scrap, leaving roughly 100 mt of cobalt in the final products. Once these products are shipped to users very little of the cobalt is returned to the cobalt flow (*41*). Some overspray and swarf generated during use might be recycled. Hardfacing on obsolete parts is not recycled for its cobalt values, although the cobalt might be downgraded if the parts are recycled to other alloys. Information on the dissipative loss of cobalt as wear during use was not available. Without further information on dissipation, disposal, and downgrading, the total estimated cobalt in final products was listed as a disposal on figure 8. As with other end uses, this estimate assumes no losses due to exports and no gains due to imports of these products.

CATALYSTS

Cobalt catalysts are used to improve the reaction rates of various processes in the chemical and petroleum industries. Approximately 700 mt, or 10%, of the cobalt consumed in the United States each year is for the manufacture of catalysts. Most of the cobalt used in catalysts is for three applications—the production of terephthalic acid (TPA) and dimethyl terephthalate (DMT), hydroformylation (the OXO process), and hydrotreating and desulfurization of petroleum. An estimated 60% is for the two chemical processes, 35% is for the petroleum catalysts, and the remaining 5% is for several other catalyst applications (*42*).

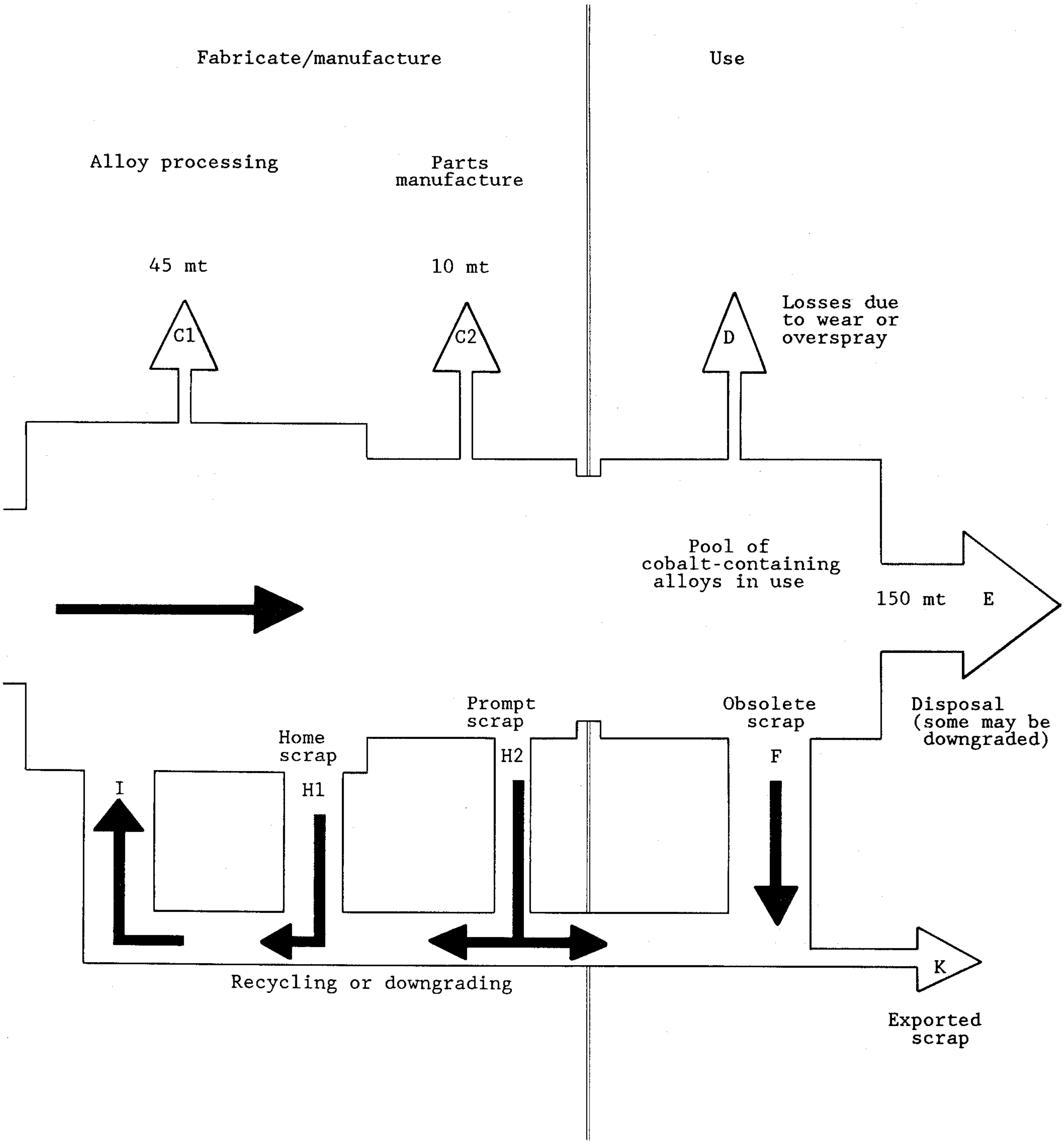

Figure 8.—Annual cobalt flow in miscellaneous metallic uses. (Losses from tool steels and hardfacing.)

In the two chemical processes, the cobalt catalyst is added as a soluble salt to the reaction mixture (homogeneous catalysis). Losses associated with the manufacture of homogeneous catalysts would be included in the "Chemical and Powder Processing" section of this report. In the production of TPA and DMT, cobalt acetate or cobalt bromide is used with manganese as a co-catalyst. TPA is an intermediate chemical used in the production of synthetic fibers and plastic films. The OXO process uses cobalt carbonyl as a catalyst in the hydroformylation of olefins to alcohols and aldehydes. The alcohols and aldehydes are then used to make plastics and detergents. For both these processes, the catalysts are separated from the product and then reused on-site. Cobalt residues are sent back to chemical processors for reprocessing to fresh catalyst material (J on figure 9). Roughly 90% of the cobalt is recovered, the remaining 10% is lost during recycle and reuse (*43*).

In the petroleum industry, hydrotreating and desulfurization processes use heterogeneous catalysts composed of cobalt and molybdenum sulfides on an alumina support. Losses associated with the manufacture of heterogeneous catalysts were estimated at roughly 3% of the cobalt consumed (*44*), or 5 mt to 10 mt of cobalt. When they become less effective, the catalysts can be regenerated for reuse, but after a number of regenerations, the catalysts are considered spent, and must be replaced. The United States currently has the capacity to process all the spent petroleum catalysts generated each year. Two U.S. metal-reclaiming facilities currently recover molybdenum, vanadium, alumina, and a mixed nickel-cobalt residue from spent petroleum catalysts. An estimated 250 mt to 450 mt of cobalt in nickel-cobalt residue is reclaimed annually from spent petroleum catalysts (*45*). Roughly one-half of the residue is exported and then refined to pure nickel and cobalt. This cobalt then reenters the world cobalt supply as primary metal. The other one-half of the residue is either stockpiled in the United States with the intention of refining the cobalt at a later date when it is economically feasible or downgraded into other products.

MISCELLANEOUS CHEMICAL USES

Driers, Pigments, Ground Coat Frit, and Others

Currently approximately 800 mt of cobalt are consumed in the United States each year to manufacture organic compounds for the drying of paints, inks, and varnishes. An additional 320 mt of cobalt is used to make inorganic pigments for paints, plastics, glass, and ceramics. There are also many other uses for cobalt chemicals. For instance, cobalt is used in ground coat frits to bond porcelain enamel to steel in cookware, appliances, and bath tubs; it acts as a decolorizer in glass, glazes, enamels, and porcelain; it improves the magnetic properties of audio and video tapes; it bonds rubber to brass-coated steel belts in radial tires; it is used in electroplating; and it is used as a moisture indicator in desiccants. These miscellaneous uses account for an additional 370 mt of cobalt used each year.

In these applications, cobalt is usually an important but very minor constituent of the final product. Dilution of cobalt makes its recovery basically impossible. Therefore, all the cobalt used in these applications is ultimately lost. This 100% loss following use greatly outweighs any losses that occur during manufacturing. Annual losses depend on the length of time the products remain in service before disposal. The fact that some of these products remain in service for decades or longer makes it very difficult to estimate disposal on an annual basis. However, since all the products will eventually be discarded, one could ignore time in service, and consider that in a given year all the cobalt used will eventually be lost.

As with other industry sectors, information on the cobalt content of imports and exports of cobalt-containing products was not available. If all the domestically produced driers, pigments, frits, etc., were used in products that stayed in the United States, and no additional products containing cobalt driers, pigments, frits, etc., were imported, then 1,490 mt of cobalt would eventually be lost in the United States. Based on a 3% loss during chemical processing (see "Chemical and Powder Processing" section), and a 5% loss during product manufacture (*46*), the remaining 1,380 mt would be lost to disposal (fig. 10). Further research would be required to determine the trade flows of cobalt in these chemical applications and to refine these estimates.

Agriculture and Feed Additives

Cobalt, as present in vitamin B_{12}, is important to the health of animals, including humans. Ruminant animals (cattle, sheep, and goats) require a certain level of cobalt in their feed to prevent anemia and death. The cobalt is converted to vitamin B_{12} by microorganisms in the animals' digestive systems. In areas with cobalt-deficient soils, cobalt must be added to the animals' diets. This can be done by adding cobalt to the soil as a fertilizer, by adding cobalt to the feedstock, or by introducing cobalt or vitamin B_{12} directly into grazing animals through various means (*47*).

Agricultural uses of materials can be considered dissipative uses—the materials are dispersed during use and are not recoverable. Similar to cobalt use in other non-catalyst chemical applications, this 100% loss as a result of use greatly outweighs any losses that might occur during production of the cobalt chemicals or feeds. U.S. cobalt consumption to produce feed additives is quite small, but is listed separately in this report to provide an example of a fully dissipative use for cobalt. Roughly 30 mt of cobalt are consumed each year by U.S. chemical processors for feed additives. Information on exports and imports of cobalt for agricultural use is not available. If all 30 mt were used in the United States, and no imported cobalt was used, then 30 mt of cobalt would be dissipated each year (fig. 11).

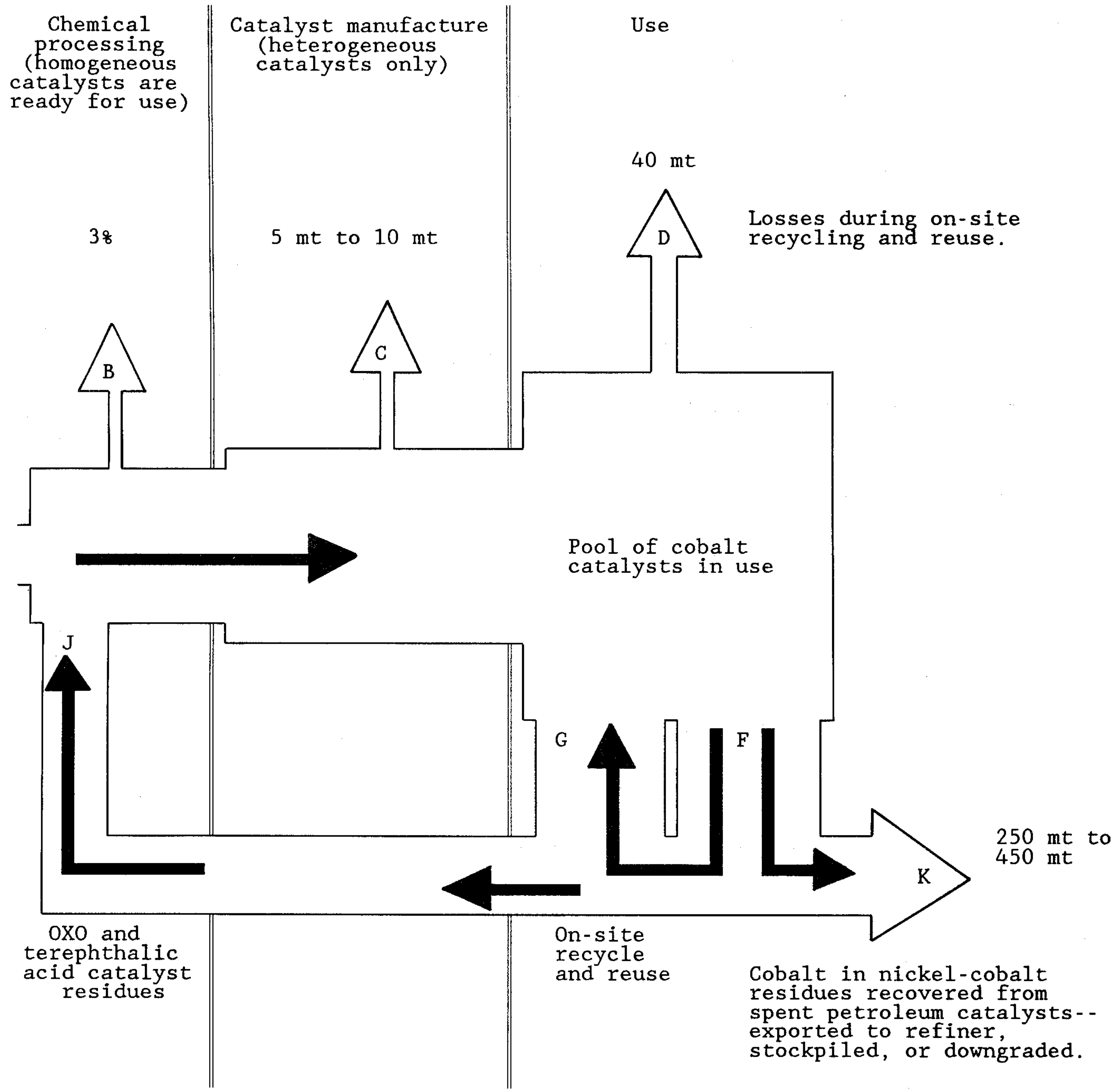

Figure 9.—Annual cobalt flow in the catalyst industry.

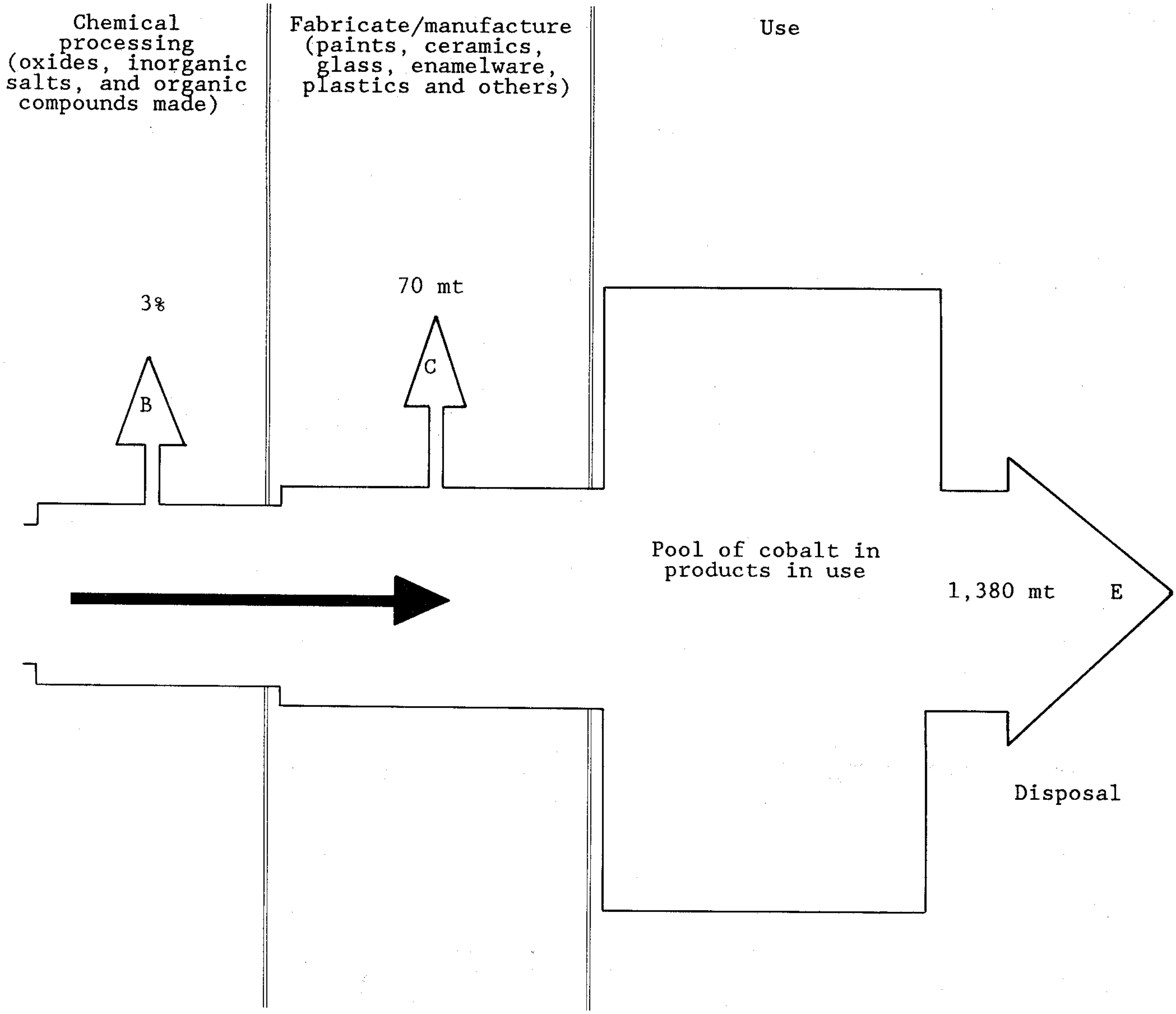

Figure 10.—Annual cobalt flow in miscellaneous chemical applications.

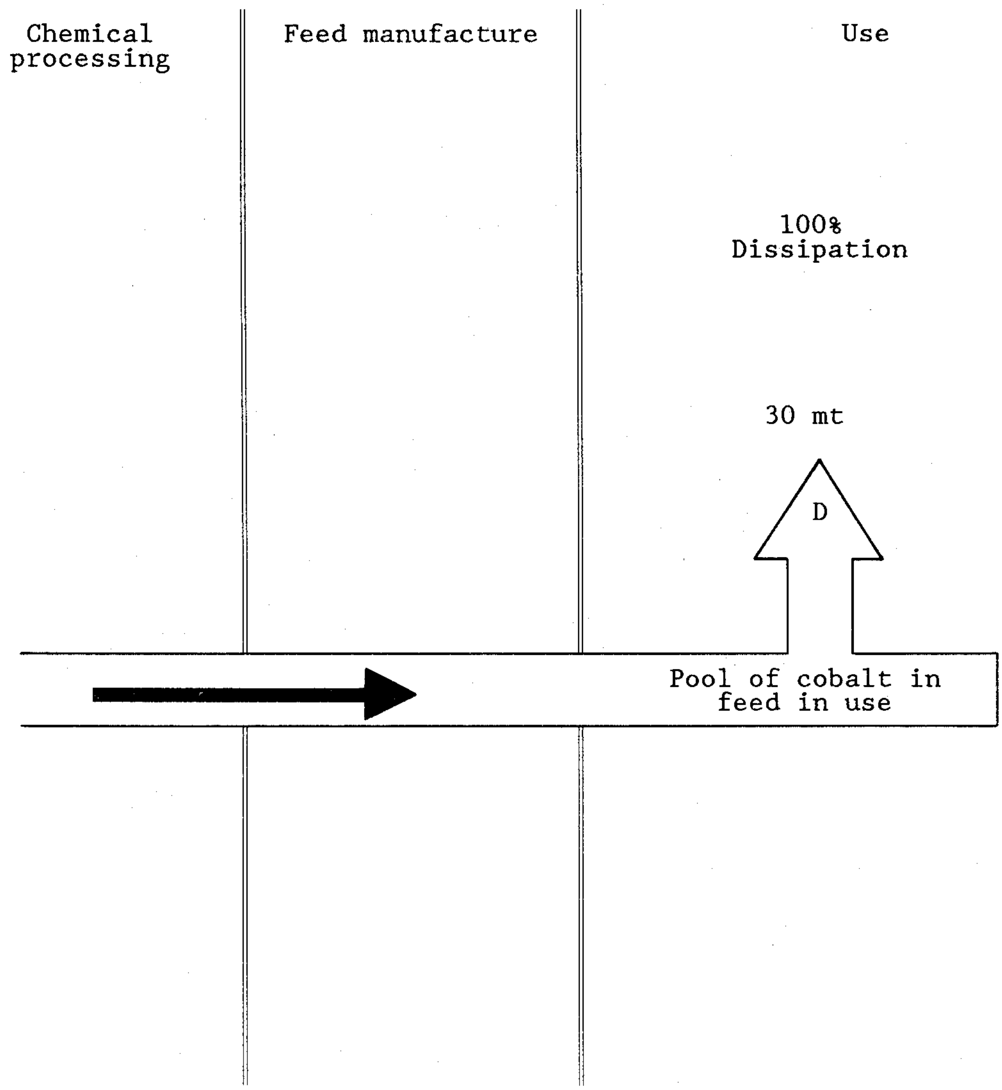

Figure 11.—Annual cobalt losses from use in agriculture and feed additives.

HISTORICAL LOSSES

Cobalt losses during consumption and use will change over time with variations in total consumption, with changes in how cobalt is used, and with changes in the price of cobalt and associated metals. Trends in total U.S. cobalt consumption over the past three decades are depicted in figure 12. Total consumption during this time period roughly paralleled economic conditions and general industrial activity. Because of its many varied applications, total cobalt consumption is the net result of the performance of many individual industries—production of military and civilian aircraft (superalloys); production of instrumentation and electrical equipment (magnetic alloys); mining, oil and gas drilling (cemented carbides); petroleum refining (catalysts); chemical processing (catalysts); etc.

Superimposed upon general economic conditions and the performance of specific industries are the effects of changing materials usage. These changes can result from various factors. For example, in the late 1970's, a sudden increase in the price of cobalt and concerns about supply vulnerability resulted in increased efforts toward cobalt conservation and substitution. A rapid decline in the use of Alnico magnets occurred at this time as a result of substitution by ferrite and samarium-cobalt magnets. Substitution in some chemical applications also occurred. Researchers examined the effects of reducing the cobalt content of various superalloys, and cobalt-base superalloys were replaced by cobalt-containing nickel-base alloys where possible (*48*).

A comparison of cobalt consumption by major industry sector at two points in time is shown in figure 13. The years 1960 and 1989 were chosen to show general trends in cobalt use. However, for each industry sector represented, considerable variation occurred in both tonnage consumed and percent of total consumption during the 30-year period. A thorough discussion of trends in cobalt consumption is beyond the scope of this paper. Generally speaking, as compared with 1960, the United States currently consumes more cobalt to produce superalloys, cutting and wear-resistant materials, and chemical and ceramic materials, and less cobalt to produce magnets and other alloys. This is true both in terms of tonnage and percent of total use.

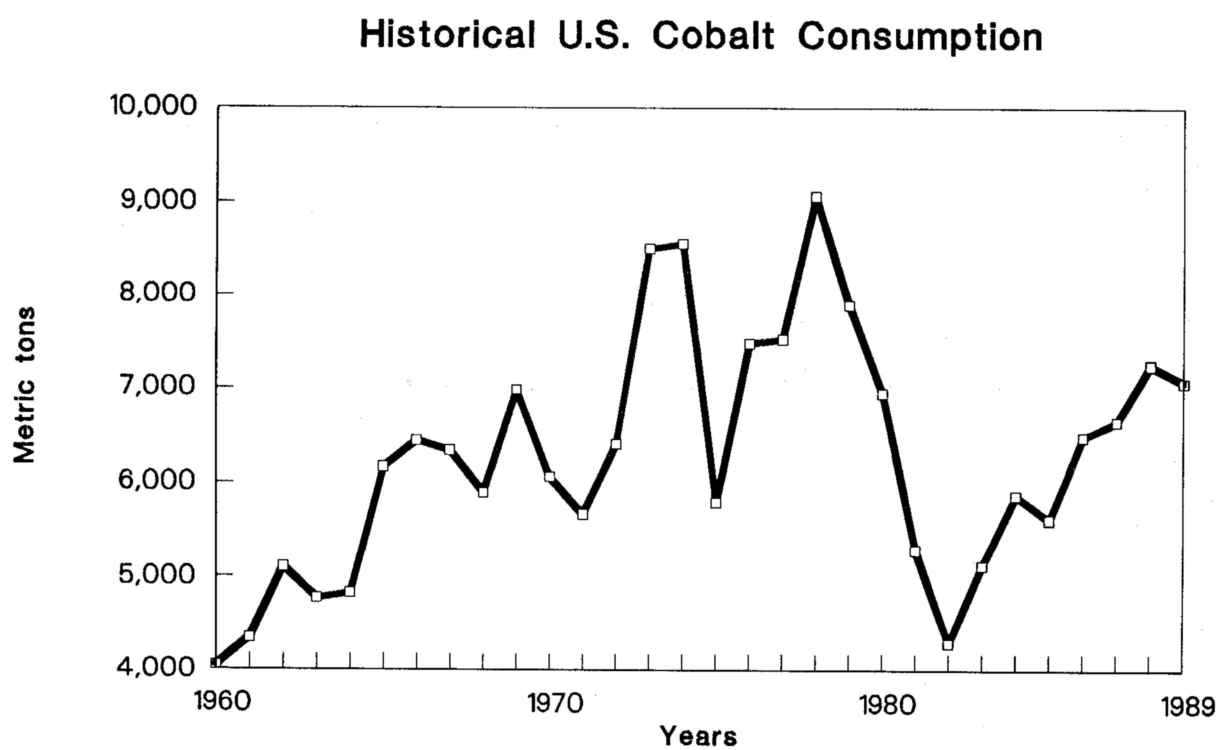

Figure 12.—U.S. reported cobalt consumption, 1960-89. Source: U.S. Bureau of Mines, Minerals Yearbooks.

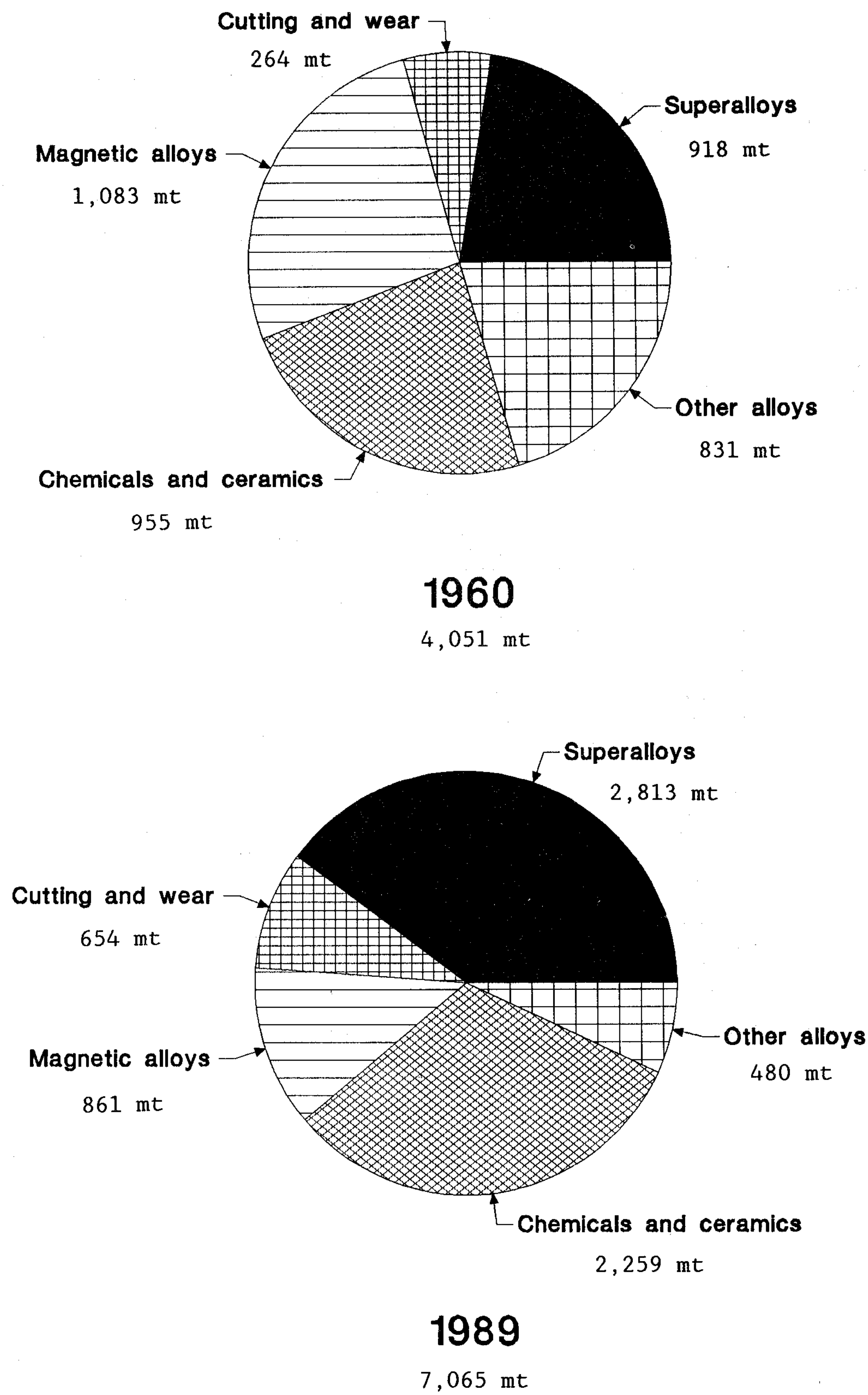

Figure 13.—Trends in cobalt use. Source: U.S. Bureau of Mines, Minerals Yearbooks.

DISTRIBUTION OF LOSSES

Information on cobalt losses is available from the U.S. Environmental Protection Agency's (EPA) Toxics Release Inventory (TRI) (*49*). TRI data are collected by the EPA as required by law under the 1986 Emergency Planning and Community Right-to-Know Act. Under the law, industries manufacturing, processing, or using certain chemicals above defined threshold limits must report estimates of emissions each year. Both "cobalt" and "cobalt compounds" (defined as "any unique chemical substance that contains cobalt as part of that chemical's infrastructure") are included in the TRI.

TRI data are divided into two types—releases to the environment (to air, water, or land) and transfers to off-site locations (municipal wastewater treatment plants or other treatment and disposal facilities). Results of the TRI for the years 1987 through 1989 are provided in tables 5 through 7. The total releases and transfers reported to EPA during this time period (table 7) are roughly equal to the combined "losses" estimated for the chemical and powder processing and fabricate/manufacture stages in the present study (fig. 2). Some mining and/or mineral processing operations are probably included in the TRI data. As a future study, an industry-by-industry comparison of TRI data with the estimates in the current study would show areas of overlap and disagreement, and might provide further insight to the quantities, character, and distribution of cobalt materials leaving the cobalt flow.

Table 5.—EPA Toxic Release Inventory data, cobalt

(metric tons, contained cobalt)

	1987	1988	1989
Releases:			
Fugitive or non-point air emissions	9	7	13
Stack or point air emissions	5	8	8
Discharge to water	6	7	6
Underground injection	0	0	0
Releases to land	9	97	108
Total	29	119	135
Transfers:			
Discharge to publicly owned treatment works[1]	4	4	5
Other off-site locations[2]	114	93	115
Total[3]	119	97	120
Grand total[3]	148	216	256

[1]Municipal wastewater treatment plants.
[2]Treatment and disposal facilities.
[3]Data may not add to totals shown because of independent rounding.

Source: U.S. Environmental Protection Agency, reference (*49*).

Table 6.—EPA Toxic Release Inventory data, cobalt compounds

(metric tons, contained cobalt)

	1987	1988	1989
Releases:			
Fugitive or non-point air emissions	6	5	6
Stack or point air emissions	16	19	28
Discharge to water	19	29	32
Underground injection	([1])	8	7
Releases to land	45	17	42
Total	86	78	115
Transfers:			
Discharge to publicly owned treatment works[2]	12	13	11
Other off-site locations[3]	193	150	198
Total	205	163	209
Grand total	291	241	324

[1]Less than 1/2 unit.
[2]Municipal wastewater treatment plants.
[3]Treatment and disposal facilities.

Source: U.S. Environmental Protection Agency, reference (*49*).

Table 7.—EPA Toxic Release Inventory data, cobalt and cobalt compounds

(metric tons, contained cobalt)

	1987	1988	1989
Releases:			
Fugitive or non-point air emissions	15	12	19
Stack or point air emissions	21	27	36
Discharge to water	25	36	38
Underground injection	([1])	8	7
Releases to land	54	114	150
Total[2]	116	197	250
Transfers:			
Discharge to publicly owned treatment works[3]	17	17	16
Other off-site locations[4]	307	243	314
Total	324	260	330
Grand total	440	457	580

[1]Less than 1/2 unit.
[2]Data may not add to totals shown because of independent rounding.
[3]Municipal wastewater treatment plants.
[4]Treatment and disposal facilities.

Source: U.S. Environmental Protection Agency, reference (*49*).

CONCLUSIONS

This study provides an initial evaluation of the flow of cobalt in the United States. The flows of cobalt-containing materials during selected mining and mineral processing operations, burning of fossil fuels, chemical and powder processing, alloy processing, and the manufacture and use of various products were identified. Where possible, estimates were made to quantify recycling rates and losses. Also identified were areas where further research is necessary to verify or improve the estimates.

Estimates of global sources of cobalt to the environment were cited from Donaldson. In terms of losses attributed to humans, on a global scale Donaldson estimated that equal quantities of cobalt are released from fossil fuel burning and from cobalt use as a metal or chemical. If we assume that losses from "cobalt use as a metal or chemical" refers to losses from the processing and manufacture of cobalt chemicals, powders, alloys, and products, and dissipation during use, but does not include losses resulting from the disposal of used products, then estimates for the United States in the present study show a similar distribution. Releases of 480 mt of cobalt were attributed to U.S. coal burning and 530 mt to 560 mt were attributed to U.S. cobalt use (50 mt to 80 mt from chemical and powder processing, 360 mt from fabricate/manufacture, and 120 mt from dissipation).

Donaldson does not attribute any significant cobalt releases to cobalt mining and refining. Preliminary estimates in the present study indicate that significant quantities of cobalt are released both during cobalt production and during the production of other metals and minerals. For example, even though the United States is not a cobalt producer, an estimated 1,700 mt of cobalt are released each year from mining and processing lead ores in Missouri and processing copper ores by heap leaching in the Western United States alone. This discrepancy between the two studies is most likely the result of a difference in definitions.

Industrial losses from cobalt chemical and powder processing, alloy processing, and parts and product manufacturing are estimated at 410 mt/yr to 440 mt/yr (50 mt to 80 mt from chemical and powder processing plus 360 mt from fabricate/manufacture). This estimate is roughly equal to releases and transfers of cobalt reported by U.S. industries to the EPA for 1987 (440 mt), 1988 (457 mt), and 1989 (580 mt).

These industrial losses are greatly outweighed by the loss of cobalt in products discarded following use. An estimated 2,780 mt of cobalt is consumed in the United States each year to make products that will ultimately be disposed. Recycling or cobalt recovery might be possible from some products currently discarded, if collection, recycling technology, and economics were amenable. Recycling of used cobalt-containing magnets are one example. In other products, such as many cobalt chemical applications, the cobalt is too diluted to make recovery feasible.

The superalloy, magnet alloy, cemented carbide, tool steel, and hardfacing industries have well-established recycling or cobalt recovery practices. These industries recycle home scrap, prompt scrap, and in some cases, obsolete scrap as well. Some metallic scrap is downgraded, but although this is a loss of usable cobalt, it is not an environmental loss. The petroleum industry has well-established recycling and metal-recovery practices for spent catalysts, and some chemical catalysts are also recycled.

Most cobalt uses are not dissipative in character. Cobalt lost from the dissipation of agricultural products, through the attrition of cemented carbides, and during the recycle and reuse of homogeneous catalysts is estimated to total 120 mt annually.

In terms of further research, a more thorough study of individual industries could be done to evaluate some of the assumptions in the present study (such as net trade flows, recycling rates, and waste generation), confirm or revise the loss estimates, and determine the effects of any technological changes since the cited references were published. As part of this study, an industry-by-industry comparison of TRI data with the estimates from the present study might provide further insight to the quantities, character, and distribution of cobalt losses.

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GLOSSARY

Cast alloys.—Alloys made from a melt that is cast into a shape.

Dissipation.—For the purpose of this study, dissipation refers to losses occurring during use or as a result of use. Attrition of cemented carbides during machining operations, mining and drilling, and the dispersal of cobalt agricultural supplements from the soil to plants to animals are examples of dissipation.

Downgrading.—The remelting of cobalt-containing alloys to make an alloy with a much lower cobalt content, such as steel. The cobalt is diluted to the level of a residual or background element in the new alloy, and does not contribute to the properties of the new alloy. Therefore, the cobalt is considered lost in terms of usable cobalt. However, it is not lost to the environment. This cobalt is still in the "use pool" and is not considered a loss for the purpose of this study.

Heterogeneous catalysts.—Catalysts that are a different phase from the reaction mixture, such as solid catalysts in a liquid reaction mixture.

Homogeneous catalysts.—Catalysts that are the same phase as the reaction mixture, such as soluble salts in a liquid reaction mixture.

Loss.—For the purpose of this study, "loss" is defined rather loosely to include various materials that leave the U.S. cobalt flow during mining and mineral processing, chemical and powder processing, manufacturing, and use. Efforts were made to distinguish between two types of losses. The first type includes losses from the U.S. cobalt flow that remain in the United States, such as industrial emissions and losses from dissipation during use or disposal following use. The second type of loss from the U.S. cobalt flow includes exports of cobalt to other countries and the transfer of cobalt to another U.S. materials flow (downgrading). Materials that temporarily leave the flow, such as stockpiled materials or scrap that leaves the cobalt flow before being recycled, are not considered losses.

Recovery.—For the purpose of this study, recovery is used to represent recycling processes that separate cobalt from other metals. The cobalt is then reused as is or is further refined. Examples of scrap materials from which cobalt is recovered include spent petroleum catalysts and some cemented carbide scrap.

Recycling.—For the purpose of this study, recycling is the reintroduction of scrap or other discarded materials to the materials flow. In the case of alloys, recycling usually involves remelting alloy scrap to make the same or another alloy. Alloy scrap can originate from various points in the cobalt cycle. Home scrap (also called revert or run-around scrap) is the scrap generated in the production of new metals, such as superalloys. This scrap is reused in the same plant in which it is generated. Prompt scrap (also called industrial, manufacturing, or new scrap) is scrap generated by metal-working industries, such as in parts manufacturing. Obsolete scrap (also called old scrap) is from products that have been in use, such as jet engine blades or cemented carbide tool inserts. Another scrap category is purchased scrap. This can be either prompt or obsolete scrap that has been bought from a scrap processor or dealer.

Wrought alloys.—Alloys suitable for forming by mechanical means at temperatures below their melting point. Ingots of wrought alloys are hot-worked into bars, sheets, or other forms. These forms are then forged into final parts.

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