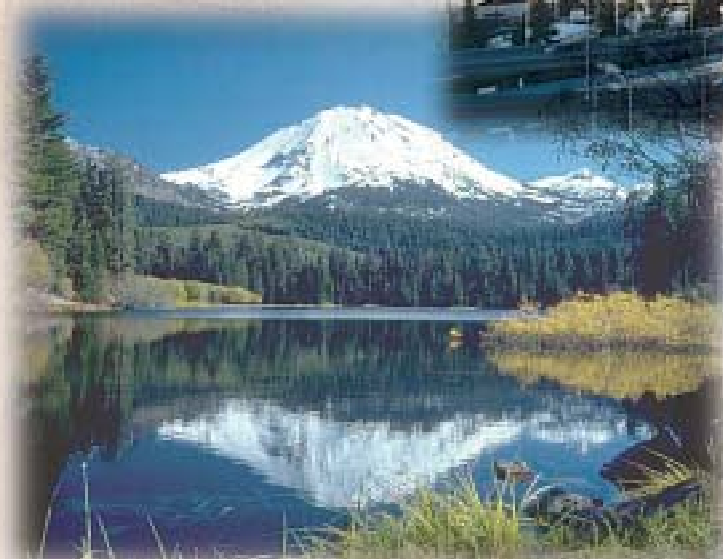
Materials in the Economy
Material Flows, Scarcity, and the Environment

U.S. Geological Survey Circular 1221



U.S. Department of the Interior
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By Lorie A. Wagner

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

First printing February 2002

Free on application to U.S. Geological Survey,
Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

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Conversion Factors

Conversion factors for SI (metric) and inch/pound (U.S. customary) units of measurement.

Multiply	By	To obtain
mile	1.609	kilometer
gallon	3.785	cubic decimeter
pound avoirdupois	0.4536	kilogram
ton, short (2,000 pounds)	0.9072	metric ton

Materials in the Economy—Material Flows, Scarcity, and the Environment

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Introduction

Increased use of goods and services, coupled with population growth, has increased the impact humans have on the environment. In the past, studies concentrated on the major environmental effects, including polluted rivers, smog, and acid rain. In the last decade, the focus has expanded to include the less obvious impacts that humans are having on the environment, such as depletion of the ozone layer, accumulation of greenhouse gases, loss of biodiversity, and bioaccumulation of toxic substances.

This report examines the environmental effects of population growth and increased use of materials, the role that materials play in the economy, and concerns over the scarcity of materials.

In the United States, the gross domestic product (GDP) exhibited nearly a five-fold increase to $9.9 trillion in 2000 from $2.0 trillion in 1950 (2000 dollars) (U.S. Bureau of Labor Statistics, 2000; International Monetary Fund, 1980, 2001). Meanwhile, U.S. population increased from 152 million in 1950 to 281 million in 2000 (International Monetary Fund, 1980, 2001). As shown in figure 1, by 2000, world population was more than 6 billion (U.S. Census Bureau, 2001).

Globally, nearly half of all people now live in cities, and an increasing number of them travel enormous distances every year by private car and in aircraft (United Nations Environment Programme, 1999). In many parts of the world, technology has transformed patterns of communications, diet, family life, health, leisure activities, and work. More materials need to be extracted or harvested, processed, manufactured, transported, and recycled or disposed to meet the changing lifestyle and growing world population. The increased use of materials transforms the landscape as more factories, warehouses, distribution terminals, and retail outlets are built to supply the increased demand for goods and services.

Given the present trends in the use of materials and the growing world population, will the resources necessary to produce the desired goods continue to be available? Will the environment be able to absorb the resulting impacts?

An understanding of the entire system of flows necessary to support our material needs, from extraction through use and end-of-life, such as is shown in figure 2, is needed. Looking at the flow of materials from the perspective of a whole system, whether for a particular material or a collection of materials, enables the sum of potential consequences to be envisioned, priorities to be set, and methods to combat negative impacts of material flows to be developed. Analyzing the entire materials-flow cycle helps to ensure that decreased use of one material does not increase the use of a less environmentally friendly material. The information derived from materials-flow analyses also aids decision-makers in making informed decisions about the impacts materials use has on the economy, the environment, and society.

Understanding materials use and its impacts is increasingly important because the global environment is being

Vast amounts of goods are available for consumers to purchase (source: Brøderbund Software, Inc., 1997).

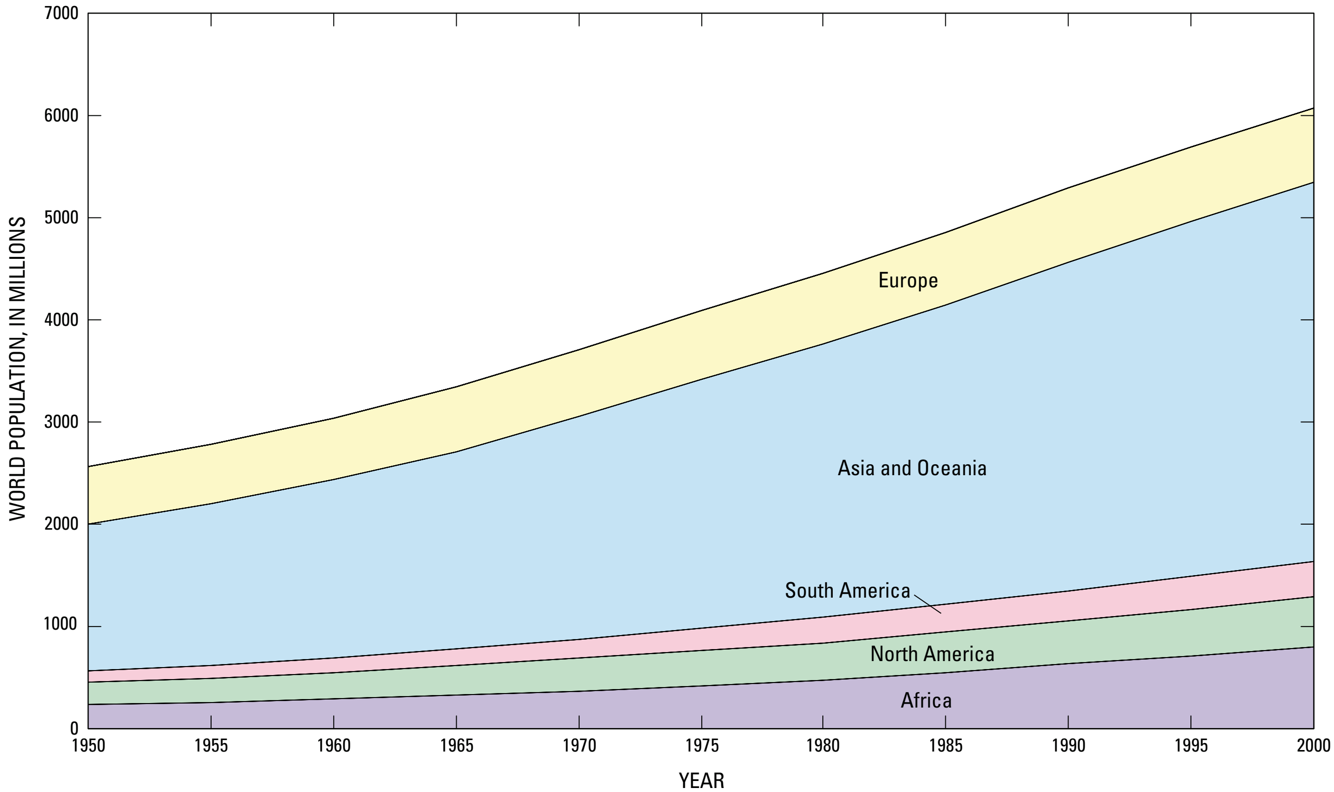


Figure 1. By 2000, world population was more than 6 billion (U.S. Census Bureau, 2001).

altered due to the use of materials on an unprecedented scale. The increased demand for materials, which may not be able to be met by current technology, is driven by population growth and the demands for a rich material life all over the world.

Growing populations and urban sprawl affect the environment (source: Brøderbund Software, Inc., 1997).

Technological improvements, and increased understanding of environmental impacts over the past half-century, have led to the development of products that both use materials more efficiently and pollute less. For example, automobiles today are more fuel efficient and produce fewer tail-pipe emissions than in the past. In addition, better public understanding of the environmental consequences of the “consumer society” has begun to bring about shifts in purchasing behavior and lifestyle choices. The challenge in the next century will be to continue efforts toward increased efficiency and wise use of natural resources.

Materials in the Economy

Food, fuel, and materials are three broad categories of commodities used in the economy to support the needs of society. This study examines materials—such as plastic, metal, and paper—and industrial mineral commodities—such as cement and sand and gravel—while providing a broad overview of all materials, emphasizing mineral-based materials.

Mineral-based materials play a vital role in the economy of the United States and the world. The value of all mineral-based products manufactured in the United States during 2000 was estimated to be $429 billion. Imports of raw and processed

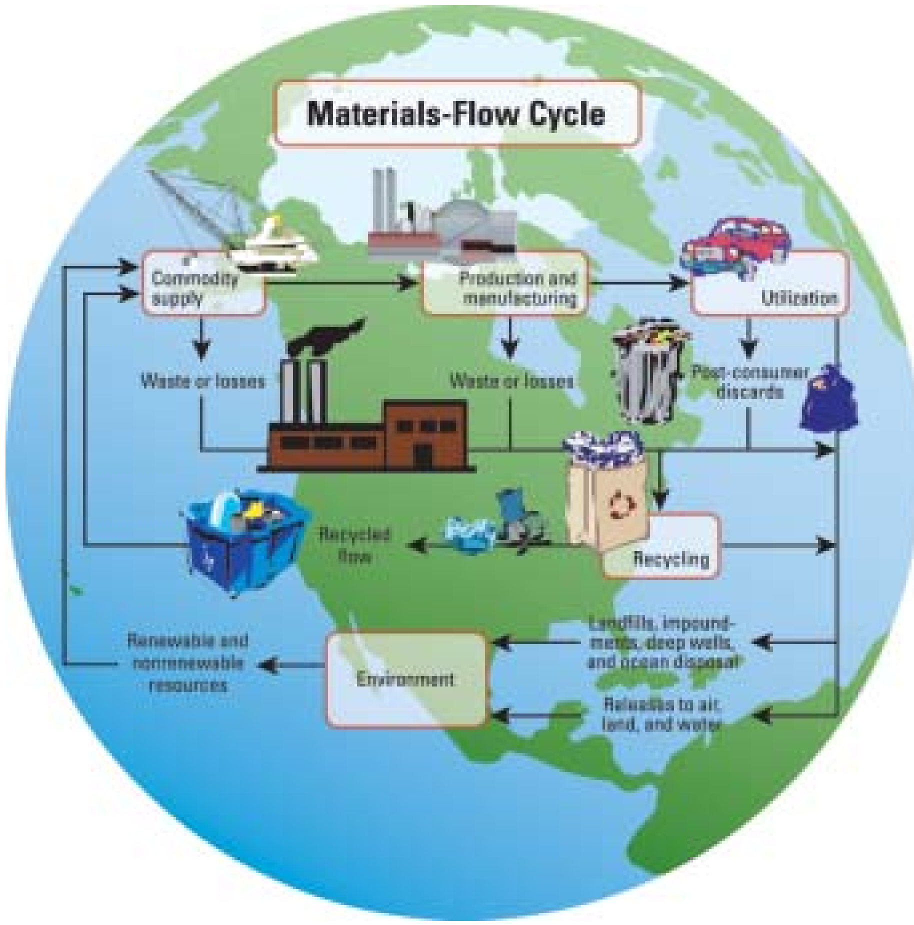


Figure 2. The materials-flow cycle aids in the analysis of the flow of materials through the environment and economy. The cycle is used to trace the flow of materials from extraction through production, manufacturing, and utilization to recycling or disposal. Throughout these processes, the potential for losses exist either through the discard of wastes or dissipation of materials to the environment. From this type of analysis, particular processes can be identified for more efficient materials use.

mineral materials rose to an estimated $71 billion in 2000. Exports of raw and processed mineral materials during the year reached an estimated value of $43 billion (U.S. Geological Survey, 2001a, p. 6).

Since the beginning of the 20th century, the types of materials used in the United States have changed significantly. In 1900, on a per-weight basis, 41 percent of the new[1] materials used domestically were renewable, as shown in figure 3 (Matos and Wagner, 1998, fig. 2).

By the end of the 20th century, only 5 percent of the 3,400 million tons[2] of new materials entering the U.S. economy in 2000 were renewable. Of all the materials used during

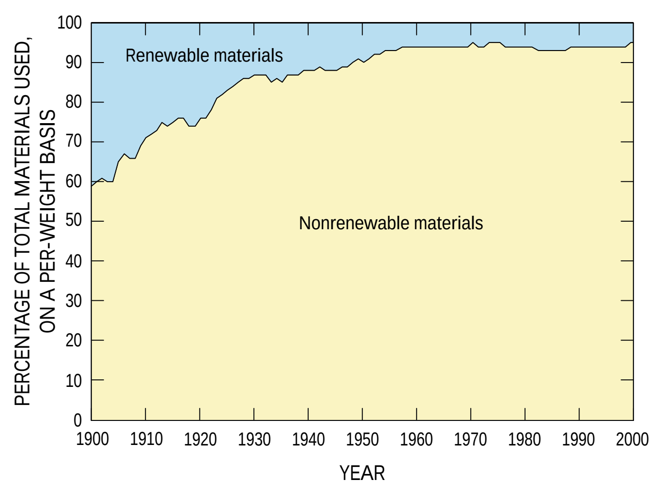


Figure 3. Renewable and nonrenewable materials used in the United States. Use of nonrenewable resources has increased dramatically in the United States during the 20th century (modified from Matos and Wagner, 1998, fig. 2).

[1]New materials in this report refers to newly produced materials—either by the extraction of resources, or by recycling—flowing into the economy. It does not include, for example, an automobile purchased in prior years that is still in use.

[2]In this report, all reference to tons are metric tons, unless otherwise stated.

The production of metals and minerals play a vital role in the economies of the United States and the world (source: Brøderbund Software, Inc., 1997).

this century, more than half were used in the last 25 years (Matos and Wagner, 1998, p. 107).

Renewable resources are those that regenerate themselves, such as agricultural, fishery, forestry, and wildlife products. If the rate they are harvested becomes so great that it drives the resource to exhaustion, the base that supports a renewable resource can be destroyed.

Nonrenewable resources form over long periods of geologic time. They include metals, industrial minerals, and organic materials (such as fossil-fuel-derived materials used to manufacture plastics).

In 1900, the quantity of new materials entering the U.S. economy was 161 million tons, as shown in figure 4. The changes in the quantity entering the U.S. economy each year mirrored major economic and military events, including the depression of the 1930's, World War I, World War II, the post-World War II boom, the energy crunch of the 1970's, and the recession of the 1980's. The U.S. economy moved rapidly from an agricultural to an industrial base. In the 1950's and 1960's, it shifted toward a service economy. These trends changed the mix of materials used, as shown in figure 5, and were accompanied by automation, computerization, electrification, more extensive processing, high-speed transport, miniaturization, and sophisticated technology. The data and detailed descriptions about the data and trends have been described by Matos and Wagner (1998, p.109–113).

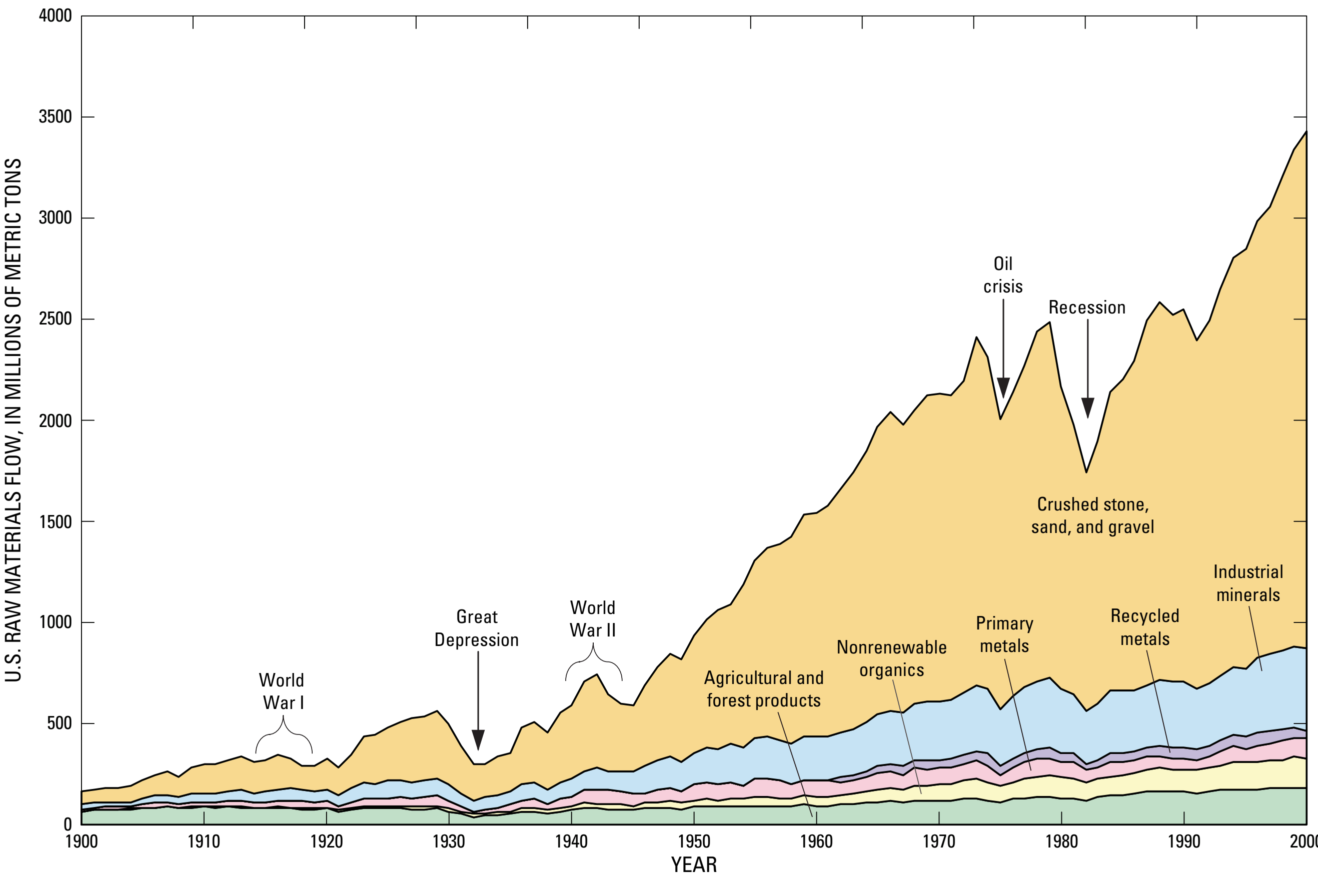


Figure 4. U.S. flow of raw materials by weight, 1900–98. The use of raw materials dramatically increased in the United States throughout the 20th century (modified from Matos and Wagner, 1998, fig. 3).

Consumption and Use of Materials

“Consumption” refers to the use of the services that goods, made from materials, provide. It means the destruction of the economic value added to a product, through design for example, not necessarily the destruction of the materials of which the product is composed. For example, consumers purchase items such as automobiles, clothing, electricity, housing, and refrigerators. When a new automobile is purchased, both the materials of which the automobile is physically composed and the assembly of these materials into a working automobile is purchased, but, more important, the services of transportation that the automobile provides is acquired. When the automobile reaches the end of its useful life and is no longer able to provide reliable transportation, the materials of which the automobile is composed are available to be transformed or recycled into other useable products. Therefore, although the use of materials is generally referred to as consumption, in many cases, the materials remain after the end of the useful life of the product to be reused or recycled into new products.

In 2000, 95 percent of all automobiles that had reached the end of their useful life were recycled (Steel Recycling Institute, 2001, photo source: Brøderbund Software, Inc., 1997).

Through use, some products are dissipated. That is, the materials of which they are made are not available for recycling at the end of the product’s useful life. An example of a dissipative use in an automobile is a brake lining. Over time much of the brake lining wears away, with the resulting small particles being dropped along roadsides. Whereas the remnant of the worn down brake lining is available for recycling, the worn away portion is not.

Consumption and Use of Materials—*Continued*

The Golden Gate Bridge, constructed in the 1930's, still serves the needs of society (source: Microsoft Corp., 2000).

A new automobile, for statistical purposes, is considered "consumed" in the year it is purchased by a consumer and driven off the showroom floor, even though it will provide many years of service. This statistical accounting is used for other commodities as well. For example, large quantities of cement, sand and gravel, and stone were "consumed" in the construction of the Hoover Dam (built from 1931 to 1936). The Hoover Dam is still providing its intended services today. The same can be said of such American icons as the Golden Gate Bridge (constructed 1933–37), the Statue of Liberty (erected 1885–86), and the Empire State Building (constructed 1930–31). Infrastructure (bridges, buildings, highways, etc.) may last 35, 50, or 100 years or more. In such cases, the use of materials today is an investment for tomorrow.

Crushed stone and construction sand and gravel make up as much as three quarters (by weight) of new resources used annually. Use of these materials greatly increased as a result of infrastructure growth (especially the Interstate Highway system) after World War II. In recent decades, construction materials have been used mainly in widening and rebuilding roads damaged from weather and heavy traffic loads and in construction of bridges, ramps, and buildings (Tepordei, 1999).

Other industrial-mineral commodities account for the next largest share of materials usage, almost equivalent, on a per-weight basis, to all of the remaining materials. Industrial-mineral commodities include cement for ready-mix concrete, potash and phosphate for fertilizer, gypsum for drywall and plaster, fluorspar for acid, soda ash for glass and chemicals, and sulfur, abrasives, asbestos, and various other materials for use in chemicals and industry.

Use of metals, by weight, declined slightly relative to other materials, although gross weight increased during the last few decades. Reasons for this include the greater proportion of lighter weight materials (such as aluminum); the introduction of high-strength, low-alloy steel in vehicles; and the availability of substitute materials.

Improvements in recycling technologies, reduced recycling costs, and increased consumer preferences for environmentally sound products have resulted in the growth of recycled metals, paper, concrete, and wood products. The sudden emergence of recycled materials shown in figure 4 in the 1960's reflects new criteria for reporting recycled material (before the 1960's, recycled material was included in total materials; Matos and Wagner, 1998). According to estimates, in 2000, 62.1 percent of all aluminum beverage cans (Aluminum Association, Inc., 2001a) and 45 percent of paper were recovered for recycling (American Forest & Paper Association, 2001). The 2000 recycling rates for steel-containing products

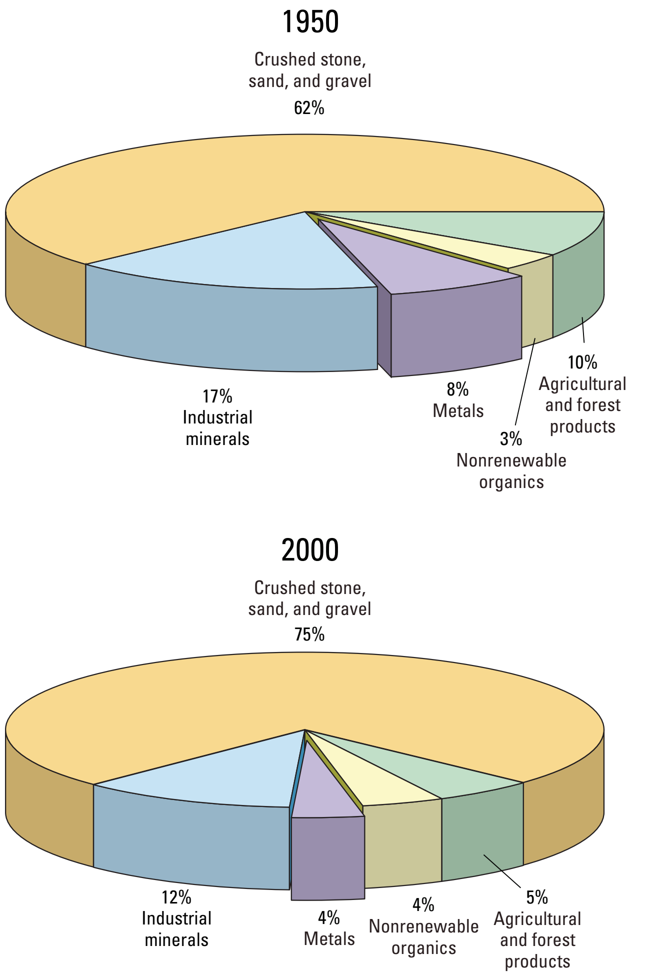


Figure 5. U.S. flow of raw materials by weight, 1950 and 2000. The mix of materials consumed from 1950 to 2000 has changed.

were 84.1 percent for appliances, 95.0 percent for automobiles, and 58.4 percent for steel cans (Steel Recycling Institute, 2001).

Nonrenewable organic material[3] is today a major component of materials use. Use of nonrenewable organics emerged gradually in the early part of the 20th century, accounting for approximately 2 million tons in 1900. It subsequently underwent rapid growth, to 148 million tons in 2000. The use of nonrenewable organic material increased as a result of the development of new products and markets and material substitutions in established markets. In some applications, synthetic fibers replaced natural fibers; plastic replaced wood, metal and other mineral-based commodities; and synthetic oil replaced natural oil. New materials replaced old because of cost advantages or more desirable properties or both.

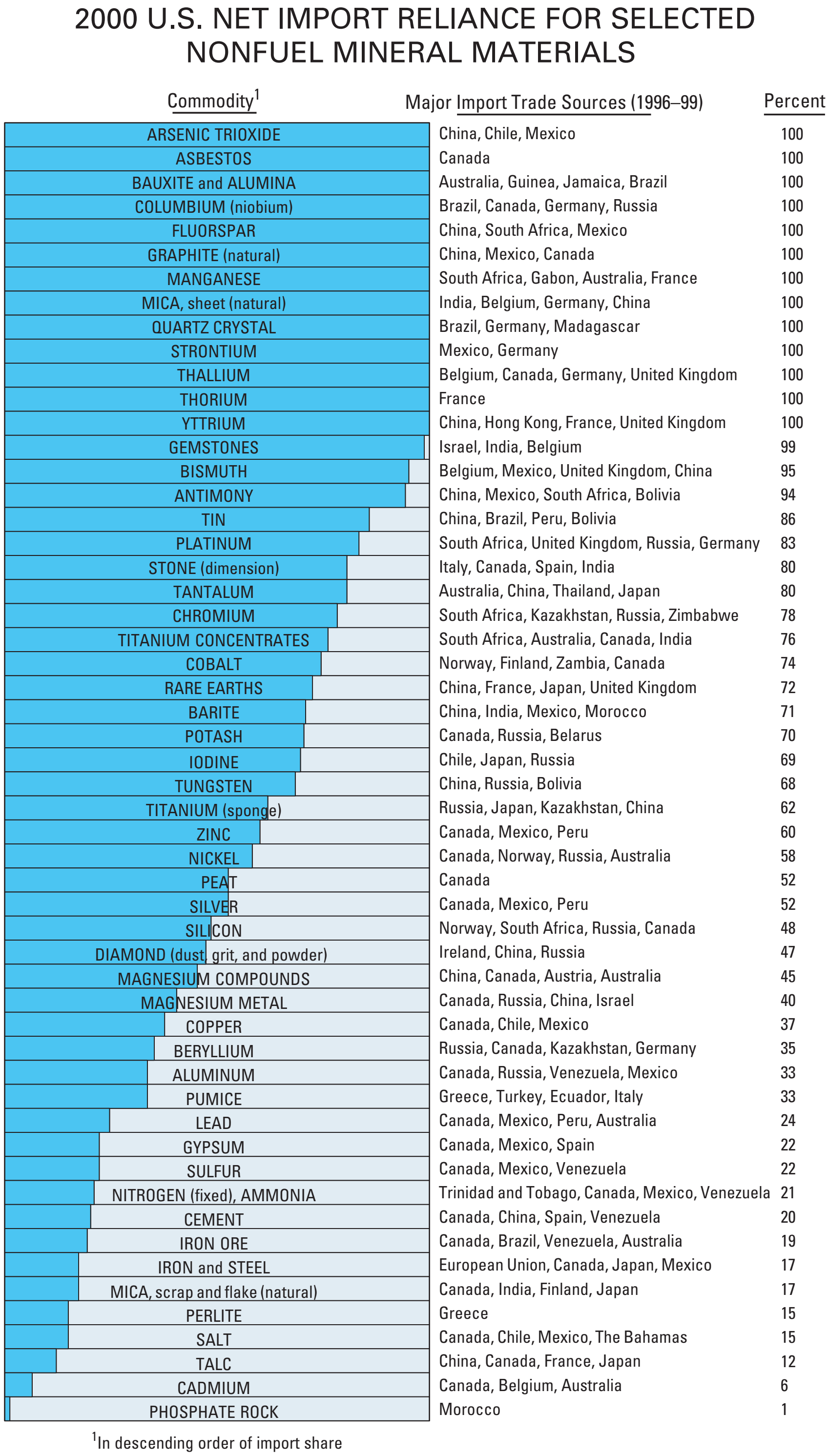
Agricultural and forestry products include nonfood materials derived from agriculture (such as cotton, wool, and tobacco), fishery products (such as fish meal), wildlife (primarily fur), and forest products (such as wood and paper).

Materials production and use play an important role in the economy of the United States and the world. In an increasingly global economy, natural resources are commonly extracted in one country, processed or converted into products in another, and consumed in a third country. Materials production occurs where the resources are present. For example, timber production must take place in a forest area where the trees exist. Processing sites may be close to or away from the main use or production areas. In some cases, it can be economically advantageous to locate processing away from the production or use site.

Given these circumstances, materials are heavily traded internationally. Examining just the U.S. net import reliance for mineral-based materials shows the global nature of U.S. mineral-based materials usage, as shown in figure 6.

In 1900, the United States used approximately 66 million tons of agricultural and forestry material such as this timber being loaded for use as pulp in making paperboard or for lumber. In 2000, the United States used more than 180 million tons of agricultural and forestry materials (source: Brøderbund Software, Inc., 1997).

[3]Organic materials are derived from feedstocks of petroleum (including natural-gas liquids), dry natural gas, and coal for nonfuel applications. This includes resins used in the production of plastics, synthetic fibers, and synthetic rubber; feedstocks used in the production of solvents and other petrochemicals; lubricants and waxes; and asphalt and road oil.



Additional mineral commodities for which there is some import dependency include:

Gallium	France, Russia, Kazakhstan, Canada	Rhenium	Chile, Germany, Kazakhstan, Russia
Germanium	Russia, Belgium, China, United Kingdom	Selenium	Philippines, Canada, Belgium, Japan
Indium	Canada, China, Russia, France	Vanadium	South Africa, China
Mercury	Canada, United Kingdom, Kyrgyzstan, Spain	Vermiculite	South Africa, China
		Zirconium	South Africa, Australia

Figure 6. 2000 U.S. net import reliance for selected nonfuel mineral materials (U.S. Geological Survey, 2001a, p. 5.)

Material Flows

Meeting the current material aspirations of people all over the world will require increasing extraction, processing, and transport of renewable and nonrenewable resources. Expected global population growth will increase these demands.

Materials use requires materials to flow from extraction through processing to use and disposal or recycling. The flow of materials has significant economic, environmental, and social impacts at each stage. Impacts occur with the original resource recovery, transportation, processing, manufacturing, and use of goods, and with the flow of material after the useful life of the good: disposal, recycling, remanufacturing, or reuse.

Material-flow studies track the movement of materials beginning with extraction, through processing and creation of final goods, to disposal or recycling of the product as shown in figure 7. These studies also identify where the materials reside over time in the form of products that are in use. These studies can identify the various processes by which emissions (or residuals) enter the environment (fig. 7) and can also identify the quantities of materials involved.

The analysis of materials flow can lead to improvements in product design, technological innovation that increases the efficiency of resource use, better waste-management practices, and policies that better integrate economic, resource, and ecosystem concerns.

As the flow of material increases to meet our increasing use, the effect on the environment may also increase. This impact on the environment can be minimized by encouraging industries to use less harmful materials, developing new processing technologies that are friendlier to the environment, substituting benign materials for environmentally harmful materials, using less material (source reduction), or recycling. As material flows increase, the residuals (e.g., emissions, leakages, etc.) could also increase. If they continue to increase, problems could arise because the Earth is a closed system and the ability of the ecosystem to absorb these residuals is bounded (Rogich, 1996, p. 208).

A vast amount of materials are moved or mobilized in our society to allow us to either extract minerals and materials or construct new structures—these are unpriced or not recorded. These flows are referred to as “hidden flows”—the flows of materials that are necessary to create the goods and services we

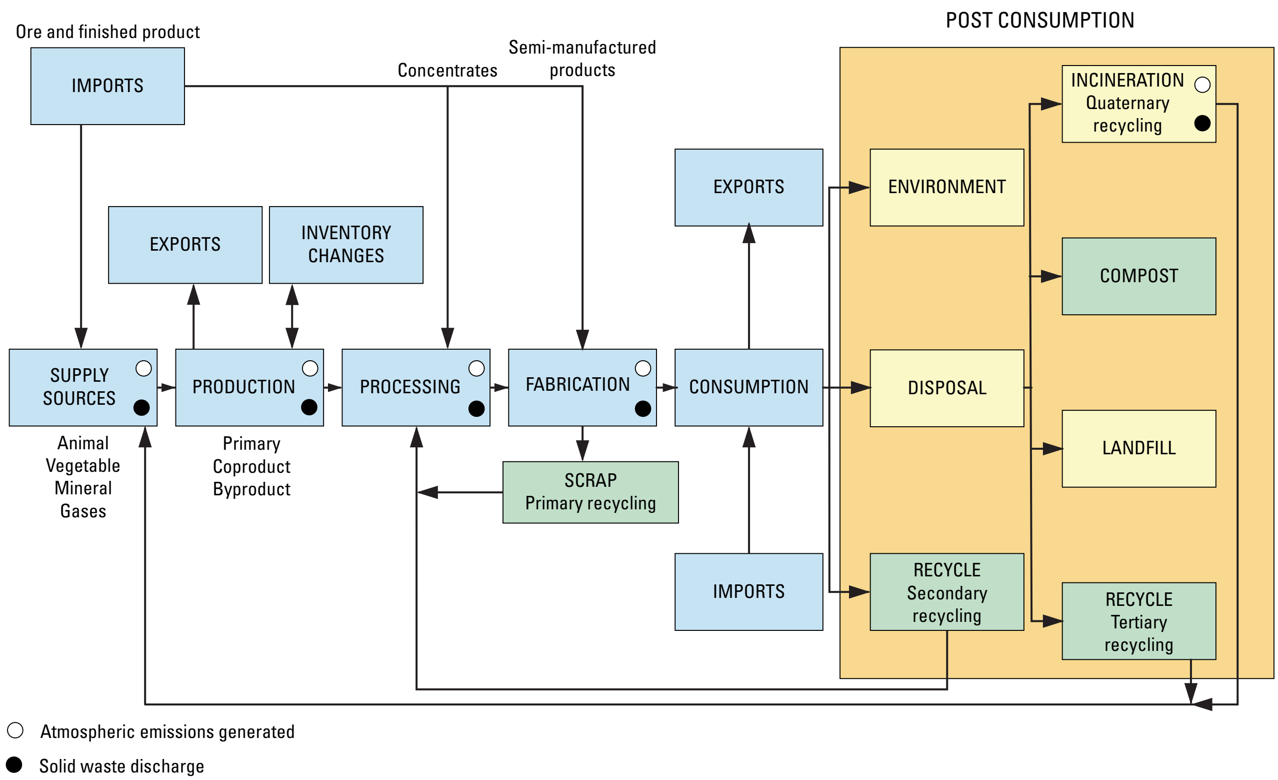


Figure 7. Generalized commodity flow cycle. The diagram shows a generic material flowchart that illustrates the path from origin through disposition for virtually any material. Resources such as water and land are beyond the scope of this flow concept; therefore they are excluded. Although some categories may not pertain to all commodities, the framework provides a perspective for material flow (Kostick, 1996, p. 213).

Ships, such as the one shown here unloading containers, transport goods to and from the United States (source: Brøderbund Software, Inc., 1997).

The Need for Data

Inherent in materials-flow analyses is the need for reliable, consistent data. As stated by the U.S. Interagency Working Group on Industrial Ecology, Material and Energy Flow (2000, p. 78–79):

> Data collected by Federal Agencies on consumption of commodities, use of energy resources, and industrial and municipal waste generation provide an essential base for analyzing the flow of physical materials through the U.S. economy. Data on environmental emissions (urban air quality, toxic releases, etc.) reveal trends in the environmental performance of U.S. industry, as well as the efficacy of policies to reduce air and water pollution. Federal Agencies also provide geological data on the U.S. land mass and scientific information on the geographic extent and impact of human activities on the landscape.
>
> National-level information is useful for an overview and a sense of the trends, problems and opportunities in materials and energy flows. Information needed to support decision-making is most useful when disaggregated to a regional, local, industry sector or enterprise level. This level of detail in the gathering and analysis of data can be expensive but is necessary to support informed decisions and more efficient use of energy and materials with less environmental degradation.

use but that do not enter into the statistics normally associated with materials usage. Examples of these hidden flows include materials such as mine tailings, which remain after the ore is extracted, and earth and stone that are moved to make way for or support the construction of buildings, dams, and highways.

In order to better understand the impact that our use of materials can have, material-flow studies target specific substances, such as mercury.

Trucks, such as the one shown here, transport vast quantities of the materials used within the United States. In 1997, in terms of value of shipments and tons, trucks transported approximately 70 percent of all goods transported (U.S. Census Bureau, 1999, p. 9) (photo source: Lorie Wagner).

Mercury Materials Flow

Although natural sources of mercury exist in the environment, both measured data and models indicate that the amount of mercury released into the biosphere each year has increased since the beginning of the Industrial Age. Mercury is distributed in the air, water, and soil in minute amounts and can be mobile within these media. Mercury, its vapors, and most of its organic and inorganic compounds are poisonous and can be fatal to humans, animals, and plants (Carrico, 1985, p. 506).

The information presented here is an excerpt of the study “The materials flow of mercury in the economies of the United States and the world” (Sznopek and Goonan, 2000). As part of an increased emphasis on materials flow, this report researched changes since 1991 and identified the associated trends in mercury flows; it also updated statistics through 1996. It looked at both domestic and international flows because all primary mercury-producing mines are currently foreign—86 percent of the mercury cell sector of the worldwide chlor-alkali industry is outside the United States—there is a large international mercury trade (1,400 tons in 1996) and environmental regulations are not uniform or similarly enforced from country to country.

Mercury Materials Flow—*Continued*

Although natural sources of mercury (such as mineral deposits, hot springs and volcanoes) exist in the environment, increased amounts of mercury have entered into the biosphere from anthropogenic (human-derived) sources. Some of the more significant anthropogenic mercury-emission sources include coal combustion, leaching of solid wastes in landfills, manufacturing-process leaks, and municipal and medical waste incinerations.

The materials-flow study addresses the life cycle of mercury from extraction through processing, manufacturing, use, reuse, and disposition. This study characterizes not only the movement of materials (including losses to the environment) but also the stocks. A stock (inventories, or products in use, for example) occurs when a specific material resides, relatively unaltered, for a period of time.

Figure 8, the domestic flow of mercury in 1996, shows that 144 tons of mercury were added to the environment in 1996. The largest source of anthropogenic mercury emissions (nearly 50 percent of all human-derived emissions) is from coal-fueled utility boilers used for electrical generation. Complete recovery of mercury emissions from this source presents a problem because mercury is present in coal in very small quantities, but the enormous amount of coal burned produces a large overall contribution. The diagram also shows that secondary production of mercury was greater than reported mercury consumption in the United States in 1996.

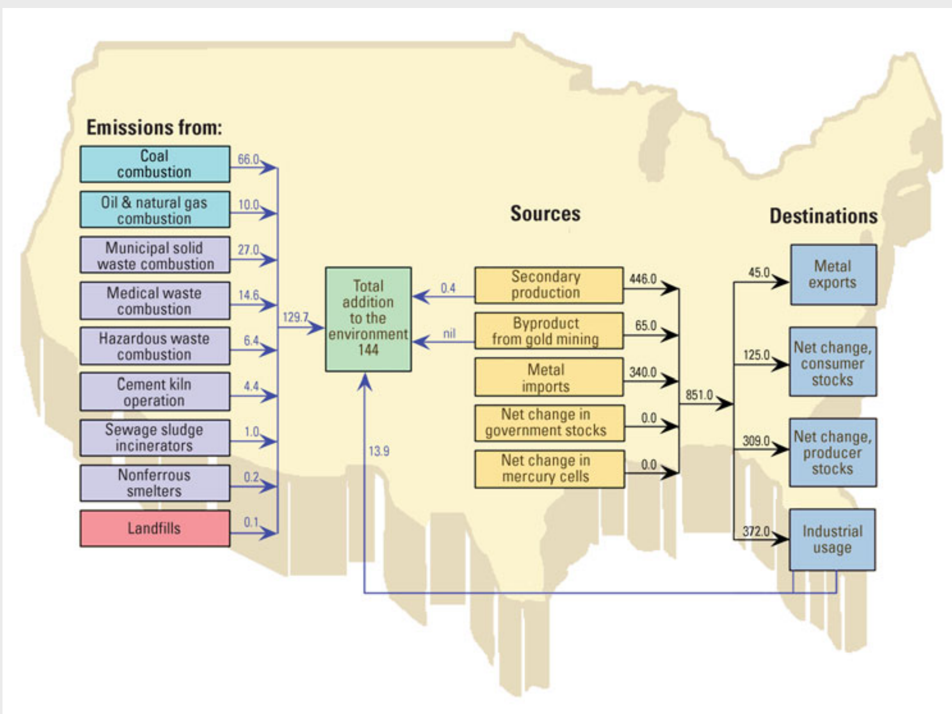


Figure 8. Domestic flow of mercury, 1996. Numbers are in metric tons (Sznopek and Goonan, 2000, p. 5).

Mercury Materials Flow—*Continued*

By examining the domestic product flow of mercury through end uses in 1996, the disposition of mercury and the stocks of mercury can be determined, as shown in figure 9. The diagram shows that most mercury in use today is used in chlor-alkali facilities, followed by wiring devices and switches, measurement and control devices, and dental uses.

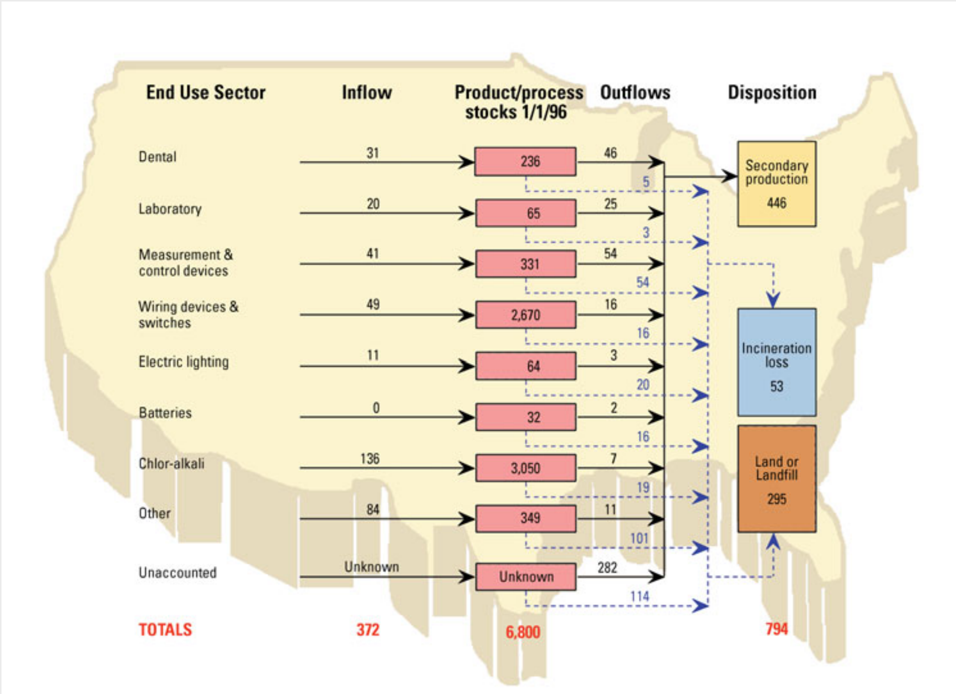


Figure 9. Domestic product flow of mercury through end uses, 1996. Numbers are in metric tons (Sznopek and Goonan, 2000, p. 7).

The consumption of mercury in products has declined over time as a result of both consumer and producer concerns over the use of mercury (fig. 10). U.S. legislation, such as designating mercury as a hazardous pollutant in 1971, restricted the sale and disposal of batteries containing mercury and restricted the disposal of fluorescent light tubes containing mercury, all of which led to the declining use and emissions of mercury.

Environmental concerns have produced many rules, regulations, and mandates that, over the years, have greatly reduced worldwide mercury use and production and have greatly reduced anthropogenic mercury emissions. Such a trend toward reduced mercury usage is expected to continue into the future but probably at a reduced rate because the only remaining uses for mercury appear to be essential ones. Even with reduced usage, the world will have to deal with large mercury inventories that have accumulated to support the past use of mercury in industrial processes and products. The large amount of mercury emissions derived from coal combustion also remains a problem.

Mercury Materials Flow—*Continued*

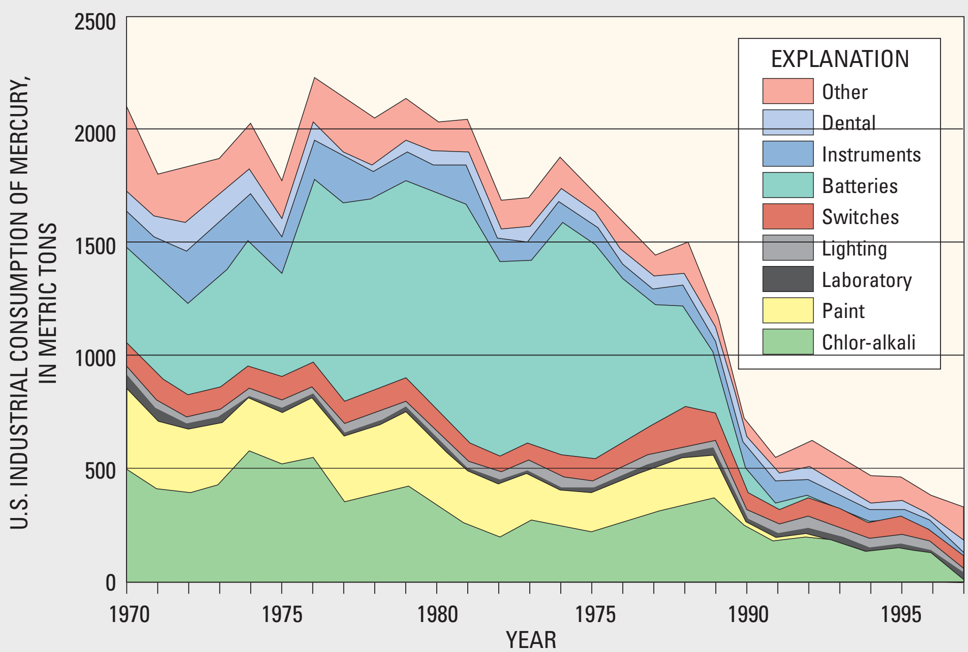


Figure 10. Reported U.S. industrial consumption of mercury, 1970–97 (Sznopek and Goonan, 2000, p. 4).

Scarcity

Scarcity is the lack of adequate supply to meet demand. As consumption and usage continue to grow, especially for nonrenewable resources, questions begin to arise over the adequacy of existing resources to meet our future needs and desires. How much of the Nation's or the world's total mineral wealth has already been discovered? How much is left? Is scarcity inevitable?

Concern that resource depletion may threaten the welfare of future generations dates back at least 2 centuries. Today the debate over this threat not only continues but seems more polarized than ever. In one school are those who contend the Earth can not for long continue to support current and anticipated levels of demand for oil and other exhaustible resources. In the opposing school are those who claim, with equal conviction, that the Earth (with the help of market incentives, appropriate public policies, and new technology) can amply provide for society's needs for the indefinite future. When interest in this topic reignited in the 1990's, the focus of concern shifted slightly from resource exhaustion per se to the environmental damage associated with mining and mineral production (Tilton, 1996).

As populations continue to expand, more pressures are placed on natural resources (source: Brøderbund Software, Inc., 1997).

Is the potential scarcity of resources an issue? Although the United States uses vast quantities of mineral-based materials, future shortages are not necessarily inevitable. Economic incentives, greater efficiencies in materials use, increased recycling, designing products for future recycling or reuse,

One of the concerns over our increasing usage of materials is whether adequate resources will be available for future generations (source: Cheryl Bloomquist, Duluth, Minn.).

pollution prevention, and advances in technology are just a few of the ways to reduce dependence on mineral-based materials.

Listed below are some of the ways in which potential future shortages of materials could be minimized.

Economic incentives.—As the price of the commodity increases, people generally use less. For example, when the price of gasoline increases, people tend to drive less or use public transportation more, thereby decreasing the use of gasoline.

Miniaturization of products.—Technologic developments in manufacturing products have resulted in products that are smaller being able to provide the same or greater services as older products that are larger in size. Examples of products that have undergone significant miniaturization are computers and their components and cellular phones.

New materials research.—Research into new materials can create specialty materials with superior performance characteristics for specific applications, or it can develop uses for materials that are available in abundance. Over time and with increasing use, these "new" materials become traditional materials. Bronze, iron, aluminum, and plastic were at one time "new" materials (U.S. Bureau of Mines, 1990).

Technologic advancements.—Development of, or improvements in, technologies can result in less material being required to manufacture products. The aluminum beverage container is an example. Technologic advancements in the manufacturing process enabled the walls of the beverage container to be made thinner and thinner. This allows more products to be manufactured per pound of aluminum. Aluminum beverage containers today are 52 percent lighter than they were 20 years ago. In fact, the number of cans per pound of aluminum has gone from about 23 in 1975 to about 33 in 2000 (Aluminum Association, Inc., 2001b).

Substitution.—Replacing one commodity for another is a way in which scarcity of a commodity can be lessened. In some applications, several commodities have the desired properties. For example, in the packaging of beverages, glass or plastic bottles, paper cartons, and aluminum or steel cans all could be used. These commodities can be considered substitutes for one another in this application. Factors such as price, ease of handling, the filling equipment used, and packaging requirements of the beverage all can influence which commodity is chosen for use.

Exploration.—The discovery of additional sources of materials decreases the possibility of scarcity. New techniques, better equipment, and new theories regarding the formation of mineral deposits all have contributed to increasing our known resources.

Mining lower grade material.—Over time, techniques have been developed that have enabled lower grade ores to be economically mined and processed. This allows more of the world's endowment of natural resources to be extracted.

Processing efficiencies.—Efficiencies in materials processing and handling have meant that more of the material is able to reach the market. Better ore-processing technologies result in more of the minerals being extracted from the ore. This causes less waste per ton of mineral recovered; therefore, less ore needs to be extracted to yield the same amount of usable minerals.

Recycling.—When materials are recycled, it means that less new "virgin" material needs to be extracted or harvested. Recycling includes the concepts of reuse and remanufacturing. In many cases recycling materials is a great energy saver. For example, recycling aluminum beverage containers saves about 95 percent of the energy needed to make primary metal from ore (Wilburn and Wagner, 1993). In addition, recycling is a significant factor in the supply of many of the key metals used in our society; it provides environmental benefits in terms of energy savings, reductions in the volume of waste, and reductions in emissions associated with energy savings (U.S. Geological Survey, 2001b, p. 62.1).

Reuse.—The reuse of a product involves the recovery or reapplication of a package, used product, or material in a manner that retains its original form or identity (U.S. Environmental Protection Agency, 1999, p. 7). Reuse of products such as refillable glass bottles, reusable plastic food storage containers, refurbished wood pallets, and discarded railroad ties being used as landscaping timbers are examples of reuse. The sale of items from garage sales or thrift stores is another example.

Remanufacturing.—Products can be rebuilt to extend their useful life. The broken or worn parts are removed and replaced, the item may be checked to make sure it is in good working order and is resold in the marketplace, many times at a greatly reduced price from a similar new product. Some remanufactured products also come with warrantees. The automotive remanufactured parts industry is a common example where rebuilt alternators and motors have been readily available for many years.

Landfill mining.—Landfills were once looked upon as the final resting place for unwanted items. However, with existing technology, some landfills can be looked upon as sources of recyclable materials and may be "mined" to reclaim and recycle the valuable materials.

Waste utilization.—Waste streams from one process can be used as an input or a valuable resource for another process, thereby reducing the need for new materials. An example is the reuse of concrete and asphalt from demolished infrastructure. As Americans go about tearing up roads and tearing down buildings, they generate large quantities of demolition waste, yielding over 200 million tons per year of recycled aggregates. The bulk of the aggregate recycled from concrete—an estimated 68 percent—is used as road base. The remainder is used in such products as new concrete mixes, asphalt hot mixes, riprap, and general fill (Goonan, 1999).

Doing without or doing with less.—Another way to reduce our dependence on minerals is to go without or to make do with less. Households today have more "stuff" than ever before. It used to be that the average home had only one television set, one car, etc. This is no longer true. To house our increased belongings, larger and larger homes are being built. For example, in 1987 the average area of a new single-family home was 1,905 ft^2, but by 2000 it had risen to 2,273 ft^2 (National Association of Home Builders, 2001). Doing without so many material possessions is an option.

Recycling Statistics

Recycling has been one of the main approaches to waste reduction and a means by which our resources can be extended. Recycling also includes reuse, repair, and remanufacturing. How are we doing at recycling?

Recycling rates can be measured at various points, for example at the industrial phase where the product is being produced, after the product is used, or at different collection points—residential, commercial, and institutional. Below are two examples of recycling rates in the United States.

Metals

Recycling, a significant factor in the supply of many of the key metals used in our society, provides environmental benefits in terms of energy savings, reduced volumes of waste, and reduced emissions associated with energy savings. The reusable nature of metals contributes to the sustainability of their use. A study examining the flow of more than 20 recycled metals is currently underway by the U.S. Geological Survey (USGS). Table 1 shows salient U.S. apparent supply and recycling statistics for selected metals. Recycling contributed 80.7 million tons of metal, valued at about $17.7 billion, or more than half of metal apparent supply by weight in 2000 (J.F. Papp, written commun., November 5, 2001).

As shown by table 1, recycled sources supplied 63 percent of lead; 55 percent of iron and steel; 50 percent of titanium; more than 30 percent of aluminum, copper, and magnesium; and more than 20 percent of chromium, tin, and zinc.

Municipal Solid Waste

Municipal solid waste, otherwise known as trash or garbage, consists of everyday items such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. Not included are materials that also may be disposed in landfills but that are not generally considered municipal solid waste, such as construction and demolition debris, municipal wastewater treatment sludges, and nonhazardous industrial wastes (U.S. Environmental Protection Agency, 2000, p. 4).

In 1999, a total of approximately 230 million short tons of municipal solid waste was generated in the United States (nearly 7 million short tons more than in 1998), according to the U.S. Environmental Protection Agency's 2000 report "Municipal solid waste in the United States: 1999 facts and figures." This total equals 4.6 pounds per person per day, as shown in table 2. The generation of paper and paperboard waste is higher than any

Table 1. Salient U.S. recycling statistics for selected metals, 2000.

[In metric tons and percent recycled for each material. Data are rounded to three significant digits; may not add to totals shown. NA, not available; W, data withheld to avoid disclosing company proprietary data. Source: J.F. Papp (written commun., November 5, 2001)]

Commodity	Recycled from new scrap[1]	Recycled from old scrap[2]	Recycled[3]	Apparent supply[4]	Percentage recycled
Aluminum[5]	2,080,000	1,370,000	3,450,000	9,610,000	36
Chromium[6]	NA	NA	139,000	589,000	24
Copper[7]	956,000	353,000	1,310,000	4,080,000	32
Iron and steel[8]	NA	NA	74,000,000	134,000,000	55
Lead[9]	35,400	1,080,000	1,120,000	1,790,000	63
Magnesium[10]	52,200	30,100	82,300	209,000	39
Tin	8,450	6,600	15,100	52,100	29
Titanium[11]	NA	NA	18,500	W	50
Zinc	369,000	66,900	436,000	1,610,000	27

[1]Scrap that results from the manufacturing process, including metal and alloy production. New scrap of aluminum, copper, lead, tin and zinc excludes home scrap. Home scrap is scrap generated in the metal-producing plant.

[2]Scrap that results from consumer products.

[3]Metal recovered from new plus old scrap.

[4]Apparent supply is production plus net imports plus stock changes. Production is primary production plus recycled metal. Net imports are imports minus exports. Apparent supply is calculated on a contained weight basis.

[5]Scrap quantity is the calculated metallic recovery from purchased new and old aluminum-based scrap, estimated for full industry coverage.

[6]Chromium scrap includes estimated chromium content of stainless steel scrap receipts (reported by the iron and steel and pig-iron industries) where chromium content was estimated to be 17 percent. Trade includes reported or estimated chromium content of chromite ore, ferrochromium, chromium metal and scrap, and a variety of chromium-containing chemicals. Stocks include estimated chromium content of reported and estimated producer, consumer, and Government stocks.

[7]Includes copper recovered from unalloyed and alloyed copper-based scrap, as refined copper or in alloy forms, as well as copper recovered from aluminum-, nickel-, and zinc-based scrap.

[8]Iron production measured as shipments of iron and steel products plus castings corrected for imported ingots and blooms. Secondary production measured as reported consumption. Apparent supply includes production of raw steel.

[9]Lead processors are segregated by primary and secondary producers. This segregation permits inclusion of stocks changes for secondary producers.

[10]Includes magnesium content of aluminum-based scrap.

[11]Percent recycled based on titanium scrap consumed divided by primary titanium sponge metal and scrap consumption.

Table 2. Generation, materials recovery, composting, and discards of municipal solid waste, 1960–99.

[In pounds per person per day; population in thousands. From U.S. Environmental Protection Agency (2000, p. 2)]

	Year					
	1960	1970	1980	1990	1995	1999
Generation	2.68	3.25	3.66	4.50	4.40	4.62
Recovery for recycling	0.17	0.22	0.35	0.64	0.94	1.02
Recovery for composting[1]	Negligible	Negligible	Negligible	0.09	0.20	0.26
Total materials recovery	0.17	0.22	0.35	0.73	1.14	1.28
Discards after recovery	2.51	3.04	3.31	3.77	3.26	3.33
Population (thousands)	179,979	203,984	227,255	249,907	263,168	272,691

[1]Composting of yard trimmings and food wastes. Does not include mixed municipal solid waste composting or backyard composting.

Recycling Statistics—*Continued*

other category, as shown in table 3. Of the total approximately 230 million short tons of municipal solid waste generated, 28 percent was recycled, up from 10 percent in 1980 and 16 percent in 1990. Disposal has decreased from 90 percent of the amount generated in 1980 to 72.2 percent of municipal solid waste in 1999. The per-capita discard rate (after recovery for recycling, including composting) was 3.3 pounds per person per day in 1999, up from 3.1 pounds per person per day in 1996.

Table 3. Generation and recovery of materials in municipal solid waste, 1999.

[Includes wastes from residential, commercial, and institutional sources. Negligible, less than 50,000 short tons or 0.05 percent. From U.S. Environmental Protection Agency (2000, p. 6)]

Material	Weight generated (millions of short tons)	Recovery (% of generation)
Paper and paperboard	87.5	41.9
Glass	12.6	23.4
Metals		
Steel	13.3	33.6
Aluminum	3.1	27.8
Other nonferrous metals[1]	1.4	66.9
Total metals	17.8	35.2
Plastics	24.2	5.6
Rubber and leather	6.2	12.7
Textiles	9.1	12.9
Wood	12.3	5.9
Other materials	4.0	21.4
Total materials in products	173.6	29.3
Other wastes, total	56.3	23.3
Food, other[2]	25.2	2.2
Yard trimmings	27.7	45.3
Misc. inorganic wastes	3.4	Negligible

[1]Includes lead from lead-acid batteries.
[2]Includes recovery of paper for composting.

Environment

Mineral-based materials occur naturally in the environment and are an inherent part of our total environment. They exist in the ecosystem; in rocks, soil, surface water, and ground water; and small amounts of mineral-based materials are considered essential for plants, animals, and humans.

Besides these natural sources, there are also anthropogenic sources. Human activities—such as driving automobiles, manufacturing products, growing food, participating in recreational activities, and receiving medical care—result in mineral-based materials being added to the environment in excess of what would normally be present.

Some mineral-based materials are considered benign—that is, they do not usually interact with or cause harm to plants, animals, or humans. Sand and gravel are examples of benign materials. Materials such as arsenic, cadmium, and mercury can be considered toxic in certain forms and amounts.

In the natural environment, the elements that make up minerals also compose rocks and soil. These elements can move throughout the ecosystem. As rocks break down due to weathering and erosion, or when volcanoes erupt, elements are

According to the US Environmental Protection Agency, driving a car is probably a typical citizen's most "polluting" daily activity (source: Microsoft Corp., 2000).

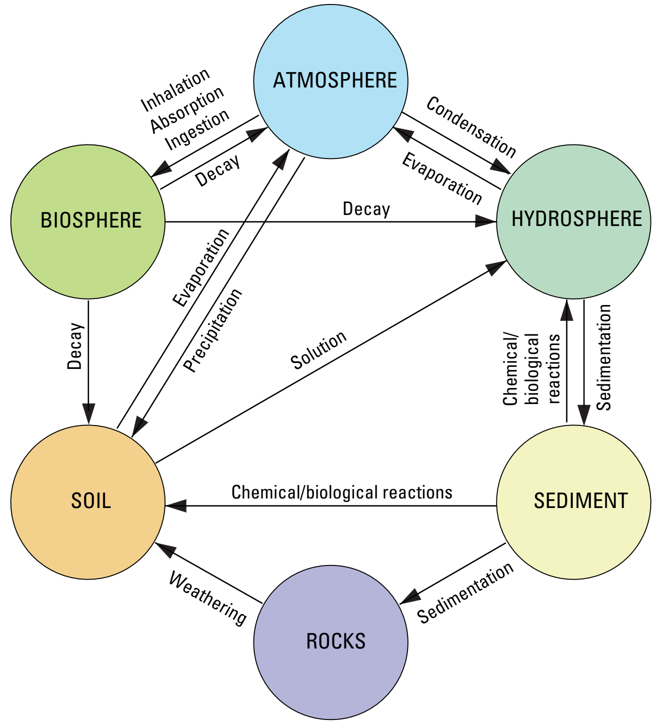


Figure 11. Mobile metal pathways. The diagram shows pathways for mineral-based materials to enter the environment (Board, 1996).

dispersed into the environment and can migrate into air, soil, or water and can become concentrated in living organisms. Figure 11 shows the ways in which materials can enter the environment naturally.

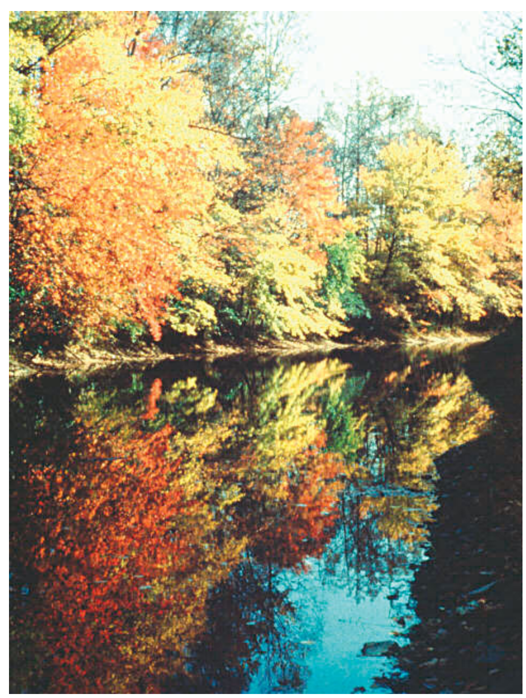
Elements can be quite mobile in water, and the majority of our environmental problems are ultimately associated with the contamination of surface and ground water (Gough, 1993, p. 3). When water comes into contact with rocks and soils, some of the minerals and organic substances dissolve and enter natural waters.

The combination of some natural processes with human activities can increase these substances to harmful or toxic levels. Therefore, toxic substances may have both natural and human sources. Natural point sources for toxic substances may include mineral deposits; anthropogenic point sources may include industrial processing facilities, mining operations, or chemical facilities; and anthropogenic nonpoint sources may include entire cities or counties (Gough, 1993, p. 3).

Natural sources of toxic substances include rocks, volcanoes, sediments, and soil. For example, sedimentary rocks in central Oklahoma contaminate ground water with arsenic, chromium, selenium, and uranium. In the west-central United States, certain sedimentary rocks contain toxic amounts of selenium. Some plants can concentrate selenium in their tissue, which can result in livestock disease and death (Gough, 1993, p. 3).

The other way materials can enter the environment is by way of human activities. Common anthropogenic sources include burning coal to produce electricity, chemical processes, disposing of and incinerating waste, emissions from automobiles, manufacturing, mining, and the use of pesticides and fertilizers in food production.

The U.S. Environmental Protection Agency (1994a) reported that, "Emissions from an individual car are generally low, relative to the smokestack image many people associate



Natural. environments may be at risk of negative environmental impacts as a result of our materials consumption (source: Brøderbund Software, Inc., 1997).

with air pollution. But in numerous cities across the country, the personal automobile is the single greatest polluter, as emissions from millions of vehicles on the road add up. Driving a private car is probably a typical citizen's most 'polluting' daily activity."

Since the 1970 census year, the American population has increased by one-third, but the number of motor vehicles on the road—cars, trucks, buses, and motorcycles—has nearly doubled (Anderson, 1999). Figure 12 shows the number of motor vehicles in various countries of the word.

Table 4 displays the annual emissions and fuel consumption for an average passenger car.

Efforts are underway to limit the impact that our materials use has on the environment. Increased environmental awareness has resulted in individual citizens, local organizations, corporations, and governments all working to decrease emissions to the environment. Regulations have been enacted to reduce air pollution, for example. Source reduction, switching to less environmentally harmful alternatives, recycling, and just plain doing without have decreased the impact of our materials use on the environment.

According to the U.S. Environmental Protection Agency (1998):

> The improvements in air quality and economic prosperity that have occurred since EPA initiated air pollution control programs in the early 1970's illustrate that economic growth and environmental protection can go hand-in-hand. Since 1970, national total emissions of the six "criteria pollutants" [carbon monoxide,

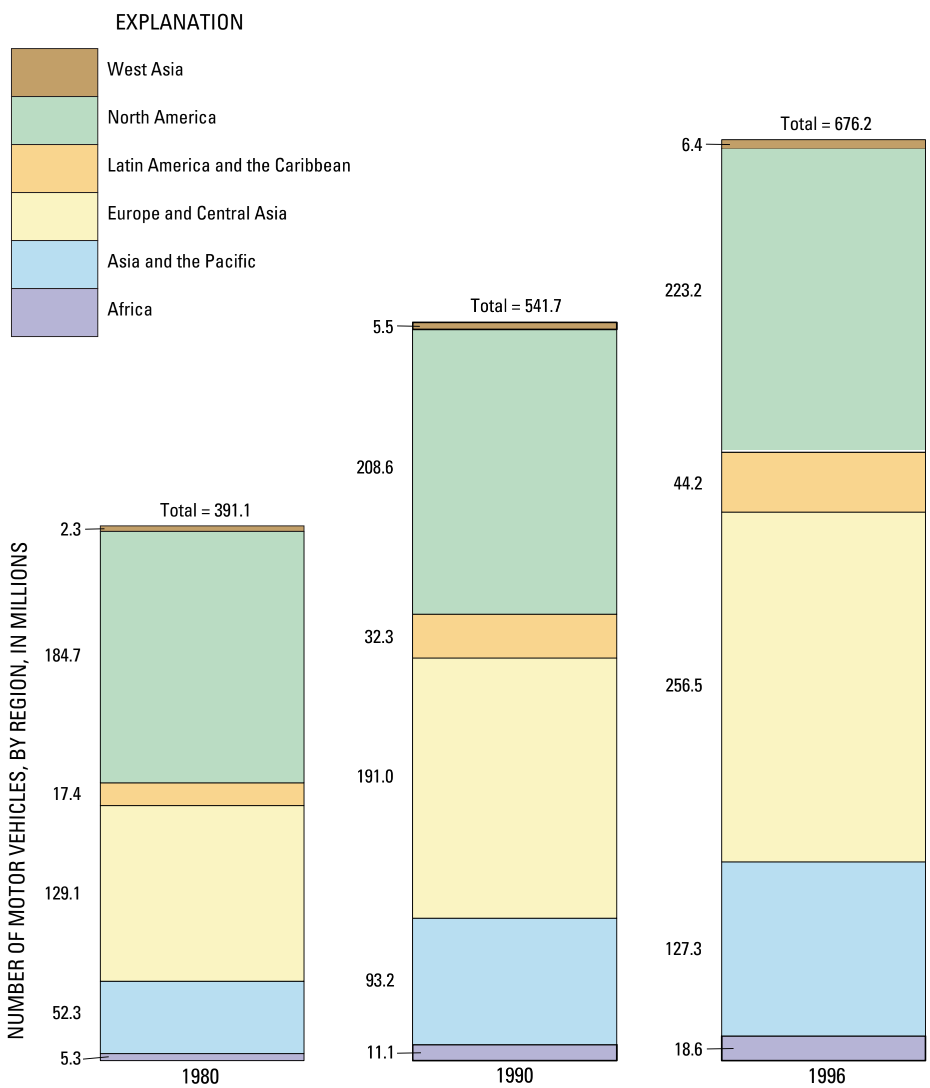


Figure 12. The number of motor vehicles in the world has nearly doubled in the last 16 years, from 391.1 million in 1980 to 676.2 million in 1996. Transportation now accounts for one-quarter of world energy use and about one-half of the world's oil production (United Nations Environment Programme, 1999).

Table 4. Annual emissions and fuel consumption for an average U.S. passenger car.

[Values are averages. Estimated mileage is 12,500 miles per year. Individual vehicles may travel more or less miles and may emit more or less pollution per mile than indicated here. Emission factors and pollution/fuel consumption totals may differ slightly from original sources due to rounding. From U.S. Environmental Protection Agency (1997, p. 1)]

Pollutant and problem	Amount[1]	Pollution or fuel consumption[2]
Hydrocarbons: Urban ozone (smog) and air toxics	2.9 grams per mile	80 lb of HC
Carbon monoxide: Poisonous gas	22 grams per mile	606 lb of CO
Nitrogen oxides: Urban ozone (smog) and acid rain	1.5 grams per mile	41 lb of NO_x
Carbon dioxide: Global warming	0.8 pounds per mile	10,000 lb of CO_2
Gasoline: Imported oil [3]	0.04 gallons per mile	550 gallons gasoline

[1]The emission factors used here come from standard EPA emission models. They assume an "average," properly maintained car or truck on the road in 1997, operating on typical gasoline on a summer day (72° to 96°F). Emissions may be higher in very hot or very cold weather.

[2]Fuel consumption is based on average in-use passenger car fuel economy of 22.5 miles per gallon and average in-use light truck fuel economy of 15.3 miles per gallon. Source: DOT/FHA, Highway Statistics (1995).

[3]Total net imports as a share of petroleum consumption reached a record high of 51 percent in 1998. Source: U.S. Energy Information Administration, 1998.

> lead, nitrogen dioxide, ground-level ozone, particulate matter, and sulfur dioxide] declined 31 percent, while U.S. population increased 31 percent, gross domestic product increased 114 percent, and vehicle miles traveled increased 127 percent.

Even though the emissions of these six "criteria pollutants" have declined, overall, the present situation appears to indicate that the absolute quantity of residuals entering the environment will increase as our use of materials increases unless our material-use preferences or methods to produce and use goods are modified. Increased recycling is one option to potentially reduce the quantity of residuals (wastes and emissions) created per unit of material flow. Decreases in the rate of goods turnover are possible, and the potential for processes that emit fewer residuals also exists. Productive uses for flows that are now considered residuals are also possible. All of these hold promise for decreasing the impact our materials use is having on the environment.

Excluding questions of energy availability and possible resource scarcity for some commodities, the magnitude of the flow of material in the economy is not a problem if the absolute quantity of residuals released to the environment does not exceed the environment's ability to absorb these residuals.

Point and Nonpoint Sources of Contamination—Industrial and Natural

—From Gough (1993, p. 27–29):

Point-source pollution

> Point-source pollution comes from a single source located in a small area such as a factory, power plant, or natural spring. There are many types of point-source pollution that degrade the quality of water, air, and soils. Examples include emissions of particulates and acidic gases into the atmosphere from active volcanoes, metalliferous springs whose waters have

Point and Nonpoint Sources of Contamination—Industrial and Natural—*Continued*

interacted with unmined mineral deposits, natural oil seeps, and acid-mine drainage from mine and mill tailings. If pollutants are released underground, then they can contaminate the ground water and the rock aquifers through which the ground water flows.

Air pollution can arise from activities such as power generation, mineral smelting, or industrial processing. Solid particles (particulates) generated by these sources can degrade air quality and visibility, and gases released from these sources (such as sulfur dioxide and various nitrogen gases) can react with atmospheric water to generate rain that is acidic or that has other chemically hazardous qualities.

Soil pollution can result from both air- and water-based pollution. For example, high concentrations of heavy metals can be found in soils near smelters and in soils through which metal-bearing surface waters or ground waters have flowed.

To effectively clean up sites that have been affected by point-source pollution, it is necessary to understand the geochemical processes that control how the pollutants interact with the environment.

The following two USGS activities involving both general research and specific site studies help address the geochemical behavior of natural and human (anthropogenic) point-source contaminants.

In Hawaii, USGS scientists are examining the origin of natural, volcano-related, acidic aerosols in the atmosphere, which can cause respiratory problems among island inhabitants. Chemical and isotopic data on the aerosols show whether they resulted from the interactions of molten lava from the Kilauea Volcano with sea water or from the reaction of sulfur dioxide of volcanic origin with moisture in the atmosphere. By understanding the origin of the aerosols, health officials can recommend measures to help humans avoid contact with the aerosols.

Another study showed that springs in areas of uranium-rich bedrock can be local point sources of dissolved uranium. The uranium is dissolved during normal weathering of uranium-rich rocks and can be reconcentrated onto organic matter as the springs emerge in organic-rich soils or wetlands. The following is an example of one such uranium-bearing spring that enters a wetland in the Colorado Rocky Mountains. The natural spring waters that help sustain this wetland contain 30 to 80 parts per billion (ppb) uranium compared to a regional background value of less than 5 ppb. The concentration of dissolved uranium by peat is very efficient and produces haloes (peat regions that are high in uranium) in the immediate vicinity of the emergent source springs. Dried samples of peat collected near the spring pools contain as much as 3,000 parts per million uranium, which represents up to a 100,000-fold concentration. This direct observation of the extraction of uranium by peat provides another example of how wetlands can improve water quality through their metal-sorption capabilities.

Nonpoint-Source Pollution

Nonpoint-source contamination has no single, clearly defined source area and can result from both natural and human-induced processes. The most commonly studied are those either introduced or exacerbated by human activities. Agriculture is an important nonpoint source of contamination. This is a result of two generalized activities—leaching of contaminants that man has added to the soil or the crops, such as organic herbicides or pesticides and nitrates or phosphates from fertilizers, and leaching of naturally occurring pollutants in the soil, chiefly as the result of irrigation, which are then concentrated to abundances incompatible with plant or animal life.

Point and Nonpoint Sources of Contamination—Industrial and Natural—*Continued*

The role of the USGS in the study of nonpoint-source pollution studies is focused on its ability to understand the chemical and physical processes controlling the pollutants in the environment. The definition of base-lines in agricultural and native soils and parent material has helped define what the pollution source is, how large the source is, the associated elements, and what the controlling processes are. With the knowledge of source and controls, remediation steps can be effectively planned and implemented with minimal impact on human health.

[One such example is uranium from marine deposits.] Marine shales and sandstones underlie large parts of the Western United States. Much of the uranium in these rocks is loosely bound and the rocks can weather under conditions typical of the semiarid West, [releasing uranium to the environment]. Irrigation can increase the natural loss of the uranium.

Runoff from irrigation may directly reenter irrigation ditches for reuse. Local ponding of runoff waters or creation of waterlogged soils can also bring uranium and other elements to the surface, where they are concentrated by evaporation. Soils thus contaminated may be rendered unfit for cultivation. Additionally, uranium and other elements concentrated at the surface may be removed by rainfall runoff and carried downstream, thus contaminating waters far beyond the irrigated fields.

Irrigation-return waters, regardless of the paths they have followed, may drain into their originating rivers via natural or artificial flow paths. Further downstream they may be taken out again and again for irrigation. When these waters become unfit for use on fields, they may be stored in permanent reservoirs and become more saline through further evaporation. These reservoirs may reach high levels of toxicity for animal or plant life. Towns and individuals may get their drinking water from aquifers that have been recharged, in part, by irrigation-return waters.

Are Electric Vehicles the Answer?

—From U.S. Environmental Protection Agency (1994b):

Electric vehicles are gaining attention as an option for improving air quality and lessening United States dependence on imported oil. Research and development is under way on advanced battery and fuel cell technology and automakers are stepping up efforts to design electric vehicles for fleets and personal use. Even though today's technology is new, battery-powered vehicles have been around for a long time. Electrics flourished before the rise of the gasoline automobile and some 50,000 electric vehicles were in use in the United States by 1912.

Electric vehicles are sometimes referred to as "zero-emission vehicles" because they produce essentially no pollution from the tailpipe or through fuel evaporation. This is important, for it means that the use of electric vehicles could greatly reduce emissions of carbon monoxide and smog-forming pollutants in cities with dirty air.

While electric cars themselves are clean, generating the electricity to charge vehicle batteries produces air pollution and solid waste. If electric powerplants produce electricity using clean energy sources such as solar or hydropower, then emissions are negligible. But power plants which combust conventional fuels like coal (used for more than half of the electricity generated in the United States today) produce emissions such as particulate matter, sulfur oxides, nitrogen oxides, hydrocarbons, and carbon monoxide. These same plants also create carbon dioxide, a combustion product of all fossil fuels, which contributes to global warming.

Are Electric Vehicles the Answer?—*Continued*

There are several factors that affect this pollution tradeoff. It may be easier to control pollution at a power plant than from individual vehicles. Power plants often are located outside major centers of urban air pollution, and finally, while only a fraction of today's power plants use renewable resources (biomass, wind, geothermal, or solar power), electricity can be produced from these clean sources of energy.

Potential health or safety risks associated with widespread electric vehicle use have not yet been fully evaluated. Many vehicle batteries contain toxic elements or produce toxic emissions, which could make battery production, transport, use, and disposal a significant solid waste issue. The United States must consider how to safely dispose of or recycle these batteries.

What about hybrid electric vehicles? Hybrid electric vehicles have batteries to provide electric power but are also equipped with a small internal combustion engine (usually powered by gasoline). The engine provides a power boost and/or can be used to recharge the batteries, as pure electrics today simply cannot achieve the range, performance, or convenience of a modern gasoline car. Unfortunately, the extra engine substantially increases pollution from the vehicle, erasing many of the air quality benefits of pure electric vehicles.

Sulfur—A Materials-Flow Analysis

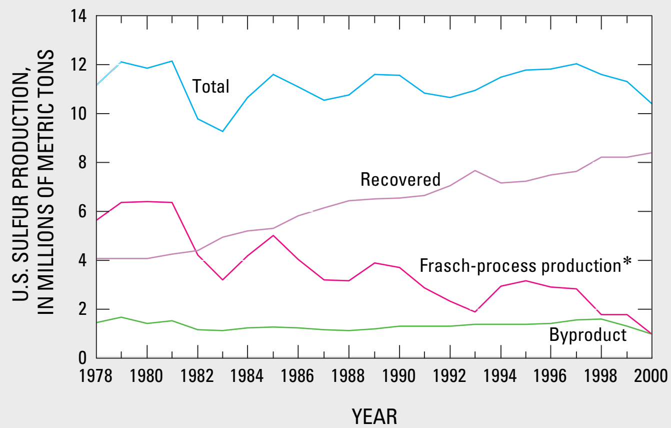
—From J.A. Ober (written commun., May 22, 2000):

Through its major derivative, sulfuric acid, sulfur ranks as one of the more important elements used as an industrial raw material. In fact, consumption of sulfuric acid has been regarded as one of the best indexes of a nation's industrial development. More sulfuric acid is produced in the United States every year than any other chemical (Ober, 2000). The USGS collects, analyzes, and disseminates information on the domestic and international supply of and demand for sulfur.

The sulfur industry is different from many other important modern mineral industries in that the disposal of excess supplies of sulfur is becoming a more important consideration than the question of how to sustain production. Unlike other industries that are searching for economical methods to produce a usable product from decreasing reserves and poorer grades of ore, sulfur producers must strive to find innovative uses for continually growing sulfur supplies. As environmental concerns increase, the trend is to minimize the effects of mining by recycling mineral materials or substituting with more environmentally friendly materials. For the sulfur industry, however, increased environmental awareness results in further increases in the sulfur supply and smaller increases in the demand for sulfur in many industrial processes.

The unusual sulfur situation is a result of the changes of sulfur supply sources throughout the past 70 years. Whereas many mineral commodities are produced as a primary product from the mining of discreet ore bodies, or as desirable byproducts from mineral processing, the majority of sulfur produced is the result of environmental measures implemented to reduce emissions of sulfur dioxide into the atmosphere at petroleum refineries and nonferrous metal smelters and to remove poisonous hydrogen sulfide gas from natural gas deposits. Voluntary sulfur production, whether in the form of mined elemental sulfur or pyrites that are produced and burned to recover their sulfur content as sulfuric acid, has become continually less important in the global sulfur supply equation as shown in figure 13.

Sulfur—A Materials-Flow Analysis—*Continued*



* Includes 10 months of Frasch-process data for 1993; the other 2 months are included with recovered sulfur data to conform with proprietary data requirements. Data are estimates for 1994 through 2000.

Figure 13. Trends in sulfur production in the United States, 1978–2000 (Ober, 2000, 2002). The Frasch process, used to mine native sulfur, is one in which superheated water is forced into the sulfur deposit for the purpose of melting the sulfur. Molten sulfur is then pumped to the surface.

The long-term prospect is that 90 percent or more of the world sulfur supply will come from environmentally regulated sources and that output from these sources will be produced regardless of world sulfur demand. As a result, new operations that produce sulfur as the primary product will probably not be developed, and more voluntary operations will be curtailed. In 2000, voluntary sources of production—Frasch-process sulfur,[4] native sulfur, and pyrites—accounted for only 14 percent of the world output of about 57.2 million tons; in 1980, these same sources supplied 50 percent of the world production of 55.0 million tons.

Voluntary production of sulfur should continue to decline, and recovered sulfur supply will continue to expand at a faster pace than demand. As more countries enact and enforce environmental legislation on a par with European and North American laws, tremendous new quantities of sulfur could be recovered. More stringent regulation and compliance will be long-term developments and cannot be quantified at this time, but changes are inevitable. In fact, the impact of projects to improve sulfur recovery, especially at copper smelters, is already being felt.

Demand for sulfur has not kept up with production, creating a growing inventory of elemental sulfur globally. This situation is not expected to change significantly as long as most energy is produced from fossil fuels. Disposal of excess sulfur may become difficult if new high-volume uses for elemental sulfur are not implemented.

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[4]The Frasch process, used to mine native sulfur, is one in which superheated water is forced into the sulfur deposit for the purpose of melting the sulfur. Molten sulfur is then pumped to the surface.

Sulfur—A Materials-Flow Analysis—*Continued*

Global Sulfur Cycle

When considering the materials flow of any mineral, the global cycle must be considered; the scope of the global sulfur cycle dwarfs those of most others. More than 50 million tons of sulfur in all forms is produced annually worldwide for industrial consumption. The natural sulfur cycle is much harder to quantify but may be comparable in size. In addition, the burning of fossil fuels, especially coal, liberates tremendous quantities of sulfur dioxide, only some of which is recovered as byproduct sulfur compounds or waste material through gas-cleaning processes; the rest is released into the atmosphere.

Although most chemical elements have a global cycle, the global sulfur cycle is unusually active and pervasive with inputs from natural and man-made sources. Much of the cycle is difficult to quantify. The amount of sulfur that is produced through mining or as environmental byproducts at oil refineries, natural gas processing plants, and nonferrous metal smelters is reasonably well defined, but the quantity of sulfur dioxide released from electric power plants and industrial facilities in developing countries is harder to measure. Estimates of sulfur emissions from natural sources are even more difficult to measure because of the variety of sources, variability of emissions over time, the wide range of compounds involved, and the difficulties in measuring in remote locations.

The Natural Sulfur Cycle

The natural sulfur cycle is extremely complex and difficult to measure. Sulfur is pervasive in nature; it is a component of many forms of rock; and it is found in most fossil fuels (in varying quantities in coal, crude oil, and natural gas). Sulfur is essential in all living things, both plants and animals (Moss, 1978, p. 23).

Natural sources of sulfur include volcanoes, sea spray, organisms, and the weathering of sulfide minerals to sulfates, as shown in figure 14. Sulfates from the weathering of sulfide minerals can eventually reach the oceans through river runoff and erosion and become components of marine sediment. Other weathered sulfates react with bacteria to form compounds that are incorporated into the soil and plant systems. Animals may then ingest the plants and the sulfur compounds and are ultimately returned to the environment as sulfates (Moss, 1978, p. 27–29).

Volcanoes are the most dramatic natural source of sulfur, emitting sulfur during eruptions and also during noneruptive periods of volcanic activity. Most volcanic emissions enter the atmosphere, but some—especially elemental sulfur deposits—are found surrounding the volcano.

Seawater contains about 2.65 mg of sulfate per gram of water, and, as bubbles of seawater break, particles of sea salt are formed and emitted into the atmosphere. This sea spray is one of the largest sources of sulfur in the atmosphere, especially over open oceans. About 90 percent of this material is believed to cycle back into the oceans, with the remainder passing over the continents (Kellogg and others, 1972). The sulfate in seawater may come from weathered minerals discussed previously or through the decay of ocean organisms.

One of the more recent estimates of natural sulfur sources in the atmosphere places the input for open-ocean biogenic production (derived from the physiological activities of organisms) at 46 percent of total natural sulfur in the atmosphere, volcanoes at 18 percent; eolian (wind-raised) dust at 16 percent, terrestrial plants and soils at 13 percent, biomass burning at 4 percent, and coastal zone and wetland biogenic sources at 3 percent (Whelpdale, 1992, p. 6).

Sulfur—A Materials-Flow Analysis—*Continued*

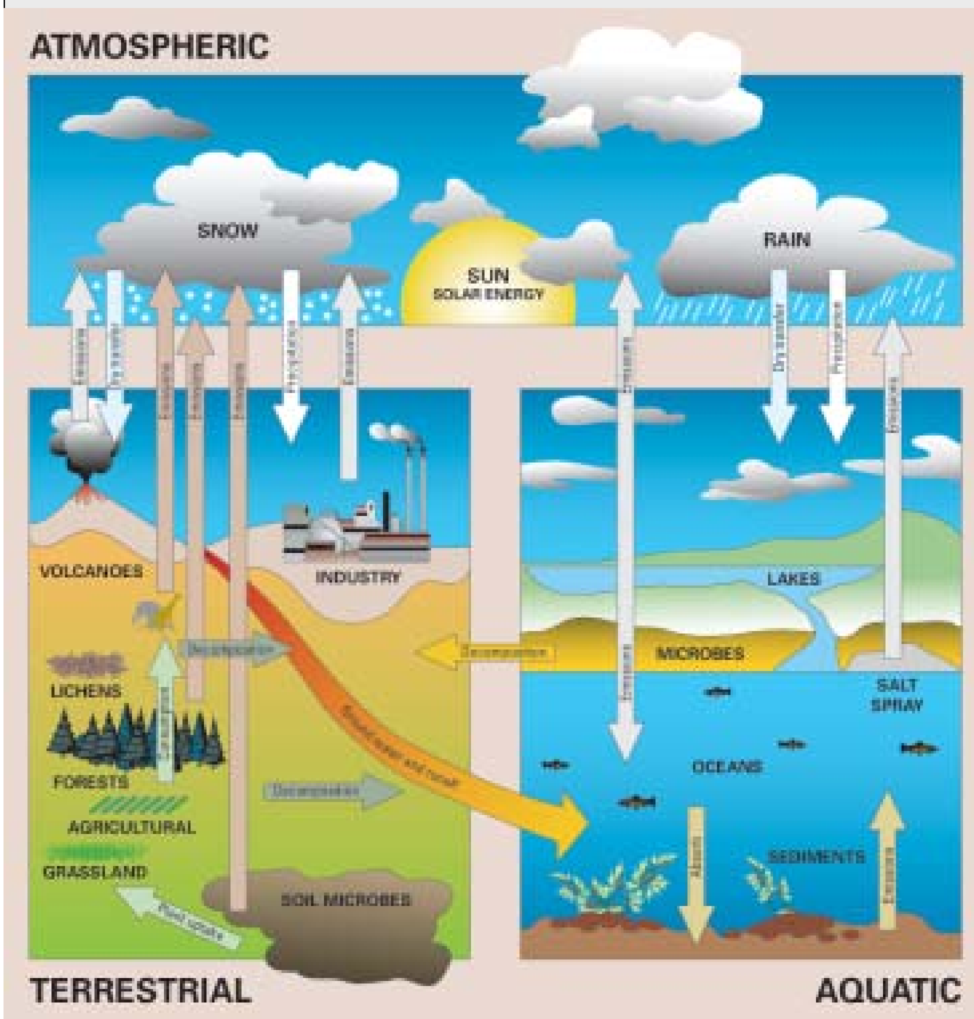

Figure 14. Contributors of sulfur to the environment are many and diverse. Natural sources of sulfur include volcanoes, oceans, plants, and animals. The burning of fossil fuels provides most of the sulfur from industrial sources.

The Anthropogenic Sulfur Cycle

The amount of sulfur entering the atmosphere through human activityÑthe anthro•pogenic sulfur cycleÑis easier to deÞne than the natural sulfur c ycle, but there remain signiÞcant uncertainties to its size in less developed areas of the world. The majority of anthropogenic sulfur emissions are in the form of sulfur dioxide resulting from the burning of fossil fuels (coal, petroleum, and natural gas) and the smelting of nonferrous metal ores and other industrial processes and burning (Whelpdale, 1992, p. 6).

Globally, man-made sulfur inputs to the atmosphere began to increase signiÞcantly early in the 20th century and continued the trend until about the mid-1970Õs when environmental regulations in North America and Western Europe began to limit allowable sulfur emissions.

Conclusions

The flows of materials generated in the world economy significantly affects peoples lives and the global environment. As population increases and people all over the world strive for a rich material life, the world is altered, wastes are generated, and the landscape is modified at a scale that is unprecedented.

In order to meet the people's future material needs, resources must be used wisely and impacts to the environment need to be minimized. There are many steps that can be taken, and many that have already been taken, to continue satisfying society's material needs and desires.

It is no easy feat to supply society's needs and desires without causing some damage to something somewhere. Building a road displaces native animals that inhabit the land. Building a dam changes fish habitats. Building a house means cutting down trees. Certain resources are required and always will be required. The challenge, then, is to find ways to satisfy society's needs sensibly, with an eye toward balancing material needs with their potential impact on the world's life-support systems and with the environmental values society holds.

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Manuscript approved for publication December 5, 2001

Published in the USGS Central Region, Denver, Colorado

Editing, layout, photocomposition—Richard W. Scott, Jr.

Cover design, figures 2, 8–10, 14—Carol A. Quesenberry

Figures 1, 3–7, 11–13—Springfield and Springfield