

New Technologies Using Trace Metals of Concern

Jozef M. Pacyna, Kyrre Sundseth, and Elisabeth G. Pacyna

Abstract

This chapter discusses the occurrence, material flows, technical applications of and pollution by platinum (Pt), palladium (Pd), thallium (Tl), rare earth elements (REEs), gold (Au), silver (Ag), and antimony (Sb), all of which are essential for global economic growth. Modern technology relies on these chemicals for the production of various industrial goods. However, their use releases pollutants into the environment, thus posing a threat to human health.

The impacts of these chemicals on human health are assessed in the context of their linkage to infectious diseases. The consequent environmental damage and political and economic implications of using these chemicals are also discussed.

To reduce environmental emissions and impacts to human health, more efficient cost-effective approaches are needed in mining and production processes. It is suggested that recycling and waste management can be improved significantly in many regions of the world to lessen the environmental impact of using these metals while contributing to a better economic situation. Information on the potential impacts that REEs and technologies using these metals have on infectious diseases is largely missing in the literature. This information gap needs to be closed through forthcoming research.

Introduction

Waste production, as measured by emission levels of pollutants to the atmosphere, impacts aquatic and terrestrial ecosystems and needs to be minimized, or even avoided, during the production of industrial goods. To this end, new innovative technologies have been designed to address this problem; their implementation, however, is still accompanied by emissions of various pollutants to the environment. This is due primarily to the presence of various chemicals as impurities of raw materials that are used in the production process (i.e., by-product emissions) or to the application of chemicals used to improve the operation of various technologies. Emissions of several trace metals have been

well studied over the last three to four decades (e.g., Nriagu and Pacyna 1988; Pacyna and Pacyna 2001; UNEP 2013).

In this chapter, we review information on the application of select trace metals in new technologies to produce industrial goods and the resulting environmental emissions of these metals. High technology and environmental applications of several metals have grown dramatically in diversity and importance over the past four decades. These applications, however, can have an adverse impact on the environment, and consequently on human health.

Our primary focus is to analyze the use and environmental emissions of trace metals with scientifically documented harmful effects on the environment and human health. Wherever heavy metals might affect infectious disease, it is of paramount importance to reduce their release into the environment. Once the most dangerous species, particle sizes, and ways of ingestion are identified, human exposure must be limited. To estimate this exposure and recognize its sources, we provide an overview of overall occurrence, material flows, technical applications of and pollution by platinum, palladium, thallium, rare earth elements, gold, silver, and antimony. Throughout, these metals will be referred to as “metals of concern.” Finally, we present an approach that analyzes the costs and benefits of reducing the emissions of these metals to the environment.

Human Health Impacts

Trace metal toxicology is one of the broadest, rapidly growing fields in toxicology. Metals have served as one of the earliest medicines as well as poisons throughout human history (e.g., Chang 1996). A great number of studies have been conducted to assess the impact of metals in terms of (a) carcinogenesis and genotoxicity, (b) neurotoxicology, (c) renal toxicology, and (d) reproductive and developmental toxicology. In addition, research has been carried out on bioresponses and reactivities to metal toxicity, immunomodulation by metals, and the effects of metals on other organ systems. Over the last two decades, clinical aspects of metal toxicity as well as environmental and human risk assessments have been reported (see, e.g., Chang 1996).

Each metal has a unique mechanism of action with regard to its impact on human health, and these impacts occur primarily on a local scale. We begin, therefore, with a short description of the human health impacts for each metal of concern.

Pure platinum is relatively nontoxic; however, Pt salts give rise to allergic symptoms, including irritation (after short-term exposure) and hypersensitivity of the skin, dermatitis, platinosis, and asthma (a result of long-term exposure). Platinum compounds can also produce toxic effects, including cumulative nephrotoxicity and sometimes neurotoxicity (Van der Voet and de Wolff 1996). Palladium, similar to platinum, is one of 15 metals that can cause

allergic contact dermatitis, a form of delayed hypersensitivity reaction of the skin (Kimber and Basketter 1996).

Thallium and its compounds are extremely toxic, and numerous cases of fatal Tl poisoning have been reported (Van der Voet and de Wolff 1996). Large doses of Tl compounds cause acute gastrointestinal symptoms with neurological effects that manifest hours to days after exposure. These symptoms comprise a demyelinating polyneuropathia and may result in mental disturbances (e.g., psychosis, paranoia, and hallucinations). Occasionally, Tl poisoning causes kidney and liver damage. In addition, thallium is a suspected human carcinogen.

Rare earth elements are a set of 17 chemical elements in the periodic table: the 15 lanthanides plus scandium and yttrium. Scandium and yttrium are considered REEs because they tend to occur in the same ore deposits as the lanthanides and exhibit similar chemical properties. Physical growth and development, immune system function, and intelligence can be affected when REEs are present in the environment. Because of this, health response indexes have been devised to measure children's environmental exposure to REEs.

Elemental gold is nontoxic and nonirritating when ingested. Soluble compounds (Au salts) such as Au chloride are, however, toxic to both the liver and kidneys. Common Au cyanide salts (e.g., potassium Au cyanide) are toxic by virtue of both their cyanide and Au content. Rare cases have been reported (Wu et al. 2001) of lethal Au poisoning from potassium Au cyanide. Gold toxicity can be ameliorated through chelation therapy that uses an agent such as dimercaprol. Gold contact allergies affect mostly women. In fact, in 2001, gold was voted the "Allergen of the Year" by the American Contact Dermatitis Society.¹

Elemental silver is nontoxic to humans; however, its impact on human health is still under debate. Most Ag salts are toxic. In large doses, Ag compounds can be absorbed into the circulatory system, where they become deposited in various body tissues, leading to blue-grayish pigmentation of skin (e.g., Zheng 1996). The eyes can also be affected. Ongoing research is currently searching for information on the toxic effects of nanosilver (e.g., the release of Ag from nanoparticle containing dressing), since nanosilver emissions to the atmosphere have become a new challenge in trace metal studies (Walser et al. 2013).

Antimony and most of its compounds are toxic. The effects of Sb poisoning are similar to arsenic (As) poisoning, although the toxicity of antimony is by far lower than that of arsenic. Fatalities from Sb poisoning are rare, but acute systematic exposure to Sb compounds causes hair and weight loss as well as dry scaly skin. Damage to the heart, liver, and kidneys can occur, and death from myocardial failure may follow. The systemic toxicity of trivalent Sb compounds is significantly less than pentavalent Sb compounds, and this fact is quite important when the use of Sb compounds is considered. A similar toxicity profile is observed for As compounds.

¹ <http://www.contactderm.org/i4a/pages/index.cfm?pageid=3467> (accessed October 9, 2014)

In Table 17.2, Ackland et al. (this volume) summarize the effects of the above-mentioned trace metals of concern on the immune system and host defenses against infection, as well as their direct antimicrobial properties. However, information on potential impacts of REEs and technologies using these metals on infectious diseases is largely missing from the literature. This gap must be addressed by future research efforts.

Major Applications

Several industrial sectors use metals of concern throughout production. For many applications, these metals are critical resources that enable modern technologies. As such, ensuring an adequate supply of these metals has become a matter of economics as well as environmental and political concern. Because they are essential for a large and expanding array of high-technology applications, long-term shortage would force significant changes in societal development in various regions of the world.

Platinum and Platinum Group Metals

Platinum and Pt group metals (PGMs) are critical components for various technologies used in the manufacture of industrial catalysts, automobile catalysts, electronics, glass products, jewelry, dentistry and other applications, including pharmaceutical production. Of the 245 tonnes of platinum sold in 2010, it is estimated that vehicle emission control devices and jewelry accounted for primary usage: 113 tonnes (46%) and 76 tonnes (31%), respectively (Loferski 2011).

Since the early nineteenth century, Pt powder has been used to catalyze the ignition of hydrogen. In automobiles, its use in catalytic converters allows the complete combustion of low concentrations of unburned hydrocarbons from the exhaust into carbon dioxide and water vapor. In the petroleum industry, platinum is used especially in the catalytic reforming of naphthalenes into higher-octane gasoline.

Production of PGMs can be regarded as primary or secondary. Primary production includes mining and smelting processes, whereas secondary production results from the recycling of wastes. Industries which use PGMs have usually developed a closed-loop management of waste with recyclers.

As one of the major users of PGMs, Europe imports its supply in the form of PGM concentrates, refined PGMs, and imported products that contain PGMs (e.g., car catalysts and electronic equipment). PGM flows in Europe have been tracked by Saurat and Bringezu (2008) using substance flow analysis. In 2004, for instance, the EU-25, Norway, and Switzerland imported 113,836 kg of platinum, palladium, and rhodium from South Africa, Russia, Canada, and the United States. Illustrating this flow of PGMs, Figure 15.1 shows the primary uses of these metals, their life cycle, the specific environmental pressures

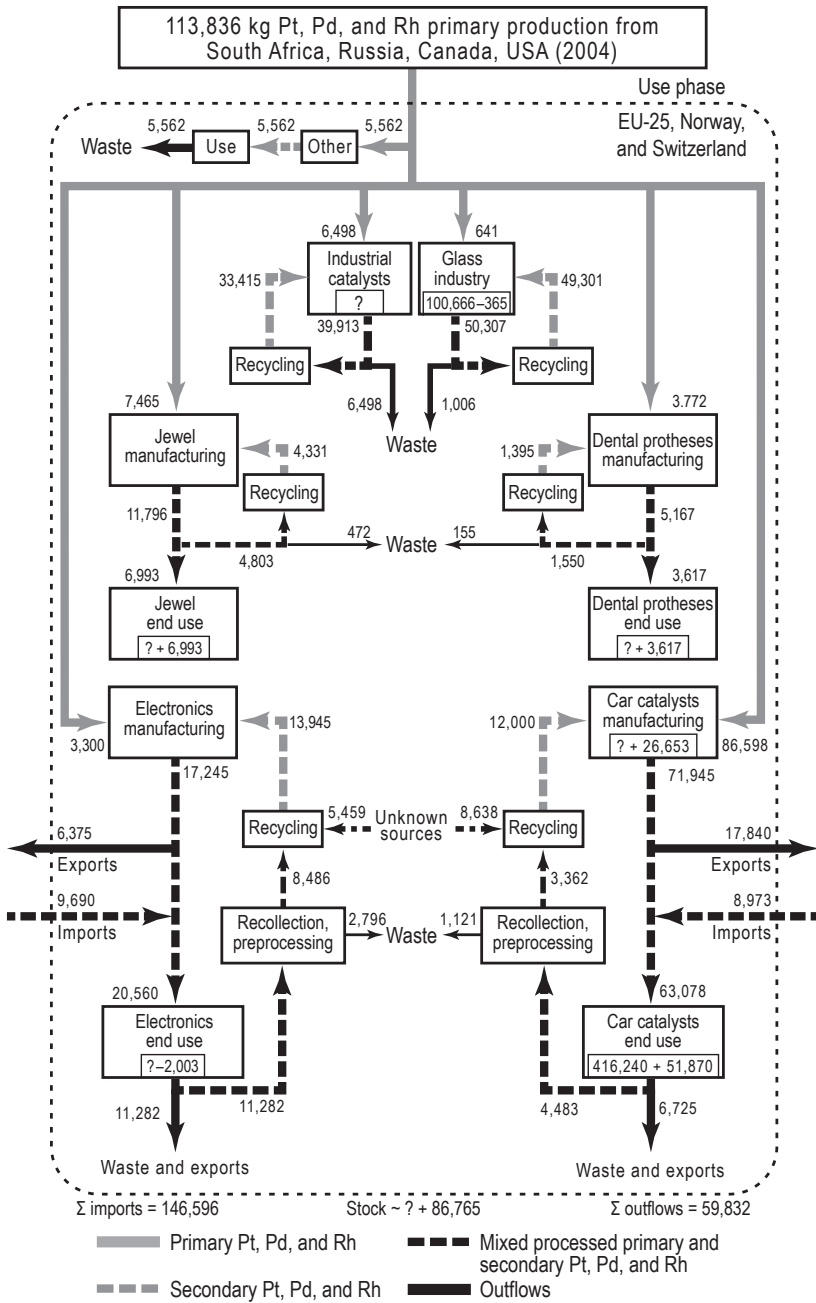


Figure 15.1 Flows of platinum, palladium, and rhodium that entered the European Union (EU-25, including Norway and Switzerland) in 2004 are depicted, based on an analysis by Saurat and Bringezu (2008).

created (particularly by secondary production of PGMs), and the recycling rate. This information provides a basis for discussing options to reduce demand for primary PGMs.

Substance flow analysis can also be used to discuss the flow of metals within a given sector. An assessment of Pd, Au, and Ag flows during the preprocessing of waste from electrical and electronic equipment has been prepared by Chancerel et al. (2009). Figure 15.2 shows the flows of these metals during preprocessing of 1 tonne of input in waste electrical and electronic equipment.

Thallium

Thallium and its compounds are used mainly in optics, electronics, high-temperature superconductivity, and various medical applications. Because they are harder than other common infrared optics, Tl compounds have been used as infrared optical material. In addition, Tl compounds transmit at significantly longer wavelengths. Thallium is also used to produce high-density glasses.

The electrical conductivity of some Tl compounds changes with exposure to infrared light. As a result, Tl compounds are used to produce photoresistors. They are also used to improve the efficiency of sodium iodide (NaI(Tl)) crystals in scintillation detectors. Finally, one of the most interesting applications of thallium is in the development of high-temperature superconducting materials for applications such as magnetic resonance imaging, storage of magnetic energy, magnetic propulsion, and electric power generation and transmission.

Rare Earth Elements

Since 1985, production of REEs has grown rapidly to meet the demand created by new and important applications (see Table 15.1). This sharp increase has been met by China (Figure 15.3), which currently produces over 95% of the world's REE supply, mostly in Inner Mongolia, even though it has only 37% of proven reserves. By 2012, these figures were reported by Bradsher (2010) to have decreased to 90% (production rate) and 23% (proven reserves).

The diverse nuclear, metallurgical, chemical, catalytic, electrical, magnetic, and optical properties of the REEs have led to a variety of applications: from everyday usage (e.g., lighter flints, glass polishing), to high-technology (e.g., phosphorus, lasers, magnets, batteries, magnetic refrigeration) and futuristic applications (high-temperature superconductivity, safe storage and transport of hydrogen for a post-hydrogen economy) (Haxel et al. 2002).

As can be seen from Table 15.1, many applications of REEs are characterized by high specificity. Some of these have led to breakthrough changes in technology. One such example is permanent magnet technology, which uses alloys that contain neodymium, samarium, gadolinium, dysprosium, or praseodymium. In addition, REE magnets have allowed for the miniaturization of numerous electrical and electronic components used in appliances, audio and

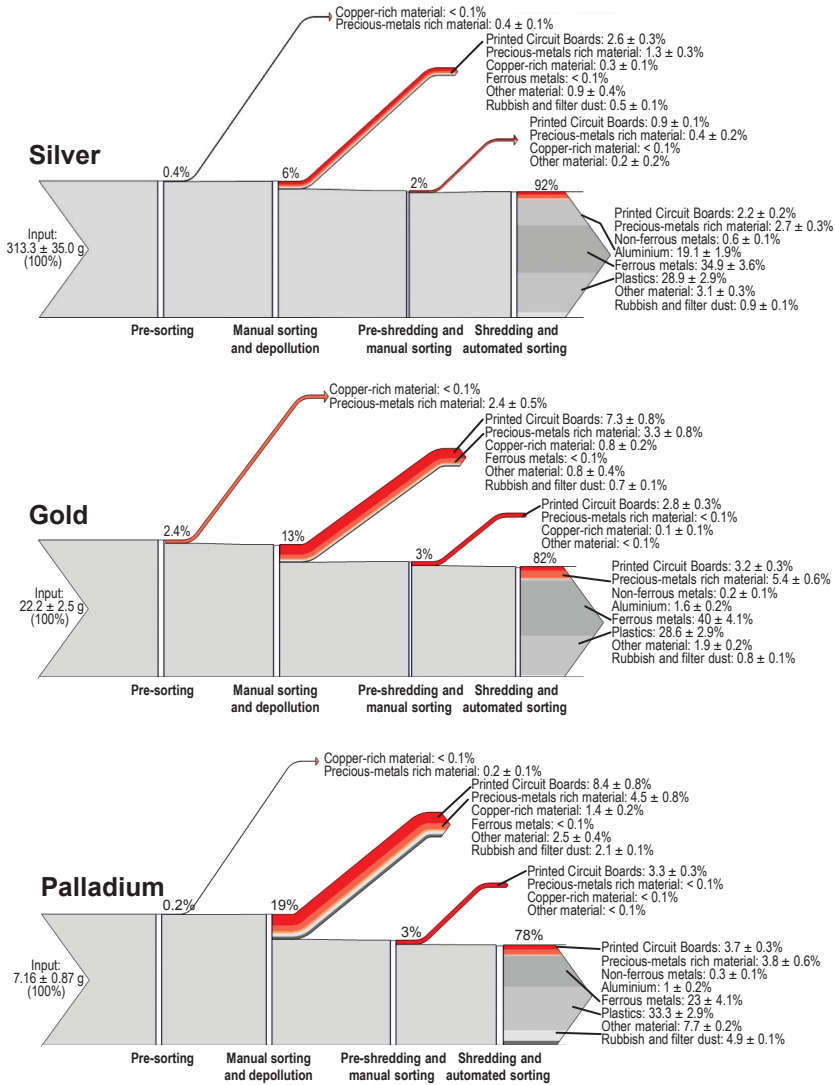


Figure 15.2 Flows of silver, gold, and palladium during preprocessing of 1 tonne of input from waste electrical and electronic equipment (from Chancerel et al. 2009; reprinted with permission from John Wiley and Sons).

video equipment, computers, automobiles, communication systems, and military gear (Haxel et al. 2002). REEs are also used in various sustainable energy generation applications (e.g., wind mills, electricity generators), primarily as powerful permanent magnets.

Several REEs are essential in the petroleum industry as fluid cracking catalysts as well as for automotive pollution control as catalytic converters.

Table 15.1 Application of rare earth elements.

Name	Selected Applications
Scandium (Sc)	Al-Sc alloys for aerospace industry components, additive in metal-halide lamps and Hg vapor lamps, radioactive tracing agent in oil refineries, catalyzer in organic chemistry
Yttrium (Y)	Yttrium aluminum garnet laser, yttrium vanadate as host for europium in TV red phosphor, $\text{YBa}_2\text{Cu}_3\text{O}_7$ high-temperature superconductors, Yttria-stabilized zirconia, yttrium iron garnet microwave filters, energy-efficient light bulbs, spark plugs, gas mantles, additive to steel, $\text{YAl}_3(\text{Ce})$ scintillation detectors
Lanthanum (La)	High-refractive index and alkali-resistant glass, flint, LaNi_5 hydrogen storage, Ni-metal hydride batteries, camera lenses, fluid catalytic cracking catalyst for oil refineries
Cerium (Ce)	Chemical-oxidizing agent, polishing powder, yellow colors in glass and ceramics, catalytic converter for CO oxidation in cars, catalyst for self-cleaning ovens, fluid catalytic cracking catalyst for oil refineries, ferro-cerium flints for lighters
Praseodymium (Pr)	High-power magnets, lasers, core material for carbon arc lighting, colorant in glasses and enamels, additive in didymium glass used in welding goggles, ferro-cerium fire-steel (flint) products
Neodymium (Nd)	$\text{Nd}_2\text{F}_{14}\text{B}$ magnets, lasers, violet colors in glass and ceramics, didymium glass, ceramic capacitors
Promethium (Pm)	Nuclear batteries
Samarium (Sm)	SmCo_5 and $\text{Sm}_2\text{Co}_{17}$ magnets, lasers, neutron capture, masers, catalysts, in ceramics and glass
Europium (Eu)	Red and blue phosphors, lasers, mercury-vapor lamps, fluorescent lamps, NMR relaxation agent
Gadolinium (Gd)	Rare-earth magnets, high-refractive index glass or garnets, lasers, X-ray tubes, computer memories, neutron capture, MRI contrast agent, NMR relaxation agent, magnetostrictive alloys such as Galfenol, steel additive
Terbium (Tb)	Dopant materials, green phosphors, lasers, fluorescent lamps, magnetostrictive alloys such as Terfenol-D in naval sonar systems and sensors
Dysprosium (Dy)	Rare-earth magnets, lasers, magnetostrictive alloys such as Terfenol-D
Holmium (Ho)	Solid-state lasers, wavelength calibration standards for optical spectrophotometers, magnets, colorant in glass
Erbium (Er)	Neutron-absorbing control rods in nuclear technology, infrared lasers, vanadium steel, fiber optic technology, photographic filter, medical applications in dermatology and dentistry
Thulium (Tm)	Portable X-ray machines, metal-halide lamps, lasers, high-temperature superconductors
Ytterbium (Y)	Infrared lasers, chemical reducing agent, decoy flares, stainless steel, stress gauges
Lutetium (Lu)	PET scan detectors, high-refractive index glass, lutetium tantalate hosts for phosphors, catalyst in petroleum cracking

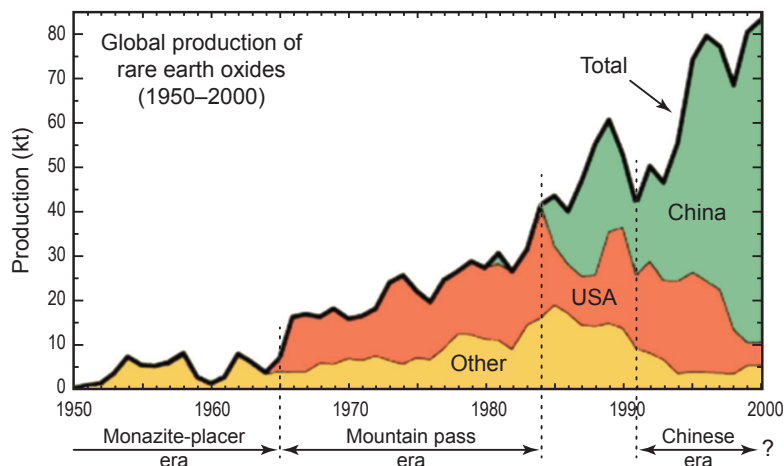


Figure 15.3 Global production of rare earth elements (1 kt = 106 kg) from 1950 to 2000 (Haxel et al. 2002).

La-Ni-hydride batteries show greater energy density, better charge-discharge characteristics, and fewer environmental problems in terms of their disposal or recycling.

Another high-technology application of REEs is related to magnetic refrigeration. This type of refrigeration came about after the discovery of the giant magneto-caloric effect in $\text{Gd}_5\text{Si}_2\text{Ge}_2$ by Pecharsky et al. (2003). It is more efficient than conventional gas compression refrigeration and is used in residential, commercial, and automotive air conditioners.

Gold

According to the Gold Fields Mineral Resources,² as of 2012, a total of 174,100 tonnes of gold have been mined throughout human history. Annually (according to 2013 figures), about 2800 tonnes of gold are mined globally for the following primary uses: 50% for jewelry, 40% for coins and ingots, and 10% for industry.

Archaeology has provided evidence of the use of gold in coins in Lydia, Asia Minor as of ca. BC 600.³ Major industrial applications include the use of gold in toners to shift the color of prints or to increase their stability in photography. In addition, because it reflects electromagnetic radiation (e.g., infrared and visible light as well as radio waves) well, gold is used for the protective coatings on many artificial satellites, in infrared protective faceplates in thermal protection suits and astronaut helmets, as well as in electronic warfare

² <http://www.gold.org> (accessed October 9, 2014)

³ <http://www.asiaminorcoins.com/gallery/thumbnails.php?album=43> (accessed October 9, 2014)

aircraft. Due to its effectivity in heat shielding, it can be used in automobiles; McLaren Racing Limited, for example, uses a Au foil in the engine compartment of its F1 model. Since it can be manufactured so thin that it appears transparent, gold is also used in the design of some aircraft cockpit windows; passing electricity through it permits de-icing or anti-icing. Finally, gold is used in electronics. Since it is a very effective conductor for electricity, it has been used in the electrical wiring of various high-energy applications.

Silver

In the Middle Ages, silver and Ag salts were used primarily to produce a strong clear yellow pigment in early stained glass. In the parish church of Le Mesnil-Villeman, Manche, France, evidence of the Ag stain technique is traceable back to 1313 (Marks 1993). Later, silver was used in currency coins, ornaments, and jewelry. More recently, silver has been used in various industrial applications: in electrical contacts and conductors, mirrors, and catalysis of chemical reactions. Some of these electrical and electronic products employ silver because of its superior conductivity (e.g., in cables and wires) and to ensure superior reflectivity of visible light (e.g., mirror production). Silver compounds are used in photographic film as well as in disinfectants, microbiocides, and antibiotics. Control rods of nuclear reactors are routinely made using the $\text{Ag}_8\text{In}_{15}\text{Cd}_5$ alloy; this permits efficient joining of high-absorption cross sections for thermic neutrons (contributions Ag 50 barn, Cd 130 barn, In 10 barn). It also ensures stability during activation, corrosion, and temperature fluctuations: the Ag fraction contributes 50 barn, the Cd fraction 125 barn.

Currently, silver is viewed as one of the “technological nutrients” without which modern society could not function. Therefore, it is of vital importance to quantify cycles of these “nutrients” with indications of their major sources, abundance, and transfer in the environment. A rather large body of information is now available (Rauch and Pacyna 2009), which makes it possible to review Earth’s global cycle of silver and seven other chemicals. Figure 15.4 illustrates the flows, stocks, and changes in net stocks of global silver (Rauch and Pacyna 2009).

Antimony

More than 50% of the world’s Sb reserves are located in China. In 2010, about 135,000 tonnes of antimony were produced worldwide, 89% of which derived from China (120,000 tonnes) (Papp et al. 2008).

Major Sb applications include alloys and flame retardants. It is also used as an alloying material for lead and tin, as well as for lead acid batteries: antimony improves charging characteristics and reduces generation of hydrogen. Antimony alloys are also used in the production of bearing metal and solders. Other metallic uses include the production of ammunition, cable covering, and castings.

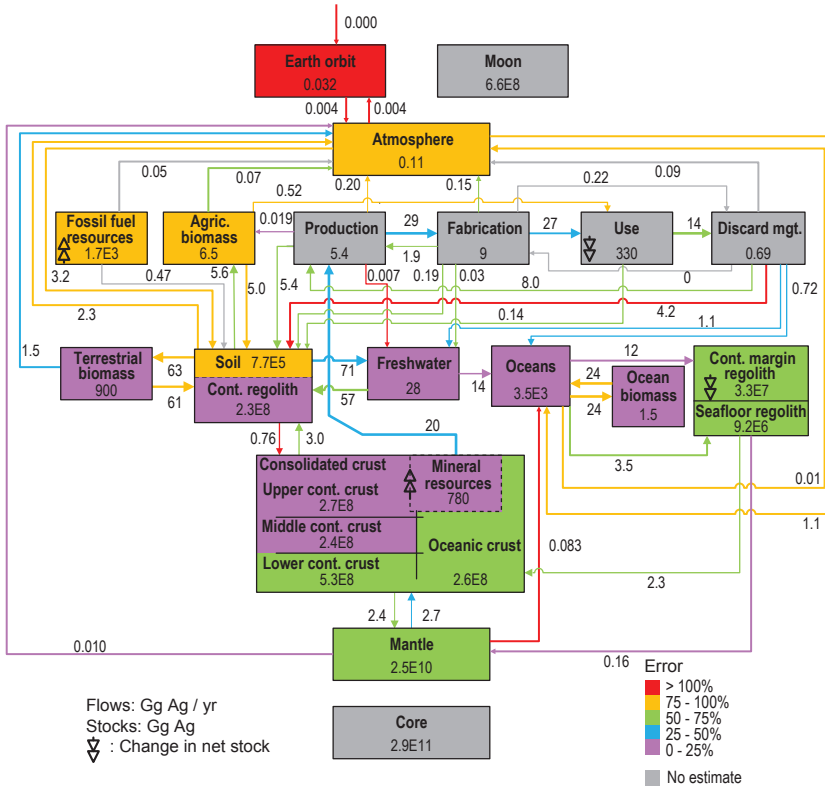


Figure 15.4 Earth’s global cycle of silver (from Rauch and Pacyna 2009, reprinted with permission from John Wiley and Sons).

Trioxide of antimony is used to make flame-proofing compounds and products. These nonmetallic uses include plastic additives in the production of stabilizers, catalysts, ceramics and glass production, and pigment production (Butterman and Carlin, Jr. 2004). Increasingly, antimony is being used in microelectronic applications, where it is being used by the semiconductor industry as a dopant in the production of diodes, infrared detectors, and other devices.

Environmental Impacts of Production and Application

Ideally, the application of metals of concern in new technologies should improve the efficiency of industrial production without damaging the environment. However, industrial processes (i.e., applications related to both primary and secondary production: mining, smelting, recycling) continue to contaminate the environment with metals and other pollutants (e.g., CO₂, sulfur and nitrogen oxides). For example, in 2004, SO₂ emissions associated with the

production of PGMs used in Europe reached 3% of the total direct SO₂ emissions for the EU-15 in 2003. At the same time, reduction of SO₂ emissions in Europe resulted in the need to provide sulfur supplementation of soils via fertilizers.

The application of new technologies that utilize metals of concern can, however, benefit the environment by reducing emissions of some contaminants. An obvious example is the reduction of automobile emissions of various gaseous pollutants that was achieved through PGM catalysts, as well as the application of these catalysts in petrochemical industry.

In the following sections, we review information on environmental damage and benefits that have resulted from the application of metals of concern.

Environmental Damage Caused by the Production

Sources of metals of concern—particularly REEs and PGMs—are placer sand deposits or side elements from ores of other major metals (e.g., zinc, copper, nickel, and lead). Ore mining, refining, and smelting can have serious environmental consequences if not properly managed. Most mining operations occur in underground mines and affect the environment well beyond the immediate area of the extraction site (due, in particular, to sulfur emissions and deposition through acid rain). To reduce aboveground pollution and costs, there is a tendency to sort lumps of ore underground in the mine galleries using automated X-ray analytical techniques. For open pit mines, pollution via dust from carrier ores that are released during digging and milling poses a major concern. Gold, for example, occasionally mined as a trace constituent of arsenopyrit (FeSAs), leads to As exposure, as exemplified around the Kinross Paracatu mine in Brazil.

Two major technological processes are involved in nonferrous metallurgy. The first is the pyrometallurgical process, where roasting is used to split sulfur from the metals in the ores. This high-temperature process is a known source of emissions of various pollutants, including metals of concern to the atmosphere. The second is based on the hydrometallurgical process: ore is dissolved in acid and digested; elements are then differentially precipitated or separated using ion chromatographic techniques, which means that discharges of pollutants to aquatic ecosystems can be expected.

Secondary metal production involves waste recycling that contains various pollutants, including metals of concern. This process usually involves high temperatures, and emissions of contaminants to the atmosphere are very difficult to avoid. Compared to secondary production technologies, primary metal production technologies are much better controlled with respect to the pollutant emissions.

Not all wastes are recycled, however. Significant quantities of metals deposited in wastes can be found in tailing and landfills. This poses a serious problem related to the contamination of terrestrial ecosystems by various contaminants.

Quantification of emissions from metals of concern to the atmosphere, land, and water has been approached only on a limited scale. This information is largely missing from the literature, particularly for emissions on scales larger than local scale (i.e., on national, continental, or global scales). Nriagu and Pacyna (1988) published the first worldwide inventory of antimony, thallium, and 14 other trace elements to air, water, and land. It was estimated that at least one-quarter of all the antimony and thallium produced and used annually at the end of the 1980s ended up as environmental contaminants.

Subsequent to this inventory, the methodology for assessing the charge of metals to the environment, as a result of their production and uses, has improved significantly. Current methodology is based on the application of substance (material) flow analysis and life cycle assessment. Several research groups have been formed to perform analyses. For example, the Stocks and Flows (STAF) Project, from the Center for Industrial Ecology at Yale University, has been involved in evaluating current and historical flows of specific technologically important materials, determining available stocks in different types of reservoirs and the flows among the reservoirs, developing scenarios of possible metal use in the future, and assessing metal supply and demand as well as emissions to the atmosphere. Figure 15.5 depicts the flow of metals during these processes and subsequent release to the environment.

Silver was one of the metals analyzed by the STAF program, as shown in Figure 15.4 (Rauch and Pacyna 2009). Earth and its orbital bodies constitute the system boundary, and all flows larger than 1 Mg/yr between reservoirs were explicitly quantified. Mass balance of atmospheric, water, and biomass reservoirs—assuming no net accumulation due to high turnover rates—was applied to estimate flow magnitudes. Estimated uncertainties are absolute errors

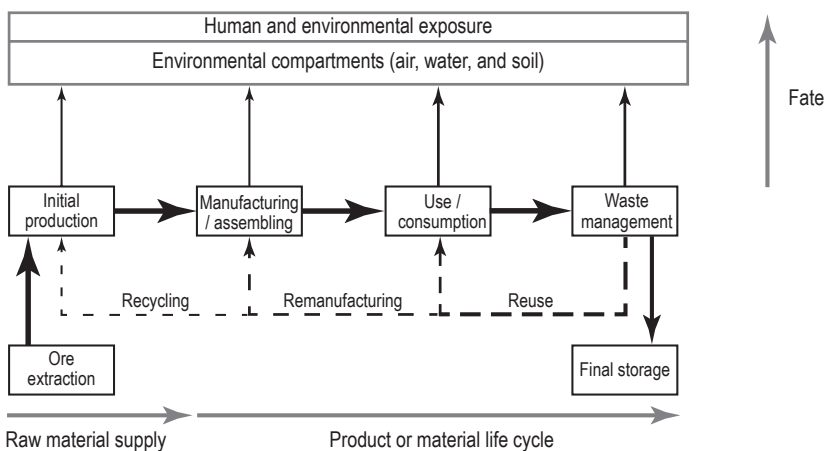


Figure 15.5 A flow scheme of the releases of pollutants to the environment during various production processes.

calculated by propagation of the estimated or standard errors associated with the source data. The entire exercise provides a diagrammatic representation of Earth's global metal cycles, combining the endogenic reservoirs of the core, mantle, and consolidated crust, the natural exogenic cycles of the pedosphere, hydrosphere, and biosphere, the anthropogenic exogenic reservoirs from production to waste management, and Earth's atmosphere and orbit.

Metals (metal groups) of concern impact the environment in different ways that are related to variations in production/use processes used in various countries. For PGM metals, the total material requirement (TMR), which represents the resource-intensive side of PGM production, is higher for South Africa (over 628,000 tonnes per 1 tonne of extracted PGMs; Saurat and Bringezu 2008) than for Russia. TMR includes wastes from precious metal mining as well as material used to generate the electricity used in mining. Thus, the TMR factor reflects CO₂ emissions: the higher the TMR factor, the higher the CO₂ emissions. In general, the production of selected metals of concern (e.g., PMGs and gold) requires very high amounts of primary energy, estimated at between 200,000 and 300,000 MJ/kg (UNEP 2013). Thus, large amounts of greenhouse gas emissions can be expected when this primary energy is produced.

A particular hazard related to the production of REEs is mildly radioactive slurry tailings, resulting from the common occurrence of thorium and uranium in the REE ores. However, other resources, such as coal, also contain these radioactive chemicals, resulting in emission of various radioisotopes during the coal combustion for electricity production (needed to produce REEs). In addition, toxic acids are required during the refining process of REEs. Improper handling of these substances may result in significant environmental contamination.

Negative Implications Related to Usage

Unfortunately, various applications that use metals of concern negatively impact the environment. As illustrated in Figure 15.5, most of these impacts relate to the disposal of wastes containing these metals. E-wastes (i.e., wastes from electrical and electronic equipment) constitute one important type of waste (e.g., Robinson 2009) and often contain REEs and PMGs compounds, among other trace elements. Concentrations of environmental contaminants found in E-wastes depend on the type of item that is discarded and the point in time when that item was produced. E-waste composition is spatially and temporally heterogeneous. China receives some 70% of all exported E-waste (Liu et al. 2006); significant quantities are also exported to India, Pakistan, Vietnam, the Philippines, Malaysia, Nigeria, and Ghana (Puckett et al. 2005), and possibly to Brazil and Mexico.

Most E-waste currently ends up in landfills (Barba-Gutierrez et al. 2008). From dumpsites where processed or unprocessed E-waste is deposited, E-waste

contaminants can enter aquatic systems via leaching. Similarly, following hydrometallurgical processes, disposal of acid into waters or onto soils and the dissolution or settling of airborne pollutants can contaminate aquatic systems.

E-waste contaminants are also dispersed into the air via dust, thus providing a major exposure pathway for humans through ingestion, inhalation, and skin absorption. Atmospheric emissions also occur through metal use in nanotechnology. Good examples are emissions of nanosilver (e.g., Walser et al. 2013) from various applications of nanoparticles in antibacterial materials, antistatic materials, cryogenic superconducting materials and biosensor materials (e.g., Zhang et al. 2006a), and emissions of nanoplatinum and nanopalladium from applications in necessary catalysts for commercially important reactions (e.g., Pauporte et al. 2006).

Beneficial Implications for the Environment

Major environmental benefits from various applications of metals of concern begin with the employment of high technologies to produce energy and various industrial and agriculture goods. The application of PGMs in catalytic converters for the automobile industry has reduced emissions of nitrogen oxides (NO_x) and NMVOCs (nonmethane volatile organic compounds), although CO_2 and SO_2 emissions increase slightly during this process due to higher fuel consumption. Still, the use of car catalysts leads to a significant overall reduction of emissions from acidifying and eutrophication agents, whereas the effect on global warming is less relevant (Saurat and Bringezu 2008). The problem, though, shifts from environmental impacts discussed above to impacts that largely affect Earth's surface through the increase in resource extraction and mining wastes. In this context, the overall environmental effect related to the application of PGMs depends on their mode of production. Beneficial effects will be larger if the PGMs are produced from recycling (i.e., through secondary production). However, since recycling rates are still relatively low in many sectors (e.g., electronics, production of catalytic converters), primary production is needed for the foreseeable future.

PGMs are used as catalyzers not only in the automobile industry but also in other industrial sectors (e.g., in electric power plants, refineries, and the chemical industry) to lower the emissions of NMVOCs and other pollutants. Particularly important is the application of catalyzers in the electricity and heat production sectors, where the application of PGMs to reduce emissions of NO_x is currently regarded as the most modern technology.

Catalytic properties of silver make it ideal to use as a catalyst in oxidation reactions in the chemical industry, where it is used, for example, to produce formaldehyde from methanol. This method of formaldehyde production is regarded as being extremely environmental friendly.

Political and Economic Implications

The special properties of the metals of concern that we have described explain why these metals are essential for hundreds of applications. Yet despite their necessity, most countries rely on imports to meet their production needs for two reasons: (a) most of the global supply originates from a few exploitable ore deposits and (b) most of the metals are difficult to extract in an economically viable and environmentally sound manner. Due to relatively lower exploitation costs (particularly in terms of labor and regulatory costs) and the transfer of processing technology from Europe and North America to Asia over the last few decades, China has emerged as the major producer of many of these metals (Haxel et al. 2002). This reality (i.e., having a single major provider on a global level) makes geopolitics and trade policies very important factors in the determination of global supply and market price. Additional factors influence market price as well: scarcity, supply-demand balance, stocks and rate of use, market disruptions, market expectations, and the level of speculative versus nonspeculative investments. From 1990–2007, for example, as the observed price of REEs declined, China raised restrictions on exports, which caused prices to increase substantially as of 2007; these restrictions failed in 2012 after threats were made that would have shifted global production (e.g., Haxel et al. 2002; Tse 2011).

Metals of concern are widely used to improve human well-being. Their application is critical in many areas of technology, transport, and defense systems, and, as such, they constitute an important part of the industrial economy. At the same time, the increasing dependency on these metals is a matter of great concern for scientists and policy makers, as future market scarcity becomes likely. New technologies and fast-growing products (e.g., cell phones, computers, electric motors for cars) use many trace metals of concern. The growth of world economies—particularly material-intensive emerging economies and heavily populated developing countries—will drive future demand for these metals. This may lead to a pressure on availability as well as on the value chain of the product, including waste-handling systems. In addition, due to REE use in many defense systems (e.g., some metals are essential for precision-guided missiles, smart bombs, aircrafts, and magnets in defense weapon systems), availability affects national vulnerability.

Final Comments

Metals of concern are essential for global economic growth. However, many of these metals are difficult to extract in an economically viable and environmentally sound manner. This contradiction needs to be taken into account when the further use of these metals is considered in new modern technologies. In addition, the recycling of waste is a very important issue that must be addressed.

New recycling technologies have been developed that enable better extraction of metals, particularly REEs and PGMs. However, effective recycling has yet to be implemented: in Japan alone, it is estimated that 300,000 tonnes of REEs are currently stored in unused electronics (Tabuchi 2010).

The “true value” of metals, including social and environmental costs and benefits, need to be taken into account when new metals are considered for application. Potential revenues from the entire value chains need to be compared holistically with cost or benefits, assessed according to a life-cycle perspective. To assist analysis, monetary valuation methods need to be employed. Research on mercury provides an example of costs and benefit analysis performance: investment and operational costs to reduce Hg emissions from anthropogenic sources, including the Hg uses, have been compared to damage costs that resulted from Hg pollution of the environment and subsequent human health impacts (Sundseth et al. 2009). It would be worth exploring whether procedures from the Hg costs and benefits analysis could be modified and used to analyze metals of concern.

Future research should find ways to improve the production and use of metals of concern that makes sense, both in economic and environmentally friendly terms. More efficient, cost-effective approaches are needed to mine and produce metals, so that air, water, and soil emissions generated during these processes can be reduced. In addition, energy requirements for primary production constitute a major concern. We need to improve energy efficiency and increase the use of renewable energy sources to reduce environmental impacts related to the use of energy in metal production.

Recycling and waste management can be improved significantly in many regions of the world. This would contribute to a better economy while lowering the environmental impacts of metal’s production and use. Recycling rates are increasing but further improvement is needed. System optimization, including a proper product design, offers the ability to do so (e.g., UNEP 2013).

