



Mineral Commodity Profiles

Cesium

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MINERAL COMMODITY PROFILES

Cesium

By William C. Buttermann¹, William E. Brooks, and Robert G. Reese, Jr.¹

Overview

Cesium is a very soft, ductile, alkali metal that is liquid at 28.4° C. It is the most electropositive and reactive of the alkali metals and forms compounds with a variety of anions and alloys with the other alkali metals and with gold.

The metal ignites spontaneously in the presence of air and reacts explosively in water. Because of this reactivity, cesium is classed as a hazardous material and must be stored and transported in isolation from possible reactants. It is a relatively uncommon element that can be mined in only a few places in the world. The world's largest deposit of pollucite, which is the principal ore of cesium, is in a zoned pegmatite at Bernic Lake, Canada, and accounts for more than two-thirds of world reserves. Other reserves are in Namibia and Zambia, although numerous low-grade occurrences are known to exist elsewhere. There are cesium occurrences in pegmatite in Afghanistan, China, and Italy, in hydrous opal in Tibet, and in brines in Chile. Although there are cesium occurrences in the United States, no ore is mined, and the metal and its compounds are produced from imported ores by one U.S. company, the Cabot Corporation (Cabot Specialty Fluids, 2003).

Cesium is used in small quantities in a variety of uses, some of which are experimental or developmental in nature. The current application that requires the most cesium is probably as a specialty high-density component in drilling mud used for petroleum exploration. Cesium also has a wide-spectrum of photoemissive properties whereby electromagnetic radiation, which includes visible light and nearby regions of the radiation spectrum, are converted to electrical current. Thus, cesium is used in television image devices, night-vision equipment, solar photovoltaic cells, and other types of photoelectric cells. Perhaps one of its best known applications is its use in the super-accurate atomic cesium clock that is used as a standard for the world's timekeeping systems. It is used also in the chemical process industry, primarily as an ingredient of metal-ion catalysts; in medical applications; in the removal of sulfur from crude oil in petroleum refining; and as an ingredient in specialty glasses used in fiber optics and night-vision devices.

The market for cesium is very small and amounts to perhaps less than 25,000 kilograms per year (kg/yr) in the United States, and not much more for the rest of the world. World reserves are vast compared with apparent world demand. The mining and processing of cesium minerals are on such a small scale that environmental hazards or damage caused by the production of cesium are minimal.

Historical Background

Cesium, which was the first element discovered by using emission spectroscopy, was detected in water from mineral springs in Germany by Robert Bunsen and Gustav Kirchhoff in 1860 (U.S. Environmental Protection Agency, 2003). This new element was named "cesium" after the two prominent blue lines of its emission spectrum (from Latin "caesius," meaning heavenly blue) (Burt, 1993, p. 751). Bunsen isolated cesium chloride from mixed alkali salts that he had crystallized by evaporation of a large quantity of the spring waters. He later prepared several

¹Retired.

other salts which included the carbonate and tartrate. In 1881, Carl Sefferberg isolated cesium metal by electrolysis of its salts (Perel'man, 1965, p. 10). Subsequently, several ores were identified from which sizable quantities of cesium could be extracted, usually as a byproduct. Deposits of these ores, which are primarily ores of lithium and the other alkali metals, were identified in several countries which included the United States.

The element found no significant application until it was used in radio vacuum tubes in the 1920s as a getter, which is a scavenger of the trace amounts of oxygen remaining in the tube after manufacture, and as a coating on the heated cathode to increase its emission of electrons and, thereby, increase the amount of electric current that could flow through the tube. Cesium became recognized as a functional, high-performance industrial metal in the field of electronics in the 1950s (Strod, 1957). In the following years, the metal and its compounds found niche markets for the variety of low-volume applications discussed in the "Uses" section. Applications of nonradioactive cesium include photoelectric cells, photomultiplier tubes, infrared spectrophotometers, catalysts for several organic reactions, and crystals for scintillation counters. As the amounts of cesium being consumed rose in the 1960s through the 1980s, most of it (70 to 80 percent in the United States) was being used in developmental research on several potential uses, of which at least one, magnetohydrodynamic (MHD) power generation, promised to consume sizable amounts of the metal. Cesium, as the oxide or carbonate, was found to be an efficient promoter of ionization in the flow of hot combustion gases from which electricity is obtained in open-cycle MHD generators. Large-scale MHD power systems, however, proved to be complex and costly to build and operate and showed little promise of being able to compete with generation systems already in use; they have yet to achieve substantial commercialization. In any case, the use of cesium in MHD power systems rather soon fell into disfavor when it became clear that its technical advantages over its chief competitor, potassium, were outweighed by its ten-fold higher cost (Messerle, 1995, p. 10). Annual cesium consumption, therefore, began to fall in the 1980s, and by the 1990s, it was largely accounted for by the niche applications.

Cesium-based formation fluids, which have a range of densities, have multiple applications in petroleum exploration and are used in drilling mud, for lubrication of drill bits, for maintaining pressure on the oil-bearing strata, and for bringing cuttings to the surface (Cabot Specialty Fluids, 2003).

Given current global reserves of cesium and current estimated global use of 30,000 kg/yr, cesium reserves are more than adequate to satisfy demand during the next 2,000 to 3,000 years (table 1).

Description

Cesium is a silvery white to silvery gold metal, the golden hue developing if the metal is allowed to come into contact with even trace amounts of oxygen. It is soft and ductile, melts at 28.4° C, and can be liquid at warm room temperature. It shares this liquid characteristic with gallium, mercury, and, at a slightly higher temperature (39.3° C), rubidium. Represented by the chemical symbol Cs, it is one of the alkali metals and is located in period 6, group 1 (or IA) of the periodic table. Its atomic number is 55; atomic weight, 132.91; and electron configuration, [Xe]6s¹. Naturally occurring cesium consists of the stable isotope Cs¹³³; the 30 artificial radioisotopes range from Cs¹¹⁶ to Cs¹⁴⁶, of which Cs¹³⁷ is the most used and well-known.

Cs¹³⁷ is a reactor byproduct with applications in agriculture, industry and construction, radiotherapy for cancer treatment, and sterilization of food, sewage sludge, and surgical equipment. Reactor byproduct Cs¹³⁷ was commercially produced at Hanford, WA (Medical Isotopes, 2003) and at Savannah River, GA (Frontiers, 2003).

Table 1. Cesium reserves and reserve base, yearend 2003.

[In kilograms, contained cesium. NA, not available. All data are rounded to two significant digits; because of independent rounding, they may not add to totals shown. Brooks, 2004; Burt, 1993, p. 752. Definitions of reserves and reserve base can be found in the appendix]

	Reserves	Reserve base
Canada	70,000,000	73,000,000
Namibia	--	9,000,000
Zimbabwe	--	23,000,000
Other countries	NA	NA
World total	70,000,000	110,000,000

Metallurgically, cesium forms alloys with the other alkali metals and gold and amalgamates with mercury. It does not alloy with cobalt, iron, molybdenum, nickel, platinum, tantalum, or tungsten at temperatures below 650° C (Burt, 1993, p. 759). Cesium also forms photosensitive intermetallic compounds with antimony, gallium, indium, and thorium.

Chemically, cesium is the most electropositive metal and bonds ionically with a wide variety of anions to form compounds, many of which are hygroscopic. In addition to forming water-soluble compounds with common anions, such as acetate, carbonate, the halides, oxide, nitrate, and sulfate, it forms water-insoluble double halides with, for example, antimony, bismuth, cadmium, copper, iron, and lead. It also forms compounds with sulfur, selenium, and tellurium. Cesium metal is extremely reactive and ignites spontaneously in the presence of air and reacts explosively with water, which it decomposes with the liberation of hydrogen; it even reacts with ice at temperatures above -116° C.

Because of its reactivity, cesium, like rubidium, is stored and shipped in dry mineral oil or in other dry saturated hydrocarbons or in an inert atmosphere or vacuum in sealed borosilicate glass ampoules. In quantities of more than about 100 grams (g), cesium is shipped in hermetically sealed stainless steel containers. When glass ampoules are used, they are shipped wrapped in foil and packed in an inert cushioning material, such as vermiculite, each in a metal can. Although cesium compounds are not as dangerous as the metal, they are handled carefully and shipped in sealed containers.

Cesium metal is marketed in three grades that contain minimums of 99 percent, 99.5 percent, and 99.9 percent cesium. Cesium compounds are prepared as technical grade, 99 percent pure, or high-purity grade, 99.9 percent pure and higher. The two principal compounds of commerce are the chloride and nitrate.

Sources of Cesium

Cesium is a relatively rare element and averages approximately 3 parts per million in the Earth's crust (Turekian and Wedepohl, 1961, p. 187). It is 45th in order of abundance of all elements and 36th in order of the metals. It is more abundant than some more-familiar metals, such as antimony, cadmium, tin, and tungsten and two orders of magnitude more abundant than mercury or silver. By contrast, it is 30 times less abundant than rubidium, with which it is so closely associated chemically. Cesium does not substitute for potassium as readily as does rubidium; the alkali evaporite minerals sylvite [KCl] and carnallite [KMgCl₃·6HO] may contain only 0.002 percent cesium. Cesium is found in significant quantities in only a few minerals. These include some uncommon types of beryl [Be₃Al₂(SiO₃)₆], which may contain as much as 9 percent cesium; avogadrite [(K,Cs)BF₄], which may contain variable amounts of cesium; and rhodizite [a hydrated borate of Al, Be, Na, Cs], which contains a maximum of about 3 percent cesium. The only economically important source mineral for cesium is pollucite [Cs₂Al₂Si₄O₁₂] which is found in very few places in the world in certain zoned pegmatites and is associated with the more commercially important lithium minerals lepidolite and petalite. The stoichiometric content of cesium in pollucite is 42.6 percent, but samples of pure pollucite from the deposit at Bernic Lake, Canada contain only about 34 percent cesium. Commercial pollucite contains 19 percent or more cesium (Norton, 1973).

In the past few decades, nearly all of the world's supply of cesium has come from zoned pegmatites at Bernic Lake (McCutcheon, 1995). Intermittent mining of zoned pegmatites takes place at Bikita, Zimbabwe (Bikita Minerals, 2004) and in the Karibib Desert, Namibia. Smaller deposits, most of which are not worked, are known in Afghanistan (Orris and Bliss, 2002, p. 10), Brazil (Quemeneur and Lagache, 1999), India (Chandrasekharam, 2000), Italy (Roskill Information Services Ltd., 1984, p. 12), Sweden (Roskill Information Services Ltd., 1984, p. 14), Tibet (Mianping and others, 1995), and the United States (Burt, 1993, p. 759). In the United States unworked occurrences are in Maine (Sundelius, 1963, p. 94) and South Dakota (Strod, 1957). The Pakeagama pegmatite in Canada has the potential to host economic quantities of cesium and other rare metals (Cumming, 1999), and one Canadian exploration company has focused on cesium, lithium, and rubidium targets in pegmatite in Spain (Solid Resources Ltd., 2004). Lithium is produced from brines in Chile that also have potential for cesium and rubidium production (Sociedad Química y Minera de Chile, 2004).

As shown in table 1, more than two-thirds of the world's reserve base is at Bernic Lake, Canada. At the present rate of world mine production, which may be between 5,000 and 10,000 kg/yr, reserves would last thousands of years. Because cesium is not recycled, there is no secondary cesium.

The mining and processing of cesium minerals are on such a small scale that environmental hazards or damage are minimal and are not expected to inhibit production.

Production Technologies

Pollucite, which is the ore of cesium, is found in a few zoned pegmatites around the world and is often associated with the more commercially important lithium ore, lepidolite. The deposits are sought and mined primarily for their lithium content. The mining of zoned pegmatites is a selective process and, by comparison with most metal mining operations, conducted on a small scale. The pollucite ore is crushed and hand-sorted, but not usually concentrated. It is ground to prepare it for conversion to cesium metal or compounds.

Cesium has been extracted from pollucite mainly by three methods—acid digestion, alkaline decomposition, and direct reduction (Burt, 1993, p. 759). Acid digestion is the principal commercial method used for pollucite ore and hydrobromic, hydrochloric, hydrofluoric, or sulfuric acids may be used. The hydrobromic and hydrofluoric acids are not used commercially in the United States owing to processing difficulties. Digestion of pollucite in hydrochloric acid at elevated temperature yields an impure CsCl solution that is converted to double chloride salts, such as cesium antimony chloride $[4\text{CsCl}:\text{SbCl}_3]$, cesium iodine chloride $[\text{Cs}_2\text{I}_2\text{Cl}_2]$, or cesium hexachloroacetate $[\text{Cs}_2(\text{CeCl}_6)]$, which are purified and then decomposed by hydrolysis to yield purified CsCl. Pollucite may also be digested in hot 35 to 45 percent sulfuric acid to yield a solution from which cesium alum is precipitated. The alum is roasted with 4 percent carbon and then leached to yield a Cs_2SO_4 solution; the sulfate may then be converted to CsCl. Alkaline decomposition involves roasting the pollucite with either a CaCO_3 - CaCl_2 mixture or a Na_2CO_3 - NaCl mixture, leaching the calcine with water or dilute ammonia to extract a dilute CsCl solution, and then converting the chloride to cesium alum $[\text{C}_2\text{SO}_4:\text{Al}_2(\text{SO}_4)_3:24\text{H}_2\text{O}]$ or Cs_2CO_3 . Direct reduction involves heating the ore mineral with calcium, potassium, or sodium metal in a vacuum or an inert atmosphere, which yields an impure cesium metal. Because of low yield, impurity of the product, and engineering difficulties, this method is not used commercially. Additional methods for extracting cesium from pollucite are discussed in Perel'man (1965, p. 10).

Cesium metal is obtained from the purified compounds derived from the ore. Cesium chloride, and the other cesium halides as well, can be reduced at 700° to 800° C with calcium or barium, and the cesium metal, distilled and collected. In the same way, the aluminate, carbonate, or hydroxide can be reduced by magnesium. Cesium azide (CsN_3), which is produced by reacting aqueous cesium sulfate and barium azide, is heated to 390° C to decompose it to cesium metal and nitrogen (Burt, 1993, p. 759).

Uses

The use of cesium in petroleum exploration, mainly a formation fluid, is the largest end-use of nonradioactive cesium (Cabot Specialty Fluids, 2003). Cesium atomic clocks, which are accurate to 1 second in 1,400,000 years, are used at the U.S. Naval Observatory Time Center in Washington, D.C., and in the aircraft, satellites, and ground systems that track the space shuttle (Breakiron, 2003); U.S. Naval Observatory Master Clock time may be obtained at 202-762-1401. Cesium clocks are also used in networks that control the timing of cell phone transmissions, and cesium devices help control and regulate information flow on the Internet (Reel, 2003). Cesium is also important for its photoemissive properties and is used in photomultiplier tubes. Cs^{137} , which is a reactor byproduct, has a half-life of 30 years and is used in agriculture, cancer treatment, industrial gauges, and sterilization of food, sewage sludge, and surgical equipment (Jensen, 1985; National Safety Council, 2003). The International Atomic Energy Agency and other sources have indicated that radioactive materials, such as Cs^{137} , may be used in radiological dispersion devices, or “dirty bombs” (Charbonneau, 2003).

Although cesium metal and some of its compounds are considered to be hazardous materials, most cesium compounds are innocuous. In any case, the transportation and use of cesium is on such a small scale that

environmental impediments to its use are minimal. In addition, cesium metal is used in low volume in a wide assortment of uses, many of them experimental or developmental in nature.

Petroleum Exploration

Aqueous solutions of cesium formate (HCOO^-Cs^+ , which is made by reacting cesium hydroxide with formic acid) were developed in the mid-1990s for use as oil well drilling and completion fluids and are especially suitable for use when downhole temperatures and pressures are high. As a drilling fluid, the function of cesium formate is to lubricate drill bits, to bring rock cuttings to the surface, and to maintain pressure on the formation during drilling of the well. As a completion fluid, maintaining the pressure is the most important. Completion refers to the emplacement of production liners, screens, valves, and other control hardware after drilling but prior to production. Conventional solids-weighted drilling muds are usually not suitable for completion of the well (Schlumberger Corporation, 2002). Cesium formate is the heaviest of the clear alkali formate fluids and has a specific gravity of 2.3, or a density of 19.2 pounds per gallon. It can be blended with potassium and sodium formates to create fluids ranging in specific gravity from 1.0 to 2.3. Its density is an intrinsic property of the fluid itself; weighting agents, such as barite (barium sulfate), which can damage tools and the producing formation, are not required. It is biodegradable and reclaimable and may be recycled, which is important in view of its high cost—about \$4,000 per barrel (von Flatern, 2001). The alkali formates are safe to handle and do not damage the producing formation or downhole metals as its corrosive alternatives (high-density brines) sometimes do. It was successfully tested on a commercial scale in 1999 as a completion fluid in three wells in the North Sea oilfield under conditions of very high temperature (200° C) and pressure (1,000 atmospheres). To supply the developing market, Cabot Specialty Fluids (a subsidiary of Cabot Corporation) built a production plant in 1997 at the parent corporation's Bernic Lake Mine (Manitoba, Canada) with a capacity of 12,000 barrels per year of cesium formate (Benton and Turner, 2000).

Chemical Uses

Chemical applications are also another important use of cesium (Burt, 1993, p. 759).

Doping with cesium compounds is used to enhance the effectiveness of several metal-ion catalysts used in the production of chemicals, such as acrylic acid, anthraquinone, ethylene oxide, methanol, phthalic anhydride, styrene and methyl methacrylate monomers, and various olefins. It is also used in the catalytic conversion of SO_2 to SO_3 in the production of sulfuric acid.

Cesium metal absorbs gases and other impurities in ferrous and nonferrous metallurgy and in the purification of carbon dioxide.

Cesium salts sometimes are used to replace potassium or sodium salts in many organic syntheses, such as cyclization, esterification, and polymerization.

Molten CsOH has been used in the desulfurizing of heavy crude oil.

Electric Power Generation

Magnetohydrodynamic (MHD) power-generating systems were researched (Messerle, 1995, p. 25) but failed the gain acceptance for widespread use. The U.S. Department of Energy stopped funding MHD research in 1993 (National Academy Press, 2001). If any cesium is still being used for research on this application, then the quantity certainly must be very small. Cesium metal has also been considered as the working fluid in high-temperature Rankine cycle turboelectric generators (Roskill Information Services Ltd., 1984, p. 25).

Cesium has been used in cesium vapor thermionic generators, which are low-power devices that convert heat energy to electrical energy. In the two-electrode vacuum tube converter, it neutralizes the space charge that builds up near the cathode and in so doing enhances current flow.

Cs_2O has been used to coat the light-sensitive surfaces of solar photovoltaic cells. The cesium salt raises cell efficiency because of its wide spectral response from near infrared through visible to mid-ultraviolet.

Electronics

Cesium is used as a getter, or scavenger of residual traces of oxygen, in electron tubes.

Cesium is used in high-energy lasers, vapor glow lamps, and vapor rectifiers.

Cesium, often in the intermetallic compound KCsSb , is used in photoemissive devices in which light energy is converted to electron flow. These include optical character recognition devices, photomultiplier tubes, and television camera image tubes.

CsI and CsBr crystals are used in scintillation counters which are widely used in mineral exploration and particle physics research. They are well suited for the detection of gamma and x-radiation.

Medical Applications

CsCl , Cs_2SO_4 , and cesium trifluoroacetate are used as density-gradient media in the ultracentrifugal separation of nucleic acids (DNA and RNA) and viruses.

Cs^{137} has been used as a radiation source in the treatment of cancer.

Cesium salts have been evaluated as antishock reagents to be used following the administration of arsenical drugs. Because of their effect on heart rhythms, however, they are less likely to be used than potassium or rubidium salts. They have also been used to treat epilepsy.

Other Uses

Cesium ion engines have been tested as thrusters on spacecraft and have been considered for propelling spacecraft on very long interplanetary or extraplanetary missions. Concerns about the corrosive action of cesium on spacecraft components have pushed development in the direction of use of inert gas propellants, such as the xenon used to propel Deep Space 1, which is an experimental spacecraft launched in 1998.

Cesium, along with rubidium, has been added as the carbonate to glass because it reduces electrical conductivity and improves stability and durability. Such special glasses are used in fiber optics and night-vision devices.

The radioisotopes Cs^{137} and Co^{60} are the most widely used sources of gamma radiation. Cs^{137} has been used for the following:

- Sterilization of sewage sludge.
- Measurement and control of fluids in industrial processes.
- Radiation treatment of cancer.
- Logging mine and oil well boreholes.
- Measuring soil density at construction sites.
- Measuring cement moisture at construction sites.

A worldwide tracer for studying rates of soil erosion and sedimentation; the radionuclide Cs^{137} tracer originated as fallout from the above-ground testing of thermonuclear weapons, beginning in the 1950s and continuing through the mid-1980s. Known year-to-year variation within that period allows correlation with soil and sediment layers.

Cesium clocks, which have been improved repeatedly over the past half century, form the basis for world's timekeeping system. The clocks use the resonant vibration frequency of Cs^{133} atoms as a reference point. The latest versions in the United States and France are accurate to 1.7 parts in 10^{15} , or about 1 second in 20 million years.

Cesium fluoride or cesium aluminum fluoride are used in fluxes formulated for the brazing of aluminum alloys that contain magnesium.

Substitutes for Cesium

Cesium substitutes, in order of decreasing suitability, include rubidium, potassium, and sodium. Potassium substitutes for and has largely or completely replaced cesium in MHD power generation. Germanium, rubidium, selenium, silicon, tellurium, and several other elements and compounds can substitute for cesium as photosensitive materials. Heavy brines, such as zinc bromide, can substitute for some cesium-sodium-potassium formate oil well fluids but are corrosive and less safe to handle; their use incurs cleanup and disposal costs. Substitute materials or processes exist for several other uses for cesium but usually at a cost in efficiency.

Industry and Market

Although no cesium is mined in the United States, it is extracted from imported ores by one domestic company, Cabot Corporation, which owns the Bernic Lake deposit, and thereby owns, by its estimate, 82 percent of the world's reported pollucite reserves. A small number of companies in Denmark, Germany, Japan, Russia, and the United Kingdom also process cesium ores. These companies produce cesium metal and/or the principal compounds and, in some instances, the associated metals lithium and rubidium and their compounds. The largest producer of cesium chemicals is Metallgesellschaft AG in Germany (McCutcheon, 1995). In addition, a larger number of specialty chemical companies produce various grades of the many cesium derivative compounds. Overall, however, the total industry and the market are very small compared with those in place for most metals.

Supply, Demand, and Adequacy of Reserves

No cesium ores are mined domestically; all ore needed is imported from Canada. Some of the required metal and compounds are also imported from Germany and elsewhere. No published data on current domestic production, imports and exports, and consumption are available.

The supply of lepidolite and pollucite ores from Canada appears to be assured. Considering the growth of the economy since 1985 balanced against the loss of interest in cesium for MHD power generation in the 1980s, current domestic consumption is estimated to be somewhat less than 25,000 kg/yr. Total world consumption is estimated to be not much more than 5,000 kg/yr. If that is valid, then the available North American reserves are vast compared to U.S. and world demand for cesium.

Economic Factors

As the market is very small and the number of producers worldwide is also small, public trading in cesium metal or its compounds is not active, and therefore prices are not quoted. The metal is sold by the gram, the per-gram price varying greatly with the amount and purity of the metal purchased. For example, in 2003, one company offered 1-g ampoules of 99.8 percent (metals basis) cesium for \$39.50 and 99.98 percent (metals basis) cesium for \$52.00. The price for 100 g of 99.8 percent (metals basis) cesium was \$1,038.00, and the same quantity of 99.98 percent (metals basis) cesium was priced at \$1,425.00. The producer price typically remains stable over several years. For example, for 25 of the years 1962 through 1991, a representative annual price from one producer (averaged over all lot sizes up to 22.7 kilograms and over a mix of sales of technical grade and high-purity grades) remained within the narrow \$0.50-to-\$0.66-per-gram range. Since 1991, producer quotes for bulk quantities have not been readily available (Reese, 1999; 2002).

U.S. mine producers are granted a 14-percent depletion allowance on their domestic and foreign production of cesium. This is a percentage of the income from mine production considered to be a return of capital and, thus, not subject to income tax in recognition that ore deposits are diminishing assets when exploited.

Imports of processed cesium metal are included in the broad category “alkali metals, other” and are subject to a 5.5-percent ad-valorem duty. Imports of cesium chloride are included in the category “chlorides, other” and are subject to a 3.7 percent ad-valorem duty. Other cesium compounds may be imported duty free.

Outlook

Cesium fills niche uses in a small market. Its rate of consumption appears unlikely to change drastically in the United States or elsewhere. Because the potential supply is vast compared with foreseen demand and most of it is located in a politically stable environment, no supply disruptions seem likely.

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Appendix

Definitions of Reserves, Reserve Base, and Resources

The term “resources,” as applied to metals, refers to those concentrations of metal-bearing minerals in the Earth’s crust that are currently or potentially amenable to the economic extraction of one or more metals from them. “Reserves” and “reserve base” are subcategories of resources. “Reserves” refers to the in-place metal content of ores that can be mined and processed at a profit given the metal prices, available technology, and economic conditions that prevail at the time the reserves estimate is made. “Reserve base” is a more-inclusive term that encompasses not only reserves proper, but marginally economic reserves and a discretionary part of subeconomic resources—“those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics” (U.S. Bureau of Mines and U.S. Geological Survey, 1980).