



Mineral Commodity Profile

Indium

By John D. Jorgenson and Micheal W. George

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Open-File Report 2004-1300

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Mineral Commodity Profiles—Indium

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Overview

Indium, like gallium and thallium, is a highly volatile chalcophile element in subgroup IIIA of the periodic table. It is a malleable, silvery-white metal found primarily in ores, in order of descending importance, of zinc, copper, and tin. It has many uses, but the principal one, which accounts for about 65 percent of the indium consumed in industry, is as thin films of indium-tin oxide (ITO) for liquid crystal displays. Indium is also used in semiconductors, in the form of indium phosphide (InP).

The value of commercial grade indium consumed in the United States in 2001 is estimated to have been greater than \$8.5 million based on domestic consumption of 58 metric tons (t).

Indium is principally a byproduct of the electrolytic refining of zinc, although a small share is a byproduct of tin refining. Primary refined indium is produced in several countries which include, in descending order of quantity produced, China, France, Japan, Canada, Belgium, Russia, and Peru (Brown, 2002a). The United States produces only secondary material, and the quantity, which is the proprietary data of the only two producers, is not published. The world reserve base for indium is estimated to be about 5,700 t, which is far in excess of probable consumption over the next several decades; the United States has about 11 percent of this base. The sustainable production and consumption of indium appears to be no impediment in future years.

Historical Background

Indium was discovered by Ferdinand Reich and H.T. Richter Germany's of Freiberg School of Mines in 1863. They were studying zinc ores from a local polymetallic vein deposit looking for thallium when they discovered an unknown coating that gave a distinctive blue color on the spectrograph. This blue coloring led to their naming the material indium for the "indigo" spectral lines it developed. The metal itself is actually a lustrous silver-white color.

Although domestic U.S. production had begun in 1926, no real research with the material began until 1934 when the Indium Corporation of America identified the first practical applications for indium (White, 1977; Indium Corporation of America, undated). In 1933, small amounts of indium were added to certain gold dental alloys, but it was not until World War II that indium was used in its first large-scale application as a coating for bearings in high-performance aircraft engines (Carlin, 1985; Slattery, 1995). Indium increased hardness and helped prevent seizure and corrosion of the bearings.

Not until 1936 did the U.S. Bureau of Mines (USBM) begin to track indium as a metal commodity (Tyler, 1937, p. 767). One of the earliest uses was as a precious metal alloy that was used to enhance brightness and to retard tarnishing. In the 1940s, the use as a special bearing-metal alloy was established, but it was not until 1952, when it started to be used in semiconductor devices, that the demand for indium became established (Weeks, 1973).

Production gradually increased as new uses for indium as a component of electronics, fusible alloys, and solders were developed. Through 1980, demand continued to increase, especially for use in nuclear control rods. Orders for nuclear control rods dropped when nuclear power expansion decreased in the United States following the Three Mile Island accident on March 28, 1979.

In the middle and late 1980s, InP semiconductors and ITO thin films for liquid crystal displays (LCDs) were developed. By 1992, the thin-film application had become the largest end use of indium (Jasinski, 1993).

In the mid-1970s, the use of indium in the United States was almost equally distributed between the use in coatings and alloys and the use in electrical components and semiconductors. Changes in accounting by category have obscured some of the U.S. information since the mid-1970s. The percentage of end uses appears to have changed little since the mid-1970s other than a steady increase in the application for coatings since 1990 and a great reduction in the percentage used in research.

The Defense Logistics Agency included indium in the list of materials to be added to the National Defense Stockpile (NDS) in 1989 (Schmitt, 1989). The NDS had acquired its largest quantity of indium (1.56 t) by 1994, but this was sold by the end of 1998 (Brown, 2002a).

In 1995, a tight supply situation combined with strong demand led to the implementation of a more-efficient recycling process. Then, in 1998, indium demand slackened owing to lower LCD production and the introduction of new thin-film coating technology that required only one-third as much indium as the older process (Roskill Information Services Ltd., 1999, p. 3).

Although the introduction of indium can be traced to individual end uses, determining the tonnages of indium produced and consumed over time is much more difficult because statistics are incomplete. The USBM began publishing the annual series on indium refinery production in the United States in 1942. Production figures were made available for 1942 through 1951, 1956, and 1966 through 1969. During these years, some of the production figures were withheld as company proprietary data. From 1942 through 1951, the United States produced most of the world's refined indium; a sizable quantity of unwrought refined material at 99.8 percent purity, was imported from the La Oroya refinery in Peru (Mills and others, 1961, p. 221). The two U.S. zinc refiners that produced indium suspended their production in the early 1970s, when ASARCO Incorporated closed their production facilities in Perth Amboy, New Jersey, and Denver, Colorado, and Anaconda Copper Mining Co. shut down its facilities at Great Falls, Montana.

Estimated domestic consumption of indium, which has appeared in the USBM/U.S. Geological Survey (USGS) Mineral Commodity Summaries since 1979, has shown a progressive increase from approximately 20 t in 1979 to 55 t in 2000. The gap between the estimated domestic consumption of indium and the apparent consumption represented by the sum of domestic refining, imports, and the change in domestic stocks appears to be large. This 20- to 40-t difference represents the indium exported in "hi-tech" end products, which was a small portion of the estimated \$153.9 billion of U.S. exports of information technology (IT) manufactured goods (Pastore, 2002).

Description

Salient Facts

Indium is element number 49 in the periodic table of the elements. Its atomic weight is 114.82, its electron configuration is $[\text{Kr}]4d^{10}5s^25p^1$, and it is located in period 5, group 13 (the boron group). The top element in the group, boron, is semimetallic. All the rest of the elements in the group (aluminum, gallium, indium and thallium) are metallic (Greenwood and Earnshaw, 1997, p. 222). Indium's principal oxidation states are +1 (the most stable) and +3. The unit cell of indium's crystal structure is an unusual face-centered tetragon.

Sixty-seven isotopes and isomers of indium are now recognized; this is more than any other element. Natural indium contains two isotopes, one of which, In^{113} , is stable. The other, In^{115} , which comprises 95.7 percent of natural indium, is slightly radioactive with a very long half-life (Spectrum Laboratories, Inc., undated).

Indium's hardness is 1.2 on the Mohs scale, its specific gravity at 20° C is 6.25, and it melts at 156.6° C. It is a soft, lustrous, silver-white metal and the pure metal gives a high-pitched cry when bent (Mills and others, 1961, p. 225). Its most notable feature is its highly plastic property even at cryogenic temperatures. It is not oxidized by air at ordinary temperatures, dissolves in mineral acids, and is not affected by alkalis, boiling water, or most organic acids.

Principal Forms, Alloys, and Compounds

Indium metal is produced in various forms, which include foil and ribbon, ingot, plates, powder, shot and pellets, and wire. The varying sizes of the ingots [0.5, 1.0 and 10 kilograms (kg)] depend on the producer selected. Indium ribbons and foil are used for sealing and bonding; shot for alloying and evaporation; and shells for easy chemical dissolution.

Indium alloys with a significant number of metals and in a number of binary and ternary systems. Alloys with bismuth, cadmium, lead, and tin are often used in low-melting-point applications, such as fire door safety links, optical lens grinding, pattern making, sprinkler heads, turbine blade machining, and other fuse-type applications. An alloy of 5 percent indium, 15 percent silver, and 80 percent cadmium has been used for nuclear reactor control rods.

Soldering alloys with melting points in the 100°-to-300° C range are made of lead-silver-indium, lead-tin-indium, and tin-indium. These solders offer improved resistance to alkaline corrosion and thermal fatigue. The most important of these soldering alloys is ITO. Other indium alloys are used for ceramics and dental work and specialty brazing and wetting glass.

Indium's properties are similar to those of gallium, the element directly above it in the periodic table. Like gallium, it remains in the liquid state over a wide range of temperatures. Indium wets glass and can form a mirror surface that is more resistant to corrosion than silver, while reflecting just as well (Lagasse and others, 2000).

The significant commercial indium compounds, cited by Slattery (1995, p. 159), are the alkyls trimethyl indium [$\text{In}(\text{CH}_3)_3$], triethyl indium [$\text{In}(\text{C}_2\text{H}_5)_3$], and triphenyl indium [$\text{In}(\text{C}_6\text{H}_5)_3$], indium dichloride (InCl_2), indium hydroxide [$\text{In}(\text{OH})_3$], indium nitrate [$\text{In}(\text{NO}_3)_3$], indium oxides (In_2O_3 , In_2O , and InO), indium phosphate (InPO_4), indium sulfide (In_2S_3), indium trichloride (InCl_3), and indium trisulfate [$\text{In}_2(\text{SO}_4)_3$].

Of some importance are the intermetallic compounds, in which indium combines with alkali and precious metals, magnesium, the iron group, and rare earths. Indium also combines with metalloids and nonmetallics. These form some of the most important semiconducting compounds of indium, such as, the antimonide (InSb), the arsenide (InAs), and the phosphide (InP).

Commercial Grades, Shapes, and Specifications

In the United States, producers determine their own indium product standards. Indium metal products produced by Indium Corporation of America include four products in the three-nines to five-nines range and an additional four products in the six-nines to seven-nines range; "nines" refers to the purity of an element or compound; for example, five-nines would refer to a product that is 99.999-percent pure. Sale pricing lots from the three major producers are as follows (Platts Metals, undated):

- 99.97-percent pure metal in 1-kg bars in lots of 10,000 troy ounces [free on board (f.o.b.), Utica, N.Y.],
- 99.97-percent pure metal in 100-troy-ounces bars in lots of 5,000 troy ounces (f.o.b., Providence, R.I.), and
- 99.99-percent pure metal in minimum lots of 50 kg (at warehouse, Rotterdam, Netherlands).

For pellets, typical commercial-grade metal varies from three-nines to six-nines indium with diameter by length sizing of as follows:

- 0.25 inch by 0.25 inch,
- 0.25 inch by 0.5 inch,
- 0.125 inch by 0.125 inch, and
- 0.125 inch by 0.25 inch.

Pellets are used for evaporation in deposition processes (Kurt J. Lesker Company, undated).

The principal uses for indium foil are as contact sheets with good thermal and electrical conductivity and as sealant material in high- and low-pressure and cryogenic applications. Foil purity is generally 99.99 percent with thicknesses that range from 50 microns (μm) to 2 millimeters (mm). It can be cut to customer's design specifications (Umicore Thin Film Products, undated).

Indium wire and ribbon is used in soldering and preparation of seals that will withstand cryogenic temperatures. The wire and ribbon come in varying shapes. For example, Indium Corporation offers several pure indium and indium alloys ribbons that vary as follows:

- Width—from 0.5 to greater than 25.4 mm,
- Thickness—from 0.025 to greater than 1.27 mm, and
- Length—from small strips for testing to large spools.

Powders of indium metal, indium oxide, indium hydroxide, and ITO are also sold. The metal is sold in -100- and -325-mesh size and in those sizes grades range from three-nines to five-nines by one producer (ESPICorp Inc., undated). Another producer sells indium oxide in grades of fine with 90 percent smaller than 15 μm and ultrafine with 100 percent less than 10 μm . That same producer sells indium hydroxide at a purity of up to five nines in grades of amorphous (90 percent less than 5 μm) or crystalline (90 percent less than 25 μm) for battery, catalytic, electrically conductive, and heat reflective applications (Teck Cominco Limited, 2002b).

Sources

Primary

Abundance

Indium is a rare element. It ranks 61st in abundance in the Earth's crust at an estimated 0.24 part per million (ppm) by weight. This makes it about three times more abundant than silver or mercury.

Indium, even in zinc concentrate, is a relatively minor proportion of the material. For example, in Kidd Creek, Ontario, Canada, concentrate, indium content represented 0.027 percent by weight, in Polaris, Northwest Territories, Canada, concentrate, 0.010 percent; and in Balmat, N.Y., concentrate, 0.004 percent (Rodier, 1990, p. 59-65).

Schwarz-Schampera and Herzig (2002, p.45-49, p. X-XII), gave an exhaustive discussion of indium levels in ore bodies around the world. For example, they showed 315 samples of ore from a volcanic-hosted massive sulfide deposit from the Kidd Creek Mine as ranging between 1 and 870 ppm indium with a mean of 106 ppm. They went on to state that the estimated bulk indium content of the ore deposit was 3,400 t.

Geochemistry and Geologic Occurrence

The geochemical properties of indium are such that it tends to occur with the base metals copper, lead, tin, and zinc and with bismuth, cadmium, and silver. It is a high-volatility, chalcophile element and tends to be associated with sulfide minerals of zinc, whose atom is of a similar size.

As described by Schwarz-Schampera and Herzig (2002, p. VII-IX), some of the major hosts for indium mineralization, include the following:

- Vein stockwork tin and tungsten deposits, as well as porphyry tin deposits;
- Volcanic-hosted massive sulfide (VMS) deposits;
- Sediment-hosted exhalative massive sulfide (SHMS) deposits;
- Polymetallic vein-type deposits;
- Epithermal deposits;
- Active magmatic systems;
- Porphyry copper deposits; and
- Skarn deposits.

Vein stockwork tin and tungsten deposits occur as individual veins, multiple-vein systems, vein and fracture stockworks, breccias, and altered wallrock adjacent to veins. The Mount Pleasant deposit, New Brunswick, Canada, is of this type and contains roughly 25 percent of the world's indium reserves. The economic potential of these deposits, in 2001, was difficult to determine because the complex mineralogy makes metallurgical recovery difficult.

The VMS deposits are important sources of base and precious metals. Strong partitioning into massive sphalerite in these deposits, as well as in the SHMS deposits, make them the major sources of indium from residues of zinc smelting. Examples of these deposits include Kidd Creek; Neves-Corvo, Portugal; Brunswick No. 12, New Brunswick, Canada; and Kuroko, Japan. The major example of the SHMS deposit is Rammelsberg, Germany, the ore from which indium was first separated and identified.

Polymetallic vein-type deposits are generally structurally controlled within fault systems and vein breccia zones. These deposits can contain high concentrations of indium and are among the world's most important indium producers. Several examples of these type deposits occur in Japan and in the Bolivian Cordillera.

Resources

No estimates are available for total resources of indium. Because most indium is recovered as a byproduct of zinc refining, known resources of indium can be inferred from the deposits of zinc being exploited in 2001, and the remainder, if any, is derived from the smelting and refining of tin ores.

The Soviet Union was a major source of indium production, but with its breakup, zinc mining and byproduct indium recovery has been significantly reduced. Over three-fourths of Commonwealth of Independent States (CIS) reserves are located in Russia. Russian reserves can cover their anticipated indium demand for several decades in spite of the fact that they have a low recovery (36 percent) from raw materials (Roskill Information Services Ltd., 1997).

Japan's Toyoha Mine, which has an average indium grade of 140 ppm, is among the leading producers of indium in the world. The contained indium in zinc concentrates is sufficient to produce 75 metric tons per year, or about one-third of the annual worldwide indium production. The Mount Pleasant deposit (New Brunswick, Canada) represents one of the largest indium deposits known with about 25 percent of the world reserves.

Almost all indium is produced from residues collected from zinc refining and recycling of flue dusts and gases generated during the smelting zinc. The remainder, if any, is derived from the smelting and refining of tin. Because of the heavy reliance on zinc as a source, the USGS bases its estimates of indium reserves and reserve base on the comparable figures for zinc. The estimates, shown in table 1, take into account that approximately one-half of the approximately 0.028 kg of indium per metric ton of zinc ore that is concentrated and later delivered for smelting is actually recovered.

Secondary

In 1996, the level of domestic recovery of secondary indium was unusually high. A \$12-per-troy-ounce price increase in 1995, which almost tripled the price, and which prompted concerns about lack of supply, encouraged the recycling of more old scrap. This recycling provided much of the domestic supply, and resulted in a decrease in imports of more than 50 percent (Fineberg, 1996).

Since then, recycled indium has remained low in the United States. In the year 2000, most of the secondary indium was recovered from new scrap, as is typical in the United States (Brown, 2002c). The quantity of secondary indium recovered is not known for 2000, but it was small.

In Japan, however, recycling has maintained its importance in recent years (McColloch, 2000). In 2000, Japanese indium demand reached a record 335 t. Slightly more than one-half of the material came from recycled scrap (Roskill's Letter from Japan, 2001).

Because most of the uses of indium are nondissipative, high tech, and short-lived in nature, scrap is generated from which secondary indium may be extracted. However, little was recovered in the United States in

Table 1. Indium reserves and reserve base, yearend 2001.

[In metric tons, recoverable indium. All data are rounded to two significant digits; because of independent rounding, they may not add to totals shown]

	Reserves	Reserve base
Canada	700	2,000
China	400	1,000
Japan	100	150
Russia	200	300
Peru	100	150
United States	300	600
Others	800	1,500
World total	2,600	5,700

Note: Estimate based on the indium content of zinc ores (Brown, 200b).

2001, but a large amount may be recovered in Japan and elsewhere from weld metal alloys, scrapped ITO, and indium phosphide in LCDs.

Production Technologies

The sources of indium material—alloys, dusts, fumes, residues, and slag from zinc and lead-zinc smelting—are leached by using hydrochloric (HCl) or sulfuric (H₂SO₄). The solutions are concentrated, and indium is recovered as 99+ percent metal. The low-grade indium is then refined to standard-grade (99.99 percent) and higher purity metal.

Early methods for indium recovery were very expensive because large quantities of indium-poor material had to be treated to obtain a small quantity of indium. The zinc industry had considered the recovery of indium and germanium as a marginal activity because they are difficult to separate from antimony, arsenic, copper, lead and tin.

While the pyrometallurgical processes are not conducive to the recovery of indium, roasting in a rotary furnace can be used for selectively fuming the metal. In the imperial smelting process (ISP), only a limited part of the indium is slagged off owing to its affinity for lead, absence of affinity for iron, and the strong reducing properties of the metal. About 50 percent of the indium is lost to lead bullion in ISP; the rest resides in the zinc residue, where it is recovered from those plants that operate a complete refinery unit.

In the electrolytic process for zinc refining, germanium and indium are concentrated in the neutral leach residue from the zinc plant. For zinc concentrates that contain high iron and silica, germanium and indium recovery is difficult if strong acid leaching is used to treat the neutral leach residue.

In the jarosite process for zinc refining where iron is always in the ferric state, a maximum of 60 percent of the germanium and indium can be dissolved from the neutral leach residue. The jarosite process plant will generally include reductive leaching and copper precipitation, two stages of neutralization, and iron removal as hematite by autoclave oxidation-precipitation. During the neutralization of the ferrous sulphate solution by calcium carbonate, gypsum is produced and later refined by several solvent extraction operations, and lastly indium is electrowon as a pure metal (Demarthe and others, 1990).

Traditionally only about 30 percent of the available indium is concentrated in flue dusts and treatable residues from which indium can be recovered. In the last few years, however, indium recoveries have improved to as high as 80 percent.

Production at Kidd Creek

Typical of the indium recovery process is the recovery from zinc concentrates in the zinc roasting and refining plant at Kidd Creek, where the indium grade of zinc concentrate has been estimated to be 0.027 percent. The concentrate is roasted to remove sulfur and passed through a two-stage leaching process. In the first stage, iron is removed as a jarosite residue, and in the second stage, Cottrell dust from the copper smelter is added to precipitate a silver-lead residue. The indium-containing liquor is then passed to a solvent extraction stage, as shown in figure 1, where refined indium metal is produced for sale (Falconbridge Limited, 2002).

Production From Tin

Indium is being recovered from tin concentrate that contains 0.01 percent indium into a 0.1 to 0.2 percent indium-lead-tin alloy by using a specialized vacuum refining apparatus. The indium alloy is then melted in a 20-t pot, and the raw indium metal is recovered in a special apparatus. The raw indium metal is then electrolytically refined in the melt. This apparatus also makes it possible to treat tailings with a primary indium content of 0.1 percent and higher (Novosibirsk City Guide, undated).

Production From Scrap

Small quantities of indium are recovered from the refining of new scrap, material generated in the production of indium-bearing products, and even smaller, from old scrap. Higher prices promote an increase

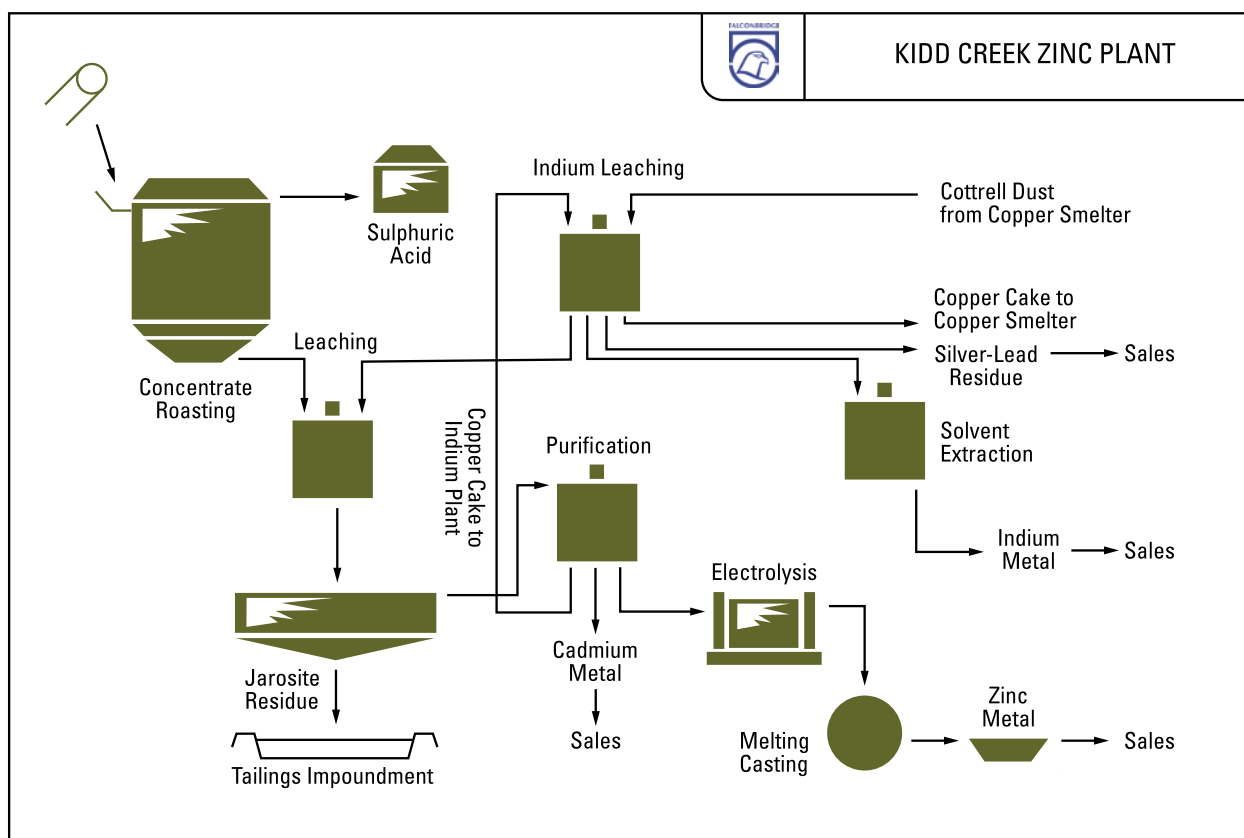


Figure 1. Flow diagram illustrating the process of zinc smelting at the Kidd Creek zinc plant. Source: Falconbridge Limited.

in reprocessing of scrap indium. An estimated price of \$400 per kilogram of indium is required to make new processing facilities for ITO scrap viable, although once the investment is made, the price to begin recycling would drop significantly (McCutcheon, 1995). One of the major producers cites the ability to recover indium from almost any industrial waste product containing the metal (Umicore Advanced Materials, undated).

Uses

Principal Uses

Some of the typical applications of indium are in bonding, high-purity, low-temperature alloys, soldering, and thin films uses. In soldering, indium alloy solders show lower crack propagation and better thermal fatigue resistance compared to conventional solders. Indium's bonding properties are unique especially with respect to such nonmetals as glass and glazed ceramics. Indium deforms easily under pressure even at extremely low temperatures.

ITO can be spread as a thin film on glass or plastic to act as a transparent electrical conductor and infrared reflector. This thin-film coating-technology is used in the manufacture of LCDs, flat panel displays, touch screens, solar panels, and energy-efficient windows. Aircraft and automobile windshields can be coated with ITO for demisting and deicing.

Indium compounds have been found to reduce the buildup of hydrogen gas in sealed alkaline batteries where they act as a replacement for toxic mercury compounds (Wyllie, 1993).

Estimates by the USGS show that in 2000, about 65 percent of the indium consumed in the United States and the world was used in display devices (Schwarz-Schampera and Herzig, 2002, p. 5). Almost 9 percent each was used in semiconductors and low-melting-point alloys and solders. Another 7 percent was used in transparent heat reflection. The remaining 10 percent was used in phosphors, plating and bearings, and other miscellaneous applications.

Coatings

Perhaps 65 percent of the indium used in coating goes into display devices, and the remainder, into transparent heat reflection. Coatings, as ITO, represent approximately 72 percent of the indium market.

Display Devices

Indium oxide has strong properties of electrical conductivity, heat reflection, and transparency. Combining with 10 percent tin oxide enhances the properties of heat reflection and electrical conduction, but has only a minor effect on the transparency of the oxide.

These properties make ITO an ideal film for converting data from electrical to optical form in flat-panel displays and LCDs. ITO is made into sputtering targets, which are then placed in a vacuum where the ITO is "sputtered" onto glass for laptop computer screens, LCD watches, appliance display panels and portable phones (Teck Cominco Limited, 2002a). In recent years, the reduction in requirements for ITO with the move to thin film transistor liquid displays, which require one-third the ITO of previous technologies, has been significant (Schwarz-Schampera and Herzig, 2002, p. 169).

Other Uses of Indium-Tin Oxide

ITO coatings also are used in architectural glass, cathode-ray tubes (CRTs), low-pressure sodium lamps, solar collectors, and windshield glass. Glass coated with ITO is used in architecture because of its superior energy efficiency. Solar panel applications have been improved by coating with high-infrared-reflectance ITO. ITO-treated automobile and aircraft windshield glasses have enhanced demisting and deicing properties.

Solders and Alloys

Indium forms alloys with precious and base metals to lower their melting point. The low-melting-point alloys are used as fusible alloys, holding agents, and solders and the precious-metal alloys are used in dentistry.

Low Melting Point Alloys

Alloying indium with alloys of bismuth, cadmium, lead, and tin lowers their melting point. These alloys can be used to grip diverse objects, such as eyeglass lenses or turbine blades while these items are being worked on. After completion, the alloy can be liquefied and removed by applying relatively low temperatures without damaging the object (Indium Corporation of America, undated b). A low-tech example of the use of a low-melting-point indium alloy is a like pop-up turkey timers (Teck Cominco Limited, 2002a).

Its low melting temperature also makes indium useful as the fusible element in safety devices, such as indoor fire sprinkler systems. Some alloys of indium and gallium can be used in applications that require a metal that is liquid at room temperature. For example, the 24 percent indium, 76 percent gallium alloy melts at 16° C and is, therefore, liquid at room temperature (Mills and others, 1961, p. 225).

Lead-free solders, indium, silver, and tin, which are less environmentally sensitive, are a potential growth market for indium.

Other Alloys

The ductile nature and casting properties of indium have encouraged the use of alloys of indium with gold and palladium in dental work. An alloy of cadmium, indium, and silver has been used in nuclear control rods because it absorbs free neutrons.

Electrical Components and Semiconductors

Gallium indium arsenide phosphide, indium antimonide, indium arsenide, indium-gallium arsenide, and indium phosphide and are used in semiconductors and phosphors.

Semiconductors

Indium's role as a semiconductor has continued to increase with a doubling in world consumption from 1990 when 10 t were used to 2000 when 20 t was consumed. Most semiconductor applications require indium of high-purity six-nines or greater.

One basis for transistor action is the p-n junction in the germanium transistor. P-type germanium carries indium with three electrons in the outer orbit compared to with four electrons in germanium, which creates a hole in the crystal lattice. The extra electrons in n-type germanium will jump to the holes in the p-type indium alloy to give the transistor its properties. In addition to these electronic properties, indium has excellent wetting properties on germanium, and its softness avoids strains on contraction in the alloying step.

Indium is used as the doping agent for gallium and germanium arsenides and in compound Group III-V semiconductors with antimony, arsenic, and phosphorous. These semiconductors are used mostly in photovoltaic cells. Other semiconductor applications, such as fiber optic telecommunications, laser diodes, light emitting diodes (LED), optoelectronic integrated circuits, and photodetectors, and are becoming important uses for high-purity indium metal. Indium phosphide provides higher frequency electronic performance than either silicon or gallium arsenide and is widely used in fiber optic lasers and detectors at wavelengths of 1,000 nanometers and longer (Performance Materials, 2002. p. 5).

Phosphors

Indium-boron oxide and manganese-indium products are used in the production of monochrome CRTs. Not much use has been reported on this technology outside of Japan.

Research and Other Uses

Potential applications under investigation are advanced semiconductors, more advanced ITO coatings for flat glass, and solar cells. Continuing research projects include additional applications for lasers for telecommunications and new consumer electronic products. Indium is being considered as a substitute for mercury in alkaline batteries (Crowson, 2001). $\text{In}(\text{OH})_3$ is a white powder used in batteries to suppress the formation of hydrogen gas.

Copper-indium diselenide is used in the production of thin-film solar cells. Although this indium alloy is more expensive, the production technique and flexibility of the thin-film solar cells makes them a viable alternative to the larger more-rigid crystalline solar cells (Perihelion, 2001).

These uses account for roughly 2 percent of the indium consumed in the United States and the world.

Research

Some of the indium consumed in research applications is considered to be under the application itself, such as alloys, ITO coating, semiconductors, and solders.

The U.S. Department of Defense is performing research into indium antimonide, a compound-semiconductor process technology that can support ultrafast transistors that operate at up to 600 gigahertz (Aslett, 2001, p. 30).

U.S. Department of Energy scientists are researching new uses for indium gallium arsenide nitride-based semiconductor as photovoltaic power sources. The addition of nitrogen, whose atoms are small and have high electronegativity, reduces gallium arsenide's bandgap energy requirements by one-third. Potential applications for this semiconductor alloy include fiber-optic lasers and communications satellites (Allan, 2000, p. 25). According to Graham (2002), nanocrystals of cadmium selenide coated with indium are being tested as artificial plant leaves that transform carbon dioxide into other organic molecules, in the dark.

Other Uses

Indium-¹¹¹, which is a radiopharmaceutical, is used with monoclonal antibodies in which all of a particular type are identical and in leukocyte scans. The monoclonal antibodies are used for imaging prostate cancer (Resource World, undated). The indium-¹¹¹ leukocyte scan is a diagnostic imaging test that displays the distribution of leukocytes in the body and can be used in specific anatomic regions for detecting infection and inflammation (Society of Nuclear Medicine, undated).

Indium is used in jewelry making to produce a specialized product, a green-tinted gold, which is 75 percent gold, 20 percent silver, and 5 percent indium. The silver provides the green tinting, and the indium is added to improve workability.

Photovoltaic (PV) solar cells convert sunlight directly to electricity. Although they are used to generate electric power in spacecraft and for instrumentation in remote land locations, the total commercial market is still very small. More than 95 percent of all PV cells in use are either monocrystalline or polycrystalline silicon cells (Solarserver, 2002).

A new direction in the use of PV cells includes surface structuring to reduce reflection loss. For example, the cell surface is constructed with a pyramidal structure so that incoming light hits the surface several times. New materials for this application include copper-indium selenide (CuInSe_2) (Solarserver, 2002).

Trends in Use

During the past decade, world indium consumption has almost doubled from 123 t in 1990 to approximately 225 t in 2000. The average annual growth of indium in the form of ITO in liquid crystal and other display devices has grown by an average 18 percent per year. The relatively high price of indium, however, has caused a drastic reduction in its use for bearings and plating where lower cost alternatives have taken over during the past decade. A steady reduction has been seen in its use as a low-melting-point alloy and solder.

The use of indium in semiconductors has grown at the same rate as the relative growth in indium consumption during the past decade, and has been moving up slightly from 8 to 9 percent of the end use market. The same might be said of its application as a transparent heat reflector, where it has maintained 7 percent of the end use market. The catch-all nature of the other two categories of use—"other alloys" and "other uses"—and the transfer of some uses between them over the years make it difficult to infer trends in consumption from the scarce data available.

Substitutes

Indium can be substituted for in many, perhaps most, of its uses, but usually at a cost in production efficiency or product characteristics. Silicon has, for the most part, replaced germanium and indium in transistors. Although more expensive, gallium can be used as a substitute for indium in some applications in several alloys. In glass-coating applications, silver-zinc oxides or tin oxides can be used. Although technically inferior, zinc-tin oxides can be used in LCDs.

Industry and Market

In 2001, almost 95 percent of the primary unwrought refined indium was estimated to have been produced in Belgium, Canada, China, France, Japan, Peru, and Russia. U.S. output, which is the proprietary data of two major secondary producers, is not published. Most of the primary indium producers are electrolytic zinc refineries. Not all zinc refineries, however, process their own slimes to recover indium, preferring to ship them to the refineries that do produce indium. In 2000, six companies in the United States (Indium Corporation of America, Asarco, Atomergic Chemicals, MCP Metalspecialties, The Wilkinson Company, and Umicore Advance Materials) and 28 companies in the rest of the world produced various forms of refined indium and indium alloys and compounds (Moreno, 2000, p. 617). No count of consumers is available, but most indium is consumed in the industrialized countries.

The value of commercial grade indium consumed in the United States in 2001 is estimated to have been about of \$8.5 million. The value of world production/consumption is estimated to have been about \$50 million.

Indium and the Environment

Metallic indium and most of its compounds are relatively inert and are not considered to be hazardous in industrial use. Exceptions include nitrogen dioxide, which may explode in the presence of indium (New Jersey Department of Health and Senior Services, 2000). Some of the advanced semiconductor materials that contain indium must be considered toxic, not for their indium content, but for the antimony and arsenic components of the compounds, which include gallium indium arsenide phosphide, indium-gallium arsenide, and indium antimonide. Radioactive materials, which are administered to patients for the diagnosis or treatment of illnesses and are reported in contaminated waste, such as indium-111, must be controlled in accordance with the Nuclear Regulatory Commission and State guidelines.

According to the Occupational Safety and Health Administration (undated) and the National Institute for Occupational Safety and Health (undated b), the United States' exposure limit for indium and its compounds is a time-weighted average of 0.1 milligram per cubic meter in any 8-hour shift of a 40-hour work-week.

Indium appears to have no essential role in animal or human nutrition, although it is being touted as a dietary supplement. Those suggesting its value as a vitamin consider that indium, as a rare trace mineral, supports several hormonal systems in the body (Harvest Moon Health Foods, undated). They further suggest that anhydrous indium sulphate may “strongly elevate immune activity and reduce the severity and duration of a myriad of human ailments” (Vital Nutrients, 2002).

The primary toxic effect of ionic indium is damage of the kidneys. It has shown no irritating effects on skin, but experimental data demonstrate that it may affect the respiratory system. Absorption as a percentage of intake through digestion is only about 0.5 percent, and through respiration, it is about 5 percent (Slattery, 1995, p. 157). Experiments on laboratory rats showed that rats that inhaled the sesquioxide form of indium at airborne concentrations range from 24 to 97 milligrams per cubic meter daily for a total of 224 hours developed widespread alveolar edema (National Institute for Occupational Safety and Health, undated a).

Although indium alone does not affect the skin, it is dissolved to an undesirable extent by organic acids, such as are found in food. Consequently, indium should not be used for any purpose in which it is brought into contact with foodstuffs or prolonged contact with skin (Simons, 1967, p. 80).

Indium, which is scarce in the environment, is considered to be relatively environmentally friendly and is used as a replacement for mercury in batteries and for lead in low-temperature soldering applications. Its major drawbacks are its relative scarcity, high cost, and tendency to oxidize in soldering applications (Sprovieri, 1999). An environmental impact assessment for an offshore Baltic pipeline stated that owing to environmental restrictions, the aluminum-zinc-indium alloys are generally the most frequently used in saltwater anode applications (BalticPipe, 2001).

Supply, Demand, and Sustainability

Supply

The world reserve base for indium in zinc deposits is estimated to be 5,700 t, of which the United States has about 10 percent. According to Roskill Information Services Ltd. (1999, p. 7-13), this reserve base would satisfy world demand for a little more 20 years, at anticipated rates of world consumption. The reserve base could be extended, however, by the additional reserves that exist in copper, lead, and tin ores, although little is being extracted in 2001. Secondary indium recovered from scrap LCDs contributes significantly to supply in Japan and will increase as “latest technology” indium-containing LCDs continue to grow in popularity as the “older technology” indium-containing screens are retired from use.

Demand

World demand for indium-phosphorus wafers began to increase sharply in spring 2000 with the spread of a new optical communications technology, dense wavelength division multiplexing (DWDM). Showa Corporation (Japan) has indicated that the system can dramatically increase the amount of information transmitted over the Internet through fiber optical glass (Furukawa, 2001).

World production of refined indium in 2001 is estimated to be 340 t; production in what was called the market economy world, until the 1990s, was probably about 225 t, but this does not include China, the CIS, or other communist countries. Information on primary production levels of indium is difficult to obtain because producers tend to treat production data as confidential. Some information is obtained from traders of minor metals, but with this information, primary production can often be mistaken for the refining of previously produced crude metal (Roskill Information Services Ltd., 1999, p. 7-13).

The estimated data plotted in figure 2 suggest that the world production during the past 15 years has increased more than six fold. When U.S. production dropped off in the late-1970s, imports, which until then had

been less than domestic production, made up the shortfall required for a continued growth in domestic supply, as shown by the data in table 2.

Indium is consumed in the industrial countries, especially in those having sizable high-technology industries. Good data on consumption by the two major consuming countries, Japan and the United States, are available. The estimated consumption data plotted in figure 3 suggest that U.S. consumption in 2000 was about 55 t. World consumption has not kept up with world production, and large stocks may become available should the price rise sufficiently. The world consumption data (using production data as a proxy) plotted in figure 2 and the U.S. consumption data plotted in figure 3 show a marked increase in consumption in the mid-1980s. The continued difference between U.S. imports and domestic consumption is the export of finished goods that contain indium metal.

The general trend in indium consumption has been toward increased consumption in high-technology applications. Growth in consumption is expected to follow trends in the use of more complex technologies.

Sustainability

Barring the advent of some high-volume application for indium, its production, use, and disposal in the environment after use appears to be easily sustainable.

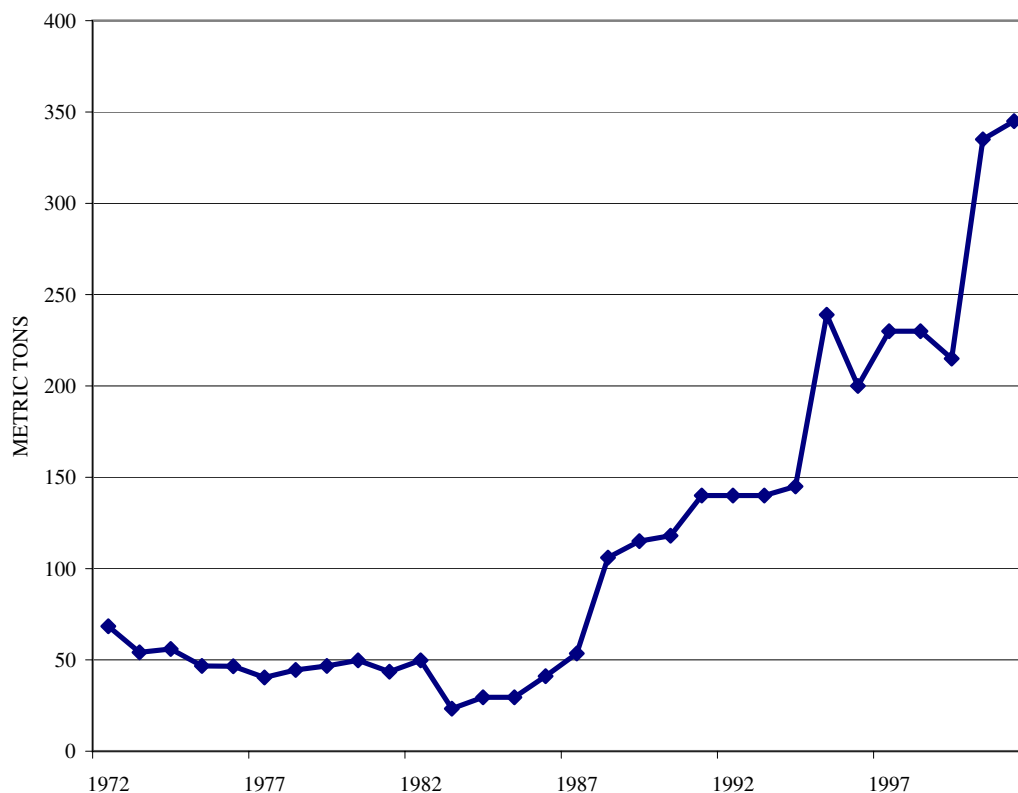


Figure 2. Graph showing world production of refined indium from 1972 to 2000. Data for 1972 to 1973 and 1983 to 1992 exclude U.S. production. Data for 1973 and 1983 to 1987 exclude some other market economies. Sources: U.S. Bureau of Mines, 1973-1996; U.S. Geological Survey, 1997-2002.

Table 2. U.S. supply and demand for unfabricated indium.

[In metric tons. NA, not available. W, y may not add to totals shown. Note change at 1995 from 5-year to 1-year intervals. Data from U.S. Bureau of Mines, 1970-1995; U.S. Bureau of Mines and U.S. Geological Survey, 1996; U.S. Geological Survey, 1997-2002]

	1970	1975	1980	1985	1990	1995	1996	1997	1998	1999	2000
Components of U.S. supply:											
Refined production	W	W	W	--	--	--	--	--	--	--	--
Imports for consumption	12	4	9	30	30	85	33	86	75	77	69
Net deliveries from industrial stocks	--	--	--	--	--	--	--	1	0	--	--
Total U.S. supply	12	4	9	30	30	85	33	87	75	77	69
Distribution of U.S. supply:											
Exports	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Net additions to industrial stocks	--	--	--	--	--	--	--	--	--	--	--
Apparent consumption	12	4	9	30	30	85	33	87	75	77	69
Total distribution of supply	12	4	9	30	30	85	33	87	75	77	69
U.S. consumption pattern, by tonnage: ¹											
Coatings	NA	1	4	12	9	38	15	39	38	39	34
Solders and alloys	NA	0	--	--	14	30	12	30	25	26	23
Electronic components and semiconductors	NA	1	4	12	5	13	5	13	9	9	10
Instruments	NA	(2)	--	--	--	--	--	--	--	--	--
Nuclear reactor controls	NA	1	--	--	--	--	--	--	--	--	--
Research and other uses	NA	1	2	6	3	4	2	4	4	4	3
Total apparent consumption	12	4	9	30	30	85	33	87	75	77	69
U.S. consumption pattern, by percentage:											
Coatings	NA	30	40	40	30	45	45	45	50	50	49
Solders and alloys	NA	--	--	--	45	35	35	35	33	33	33
Electronic components and semiconductors	NA	18	40	40	15	15	15	15	12	12	14
Instruments	NA	6	--	--	--	--	--	--	--	--	--
Nuclear reactor controls	NA	30	--	--	--	--	--	--	--	--	--
Research and other uses	NA	16	20	20	10	5	5	5	5	5	4

¹Calculated by applying the reported percent consumption pattern to the apparent total consumption.²Less than 1/2 unit.

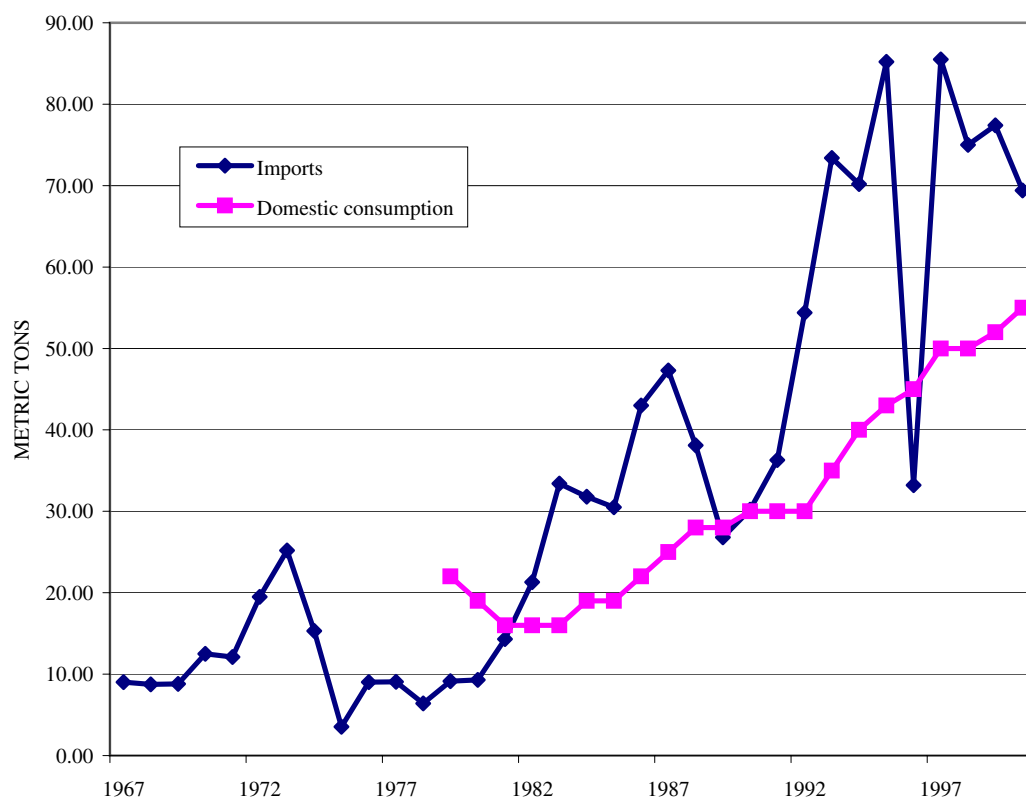


Figure 3. Graph showing imports and domestic consumption of indium from 1967 to 2000. Sources: U.S. Bureau of Mines, 1973-1996; U.S. Geological Survey, 1997-2002.

Economic Factors

The costs of exploration, mining, and metallurgical extraction associated with indium are grouped with those for zinc, tin, and other byproduct metals and embedded mainly in those of zinc. Thus, they are not readily available.

U.S. indium prices have been almost cyclical in the past quarter century with peaks in prices in 1980, 1988, and 1995 followed by a relatively gradual decline (Brown, 1999). Unexpectedly low producer prices in 1993 and 1994 led to short supply and a subsequent price spike in 1995. Lack of confidence in world economies, new technology that requires less indium in LCD screen applications, and uncertainty concerning a Ukrainian stockpile release led to an indium price decline following this 1995 peak (fig. 4).

Although the demand for indium is much influenced by the technological requirements of its end uses, the cost is sufficiently high to be vulnerable to substitution by other metals when its price is high, although the substitute is generally technically inferior or of an equally expensive nature. Silicon has already been substituted for germanium and indium in transistor technology. When indium prices are low, the supply is reduced as refiners and secondary producers respond by stockpiling metal or metal-containing slimes.

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

The U.S. Government no longer stockpiles indium. Imports into the United States of unwrought indium metal waste and scrap are duty-free.

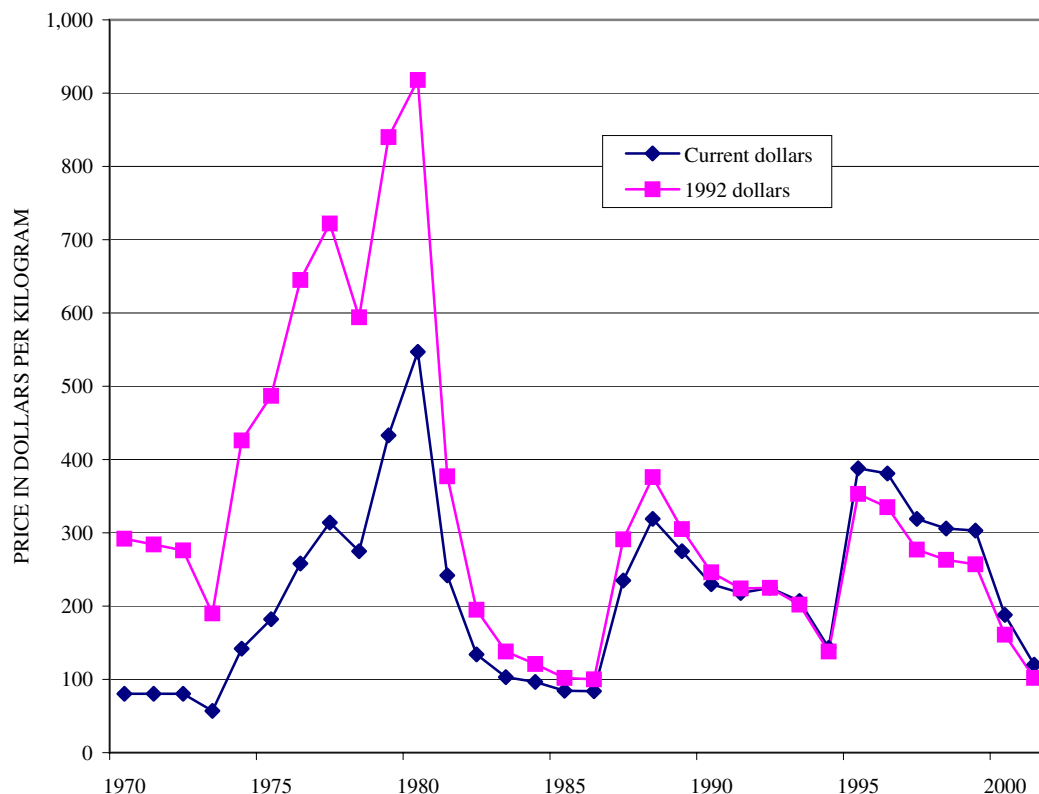


Figure 4. Graph showing average price for indium from 1970 to 2000. Prices are for 99.97-percent pure indium. Sources: Brown, 1999, 2000b.

Outlook

World and U.S. consumption has greatly increased during the past decade, and primary production of indium has been essentially static for the last several years. The end uses of indium are primarily in high-technology applications and are being improved continuously. Much research is being done into the uses for indium, and new sizable uses could possibly result. The distribution of indium among end uses has undergone drastic changes during the last decade and other changes could be realized in the short term. Supplying primary indium to meet the past demand in the United States has often been difficult, but this has been absorbed by secondary supply.

No credible environmental constraints on the production or use of indium appear to exist. In fact, indium appears to be a substitute for other materials considered to be more environmentally hazardous.

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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).