CADMIUM

By Jozef Plachy

Domestic survey data and tables were prepared by Jason T. Collins, statistical assistant, and the world production table was prepared by Regina R. Coleman, international data coordinator.

In 2000, production of cadmium metal in the United States increased by nearly 60% compared with very low production in 1999; production of cadmium compounds, including cadmium sulfide, declined by more than 30% (tables 1, 2). Apparent consumption increased by nearly 9%, but, for the fifth consecutive year, exceeded production (tables 1, 3). The difference was made up by imports and sales from the National Defense Stockpile, operated by the Department of Defense. After years of consecutive decline, the price for cadmium metal registered a modest increase in 2000.

In the United States, two companies, one in Illinois and another in Tennessee, produced primary cadmium as a byproduct of the smelting and refining of zinc concentrates in 2000. A third company, in Pennsylvania, recovered cadmium from scrap, mainly from spent nickel-cadmium (Ni-Cd) batteries. In 2000, the value of cadmium produced was calculated to be about $670,000. Although definitive consumption data do not exist, the International Cadmium Association (ICdA) has made the following estimates of cadmium consumption for various end uses in 2000: batteries, 75%; pigments, 12%; coatings and plating, 8%; stabilizers for plastics and similar synthetic products, 4%; and nonferrous alloys and other uses, 1% (Hugh Morrow, President, International Cadmium Association, oral commun., 2001).

In 2000, as in most years, the United States was a net importer of cadmium metal. The major source of U.S. imports was Belgium, accounting for about 23% of all imports, followed by Mexico and Australia, with 20% and 18%, respectively (table 6). Cadmium compounds and pigments were subject to import duties, but unwrought and powdered metal, as well as waste and scrap, entered duty free in all but a few cases. Cadmium, in all forms, from North American Free Trade Association member nations (Canada and Mexico) entered the United States duty free. As in 1999, the United States was a net exporter of cadmium sulfide, most of which was exported to China (84%), followed by the Philippines (8%) and Hong Kong (5%) (table 5). Trade data for other cadmium compounds were not available.

Cadmium was refined in 28 countries in 2000 (table 7). The six largest producers, in decreasing order, were Japan, China, the United States, Belgium, Canada, and Mexico. These countries accounted for more than one-half of world production; the United States accounted for nearly 10%. Identified world cadmium resources at yearend 1999 were estimated by the U.S. Geological Survey (USGS) to be 6 million metric tons (Mt), a figure based on zinc resources typically containing about 0.3% cadmium. The world reserve base was estimated to be 1.2 Mt, and reserves were 600,000 metric tons (t).

Legislation and Government Programs

During the last decade, regulatory pressure to reduce or even eliminate the use of cadmium, a metal which is toxic in certain forms and concentrations, has gained momentum, mainly in the European Union (EU), and some other developed countries as well. In the United States, many Federal and State agencies regulate the cadmium content of air, water (including bottled water), pesticides, color and food additives, waste, etc. In 1999, the U.S. Environmental Protection Agency (EPA) created a draft list of persistent, bioaccumulative, and toxic (PBT) pollutants. Since its publication, the PBT list continues to be controversial not only in the cadmium industry but also in the base metal industry since all nonferrous metallic elements are inherently persistent but not necessary bioavailable.

Cadmium is 1 of 11 metals among 53 chemicals on the draft PBT list targeted by the EPA for a 50% reduction by 2005. The ICdA objected to the inclusion of any metal, particularly cadmium, on the PBT list. One of the reasons for its objection was that no distinction was made between various cadmium compounds and cadmium metal itself. According to ICdA, it is not possible to give a single rating for cadmium and all of its compounds because of their widely varying solubilities and bioavailabilities. Highly soluble and bioavailable cadmium chloride and cadmium ions, for example, will have a much

Cadmium in the 20th Century

Germany produced the first commercial cadmium metal at the end of 19th century and was the most important producer until the outbreak of World War I. Production in the United States began in 1907 when the Grasselli Chemical Co. of Cleveland, OH, recovered 6 metric tons of cadmium metal as byproduct of zinc smelting. As imports from Germany were curtailed during World War I, domestic production rapidly increased, and by 1917 the United States became the world's leading producer of cadmium. Increased production was spurred by the development of the cadmium electroplating process in 1919 to coat mainly iron and steel.

By the 1940s, electroplating represented about three-fourths of cadmium consumption. Production and consumption of cadmium in the United States peaked in 1969, at 5,700 tons and 6,800 tons, respectively. Since then, both production and consumption declined because of environmental concerns due to toxicity of certain forms of cadmium. During the second half of the 20th century, the primary use of cadmium was for plates in batteries. By 2000, about three-fourths of the cadmium consumption was for batteries and the remaining one-fourth is used for pigments, coatings and plating, and as stabilizers for plastics.

different risk than cadmium metal, cadmium oxide, cadmium sulfide, and other insoluble compounds. Therefore, ICdA claims that the PBT rating for cadmium should recognize differences between the various forms of cadmium, their relative bioavailability, and thus their relative effects on human health and the environment. In addition, the draft PBT list failed to recognize that naturally occurring metallic elements are inherently persistent, but that such persistence results in less not more adverse environmental and human health effects. It is the bioavailable amounts of cadmium, according to ICdA, which are likely to lead to adverse health effects not the persistent amounts. During 2000, the opposition to the draft PBT list from various segments of industry, government, and academia continued to grow. Representatives of over 55 industry trade associations became signatories to a letter to EPA requesting a review of scientific documentation on which the list was based by its Science Advisory Board and seeking to defer inclusion of all metals in PBT programs until completion of that review. The trade associations assert that metals and inorganic metal compounds should be assessed under different criteria than synthetic organic chemicals for which the PBT methodology was first developed. The U.S. House of Representatives Committee on Science supported the industry by strongly encouraging EPA to review, as soon as possible, the scientific soundness of the methodology used in creating the PBT list (ILZRO Environmental Update, 2000b).

On another issue involving cadmium, the EPA decided to amend the existing Clean Water Act of 1995. The act requires the EPA to develop and, as warranted, revise water quality criteria so that its standards accurately reflect the latest scientific knowledge. The act also requires that water quality criteria be based solely on water data and scientific judgments; it does not consider economic impacts or the technological feasibility of meeting the criteria in ambient water. The latest revision involving cadmium was introduced on October 29, 1999, when EPA published the 2000 "Update of Ambient Water Quality Criteria for Cadmium" in the Federal Register. With this publication, the EPA made available to the public all references identified by a recent literature review and asked the public to submit any additional pertinent data or scientific views that would be useful in revising the aquatic life criteria for cadmium. The deadline for comments was October 17, 2000. After a careful review and incorporation of comments, an update of the Clean Water Act will be published in 2001 (U.S. Environmental Protection Agency, August 17, 2000, Notice of availability of draft aquatic life criteria document for cadmium, accessed November 25, 2000, at URL http://www.epa.gov/fedrgstr/EPA-WATER/2000/August/Day-17/w20972.htm). Most of the comments during the review period urged the EPA not to proceed with the cadmium update until the Biotic Ligand Model for cadmium was developed by the EPA which is considered a scientifically appropriate model to assess the toxicity of metals in aquatic environments. The model would integrate the physicochemical properties of the site-specific aquatic system, including pH, dissolved organic content, hardness, chloride content and alkalinity, with the biological component being protected. Consequently, the model would predict the bioavailability and toxicity of metals far more accurately than current methodologies. In many cases, this will result in more realistic criteria than those currently existing due to the incorporation of additional modifying factors (ILZRO Environmental Update, 2000d).

Because spent batteries are one of many sources of heavy metals emissions when incinerated or disposed of in landfills, certain European countries have adopted individual environmental standards on batteries containing cadmium, lead, and mercury. To avoid trade barriers created by disparities in such restrictions, the European Commission (EC) in 1991 unified these individual measures into Directive 91/157/EEC, which is binding for all EU member countries. The latest one, EU Directive 2000/60/EC on water, recommends phasing out the use of 32 chemicals over the next 20 years. The ban on Ni-Cd batteries is to start in 2008. If approved by the European Parliament, this directive will require all EU member countries to phase out the discharge of these hazardous chemicals into aquatic environments. Similar to the EPA, the Commission identified 11 of the chemicals for inclusion on a priority list of chemicals that they consider to be toxic, persistent, and liable to be bioaccumulate in the environment—the PBT list. Chemicals on this list, which includes cadmium, will be the first to be addressed by the Commission for possible phase out (ILZRO Environmental Update, 2001). In opposition to such a ban, the battery industry has proposed an EU-wide used battery collection scheme that would ensure recycling of at least 75% of Ni-Cd batteries possibly by 2004. ICdA argued that if the recycling goal is not achieved, cadmium could still be banned in time for the proposed deadline (The Lycos Network, August 3, 1999, Cadmium industry makes last charge against battery ban, accessed March 7, 2001, at URL http://ens.lycos.com/ens/aug99/1999L-08-03-02.html). In its November 2000 Organization for Economic Cooperation and Development (OECD) joint meeting of the Chemicals Committee and the Working Party on Chemicals, however, the EC representatives blocked any attempt to adopt an OECD-wide Ni-Cd battery recycling label (ILZRO Environmental Update, 2000c). In addition to the battery and cadmium industries, manufacturing companies and organizations also expressed reservation about EC's efforts to ban cadmium-containing devices. The American Electronics Association and the Electronics Industries Alliance expressed concern that the ban was being proposed without any analysis of the environmental impacts of replacement materials and processes. The Electric Vehicle Association of Great Britain also opposed the proposed ban, which the association claims could set back the cause of electric vehicles in the EU by 20 years (Advanced Battery Technology, 2000).

In 1991, the U.S. Congress authorized the disposal of the entire stockpile of 2,872 t of cadmium from the National Defense Stockpile. In 2000, the Defense Logistics Agency, which manages the stockpile, sold 319 t of cadmium metal, leaving 807 t still to be sold.

Production

The most common cadmium mineral is greenockite, which is almost always associated with the zinc ore mineral, sphalerite. The average ratio between contained zinc and cadmium in sphalerite is about 400:1 or 0.25%. At least 80% of cadmium output worldwide is estimated to be a byproduct of primary zinc production. The remaining 20% is obtained from secondary sources, such as baghouse dust and the recycling of cadmium products, and from the production of other primary metals. Because of depressed cadmium prices in recent years, the processing of many wastes to recover cadmium has not been economically viable. Thus, cadmium is usually extracted to remove it from zinc, lead, or copper production or to recycle cadmium-containing products.

In the United States, only two companies produced primary cadmium during 2000—Big River Zinc Corp., Sauget, IL, and Pasminco Ltd., Clarksville, TN. Both companies used an electrolytic process and recovered the cadmium as a byproduct during the roasting and leaching of zinc concentrate. After removing various impurities, cadmium can be processed to final form by either refining or electrowinning.

The Sauget operation, owned by Korea Zinc Co. Ltd., can produce up to 1,400 metric tons per year (t/yr) of cadmium metal and oxide. About 80% of its concentrate feed was supplied by mines in Missouri and Tennessee, and the remaining 20% was imported, mainly from Canada, Mexico, and Peru (Mining Journal, 1999). The cadmium content of zinc sulfide concentrate is usually between 0.1% and 0.8%. The concentrate is heated in fluidized bed roasters to produce an impure zinc oxide (calcine) suitable for acid leaching. Between 60% and 85% of the calcine, which contains cadmium and other impurities, is volatized with the sulfur dioxide gas generated during the roasting process. Calcine and fume are separated from the gas and collected in waste heat boilers, cyclones, and electrostatic precipitators. The collected calcine dust is combined with the unvolatilized portion of the calcine and dissolved in sulfuric acid at a leaching plant. Generally, manganese dioxide is added to the leaching tank to remove iron and significant amounts of other impurities. These insoluble residues are sold to other smelters for further processing as iron cake. The leachate is sent to a series of cold and hot purification tanks where cadmium and other remaining undesirable metals are removed from the solution. After the first stage of zinc sulfate purification, discharged impurities form a copper cake, which, like the previously captured leach residues, are sold for processing. The bulk of cadmium is precipitated in the second stage of purification, and the remainder is precipitated in a third stage. The cadmium precipitate is filtered and forms a cake containing about 12% cadmium, 25% zinc, and small amounts of other impurities. The cake is then redissolved in sulfuric acid. After two additional acid treatments, a cadmium sponge is produced, which is dissolved in another sulfuric acid bath, and the solution, if sufficiently pure, is passed into electrolytic cells where the cadmium is deposited on cathodes. The resulting more than 99.99%-pure cadmium metal is melted and cast into 50-millimeter (mm)-diameter ball anodes or 250-mm-long sticks or oxidized in a controlled atmosphere to produce cadmium oxide powder. Higher purity cadmium for special purposes, such as for semiconductors, can be produced by vacuum distillation (U.S. Environmental Protection Agency, 1987).

In 1999, Pasminco Ltd. of Australia acquired Savage Zinc Inc. and its parent company, Savage Resources Ltd., also from Australia (Pasminco Ltd., [undated], Welcome to Pasminco, accessed June 1, 2000, at URL http://www.pasminco.com.au). The acquisition extended Pasminco's zinc distribution network into the U.S. market. After the acquisition, Pasminco stated that a plan to triple zinc production capacity at its Clarksville smelter would be postponed (Financial Express, [undated], Pasminco's U.S. smelter expansion plan put on hold, accessed May 3, 2000, at URL http://www.financialexpress.com/fe/daily/19990904/fco04016p.html). In 2000, most concentrate for the Clarksville smelter was supplied by local mines owned by Pasminco and ASARCO Incorporated. When more favorable market conditions develop, Pasminco may expand the smelter. If the capacity of the smelter is increased, domestic production will need to be augmented by imported zinc concentrate, most likely from the newly opened Century Mine in Australia. Increased zinc production could affect cadmium production at the Clarksville smelter, which at present can produce up to 500 t/yr.

The amount of cadmium that is recycled is difficult to estimate for a number of reasons. For example, cadmium from baghouse dust generated at lead and copper smelters enters the primary cadmium production circuit at zinc refining operations and may or may not be included in reported production statistics for primary cadmium metal. Although the reported amount of cadmium produced from the recycling of Ni-Cd batteries is fairly accurate, there are no firm data on the amounts of cadmium recovered from other sources such as electric arc furnace dust, electroplating wastes, filter cakes, sludges, and other cadmium-containing materials. Electric furnace dust, which contains about 0.05% cadmium, is recovered only because it is mandated by environmental regulations; cadmium prices were so depressed in 2000 that the processing of furnace dust for any other purpose was not economically feasible.

In 1995, International Metals Reclamation Co. Inc. (INMETCO), a subsidiary of the International Nickel Co., began reclaiming cadmium from spent batteries at its Ellwood City plant northwest of Pittsburgh, PA. The $5 million high-temperature metal recovery plant addition, built by Davy International Ltd., was the first facility of its kind in the world. It is capable of processing more than 2,500 t/yr of spent Ni-Cd batteries. Cadmium recycling at the facility thus far has been practical only for Ni-Cd batteries, some alloys, and dust from electric arc furnaces. The most difficult aspect of Ni-Cd battery recycling is the collection of spent batteries. Large industrial batteries, containing 20% of the cadmium used for batteries, are easy to collect and are recycled at a rate of about 80%. The remaining 80% of the cadmium used in batteries goes into small consumer Ni-Cd cells and batteries, which for the most part are usually discarded with municipal solid wastes. Therefore, voluntary industry-sponsored collection programs and Government agencies are devising ways to improve the collection of these small batteries. Economies of scale are very important, and the larger a recycling operation, the lower its unit cost is likely to be. Several different collection programs have been developed by INMETCO to meet the needs of battery manufacturers and the numerous consumers, firms, organizations, and agencies that use many diverse products, such as power tools, cordless phones, and personal computers (Industrial Heating, 2000). Rechargeable Battery Recycling Corp. (RBRC) operates the "Charge Up to Recycle!" program, established in 1995, which has organized a multifaceted collection program to collect rechargeable consumer batteries. The RBRC generates revenue for the program by licensing its seal of approval to individual companies involved in the manufacturing, importation, and distribution of rechargeable batteries or battery-operated products. The "Charge Up to Recycle!" program contains several key elements that are specified both in EPA regulations (40 CFR part 273), Federal law (The Mercury-Containing and Rechargeable Battery Management Act of 1996), and in various State laws. These elements include uniform battery labeling, removability from appliances, national network of collection systems, regulatory relief to facilitate battery collection, and widespread publicity to encourage public participation. For that purpose, RBRC has undertaken an extensive public education campaign and has established several recycling programs in the United States, such as the Retail Recycling Plan (8,500 participants), the Community Recycling Plan (300 enlisted), and the Business & Public Agency Recycling Plan (1,000 enrolled) (Hugh Morrow, President, International Cadmium Association, written commun., 2001). The RBRC program has about 30,000 collection sites in the United States and Canada, including many at the outlets of major participating retailers. Most of the industrial wet Ni-Cd batteries were recycled through collection programs in which producers of industrial batteries collect and send their spent batteries to INMETCO. A smaller portion of industrial batteries was collected and shipped by various environmental organizations (Bleakney, 1998).

The process of cadmium recovery from industrial and consumer sealed batteries, both of which contain about 15% cadmium by weight, differs only in the manner of battery preparation. Processing of industrial batteries consists of draining the sodium hydroxide electrolyte, cutting the tops off the batteries, and separating the nickel and cadmium plates. Small batteries must be handsorted because only newer batteries are color coded and very few of them carry bar codes, making optical scanning and other automated sorting very difficult.

The cadmium plates from the industrial batteries and the small batteries, from which the plastic casing has been removed in INMETCO's patented thermal oxidizer, are charged into a cadmium recovery furnace. In the furnace, carbon is added as a reductant. The charge is heated and the cadmium is distilled, then collected in a water bath. The final products, called Cadmet shot, are small flattened discs, 4 to 6 mm in diameter, to facilitate handling and to reduce erratic rolling, and have a purity of greater than 99.95% cadmium, some as high as 99.999% cadmium. Cadmet is drummed, weighted, assayed, and shipped to Ni-Cd battery manufacturers for reuse in new batteries, but may also be used in the manufacture of corrosion-resistant coatings or in the manufacture of cadmium-containing stabilizers, alloys or pigments.

In addition to the pyrometallurgical process for recycling cadmium, in which cadmium vapor is collected and then solidified by condensation or oxidation, there are hydrometallurgical cadmium recycling processes as well. In these wet chemical processes, batteries are dissolved in strong acids, then subjected to selective precipitation or ion exchange reactions to separate cadmium compounds from nickel and iron compounds.

Although secondary production has been increasing at about 6% per year and most likely will increase even faster in the future, worldwide primary production will remain basically unchanged for the next few years. Any future increases in domestic production of virgin cadmium will likely come from the Crandon/Rhinelander zinc-copper deposit in northeastern Wisconsin. Its development will depend on the zinc market and on Nicolet Minerals Co., a wholly owned subsidiary of Rio Algom Mining Corp., acquiring some remaining permits from the Wisconsin State Government. Nicolet's proposal of a future mine near the headwaters of the Wolf River, however, is opposed by those who feared the pollution of underground water and altered water levels of nearby lakes caused by pumping of water to keep the shafts dry. The deposit contains an estimated 62 Mt of ore grading 5.6% zinc, 1.1% copper, and 0.01% to 0.23% cadmium (Skillings' Mining Review, 1978). Sphalerite from one particular stratigraphic sequence, the Skunk Lake unit, consistently had the highest cadmium values, averaging 0.09% cadmium (Lambe and Rowe, 1987). Pyrite is ubiquitous throughout most of the deposit. Development of the deposit would include the building of a 2-Mt-capacity mill with an annual production of between 200,000 t and 300,000 t of zinc concentrate and about 20,000 t combined copper-lead concentrate (Metal Bulletin, 1996).

Environmental Issues

Despite being toxic in high concentrations of soluble or respirable forms, dermal contact with cadmium metal results in negligible absorption. However, prolonged exposure to high concentrations of the respirable and soluble forms of cadmium is known to have toxic health effects and adverse environmental impacts. Inhaled cadmium fumes or fine dust are much more readily absorbed than ingested cadmium. Repeated exposure to excessive levels of dust or fumes can have irreversible effects on kidneys and on lungs, producing shortness of breath and emphysema. Because of these potential adverse effects, occupational exposure to cadmium in the United States is regulated by the Occupational Safety and Health Administration (OSHA). OSHA's permissible limit for cadmium exposure through inhalation is 5 micrograms per cubic meter of air breathed (Golden Artist Colors, [undated], Will cadmium always be on the palette?, accessed March 7, 2001, at URL http://www.goldenacrylics.com/cadmiums.htm). Similarly, strict air and water emission limits on cadmium as well as land disposal restrictions on the metal are in effect in the United States and other countries. In the United States, any cadmium-containing waste that leaches more than 1 milligram per liter is considered hazardous waste. Any discharge of cadmium chemicals above a specific threshold level into navigable waters is subject to reporting requirements. The Reference Dose for cadmium in drinking water is 0.0005 milligrams per kilogram per day (mg/kg/d) and in food is 0.001 mg/kg/d (U.S. Environmental Protection Agency, [undated], Cadmium and compounds, accessed March 7, 2001, at URL http://epa.gov/ttnuatw1/hlthef/cadmium.html).

The four main environmental and human health concerns involved with Ni-Cd batteries are occupational exposure, manufacturing emissions and wastes, product use, and product disposal. Because most of the environmental and health problems involved in the production of Ni-Cd batteries can easily be controlled, recent regulations have focused on disposal options. Basically, only four disposal options are available—composting, incineration, landfilling, and recycling. The first two options are not practical; landfilling was the most frequently used alternative and recycling was the one most preferred by the industry and environmentalists. Because most cadmium is produced as a byproduct, mainly of zinc production, restrictions on the use of cadmium in batteries could increase the amount of unprocessed cadmium that is disposed in landfills by zinc producers. Therefore, an effective collection and recycling system for spent batteries would probably protect the environment more than a ban on cadmium in batteries.

Consumption

The USGS does not collect consumption data on either cadmium metal or cadmium compounds. Apparent consumption of cadmium metal in the United States is calculated by the USGS from production, trade, and stock changes. Apparent consumption in 2000 increased by nearly 9%, compared with that of 1999. Estimated consumption of cadmium by end use in 2000 was as follows: batteries, 75%; pigments, 12%; coatings and plating, 8%; stabilizers for plastics and similar synthetic products, 4%; and nonferrous alloys and other uses, 1%.

Cadmium metal has a low melting temperature, good electrical conductivity, excellent corrosion resistance in alkaline and saline environments, and the ability to improve the mechanical properties of other metals. Therefore, cadmium metal is commercially used mainly as a corrosion-resistant coating on steel, aluminum, and other nonferrous metals, especially where low friction or low electrical resistivity is needed. Cadmium metal is also added to some nonferrous alloys to improve properties such as strength, hardness, wear resistance, castability, and electrochemical behavior. All cadmium compounds are made from cadmium metal and are primarily used in batteries, pigments, ultraviolet light and weathering stabilizers, and semiconductor applications.

Although cadmium consumption for batteries has been growing steadily for more than 15 years, other cadmium markets, such as pigments, stabilizers, coatings, and alloys, are regarded as mature because they are not expected to grow; in fact, some of the markets have already started to decline. Consumption of cadmium for these dispersible and dissipative applications probably will continue to decline because of increasingly stringent environmental regulations, concerns of manufacturers about long-term liability, and the development of less toxic substitutes. Use of organic cadmium compounds as stabilizers in polyvinyl chloride (PVC) continues to decline since the barium-cadmium stabilizers used in the past can now readily be substituted by barium-zinc, calcium-zinc, or organo-tin stabilizers. Consumption patterns of cadmium compounds varied significantly among countries because of differences in environmental regulations, industrial development, natural resources, and trading patterns. In the United States, Ni-Cd batteries provided the power for three-fourths of the most common portable products, such as cordless telephones, portable household appliances, power tools, battery-powered toys and hobbies, and emergency and remote area power. It is estimated that there are more than 450 million cordless electronic products in the United States.

The consumption of cadmium in batteries could receive a boost from manufacturers of hybrid electric vehicles and providers of telecommunications in remote areas. Although preference for Ni-Cd batteries over other kinds of batteries in hybrid vehicles has not been indisputably established due to environmental restrictions, application as a power source for telecommunications in remote areas holds considerable promise for future cadmium use. Compared to traditional valve-regulated lead acid batteries, the Ni-Cd batteries have longer life, are more reliable, require lower maintenance, have unlimited shelf life, and have the lowest life cycle cost. Replacement and new production of these batteries for telecommunications could translate into an annual requirement of about 2,000 t, or over 10% of the current world's production (Vigerstol, 1998). One of the most promising applications from the cadmium industry's perspective is the use of cadmium telluride solar cells to convert sunlight into electricity and the use of Ni-Cd batteries to store that electrical energy for remote power systems. Consumption for this application could be as high as 5,000 t/yr (Hugh Morrow, President, International Cadmium Association, oral commun., 2001).

A wide variety of cadmium sulfide-based compounds are used as yellow, orange, and red pigments for plastics, glasses, ceramics, enamels, and artists' colors. Organic alternatives still cannot match many of the popular properties of cadmium pigments, especially color brightness, opacity, and processability. One of the more promising noncadmium colorants is a cerium sulfide developed in France (American Metal Market, 1997). Cadmium pigments are particularly well suited for applications requiring high temperature or high-pressure processing or applications where other pigments will readily degrade. Cadmium carboxylates, such as laurate and stearate, are used as ultraviolet light and weathering stabilizers for PVC. The finished PVC product usually contains no more than 0.2% cadmium. The cadmium is locked into the polymer matrix and has extremely low leachability (Donelly, 1996).

Prices

As the byproduct of other metals production, cadmium is not subject to the normal supply-demand dynamics of most metals. The inelastic supply-demand situation associated with byproduct commodities invariably leads to volatile pricing, and such has been the case for cadmium over the past 20 to 30 years. Until the late 1980s, cadmium was used mainly in pigments and alloys. After the Ni-Cd battery was developed, the battery market expanded by 20% per year, and the price of cadmium increased to $9.10 per pound by March 1988. With the exception of 1995, the 1990s were marked by a steady decline in cadmium prices due to tightening regulatory controls and thus reduced consumption in some traditional cadmium markets such as pigments, stabilizers, and coatings. In addition, recycling of cadmium batteries has also led to the availability of secondary cadmium. Cadmium prices remained at historically low levels in 2000. As world supply tightened toward the end of year, however, prices for high purity cadmium (99.99%) began to inch upward. Reduced primary production, offsetting increased secondary cadmium output, and continued moderate demand in spite of regulatory concerns led to a balanced world cadmium market in 2000. Despite increased supply, the price for cadmium in the United States began to increase at the end of 2000 (table 1).

Current Research and Technology

A relatively new process for secondary production of cadmium from recycled Ni-Cd batteries was developed in the past 5 years by a German firm, ACCUREC GmbH. The new process, know as Vacuum Thermal Recycling, is the first ultralow emission process that can be installed modularly with capacities of between 500 t/yr and 5,000 t/yr. The vacuum process has advantages because under vacuum all elements evaporate at a significantly lower temperature and the hermetic construction prevents contamination by escaped gases. A charge of about 500 kilograms of spent batteries is inserted in a quartz pipe that is vacuum-sealed and is heated to 100° C to 150° C. After all water has evaporated, the charge can be heated to the operating temperature of about 750° C. Following the inclusion of various additives, the cadmium oxide is reduced and evaporated. The metal vapor is then water-cooled in a metal condenser, where it forms a metallic cadmium block (Wehye and Melber, 2000a).

In rare welcome news for the cadmium industry, a Princeton University study found that, under certain conditions, some organisms grow better when they contain cadmium. According to the study, cadmium joins a group of elements (such as selenium, nickel, tungsten, and iron) that can have either a toxic effect or perform an essential biological function, depending on environmental conditions. The enzymes that help interconversion of carbon dioxide, essential for respiration in animals and fixation of carbon dioxide during photosynthesis in plants, require a metal, which is usually zinc. However, under conditions where zinc is scarce, some marine organisms produce a cadmium-specific carbonic anhydrase. For example, the marine diatom *Thalassiosira weissflogii* produces a cadmium-specific carbonic anhydrase when it is starved of zinc and cannot make enough of the zinc-requiring carbonic anhydrase (ILZRO Environmental Update, 2000a).

A University of Arkansas research team has found a way to replace dimethylcadmium with cadmium oxide to form nanocrystals, which are used in applications such as special electronics and optoelectronic devices. Dimethylcadmium is a toxic chemical that is unstable at room temperature and explosive at higher temperatures. The researchers discovered that from a base of safer cadmium oxide they can make a variety of nanocrystals incorporating several different materials (Business Week, 2001a).

At the University of California at Berkeley, new forms of cadmium selenide crystals have been developed for use in the manufacture of solar panels. The new crystals facilitate electron flow and could boost efficiency to over 20%, compared to far more expensive existing solar cells (Business Week, 2001b).

Outlook

Historically low prices, limited growth in many mature cadmium markets, and pending environmental restrictions are factors that must be considered in forecasts for the cadmium industry. Zinc mining companies that produce cadmium as a byproduct, have begun to regard the metal as a cost rather than a credit. The cost of producing cadmium, which is difficult to determine apart from zinc, probably has exceeded the sale price in some cases. The immediate future of the cadmium industry rests largely with the Ni-Cd battery market, which is the only market that continues to grow, especially in certain sectors, such as power tools and telecommunication uses. Following declines in recent years, the coatings and pigments markets for cadmium have stabilized and are not expected to erode any further in the future. The stabilizers and alloys markets, however, are expected to diminish and eventually close due to substitution by cadmium-free products. However, several new applications, such as telecommunications, electric and hybrid electric vehicles, remote area storage systems, and solar cells could become significant cadmium markets.

The future of the cadmium market will be determined by the extent to which industry is able to fully implement the collection and recycling of cadmium products. The success of new cadmium recycling technologies is critical not only in battery markets, but also for other principal end-use products. Recycling of industrial Ni-Cd batteries, which retain nearly 100% of the market for emergency lighting, alarms, and power tools, and have a production rate that is growing by about 3% per year, has begun and is expanding. The rechargeable battery industry has been growing significantly in recent years and is expected to continue growing well into the 21st century. State and Federal mandates now require manufacturers and battery resellers (companies that use Ni-Cd batteries in their products) to recycle rechargeable batteries and prohibit commercial users from discarding them in municipal solid waste. Further increases in the recycling rate for rechargeable batteries will depend on the cooperation of consumers, which in turn will reflect the convenience of collection systems (Rechargeable Battery Recycling Corp., [undated], The non-profit company that recycles Ni-Cd rechargeable batteries, accessed April 25, 2000, at URL http://www.rbrc.org). According to a survey conducted by the RBRC, 95% of Americans own cordless electronic products, but just 16% recycle their power sources (American Metal Market, 1999). Because spent Ni-Cd batteries are 100% recyclable, battery collection and recycling systems that are economically viable as well as environmentally sound may be possible. Collection and recycling rates must continue to increase to reassure regulators and the general public that any human health or environmental risks associated with cadmium will be well managed. Improved recycling of Ni-Cd batteries is also necessary to forestall a ban on the use of cadmium in Europe. Recycling of cadmium products other than batteries, however, will be considerably more difficult. The proper disposal of discarded plastics, obsolete electronic parts, incinerator residues, and municipal sewer sludge—all of which often contain low levels of dispersed cadmium—remains a difficult problem. Moreover, even though increased cadmium recycling is environmentally desirable, it will have only a limited effect on the amount of cadmium in the environment: According to recent estimates, just 2% of cadmium present in the environment is attributable to all uses of the metal. Most of the cadmium released into the environment results from the burning of fossil fuels and from iron and steel production (Metal Bulletin, 1999).

U.S. collection and recycling programs for small rechargeable batteries are expected to expand further, and has now moved into Canada. The Portable Rechargeable Battery Association has helped to enlist the participation of county and municipal governments, hospitals, and fire departments. Spent Ni-Cd, nickel-metal hydride, lithium-ion, and small sealed lead-acid batteries are now all being collected under the program (Greg Broe, Portable Rechargeable Batteries Association, oral commun., 2001). According to the RBRC, about 1,700 t of rechargeable batteries was recycled in 2000. Assuming an average cadmium content of 15% per battery, more than 255 t of cadmium was recycled rather than discarded in landfills (Greg Broe, Portable Rechargeable Battery Association, oral commun., June 2001).

References Cited

Advanced Battery Technology, 2000, EVA says ban could kill market: Advanced Battery Technology, v. 36, no. 7, July, p. 4.

American Metal Market, 1997, Color me cadmium.....or Neolor: American Metal Market, v. 105, no. 144, July 28, p. 7.

———1999, Most Ni-Cd batteries wind up in landfills, trade group claims: American Metal Market, v. 107, no. 223, November 18, p. 7.

Bleakney, Russ, 1998, The collection and processing of spent nickel cadmium batteries in North America and INMETCO's role, in International Nickel Cadmium Conference, 8th, Prague, Czech Republic, September 21-22, 1998, Proceedings: Brussels, Belgium, International Cadmium Association.

Business Week, 2001a, Innovations: Business Week, no. 3722, March 5, p. 30B.
———2001b, Making solar cells on the cheap: Business Week, no. 3722, March 5, p. 100.
Donelly, P.J., 1996, Cadmium compounds as stabilizers for PVC, in Sources of cadmium in environment, OECD Cadmium Workshop, Saltsjöbaden, Sweden, October 16-20, 1995, Proceedings: Brussels, Belgium, European Commission, p. 276-280.
ILZRO Environmental Update 2000a, Cadmium reported to have essential biological function under certain oceanic environments: International Lead Zinc Research Organization, Inc., v. 10, no. 5, May, p. 2.
———2000b, Debate continues on PBT classification for metals: International Lead Zinc Research Organization, Inc., v. 10, no. 8, August, p. 3.
———2000c, European Commission rejects OECD Ni-Cd battery recycling label: International Lead Zinc Research Organization, Inc., v. 10, no. 12, December, p. 2.
———2000d, USEPA proposes revision to the aquatic life criteria for cadmium: International Lead Zinc Research Organization, Inc., v. 10, no. 9, September, p. 2.
———2001, Global organizations issue new directives on chemicals in the environment: International Lead Zinc Research Organization, Inc., v. 11, no. 2, February, p. 1.
Industrial Heating, 2000, Reclaiming alloy and ingot from nickel-based batteries: Industrial Heating, v. 67, no. 8, August, p. 16.
Lambe, R.N., and Rowe, R.G., 1987, Volcanic history, mineralization, and alteration of the Crandon massive sulfide deposit, Wisconsin: Economic Geology, v. 82, no. 5, August, p. 1204-1238.
Metal Bulletin, 1996, Crandon Mining plans to develop Rhinelander deposit: Metal Bulletin, no. 8096, July 15, p. 6.
———1999, Battery scrap collection “key to prevent Cd ban”: Metal Bulletin, no. 8378, May 24, p. 17.
Mining Journal, 1999, Korea Zinc completes Big River takeover: Mining Journal, v. 326, no. 8373, April 12, p. 12.
Price, L.J., 1998, Cadmium and lead recovery in Florida from rechargeable battery product stewardship, in International Seminar on Battery Waste Management, 10th, Deerfield Beach, FL, October 27, 1998, Proceedings: Boca Raton, FL, Florida International Seminars, Inc., p. 1-10.
Skillings’ Mining Review, 1978, Zinc-copper resources of Wisconsin: Skillings’ Mining Review, v. 67, no. 12, March 25, p. 15-20.
U.S. Environmental Protection Agency, 1987, Cadmium emission from cadmium refining and primary zinc/zinc oxide smelting—Phase I technical report: U.S. Environmental Protection Agency, 212 p.
Vigerstol, Ole, 1998, NiCd batteries for telecommunications, in International Nickel Cadmium Conference, 8th, Prague, Czech Republic, September 21-22, 1998, Proceedings: Brussels, Belgium, International Cadmium Association.
Wehye, Reiner, and Melber, Albrecht, 2000, Vacuum thermal recycling of used batteries, Battery recycling meeting: Singapore, May 8-10, 2000.

GENERAL SOURCES OF INFORMATION

U.S. Geological Survey Publications

Cadmium. Ch. in Mineral Commodity Summaries, annual.
Cadmium. Ch. in Minerals Yearbook, annual.
Cadmium. Ch. in United States Mineral Resources, Professional Paper 820, 1973.

Other

American Metal Market.
Cadmium. Ch. in Mineral Facts and Problems, U.S. Bureau of Mines Bulletin 675, 1985.
Engineering and Mining Journal.
International Cadmium Association technical publications.
Metal Bulletin (London).
Mining Journal (London).
Platt’s Metals Week.

TABLE 1
SALIENT CADMIUM STATISTICS 1/

(Metric tons, cadmium content, unless otherwise specified)

	1996	1997	1998	1999	2000
United States:					
Production of metal 2/	1,530	2,060	1,240	1,190	1,890
Shipments of metal by producers 3/	1,310	1,370	1,570 r/	1,020 r/	1,580
Exports of metal, alloys, scrap	201	554	180	20	312
Imports for consumption, metal	843	790	514	294	425
Stocks of metal, Government, yearend	2,030	1,870	1,680 r/	1,130 r/	807
Apparent consumption of metal	2,250	2,510	2,100 r/	1,850 r/	2,010
Price, average per pound, New York dealer 4/	1	1	0	0	0
World, refinery production	18,900	19,500	19,200 r/	19,700 r/	19,700 e/

e/ Estimated. r/ Revised.
1/ Data are rounded to no more than three significant digits, except prices.
2/ Primary and secondary cadmium metal. Includes equivalent metal content of cadmium sponge used directly in production of compounds.
3/ Includes metal consumed at producer plants.
4/ Price for 1- to 5-short-ton lots of metal having a minimum purity of 99.95% (Platt's Metals Week).

TABLE 2
U.S. PRODUCTION OF CADMIUM COMPOUNDS

(Metric tons, cadmium content)

Year	Cadmium sulfide 1/	Other cadmium compounds 2/
1999	64	604
2000	42	417

1/ Includes cadmium lithopone and cadmium sulfoselenide.
2/ Includes oxide and plating salts (acetate, carbonate, nitrate, sulfate, etc.).

TABLE 3
SUPPLY AND APPARENT CONSUMPTION OF CADMIUM METAL 1/

(Metric tons)

	1999	2000
Industry stocks, January 1	729	893
Production	1,190	1,890
Imports for consumption of metal, alloy, scrap	294	425
Shipments from Government stockpile excesses	554 r/	319
Total supply	2,760 r/	3,530
Exports of metal, alloys, scrap	20	312
Industry stocks, December 31	893	1,200
Consumption, apparent 2/	1,850 r/	2,010

r/ Revised.
1/ Data are rounded to no more than three significant digits; may not add to totals shown.
2/ Total supply minus exports and yearend stocks.

TABLE 4
INDUSTRY STOCKS, DECEMBER 31 1/

(Metric tons)

	1999		2000	
	Cadmium metal	Cadmium in compounds	Cadmium metal	Cadmium in compounds
Metal producers	800	W	1,130	W
Compound manufacturers	93	15	73	17
Distributors	W	(2/)	W	W
Total	893	15	1,200	17

W Withheld to avoid disclosing company proprietary data; included with "Compound manufacturers."
1/ Data are rounded to no more than three significant digits; may not add to totals shown.
2/ Less than 1/2 unit.

TABLE 5
U.S. EXPORTS OF CADMIUM PRODUCTS, BY COUNTRY 1/

	1999		2000	
Country	Quantity (kilograms)	Value	Quantity (kilograms)	Value
Cadmium metal: 2/				
Argentina	--	--	66,000	$68,000
Austria	--	--	2,800	6,800
Belgium	9,420	$15,000	--	--
Brazil	--	--	784	105,000
Canada	917	19,200	20,300	259,000
China	--	--	4,980	56,400
France	2,940	136,000	171,000	226,000
Germany	332	110,000	2,740	39,300
Hong Kong	--	--	948	83,100
India	2	4,730	--	--
Japan	2,330	113,000	17,000	20,800
Korea, Republic of	67	11,500	504	42,900
Malaysia	--	--	172	3,340
Mexico	2,490	76,900	6,570	180,000
Taiwan	1,040	17,400	--	--
United Kingdom	811	19,500	18,500	50,000
Total	20,400	523,000	312,000	1,140,000
Cadmium sulfide: (gross weight)				
Canada	11,100	4,240	--	--
China	--	--	937,000	509,000
France	--	--	5,840	3,030
Hong Kong	--	--	52,700	27,400
Japan	96,200	24,000	--	--
Philippines	--	--	92,500	48,100
Taiwan	--	--	20,700	19,600
Total	107,000	28,200	1,110,000	607,000

-- Zero.
1/ Data are rounded to no more than three significant digits; may not add to totals shown.
2/ Includes exports of cadmium in alloys and scrap.

Source: U.S. Census Bureau.

TABLE 6
U.S. IMPORTS FOR CONSUMPTION OF CADMIUM PRODUCTS, BY COUNTRY 1

Country	1999		2000	
	Quantity (kilograms)	Value	Quantity (kilograms)	Value
Cadmium metal:				
Algeria	3,000	$6,940	--	--
Australia	76,000	26,800	76,900	$30,900
Belgium	60,800	244,000	99,400	329,000
Canada	98,200	461,000	40,200	954,000
China	--	--	35	16,600
France	3,990	4,590	--	--
Germany	--	--	73,100	28,000
Japan	170	28,100	--	--
Kazakhstan	--	--	103	5,140
Mauritania	--	--	10,000	28,700
Mexico	9,300	10,700	85,800	60,000
Netherlands	--	--	21,900	7,060
Peru	17,700	41,300	--	--
Russia	5,000	15,100	16,700	47,900
Spain	20,000	9,700	--	--
United Kingdom	--	--	1,200	5,520
Total	294,000	848,000	425,000	1,510,000
Cadmium sulfide: (gross weight)				
Germany	--	--	54	5,250
Japan	13,800	37,900	43,100	138,000
Russia	26	2,630	--	--
United Kingdom	4,640	54,300	2,270	26,500
Total	18,400	94,800	45,400	169,000

-- Zero.
1/ Data are rounded to no more than three significant digits; may not add to totals shown.

Source: U.S. Census Bureau.

TABLE 7
CADMIUM: WORLD REFINERY PRODUCTION, BY COUNTRY 1/

(Metric tons)

Country	1996	1997	1998	1999	2000 e/
Algeria e/	75	75	75	75	75
Argentina	40	45	34	-- r/	-- 2/
Australia	639	632	585 r/	462 r/	552 2/
Belgium	1,579	1,420	1,318	1,400 e/	1,400
Brazil e/	300	300	300	300	300
Bulgaria e/	250	250	200	200	200
Canada	2,537	1,272	1,361	1,390	1,390 p/
China e/	1,570	1,980	2,130	2,150 r/	2,200
Finland 3/	648	540 e/	520	500 e/	550
France	92	309	177 r/	195 r/	200
Germany	1,150 e/	1,145	1,020	1,100 e/	1,000
India	271	298	300 e/	300 e/	300
Italy	296	287	328	360 r/	350
Japan	2,344	2,473	2,337	2,567 r/	2,472 2/
Kazakhstan e/	800	1,000	1,450	1,061 2/	1,060
Korea, North e/	100	100	100	100	100
Korea, Republic of	501	570	1,178 r/	1,791 r/	1,180
Macedonia e/	(4/)	(4/)	(4/)	(4/)	(4/)
Mexico 5/	784	1,223	1,218 r/	1,352 r/	1,350
Namibia 6/	14	2	--	-- e/	--
Netherlands	603	718	739	731 r/	730
Norway	274	290	270 e/	211 r/	200
Peru	405	474	474	480 e/	480
Poland	--	22	-- r/	-- r/	--
Romania e/	5	4	-- r/	-- r/	--
Russia e/	730 2/	790	800	900	925 2/
Serbia and Montenegro e/	79 2/	80	80	15	15
Spain	307	301	196	--	--
Thailand	385	238	238 r/	238 r/	240
Turkey	42	89	69	60	30
Ukraine e/	25	25	25	25	25
United Kingdom 7/	541 e/	455	440 e/	547 r/	500
United States 7/	1,530	2,060	1,240	1,190	1,890 2/
Total	18,900	19,500	19,200 r/	19,700 r/	19,700

e/ Estimated. p/ Preliminary. r/ Revised. -- Zero.

1/ This table gives unwrought production from ores, concentrates, flue dusts, and other materials of domestic and imported origin. Sources generally do not indicate if secondary metal (recovered from scrap) is included or not; where known, this has been indicated by a footnote. Data derived in part from World Metal Statistics (published by World Bureau of Metal Statistics, Ware, the United Kingdom) and from Metal Statistics (published jointly by Metallgesellschaft AG, of Frankfurt am Main, Germany, and World Bureau of Metal Statistics). Cadmium is found in ores, concentrates, and/or flue dusts in several other countries, but these materials are exported for treatment elsewhere to recover cadmium metal; therefore, such output is not reported in this table to avoid double counting. This table includes data available through May 11, 2001.

2/ Reported figure.

3/ Excludes secondary production from recycled nickel-cadmium batteries.

4/ Less than 1/2 unit.

5/ Excludes significant production of cadmium oxide and cadmium contained in exported concentrates.

6/ Tsumeb Smelter closed in April 1998.

7/ Includes secondary.