CADMIUM

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Compared with 2000, both production and consumption of cadmium in the United States declined during 2001. Domestic production of cadmium metal declined by 64%, while production of cadmium compounds, including cadmium sulfide, declined by more than 93% (tables 1, 2). Apparent consumption declined by about 66%, and, for the first time in 6 years, it was about the same as cadmium production (tables 1, 3). Also, sales from the National Defense Stockpile, operated by the U.S. Department of Defense, were much smaller than in previous years. Of all the economic indicators, only the price for cadmium metal registered an increase in 2001. After years of continuous decline, it increased by 7 cents per pound, or by about 44%.

In the United States, only two companies produced cadmium during 2001: Pasminco Ltd. produced primary cadmium as a byproduct of the smelting and refining of zinc concentrates; and the International Metals Reclamation Company Inc. (INMETCO) produced secondary cadmium from scrap, almost entirely from spent nickel-cadmium (NiCd) batteries. At the end of 2000, the Big River Zinc Corp., owned by Korea Zinc Co. Ltd., ceased production of cadmium at its zinc smelter in Sauget, IL, in response to low cadmium prices. The total value of cadmium produced in the United States during 2001 was calculated to be about $366,000. 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 2001: 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., April 2002).

In 2001, the United States became a net exporter of cadmium metal. Nearly one-half of U.S. cadmium was exported to China, followed by Pakistan (14%), France (8%), Canada (7%), and the United Kingdom (7%). The major source of U.S. imports was Australia, accounting for about 60% of all imports, followed by Belgium and Mexico, with 16% each (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 2000, the United States was a net exporter of cadmium sulfide, most of which was exported to the Philippines (59%), followed by Germany (26%), and Saudi Arabia (10%) (table 5). Trade data for other cadmium compounds were not available.

Cadmium was refined in 26 countries in 2001 (table 7). The six largest producers, in decreasing order, were Japan, China, the Republic of Korea, Canada, and Belgium. These countries accounted for more than one-half of world production; the United States accounted for nearly 4%. Identified world cadmium resources at yearend 2001 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 past 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. Cadmium is also included in a draft list of persistent, bioaccumulative, and toxic (PBT) pollutants prepared by the U.S. Environmental Protection Agency (EPA) in 1999.

Concurrently with EPA, some of the States are proposing individual requirements for cadmium and other metals and chemicals. In May 2001, the Office of Environmental Health Hazard Assessment of California proposed new procedures and regulatory levels for cadmium metal and compounds that pose No Significant Risk Levels (NSRL) and No Observable Effect Levels (NOEL) to be included in an amendment to the Safe Drinking Water Toxic Enforcement Act of 1986 (commonly known as Proposition 65). According to this proposal, a person in a paid occupation would be prohibited from knowingly and intentionally exposing any individual to a chemical that has been determined to cause cancer or reproductive toxicity without first giving clear and reasonable warning to the individual (ILZRO Environmental Update, 2001a). The NSRL for cadmium by inhalation, specified by California's Development and Reproductive Toxicant Identification Committee, is 50 nanograms per day, while the NOEL for reproductive toxicity is 4.1 nanograms per cubic meter. For comparison, the U.S. Occupational Safety and Health Administration specifies 5,000 nanograms per cubic meter of Permissible Exposure Level (Hugh Morrow, President, International Cadmium Association, written commun., April 2002).

The California Air Resources Board approved a measure to prohibit the intentional introduction of hexavalent cadmium into paints and coatings for motor vehicles and any "mobile equipment"—defined broadly to include wheelchairs and any equipment that moves on roads or rails. The proposal was originally introduced as a less inclusive measure early in 2000, but evolved into a comprehensive ban for use and sale of coatings for all mobile equipment. The ban is to take effect on January 1, 2003, allowing enough time for a sell-through period for manufacturers to remove the materials from product lines (California Air Resources Board, 2001§[1]).

The Department of Ecology of Washington State proposed its own PBT list of 65 chemicals, including 3 metals—cadmium, lead, and vanadium—in order to reduce the release of harmful chemicals within the State. Together with other organizations, the ICdA objected to the inclusion of any metal, particularly cadmium, on the PBT list. The reason for objection was the same as their opposition to the PBT list proposed by EPA in 1999: 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 different risk than cadmium metal, cadmium oxide, cadmium sulfide, and other insoluble compounds. Therefore, ICdA claims that any rating of toxic materials should recognize differences between the various forms of that material, 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. In response to this information, the legislative proposal was withdrawn and the Washington Department of Ecology has indicated that it will take no further action until a review by the Federal Science Advisory Board is completed (Hugh Morrow, President, International Cadmium Association, written commun., April 2002).

Canada's National Pollutant Release Inventory (NPRI) Working Group failed to reach consensus on a number of issues related to a proposal to lower the reporting threshold for cadmium and other metals. The Working Group was formed by Environment Canada in 2001 with a 2-year mandate to address the addition of substances to the NPRI list and the proposal for alternate thresholds for certain metals (ILZRO Environmental Update, 2002).

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.

Worldwide production of cadmium in 2001 declined to about 18,200 t from 20,100 t in 2000. Asia continued to dominate world cadmium production with Japan, China, and the Republic of Korea being the three largest producers in the world. European production diminished somewhat from previous years, presumably because of the anticadmium regulations attempted by the European Commission (EC). Most of the Europe's share of about 27% of world production was supplied by Belgium, followed by Germany and Finland. North America supplied about 17% of world production, with Canada and Mexico contributing about 1,400 t each.

In the United States, the sizable decline in cadmium output was caused by the withdrawal of Big River Zinc from cadmium production. Owing to low prices and the exodus of many battery manufacturers from the United States to China and Mexico, Big River lost most of its domestic market for cadmium metal and oxide. Consequently, it was more expeditious for the company to dispose of its raw cadmium output rather than to refine it. The production that Big River decided to forgo amounted to about 1,300 t of cadmium metal and cadmium oxide. Currently, the only remaining primary cadmium producer in the United Sates is Pasminco Ltd. of Australia. At its Clarksville, TN, smelter, Pasminco produces about 390 t of cadmium metal using an electrolytic process where the metal is recovered as a byproduct during the roasting and leaching of zinc concentrate. After removing various impurities, cadmium is processed to final form by either refining or electrowinning. The whole process consists of heating the zinc concentrate 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

[1]References that include a section twist (§) are found in the Internet References Cited section.

vacuum distillation (U.S. Environmental Protection Agency, 1987, p. 9).

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 NiCd 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 remained so depressed in 2001 that the processing of furnace dust for any other purpose was not economically feasible.

In 1995, INMETCO (a subsidiary of the International Nickel Co.) began reclaiming cadmium from spent batteries at its Ellwood City plant northwest of Pittsburgh, PA, and currently produces about 290 t of cadmium metal (Cassidy, 2001). 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 metric tons per year (t/yr) of spent NiCd batteries. Cadmium recycling at the facility thus far has been practical only for NiCd batteries, some alloys, and dust from electric arc furnaces. The most difficult aspect of NiCd battery recycling is the collection of spent batteries. Elements such as cadmium, iron, and nickel follow certain physical and chemical laws, and thus the reactions during processing are very predictable and dependable. Changing the attitudes and habits of the public about recycling is much more complicated. Although 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 small consumer NiCd batteries, are usually discarded by the public. Therefore, voluntary industry-sponsored collection programs and Government agency programs are being devised and are devising ways to improve the collection of these small consumer batteries because, in addition to improving the environment, economies of scale are very important: larger recycling operation lowers the unit cost. Several different collection programs have been developed by INMETCO to meet the varied needs of battery manufacturers and the numerous consumers, firms, organizations, and agencies that use many diverse products containing NiCd batteries, such as power tools, cordless phones, and personal computers. The most successful recycling program is operated by the Rechargeable Battery Recycling Corp. (RBRC). Established when INMETCO begun cadmium recycling in 1995, RBRC has organized a multifaceted collection program financed with proceeds from licensing its seal of approval to individual companies involved in the manufacturing, importation, and distribution of rechargeable batteries or battery-operated products. The RBRC recycling program contains several key elements that are specified both in EPA regulations (40CFR, 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, a 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 collection sites in the United States and Canada. Another successful collection program is INMETCO's prepaid container program where companies generating spent batteries purchase a 14-kilogram container for collection and shipment of spent batteries. The fee for the container includes shipping by UPS, handling, sorting, and processing. Additional collection programs, initiated by INMETCO include mail-back envelopes, a small package program, and so-called "milk runs". Because most of the industrial NiCd batteries are not allowed to be discarded in municipal waste dumps, they are recycled through collection programs in which producers of these batteries collect and send their spent batteries to INMETCO (Money, Tomaszewski, and Bleakney, [no date]).

The process of cadmium recovery from industrial and consumer sealed batteries, differs only in the manner of battery preparation. Processing of industrial batteries, containing up to 7% cadmium, consists of draining the sodium hydroxide electrolyte, cutting the tops off the batteries, and separating the nickel and cadmium plates. Small batteries, containing up to 16% cadmium, 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 NiCd 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, 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.

Environmental Issues

Although cadmium can be toxic in high concentrations of its 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 are known to have toxic health effects and adverse environmental impacts. Inhaled cadmium fumes or fine dust are much more readily absorbed than is ingested cadmium. The atmosphere contains small, usually harmless amounts of cadmium, released by some electric powerplants and smelters. In fact, most of the cadmium released into the environment results from the burning of fossil fuels and from iron and steel production (Metal Bulletin, 1999). Repeated exposure to excessive levels of dust or fumes, found usually at cadmium producing and/or consuming plants, can have irreversible effects on kidneys and lead to reduced lung capacity and emphysema. Because of these potential adverse effects, occupational exposure to cadmium in the United States is stringently regulated by OSHA. OSHA's permissible limit for cadmium exposure through inhalation is 5 micrograms per cubic meter of air breathed (Golden Artist Colors, [undated]§). 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 it is 0.001 mg/kg/d (U.S. Environmental Protection Agency, [undated]§).

The four main environmental and human health concerns involved with NiCd 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 NiCd 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.

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), as amended by the Superfund Amendment and Reauthorization Act, requires the Agency for Toxic Substances and Disease Registry (ATSDR) and EPA to prepare a priority list of hazardous substances that are most commonly found at facilities on the National Priorities List and which pose the most significant potential threat to human health. This CERCLA priority list is revised and published on a 2-year schedule and then becomes the basis for preparing or updating the ATSDR Toxicological Profiles for these substances. According to ATSDR, the list is not an enumeration of the most toxic substances, but is rather a prioritization of substances based on the combination of their frequency of occurrence, toxicity, and potential for human exposure.

Consequently, it is possible for substances with low toxicity but high frequency of occurrence and exposure to be on the list. Presently, arsenic is listed as the number one priority substance while cadmium is listed as seventh (Advanced Battery Technology, 2002).

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 among countries in such restrictions, the EC in 1991 unified these individual measures into its Directive 91/157/EEC, binding for all EU member countries. The latest directive, EU's Directive 2000/60/EC on water, recommended that the use of 32 chemicals be phased out over the next 20 years. According to the recommendation, the ban on NiCd batteries was to start in 2008. The EC identified 11 of the chemicals for inclusion on a priority list of chemicals that it considered to be toxic, persistent, and liable to be bioaccumulate in the environment—essentially a European "PBT list". Chemicals on the list, which includes cadmium, were the first to be addressed by the EC for possible phaseout (ILZRO Environmental Update, 2001b). However, the approach proposed in 2000 was somewhat moderated in 2001. Rather than banning cadmium, the EC is trying to determine the most appropriate measures that reduce risk to human health and environment posed by NiCd batteries. Potential measures include mandatory take back systems, deposit schemes, and/or marketing and use restrictions. Selection of the best measure is to be based on the analysis of the relative benefits of a cadmium ban in comparison with other economic instruments, including a deposit system (Hugh Morrow, President, International Cadmium Association, written commun., April 2002). This approach disappointed the EU's three Nordic members. In a joint letter, the environment ministers of Denmark, Finland, and Sweden urged the EU Environment Commissioner to maintain the timetable outlined in the Directive 2000/60/EC. The letter claims that even if cadmium is prohibited in batteries beginning in 2008, cadmium will still occur in waste after the year 2020—more than 30 years after the EU Council of Ministers called for cadmium substitution in 1988. Given that only about 4% of NiCd batteries have been collected over the past 20 years, despite a legal obligation to do so, the letter alleges, it is hard to imagine that an efficient collection could result from a deposit system. According to the ministers, it is possible to substitute up to 75% of the NiCd batteries used today with environmentally more benign batteries (Advanced Battery Technology, 2001).

Consumption

According to the World Bureau of Metal Statistics, cadmium consumption in 2001 was about 16,000 t, 17% less than in 2000. Japan remained the world's largest consumer of cadmium, using the metal mainly for production of small NiCd batteries, followed by Belgium and the United States.

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 2001 declined by about 70%, compared with that of 2000 as more and more batteries were manufactured overseas. Estimated consumption of cadmium by end use in 2001 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%.

Worldwide consumption of cadmium for production of rechargeable batteries, the dominant use of cadmium, 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 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, rechargeable NiCd batteries provided the power for about three-fourths of the most common portable products, such as power tools, cordless telephones, portable household appliances, battery-powered toys, and sources of emergency and remote area electric power. The rechargeable battery market has seen some dramatic technology shifts in recent years. The rapid development of personal communication devices is pushing the demand for more powerful, reliable, and less expensive batteries. The most common chemistry used in rechargeable batteries is nickel-based, including nickel-cadmium, which, however, is being replaced by nickel metal-hydride (NiMH). The reason is that the prices have become comparable to NiCd batteries and because of the so-called "memory effect": The more times NiCd batteries are charged, the life span between charges becomes shorter and shorter (Advanced Battery Technology, 2002).

The consumption of cadmium for industrial batteries, a market that NiCd batteries still dominate, could receive a boost from manufacturers of hybrid electric vehicles and providers of telecommunications in remote areas. The preference for NiCd batteries over other types of batteries in hybrid vehicles, however, has not been indisputably established owing to environmental concerns. In 2000, the EC proposed a ban on the use of cadmium batteries in electric vehicles starting at yearend 2005. According to the commission, there are already viable alternatives to cadmium on the market and that by December 31, 2005, the transition to cadmium-free vehicles should be completed (Metal Bulletin, 2002). Currently, the hopes of the cadmium industry rest mainly on the application NiCd batteries as a power source for telecommunications in remote areas. The security of fragile modern telecom networks would be jeopardized without reliable power backup, especially in hot or otherwise extreme environments. Compared to traditional valve-regulated lead acid batteries, the NiCd 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 of cadmium, or about 10% of current world 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 NiCd 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).

Other uses of cadmium are based on the metal's physical and chemical attributes. It 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 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 addition to batteries, in pigments, ultraviolet light and weathering stabilizers, and semiconductor applications.

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 NiCd 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 more strict regulatory controls that 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 and by 2001 it reached an average of \$0.23 per pound for the year. Reduced primary production, offsetting increased secondary cadmium output, and the continuation of moderate demand despite regulatory concerns led to a balanced world cadmium market in 2001 (table 1).

Current Research and Technology

A University of Arkansas research team developed a method to replace dimethylcadmium with a more stable cadmium oxide to form nanocrystals, 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. Consequently, it appears that a variety of nanocrystals can be made more safely by replacing dimethylcadmium with cadmium oxide in the production process (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 by more than 20%, compared with far more expensive existing solar cells (Business Week, 2001b).

Outlook

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, exceeded cadmium prices in some cases. The immediate future of the cadmium industry rests largely with the NiCd battery market, which is the only market that continues to grow, especially for certain uses, such as in power tools and telecommunication devices. Following declines in recent years, coating and pigment markets for cadmium have stabilized and are not expected to erode any further in the future. The stabilizer and alloy markets, however, are expected to diminish and eventually close due to substitution by cadmium-free products. However, several new applications (such as in electric and hybrid electric vehicles, remote area power 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 NiCd 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 to grow well in this decade. State and Federal mandates now require manufacturers and battery resellers (companies that use NiCd 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§). According to a survey conducted by the RBRC, 95% of Americans own cordless electronic products, but only about 16% recycle their power sources (American Metal Market, 1999). Because spent NiCd 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. 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 because only about 2% of cadmium present in the environment is attributable to all uses of the metal.

U.S. and Canadian collection and recycling programs for small rechargeable batteries are expected to expand further. The Portable Rechargeable Battery Association has helped to enlist the participation of county and municipal governments, hospitals, and fire departments. Spent NiCd, nickel-metal hydride, lithium-ion, and small sealed lead-acid batteries are now all being collected under the programs (Greg Broe, Portable Rechargeable Batteries Association, oral commun., 2001). According to the RBRC, about 1,700 t of rechargeable batteries were 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)

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TABLE 1
SALIENT CADMIUM STATISTICS 1/

(Metric tons, cadmium content, unless otherwise specified)

	1997	1998	1999	2000	2001
United States:					
Production of metal 2/	2,060	1,240	1,190	1,890	680 e/
Shipments of metal by producers 3/	1,370	1,570	1,020	1,580	954
Exports of metal, alloys, scrap	554	180	20	314 r/	272
Imports for consumption, metal	790	514	294	425	107
Stocks of metal, Government, yearend	1,870	1,680	1,130	807	755
Apparent consumption of metal	2,510	2,100	1,850	2,010	679
Price, average per pound, New York dealer 4/	$0.51	$0.28	$0.14	$0.16	$0.23
World, refinery production	20,300 r/	20,200 r/	20,300 r/	20,100 r/	18,200 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% (Platts Metals Week).

TABLE 2
U.S. PRODUCTION OF CADMIUM COMPOUNDS

(Metric tons, cadmium content)

Year	Cadmium sulfide 1/	Other cadmium compounds 2/
2000	42	417
2001	31	--

-- Zero.
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)

	2000	2001
Industry stocks, January 1	893	1,200
Production	1,890	680 e/
Imports for consumption of metal, alloy, scrap	425	107
Shipments from Government stockpile excesses	319	52
Total supply	3,530	2,040
Exports of metal, alloys, scrap	314 r/	272
Industry stocks, December 31	1,200	1,090
Consumption, apparent 2/	2,010	679

e/ Estimated. 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)

	2000		2001	
	Cadmium metal	Cadmium in compounds	Cadmium metal	Cadmium in compounds
Metal producers	1,130	W	1,080	--
Compound manufacturers	73	17	12	17
Distributors	W	W	W	W
Total	1,200	17	1,090	17

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

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

	2000		2001	
Country	Quantity (kilograms)	Value	Quantity (kilograms)	Value
Cadmium metal: 2/				
Argentina	66,000 r/	$84,000 r/	--	--
Austria	2,800	6,800	--	--
Brazil	784	105,000	9,110	$1,180,000
Canada	20,300	259,000	19,700	284,000
China	4,980	56,400	88,200	206,000
Egypt	--	--	4,540	5,960
France	171,000	226,000	26,500	35,300
Germany	2,740	39,300	7,600	258,000
Hong Kong	948	83,100	40,000	38,900
Italy	2,050	14,900	--	--
Japan	17,000	20,800	4,210	17,100
Jordan	--	--	9,550	16,000
Korea, Republic of	504	42,900	--	--
Malaysia	172	3,340	--	--
Mexico	6,570	180,000	1,160	324,000
New Zealand	--	--	85	8,440
Pakistan	--	--	37,600	76,000
South Africa	--	--	5,200	17,700
Sweden	--	--	10	12,100
Taiwan	--	--	36	3,060
United Kingdom	18,500	50,000	18,200	71,700
Total	314,000 r/	1,170,000 r/	272,000	2,560,000
Cadmium sulfide (gross weight):				
China	937,000	509,000	--	--
France	5,840	3,030	--	--
Germany	--	--	13,500	7,000
Hong Kong	52,700	27,400	--	--
Philippines	92,500	48,100	30,800	16,000
Saudi Arabia	--	--	5,100	2,650
Singapore	--	--	3,000	6,000
Taiwan	20,700	19,600	--	--
Total	1,110,000	607,000	52,400	31,700

r/ Revised. -- 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	2000 Quantity (kilograms)	2000 Value	2001 Quantity (kilograms)	2001 Value
Cadmium metal:				
Australia	76,900	$30,900	58,900	$40,100
Belgium	99,400	329,000	15,700	126,000
Canada	40,200	954,000	13,200	1,630,000
China	35	16,600	--	--
Germany	73,100	28,000	2	2,490
Hong Kong	--	--	32	4,300
Kazakhstan	103	5,140	--	--
Mauritania	10,000	28,700	--	--
Mexico	85,800	60,000	16,400	13,600
Netherlands	21,900	7,060	--	--
Russia	16,700	47,900	--	--
United Kingdom	1,200	5,520	3,200	17,600
Total	425,000	1,510,000	107,000	1,830,000
Cadmium sulfide: (gross weight)				
Germany	54	5,250	--	--
Japan	43,100	138,000	5,160	24,000
Russia	--	--	106	11,600
United Kingdom	2,270	26,500	2,280	26,600
Total	45,400	169,000	7,550	62,200

-- 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/ 2/

(Metric tons)

Country	1997	1998	1999	2000	2001 e/
Algeria e/	75	70 r/	70 r/	70 r/	70
Argentina	45	34	--	--	--
Australia	632	585	462	525 r/	378 3/
Belgium	1,420	1,318	1,235 r/	1,148 r/	1,236 3/
Brazil e/	300	300	300	300	300
Bulgaria e/	280 r/ 3/	250 r/	150 r/	150 r/	150
Canada	2,260 r/	2,090 r/	1,911 r/	2,024 r/	1,429 3/
China e/	1,980	2,130	2,150	2,370 r/	2,400
Finland 4/	650 r/	520	700 r/ e/	680 r/ e/	700
France	309	177	195	160 r/	176 3/
Germany	1,145	1,020	1,145 r/	1,130 r/	1,100
India	298	304 r/	269 r/	314 r/	436 3/
Italy	287	328	360	284 r/	312 3/
Japan	2,473	2,337	2,567	2,472	2,486 3/
Kazakhstan	745 r/	1,622 r/	1,246 r/	257 r/	170 3/
Korea, North e/	100	100	100	100	150
Korea, Republic of	570	1,178	1,791	1,911 r/	2,000
Macedonia e/	(5/)	(5/)	(5/)	(5/)	(5/)
Mexico 6/	1,223	1,218	1,275 r/	1,268 r/	1,050 p/
Namibia 7/	2	--	--	--	--
Netherlands	718	739	731	628 r/	455 3/
Norway	290	270 e/	211	298 r/	318 3/
Peru	474	535 r/	465 r/	458 r/	473 3/
Poland	22	--	--	--	--
Romania e/	5 r/	--	--	--	--
Russia e/	790	800	900	925 3/	950
Serbia and Montenegro	80 e/	17 r/	-- r/	-- r/	--
Spain	301	196	--	-- e/	--
Thailand	238	238	238	238 r/	240
Turkey	89	69	64 r/	-- r/	--
Ukraine e/	25	25	25	25	25
United Kingdom 8/	455	440 e/	547	503 r/	485 3/
United States 8/	2,060	1,240	1,190	1,890	680
Total	20,300 r/	20,200 r/	20,300 r/	20,100 r/	18,200

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

1/ This table gives unwrought production from ores, concentrates, flue dusts, and other materials of both 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 Maine, 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 13, 2002.

2/ World totals, U.S. data, and estimated data are rounded to no more than three significant digits; may not add to totals shown.

3/ Reported figure.

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

5/ Less than 1/2 unit.

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

7/ Tsumeb Smelter closed in April 1998.

8/ Includes secondary.