Material Use in the United States—Selected Case Studies for Cadmium, Cobalt, Lithium, and Nickel in Rechargeable Batteries

Scientific Investigations Report 2008–5141

U.S. Department of the Interior
U.S. Geological Survey

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Contents

Abstract 1
Introduction 1
Study Methodology 3
Case Study 1—Cell Phones 4
Case Study 2—Cameras and Camcorders 6
Case Study 3—Portable Computers 8
Case Study 4—Hybrid Vehicles 11
Summary and Conclusions 12
References Cited 15
Appendix 19

Figures

1. Graph showing percentage of global rechargeable battery sales for the principle battery types from 1994 through 2005 2
2. Graph showing U.S. cell phone subscription and import data compared with estimates for the number of cell phones available for disposal at the end of life 5
3. Graphs showing estimated U.S. net imports of cameras and camcorders by battery type 7
4. Graph showing estimated amounts of cadmium, cobalt, lithium, and nickel contained in rechargeable camera and camcorder batteries used in the United States from 1996 through 2005 9
5. Graph showing estimated imports of portable computers by battery type and amounts of cobalt, lithium, and nickel contained in rechargeable portable computer batteries used in the United States from 1996 through 2005 10

Tables

1. Content of key material components contained in hybrid electric vehicle batteries 13
2. Reported U.S. apparent consumption for selected metals and the content of these metals in batteries used in popular consumer products for the period 1996 through 2005 14

Conversion Table

Multiply	By	To obtain
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)

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By David R. Wilburn

Abstract

Consumer preferences, environmental regulations, new end-use markets, reduced production costs, and technological advances have contributed to the consumption and substitution patterns of rechargeable batteries, particularly in automotive and consumer electronic product applications; therefore, a thorough understanding of the use and disposal of the metals used in such batteries is warranted. Four case studies assessing the material use patterns for cadmium, cobalt, lithium, and nickel contained in cell phone, camera and camcorder, portable computer, and hybrid vehicle batteries were conducted for 1996 through 2005 based on an analysis of U.S. International Trade Commission trade data.

The cadmium content of camcorder, camera, and cell phone batteries used annually in the United States declined to about 7 metric tons (t) in 2005 from about 100 t in 1995, as a result of the implementation of regulations affecting nickel-cadmium battery recycling and disposal and the introduction of technological advancements in lithium-ion and nickel-metal-hydride (NiMH) batteries that are increasingly used as alternatives. An analysis of cell phone recycling data suggests that up to 91 t of cadmium contained in cell phone batteries was available for recovery between 1996 and 2005. Some of this material resides in storage.

The cobalt content of rechargeable batteries used annually in camcorders and cameras, cell phones, and portable computers in the United States increased to about 2,300 t in 2005 from 55 t in 1996 because of increased demand and technological improvements that have reduced the cost of these products while making them more efficient. Analysis of cell phone data suggests that 410 t of cobalt may have been recovered from recycled cell phone batteries, and about 4,700 t of cobalt contained in cell phone batteries was available for recovery during the 10-year study period.

The lithium content of rechargeable batteries used annually in consumer electronic products in the United States increased to about 290 t in 2005 from about 87 t in 1996. Estimates of U.S. lithium apparent consumption, which exclude products such as batteries that are contained in imported manufactured products, decreased during much of this period. Lithium used in cell phone batteries in the United States increased between 1996 and 2005 to about 170 t in 2005 from 1.8 t in 1996. Lithium used in portable computer batteries increased for this same period to about 99 t in 2005 from 3.3 t in 1996. Technological developments in camcorder and camera technology for the period had the net effect of reducing the lithium content per battery for these applications, but the increasing popularity of the digital camera led to an increase to 19 t of lithium in camera batteries in 2005 from 100 kilograms in 1996. Less than 10 t of lithium contained in cell phone batteries was recycled during the 1996–2005 period, suggesting that up to 580 t of lithium in cell phone batteries was available for recovery, primarily after 2001.

Nickel content in batteries used annually in camcorders and cameras, cell phones, and portable computers in the United States increased to about 3,000 t in 2005 from 280 t in 1996, mostly a result of increased use of the NiMH battery in these applications. Estimates of nickel use in batteries for hybrid vehicles increased to 2,700 t in 2005 from a negligible amount in 1996. By the year 2010, it is estimated that the amount of nickel used in hybrid vehicle batteries could exceed 7,300 t. Cobalt content of hybrid vehicle batteries used in the United States is expected to reach about 210 t in 2010. An analysis of cell phone recycling data suggests that about 410 t of nickel in batteries was recycled between 1996 and 2005; about 3,100 t was likely available for recovery, although some of this material resides in storage.

Introduction

This report examines the changes that have taken place in the consumer electronic product sector as they relate to the use of cadmium, cobalt, lithium, and nickel contained in batteries that power camcorders, cameras, cell phones, portable (laptop) computers and the use of nickel in vehicle batteries for the period 1996 through 2005 and discusses forecasted changes in their use patterns through 2010. Market penetration, material substitution, and technological improvements among nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), and lithium-ion (Li-ion) rechargeable batteries are assessed. Consequences of these changes in light of material consumption factors related to disposal, environmental effects, retail price, and serviceability are analyzed in a series of short case studies.

This study supplements U.S. Geological Survey (USGS) mineral commodity production and consumption statistics by providing estimates of the amount of materials consumed by important market sectors. It provides information that allows government, nongovernmental organizations, and the public to gain a better understanding of how much and where these materials are used and to draw inferences on how the substitution of different battery chemistries may affect the amount of these materials available for disposal or recycling. The study is part of a series of USGS materials flow assessments on cell phones (Sullivan, 2006), lead-acid batteries (Wilburn and Buckingham, 2006), and NiCd batteries (Wilburn, 2007) and draws in part on data collected for and estimates derived from these previous studies.

Environmental regulations, new end-use markets, and technological advances all have played a role in the changing consumption and substitution patterns of rechargeable batteries, particularly in automotive and consumer electronic product applications. Figure 1 illustrates how the nonautomotive rechargeable battery sector has changed since 1994. In 1994, NiCd batteries accounted for about 88 percent of the world market for rechargeable batteries in terms of the number of batteries sold. By 1999, the market share for NiCd batteries had dropped to below 50 percent, and the NiMH battery market share had grown to about 40 percent. By 2005, the market share of NiCd battery sales had declined to about 34 percent, the NiMH market share had decreased to about 23 percent, and a new battery technology—the Li-ion battery—had developed a market share of almost 40 percent.

In 2002, it was estimated that 350 million rechargeable batteries were purchased annually in the United States (U.S. Environmental Protection Agency, 2002a). The number of batteries has since increased to provide power for the increasing number of cell phones, portable (laptop) computers, and other electronic consumer products used in the United States. The large quantity of batteries in use makes a quantitative assessment of the use and flow of the mineral constituents contained in these batteries essential to understanding the level of risk to human health and the ecosystem associated with these materials.

Some materials contained in batteries can potentially cause harm to the environment and humans if they are manufactured, used, or discarded improperly. In 1992, the U.S. Environmental Protection Agency classified cadmium as a Group B1 probable human carcinogen (U.S. Environmental Protection Agency, 2000). In that same year, about 146,000 t of consumer batteries of all types, some of which contained cadmium, was discarded in the United States (Klimasauskas and others, 2006). NiCd batteries accounted for an estimated 75 percent of the cadmium found in U.S. municipal solid waste (MSW) landfills in 1995 (U.S. Environmental Protection Agency, 2002b); however, the leaching of cadmium into the soil over time from NiCd batteries that are deposited in properly designed landfills is mitigated by lining the landfills with impenetrable materials. In recognition of the potential environmental hazards associated with cadmium metal exposure, some States have limited cadmium use in some consumer

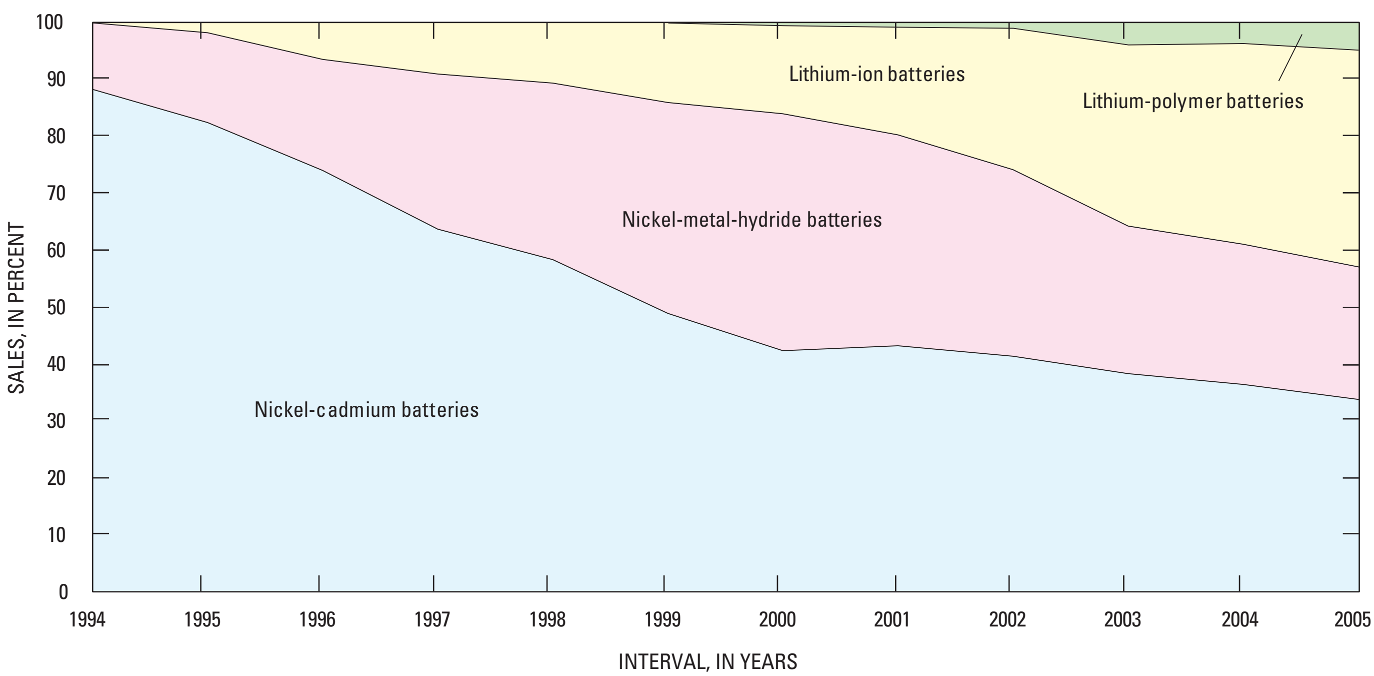


Figure 1. Graph showing percentage of global rechargeable battery sales for the principle battery types from 1994 through 2005. (Data from Pillot, 2005b, p. 19.)

products and are regulating cadmium battery disposal (Klimasauskas and others, 2006). The U.S. Congress passed the Mercury Containing and Rechargeable Battery Act (referred to as the Battery Act) in 1996 to facilitate the recycling of NiCd and other rechargeable batteries by standardizing the collection, disposal, and labeling requirements previously enforced by State agencies (U.S. Environmental Protection Agency, 2002a). The battery industry is expected to be further affected by European Union directives issued in 2000 (2000/52/EC) and 2006 (2006/66/EC) that are designed to limit the use of batteries containing cadmium and mercury and to regulate the disposal and recycling of batteries.

The development and subsequent growth in the number and use of new products that require batteries have provided (and likely will continue to provide) opportunities for technological development within the battery sector. The use of cell phones in the United States, which grew to about 180 million units in 2004 from 340,000 units in 1985, is just one example where the growth of an industry has led to technological improvements in batteries designed to supply that end use (Most, 2003; Charny, 2005). Similarly, statistics reported by the U.S. International Trade Commission (ITC) show that significant expansion has transpired in the number of U.S. imports of portable computers (1,200 percent growth from 1996 to 2005), digital cameras (5,600 percent growth from 1996 to 2005), and other electronic games, toys, and music devices (data not reported separately). In the automotive sector, the development of advanced battery technology is expanding and is supported by industry and the U.S. Government. The Advanced Energy Initiative, announced in 2006 by President Bush, proposed to provide $31 million toward advanced battery research (National Economic Council, 2006). Studies suggest that U.S. sales of hybrid vehicles powered by rechargeable NiMH and Li-ion batteries are likely to achieve 550,000 units by 2010, which is up from the 2005 level of about 190,000 units (U.S. Department of Energy, 2006). Consumer acceptance, cost considerations, energy requirements, supply issues, and size considerations of such products often determine which batteries will best meet the needs of such new applications. Technological changes by product manufacturers can lead to battery substitution from one type to another. Battery substitutions result in material use changes associated with these batteries; therefore, understanding the material requirements of available options is essential in order to assess present and future changes in material use, environmental consequences, and source of supply.

Environmental regulation and product end-use research and development have led to changes in battery composition, efficiency, and size. To date, however, no single battery technology has the cost, power, and efficiency requirements to meet the needs of the consumer for all applications. Consequently, battery manufacturers develop batteries that fit the requirements of a broad spectrum of products, thereby maximizing the power and efficiency profiles of the batteries to fit the requirements of those products. Technological advances further change the materials used in consumer batteries. As a result, batteries with a broad range of chemistries, shapes, and sizes are produced. Industry competition, rapid technological change, and the wide variety of batteries available all create challenges to gathering data about batteries used in the United States.

Because U.S. production of rechargeable batteries is limited to small-scale, high-profit-margin niche markets, such as medical, military, or space applications, most of the rechargeable batteries used in applications considered in this analysis are imported, primarily from China, Japan, and the Republic of Korea (Brodd, 2005). Comprehensive information on U.S. battery consumption, composition, recycling, and trade by end-use application often is not compiled or not made available to the public. The ITC reports data on the number of individual batteries imported into and exported from the United States annually and separately reports data on the number of manufactured products that use batteries. The ITC does not report the material content of these batteries. Battery recycling data have been reported since 1994 by the Rechargeable Battery Recycling Corporation (RBRC), but RBRC data are reported in terms of pounds of batteries recycled, and statistics on specific batteries collected and their material content are not reported over the range of years studied in this report. Although the RBRC is the largest U.S. rechargeable battery recovery organization, some municipalities, armed services, and government agencies also have conducted battery collection programs; and some larger battery manufacturers collect batteries and send them either to the International Metals Reclamation Company (INMETCO), the principal U.S. battery recycler, or to Asian or European recyclers (Boehme and Panero, 2003, p. 41).

Because comprehensive data on rechargeable battery use by type are not uniformly available, selected case studies were performed to provide the reader with several sets of data pertaining to material consumption issues related to the rechargeable battery industry. Each case study of selected battery end uses provides complementary assessments of the rechargeable battery industry. A more comprehensive picture of the industry can be developed by looking at a composite of these case studies.

Study Methodology

To gain a more complete understanding of the amount of material derived from mineral commodities that is used in the United States over time, it is useful to assess the amount of the material used both in its raw forms (ore, concentrate, or refined metal) and in manufactured products. The USGS reports annual production and consumption statistics for many mineral commodities in such annual publications as the Mineral Commodity Summaries and the Minerals Yearbook. The USGS does not, however, include in its annual assessments materials contained in manufactured products that are imported into or exported from the United States. Collection or estimation of these data is often impractical because of the number and variety of products involved and the amount of time required to collect and publish the data. Estimating the amount of a specific mineral commodity used in a product is difficult if that product comes in a variety of sizes and is produced using a variety of chemistries (as in the case of rechargeable batteries). Estimates can be made, however, if the industry uses a high percentage or large tonnage of the targeted mineral constituent in the end-use product, the product has a well-defined market structure, and data useful for estimating material usage of that mineral commodity are available.

Most of the rechargeable batteries used for consumer electronics and hybrid vehicles in the United States are imported, so a thorough study of the rechargeable battery sector requires data on the quantity of batteries, by type, which are imported and exported by the United States. The author selected data collected by the U.S. Bureau of the Census and reported by the ITC (U.S. International Trade Commission, 2006); these data are based on Harmonized Tariff Schedule of the United States (HTS) product classifications. The reported trade data are for batteries of different chemistries and are expressed in terms of the number of batteries or the number of products that contain batteries. The author used annual import and export data for 8 types of nonrechargeable (primary) batteries as indicated by the HTS code and 15 types of rechargeable (storage) batteries, as well as trade data for selected manufactured products that typically contain a battery as part of the prepackaged product. Products considered in this report include battery-powered automobiles and other vehicles, camcorders, cameras, cell phones, clocks and watches of different types, portable computers, power tools, and other small consumer devices.

Because ITC data are most often expressed in terms of the quantity of batteries, an estimate for the average amount of cadmium, cobalt, lithium, or nickel contained within each HTS battery classification or product code (which depends on the end use) was developed. Generalized material content specifications for each major battery chemistry or end-use application were developed from data reported in published material safety data sheets by selected manufacturers that produce the specified battery. Representative mineral content values were assigned by averaging the generalized material content data reported by these manufacturers. Based on the reported description for each HTS classification, a specific battery or group of batteries was selected to depict the "representative" battery for that classification. Cadmium, cobalt, lithium, and nickel content were estimated for each HTS classification on the basis of average weight of all batteries included in that classification as reported by the manufacturers and estimates of the typical material content for that battery type (Vangheluwe and others, 2005, p. 11). The HTS classifications for each battery chemistry and end-use application used in this study are included in the appendix. In cases where an HTS classification was thought to contain multiple battery chemistries or shapes, a determination was made as to what percentage of the classification was attributable to each battery chemistry or shape based on the reported worldwide distribution of batteries by application (Pillot, 2004, p. 29–31; 2005b, p. 14). Annual worldwide rechargeable battery sales data were used as an approximation for the types of batteries included in each of the major U.S. end-use applications (Pillot, 2004, p. 29–31).

Details on the estimation methods and the estimates of the average amount of cadmium, cobalt, lithium, and nickel contained in representative battery chemistries by end-use application for this report are summarized in the appendix. Not all battery constituents were assessed for this study; only the content of cadmium, cobalt, lithium, or nickel as metals or selected compounds was considered. Of the principal battery chemistries, NiCd batteries of a type used in selected end-use applications were evaluated for cadmium, cobalt, and nickel content; NiMH batteries were evaluated for their cobalt and nickel content; and primary lithium and Li-ion batteries types were evaluated for their cobalt and lithium content.

Although a variety of battery chemistries exist and other battery chemistries are being developed, only a select number of battery chemistries was analyzed for their cadmium, cobalt, lithium, and nickel content in this study. It should be noted that there is no lithium metal in the Li-ion batteries analyzed in this study; lithium occurs primarily in the form of lithium cobalt oxide ($LiCoO_2$) or lithium hexafluorophosphate ($LiPF_6$) compounds. Cobalt and nickel most commonly occur as cobalt hydroxide ($Co(OH)_2$) or nickel hydroxide ($Ni(OH)_2$) in positive electrodes of NiCd or NiMH batteries or as material components mixed with other metals contained in negative electrodes of NiMH batteries. Cadmium occurs as cadmium hydroxide ($Cd(OH)_2$) in positive electrodes of NiCd batteries.

Case Study 1—Cell Phones

The goals of the cell phone case study are as follows: illustrate the material changes that have taken place in the cell phone battery industry since 1995, estimate the growth in U.S. consumption of batteries used to power cell phones during the past 10 years, and discuss the effects of that growth on disposal alternatives (household storage, incinerating, landfilling, or recycling). Estimates were developed for the amount of material contained in cell phone batteries in the United States, the amount available for disposal at municipal solid waste (MSW) facilities, and the amount that was recycled.

The types of batteries used in cell phones worldwide have changed significantly since the early 1990s, when NiCd batteries dominated the world market. In 1996, the first year analyzed in this study, NiMH batteries represented an estimated 40 percent of the cell phone market, NiCd batteries represented an estimated 37 percent, and Li-ion batteries represented an estimated 23 percent (Pillot, 2005b, p. 19). Since 1996, the use of NiCd batteries in the world market has decreased while Li-ion battery use has significantly increased, first at the expense of NiCd batteries and then at the expense of NiMH batteries. Estimates suggest that, by 2005, NiCd batteries had been completely replaced by Li-ion batteries for use in cell phones and that the NiMH battery market share had decreased to about 4 percent (Pillot, 2005b, p. 19). Since 2004, the Li-ion battery market share has fallen in favor of lithium-polymer batteries, which represented about 17 percent of cell phone batteries in use in 2005 (Pillot, 2005b, p. 19).

Figure 2 summarizes estimated U.S. cell phone battery use and disposal data for the period from 1996 through 2005. U.S. cell phone subscription data were derived from Most (2003) and Charny (2005). Estimates of the number of imported batteries (by type) were derived from ITC data (U.S. International Trade Commission, 2006) that are based on the number of cell phones imported into and exported from the United States annually; because data on the number of individual batteries traded annually could not be differentiated by chemical type, they were excluded from this assessment. Estimates of the number of batteries available for disposal during the 10-year period were developed based on an average cell phone life of 2 years (Environmental Literacy Council, 2004; Ramamoorthy, 2006), the assumption that cell phones may be available for recycling or disposal at the time of service contract termination, and that the average cell phone requires only one rechargeable battery during its short life. For this analysis, it was assumed that 20 percent of batteries used in cell phones entering service in any given year would be retired in that year; 70 percent of these batteries would be retired in the second year, and the remaining 10 percent would be retired in the third year. Data suggest that about 90 percent of all cell phone batteries that are considered obsolete are either placed in temporary household storage or are discarded as MSW, and about 10 percent are recycled, according to estimates derived from data reported by the Rechargeable Battery Recycling Corporation (2005).

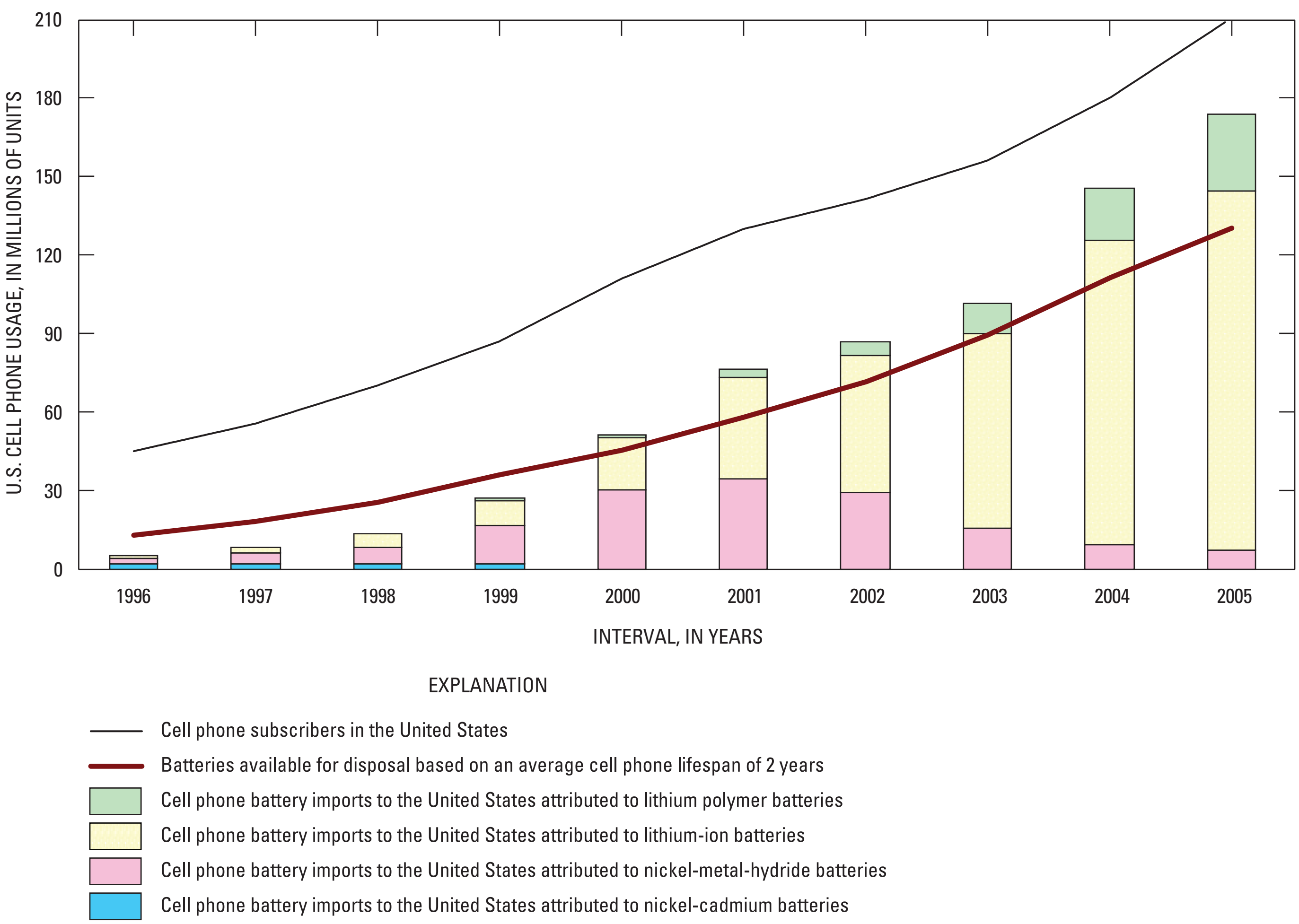


Figure 2. Graph showing U.S. cell phone subscription and import data compared with estimates for the number of cell phones available for disposal at the end of life. U.S. cell phone battery production data are not available but are to be assumed negligible when compared to the number of imported batteries. Subscriber data from Most (2003) and Charny (2005); import data from U.S. International Trade Commission (2006). Estimates for cell phone end-of-life data are based on an assumed contract life of 2 years (Fishbein, 2002), the assumption that each cell phone requires only 1 battery during its life, and the assumption that cell phones are available for disposal at the time of contract termination.

The results of this study suggest that about 12 million cell phone batteries were available for disposal in 1996, which increased to about 130 million batteries in 2005. This increase is consistent with an estimate of 130 million cell phones anticipated to be retired by 2005, as reported by the U.S. Environmental Protection Agency (2005).

For this study, an assumption was made that the worldwide cell-phone-battery chemistry distribution, as reported by Pillot (2005b), is equivalent to the United States cell-phone-battery chemistry distribution. The material requirements reported in the appendix for the selected battery chemistries were used to develop estimates for the amount of cadmium, cobalt, lithium, and nickel contained in these batteries. The relative proportions of these materials in cell phone batteries are highly dependent on battery technology. Environmental regulations, changing cell phone technologies, and shifting consumer preferences during the 10-year study period led to substitution for NiCd batteries in cell phones, first by NiMH batteries, and then by Li-ion batteries. By 2005, lithium-polymer batteries began to erode the market share of the Li-ion batteries in cell phones. The estimates for battery distribution on an annual basis are necessary because of the rapid changes taking place in the types of batteries that were used in cell phones during the study period.

Technological innovation not only stimulated changes in cell phone battery technology, but also led to a noticeable reduction in cell phone size and weight because lithium-based batteries are lighter than NiCd batteries and electronic circuitry refinements lead to increased miniaturization. The Environmental Literacy Council (2004) reported that the weight of a typical cell phone in the early 1990s was about 11 ounces and in 2000 was 7.7 ounces. In 2006, a typical cell phone weighed about 4.1 ounces (Nokia Corporation, 2006). The newest and most widely used lithium-based battery chemistries (Li-ion and lithium-polymer) weigh much less than older NiMH and NiCd batteries.

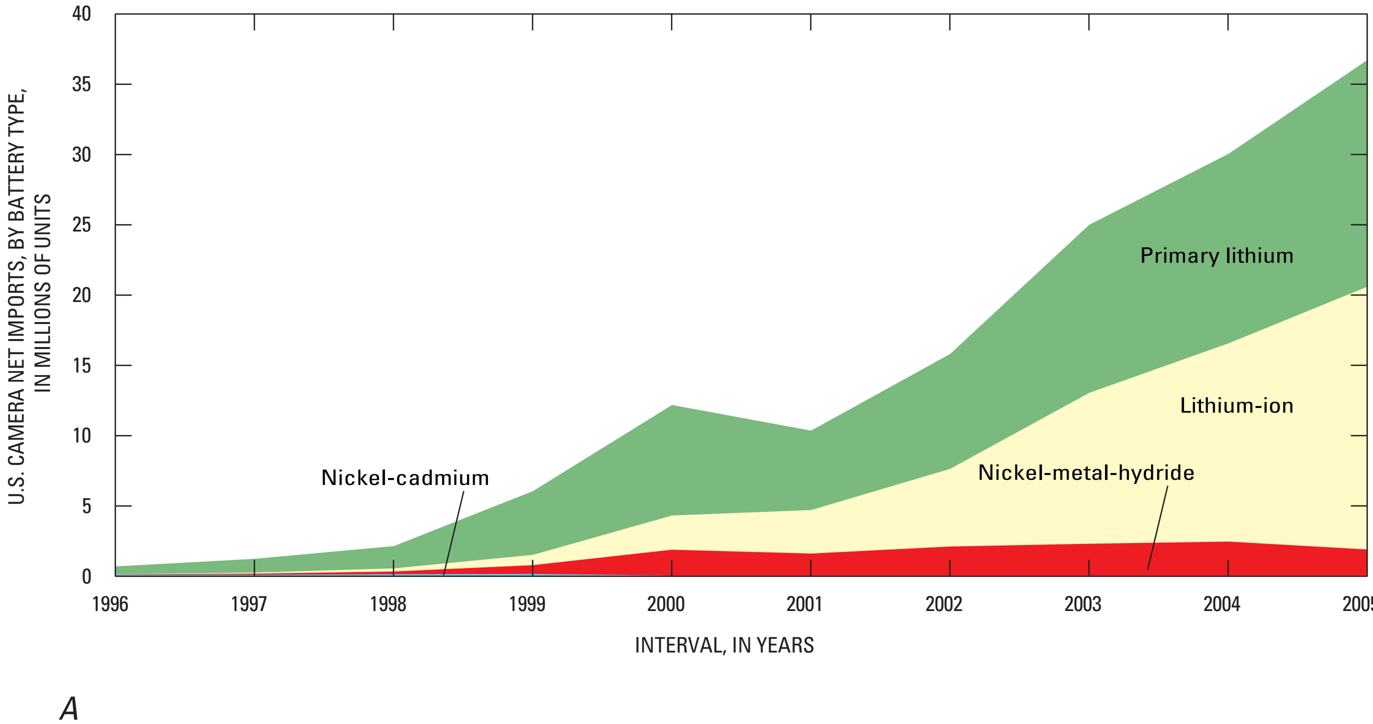
The study results suggest that about 4,700 metric tons (t) of cobalt, 3,100 t of nickel, 580 t of lithium, and 91 t of cadmium were contained in cell phones that were estimated to be available for disposal from 1996 to 2005 in the United States. Estimates based on recycling data provided by the Rechargeable Battery Recycling Corporation (2005) suggest that about 410 t of cobalt, 170 t of nickel, and less than 10 t each of cadmium and lithium contained in cell phone batteries may have been recovered from batteries recycled between 1999 and 2005. Thus, it is likely that about 4,300 t of cobalt, 2,900 t of nickel, 570 t of lithium, and 83 t of cadmium were contained in cell phone batteries discarded during the same period. Discarded material includes batteries retained in household storage for a time before entering the MSW landfills. Most of the cadmium, which is attributable to NiCd batteries, was discarded prior to 2001; most of the lithium was discarded after 2001. A significant quantity of nickel is contained in NiCd and NiMH batteries which were discarded during the entire 10-year period. A small amount of the discarded cell phone batteries was likely incinerated at MSW facilities.

The United States used about 28 percent of the 734 million cell phones that were sold worldwide in 2005 (Charny, 2005; Gartner, Inc., 2005). Growth in cell phone sales is taking place most rapidly in China and India; by 2008, it is estimated that these two countries may possibly account for about 45 percent of world cell phone use (Pillot, 2004, p. 26). By 2010, cell phone use in the United States may require about 250 million batteries, mostly of the Li-ion and lithium-polymer type. If current trends in battery use continue, the tonnage of cadmium from cell phone batteries that may potentially enter landfills in 2010 will be very small, the amount of lithium and nickel that may potentially enter landfills will likely be similar to what was entered in 2005, and the amount of cobalt destined for landfills or household storage is likely to increase. These estimates assume that the recycling rate for cell phone batteries will increase at a rate similar to that forecasted for total battery recycling in the United States; the estimates do not account for an increased rate of substitution of cobalt by nickel and other metals. It is assumed that State regulations will continue to govern the types of batteries that will be allowed in MSW landfills in the States.

Case Study 2—Cameras and Camcorders

The focus of the camera and camcorder (video recording camera) case study is to show how the growth in the use of batteries that power these popular business and consumer products during the past 10 years in the United States has changed and to discuss the effects of this change on materials use and disposal. Estimates were developed for the amount of cadmium, cobalt, lithium, and nickel contained in camera and camcorder batteries that are used in the United States for each of the principal battery chemistries associated with these products, as summarized in the study methodology section and shown in the appendix.

The quantity and composition of materials used in nonrechargeable (primary) and rechargeable camera batteries and in analog and digital camcorder batteries have changed during the past 10 years because of technological developments associated with the products. Imports of still-image cameras (digital and film-based types) into the United States have grown to about 38 million in 2005 from about 680,000 in 1996 (U.S. International Trade Commission, 2006) because more cameras are manufactured outside the United States. Imports of video cameras and camcorders (both digital and analog types) into the United States also have increased, but at a slower rate—to about 5.9 million units in 2005 from about 3.7 million units in 1996. Figure 3 shows the quantity of U.S. net imports (imports minus exports) of cameras (fig. 3*A*) and camcorders (fig. 3*B*) for the period from 1996 through 2005. In 1996, about 90 percent of cameras used various types of primary (nonrechargeable) batteries, and about 10 percent used rechargeable NiCd batteries; by 2005, however, worldwide sales data suggest that



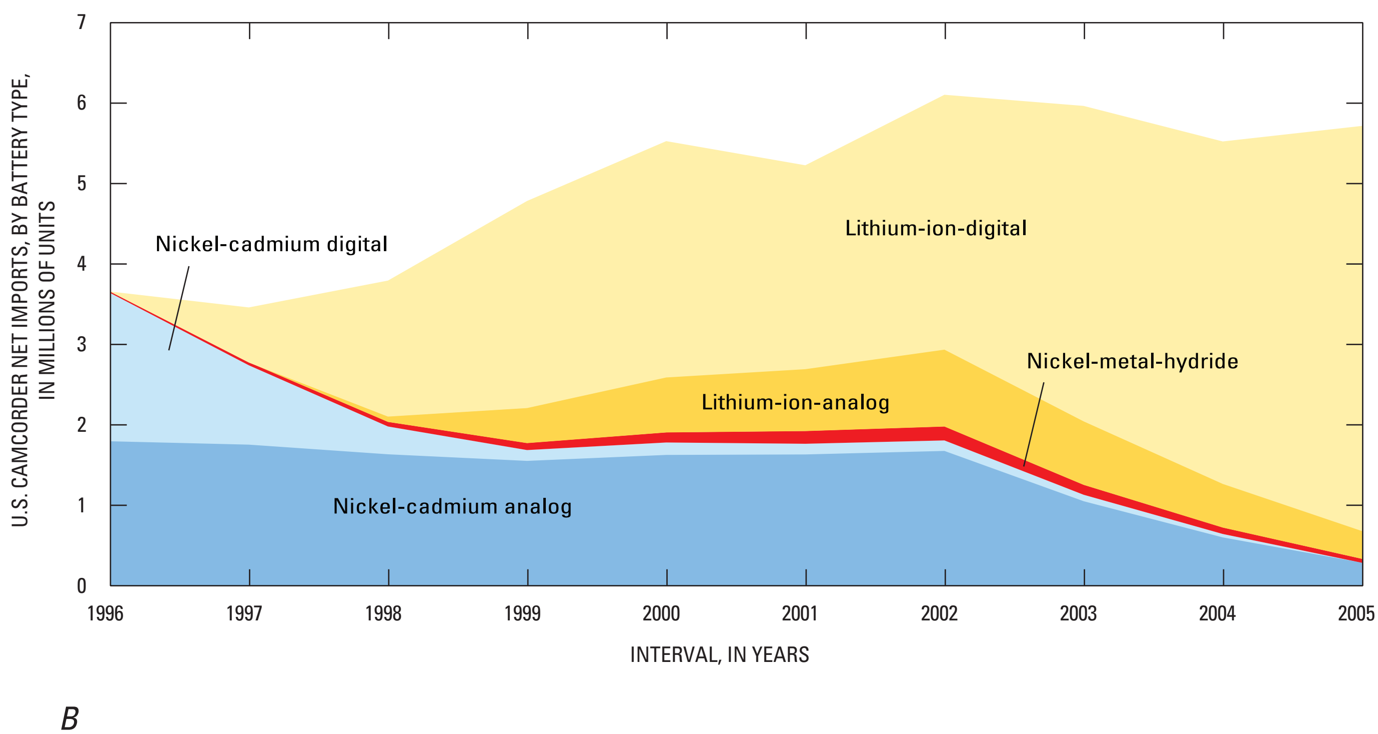


Figure 3. Graphs showing estimated U.S. net imports of *A*, cameras, and *B*, camcorders by battery type, in millions of units. Estimates were developed based on trade data from U.S. International Trade Commission (2006), net import data (imported products minus exported products) for each year, and percentage allocations by product type for each given year. World estimates for the camera and camcorder markets (Pillot, 2005a, p. 7) were assumed to apply to the United States.

about 51 percent of camera batteries were Li-ion rechargeable batteries, 44 percent were primary batteries, and about 5 percent were NiMH rechargeable batteries (Pillot, 2004, p. 27). In 1996, about one-half of all U.S. camcorders were analog (8-millimeter) types; by 2005, about 88 percent of all camcorders imported into the United States were digital types (U.S. International Trade Commission, 2006). Modern cameras and camcorders have become much more compact than those produced in the 1990s, primarily because of circuitry miniaturization; additionally, batteries contained in newer products have become more energy efficient, although most batteries used in these applications are similar in size to those used in 1996.

Significant material consumption patterns have changed within the camera sector as a result of cheaper prices, shifts in consumer preferences, and technological improvements. The changes are based on the assumption that observed variations in the quantity of selected U.S. imported products over time indicate trends. The increase in the use of camera batteries containing lithium (fig. 3*A*) represents the most significant change for the camera sector during the 10-year study period. The estimate for the aggregated total lithium content of batteries contained in digital and film-based cameras sold in the United States has increased to more than 19 t of lithium in 2005 from 100 kilograms of lithium in 1996. The NiCd batteries used in this application were phased out by 2000. The total cobalt content of camera batteries used in the United States increased to almost 50 t in 2005 from a negligible amount in 1996. The total nickel content of batteries used in this sector increased slightly to about 10 t in 2005 (attributed primarily to NiMH batteries) from about 2 t in 1996 (attributed to both NiCd and NiMH battery chemistries).

Although figure 3 shows a more modest growth pattern overall for the U.S. camcorder sector, the pattern of change in battery chemistry used during the 1996–2005 period is quite significant. Within this modest growth, some rather dramatic changes can be seen. Figure 3*A* shows that growth within the camera battery sector happened mainly with primary lithium and rechargeable Li-ion batteries. Figure 3*B* suggests that most of the growth in imports within the camcorder sector occurred during a transition from camcorders with NiCd batteries to camcorders with lithium-based batteries. In 1996, the number of camcorders using rechargeable Li-ion batteries was negligible; by 2005, about 50 percent of analog camcorders and almost 100 percent of digital camcorders used Li-ion batteries (Pillot, 2005a, p. 7). NiCd battery use correspondingly decreased during the period to about 5 percent of camcorders (mostly analog) in 2005 from approximately 100 percent of all camcorders because of changes in consumer preference, battery availability, and technological factors. Figure 3*B* shows the following three distinct periods of change for camcorder battery consumption:

1. From 1996 to 1998—Characterized by a rapid decrease in NiCd battery imports for digital camcorders and a corresponding increase in Li-ion battery imports for this application.
2. From 1998 to 2002—Characterized by an increase in Li-ion battery imports in analog and digital camcorders.
3. From 2002 to 2005—Characterized by a decrease in imports of analog camcorders coupled with a decrease in imports of all principle battery chemistries except Li-ion batteries.

Since 1996, some States have placed limitations on the use of consumer batteries containing mercury, enacted guidelines for battery disposal, and encouraged increased recycling for all battery chemistries. During this same period, more efficient and powerful battery technologies have been developed that have increased the use of rechargeable batteries in a large number of end-use applications. In general, the material content of electronic consumer-product batteries used and disposed of in the United States has changed significantly in the past 10 years. Figure 4 illustrates some of the changes that have taken place since 1996 for camera and camcorder batteries. In the case of cameras and camcorders, the amount of cadmium contained in camera and camcorder batteries has decreased to about 7 t in 2005 from about 83 t in 1996. The amount of nickel contained in camera and camcorder batteries has similarly decreased to about 22 t in 2005 from about 130 t in 1996, primarily as a result of decreasing use of NiCd batteries within the sector. With the increase in use of lithium-based batteries in the sector, the amount of lithium contained in camera and camcorder batteries has increased to about 26 t in 2005 from about 82 t in 1996, and the amount of contained cobalt has increased to 96 t in 2005 from about 5 t in 1996. Recycling of used batteries in this sector has also increased. The net effect is that consumer preferences, government regulations, and technological advancements have combined to effectively reduce the amount of cadmium and nickel from batteries disposed of in MSW landfills because of an increase in the use of Li-ion batteries in end-use applications, such as cameras and camcorders.

Case Study 3—Portable Computers

As the price of the average portable (laptop) computer has decreased to the average price of a desktop computer 5 years ago, and as wireless Internet connections have become more available, the number of portable computers in use in the United States has grown. Net imports of portable computers into the United States have grown to about 20.6 million in 2005 from about 1.4 million in 1996 (U.S. International Trade Commission, 2006). In 2005, for the first time in U.S. history, portable computers outsold desktop computers and accounted for 51 percent of all U.S. personal computer sales (Kanellos, 2006). The focus of this case study is to show how technological advances in computers and the batteries used to power them led to the growth in portable computer use during the past 10 years, to discuss the changes in battery chemistry used in these products and the changing material

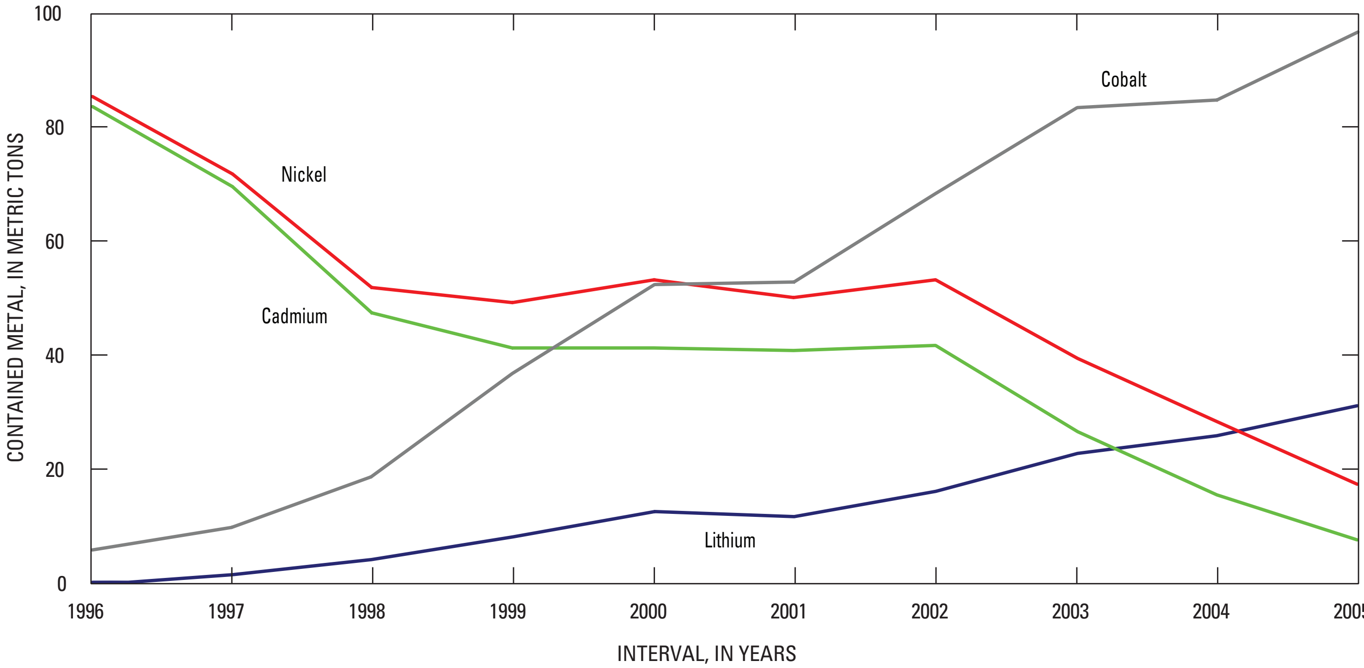


Figure 4. Graph showing estimated amounts of cadmium, cobalt, lithium, and nickel contained in rechargeable camera and camcorder batteries used in the United States from 1996 through 2005. Estimates were developed based on trade data from the U.S. International Trade Commission (2006), net import data (imported batteries minus exported batteries) for each year from the U.S. International Trade Commission (2006), assumed average metal content of batteries, and percentage allocations by battery chemistry for each given year. The worldwide rechargeable battery distribution by chemical type as reported by Pillot (2004, p. 27–31) is assumed to be equivalent to the United States rechargeable battery market distribution for cameras and camcorders.

needs of these batteries, and to discuss the ramifications of these changing growth patterns on material consumption and disposal. Estimates were developed for the amount of cobalt, lithium, and nickel contained in the Li-ion and NiMH batteries used in these computers. The estimates are based on ITC trade statistics and the average material requirements for specified battery classifications as determined by averaging the battery specifications reported by selected manufacturers.

Data for Li-ion and NiMH batteries used in portable computers show different trends. The shaded areas in figure 5 show that the use of Li-ion batteries in portable computers increased at a much faster rate than the use of NiMH batteries, primarily because of technological improvements in the Li-ion batteries that resulted in a lower unit price and increased energy efficiency. In 1996, NiMH batteries represented 55 percent of all net battery imports used in U.S. portable computers, as reported by the ITC; by 2005, the market share of NiMH batteries used in portable computers had dropped to about 8 percent (Pillot, 2005a, p. 6). Conversely, Li-ion batteries represented about 92 percent of the market share in 2005 and about 45 percent in 1996 (U.S. International Trade Commission, 2006).

Li-ion batteries have grown in popularity as a function of both price and efficiency relative to other principle battery chemistries. The Li-ion batteries are priced higher than other comparable battery types, but the average price of a Li-ion battery dropped from about $5 per cell in 2000 to about $2.50 per cell in 2005, compared with a 2005 price estimate of about $0.75 per cell for NiCd and $1.00 per cell for NiMH batteries (Pillot, 2005b, p. 18; Pillot, 2006b, p. 17). The Li-ion battery, however, has a higher energy density (greater energy storage capacity per weight) and is lighter (less dense) than NiCd or NiMH products, which makes it preferable as a power source for portable items such as cell phones, camcorders, and portable computers. Technological advances have improved the performance characteristics of Li-ion batteries. In 1992, when they were first introduced, the Li-ion battery had only a 10 percent higher energy density than a comparable NiMH battery; by 2005, the Li-ion battery had an average energy density about 80 percent greater than the NiMH battery (Pillot, 2005b, p. 16). As the price difference between these two types of batteries decreases, consumers and manufacturers may be more willing to use batteries with the higher energy density and lower weight.

Estimates of the quantity of cobalt, lithium, and nickel contained in batteries consumed by the portable computer sector from 1996 to 2005 are illustrated on figure 5. Assumptions used in developing these estimates are reported in the appendix (table A–6). ITC trade data for the United States were used to estimate the amount of net imports by battery chemistry, and battery data reported by selected manufacturer's material safety data sheets were used to assign average composition values for each of the principal rechargeable battery chemistries. HTS classifications for each battery chemistry and end

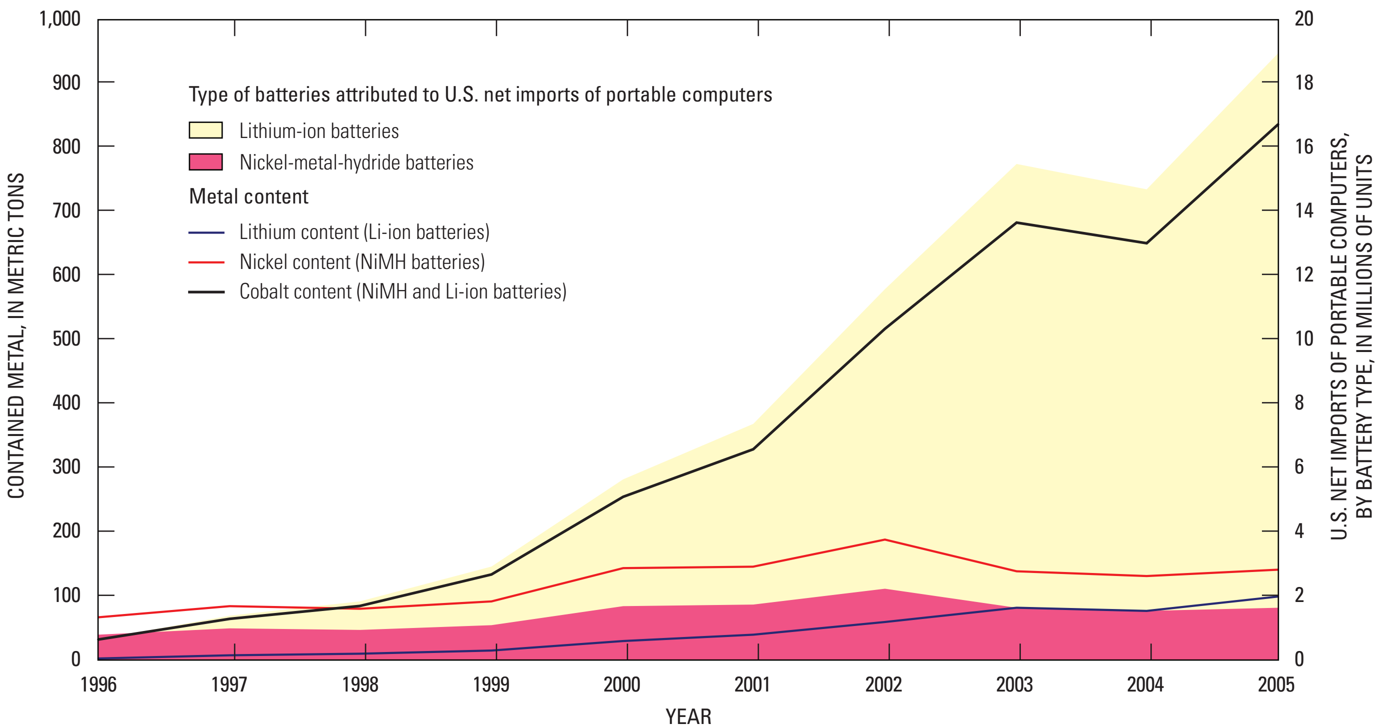


Figure 5. Graph showing estimated imports of portable computers by battery type and amounts of cobalt, lithium, and nickel contained in rechargeable portable computer batteries used in the United States from 1996 through 2005. Estimates are based on trade data from the U.S. International Trade Commission (2006), net import data (imported batteries minus exported batteries) for each year from the U.S. International Trade Commission (2006), assumed average metal contents of these batteries, and percentage allocations by battery chemistry for each given year. The worldwide personal computer rechargeable battery market distribution as reported by Pillot (2005a, p. 6) is assumed to be equivalent to the United States rechargeable battery market distribution for portable computers.

use analyzed in this study are listed in the appendix (table A–11).

The total amount of lithium contained in Li-ion batteries used by portable computers in the United States has increased to nearly 100 t in 2005 from less than 4 t in 1996 owing to the increased use of Li-ion batteries in portable computers. Total nickel content of NiMH batteries used in portable computers increased to about 190 t of nickel by 2002 from about 67 t of nickel in 1996, then dropped to about 140 t of nickel by 2005. Assuming that the predominant Li-ion battery chemistry is $LiCo(OH)_2$, the total cobalt content of Li-ion and NiMH batteries used in portable computers increased to about 840 t (about 8 t in NiMH and 830 t in Li-ion) in 2005 from 32 t (4 t in NiMH and 28 t in Li-ion) in 1996. The number of portable computers sold worldwide is projected to increase by 35 percent from 2005 to 2010, and estimates suggest that Li-ion batteries will hold a near 100 percent market share of rechargeable batteries used in portable computers in 2010 (Pillot, 2005a, p. 6), barring the commercial implementation of new technologies, such as fuel cells, which have different material requirements. Applying these figures to the most recent U.S. trade data suggests that in 2010 the U.S. portable computer sector may use more than 1,100 t of cobalt and 130 t of lithium for the manufacture of portable computer batteries. From 2005 through 2010, nickel consumption is expected to decrease as NiMH batteries are further replaced by Li-ion batteries in portable computers.

These estimates assume that there are no large changes in the overall chemical composition of rechargeable batteries from 2005 through 2010; it is expected, however, that continued technological improvement could result in small variations in battery composition and that some market penetration by lithium-polymer or fuel cells could take place by 2010. Changing commodity prices could also influence substitution. Pillot (2005a, p. 14) suggests that fuel cell use in portable computer applications may well account for as much as 4 percent of the market by 2010; other researchers report that widespread use of fuel cells to power small consumer products is more likely to take place after 2010.

Li-ion batteries used in selected models of portable computers have been recalled by various computer manufacturers since 2005 because of a possible fire hazard posed by the battery overheating. This study does not attempt to assess the effect of such recalls on future battery consumption, but it does assess the effect of these recalls on the amount of lithium that has entered recycling and disposal flows. Based on the data reported by the U.S. Consumer Product Safety Commission, approximately 235,000 Li-ion batteries were recalled in the United States in 2005, and about 4.3 million additional batteries were recalled in the United States as of November

2006 (U.S. Consumer Product Safety Commission, 2007). If it is assumed that each of these recalled battery packs contained nine individual cells, and each cell contains an average of 4.9 grams (g) of cobalt and 0.58 g of lithium per cell, then the cumulative amount of cobalt contained in the recalled batteries is estimated to be about 10 t of cobalt and 1.2 t of lithium in 2005 and about 190 t of cobalt and 22 t of lithium in 2006. However, because these recalls are voluntary, the amount of batteries actually returned by the consumer may be lower. While it is uncertain how much of this material will end up in U.S. landfills, Li-ion batteries are generally considered less toxic than NiCd batteries, and the environmental effect of these sudden recalls is expected to be minimal (Ames, 2006). Many of the computer manufacturers have contracts with the RBRC to recycle discarded batteries, so it is likely that most of those batteries that are returned to the manufacturers will be recycled; the recycled material is then returned to the manufacturers as feed material for new batteries. Metals recovered from battery recycling by INMETCO may be used in steelmaking. The RBRC reported a 6.4 percent increase in batteries recycled during the first 6 months of 2006 compared with the same time period in 2005; some of this increase could be attributable to Li-ion batteries that were recycled as a result of the recalls.

Case Study 4—Hybrid Vehicles

A study of rechargeable batteries would not be complete without considering the effect of the growth in the hybrid electric vehicle (HEV) industry on the rechargeable battery industry. HEVs combine the internal combustion engine of a conventional vehicle with the battery and electric motor of an electric vehicle. The first commercially produced HEV was introduced into the U.S. market in 1999; since that time, more U.S. and foreign automobile manufacturers have included HEVs in their U.S. automotive lineup, and demand for vehicles equipped with hybrid electric technology is increasing. Because this market sector for rechargeable batteries is changing rapidly, this case study evaluates not only 1996–2005 material use levels, as was done in the other case studies, but also assesses anticipated cobalt, lithium, and nickel use in this sector from 2005 to 2010. Material use estimates for this period were derived from U.S. HEV sales estimates reported by the U.S. Department of Transportation and the U.S. Department of Energy, Energy Information Administration, and from estimates of the percentage of vehicles that use various types of HEV batteries, as reported by Madani (2005).

Much research into improving automotive battery technology by the creation of low-cost but energy-efficient battery systems is ongoing. As of 2008, all commercially available HEVs are powered by NiMH battery systems and internal combustion engines. Li-ion battery systems, improved NiMH systems, and hydrogen-powered fuel cells are in development, but NiMH battery systems are expected to remain the predominant source of electric power for HEVs until at least 2010.

The two main hindrances to the establishment of a strong, growing HEV sector in the short term are the time required for battery development and the high price of HEV batteries. Research suggests that the period of battery development to commercial implementation is from 4.5 to 7 years (Madani, 2005, p. 15). Consequently, battery technologies undergoing initial research in 2005 are not likely to be placed in service before 2010. A number of research initiatives conducted jointly by automobile manufacturers and battery producers to develop commercially viable Li-ion batteries for vehicles have been initiated since 2003. Batteries generated from these collaborative efforts, however, are unlikely to reach the market before 2008. Large-scale Li-ion battery production suitable for HEVs is therefore unlikely before 2010.

Although the technology required to produce the small cells used in portable consumer electronics is transferable to the production of battery packs suitable for HEVs, the optimum energy storage characteristics of HEV batteries are different and make these batteries more costly. One first-generation HEV battery weighed about 50 kg and required 228 D-size NiMH cells. Another first-generation HEV battery used 240 to 250 D-size NiMH cells that weigh a combined 144 kg (Madani, 2005, p. 9). The higher cost of such battery packs requires automobile manufacturers to charge a premium for their HEVs over conventionally powered automobiles that use lead-acid batteries to power internal combustion engines.

Battery electrical energy requirements vary by battery chemistry and the intended battery use. The more popular HEVs use batteries primarily designed to provide rapid acceleration rather than as the primary source of motive power. One desirable attribute of this kind of battery is high specific energy [the amount of energy stored in watthours (Wh) per unit mass in kilograms (kg)] or energy density [energy stored in Wh per unit volume in liters (L)]. A main advantage of the Li-ion battery technology is its ability to provide a high energy density that ranges from 175 to 310 Wh/L (144 to 255 Wh/kg). A conventional lead-acid battery designed to be the primary power source for a vehicle typically achieves only 89 Wh/L (73 Wh/kg) (Gaines and Cuenca, 2000, p. 6). The specific energy for a NiMH battery system used in HEVs is about 56 Wh/L (46 Wh/kg) (Panasonic EV Energy Co., Ltd., 2006).

The cost to provide the high level of specific energy necessary for an HEV battery is significant. In 2005, the cost of a typical NiMH battery was $0.50 per watthour, while the cost of a Li-ion battery was about $2.20 per watthour (Madani, 2005, p. 18). At an average energy requirement of 1,300 watts (W), this translates to an average cost of about $650 per NiMH battery and about $2,860 per Li-ion battery. Battery costs are projected to drop to an estimated $0.28 per watthour for a NiMH battery and $0.80 per watthour for a Li-ion battery by 2010 (Madani, 2005, p. 19). If so, the typical cost of an 1,800-W battery in 2010 would be about $500 for a NiMH battery and about $1,400 for a Li-ion battery. Improvements in battery technology could result in further cost reductions.

Given the cost and technology constraints, what effect did the changing vehicle battery market have on the use of cobalt, lithium, and nickel in hybrid vehicle batteries for the period 1996 through 2005 and their projected use for 2006 through 2010? Vehicle production statistics reported by the U.S. Department of Transportation, vehicle sales projections reported by the U.S. Department of Energy, trade statistics reported by the ITC, HEV sales forecasts provided by Pillot, (2006a, p. 17), Paumanok Publications, Inc. (2006), and the National Renewable Energy Laboratory (Pesaran, 2006) were used to estimate the relative amount of these materials consumed in vehicle batteries through 2005 to provide estimates of selected material use based on projections of HEV vehicle sales for the period from 2005 through 2010.

Table 1 provides estimates of the amount of cobalt, nickel, and lithium contained in batteries from domestic and imported HEVs in the United States from 1996 to 2010. The estimates are based on the number of HEVs reported as sold or leased from 1996 to 2003 and projections of U.S. vehicle sales from both domestic and foreign manufacturers to 2010 (U.S. Department of Energy, 2006; U.S. Department of Transportation, 2006). These estimates assume one battery pack per vehicle sold during the period considered for this study and do not take into account defective or replacement batteries. HEVs were first introduced commercially to the U.S. market in 1999. Since that year, HEV vehicle imports to the United States gradually increased until 2004, when some U.S. automobile manufacturers added HEVs to their product lines. Available data suggest that the rate of HEV vehicle sales after 2004 will grow more rapidly, such that the quantity of HEVs sold in the United States may reach 550,000 units in 2010. Projections by Madani (2005), Paumanok Publications (2006), and The Freedonia Group Inc. (2006) suggest a higher level of future HEV sales than do estimates from the U.S. Department of Energy (2006) used in this analysis, because they include sales of replacement HEV batteries in their estimates. Projections, however, can be affected by changes in energy prices, technological breakthroughs, and other unanticipated factors.

Estimates for the amount of nickel contained in NiMH batteries used in HEV passenger vehicles and light trucks is expected to increase by a factor of 10 between 2003 and 2010, reaching about 7,300 t, as demand for HEVs that use this type of battery increases. Estimates for the amount of cobalt used in HEV batteries are likely to increase gradually from 2003 to 2008, at which time commercial production of Li-ion batteries for HEVs is expected to come online. If this takes place, then cobalt use in HEV batteries is projected to increase to about 210 t in 2010 from about 7 t in 2007, including both NiMH and Li-ion HEV batteries. Data suggest that in 2010, NiMH batteries would still be found in about 95 percent of HEVs, or more than 3 percent of the vehicles sold in the United States. The amount of lithium in HEV batteries is expected to remain at low levels until 2010, a function of low HEV battery production levels, the small percentage of HEVs that use Li-ion batteries, and the small amount of lithium contained within a Li-ion battery.

Summary and Conclusions

Consumer preferences, decreasing battery costs, environmental regulation, increasing fuel costs, new end-use markets, and technological advances have all played a role in the changing consumption and substitution patterns of rechargeable batteries, particularly in automotive and consumer electronic product applications. Table 2 summarizes cadmium, cobalt, lithium, and nickel consumption estimates for batteries used in selected consumer products assessed in this report for the period from 1996 through 2005. For each of the four mineral-based commodities evaluated, the amount of material used in selected end-use applications is given along with reference values of total annual U.S. apparent consumption for these metals as reported by the USGS. Although comparison of such data may be used to suggest gross trends in material consumption, direct comparison is not recommended because calculations of total U.S. apparent consumption do not include material contained in manufactured products imported to or exported from the United States, so total material consumption may be underestimated (Wilburn and Buckingham, 2006).

Total U.S. apparent consumption of cadmium appeared to decrease in a manner similar to that of the overall decline for the analyzed end-use sectors. U.S. apparent consumption of cobalt remained generally constant during the 10-year study period. In contrast, cobalt use attributed to rechargeable cell phone and portable computer batteries increased. In 2005, the cobalt content of cell phone batteries in use in the United States was estimated to be 1,400 t, or about 12 percent of the calculated 2005 U.S. apparent consumption value. Similarly, the estimated 2005 cobalt content of portable computer batteries in use in the United States was 840 t, or about 7 percent of the calculated 2005 U.S. apparent consumption value. U.S. apparent consumption of lithium decreased from 2001 through 2004 primarily as a result of decreased U.S. aluminum production (Ober, 2002). Lithium use in the United States that is attributable to the rechargeable battery sector, however, increased since 2002, primarily in such popular consumer products as cell phones and portable computers. The most noticeable trends in nickel use in rechargeable batteries relate to the decrease in the amount of nickel used in cell phone batteries as Li-ion batteries have increasingly replaced NiMH batteries in cell phones, and the increasing amount of nickel used in HEV batteries. As the number of hybrid vehicles in use increases, the use of nickel in NiMH batteries that power such vehicles also will increase, until such time as alternative technology supplants the use of NiMH in batteries.

U.S. cadmium use in consumer electronic batteries has generally declined (table 2) since cadmium was recognized as a possible human carcinogen in 1992. This finding resulted in the implementation of regulations affecting battery recycling and disposal and the introduction of technological advancements in other battery chemistries that are increasingly used as alternatives. For the period 1996 through 2000, camcorder batteries imported into the United States used more cadmium (up to 82 t)

Table 1. Content of key material components contained in hybrid electric vehicle batteries.

[HEV, hybrid electric vehicle. NiMH, nickel-metal hydride. XX, negligible]

Category	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Estimated U.S. car and light truck HEV sales[1]	0	0	0	3,500	18,000	30,000	25,000	49,000	92,000	190,000	310,000	300,000	480,000	490,000	550,000
Percentage of vehicles by battery type:[2]															
NiMH batteries	0	0	0	XX	0.1	0.2	0.2	0.3	0.6	1.3	2.1	2.0	3.1	3.1	3.1
Lithium-ion batteries	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.2	0.5
Metal content of NiMH HEV batteries, in metric tons:[3]															
Cobalt content	0	0	0	XX	XX	0.7	0.6	1.2	2.2	4.6	7.4	7.2	80	120	210
Nickel content	0	0	0	49	250	420	350	690	1,300	2,700	4,300	4,200	6,600	6,700	7,300
Lithium content	0	0	0	0	0	0	0	0	0	0	0	0	8	13	23

[1]Estimates for 1996 through 2002 are based on manufacturer press releases. Estimates for 2003 through 2010 are based on data from the U.S. Department of Energy (2006).

[2]Estimates are reported by Madani, 2005b, p. 20.

[3]Cobalt, lithium, and nickel content estimates are based on representative battery manufacturer data for batteries of D-cell type and HEV battery data provided by Geelan and Kirkpatrick (2006).

Table 2. Reported U.S. apparent consumption for selected metals and the content of these metals in batteries used in popular consumer products for the period 1996 through 2005.

[Units expressed as metric tons. XX, negligible]

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Cadmium										
U.S. apparent consumption[1]	2,250	2,510	2,100	1,850	2,010	1,000	1,460	637	1,170	656
Cadmium content, by battery type:[2]										
Camcorder batteries[3]	82	68	45	38	41	40	41	26	15	6.9
Camera batteries[3]	1.2	1.1	2	2.3	0	0	0	0	0	0
Cell phone batteries[3]	20	22	19	18	12	0	0	0	0	0
Total	100	91	66	58	53	40	41	26	15	7
Cobalt										
U.S. apparent consumption[4]	9,380	11,200	11,500	10,700	11,600	11,800	9,830	10,000	9,920	11,900
Cobalt content, by battery type:[2]										
Camcorder batteries[3]	5.2	9	17	33	43	43	52	52	47	47
Camera batteries[3]	XX	0.4	0.9	3	8.6	9.8	15	31	37	49
Cell phone batteries[3]	18	44	73	160	310	380	510	730	1,100	1,400
Hybrid vehicle batteries[5]	0	0	0	XX	XX	0.7	0.6	1.2	2.2	4.6
Portable computer batteries[3]	32	65	84	130	260	330	520	690	650	840
Total	55	120	170	330	620	760	1,100	1,500	1,800	2,300
Lithium										
U.S. apparent consumption[6]	2,700	2,800	2,800	2,800	2,800	1,400	1,100	1,400	1,900	2,500
Lithium content, by battery type:[2]										
Camcorder batteries[3]	82	68	45	38	40	40	43	26	15	6.9
Camera batteries[3]	0.1	0.3	0.5	1.7	4.1	3.9	6.5	12	15	19
Cell phone batteries[3]	1.8	4.9	8	18	34	45	62	92	140	170
Portable computer batteries[3]	3.3	7.1	10	15	29	38	60	81	77	99
Total	87	80	63	73	110	130	170	210	250	290
Nickel										
U.S. apparent consumption[7]	206,000	222,000	212,000	211,000	233,000	210,000	205,000	200,000	212,000	213,000
Nickel content, by battery type:[2]										
Camcorder batteries[3]	130	100	74	65	71	72	74	48	28	13
Camera batteries[3]	1.8	2.2	3.6	6.5	9.3	7.9	10	11	12	9.4
Cell phone batteries[3]	84	120	210	430	830	540	450	230	140	110
Hybrid vehicle batteries[5]	XX	XX	XX	49	250	420	350	690	1,300	2,700
Portable computer batteries[3]	67	84	79	92	140	150	190	140	130	140
Total	280	310	370	640	1,300	1,200	1,100	1,100	1,600	3,000

[1]Source data for 1996-2003, U.S. Geological Survey (2005); source data for 2004-05, Cooper and Kuck (2007). Apparent consumption is reported here for reference only, as it does not include materials contained in manufactured products imported to or exported from the United States.

[2]Sum of the metal contained in net imports of batteries applicable to each end use evaluated in this study. Values rounded to 2 significant digits and totaled to nearest whole number.

[3]Estimates derived from U.S. International Trade Commission (2006).

[4]Source data for 1996-2003, U.S. Geological Survey (2005); source data for 2004-05, Shedd (2007).

[5]Estimates derived from U.S. Department of Energy (2006), U.S. Department of Transportation (2006), U.S. International Trade Commission (2006).

[6]Source data for 1996-2005, Ober (1997-2007), Ober (2002), Ober (2003), Ober (2004), Ober (2005), Ober (2006), Ober (2007).

[7]Source data for 1996-2003, U.S. Geological Survey (2005); source data for 2004, Kuck (2005); source data for 2005, Kuck (2007).

than any other application examined in this study. Cadmium use in camcorder batteries declined to about 7 t in 2005 from 82 t in 1996. NiCd rechargeable batteries have been replaced by Li-ion and NiMH rechargeable batteries in cameras since about 2000 and in cell phones since about 2001. In contrast to the decline in NiCd battery usage, the number of spent NiCd batteries that end up in landfills has increased in the past 10 years. Study data suggest that about 91 t of cadmium was contained in cell phone batteries available for recovery or disposal from 1996 through 2005, although much of this material was discarded prior to 2001. Efforts to recycle NiCd batteries have increased. The percentage of cadmium metal recovered from the reservoir of available NiCd batteries of all types was estimated by the USGS to range from 10 to 27 percent for the 1996 to 2007 period. The collection rate for large industrial NiCd batteries in the United States was reported to be approximately 80 percent, while the collection rate for small portable rechargeable batteries in the United States was reported to range from 5 to 21 percent (Hawkins and others, 2006).

During the period from 1996 through 2005, cobalt use in rechargeable batteries grew in all the end-use applications assessed in this study (table 2). Cell phones and portable computers consumed the greatest amount of cobalt in 1996, the former because of the large number of battery cells in circulation and the latter because of the larger cobalt content in computer battery packs. Estimates suggest that in 1996, cell phone batteries accounted for about 18 t of cobalt; by 2005, the amount of cobalt contained in cell phone batteries had increased to about 1,400 t. The use of cobalt in portable computer batteries similarly increased to about 840 t in 2005 from about 32 t in 1996 because of increased use of Li-ion batteries in portable computers. Of the estimated 4,700 t of cobalt from cell phones available for recovery or disposal between 1996 and 2005, about 410 t was recycled, and about 4,300 t was exported, stored, or disposed of in MSW landfills.

Lithium use in rechargeable batteries has grown with the increased use of Li-ion and lithium-polymer battery chemistries in consumer electronics. Although U.S. apparent consumption of lithium (excluding materials contained in manufactured imported products) decreased from 2000 through 2004 (table 2) primarily as a result of decreased U.S. aluminum production (Ober, 2002), increased U.S. consumption of lithium as a component of rechargeable batteries contained in consumer electronic products imported to the United States may have helped offset reduced U.S. consumption from other sectors. Cell phones and portable computers consumed the greatest amount of lithium in 2005, the former because of the large number of battery cells in circulation and the latter because of the larger lithium content in computer battery packs. In 1996, cell phone batteries accounted for 1.8 t of lithium; by 2005, the amount of lithium contained in cell phone batteries had increased to 170 t. Similarly, portable computer batteries accounted for 3.3 t of lithium in 1996 and 99 t in 2005. Study data suggest that up to about 580 t of lithium was contained in cell phone batteries available for recovery or disposal from 1996 through 2005. Changes in camcorder and camera technology from 1996 through 2005 had the net effect of reducing the lithium content per battery for these applications; because the number of cameras (primarily digital) used in the United States increased during this period, however, the total quantity of lithium contained in camera batteries used in the United States increased.

The overall pattern of U.S. nickel consumption for the electronic consumer products studied changed significantly during the period from 1996 through 2005. Nickel consumption derived from NiCd batteries that powered cell phones increased to 830 t in 2000 from 84 t in 1996, then decreased to 110 t in 2005 (table 2) as lithium-based batteries increasingly substituted for NiCd batteries and then for NiMH batteries, and as cell phone batteries became smaller and used less nickel per cell. Nickel consumption in portable computer batteries gradually increased to 140 t in 2005 from 67 t in 1996; nickel consumption in camera batteries remained below 13 t for the entire period; and nickel consumption in camcorder batteries decreased to 13 t in 2005 from 130 t in 1996. Technological and consumer preference changes are the primary reasons for these consumption pattern changes. Of the estimated 3,100 t of nickel in cell phones available for recovery or disposal between 1996 and 2005, about 170 t of nickel was recycled and about 2,900 t was exported, stored, or disposed of in MSW landfills.

As the number of HEV vehicles increase, nickel use in HEV NiMH batteries is expected to increase by a factor of 10 by 2010 to about 7,300 t of nickel. Changes in energy prices, technological breakthroughs, and other unanticipated factors may affect the rate and size of this anticipated increase. NiMH batteries will continue to be the most widely used HEV battery in 2010. Based on available data, nickel used in HEV batteries may represent about 1.5 percent of total nickel apparent consumption in the United States in 2010.

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Appendix

The appendix lists the assumptions and estimates used in this study. Table A–1 summarizes material content assumptions and estimates for nickel-cadmium batteries; table A–2 summarizes material content assumptions and estimates for primary lithium-based batteries; table A–3 summarizes material content assumptions and estimates for nickel-metal-hydride batteries; and table A–4 summarizes material content assumptions and estimates for lithium-ion and lithium-polymer batteries. Manufacturers' data were derived from selected Material Safety Data Sheets, which where publicly available from battery manufacturers having a sizeable U.S. presence. Average battery weights and material contents for each HTS classification applicable to each manufactured product under review were developed from these data. Table A–5 summarizes specific material content assumptions for cell phone batteries; table A–6 summarizes specific material content assumptions for portable (laptop) computer batteries; table A–7 summarizes specific material content assumptions for camera batteries; table A–8 summarizes specific material content assumptions for video camera (camcorder) batteries; and table A–9 summarizes material content assumptions for batteries designated for hybrid vehicles considered in this study.

HTS classes applied to each end use are listed for nickel-cadmium batteries in table A–10 and for lithium-ion and nickel-metal-hydride batteries in table A–11. Some classifications apply only to either export or import data; most apply to both export and import data. Tables A–10 and A–11 report the years for which each HTS class was applicable for the study period, and whether the class applies to export data, import data, or both.

Table A–1. Selected material content assumptions and estimates for nickel-cadmium batteries used in this study to determine the flow of cadmium in the United States from 1996 through 2005.

[NA, not available; XX, not applicable; —, zero]

Battery class (based on end use)	Manufacturer and/or battery type	Cell weight range[2], in grams	Average weight of cell[2], in grams	Cadmium content[2], in percent	Cadmium content/cell or pack[3], in grams	Cobalt content[2], percent	Cobalt content/cell or pack[3], in grams	Nickel content[2], percent	Nickel content/cell or pack[3], in grams	Nickel-cadmium, in percentage of total estimate[4]	Years for which data applied
General nickel-cadmium storage battery[5]	NA	NA	NA	14	NA	0	NA	22	NA	NA	1996–2005
Storage batteries, separate:											
Electrically-powered vehicle batteries	Saft STM	12,900–17,000	14,400	16	2,300	1	100	22	3,200	100	1996–2005
Sealed consumer batteries	Saft VRE	19–150	60	10–15	8.4	0.4–1	0.4	20–28	13.2	100	1996–2005
	Sanyo Cadnica	NA	NA	11–26	NA	0	0	13–29	NA	100	1996–2005
Industrial batteries	Saft SLM	1,000–45,000	14,900	8	1,200	0.2	30	9	1,300	100	1996–2005
	Saft SPH	NA	NA	16	NA	1	0	22	NA	100	1996–2005
Batteries enclosed in products:											
Power tools	Saft VRE–C	NA	43	10–15	6	0.4–1	0.3	20–28	9.5	91	1996–2005
Cordless phones	Battery selection[6]	63–113	80	14	11.2	0.9	0.7	22	17.6	40	1996–2005
Camcorders	Battery selection[6]	59–376	160	14	22	0.9	1.4	22	35	30	1996–2003
	XX	XX	XX	XX	XX	XX	XX	XX	XX	18	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	6	2005
Cameras	Battery selection[6]	20–318	130	14	19	0.5	0.5	22	29	30	1996–1999
Portable radios	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	6	1996–2005
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	6	1996–2005
Shavers	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	45	1996–2003
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	34	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	22	2005
Electric toothbrushes	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	45	1996–2003
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	34	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	22	2005
Portable vacuum cleaners	Saft VRE–Cs	43–150	97	10–15	13.6	0.4–1	0.7	20–28	21.3	45	1996–2003
	Saft VRE–D	NA	NA	10–15	NA	0.4–1	NA	20–28	NA	34	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	22	2005
Flashlights	Sanyo Cadnica	19–145	49	11–26	6.9	0	0	13–29	10.8	4	1996–2003
	XX	XX	XX	XX	XX	XX	XX	XX	XX	3	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	2	2005
	Energizer	NA	NA	13–22	NA	0.5–2	NA	20–32	NA	—	1996–2005
	Panasonic	26–51	40	NA	NA	NA	NA	NA	NA	—	1996–2005
Portable electric lamps (bicycle lamps, for example)	Saft VE	18–150	64	10–15	9	0.4–1	0.4	20–28	14	24	1996–2003
	XX	XX	XX	XX	XX	XX	XX	XX	XX	18	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	12	2005
Clock batteries, reported separately	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	4	1996–2003
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	3	2004
	XX	XX	XX	XX	XX	XX	XX	XX	XX	2	2005
Military batteries, reported separately	Saft VRE–AA	14–32	21	10–15	2.9	0.4–1	0.1	20–28	4.6	16	1996–2005
	Sanyo Cadnica-AA	NA	NA	11–26	NA	0	0	13–29	NA	16	1996–2005

[1]Manufacturer was selected based on the volume of production and the availability of data. Battery selection was based on the applicability to the end-use category. Batteries selected are assumed to be representative for the given classification.

[2]Based on reported weights given by the manufacturer for all batteries in that classification. Data were obtained from the specified manufacturer's Web site.

[3]Calculated using (average weight of cell or pack) × (specified commodity content). When a percent range is shown, the average percentage reported by Vangheluwe, Verdonck, and Versonnen (2005) was used for calculations.

[4]Percent allocation of the number of batteries listed as nickel-cadmium batteries, based on end-use distributions reported by Pillot (2004, p. 29–31; 2005a, p. 5–8). In some cases, the 2004 and 2005 percentages were reported to be lower than the percentages of previous years. Where no years are reported, value applies to entire study period.

[5]Vangheluwe, Verdonck, and Versonnen (2005).

[6]Based on a random selection of batteries used for each of these applications (Zbattery.com, written commun., November 22, 2006).

Table A–2. Selected material content assumptions and estimates for primary lithium-based batteries used in this study.

[NA, not available; V, volt]

Battery class (based on chemistry)	Battery type[1]	Manufacturer[1]	Cell weight/range[2], in grams	Average weight of cell[2], in grams	Lithium content[2], in percent	Lithium content per cell[3], in grams
Manganese-dioxide-lithium primary (alkaline type)	CR coin type	Sanyo Electric Co. Ltd.	0.8–6.9	3.2	~3	0.065
	CR coin type	Energizer Battery Manufacturing Inc.	0.7–6.9	2.4	1–6	0.051
	CR coin type	Sony Corporation	0.7–10	3.2	NA	0.096
	CR coin type	Panasonic Corp.	0.7–6.8	2.6	NA	0.078
	Button/coin type	AA Portable Power Corp.	0.7–10.5	2.8	NA	0.084
	BR cylindrical type	Sanyo Electric Co. Ltd.	3.3–38	20.7	~3	0.64
	SE cylindrical type	Sanyo Electric Co. Ltd.	9–42	21	NA	0.69
	CR cylindrical type	Energizer Battery Manufacturing Inc.	3–40	23	NA	0.73
	LM series cylindrical type 3.2 V	Saft Group SA	2.9–6	4.3	~3.3	0.142
	AAA size cylindrical type	Panasonic Corp.	11	11	NA	NA
	AAA size	U.S. average (1996)	NA	12	NA	NA
	AA size	U.S. average (1996)	NA	30	NA	NA
	AA size cylindrical type	Panasonic Corp.	23	23	NA	0.69
	C size	U.S. average (1996)	NA	70	NA	NA
	C size cylindrical type	Panasonic Corp.	70	70	NA	NA
	C size cylindrical type	Ultralife Batteries Inc.	61	61	1–4	1.52
	LM series cylindrical type C-cell	Saft Group SA	55	55	~3.3	1.81
	D size	U.S. average (1996)	NA	140	NA	NA
	D size cylindrical type	Panasonic Corp.	141	141	NA	NA
	D size cylindrical type	Ultralife Batteries Inc.	115	115	3–4	4
	LM series cylindrical type D-cell	Saft Group SA	116	116	~3.3	3.8
	9V type	Ultralife Batteries Inc.	33.8–36.4	35	1–4	0.87
	9V size	U.S. average (1996)	NA	50	NA	NA
	Prismatic type	Ultralife Batteries Inc.	3.5–15	9	5–8	0.59
	Military type	Ultralife Batteries Inc.	10–61	44	1–4	1.1
Lithium iron disulfide primary	Cylindrical type	Energizer Battery Manufacturing Inc.	34–36	35	5–8	1.35
Lithium thionyl chloride primary	LS/LST series cylindrical type	Saft Group SA	8.9–23.5	14.4	3.5–5	0.61
	LSH series cylindrical type	Saft Group SA	24–100	65	3.5–5	2.76
Lithium sulfur dioxide primary	LO/G series cylindrical type	Saft Group SA	8–300	72	<3	2.1

[1]Manufacturer was selected based on the volume of production and the availability of data. Battery selection was based on the applicability to the end-use category. Batteries selected are assumed to be representative for the given classification.

[2]Based on reported weights of cell or pack given by the manufacturer for all batteries in that classification. Data were obtained from the specified manufacturer's Web site.

[3]Calculated from (average weight of cell or pack) × (specified commodity content). When a percent range is shown, the average weight percentage was derived by averaging all batteries of similar type.

Table A–3. Selected material content assumptions and estimates for nickel-metal-hydride batteries used in this study.
[e, estimate; NA, not available]

Battery type[1]	Manufacturer[1]	Cell weight range[2], in grams	Average weight of cell or pack[2], in grams	Cobalt content from Co or $LiCo(OH)_2$[2], in percent	Cobalt content/ cell[3], in grams	Nickel content[2], in percent	Nickel content/cell or pack[3], in grams
AA size cylindrical type	Saft Group SA	25–26	25.5	0.6–3	0.56	30–45	9.4
C size cylindrical type	Saft Group SA	59	59	0.6–3	1.3	30–45	22
D size cylindrical type	Saft Group SA	160	160	0.6–3	3.5	30–45	59
D size hybrid vehicle type	Sanyo/Saft	NA	43,600	0.4–1e	300	40	17,000
D size hybrid vehicle type	Matsushita/Panasonic	NA	39,500	NA	NA	35.5	14,000
Cylindrical type battery pack	Panasonic Corp.	12– 170	51	NA	NA	NA	NA
Cylindrical type	Energizer Battery Manufacturing Inc.	NA	NA	1.5–3.6	NA	30–50	NA
Button type	AA Portable Power Corp.	1.8– 13	6.9	NA	NA	NA	NA
Prismatic type	AA Portable Power Corp.	9– 26	18	NA	NA	NA	NA
Button type	Linden, David, 1995: Handbook of Batteries, 1995, p. 33.28	NA	NA	NA	NA	NA	NA
Cylindrical type	Linden, David, 1995: Handbook of Batteries, 1995, p. 33.28	25– 52	37	NA	NA	NA	NA
Prismatic type	Linden, David, 1995: Handbook of Batteries, 1995, p. 33.28	17– 24	21	NA	NA	NA	NA
Average of all types	Rydh and Svard, 2003, Impact on global metal flows arising from the use of portable rechargeable batteries: table 3, p. 172.	NA	NA	2.5–4.3	NA	25–46	NA

[1]Manufacturer was selected based on the volume of production and the availability of data. Battery selection was based on the applicability to the end-use category. Batteries selected are assumed to be representative for the given classification.
[2]Based on reported weights of cell or pack given by the manufacturer for all batteries in that classification. Data were obtained from the specified manufacturer's Web site.
[3]Calculated from (average weight of cell or pack) × (specified commodity content). When a percent range is shown, the average weight percentage was derived by averaging all batteries of similar type.

Table A–4. Selected material content assumptions and estimates for lithium-ion and lithium-polymer batteries used in this study.
[AH, amp-hours; g, grams; NA, not available]

Battery class (based on chemistry)	Battery type[1]	Manufacturer[1]	Cell or pack weight range[2], in grams	Average weight of cell or pack[2], in grams	Cobalt content from Co or $LiCo(OH)_2$[2], in percent	Cobalt content/cell[3], in grams	Lithium content from Li or $LiCoO_2$[2], in percent	Lithium content/cell or pack[3], in grams
Lithium cobalt dioxide ion rechargeable	Theoretical equivalent lithium content	Source: Linden, 1995, p. 36.48	NA	NA	NA	NA	NA	0.3 × capacity (AH)
	Cylindrical type	Panasonic Corp.	42–46.5	44.8	NA	NA	NA	NA
	Cylindrical type	Sanyo Electric Co. Ltd.	15–21	18.6	15	2.8	1.8	0.34 g/cell
	Cylindrical type	Sanyo Electric Co. Ltd.	15–80	36.7	15	5.5	1.8	0.66 g/cell
	Cylindrical type	Ultralife Batteries Inc.	15–41	22.6	20	4.5	2.4	0.55 g/cell
	Cylindrical type	Source: Linden, 1995, p. 36.48	18–39	30	NA	NA	NA	NA
	LC cylindrical type	AA Portable Power Corp.	5.6–53	26	15–24	5.1	1.8–2.8	0.6 g/cell
	LC cylindrical type	Sanyo Electric Co. Ltd.	11.5–46	22.2	1 5– 24	4.3	1.8–2.8	0.51 g/cell
	Prismatic type	Source: Linden, 1995, p. 36.48	20–65	41.5	NA	NA	NA	NA
	Prismatic type	Panasonic Corp.	15–40	25	NA	NA	NA	NA
	Prismatic type	AA Portable Power Corp.	13.5–39.6	25	NA	NA	NA	NA
	Prismatic type	Energizer Battery Manufacturing Inc.	NA	NA	9–18	NA	1.1–2.1	NA
	MP series prismatic type	Saft Group SA	68–153 per pack	117 per pack	18	21 per pack	~2.1%	2.46 g/cell
	VLE series hybrid vehicle battery pack	Saft Group SA	8,000 per module × 5 modules	40,000 per pack	18	7,200 per pack	~2.1%	860 g/pack
Lithium-ion industrial battery pack	VLM series	Saft Group SA	770–1070 per pack	920 per pack	18	166 per pack	~2.1%	19 g/cell
	VLP series	Saft Group SA	370–1,100 per pack	760 per pack	18	137 per pack	~2.1%	16 g/cell
	Military type	Ultralife Batteries Inc.	925–1440	1146	15–24	223	1.8–2.8	26 g/cell
	Military type	Matsushita Battery Industrial Co. Ltd.	NA	NA	12–19	NA	1.4–2.5	NA
Lithium cobalt dioxide polymer rechargeable	UPF series prismatic type	Sanyo Electric Co. Ltd.	8.3–46	21.7	6–12	0.5–5.5	1.1–2.2	0.36 g/cell
	Prismatic type	Ultralife Batteries Inc.	3–85	17	1.8–2.6	0.37	15–21	3.1 g/cell
	Prismatic type	Ascent Battery Supply Corp.	NA	NA	15–18	NA	1.8–2.1	NA

[1]Manufacturer was selected based on the volume of production and the availability of data. Battery selection was based on the applicability to the end-use category. Batteries selected are assumed to be representative for the given classification.
[2]Based on reported weights of cell or pack given by the manufacturer for all batteries in that classification. Data were obtained from the specified manufacturer's Web site.
[3]Calculated from (average weight of cell or pack) × (specified commodity content). When a percent range is shown, the average weight percentage was derived by averaging all batteries of similar type.

Table A–5. Material content assumptions for selected metals and materials in batteries designated for cell phones, by year.

[Li, lithium; Li-ion, lithium-ion battery; Li-polymer, lithium-polymer battery; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 23; 2005a, p. 5; 2005b, p. 19). Values may not add to totals shown owing to rounding]

Year	Cell chemistry	Number of units	Cell mass, grams per battery	Cadmium fraction, in percent	Cobalt fraction, in percent	Lithium fraction, in percent	Nickel fraction, in percent	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
1996	NiCd	1,800,000	80	14	0.9	0	22	20,000	1,300	0	31,000
	NiMH	1,900,000	74	0	2.2	0	37	0	3,100	0	53,000
	Li-ion	1,100,000	72	0	17.6	2.3	0	0	14,000	1,800	0
	Li-polymer	0	47	0	15.9	1.7	0	0	0	0	0
1997	NiCd	2,000,000	80	14	0.9	0	22	22,000	1,400	0	34,000
	NiMH	3,300,000	74	0	2.2	0	37	0	5,300	0	89,000
	Li-ion	2,900,000	72	0	17.6	2.3	0	0	37,000	4,900	0
	Li-polymer	0	47	0	15.9	1.7	0	0	0	0	0
1998	NiCd	1,700,000	80	14	0.9	0	22	19,000	1,200	0	30,000
	NiMH	6,500,000	74	0	2.2	0	37	0	11,000	0	180,000
	Li-ion	4,800,000	72	0	17.6	2.3	0	0	61,000	8,000	0
	Li-polymer	0	47	0	15.9	1.7	0	0	0	0	0
1999	NiCd	1,600,000	80	14	0.9	0	22	18,000	1,200	0	29,000
	NiMH	15,000,000	74	0	2.2	0	37	0	24,000	0	400,000
	Li-ion	10,000,000	72	0	17.6	2.3	0	0	130,000	17,000	0
	Li-polymer	270,000	47	0	15.9	1.7	0	0	2,000	220	0
2000	NiCd	1,000,000	80	14	0.9	0	22	12,000	700	0	18,000
	NiMH	30,000,000	74	0	2.2	0	37	0	48,000	0	810,000
	Li-ion	20,000,000	72	0	17.6	2.3	0	0	260,000	33,000	0
	Li-polymer	1,000,000	47	0	15.9	1.7	0	0	7,700	830	0
2001	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	35,000,000	42	0	2.2	0	37	0	32,000	0	540,000
	Li-ion	39,000,000	48	0	17.6	2.3	0	0	330,000	43,000	0
	Li-polymer	3,100,000	42	0	15.9	1.7	0	0	21,000	2,200	0
2002	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	29,000,000	42	0	2.2	0	37	0	27,000	0	450,000
	Li-ion	52,000,000	48	0	17.6	2.3	0	0	440,000	58,000	0
	Li-polymer	6,100,000	42	0	15.9	1.7	0	0	41,000	4,400	0
2003	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	15,000,000	42	0	2.2	0	37	0	14,000	0	230,000
	Li-ion	75,000,000	48	0	17.6	2.3	0	0	630,000	83,000	0
	Li-polymer	12,000,000	42	0	15.9	1.7	0	0	83,000	8,800	0
2004	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	8,800,000	42	0	2.2	0	37	0	8,100	0	140,000
	Li-ion	120,000,000	48	0	17.6	2.3	0	0	990,000	130,000	0
	Li-polymer	20,000,000	42	0	15.9	1.7	0	0	140,000	15,000	0
2005	NiCd	0	80	14	0.9	0	22	0	0	0	0
	NiMH	7,000,000	42	0	2.2	0	37	0	6,400	0	110,000
	Li-ion	140,000,000	48	0	17.6	2.3	0	0	1,200,000	150,000	0
	Li-polymer	30,000,000	42	0	15.9	1.7	0	0	200,000	21,000	0

Table A–6. Material content assumptions for selected metals and materials in batteries designated for portable (laptop) computers, by year.

[Li-ion, lithium-ion battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 29; 2005a, p. 6). Values may not add to totals shown owing to rounding]

Year	Cell chemistry	Number of units	Cobalt mass, in grams per battery pack	Lithium mass, in grams per battery pack	Nickel mass, in grams per battery pack	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
				U.S. import data				
1996	NiMH	1,000,000	5	0	85	5,100	0	86,000
	Li-ion	830,000	46	5.2	0	36,000	4,300	0
1997	NiMH	1,200,000	5	0	85	6,300	0	110,000
	Li-ion	1,700,000	46	5.2	0	75,000	8,900	0
1998	NiMH	1,200,000	5	0	85	5,900	0	99,000
	Li-ion	2,300,000	46	5.2	0	99,000	12,000	0
1999	NiMH	1,300,000	5	0	85	6,500	0	110,000
	Li-ion	3,500,000	46	5.2	0	150,000	18,000	0
2000	NiMH	1,900,000	5	0	85	9,700	0	160,000
	Li-ion	6,400,000	46	5.2	0	280,000	33,000	0
2001	NiMH	1,900,000	5	0	85	9,800	0	160,000
	Li-ion	8,300,000	46	5.2	0	360,000	43,000	0
2002	NiMH	2,400,000	5	0	85	12,000	0	200,000
	Li-ion	13,000,000	46	5.2	0	550,000	66,000	0
2003	NiMH	1,800,000	5	0	85	8,900	0	150,000
	Li-ion	17,000,000	46	5.2	0	740,000	88,000	0
2004	NiMH	1,900,000	5	0	85	9,500	0	160,000
	Li-ion	18,000,000	46	5.2	0	790,000	94,000	0
2005	NiMH	1,900,000	5	0	85	9,600	0	160,000
	Li-ion	22,000,000	46	5.2	0	960,000	110,000	0
				U.S. export data				
1996	NiMH	230,000	5	0	85	1,100	0	19,000
	Li-ion	190,000	46	5.2	0	8,100	1,000	0
1997	NiMH	250,000	5	0	85	1,300	0	21,000
	Li-ion	350,000	46	5.2	0	15,000	1,800	0
1998	NiMH	230,000	5	0	85	1,200	0	19,000
	Li-ion	440,000	46	5.2	0	19,000	2,300	0
1999	NiMH	200,000	5	0	85	1,000	0	17,000
	Li-ion	540,000	46	5.2	0	24,000	2,800	0
2000	NiMH	230,000	5	0	85	1,200	0	19,000
	Li-ion	770,000	46	5.2	0	34,000	4,000	0
2001	NiMH	210,000	5	0	85	1,100	0	18,000
	Li-ion	910,000	46	5.2	0	40,000	4,800	0
2002	NiMH	200,000	5	0	85	1,000	0	17,000
	Li-ion	1,000,000	46	5.2	0	46,000	5,500	0
2003	NiMH	150,000	5	0	85	700	0	13,000
	Li-ion	1,400,000	46	5.2	0	61,000	7,300	0
2004	NiMH	350,000	5	0	85	1,700	0	29,000
	Li-ion	3,300,000	46	5.2	0	140,000	17,000	0
2005	NiMH	260,000	5	0	85	1,300	0	22,000
	Li-ion	3,000,000	46	5.2	0	130,000	15,000	0

Table A–6. Material content assumptions for selected metals and materials in batteries designated for portable (laptop) computers, by year.—Continued

[Li-ion, lithium-ion battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 29; 2005a, p. 6). Values may not add to totals shown owing to rounding]

Year	Cell chemistry	Number of units	Cobalt mass, in grams per battery pack	Lithium mass, in grams per battery pack	Nickel mass, in grams per battery pack	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
Net import data								
1996	NiMH	770,000	5	0	85	4,000	0	67,000
	Li-ion	640,000	46	5.2	0	28,000	3,300	0
1997	NiMH	990,000	5	0	85	5,000	0	84,000
	Li-ion	1,400,000	46	5.2	0	60,000	7,100	0
1998	NiMH	940,000	5	0	85	4,700	0	79,000
	Li-ion	1,800,000	46	5.2	0	79,000	9,500	0
1999	NiMH	1,100,000	5	0	85	5,500	0	92,000
	Li-ion	2,900,000	46	5.2	0	130,000	15,000	0
2000	NiMH	1,700,000	5	0	85	8,500	0	140,000
	Li-ion	5,600,000	46	5.2	0	250,000	29,000	0
2001	NiMH	1,700,000	5	0	85	8,700	0	150,000
	Li-ion	7,400,000	46	5.2	0	320,000	38,000	0
2002	NiMH	2,200,000	5	0	85	11,000	0	190,000
	Li-ion	12,000,000	46	5.2	0	510,000	60,000	0
2003	NiMH	1,600,000	5	0	85	8,200	0	140,000
	Li-ion	15,000,000	46	5.2	0	680,000	81,000	0
2004	NiMH	1,500,000	5	0	85	7,800	0	130,000
	Li-ion	15,000,000	46	5.2	0	640,000	77,000	0
2005	NiMH	1,600,000	5	0	85	8,300	0	140,000
	Li-ion	19,000,000	46	5.2	0	830,000	99,000	0

Table A–7. Material content assumptions for selected metals and materials in batteries designated for cameras, by year.

[Li-ion, lithium-ion battery; NA, not available; XX, not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery; Primary Li, primary lithium battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30; 2005a, p. 7). Number of units reflects the number of net camera imports to the United States. Net export situations are represented by a 0 value. Domestic camera battery production is assumed negligible. Values may not add to totals shown owing to rounding]

Year	Cell chemistry/ product type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
1996	NiCd	61,000	19	0.5	0	29	1,200	31	XX	1,800
	Analog	61,000	19	NA	0	29	1,200	NA	XX	1,800
	Digital	0	0	NA	0	0	0	NA	XX	0
	NiMH	0	0	NA	0	NA	XX	0	XX	0
	Analog	0	0	1.1	0	19	XX	0	XX	0
	Digital	0	0	0.3	0	5.2	XX	0	XX	0
	Li-ion	0	0	NA	NA	0	XX	0	0	XX
	Analog	0	0	9	1.1	0	XX	0	0	XX
	Digital	0	0	2.4	0.72	0	XX	0	0	XX
	Primary Li	550,000	0	0	1.3	0	XX	0	110	XX
	Analog	550,000	0	0	1.3	0	XX	0	110	XX
	Digital	0	0	0	1.3	0	XX	0	0	XX
1997	NiCd	58,000	19	0.5	0	29	1,100	29	XX	1,700
	Analog	32,000	19	NA	0	29	620	NA	XX	950
	Digital	26,000	0	NA	0	0	480	NA	XX	750
	NiMH	58,000	0	NA	0	NA	XX	41	XX	700
	Analog	32,000	0	1.1	0	19	XX	NA	XX	580
	Digital	26,000	0	0.3	0	5.2	XX	NA	XX	120
	Li-ion	58,000	0	NA	NA	0	XX	330	54	XX
	Analog	32,000	0	9	1.1	0	XX	NA	36	XX
	Digital	26,000	0	2.4	0.72	0	XX	NA	18	XX
	Primary Li	990,000	0	0	1.3	0	XX	0	220	XX
	Analog	550,000	0	0	1.3	0	XX	0	120	XX
	Digital	440,000	0	0	1.3	0	XX	0	100	XX
1998	NiCd	100,000	19	0.5	0	29	2,000	52	XX	3,000
	Analog	28,000	19	NA	0	29	530	NA	XX	820
	Digital	75,000	0	NA	0	0	1,400	NA	XX	2,200
	NiMH	160,000	0	NA	0	NA	XX	76	XX	1,300
	Analog	45,000	0	1.1	0	19	XX	NA	XX	740
	Digital	120,000	0	0.3	0	5.2	XX	NA	XX	530
	Li-ion	210,000	0	NA	NA	0	XX	750	170	XX
	Analog	56,000	0	9	1.1	0	XX	NA	50	XX
	Digital	150,000	0	2.4	0.72	0	XX	NA	120	XX
	Primary Li	1,600,000	0	0	1.3	0	XX	0	370	XX
	Analog	430,000	0	0	1.3	0	XX	0	100	XX
	Digital	1,200,000	0	0	1.3	0	XX	0	270	XX
1999	NiCd	120,000	19	0.5	0	29	2,300	61	XX	3,500
	Analog	25,000	19	NA	0	29	480	NA	XX	730
	Digital	95,000	0	NA	0	0	1,800	NA	XX	2,700
	NiMH	600,000	0	NA	0	NA	XX	270	XX	4,600
	Analog	130,000	0	1.1	0	19	XX	NA	XX	1,000
	Digital	470,000	0	0.3	0	5.2	XX	NA	XX	3,600
	Li-ion	720,000	0	NA	NA	0	XX	2,600	580	XX
	Analog	150,000	0	9	1.1	0	XX	NA	120	XX
	Digital	570,000	0	2.4	0.72	0	XX	NA	460	XX
	Primary Li	4,500,000	0	0	1.3	0	XX	0	1,100	XX
	Analog	950,000	0	0	1.3	0	XX	0	230	XX
	Digital	3,600,000	0	0	1.3	0	XX	0	870	XX

Table A–7. Material content assumptions for selected metals and materials in batteries designated for cameras, by year.—Continued

[Li-ion, lithium-ion battery; NA, not available; XX, not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery; Primary Li, primary lithium battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30; 2005a, p. 7). Number of units reflects the number of net camera imports to the United States. Net export situations are represented by a 0 value. Domestic camera battery production is assumed negligible. Values may not add to totals shown owing to rounding]

Year	Cell chemistry/ product type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
2000	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	1,800,000	0	NA	0	NA	XX	740	XX	12,000
	Analog	250,000	0	1.1	0	19	XX	NA	XX	4,600
	Digital	1,600,000	0	0.3	0	5.2	XX	NA	XX	7,800
	Li-ion	2,400,000	0	NA	NA	0	XX	7,900	1,800	XX
	Analog	340,000	0	9	1.1	0	XX	NA	250	XX
	Digital	2,100,000	0	2.4	0.72	0	XX	NA	1,500	XX
	Primary Li	7,900,000	0	0	1.3	0	XX	0	2,200	XX
	Analog	1,100,000	0	0	1.3	0	XX	0	310	XX
	Digital	6,800,000	0	0	1.3	0	XX	0	1,900	XX
2001	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	1,500,000	0	NA	0	NA	XX	580	XX	9,700
	Analog	150,000	0	1.1	0	19	XX	NA	XX	2,800
	Digital	1,400,000	0	0.3	0	5.2	XX	NA	XX	6,900
	Li-ion	3,100,000	0	NA	NA	0	XX	9,200	2,300	XX
	Analog	310,000	0	9	1.1	0	XX	NA	230	XX
	Digital	2,800,000	0	2.4	0.72	0	XX	NA	2,100	XX
	Primary Li	5,700,000	0	0	1.3	0	XX	0	1,600	XX
	Analog	570,000	0	0	1.3	0	XX	0	160	XX
	Digital	5,100,000	0	0	1.3	0	XX	0	1,500	XX
2002	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	2,100,000	0	NA	0	NA	XX	690	XX	12,000
	Analog	100,000	0	1.1	0	19	XX	NA	XX	1,800
	Digital	1,900,000	0	0.3	0	5.2	XX	NA	XX	9,700
	Li-ion	5,500,000	0	NA	NA	0	XX	15,000	4,100	XX
	Analog	280,000	0	9	1.1	0	XX	NA	200	XX
	Digital	5,200,000	0	2.4	0.72	0	XX	NA	3,900	XX
	Primary Li	8,200,000	0	0	1.3	0	XX	0	2,400	XX
	Analog	410,000	0	0	1.3	0	XX	0	120	XX
	Digital	7,800,000	0	0	1.3	0	XX	0	2,300	XX
2003	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	2,200,000	0	NA	0	NA	XX	780	XX	13,000
	Analog	130,000	0	1.1	0	19	XX	NA	XX	900
	Digital	2,100,000	0	0.3	0	5.2	XX	NA	XX	12,000
	Li-ion	11,000,000	0	NA	NA	0	XX	30,000	8,000	XX
	Analog	640,000	0	9	1.1	0	XX	NA	480	XX
	Digital	10,000,000	0	2.4	0.72	0	XX	NA	7,500	XX
	Primary Li	12,000,000	0	0	1.3	0	XX	0	3,800	XX
	Analog	720,000	0	0	1.3	0	XX	0	230	XX
	Digital	11,000,000	0	0	1.3	0	XX	0	3,600	XX

Table A–7. Material content assumptions for selected metals and materials in batteries designated for cameras, by year.—Continued

[Li-ion, lithium-ion battery; NA, not available; XX, not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery; Primary Li, primary lithium battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30; 2005a, p. 7). Number of units reflects the number of net camera imports to the United States. Net export situations are represented by a 0 value. Domestic camera battery production is assumed negligible. Values may not add to totals shown owing to rounding]

Year	Cell chemistry/ product type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
2004	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	2,400,000	0	NA	0	NA	XX	780	XX	13,000
	Analog	100,000	0	1.1	0	19	XX	NA	XX	1,900
	Digital	2,300,000	0	0.3	0	5.2	XX	NA	XX	11,000
	Li-ion	14,000,000	0	NA	NA	0	XX	36,000	11,000	XX
	Analog	560,000	0	9	1.1	0	XX	NA	720	XX
	Digital	13,000,000	0	2.4	0.72	0	XX	NA	10,000	XX
	Primary Li	14,000,000	0	0	1.3	0	XX	0	3,900	XX
	Analog	540,000	0	0	1.3	0	XX	0	160	XX
	Digital	13,000,000	0	0	1.3	0	XX	0	3,700	XX
2005	NiCd	0	19	0.5	0	29	0	0	XX	0
	Analog	0	19	NA	0	29	0	0	XX	0
	Digital	0	0	NA	0	0	0	0	XX	0
	NiMH	1,800,000	0	NA	0	NA	XX	600	XX	10,000
	Analog	83,000	0	1.1	0	19	XX	NA	XX	1,500
	Digital	1,800,000	0	0.3	0	5.2	XX	NA	XX	9,500
	Li-ion	19,000,000	0	NA	NA	0	XX	49,000	14,000	XX
	Analog	840,000	0	9	1.1	0	XX	NA	570	XX
	Digital	18,000,000	0	2.4	0.72	0	XX	NA	13,000	XX
	Primary Li	16,000,000	0	0	1.3	0	XX	0	5,400	XX
	Analog	730,000	0	0	1.3	0	XX	0	260	XX
	Digital	15,000,000	0	0	1.3	0	XX	0	5,100	XX

Table A–8. Material content assumptions for selected metals and materials in batteries designated for video cameras (camcorders), by year.

[Li-ion, lithium-ion battery; NA, Not available; XX, Not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30). Values may not add to totals shown owing to rounding]

Year	Cell type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
1996	NiCd	3,700,000	22	1.4	0	35	82,000	5,100	XX	130,000
	Analog	1,800,000	22	1.4	0	35	41,000	2,600	XX	64,000
	Digital	1,900,000	22	1.4	0	35	41,000	2,600	XX	65,000
	NiMH	18,000	0	3.4	0	NA	XX	62	XX	1,000
	Analog	18,000	0	3.4	0	57	XX	62	XX	1,000
	Li-ion	0	0	NA	NA	0	XX	0	0	XX
	Analog	0	0	27	3.3	0	XX	0	0	XX
	Digital	0	0	7.3	2.2	0	XX	0	0	XX
1997	NiCd	2,800,000	22	1.4	0	35	68,000	3,900	XX	98,000
	Analog	1,800,000	22	1.4	0	35	40,000	2,500	XX	63,000
	Digital	990,000	22	1.4	0	35	28,000	1,400	XX	35,000
	NiMH	36,000	0	3.4	0	NA	XX	120	XX	2,100
	Analog	36,000	0	3.4	0	19	XX	120	XX	2,100
	Li-ion	690,000	0	NA	NA	0	XX	5,000	1,500	XX
	Analog	0	0	27	3.3	0	XX	0	0	XX
	Digital	690,000	0	7.3	2.2	0	XX	5,000	1,500	XX
1998	NiCd	2,000,000	22	1.4	0	35	45,000	2,800	XX	71,000
	Analog	1,700,000	22	1.4	0	35	37,000	2,300	XX	58,000
	Digital	350,000	22	1.4	0	35	7,800	500	XX	12,000
	NiMH	54,000	0	3.4	0	NA	XX	180	XX	3,000
	Analog	54,000	0	3.4	0	19	XX	180	XX	3,000
	Li-ion	1,800,000	0	NA	NA	0	XX	14,000	3,900	XX
	Analog	71,000	0	27	3.3	0	XX	1,900	240	XX
	Digital	1,700,000	0	7.3	2.2	0	XX	12,000	3,700	XX
1999	NiCd	1,800,000	22	1.4	0	35	38,000	2,400	XX	60,000
	Analog	1,600,000	22	1.4	0	35	35,000	2,200	XX	56,000
	Digital	140,000	22	1.4	0	35	3,100	190	XX	4,800
	NiMH	80,000	0	3.4	0	NA	XX	280	XX	4,800
	Analog	80,000	0	3.4	0	19	XX	280	XX	4,800
	Li-ion	3,000,000	0	NA	NA	0	XX	31,000	7,100	XX
	Analog	440,000	0	27	3.3	0	XX	12,000	1,500	XX
	Digital	2,600,000	0	7.3	2.2	0	XX	19,000	5,600	XX
2000	NiCd	1,800,000	22	1.4	0	35	41,000	2,500	XX	64,000
	Analog	1,700,000	22	1.4	0	35	37,000	2,300	XX	58,000
	Digital	160,000	22	1.4	0	35	3,500	220	XX	5,500
	NiMH	120,000	0	3.4	0	NA	XX	420	XX	7,000
	Analog	120,000	0	3.4	0	19	XX	420	XX	7,000
	Li-ion	3,700,000	0	NA	NA	0	XX	40,000	8,700	XX
	Analog	690,000	0	27	3.3	0	XX	19,000	2,300	XX
	Digital	3,000,000	0	7.3	2.2	0	XX	22,000	6,400	XX
2001	NiCd	1,800,000	22	1.4	0	35	40,000	2,500	XX	63,000
	Analog	1,700,000	22	1.4	0	35	37,000	2,300	XX	59,000
	Digital	140,000	22	1.4	0	35	3,000	190	XX	4,800
	NiMH	160,000	0	3.4	0	NA	XX	520	XX	8,800
	Analog	160,000	0	3.4	0	19	XX	520	XX	8,800
	Li-ion	3,400,000	0	NA	NA	0	XX	40,000	8,100	XX
	Analog	780,000	0	27	3.3	0	XX	21,000	2,600	XX
	Digital	2,600,000	0	7.3	2.2	0	XX	19,000	5,500	XX
2002	NiCd	1,800,000	22	1.4	0	35	41,000	2,600	XX	65,000
	Analog	1,700,000	22	1.4	0	35	39,000	2,400	XX	60,000
	Digital	130,000	22	1.4	0	35	2,000	190	XX	4,700
	NiMH	170,000	0	3.4	0	NA	XX	570	XX	9,600
	Analog	170,000	0	3.4	0	19	XX	570	XX	9,600
	Li-ion	4,200,000	0	NA	NA	0	XX	49,000	10,000	XX
	Analog	970,000	0	27	3.3	0	XX	26,000	3,200	XX
	Digital	3,200,000	0	7.3	2.2	0	XX	23,000	6,900	XX

Table A–8. Material content assumptions for selected metals and materials in batteries designated for video cameras (camcorders), by year.—Continued

[Li-ion, lithium-ion battery; NA, Not available; XX, Not applicable; NiCd, nickel-cadmium battery; NiMH, nickel-metal-hydride battery. Estimates were derived from U.S. International Trade Commission data and material distribution data provided by Pillot (2004, p. 27, 30). Values may not add to totals shown owing to rounding]

Year	Cell type	Number of units	Cadmium mass, in grams per pack	Cobalt mass, in grams per pack	Lithium mass, in grams per pack	Nickel mass, in grams per pack	Cadmium mass, in kilograms	Cobalt mass, in kilograms	Lithium mass, in kilograms	Nickel mass, in kilograms
2003	NiCd	1,200,000	22	1.4	0	35	26,000	1,600	XX	41,000
	Analog	1,100,000	22	1.4	0	35	25,000	1,500	XX	39,000
	Digital	81,000	22	1.4	0	35	1,800	110	XX	2,000
	NiMH	120,000	0	3.4	0	NA	XX	400	XX	6,800
	Analog	120,000	0	3.4	0	19	XX	400	XX	6,800
	Li-ion	4,800,000	0	NA	NA	0	XX	50,000	11,000	XX
	Analog	810,000	0	27	3.3	0	XX	22,000	2,700	XX
	Digital	4,000,000	0	7.3	2.2	0	XX	28,000	8,600	XX
2004	NiCd	690	22	1.4	0	35	15,000	930	XX	24,000
	Analog	650,000	22	1.4	0	35	14,000	870	XX	23,000
	Digital	44,000	22	1.4	0	35	1,000	61	XX	1,500
	NiMH	78,000	0	3.4	0	NA	XX	250	XX	4,200
	Analog	78,000	0	3.4	0	19	XX	250	XX	4,200
	Li-ion	4,900,000	0	NA	NA	0	XX	46,000	11,000	XX
	Analog	570,000	0	27	3.3	0	XX	15,000	1,900	XX
	Digital	4,300,000	0	7.3	2.2	0	XX	31,000	9,400	XX
2005	NiCd	320,000	22	1.4	0	35	6,900	430	XX	11,000
	Analog	320,000	22	1.4	0	35	6,900	430	XX	11,000
	Digital	0	22	1.4	0	35	0	0	XX	0
	NiMH	44,000	0	3.4	0	NA	XX	140	XX	2,400
	Analog	44,000	0	3.4	0	19	XX	140	XX	2,400
	Li-ion	5,600,000	0	NA	NA	0	XX	46,000	12,000	XX
	Analog	360,000	0	27	3.3	0	XX	9,000	1,200	XX
	Digital	5,200,000	0	7.3	2.2	0	XX	37,000	11,000	XX

Table A–9. Material content assumptions for selected metals and materials in batteries designated for hybrid vehicles, by year.

[Co, cobalt; HEV, hybrid-electric vehicle; kg, kilograms; Li-ion, lithium-ion battery; NA, not available; Ni, nickel; NiMH, nickel-metal-hydride battery; %, percent]

Manufacturer	2005 market share, in percent	Cell mass, in grams per cell	Number of cells	Battery mass, in kilograms	Nickel fraction, in percent
Matsushita/Panasonic	92	173	228	39.5	35.5
Sanyo Electric Co. Ltd.	8	178	245	43.6	40

2. Calculation: 0.92 × [39.5 kg/battery × 35.5% Ni] + 0.08 × [43.6 kg/battery × 40% Ni] = 14 kg Ni
0.92 × [39.5 kg/battery × 0% Co] + 0.08 × [43.6 kg/battery × 0.7% Co] = 24 g Co

Li-ion type battery

Manufacturer	Market share, in percent	Cell mass, in grams per module	Number of modules	Battery mass, in kilograms	Lithium fraction, in percent
Saft/Johnson Controls	0	8,000	5	40	2.15

3. Calculation: 40 kg/battery × 2.15% Li = 0.86 kg Li; 40 kg/battery × 18% Co = 7.2 kg Co

4. Hybrid vehicle sales and sales projections from selected sources

Data source	Units × 1,000	2002	2003	2004	2005	2006	2007	2008	2009	2010
NREL/Avicenne (2006)[1]	World sales	NA	NA	NA	200	300	900	1,200	1,700	2,050
	% Li-ion	NA	NA	NA	0	0	1	2	3	4
Johnson Controls (2006)[2]	World sales	NA	100	150	200	340	510	780	1,100	1,600
TTI. Inc. (2006)[3]	World sales	NA	NA	NA	NA	NA	NA	NA	NA	3,000
Advanced Automotive (2006)[4]	World sales	NA	NA	NA	NA	400	NA	NA	1,000	NA
Avicenne (2005)[5]	World sales	NA	NA	160	320	550	860	1,220	1,650	2,100
	% Li-ion	NA	NA	NA	0	0	0	2	3	5
	U.S. HEV sales	61	81	166	190	240	370	500	650	800
Caltrans/UC Davis (2004)[6]	U.S. HEV sales	NA	NA	NA	200	300	400	500-700	750-1,000	1,200-1,500
U.S. Department of Transportation[7]	U.S. HEV sales	25	49	92	190	310	300	480	490	550

5. Summary estimates used in this study

		2002	2003	2004	2005	2006	2007	2008	2009	2010
U.S. HEV sales		25	49	92	190	310	300	480	490	550
NiMH percent of U.S. HEV sales		100	100	100	100	100	100	98	97	95
Li-ion percent of U.S. HEV sales		0	0	0	0	0	0	2	3	5
NiMH units x 1000		25	49	92	190	310	300	470	470	520
Li-ion units x 1000		0	0	0	0	0	0	10	20	30
Metric tons of contained cobalt		1	1	2	5	7	7	80	120	210
Metric tons of contained nickel		350	690	1,300	2,700	4,300	4,200	6,600	6,700	7,300
Metric tons of contained lithium		0	0	0	0	0	0	8	13	24

[1]Pesaran (2006). [2]Fredonia Group Inc. (2006). [3]Paumanok Publications Inc. (2006). [4]Advanced Automotice Batteries (2006). [5]Madani (2005).
[6]Cao and Mokhtarian (2004). [7]U.S. Department of Transportation (2006).

Table A–10. Harmonized Tariff Schedule (HTS) classes applied to selected end uses of nickel-cadmium batteries for this study.

Battery class (based on end use)	HTS numbers applied to this battery classification	Years classification was used	Trade source (import or export)
Storage batteries, separate:			
Electrically-powered vehicle batteries	8507304000	1996-2005	Import
Sealed consumer batteries	8507308010	1996-2005	Import
	8507300050	1996	Export
	8507300000	1997-2005	Export
Industrial batteries	8507308090	1996-2005	Import
Batteries enclosed in products:			
Power tools	8508100010	1996-2001	Import/Export
	8467210010	2002-2005	Import/Export
Cordless phones	8517110000	1996-2005	Import/Export
Camcorders	8525408020	1997-2005	Import/Export
	8525400020	1996-1997	Import
	8525408050	1997-2005	Import/Export
	8525400050	1996-1997	Import
Cameras	8525400000	1996-1998	Export
	8525400090	1996-1997	Import
	8525404000	1997-1999	Import/Export
	8525408085	1997-1999	Import/Export
Portable radios	8527120000	1996-2005	Import/Export
Shavers	8510100000	1996-2005	Import/Export
Electric toothbrushes	8509800045	1996-2005	Import
Portable vacuum cleaners	8509100020	1996-2005	Import/Export
Flashlights	8513102000	1996-2005	Import
Portable electric lamps (bicycle lamps, for example)	8513104000	1996-2005	Import
	8513100000	1996-2005	Export
Watch batteries, reported separately	9101110000	1996-2005	Export
Clock batteries, reported separately	9103100000	1996-2005	Export
	9103102020	1996-2005	Import
	9103102040	1996-2005	Import
	9103104030	1996-2005	Import
	9103104060	1996-2005	Import
	9103108030	1996-2005	Import
	9103108060	1996-2005	Import
	9105114030	1996-2005	Import
	9105114050	1996-2005	Import
	9105108040	1996-2005	Import
	9105118070	1996-2005	Import
	9105214030	1996-2005	Import
	9105218050	1996-2005	Import
	9105914030	1996-2005	Import
	9105918050	1996-2005	Import
	9106905520	1996-2005	Import
	9109111030	1996-2005	Import
	9109112030	1996-2005	Import
	9109114030	1996-2005	Import
	9109116030	1996-2005	Import
	9109191030	1996-2005	Import
	9109192030	1996-2005	Import
	9109194030	1996-2005	Import
	9109196030	1996-2005	Import
Military batteries, reported separately	9104000000	1996-2005	Export
	9104000520	1996-2005	Import
	9104001020	1996-2005	Import
	9104002520	1996-2005	Import
	9104003020	1996-2005	Import
	9104004520	1996-2005	Import
	9104005030	1996-2005	Import

Table A–11. Harmonized Tariff Schedule of the United States (HTS) classes applied to selected end uses of lithium-ion and nickel-metal-hydride batteries for this study.

General battery class[1]	Specific battery class (based on end use)[1]	HTS number applied to this battery class	Years HTS class used	Trade source (import or export)
Lithium batteries, separate	Primary batteries, lithium	8506500000	1996–2005	Import and export
Lithium storage batteries, separate	Rechargeable storage batteries used as the primary source of electrical power for electrically-powered vehicles of subheading 8703.90	8507804000	1996–2005	Import
Lithium storage batteries, separate (rechargeable)	Other storage batteries, not otherwise specified or indicated (NESOI)	8507800000	1996–2005	Export
Do.	Other storage batteries, NESOI	8507808000	1996–2005	Import
Enclosed in electrically-powered vehicles	Passenger motor vehicles, NESOI	8703900000	1996–2005	Import and export
Enclosed in cell phones	Radio telephones designed for the public cellular radio telecommunication service, weighing 1 kilogram (kg) or under	8525209070	1996–2005	Import and export
Enclosed in portable computers	Portable digital ADP machine weighing not more than 10 kg, consisting of at least a CPU, keyboard, and display unit	8471300000	1996–2005	Import and export
Enclosed in video cameras (camcorders)	Camcorders, 8 millimeter (mm), analog	8525408020	1996–2005	Import and export
Do.	Camcorders, color, 8 mm, analog	8525400020	1996–1997	Import
Do.	Camcorders, other than 8 mm, digital	8525408050	1997–2005	Import and export
Do.	Camcorders, color, other than 8 mm, digital	8525400050	1996–1997	Import
Enclosed in digital cameras	Still image video cameras	8525400090	1996–1997	Import
Do.	Still image video cameras and other video camera recorders	8525400000	1996–1998	Export
Do.	Digital still image video cameras	8525404000	1997–2005	Import and export
Do.	Still image video cameras, NESOI	8525408085	1997–2005	Import and export
Clock batteries, reported separately	Batteries for travel clocks, battery powered with opto-electronic display, excluding subheading 9104	9103102020	1996–2005	Import
Do.	Clocks with watch movements, electrically operated, excluding subheading 9104	9103100000	1996–2005	Export
Do.	Batteries for clocks, except travel clocks, battery powered, with opto-electronic display, excluding subheading 9104	9103102040	1996–2005	Import
Do.	Batteries for clocks, battery powered, having no jewels or only one jewel in the movement, excluding subheading 9104	9103104030	1996–2005	Import
Do.	Batteries for clocks, except travel clocks, battery powered, having no jewels or only one jewel in the movement, excluding subheading 9104	9103104060	1996–2005	Import
Do.	Batteries for travel clocks, battery powered, NESOI	9103108030	1996–2005	Import
Do.	Batteries for clocks, except travel clocks, battery powered, NESOI	9103108060	1996–2005	Import
Do.	Batteries for travel alarm clocks, battery powered, with opto-electronic display	9105114030	1996–2005	Import
Do.	Alarm clocks, battery powered	9105100000	1996–2005	Export
Do.	Batteries for alarm clocks, except travel, battery powered with opto-electronic display	9105114050	1996–2005	Import
Do.	Batteries for travel alarm clocks, with opto-electronic display	9105118040	1996–2005	Import
Do.	Batteries for alarm clocks, except travel, battery powered, with opto-electronic display	9105118070	1996–2005	Import
Do.	Batteries for wall clocks, battery powered, with opto-electronic display	9105214030	1996–2005	Import
Do.	Wall clocks, battery powered	9105210000	1996–2005	Export
Do.	Batteries for wall clocks, battery powered, with opto-electronic display	9105218050	1996–2005	Import
Do.	Batteries for other clocks, battery powered, with opto-electronic display only	9105914030	1996–2005	Import

Table A–11. Harmonized Tariff Schedule of the United States (HTS) classes applied to selected end uses of lithium-ion and nickel-metal-hydride batteries for this study.—Continued

General battery class[1]	Specific battery class (based on end use)[1]	HTS number applied to this battery class	Years HTS class used	Trade source (import or export)
Clock batteries, reported separately (continued)	Other clocks, battery powered	9105910000	1996–2005	Export
Do.	Batteries for other clocks, battery powered, except opto-electronic display	9105918050	1996–2005	Import
Do.	Batteries for device with opto-electronic display for measuring, recording time, battery powered	9106905520	1996–2005	Import
Do.	Other time of day device, NESOI	9106900000	1996–2005	Export
Do.	Batteries for clock movements of alarm clocks, complete and assembled, battery powered, with opto-electronic display only	9109111030	1996–2005	Import
Do.	Clock movements of alarm clocks, complete and assembled, battery powered	9109110000	1996–2005	Export
Do.	Batteries for clock movements of alarm clocks, complete and assembled, battery powered, measuring not over 50 mm in width or diameter	9109112030	1996–2005	Import
Do.	Batteries for clock movements of alarm clocks, complete and assembled, battery powered, measuring over 50 mm in width or diameter, value not over $5 each	9109114030	1996–2005	Import
Do.	Batteries for clock movements of alarm clocks, complete and assembled, battery powered, measuring over 50 mm in width or diameter, valued over $5 each	9109116030	1996–2005	Import
Do.	Batteries for clock movements, complete and assembled, except for alarm clocks, battery powered, with opto-electronic display only	9109191030	1996–2005	Import
Do.	Clock movements, complete and assembled, electronically powered, except for alarm clocks, NESOI	9109190000	1996–2005	Export
Do.	Batteries for clock movements, complete and assembled, except for alarm clocks, battery powered, measuring not over 50 mm in width or diameter	9109192030	1996–2005	Import
Do.	Batteries for clock movements, complete and assembled, except for alarm clocks, battery powered, measuring over 50 mm in width or diameter, valued not over $5 each	9109194030	1996–2005	Import
Do.	Batteries for clock movements, complete and assembled, except for alarm clocks, battery powered, measuring over 50 mm in width or diameter, valued over $5 each	9109196030	1996–2005	Import
Batteries for military application, reported separately	Batteries for instrument panel clocks, with clock movements measuring over 50 mm in width or diameter, valued not over $10, with opto-electronic display only	9104000520	1996–2005	Import
Do.	Batteries for military application, reported separately	9104000000	1996–2005	Export
Do.	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, measuring over 50 mm in width or diameter, valued not over $10, including battery	9104001020	1996–2005	Import
Do.	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, or vessel, measuring over 50 mm in width or diameter, valued over $10, with opto-electronic display	9104002520	1996	Import
Do.	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, or vessel, measuring over 50 mm in width or diameter, valued over $10, electric including battery	9104003020	1996–2005	Import

Table A–11. Harmonized Tariff Schedule of the United States (HTS) classes applied to selected end uses of lithium-ion and nickel-metal-hydride batteries for this study.—Continued

General battery class[1]	Specific battery class (based on end use)[1]	HTS number applied to this battery class	Years HTS class used	Trade source (import or export)
Watch batteries, reported separately	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, or vessel, with opto-electronic display, NESOI	9104004520	1996–2005	Import
Do.	Batteries for instrument panel clocks and similar for vehicles, aircraft, spacecraft, or vessel, measuring over 50 mm in width or diameter, valued over $10, electric including battery, NESOI	9104005030	1996–2005	Export
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, with mechanical display only, having no jewels or only one jewel	9101114040	1996–2005	Import
Do.	Wrist watches, cases of precious metal and mechanical display	9101110000	1996–2005	Export
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, mechanical display only, with more than one jewel	9101118040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, having no jewels or only one jewel, NESOI	9101194040	1996–2005	Import
Do.	Wrist watches, with cases of precious metal, NESOI	9101190000	1996–2005	Export
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, having more than one jewel, NESOI	9101198040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having no jewels or one jewel, with band of base metal with gold/silver case	9102111040	1996–2005	Import
Do.	Wrist watches, battery powered, mechanical display only, with cases of base metal	9102110000	1996–2005	Export
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having no jewels or one jewel, with band of textile or with base metal case	9102112540	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having no jewels or one jewel, with gold/silver-plated case	9102113040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with base metal case	9102114540	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with band of textile or base metal, gold/silver-plated case	9102115040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with band of textile or base metal, base metal case	9102116540	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with gold/silver-plated case	9102117040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with mechanical display only, having more than one jewel, with base metal case, NESOI	9102119540	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with other display, having no jewels or one jewel, with band of textile or base metal	9102192040	1996–2005	Import
Do.	Wrist watches, battery powered, other display, cases of base metal	9102190000	1996–2005	Export

Table A–11. Harmonized Tariff Schedule of the United States (HTS) classes applied to selected end uses of lithium-ion and nickel-metal-hydride batteries for this study.—Continued

General battery class[1]	Specific battery class (based on end use)[1]	HTS number applied to this battery class	Years HTS class used	Trade source (import or export)
Watch batteries, reported separately (continued)	Batteries for wrist watches, battery powered, with other display, having no jewels or one jewel, NESOI	9102194040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with other display, having more than one jewel, with band of textile or base metal	9102196040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with other display, having more than one jewel, NESOI	9102198040	1996–2005	Import
Do.	Batteries for wrist watches, battery powered, with cases of precious metal, having no jewels or one jewel	9101914030	1996–2005	Import
Do.	Other watches, with cases of precious metal, battery powered, except wrist watches	9101910000	1996–2005	Export
Do.	Batteries for other watches, battery powered, with cases of precious metal, NESOI	9101918030	1996–2005	Import
Do.	Batteries for other watches, battery powered, with base metal case, with opto-electronic display only	9102912020	1996–2005	Import
Do.	Other watches, with cases of base metal, battery powered, except wrist watches	9102910000	1996–2005	Export
Do.	Batteries for other watches, battery powered, having no jewels or one jewel	9102914030	1996–2005	Import
Do.	Batteries for other watches, battery powered, with base metal case, NESOI	9102918030	1996–2005	Import

[1]General and specific battery classification descriptions as reported by the U.S. International Trade Commission, modified where necessary for consistency.

Wilburn—**Material Use inthe United States—Selected Case Studies for Cd, Co, Li, and Ni in Rechargeable Batteries**—SIR 2008–5141