# Rechargeable Battery Management and Recycling: A Green Design Educational Module

**Rebecca Lankey and Francis McMichael**

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## Abstract

Rechargeable battery use is expected to continue growing with the increasing prevalence of portable electronics, appliances, and tools. Batteries represent a large volume of toxic and hazardous materials in common use, and these materials must be managed to avoid or minimize dissipation into the environment. One type of battery widely used in portable applications is nickel-cadmium batteries (NiCds).

This module introduces rechargeable battery characteristics and use, focusing on nickel-cadmium batteries. The definition of a green battery is developed. To determine the total environmental impact of a battery system, all stages of battery life must be considered. In this module life cycle emissions and energy use are estimated for NiCd batteries. Current battery collection and recycling practices are briefly explained, and an expression for estimating NiCd recycling rate is given. Public policy and consumer education concerning batteries is considered.

## 1. Introduction

The use of toxic materials has long been a concern, and dissipative uses of toxic materials, where human and environmental health may be affected, are especially significant. In many areas of materials use, toxic materials have been regulated and decreased, and substitute materials have often replaced toxic materials where possible. The battery industry represents one important and growing sector where the use of non-toxic and non-hazardous substitute materials has not rapidly developed. As regulations increase and concern for the environment and human health becomes more prevalent, the fate of toxic and hazardous materials in the environment should be more carefully considered. In the environment the dissipation of toxic metals can harm fish, wildlife, and invertebrates through exposure by inhalation or ingestion of airborne contaminants, or by accumulation of toxins from ground and surface water [NY DEC 92]. Currently, batteries represent a large volume of toxic and hazardous materials in common use, and these materials must be managed throughout their life cycle to avoid harm to the environment and human health.

The use of rechargeable consumer batteries is expected to continue growing with the increasing prevalence of laptop computers, telecommunications equipment, cordless tools, and other portable electronic devices. The many industrial applications of batteries include emergency backup power for hospitals, airplanes, and subway cars. People are willing to pay for the convenience of portability, so the use of secondary batteries is expected to continue increasing. Indeed, we are beginning to expect these conveniences as a normal part of our daily routines.

The fate of rechargeable batteries is an important and timely issue, primarily because of the toxic and hazardous materials that are used. The design, manufacture, recycling, and disposal of batteries all necessitate some form of hazardous waste management. Hazardous wastes may be more of a problem in one stage of the life cycle than others, and more than one hazardous waste may be produced in a given stage. While the management of lead-acid batteries is well-established, that of NiCd batteries and more recently applied technologies such as nickel-metal hydride or lithium-based batteries are still in the formative stages.

## 2. Battery Use

Battery consumption in the United States has been increasing rapidly over the past decade as portable applications become increasingly accessible and affordable. Jacoby [98] reported that in 1997 battery manufacturers produced 1.5 billion NiCd batteries, 500 million NiMH batteries, and almost 200 million Li-ion batteries. Table 1 gives battery performance characteristics for several currently used and emerging battery systems. Data for alkaline dry cell batteries are given as a comparison.

**Table 1** Some battery performance characteristics

| **Cell type** | **Nominal voltage, V** | **Specific energy, Wh/kg** | **Energy density, Wh/L** | **Specific power, W/kg** | **Power density, W/L** | **Self-discharge %/month** | **Estimated cycle life** |
|---|---|---|---|---|---|---|---|
| Alkaline | 1.5 | 150 | 375 | 14 | 35 | 0.3 | 1 |
| PbA | 2.0 | 25[a], 35 | 70, 80[a], 85[b] | ~200 | ~400 | 4-8, 5-10[b] | 200[a], 250-300 |
| NiCd | 1.2 | 40[a], 40-60, 45[b] | 60-100, 90[a], 150[b] | 140-220 | 220-360 | 10-20, 25[b] | 300-2000[c], 1000[a] |
| NiMH | 1.2 | 50[a], 55[b], 60, 55-70[d], 80[e] | 175[a], 180[b], 220, 260[e] | 130 | 475 | 20-25[b], 30 | 300-600, 600[a] |
| Li-ion | 3.6 | 90[a], 100[b], 115 | 200[a], 225[b], 260 | 200-250 | 400-500 | 5-10, 8[b] | 500-1000, 1200[a] |
| Li-polymer | 3.0 | 100-200, 140[b] | 150-350, 300[b] | >200 | >350 | ~1, 1-2[b] | 200-1000 |
| Na-NiCl[f] |  | 100 | 160 | 150 | 250 |  | 1000 |
| Zinc-air | 1.2 | 146, 155-175[g] | 204 | 150 | 190 | ~5 | ~200 |

a. [Ehrlich et al. 97]
b. [Dan 96]
c. [Cornu 95]
d. [Brown and Klein 97]
e. [Ovshinsky et al. 97]
f. “Zebra” batteries, data are from [Sudworth 94]
g. [Crompton 96]

A 1995 estimate of total batteries purchased in the U.S. varied from one to three pounds per person annually, and 1995 sales statistics showed that NiCd batteries comprised 10% of the total batteries sold [Meador 95]. This gives between 245 and 735 million pounds of battery solid waste were expected to be discarded annually by the U.S. population [Meador 95]. By the year 2000 the annual demand for batteries is predicted to exceed $17 billion. The estimated number of NiCd batteries sold for the years 1985 though 1992 are given in Table 2. The Portable Rechargeable Battery Association (PRBA) estimates that the number of NiCds sold in the US will grow at a rate of 5% each year through 2001. The growth rate for industrial NiCds is expected to be 2% to 4% each year, independent of the market for electric vehicles [Morrow and Cook 95].

**Table 2** Estimated number of NiCd Units Sold in the U.S.

| Year | $10^6$ units sold[a] | % increase from previous year | U.S. estimated population (1000s)[b] | Per capita consumption |
|---|---|---|---|---|
| 1985 | 189 | --- | 238,466 | 0.79 |
| 1986 | 205 | 8.47 | 240,651 | 0.85 |
| 1987 | 221 | 7.80 | 242,804 | 0.91 |
| 1988 | 239 | 8.14 | 245,021 | 0.98 |
| 1989 | 259 | 8.37 | 247,342 | 1.0 |
| 1990 | 280 | 8.11 | 249,949 | 1.1 |
| 1991 | 302 | 7.86 | 252,636 | 1.2 |
| 1992 | 326 | 7.95 | 255,382 | 1.3 |

a. [NY DEC 92]
b. Data from the 1998 U.S. Statistical Abstract [Stats 98].

## 3. Green Battery

The definition of what constitutes an environmentally friendly (“green”) battery is a matter of ongoing discussion and development. Possible methods of classification include establishing quantitative and qualitative metrics by which a battery can be determined to be green or not. The environmental, ecological, and health concerns that result from the use of toxic materials encourage the development of metrics by which we can determine the environmental impact of the use of a particular battery. These qualitative and quantitative metrics can be used to evaluate the life cycle of a battery.

A secondary (rechargeable) battery is considered to be more environmentally friendly than a primary (non-rechargeable) battery because the primary battery is thrown away after only one use. This results in a significant amount of waste materials generated and energy used to manufacture the number of alkaline batteries that would be equivalent to one rechargeable battery over the course of its useful life. In addition, alkaline batteries are typically not collected and recycled, resulting in the use of more virgin materials. For these reasons primary batteries are not considered to be environmentally friendly.

The New York State Battery Task Force defines the “ideal battery” as one which has no toxic components, never needs to be discarded or is easily and economically recycled, can be safely handled, and has superior performance characteristics for the particular application [NY DEC 92]. A basic comprehensive question regarding a battery technology might be whether or not we would be completely comfortable with putting the battery into municipal solid waste [Barnett and Wolsky 90].

A list of environmental metrics by which battery systems can be compared is given in Table 3. Three categories of metrics are given, rechargeability, materials and energy use, and battery characteristics. The second column gives the environmental metric, and the third column gives the desirable characteristic to be exhibited in a green battery.

**Table 3** Environmental metrics for battery systems

| Category | Green Metric | Desirable Feature |
|---|---|---|
| Rechargeability | Primary (non-rechargeable) vs. secondary (rechargeable) | Rechargeable |
| Materials and energy use | Amount of toxic materials used per unit energy (mg/Wh) | Less use of toxic materials |
| | Amount of hazardous or reactive materials used per unit energy (mg/Wh) | Less use of hazardous or reactive materials |
| | Demands on renewable and non-renewable resources for materials extraction and battery manufacturing | Decreased demand on renewable and non-renewable resources |
| | Energy use and associated emissions over the battery life cycle | Lower energy use and emissions |
| Recycling | Open-loop vs. closed-loop recycling processes | Closed-loop or equivalent open-loop process |
| | Economically recyclable vs. technically feasible recycling [Putois 95] | Economically feasible recycling |
| | Collection system in place for spent batteries | Nation-wide collection program |
| Battery characteristics | Number of usable life cycles before battery is spent | High number of recharges |
| | Mechanical and electrical durability of battery | Better mechanical and electrical durability |

A formulaic way to quantitatively compare environmental metrics is desirable. An example of a quantitative metric is the calculation of the mass of heavy metal used per unit energy for a battery type. A potential calculation for the amount of toxic and hazardous materials used per unit energy is demonstrated in Table 4 for specific cell models. In this calculation the amount metal used per Wh = M/(W*S), where M is the mass of the specified metal, W is the total cell weight, and S is the specific energy. The metal contents and specific energies used in the calculations are specified in the table footnotes.

**Table 4** Metal per unit Wh

| Battery system | Metal | Cell type | Cell weight (g) | Metal weight (g) | (mg metal)/Wh |
|---|---|---|---|---|---|
| PbA (SLA) | lead | D | 180[a] | 126[b] | 20,000[c] |
| Li-ion | lithium | cylindrical, 65 mm x 18.3 mm | 42 | 1.26[d] | 227[g] |
| Li-ion | cobalt | cylindrical, 65 mm x 18.3 mm[e] | 42 | 7.56[f] | 1360[g] |
| NiCd | cadmium | sub C (standard) | 50 | 7.5 - 12.5[h] | 3000 - 5000[i] |
| NiCd | nickel | sub C (standard) | 50 | 10 - 12.5[j] | 4000 - 5000[i] |
| NiMH | nickel | AA, 50.3 mm x 14.0 mm[k] | 24[k] | 5.76[l] | 4000[m] |

a. [Hammel 84]
b. Assuming a lead content of 70% by weight
c. Using a specific energy of 35 Wh/kg
d. Assuming a lithium content of 3 percent by weight
e. Data from Moli Energy at [http://www.molienergy.bc.ca/icr18650.htm]
f. Assuming a cobalt content of 18 percent by weight
g. Using a specific energy of 132 Wh/kg from Moli Energy at [http://www.molienergy.bc.ca/icr18650.htm]
h. Using a cadmium content between 15 - 25% by weight
i. Using a specific energy of 50 Wh/kg
j. Using a nickel content between 20 - 25% by weight
k. Data from Harding Energy at [http://www.harding energy.com/cylindrical cells.html]
l. Using a nickel content of 24% by weight
m. Using a specific energy of 60 Wh/kg

As shown above, lithium-ion batteries use much less lithium or cobalt metal per unit energy than other battery types. NiCd and NiMH batteries use approximately the same amount of nickel per unit energy, while PbA batteries use about five times this mass in lead per unit energy. For this one metric of metal use per unit energy, lithium-ion batteries appear to be the most environmentally friendly. However, for a complete analysis of this metric, the emissions and energy use associated with the acquisition of the raw materials for each battery type must be considered in conjunction with the above calculation.

It is important to note that the greenness of a battery does not depend solely on what materials are used in the battery, but also on how well the battery is managed throughout its life. In fact, battery system characteristics such as emissions, energy use, and waste generation considered over the entire life of the battery are potentially more damaging to the environment than the hazardous nature of the metals used.

Another issue associated with environmentally-friendly batteries is whether or not a non-hazardous battery can or will be developed. Currently there is no battery technology that can be considered absolutely environmentally friendly, nor does this appear likely in the near-term future. Instead, battery systems may be considered more or less environmentally friendly as compared to other systems. However, such an analysis must take into account all of the metrics listed in Table 3. It is not appropriate to make a judgment based on just one of these metrics. In addition, the performance of a battery type in a specific application must also be considered. For example, if one battery type does not last as long as another battery type in a specific application, the environmental effects of this more frequently needed replacement must be considered.

## 4. Life Cycle Emissions and Energy

Three primary goals of waste management are to decrease the use of non-renewable resources, decrease the use of renewable resources to sustainable levels, and to decrease the use of toxic materials [Conway and Lave 96]. One goal of battery waste management is to determine if the amount of hazardous wastes can be decreased. We would like to know how to manage toxic materials with the least environmental impact. We would also like to determine if substitutes can be found for the materials used in batteries, or if the toxic materials used can be recycled and controlled later. Studying the issues associated with batteries in each stage of a battery's life provides a more complete picture of the flow of materials end energy used throughout the total life of the product.

Life Cycle Assessment is an emerging tool in the area of green design and environmental engineering through which material flows can be studied. For nickel-cadmium batteries, the flows of cadmium and nickel can be traced through each stage of life. Extraction and processing of primary materials are significant sources of waste production and energy use.

During the life cycles stages of NiCd batteries, cadmium and nickel emissions are a concern. The primary stages in which such emissions are likely to occur are raw materials acquisition, battery manufacturing, and battery recycling. The estimated emissions per kilogram of NiCd batteries manufactured or recycled during these stages are given in Table 5. Data on cadmium emissions are more readily available in the literature than on nickel emissions. The emissions of nickel in the battery manufacturing and recycling stages is a topic for further study.

**Table 5** Cadmium and Nickel Emissions per kg of NiCd Batteries

| Life Cycle Stage | g Cd emitted/ kg of NiCd batteries | g Ni emitted/ kg of NiCd batteries |
|---|---|---|
| Raw materials acquisition | 1.2[a] | 2.25[b] |
| Battery manufacturing | 0.4 | 0.5[c] |
| Battery recycling | 0.01 | 0.0125[c] |

a. Sum of estimated emissions from mining and refining based on data in the literature.
b. Includes mining and refining, based on data in the literature.
c. No emission factors are available in the literature for nickel; the calculations were made using cadmium emission factors from the literature.

During the use and collection phases indirect emissions of materials other than nickel and cadmium can be attributed to batteries. In the use phase, the electricity used to recharge batteries will have some associated emissions. In the collection phase, typically emissions will be associated with the transportation required to move batteries from the place of use to the recycling facility. Collection and recycling programs in the United States have been encouraged by the Portable Rechargeable Battery Association and the Rechargeable Battery Recycling Corporation and by the passage of the 1996 "Mercury-Containing and Rechargeable Battery Management Act."

A summary of the energy use in the various stages of life for a NiCd battery as estimated in [Lankey 98] are shown in Figure 1. According to INMETCO, the energy required to process stainless steel waste materials into usable raw materials is less than half of the energy required to produce those materials in primary production. This statement is in agreement with the life cycle energy demands for NiCd batteries, which are comprised of about 15-20% steel by weight. However, as can be seen, the largest energy demand is during the use phase.

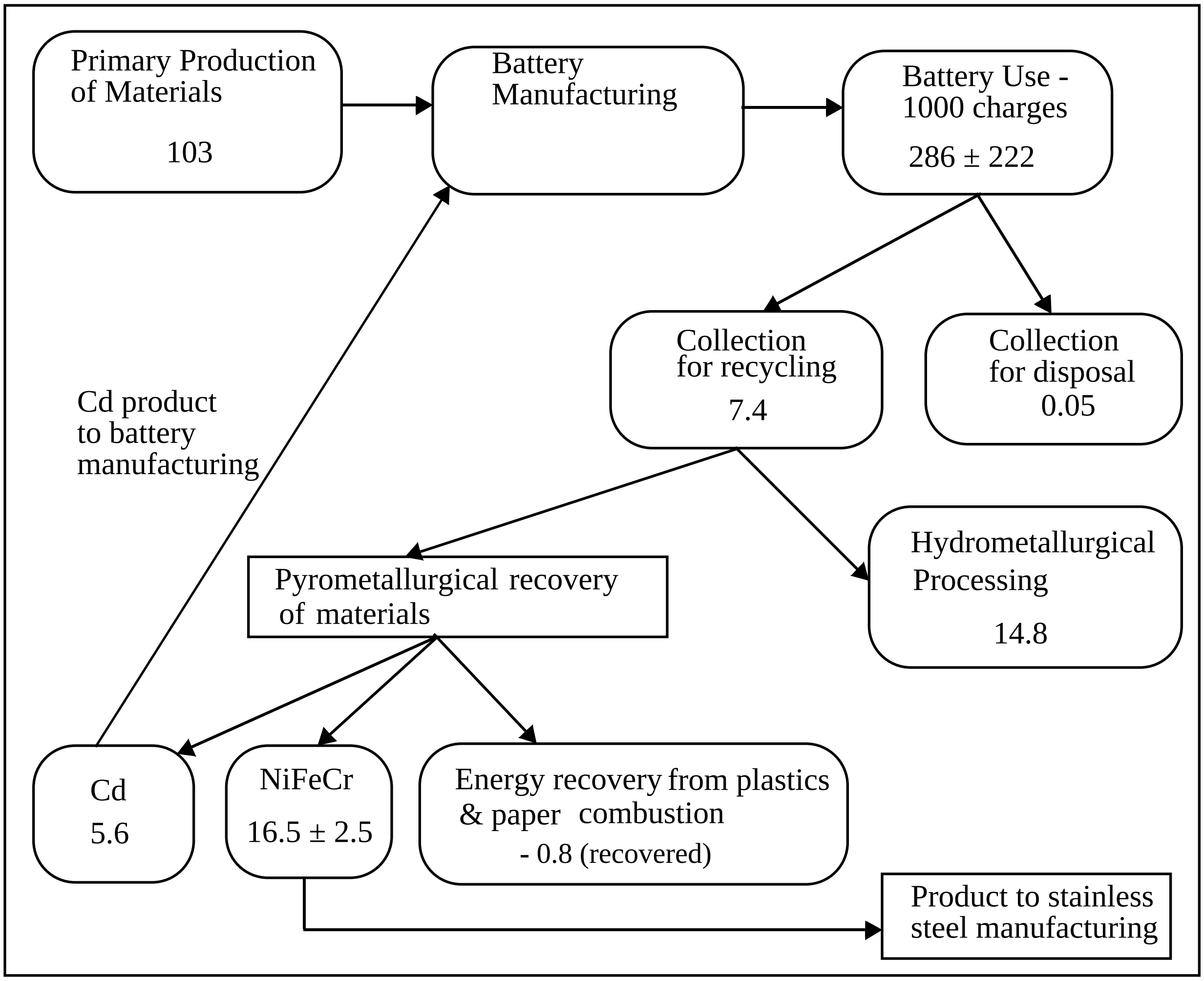

**Figure 1** Life cycle energy summary for NiCd batteries given in MJ per kg of NiCd batteries.

Considering the energy for primary production of materials, the energy used to recover materials from spent batteries, transportation energy for recycling, and energy recovery from the combustion of the plastics and paper used in spent batteries, less energy is consumed when NiCd batteries are recycled and the recovered materials are used in the production of new batteries, instead of manufacturing batteries from primary materials only. The energy use during the manufacturing stage is not known, although the energy use in the manufacturing and use phases is expected to remain constant.

## 5. NiCd Collection and Recycling

Spent batteries will need some kind of collection system whether or not the batteries are recycled. If spent consumer batteries are not recycled, then they are expected to be primarily collected along with municipal household wastes. For consumer batteries to be recycled, special collection programs must be implemented. To encourage the return of batteries by consumers, possible options include deposit systems, return incentive fees, buy-back of batteries, and rebate or mail-back programs [NY DEC 92]. The Portable Rechargeable Battery Association (PRBA) and the

Rechargeable Battery Recycling Corporation (RBRC) are involved in organizing collection programs and recycling opportunities in the United States.

The PRBA was established in June 1991 by the world's five leading manufacturers of NiCd batteries, Sanyo Energy, Panasonic, Gates Energy, Saft, and Varta Batteries [Mossbarger 93]. The PRBA was formed as a trade association to address the challenges of collecting and recycling NiCd batteries and to provide a forum through which to lobby and educate legislators and public officials [Mossbarger 93]. By October 1993 the PRBA had established pilot collection programs in Minnesota, Vermont, and New Jersey [Mossbarger 93].

The RBRC was incorporated in March 1994. The RBRC was formed to protect industry members participating in the battery collection programs from Superfund liabilities [Mossbarger 93]. As of January 1995 there were over 125 members, comprised of manufacturers, distributors, assemblers, users, suppliers and retailers of rechargeable batteries and rechargeable consumer products [England 95a]. The primary mission of the RBRC is to operate a cost-effective and safe national collection and recycling program [Thompson 95]. The RBRC provides for battery collection under four programs, the retail program, the county and municipality program, the commercial and institutional generator program, and the licensee rebate program [Thompson 95]. These programs are funded through the sale of a licensed RBRC seal [Thompson 95], which can currently be found on the packaging for many consumer electronics. As of November 1995, 160 companies were licensees of the RBRC seal. Typical fees on NiCd batteries are about 10 cents for a battery used in portable computer, four to 12 cents for a battery used in a portable tool, and five cents for a battery to be used in a cellular phone [Fishbein 97]. The RBRC estimated its 1996 collection and recycling costs for NiCd batteries to be about $5.5 million, or about 1% of NiCd sales that year [McMichael and Hendrickson 98].

The NiCd batteries collected in the program are recycled at INMETCO in Ellwood City, PA. According to INMETCO, the volume of batteries shipped to INMETCO increased by 69% in the fourth quarter of 1996 as compared to the previous quarter due to the efforts of the RBRC [Marley 97]. In December 1995 INMETCO's $5 million cadmium recovery facility began operation. Instead of having the cadmium recovered as part of the waste products, INMETCO recovers the cadmium in a form that can be sold to battery manufacturers.

To process industrial batteries, the tops are first sawed off to remove and collect the alkaline electrolyte, usually potassium hydroxide. This electrolyte then replaces slaked lime in controlling pH in INMETCO's on-site wastewater treatment plant. The positive and negative plates are separated by hand from their plastic or steel cases. The positive (nickel) plates and the stainless steel cases are shredded and fed into the rotary hearth furnace (RHF) and then smelted in INMETCO's submerged electric arc furnace (EAF), where they join the process to recycle stainless steel waste and are added to the stainless steel remelt alloy [Hanewald et al. 97]. The negative, cadmium-containing plates are rinsed and dried to remove trace amounts of electrolyte.

A charge of cadmium plates and preprocessed consumer cells are put into the furnace along with carbon at a temperature of 850 °C and heated in a low-oxygen atmosphere for 12 to 48 hours. Carbon is added to reduce the metal oxides to their metallic state. The cadmium is distilled, and the vapor is routed to a receiver. The cadmium is condensed into metal shot which can then be sold or reheated and cast into other shapes. The resulting cadmium product has a purity greater than or equal to 99.95%. This cadmium can be returned and resold to NiCd manufacturers for use in new nickel-cadmium batteries [Hanewald et al. 97]. The material remaining after the cadmium vapor has been distilled off is transferred to the EAF. Off-gases from this distillation step are processed through a baghouse.

Consumer NiCd batteries are first processed in a natural-gas powered thermal oxidation step along with the plastic cases from industrial batteries to vaporize the paper, plastic, and electrolyte gel used in the cells. The thermal oxidizer is physically connected to the RHF, allowing the thermal oxidizer fumes to be completely combusted at 1250 °C. The consumer cells are then processed along with the cadmium plates from as the industrial batteries as described above. The battery residual is shredded and fed to the EAF [Hanewald et al. 97]. A battery processing flow sheet for both the consumer and industrial batteries is given in Figure 2.

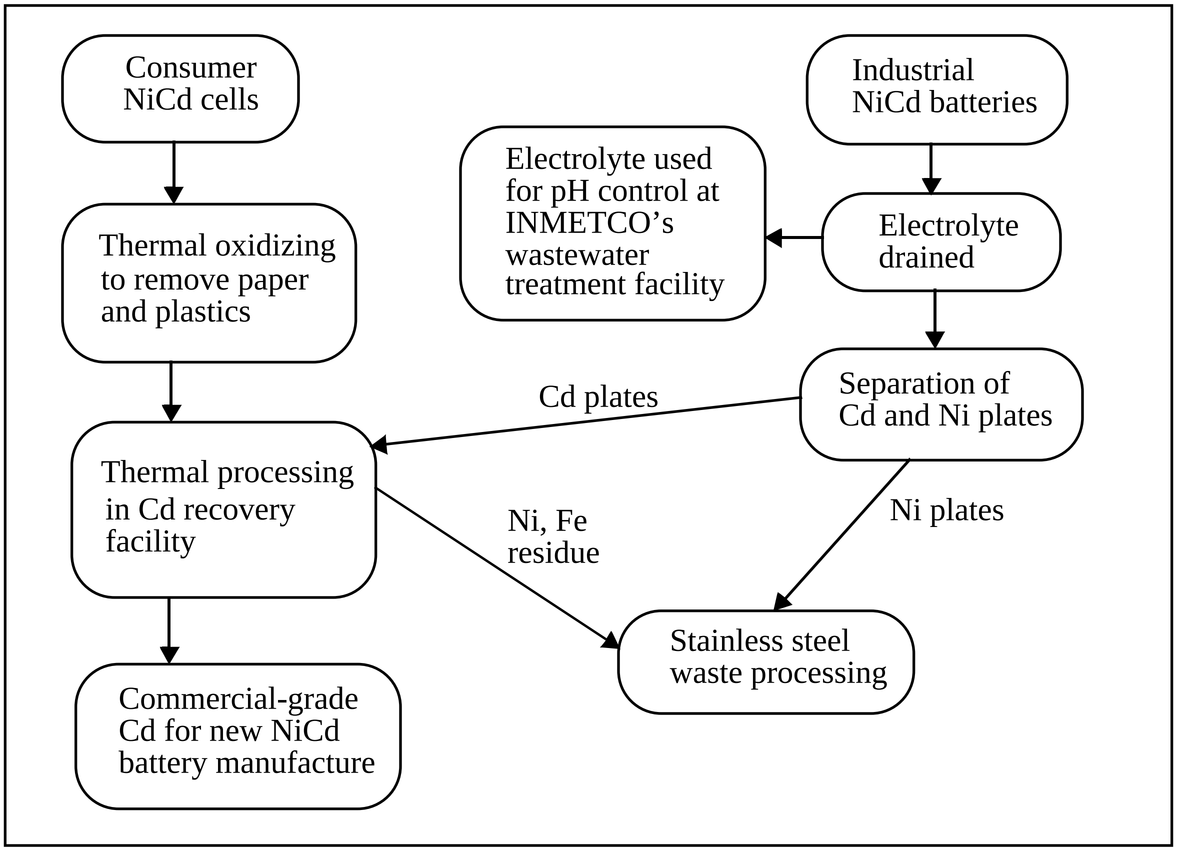

**Figure 2** Flow diagram for battery processing with cadmium recovery facility [Hanewald et al. 95a]

The rate of product collection at end of life is important to the success of any recycling program. Of interest for NiCd batteries is the rate at which they are being recycled. The data that would be required or useful to define and calculate an accurate NiCd recycling rate for the United States include:

- Industry data on the number of consumer batteries and industrial batteries sold each year
- Battery imports or exports for those years
- Average weight and composition of consumer and industrial batteries
- Number and/or amount (mt) of both consumer and industrial batteries sent to INMETCO in a given year
- Source of batteries, ex. industry, Apple, Compaq, Motorola, or individual generators would be useful
- Expected life time of consumer and industrial batteries

A crude estimation of the NiCd recycling rate can be made by dividing the amount of batteries recycled in a given year by the number of batteries sold in a previous year. A usable life for the batteries must be chosen. The recycling rate RR for NiCd batteries could be given as

$$RR = \frac{R}{S}$$

where R is the amount of batteries recycled in a given year, and S is the amount of batteries sold in a previous year, chosen to reflect the life of the batteries.

A possible calculation of the recycling rate of consumer NiCd batteries is as follows. If 12,000 tons of consumer NiCd batteries were sold in 1992 [NY DEC 92], these batteries may have an average life time of two years. These batteries would then be available for recycling in 1994. In 1994 INMETCO recycled approximately 2300 tons (2088 mt) of NiCd batteries, which can probably be considered a maximum amount. No information is given on the breakdown between industrial and consumer cells processed in 1996, so this number must be estimated. Assuming that 20% by weight of the batteries recycled were consumer cells, this would give 460 tons of consumer cells processed in 1994. In this example, S is 12,000 tons and R is 460 tons, giving a 1994 recycling rate for consumer batteries of only about 4%. This result is not surprising, considering that between 1992 and 1996 consumer NiCd batteries were typically not actively collected. Most of these batteries were likely put into the household municipal solid waste stream.

## 6. Public Policy and Consumer Education

Within the past decade, battery initiatives and regulations have gone from being virtually nonexistent to being national law for certain battery types in the United States. As concern increases over the hazardous characteristics of the materials used in batteries, other current and developmental battery types can expect similar attention in the next decade. Various factors have influenced the development of regulatory initiatives regarding batteries, such as increasing public focus on recycling and resource conservation, the rise in green consumerism, changes in how batteries are viewed by RCRA, and increasing concern about the environmental and health effects of the materials used in batteries [Smith 95].

According to the “Mercury-Containing and Rechargeable Battery Management Act” (Public Law 104-142), the collection, storage and transportation of spent NiCd batteries is now nationally regulated under EPA’s “Universal Waste Rule,” (UWR) as published in the Federal Register on May 11, 1995 (60 CFR 25492). Thus, in all states, persons collecting, storing and transporting spent NiCd batteries are subject to the hazardous waste handling requirements of the UWR [RBRC 98]. State requirements for labeling and easy removal of NiCd batteries have been replaced by the federal requirements contained in the “Mercury-Containing and Rechargeable Battery Management Act,” but other state requirements remain in effect [RBRC 98].

In the United States legislative initiatives have been primarily directed towards collecting and recycling lead-acid, nickel-cadmium, and mercury-containing batteries. While this is an encouraging step, the collection of other battery types for which recycling is possible is currently not being promoted. Unfortunately, it cannot be expected that consumers will pay attention to the type of their battery. A more likely scenario is that all battery types will be disposed of or that mixed battery types will be recycled where only NiCd batteries are expected.

A crucial step in battery collection programs will be consumer participation, since most likely consumers will not be held accountable if they throw batteries in the trash. Consumers will be less likely to recycle batteries as the process becomes more time-consuming. If a consumer can recycle all battery types without having to sort them at home, the battery collection program will be more successful. Battery types can be sorted at the point of collection. Consumer participation in sorting seems more likely after the consumer has arrived at the point of collection, as opposed to having to do the sorting at home. However, since consumers may make mistakes or be careless, responsible parties at the collection site may need to verify sorting.

In addition to increasing the ease of consumer recycling, the dispersion of toxic and hazardous materials to the environment will be decreased if other battery types are collected in addition to NiCds. All batteries use toxic and hazardous materials, but currently only NiCd and PbA batteries are regulated. Nickel-metal hydride batteries are not necessarily an “environmentally-friendly” alternative to NiCd batteries. Nickel is less toxic than cadmium, but it is a more toxic material than lead. If consumers think that NiMH batteries are environmentally safe and if the recycling of these batteries is not required or encourages, consumers will be more likely to throw them in the trash. In addition, lithium-based batteries are potentially reactive and are not always safe as advertised.

Within Europe the banning of the use of cadmium below a certain small percentage is being considered. If this law were to go into effect, currently used NiCd batteries may not be able to be used. Currently, NiCd batteries fill niche markets which other batteries do not seem to fill as well. If these other batteries types were to be forced into markets currently held by NiCd batteries, such as power tools, this may not lead to any real environmental benefit. If batteries such as NiMH do not perform as well as NiCd batteries in an application such as power tools, then the NiMH batteries may need to be replaced more often than the NiCd batteries would require. In addition, the use of cadmium should not be banned at least until the collection and recycling of the alternative battery types is legislated, and preferably not until recycling facilities of sufficient capacities are processing NiMH and Li-ion batteries. However, a restriction on cadmium use does not seem to be the most appropriate measure.

To recycle batteries at levels using sound collection programs, education of the public must be increased. Knowing that batteries can be recycled and knowing that collection points are accessible may not be enough to motivate people to recycle. Increasing public awareness that batteries contain toxic and hazardous materials and providing more information about the goals of avoiding dissipation of these materials may help to change the disposal habits of more people.

Consumer education is enhanced through public services such as being able to call a toll-free number to find out where batteries can be recycled. Portable electronics which use NiCd batteries include information in the instructions about what to do with the battery at the end of its life. However, a system of public education needs to ensure that every consumer of rechargeable batteries understands the regulations for proper disposal of batteries.

Currently, only NiCd batteries are actively collected in the United States. This is primarily due to the attention that has been paid to the toxic effects of cadmium on humans. However, collecting only NiCd batteries may give the public the erroneous impression that other battery types can be safely disposed of in household waste, or that there is no need to collect these batteries. As previously discussed, nickel is a toxic, carcinogenic material. Exposure to nickel and nickel compounds in the forms found inside batteries must be avoided. NiMH batteries should be collected and recycled like NiCd batteries to avoid the dissipation of nickel into the environment. Nickel and nickel compounds can be recycled in either a closed-loop or open-loop process. It is misleading to market NiMH batteries as an “environmentally-friendly” alternative to NiCd batteries while providing no options other than unmonitored disposal. Without better information, consumers are more likely to throw them in the trash instead of making an effort to recycle them. Lithium, while not considered a carcinogen, is a potentially hazardous material. Simply disposing of lithium batteries in household waste leads to increased demand and production of primary lithium, with all the wastes, emissions, and energy loss associated with primary metal production.

## 7. Conclusions

Product management and determination of life-cycle environmental impacts are essential for commonly-used consumer goods which contain toxic and hazardous materials. For rechargeable batteries, consumption is increasing each year. Currently, no substitutes are available for the metals used in batteries. The development of quantitative and qualitative metrics for the environmental impact of a battery system can help to determine how green a specific battery type may be.

For NiCd batteries, emissions and waste generation are most significant in the raw materials acquisition stage of life. Considering energy use, after battery recharging, the raw materials acquisition stage uses the most energy. Over the life cycle of a battery emissions and energy use are greater in the initial stage of production than in the phases after the useful life of the battery.

One measure of success of product management and recycling initiatives is the calculation of a recycling rate. Battery organizations have implemented various programs to improve NiCd collection and increase consumer education. 1996 U.S. legislation mandated the easy removal and labeling of NiCd batteries, but consumers must be motivated to recycle household NiCd batteries instead of throwing them away. Currently only NiCd and lead-acid batteries are regulated. However, if other battery types for which recycling is available are also collected, waste generation, energy use, and the dissipation of toxic and hazardous materials to the environment can be decreased.

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## Student Assignments

**1.** Based on trends in the data given by the PRBA and the U.S. Statistical Abstract, estimate the per capita consumption of NiCd batteries for 2000.

**2.** Assume that alkaline batteries have an energy demand similar to NiCd batteries for the life cycle stages of raw materials acquisition and collection for disposal. Calculate the total energy demand for the amount of alkaline batteries equivalent to a kilogram of NiCd batteries that can be recharged 1000 times.

**3.** Estimate a life cycle energy demand for NiCd battery manufacturing.

**4.** Discuss ways in which the energy demand during the use phase of batteries could be decreased. For one of your methods, quantitatively estimate the reduction in energy use that could be achieved.

**5.** Formulate an equation for a complete recycling rate for NiCd batteries, taking into account the desired battery data discussed in the module.

**6.** List at least three ways in which battery recycling in the U.S. could be increased. For one of these options, fully discuss the pros and cons of your suggestion, how it would be implemented, and the expected time to implementation and compliance.

**7.** Investigate the state of NiCd recycling at your local drop-of center (most Radio Shacks and some local businesses), which can be located using the PRBA web site. Determine: (a) if a collection box is easily visible and labeled for the customer and (b) the level of store worker knowledge, e.g. what type of battery is being collected, where the battery is sent next, etc. Report your findings and the location of your chosen store.

**8.** You have been hired to help a company, concerned with the environment, that wants to decide whether to buy alkaline AA batteries or rechargeable batteries. Your goal is to help the company to decide which of two batteries is more environmentally friendly. You must recommend one battery type and justify your decisions. Use the information given and Economic Input-Output Life-Cycle Assessment (EIO-LCA) software (see

[Cobas-Flores et al. 96, Hendrickson et al. 98], a version of the software is available on the web at http://www.eiolca.net) to make your decision and answer the questions below.

Data: The company needs to buy batteries for 1,000,000 devices for the year 2000. Each device requires 8 AA batteries. The cost of an (AA) alkaline battery is $0.89, and the price of a (AA) rechargeable battery is about $3.50. Assume that each rechargeable battery can be recharged 700 times and that each battery lasts 1 month. A battery charger costs $28 (4 battery capacity). The price of 1 kWh is $0.04. For an AA battery use the following data:

- Weight: 24 grams
- Average charge rate: 60 mA
- Charge tim:e 16 - 20 hours
- Average energy used in one battery charge: 0.648 MJ/kg

Problem Definition:

1. Explain the assumptions you made to define the problem.
2. Briefly discuss the LCA stages considered in your analysis.
3. Describe the unit of analysis (mass, piece, assembly, area) used to solve the problem. Include any numerical computations used to determine the analysis unit.
4. List the economical sectors that you chose to solve the problem. Explain why you made those selections.
5. Describe any computations you made to obtain the inputs into the final demand vector (the final demand vector is the group of values that you give to the EIO-LCA as inputs).

Data Analysis:

1. Which battery type did you select?
2. Why was this type selected? Which parameters were most important to you in making your decision?
3. Present the numerical data obtained from the EIO-LCA computation that support your decision.