At a plant for recycling batteries, employes remove cardboard dividers [below] as spent batteries are dumped onto a conveyor; molten lead is poured into ingots called "pigs" and "hogs" [right]; and an employe guides placement of recycled lead hogs [bottom, right].

PHOTOS: GNB TECHNOLOGIES INC.

environment

Recycling batteries

With little profit to be reaped from recycling, regulations must step in to save the environment from the toxic effects of used small batteries

Portable" electricity has become a part of daily living. Batteries literally empower many kinds of portable electric and electronic devices, such as telephones, computers, radios, compact disks, tape recorders, cordless tools, and even electric cars [Table 1]. But at end-of-life they can come back to haunt us.

Batteries in general may be classified as either primary—lasting for a single life cycle—or secondary, in which case they are rechargeable and may last for thousands of cycles. From an environmental viewpoint, a secondary battery is preferable to the primary kind; in mass of materials alone, a single rechargeable cell may be functionally equivalent to dozens of primary cells. Even so, secondary batteries lose out to primary batteries for consumer cells, where the life-cycle cost is not the customer 's prime concern.

Worldwide, hundreds of millions of large batteries and billions of small ones, containing tons of toxic and hazardous metals, are produced and used up each year. Until recently, most of them were simply discarded. Even today, only automotive-sized lead-acid and industrial nickel-cadmium types are systematically collected for the sake of recycling their materials.

Consumers' batteries are much smaller and have for the most part ended up with other discarded products in municipal solid waste. When the waste went to a landfill, water leached the nickel, cadmium, and mercury from the broken batteries, and high concentrations of the metals showed up in the leachates collected from the landfill base. When the waste went to incinerators, the batteries contributed high levels of metal fumes to the stack emissions and ash, so that the cost of environmental control went up, too. Used batteries accounted for nearly 1.5 million metric tons of municipal solid waste in 1994. (From here on, the term ton will stand for metric ton, or 0.907 of a short ton.) This quantity was less than 1 percent of the total municipal solid waste generated, yet accounted for nearly two-thirds of the lead, 90 percent of the mercury, and over half of the cadmium found in that waste. In the United States, regulations in most states mandate removal of lead-acid batteries from municipal solid-waste incinerators and landfills, requiring the items to be recycled or else disposed of in landfills intended for hazardous waste. In many other countries, regulations require either the return and recycling or the safe disposal of used batteries.

The concern stems from the toxic nature of many battery materials. Toxicity limits are set for workers han-

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dling the materials, and drinking water and ambient air standards are set for everyone. For example, a worker's maximum allowable inhalation of the substances is measured in milligrams per cubic meter during an 8-hour period. For nickel, it is 1 mg/m^3; for lead, it is 0.15 mg/m^3; and for cadmium, 0.005 mg/m^3.

As guidelines for water supply facilities, countries set maximum contaminant levels (MCLs) beyond which water is judged unsafe to drink. The U.S. MCL for lead is 0.05 milligram per liter, while for cadmium it is 0.01 mg/L; no nickel MCL has been set yet.

Lead, cadmium, mercury, nickel, and their compounds are included in the U.S. Environment Protection Agency's list of toxic release inventory (TRI) chemicals, and highest priority was assigned to the reduction of their emissions under the agency's 33/50 voluntary toxics reduction program (its goal being a one-third reduction of such pollutants by 1992 and their halving by 1995). Lead is regulated as one of six ambient air pollutants under the U.S. Clean Air Act. It is the reason why 10 air quality regions in the United States fail to comply with the regulation that the quarterly lead average be less than 1.5 micrograms per cubic meter of air.

Recycling a post-requisite

Disposing of millions of tons of toxic materials is an enormous problem for solid waste management and presents varied risks to the environment. As the demand for batteries climbs throughout the world, the damage and riskiness could climb, too. So it is just as well that the current end-of-life treatment of many batteries is being changed by greater incentives and requirements for recycling [Table 2]. Toxic metals and metal compounds, corrosive electrolytes and mixed residues of these materials and plastics pose challenges for managing the afterlife of this consumer product.

Worse still, from the standpoint of sustainable economic development, batteries have their down side. On the one hand, to promote environmental sustainability, it is desirable to limit toxic emissions and ensure re-use of resources such as battery metals—goals that encourage interest in battery recycling. On the other, the cost of collecting and processing discarded batteries is generally more than the revenue to be obtained from the metals recovered, so that dead batteries lack a positive value, unlike automobiles and many electronic components, including computers. In effect, they will rarely get recycled without regulatory requirements or special financing arrangements such as deposit/refund programs. Otherwise, it can be difficult to meet aggressive goals for voluntary recycling programs.

Effective recycling involves changes at all earlier stages of battery life as well, starting with production. Manufacturers should attempt to use recycled materials themselves, label batteries clearly for easier sorting, and ensure that batteries can be effectively recycled. Consumers need to take part in recycling programs by separating batteries from other wastes—doing so after their disposal in general municipal solid wastes is quite expensive per ton of battery material recovered. Retailers and shippers are needed to collect and return post-consumer batteries to recyclers. Finally, recycling plants and processes are needed for each of the various battery types and materials.

Materials management

Requirements for battery recycling vary from country to country, with a clear trend toward stricter controls of those requirements as well as disposal options. Still more sweeping regulations are under active consideration. For example, the European Union has drafted a directive that would require recycling of at least 75 percent of all used consumer batteries and 95 percent of all industrial and automotive batteries.

Reported recycling rates can be easily misinterpreted. The fraction of battery material actually recovered is the product of three factors: the fraction of batteries sold that is returned, the fraction of material recoverable from each one, and the fraction of the recoverable material actually recovered. Take the retrieval of lead from lead-acid batteries: here, the return rate is roughly 95 percent, the recoverable lead in the battery mass is roughly 60 percent, and the efficiency of a secondary smelter is roughly 95 percent. All in all, the material recycle fraction of the battery mass would then be 54 percent.

It is also common for recycling rates to be

1. Battery applications

Type	Major components	Key uses
Rechargeable batteries		
Nickel cadmium	Nickel, cadmium, potassium hydroxide	Power tools, cordless products
Nickel metal hydride	Nickel, various rare metals	Computers, cellular phones, camcorders
Lithium ion	Graphite, lithium, cobalt oxide	Computers, cellular phones, camcorders
Sealed lead-acid	Lead, sulfuric acid	Emergency lighting, backup power
Lead acid	Lead, sulfuric acid	Automotive starting, lighting, ignition (SLI)
Alkaline-manganese	Zinc, manganese dioxide, basic electrolyte	Radios, flashlights, toys
Advanced zinc air	Zinc	Early stages of commercialization
Primary batteries		
Alkaline-manganese	Zinc, manganese dioxide, basic electrolyte	Radios, flashlights, toys
Zinc carbon	Zinc, manganese dioxide, acid electrolyte	Flashlights, toys, remote controls, clocks
Lithium	Lithium and manganese dioxide or polycarbon monofluoride[a]	Cameras, pagers, keyless locks
Mercuric oxide	Zinc, mercuric oxide	Specialized medical equipment, military and emergency response equipment
Silver	Zinc, silver oxide	Watches, calculators, hearing aids
Zinc air	Zinc	Hearing aids, pagers

[a] Most commonly used types.

2. Some legislation and initiatives for batteries

Political entity	Act or plan	Type of battery	Key elements	Mandatory?
United States	Resource Conservation and Recovery Act (RCRA), 1985	Lead acid	• Declares such batteries to be hazardous waste • Exempts them from shipping manifests	Yes
	Environmental Protection Agency (EPA) Agenda for Action, 1989	Lead acid, nickel cadmium	• Proposes source reduction and recycling to reduce amount of lead and cadmium sent to landfills • Proposes to investigate mandatory takeback	No
	Universal Waste Rule (Part 273), 1995	Rechargeable	• Requires used batteries to be stored and shipped for recycling • Does not require RCRA hazardous waste manifests. • Must manage the waste so as to prevent losses to environment	Yes
	Mercury-Containing and Rechargeable Battery Management Act, 1996	Nickel cadmium, mercuric oxide, alkaline	• Prohibits addition of mercury to any battery type • Bans sale of mercuric oxide batteries for domestic use • Requires labels and ease of removal • Mandates industry-managed recycling program for NiCds	Yes
European Union (EU)	Directive 91/157/EEC, March 1991	All	• All manufacturers must meet standards for battery production, recycling, and disposal, with particular attention to heavy metal content	Yes
	Germany's Eco-Cycle, 1997	—	Defines batteries as hazardous materials on basis of their metal content: • Over 25 mg of mercury per cell • Over 250 ppm of alkaline manganese by weight per cell • Over 0.4 percent of lead by weight	Yes
	Eco-Cycle, 1997	All	• Forbids manufacturers to sell batteries without a return system in place • Requires labels and ease of removal	Yes
	Proposals by Sweden, Austria	NiCd	Are proposing more restrictive regulations, including ban on sales	—
Japan	Law for Promotion of Utilization of Recyclable Resources, 1991	NiCd	• Promotes collection and recycling • Requires labels	Yes

quoted with little attention to how much of an item is actually being recycled. Whole batteries are rarely recycled. As metal electrodes are the easiest element to retrieve, lead electrodes are routinely recycled, whereas lead in spent electrolyte or sorbed in used battery cases is typically not recovered.

Dead batteries, after all, are not what they were to begin with. Their use changes them physically and chemically. Electrodes may corrode and deform so that an electrical circuit fails. Chemical reactions may not be wholly reversible upon recharging. Consequently, battery components may not be reusable directly, but need processing before being recycled, whether into new batteries or for other uses.

Battery recycling divides into several distinct steps: collection of used batteries (the converse of distribution), sorting, recovery of recycled material, its purification, and disposal of nonrecycled material. By and large, recycling of lead-acid batteries is pretty common; commercial processes for nickel-cadmium and nickel-metal hydride batteries are in place; and experimental or bench-scale process demonstrations exist for other battery types but they undergo little actual recycling.

Battery design issues

A systems approach to battery recycling based on a life cycle analysis begins at the product design stage with some critical questions. Specific design issues would include:

- Does the product that runs on batteries allow for or encourage the use of the rechargeable type?
- Are labels included that encourage recycling and proper disposal?
- Are labels for material content attached, so that it is easy to sort used batteries?
- Are products designed so that batteries can be removed easily?
- Are recycling processes available for exotic battery materials such as lithium?

More fundamentally, there is sporadic interest in ridding batteries entirely of particular toxic materials such as mercury. Even without going so far as to eliminate them, systems to ensure that these harmful substances are re-used, rather than being unleashed on the environment, are needed.

Systematic collection

The collection stage of a recycling system consists of separating a battery from the product it powers, storing it, and transporting it to a processing or disposal facility. Many of the most costly decisions about recycling arise at this stage, like whether to establish a reverse logistics system that would recover post-consumer batteries.

A collection system for used batteries is the first step. In Europe and Japan, all battery types are collected by retailers or recycling stations, but in the United States things are more complicated. Still, everywhere batteries are sorted by type and either recycled or disposed of in bulk. Practices for different battery types vary from country to country.

Large batteries, weighing tens of kilograms or more, present less of a problem than smaller sizes. Historically, large industrial cells were sent to a metal recovery facility if that procedure cost less than disposal to a hazardous-waste landfill. Conversely, U.S. Federal waste regulations exempt small consumer cells if the quantity of used batteries is less than the rate required to exceed the small generator limit (100 kilograms per month) or if the used cells are mixed with other municipal waste.

The lead-acid batteries used in vehicles must by law in the United States and many other countries be collected for recycling. Thirty-two of the United States have laws banning the disposal of these batteries in landfills or incinerators. Retailers are required to take a used starting, lighting, and ignition (SLI), or automotive, battery in exchange for a new one or to charge a penalty until the used battery is dropped off. The sealed lead-acid cells used in electronic devices are not covered by these regulations, but they form only a small fraction of all lead-acid batteries.

The recycling rate of nickel-cadmium batteries is quite low but rising. Common uses for these types are in portable devices such as computers, telephones, and cordless tools. Larger U.S. retail chains, like Radio Shack, Kmart, and Wal-Mart, maintain drop-off cases in their stores as a service to customers who may bring in used batteries. This system calls for vigilance to keep unwanted battery types from being mixed in with the NiCd discards. Alternatively, used NiCd cells may be sent to recyclers through commercial parcel services.

The 1996 U.S. Rechargeable Battery and Mercury Removal Act mandated labeling of NiCd batteries and called for the establishment of a collection system, including the processing of batteries for the safe recovery or disposal of their materials. The Rechargeable Battery Recycling Corp., Gainesville, Fla., is an independent, nonprofit, service corporation whose mission it is to educate the public on the importance of recycling NiCd batteries.The organization works with retailers, municipalities, and counties in the United States to develop recycling programs.

It gives retailers containers in which to collect used NiCd batteries and it pays for their shipping to a recovery firm. Its work is financed by licensing the use of its corporate seal on NiCd products. More than 155 companies, which manufacture 80 percent of the NiCd batteries sold in the United States, have signed licensing agreements. In May 1997, the organization expanded its program to Canada.

Besides its licensees, the recycling corporation collects from three other sources: retailers, communities, and business and public agencies. Shipments originating from 11 states west of the Rockies are sent to a consolidation facility in Anaheim, Calif., before being passed for recycling to International Metals Reclamation Co. (Inmetco), an Ellwood City, Pa., subsidiary of International Nickel Corp. Other locations ship directly to Inmetco. Small shipments of batteries, less than 70 kg, are shipped by United Parcel Service and larger quantities by common carriers. The organization estimates it recovered about 15 percent of the batteries sold in 1995; they came primarily from the commercial sector, with less than 4 percent of the total from households.

Retailers of specialty electronic devices serviced with button cells have sometimes installed drop-off containers for these batteries. The service was offered to customers when they visited the store. Button batteries are not labeled explicitly, so it is not easy to distinguish between high-value cells with large fractions by weight of mercury or silver, and low-value or valueless batteries like alkaline manganese or aluminum oxide.

As for consumer primary batteries of the carbon zinc or alkaline manganese type, they are produced in the largest numbers worldwide. U.S. Federal waste regulations classify them as nonhazardous, and the United States has no widespread systematic program for their collection and recycling. Under certain conditions, broken or damaged battery cases will cause these batteries to fail the chemical extraction tests of the Environmental Protection Agency (EPA), based in Washington, D.C., whereupon they are classified as hazardous waste. Battery manufacturers are treated differently from the general public; their spent or off-specification batteries are viewed as hazardous waste.

The collection of used batteries and their delivery to a processing facility and storage there is followed by sorting. Labeling should assist the sorter to separate incompatible materials. For example, lead batteries should be kept apart from cadmium batteries. The sorting is important because different industrial processes are used to extract material from the different types of batteries.

Technologies of recycling

Several processes may be used to recycle battery materials [Fig. 1]. The metals are recovered by pyrometallurgy, which uses elevated temperatures; hydrometallurgy, which uses water extraction typically at ambient temperatures and pressures; and electrometallurgy, which uses electricity.

Most of the methods of recovering lead [Fig. 2] use the first of these techniques, employing primary smelting operations mainly for ore or secondary smelting operations mainly for scrap. Nickel and cadmium recovery is also mainly done with pyrometallurgical processes. Facilities designed to handle all types of batteries are likely to include a mix of all kinds of metallurgy in addition to techniques of size reduction and physical separation.

Lead-acid batteries have the most advanced system for end-of-life management worldwide. In the United States, the program for the industry is managed and monitored by the Battery Council International, Chicago. The average recycling rate for the lead in automotive batteries was calculated as 95 percent by the council for the years 1990–95. As roughly 60 percent of all U.S. lead production is used by batteries, their return rate of 95 percent is an important material flow. Other components of starting, lighting, and ignition (SLI) batteries are usually not recycled.

A typical process for lead-acid battery recycling would start with used batteries stored at a secondary smelter as whole or drained units. Any whole batteries are drained of electrolyte and sludge, all the cases are broken up, and materials other than lead separated from the mainly lead and lead oxide electrodes. Heating and thermal processing produces a refined lead that can be reused. Materials other than lead may be handled as hazardous waste or possibly converted into a product for a secondary market—for instance, a major auto manufacturer processes the polypropylene cases of SLI batteries into automobile mud-flaps. The expectation is that retrieval of materials other than lead will increase in the future.

Smelting operations, of course, have their own environmental costs. Without proper waste controls, their air and water emissions can exceed Federal and state standards. Outside the United States, Italy affords another approach to lead-acid battery recycling. In 1988, Italian law established a consortium, Cobat, to organize an efficient collection network for spent lead-acid batteries and lead scrap and their recycling throughout Italy.

Cobat's domain includes: organization of the collection and storage of these materials; their delivery to national or foreign industries for recycling; ensuring that, if battery materials cannot be economically recycled, the waste is "eliminated in compliance with strict environmental standards"; and promotion of research for improved recycling and disposal of lead.

Italy's annual demand for battery lead is about 240 thousand metric tons, of which 40 thousand are imported and 200 thousand are produced domestically, including 80 thousand metric tons from recycled lead. The consortium's five recycling plants serve the whole country. Cobat estimates that the collection system misses about 6 percent of all of the discarded lead batteries in the do-it-yourself small operators dealing with marine, personal auto, and agricultural sectors.

Nickel and cadmium recovery

In the United States, nickel and cadmium battery recovery is served by only one facility: Inmetco, which has been processing hazardous metal wastes from the stainless steel industry since 1976. It has processed large industrial NiCd batteries for the same length of time, but for nickel recovery only. In its early days, it sent cadmium combined with zinc off-site to a zinc processor, but in 1996, it started a process for recovering cadmium.

Inmetco outputs two products: a ferrous, nickel, chromium material that is used by its stainless steel customers as an alloy additive, and cadmium pellets (99.9 percent cadmium) suitable for any use, but directed for feedstock for cadmium anodes in NiCd batteries. Battery inputs to Inmetco more than doubled each year, beginning at 45 tons in 1989 and reaching 2000 tons in 1993. In 1994, the company processed over 2100 tons of NiCd batteries. In 1996, Inmetco recovered about 36 tons of refined cadmium during five months of operations (an annual rate of approximately 90 tons of cadmium production).

The general process for recycling NiCd batteries at Inmetco involves separating the nickel and the cadmium into two process streams. For large batteries, weighing more than several kilograms, the separation is done by hand, using a bandsaw to cut the top off the case and removing and separating the cadmium-containing anode from the nickel oxyhydroxide cathode. The caustic liquid electrolyte is sent to treat waste water, where it is used for alkalinity (pH) control. The cadmium material goes to its own recovery facility and the nickel to the ferrous-nickel-chromium facility.

Smaller batteries used in hand-held consumer products are sent to a thermal oxidizer unit, which burns the plastic cases and recovers the heat for use in the ferrous-nickel-chromium facility. These batteries, after the cases have been burned off, are sent to the facility for cadmium recovery. Its output is a high-purity cadmium product and a ferrous-nickel product that is added to the feedstock of the ferrous-nickel-chromium facility.

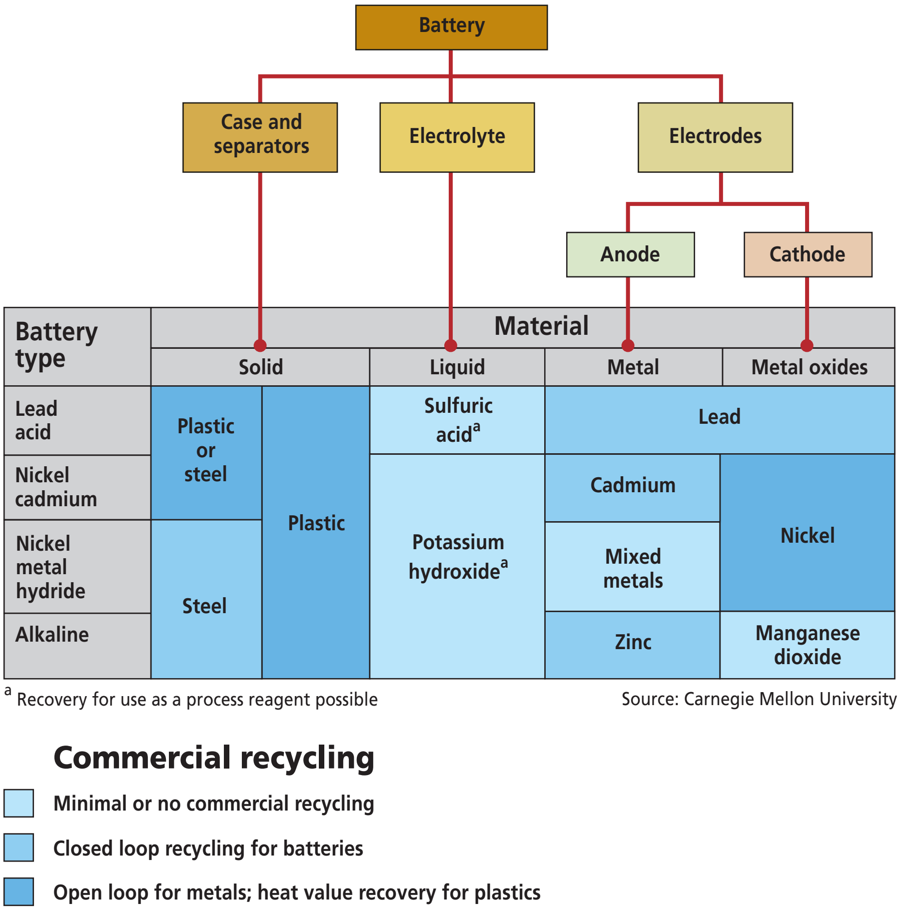
Several European countries and Japan concern themselves with recycling NiCd batteries. To start from the north, SAFT NIFE Inc., Oskarshamn, Sweden, is the world's largest manufacturer of NiCd batteries for industrial, aircraft, and portable applications. Its recycling technology is the basis for the pyrometallurgical process now in operation at Inmetco. SAFT was a founding member of the Portable Rechargeable Battery Association (PRBC) in the United States and a member of Eurobat, the Association of European Accumulator (battery) Manufacturers. It collects batteries at a facility in Greenville, N.C., and, until recently, collected and shipped cadmium plates from used cells under a hazardous waste manifest to its Swedish plant for recycling. This plant has an annual capacity of about 1000 tons and has been operating since 1986.

Elsewhere in Sweden, processing facilities that can accept NiCd batteries are the SAB NIFE at an annual 1000 tons and SNAM at 1400 tons.

Next, Germany discards about 30 000 metric tons' worth of batteries annually in its private and industrial sectors. The NiCd type form about 10 percent of the total. In 1995, Accurec, in Mülheim, invested 2.5 million DM in a vacuum distillation plant for recovering cadmium [Fig. 3]. Compared with open, continuous systems, this closed, batch reactor system has much lower emissions, and it cuts back on energy use as well, operating as it does at about 1 millibar of pressure. Accurec's single reactor has a capacity of 1 ton per batch with about an 8-hour cycle time. The plant processes in the region of 1000 tons of used batteries a year, yielding a cadmium product suitable for battery use, plus a steel-nickel product marketable as ferrous scrap. German batteries that are not recycled at Accurec are exported to other countries for recycling or sent to hazardous landfills.

Elsewhere in Europe, NiCd processing facilities include the Société Aveyronnaise de Valorisation des Méteaux (Savam) in France, extracting 4000 tons a year. And on the opposite side of the world, three Japanese facilities have a total annual capacity of 4000 tons of batteries.

Overall, Europe's estimated annual capacity in 1992 was about 5000 tons of cadmium. By way of comparison, the 1992 U.S. figure might be put at about 1800 tons, assuming that the 1200 tons of NiCd consumer-sized batteries sold that year was



[1] Batteries are not recycled in their entirety but in terms of their components—in the main, the electrodes, the electrolyte, and the electrode separators and case.

Recycling is different for each component. Metal electrodes are recycled most. Metal cases are recycled more than plastic cases. Electrolytes may be reused as reagents, but in some circumstances may be recycled for other uses.

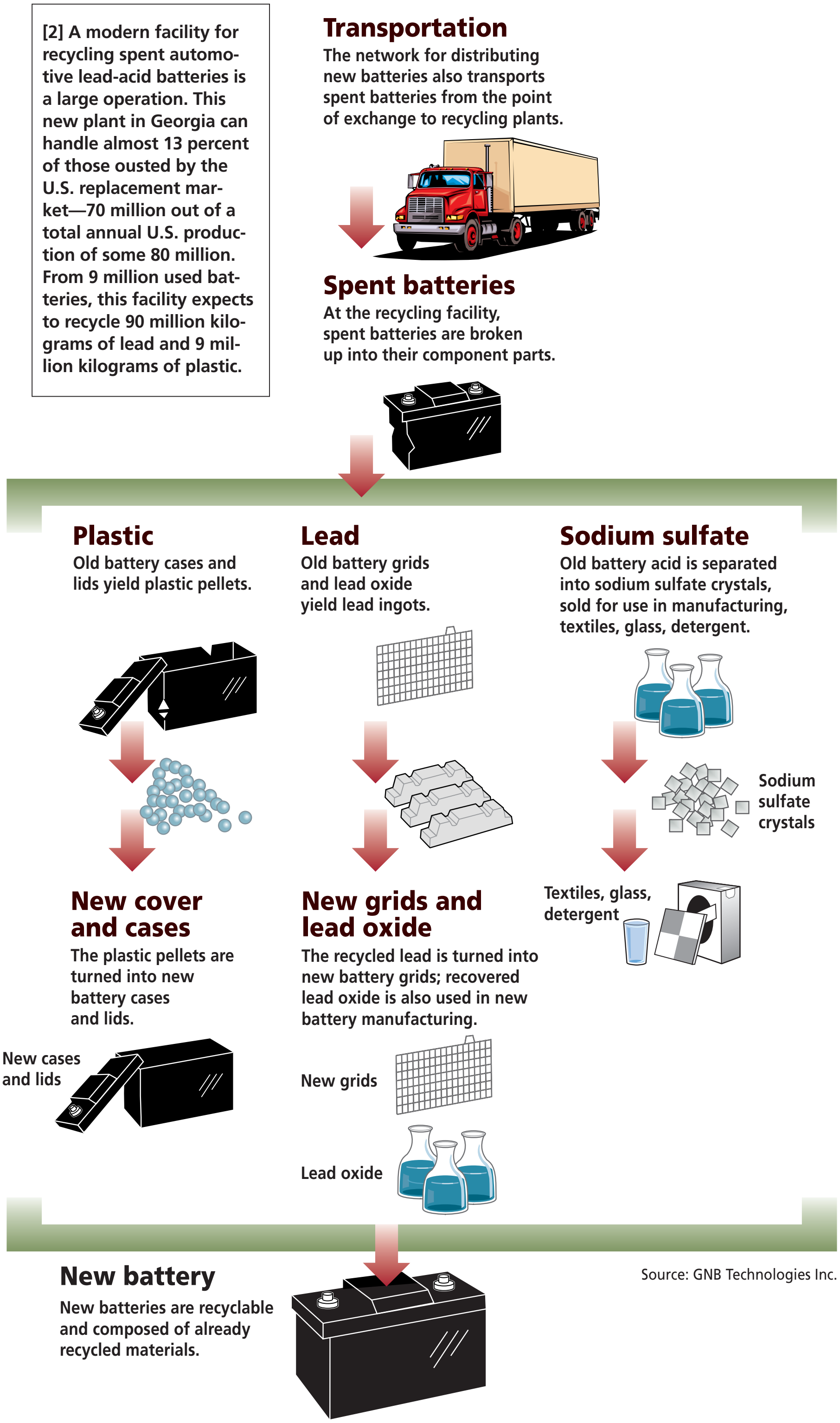
Lead is the battery material most recycled; cadmium is the focus of recent efforts and ranks second. Records for other components are not maintained systematically.

about 15 percent cadmium. And world capacity was slightly more than 10 500 tons for used NiCd batteries.

Nickel metal hydride batteries are recycled primarily to recover the nickel-plated steel components. Most of them are sent to landfills, though in the United States, Inmetco can, and does, process these along with NiCd batteries. At a research level, the U.S. Bureau of Mines in 1993 investigated the application of strong acids to crushed NiMH consumer cells, with a view to determining the feasibility of recovering various metals. But this metal recovery would be only a first step in the development of a recycling program. Although some manufacturers advertise that NiMH are green batteries and are 100 percent recyclable, they are extrapolating misleadingly from the simpler bench-level investigations to full-scale recycling systems.

Tests were sponsored by the U.S. Department of Energy's National Renewable Energy Laboratory, in Golden, Colo. Researchers there used the U.S. EPA leaching procedure for determining toxicity characteristics in order to anticipate the waste treatment needed for used, nickel-based batteries of both types.

The results showed that all metals tested—cadmium, chromium, and nickel—leached at levels below EPA standards for NiMH. Less happily, the NiCd group leached cadmium in excess of the EPA standard level. And less happily still, nickel concentrations for the NiMH were above the standards set in California and by the European Community, so that used NiMH batteries would be classified as hazardous waste in California and Europe.



[2] A modern facility for recycling spent automotive lead-acid batteries is a large operation. This new plant in Georgia can handle almost 13 percent of those ousted by the U.S. replacement market—70 million out of a total annual U.S. production of some 80 million. From 9 million used batteries, this facility expects to recycle 90 million kilograms of lead and 9 million kilograms of plastic.

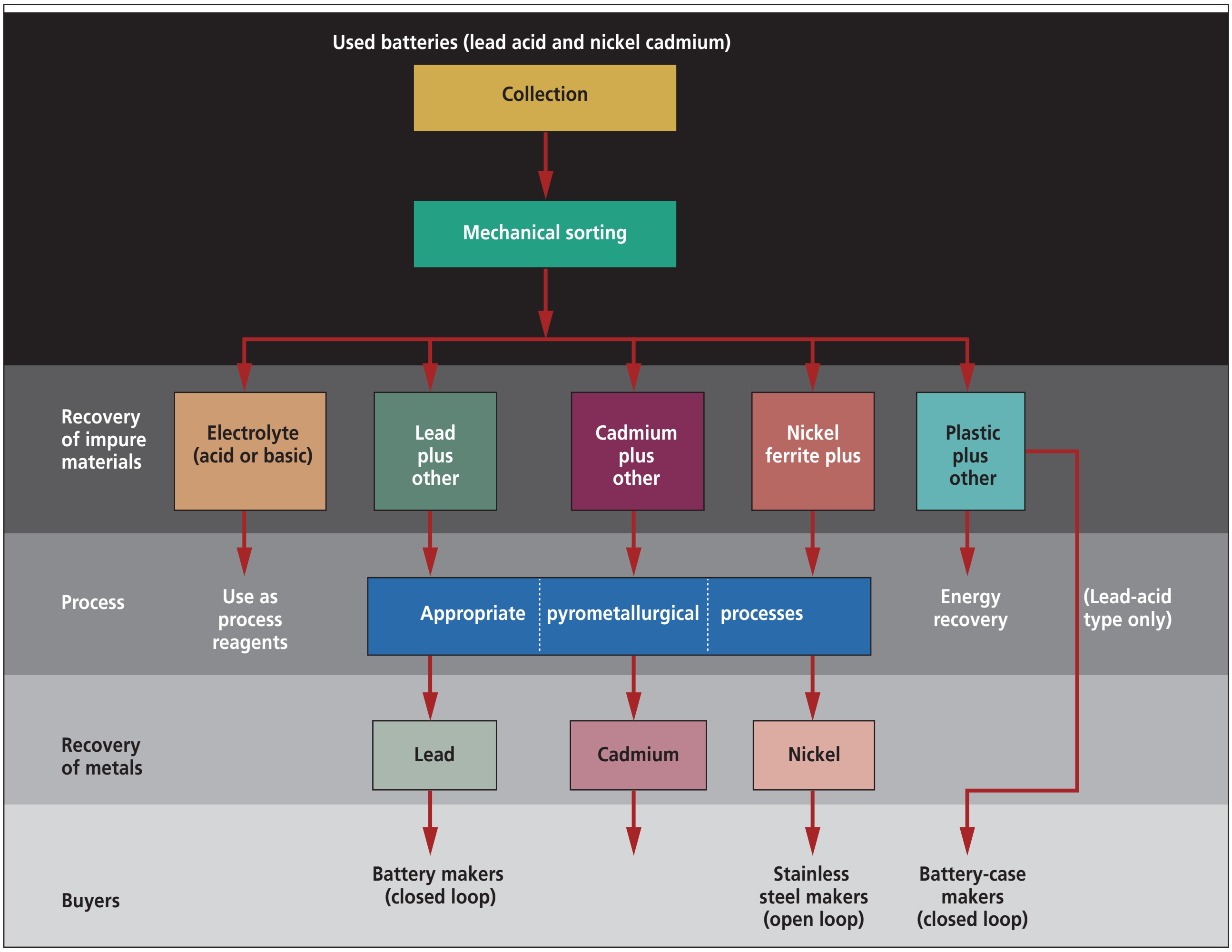
Consumer cell recycling

Consumer cells are a problem, at least in the United States. Programs for recycling these primary and small secondary batteries have generally failed because of the high collecting and sorting costs.

In 1987, Allen Hershkowitz and Eugene Salerni, working for the nonprofit research organization, Inform Inc., in New York City, reported on two Japanese collection programs. One was for cylindrical (carbon-zinc and alkaline-manganese) primary consumer batteries and a second was for button cells (mercury batteries). About 73 percent of Japan's 3255 municipalities participated in the collection of used cylindrical batteries; this represented more than 82 million people, or 72 percent of the total population.

Button-shaped batteries were collected through retail stores, without involving the municipalities. The two researchers estimate that despite widespread knowledge of the program, only 9 percent by weight of the cylinder-shaped batteries were recovered and only 27 percent by number of the button cells.

A decade ago, moreover, options after collection were limited. Of the municipalities that collected the cylindrical type, 548 sent the batteries to a mercury refinery; 47 mixed them into concrete and sent the mixture to landfills; and 1762 planned to store them until safe and economical reprocessing or disposal options became available. While these activities diverted batteries from conventional waste disposal, they did not lead to recovery and reuse of most of the battery materials. Hershkowitz and Salerni's report, incidentally, was part of a larger study, *Garbage Management in Japan, Leading The Way*, put out by Inform Inc. in 1987.



[3] The lead from lead-acid batteries and the cadmium from nickel-cadmium batteries are recycled in a closed loop—they are used to manufacture more batteries. But recycled nickel disappears into another industry. ˆ Electrolytes, too, are rarely recycled into battery electrolytes. A drawback is that environmentally harmful emissions are generated from the pyrometallurgical processes.

Switzerland has since gone a step further. In 1992, the Batrec AG process was designed there, using technology from Tokyo-based Sumitomo Heavy Industries Ltd. Processing 2000 tons of mixed consumer cells yields four types of product. Every year, 780 tons of ferromanganese product are marketed to steel producers; 400 tons of zinc are sold as a commodity; 3 tons of high-purity mercury are generated; and 20 tons of slag are produced, to meet strict Swiss leaching limits for waste disposal.

Costs of detoxification

Concern for the environment exacts a price. Neither recycling nor disposal comes cheap. Primary batteries have been made more benign by U.S. and European regulatory change in their chemical composition: mercury may no longer be added to the anode, and limits on the acceptable level of mercury are being progressively lowered–at present to less than 1–5 ppm by state and Federal laws. Granted, the chemicals that replace mercury lead to less efficiency and higher costs, but mercury-less batteries are accounted nonhazardous waste in the United States.

Secondary batteries, too, are dogged by higher life-cycle costs due to requirements for collection and recycling. When lead-acid automotive batteries were declared a hazardous waste by EPA in 1995, the regulation did not call for a change in battery composition, but required retailers to take a worn-out battery in exchange for each replacement they sold or else collect a penalty charge or receive evidence of proper disposal of the spent battery. Used automotive batteries are purchased by scrap metal dealers in the United States for 3–5 cents per pound. At these prices, a typical auto battery weighing about 18 kg can bring $2 at its demise.

The Portable Rechargeable Battery Association, representing the major secondary battery manufacturers, and the Rechargeable Battery Recycling Corp. changed the end-of-life options for owners of used NiCd batteries. The corporation's system holds manufacturers responsible for the main costs of collection and processing—nominally about 57 cents per kilogram for the right to use the corporation's recycling seal.

Choosing to pay for the seal is voluntary, but all NiCd with or without the seal must be labeled and recycled or disposed of as hazardous waste. The recycling corporation estimates its costs for collecting and recycling NiCd batteries in 1996 at $5.5 million, or about 1 percent of NiCd sales. At a recycling level of more than 2.25 million kilograms in 1996, this is about $2.20/kg, similar to the costs of disposing of hazardous waste. Since most NiCd batteries are contained within products, the added costs may escape the consumer's notice.

Italy, as before, does it differently. To finance its activities in collecting and processing used lead-acid batteries in that country, Cobat has two sources of revenue. One is levies from battery sales: the purchase price of the battery includes the levy, which is paid directly to the consortium by producers and importers. The other is the proceeds from the sale of scrap batteries to recycling plants, subject to variations of the price of lead on the London Metal Exchange, and to the varying cost of processing and disposal of toxic wastes.

Average results of the Italian scrap lead battery system for 1992–95 were: per kilogram, costs of $0.12 and proceeds from sales of $0.05 to yield a net operating deficit of $0.07/kg. Collection costs are on average $0.10/kg, or about 87 percent of the operating costs, and represent the major financial issue for the whole operation.

France did something similar. In 1989, Savam developed a charging formula, which it based on the world price of nickel and cadmium, and estimated from expected sales revenues that battery materials returned in 1989 would be charged $3.20/kg.

Two years later, Switzerland's Recymet reported processing fees of about $6.60/kg, exclusive of collection and shipping costs to Switzerland.

Proper disposal of batteries has no direct monetary reward. Landfill "tipping" fees for hazardous materials are usually five to 10 times higher than for ordinary municipal solid waste. Consumers find it cheaper and more convenient simply to throw their batteries away with other garbage (or let them commingle with other municipal solid waste), giving rise to contaminated landfill leachate or incinerator emissions, as noted earlier. Full cost-accounting of disposal streams should be a priority for corporations or organizations charged with managing battery disposal.

One sizable expense in battery disposal is the cost of reverse logistics. To the extent that batteries can be consolidated in retail stores, the costs of retrieving particular battery types is lower. In the extreme, batteries may be returned individually by parcel post.

Still, as nickel-cadmium battery recycling becomes more common, reverse logistics costs should decline to a level closer to the costs of lead-acid battery collection.

Prospects ahead

A 1992 study by a New York State task force defined an ideal battery as one that: 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. This system definition uses "ideal" in the sense that the life cycle characteristics must all be examined before it can be decided if a battery type meets this ideal or green description.

Recycling, a reality now for some battery types, is likely to become important for all batteries in the future. Consumer demands, regulatory pressures, and corporate policies are all motivating more recycling. Most of the interest centers on removing toxic materials from the waste stream, but reuse of resources, particularly the scarcer metals, also counts.

For managing the recycling of batteries, product-takeback is the emerging paradigm. In this approach, manufacturers bear the responsibility for arranging reverse logistics systems and battery recycling. The arrangement can be instituted by the manufacturer, either individually or as a consortium or a third party financed by manufacturers. The advantage is that it takes disposal decisions out of the hands of consumers who are often confused about the consequences of different end-of-life choices. In fact, product takeback responsibilities are likely to extend to other electronic products in the future, as can be seen in Germany already.

Recycling all the parts of batteries is not common. Research has shown that recycling of more of their components and materials may be technically feasible, but markets for materials other than metal are generally not available. An exception here would be the growing recycling of lead-acid battery components like cases.

Metal recycling is not invariable. Retrieval of lead from batteries is widely practiced and accepted as a regulatory requirement. A concern here is how far trace losses of lead to the environment can be prevented during collection or smelting so that a closed-loop lead-use-and-recycle system can be sustained indefinitely. Achieving this type of system is the ambition of the emerging discipline of industrial ecology.

Recycling nickel-cadmium batteries is now emerging as a commercial enterprise, with both metals being recoverable. As with the lead-acid battery, recycling NiCd cells is typically either subsidized by manufacturers or required by regulation. Efforts aim at recovery of cadmium for the battery market and recovery of nickel for other markets.

In fact, the success of the fledgling attempts to recycle NiCd batteries may be crucial for their growth and use over the long term. Given the toxicity of cadmium, active efforts are being made to eliminate its use in other applications and to restrict disposal options. So far, the market for the metal has been fairly stable since other uses have diminished while NiCd battery production has soared. As those other uses are eliminated, cadmium could become really scarce, further spurring pursuit of effective collection and recycling processes. Indeed, without effective recycling and cadmium reuse, there may be long-term supply problems.

As for other battery types, recycling is technically feasible but has not been applied widely. Exotic battery materials are an active area of research, and some attention should be paid to developing recycling processes for these materials. And some of the newer battery types are advertised as "green" on the basis of their high power densities or lower material toxicities. Debate continues on what constitutes a green battery, but certainly lower resource requirements and good systems for recycling are critical.

Environmental concerns might also influence device design and choice of alternative battery types. For example, electronic devices should be designed to ensure that toxic battery metals can be extracted. This typically involves opportunities for removing batteries and proper labeling.

Eliminating reliance on toxic materials is also to the point. Any use of such materials involves environmental risks and sends trace emissions into land, water, and air. If pollution is to be prevented, everyone would benefit if cost-effective and efficient alternatives to the use of toxic materials such as cadmium and lead could be found. Batteries such as the aluminum air or lithium polymer or new technologies such as fuel cells may in the future circumvent the toxic metal problem altogether. ◆

To probe further

Additional information on this field may be found in *Recycling of Consumer Cell Batteries* by D.J. Hurd and others (Noyes Data Corp., Park Ridge, N.J., 1993), and in a paper available on the World Wide Web, "Industry Program to Collect and Recycle Nickel-Cadmium Batteries" by Bette Fishbein, of Inform Inc., New York City, at http://www.informinc.org/battery. html.

The Rechargeable Battery Recycling Corp. (RBRC), at Box 141870, Gainesville, FL 32614, as well as an RBRC in Canada, supplies information on recycling batteries containing nickel and nickel cadmium. Look up its Web site, http://www.rbrc.com.

The same is done for lead-acid batteries by the Battery Council International (BCI), at 401 N. Michigan Ave., Chicago, IL 60611; Web, http://www.recycle.net/recycle/battery.

For information on associations, vendors for scrap batteries, and current market prices or charges, see the Web site, Recycler's World, at http://www.recycle.net.

Worldwide inputs on battery recycling, as well as other topics in commercial recycling and materials reclamation, are stored at http://tecweb.com/recycle/eurorec.htm.

Statistics on battery materials, including supply, demand, scrap, and materials flows, may be obtained from the U.S. Geological Survey's Mineral Resources Program at http://minerals.er.usgs.gov.

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