Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Power Sources 130 (2004) 291–298
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Recycling of batteries: a review of current processes and technologies

A.M. Bernardes [a], D.C.R. Espinosa [b], J.A.S. Tenório [b,*]

[a] PPGEM–UFRGS, Av. Osvaldo Aranha 99/706, Porto Alegre 90035-076, RS, Brazil

[b] Department of Metallurgical and Materials Engineering, University of Sao Paulo, Av. Prof. Mello Moraes 2463, Sao Paulo 05508-900, SP, Brazil

Received 15 November 2003; accepted 8 December 2003

Abstract

A great effort to recycle batteries has been performed in the last two decades. During this period new directives have been published specially in Europe. The aim of this paper is to review the current status of technologies applied to recycle portable batteries, e.g. lead acid will not be described here. Essentially, this paper presents the current status of the technologies involved in the collection, sorting and processing of portable batteries.

Keywords: Battery recycling; Battery collection; Battery disposal

1. Batteries characteristics

A battery is an electrochemical device that has the ability to convert chemical energy to electrical energy. The basic battery consists of an anode, a cathode, an electrolyte, separators and the external case. The main difference between different battery systems is the materials used as electrodes and electrolyte, which determine the specific characteristics of the systems. Separators are made of polymeric materials, paper or paperboard. The external case is composed of steel, polymeric materials or paperboard. Electrodes and electrolytes change as a function of the different applications of batteries. Typical household-type batteries are used in consumer items such as telephones, flashlights, radios, watches and so on. The potentially hazardous components of batteries include mercury, lead, copper, zinc, cadmium, manganese, nickel and lithium [1].

The household battery industry in the USA is estimated to be a US$ 2.5 billion industry with annual sales of nearly 3 billion batteries. These batteries, also know as dry cells, are used in over 900 million battery-operated devices [1]. In Europe 5 billion units of batteries were produced in year 2000 [2].

There are two basic types of household batteries: single-use primary cells and rechargeable secondary cells [3,4].

Among primary cells, the most used are the zinc-carbon and the alkaline-manganese batteries. Typically these batteries come in sizes AAA, AA, C, D and 9 V. The zinc-carbon represent 39% of the European portable battery market while the alkaline cells are 51% of the European market [2].

The zinc-carbon batteries contain a zinc electrode that used to have lead concentrations varying from 0.05 to 0.5% and cadmium from 0.01 to 0.05%. The elements were added to improve mechanical properties of the electrode. Besides cadmium and lead some batteries used to contain mercury, which was most commonly used to coat the zinc electrode to reduce corrosion and thereby enhance battery performance. Nowadays batteries are usually produced without these elements [1,3–5].

In general, zinc-carbon batteries have a carbon rod in contact with carbon and MnO_2 as cathode and a zinc case as anode. A paste of NH_4Cl and $ZnCl_2$ is the acid electrolyte. On the cylindrical cell the zinc electrode is usually recovered with a stainless steel jacket. A plastic or paperboard separator and an asphalt seal are usually present.

Alkaline-manganese batteries were developed after the zinc-carbon. These are usually composed of a brass rod in contact with powdered zinc as anode and a steel case in contact with carbon and MnO_2 as cathode. A paste of KOH is used as alkaline electrolyte (pH $\sim$ 14) [1,3,4].

It is best to distinguish between lead acid automotive-type batteries and typical household-type batteries. This paper discusses just other secondary systems, which do not have a well-established collection and recycling process, so the recycling of lead acid batteries will not be presented here.

* Corresponding author. Tel.: +55-11-30915546; fax: +55-11-30915243.
E-mail addresses: amb@vortex.ufrgs.br (A.M. Bernardes), espinosa@usp.br (D.C.R. Espinosa), jtenorio@usp.br (J.A.S. Tenório).

0378-7753/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2003.12.026

The rechargeable batteries represent 8% of the European portable battery market. Among the rechargeable batteries, nickel-cadmium (NiCd) represents 38%, nickel-metal-hydride (NiMH) 35% and lithium-ion 18% of the European market [2,6,7].

The rechargeable NiCd batteries are being used in household (portable) and industrial applications. In 1995 more than 80% of the NiCd batteries were portable [8]. Over 75 million NiCd batteries were sold in the US during the year 2000. NiCd system is considered one of the most hazardous in terms of disposal [9]; this fact was the main impulse to the development of other rechargeable systems.

NiMH batteries are considered environmental friendly and can replace NiCd batteries in many applications. However, the costs of production are higher when compared to NiCd [8].

In the 1990s a new rechargeable battery was put on the market: Li-ion. Primary lithium (metal) batteries contain no toxic metals; however there is the possibility of fire if metallic lithium is exposed to moisture while the cells are corroding. For proper disposal, these batteries must be fully discharged in order to consume all metallic lithium content. Li-ion batteries (rechargeable), on the other hand, do not contain metallic lithium. However, most lithium systems contain toxic and flammable electrolyte. Lithium-ion-polymer batteries are similar to Li-ion, but the system enables slim geometry and simple packing at the expense of higher cost per watt/hour [9,10].

For many years, the NiCd was the only suitable battery for portable applications such as wireless communications and mobile computing, as they are commercially used since 1950. The cathode is made of cadmium. The anode comprises Ni(OH). The electrolyte is usually a mixture of KOH and $Li(OH)_2$ [3,4,11,12]. NiCd batteries can be classified as open on closed batteries. Open batteries are usually used in industrial applications. Closed batteries (cylindrical, button, prismatic) are generally associated with household devices [13].

Nickel metal hydride (NiMH) batteries were developed in 1989 and commercialized primarily in Japan in 1990. Such systems have high electrochemical capacity, as well as safety and good environmental compatibility. In addition, NiMH batteries are found to function efficiently within a wide range of temperatures (-20 to $60\,^{\circ}C$) and to possess long lives (500–1000 cycles) and low self-discharge rates. The positive electrodes comprise porous Ni plate with nickel hydroxide as the activating agent. The negative electrodes consist of a hydrogen storage alloy powder such as Mm–Ni–Co (Mm = misc. metal) on a metal-mesh substrate. An inert insulating layer separates the two electrodes [14]. The electrolyte is usually potassium hydroxide [3,4].

Considering lithium batteries, there is an important difference between the primary and secondary batteries. Primary cells use metallic lithium as cathode. Rechargeable batteries use a material like $LiXMA_2$ at the positive electrode and graphite at the negative electrode. Some materials used at the cathode include $LiCoO_2$, $LiNiO_2$ and $LiMn_2O_4$. The electrolyte is an organic liquid with dissolved substances like $LiClO_4$, $LiBF_4$ and $LiPF_6$ [15–17]. The lithium battery family is very often used on prismatic geometry. The prismatic geometry was developed in the early 1990 to response to consumer demand for thinner geometry. The Li-ion-polymer version is exclusively prismatic [10].

2. Alternatives to the final disposition of batteries

There are different alternatives to the final disposition of batteries:

- Landfill: Until the present moment most household batteries, especially the primary batteries, are disposed of in MSW and are sent to a sanitary landfill.
- Stabilization: The process represents a previous treatment of batteries in order to avoid the contact of metals with the environment in a landfill. The process is not much used because of high costs involved.
- Incineration: It is used when household batteries are disposed of in MSW and are sent to a municipal waste combustion facility. Incineration of batteries can cause mercury, cadmium, lead and dioxins emissions to the environment.
- Recycling: Hydrometallurgical and pyrometallurgical processes can be used to recycle metals present in the batteries. These recycling processes are currently being studied in different parts of the world.

2.1. Batteries and heavy metals in the environment

When solid materials are in contact with a liquid some compounds can dissolve. The dissolution of individual compounds determines the composition of the leachate. A leaching process can occur through the exposition of the materials to natural infiltration processes. There are a great number of factors that can act on the rate at which compounds are dissolved from the material. These factors can usually be seen also as chemical factors like pH, Eredox, etc. [18,19].

Understanding the environmental fate of metals contributed by batteries in a landfill is a function of the conditions of the batteries when landfilled and the conditions of the landfill itself. The casings of household batteries are most commonly made of paper, plastic or metal. The various conditions that can develop in a landfill affect the rate at which the casings will degrade or decompose. The following conditions can affect the rate of degradation: the nature of the casing, the degree of electrical charge left in the battery, the extent of exposure to landfill leachate and the oxygen content of the landfill. The mobility of the metals in a landfill and the potential for groundwater contamination are also controlled by numerous conditions. These conditions include the design, construction, operation and maintenance of the landfill (e.g. the liner, soil characteristics, leachate collection and detection systems, daily cover, final cover, etc.) [1].

The release of metals from a battery into a landfill may not however, in and of itself, be problematic. The principal issue is the potential for those metals to contaminate groundwater, which is a function of the landfill's construction, its soil characteristics and its proximity to groundwater [1].

The incineration of batteries also poses two major potential environmental concerns. The first is the release of metals into the ambient air and the second is the concentration of metals in the ashes that must be landfilled. Among the metals present in batteries, mercury, cadmium and lead present the major environmental problems. Generally, mercury is more likely to be emitted in the stack gas, and cadmium and lead will concentrate in the fly ash. The fate of metals released from batteries during incineration is mainly a function of the combustion temperature, the metal's volatilization temperature and the presence of other non-metallic compounds. The fate of metals in the fly ash will be the same as those previously stated for landfills [1].

The impact of the metals present in batteries on the environment is still being researched, since the requirements for pollution control at landfills and incinerators are becoming increasingly more stringent. Also, pollutant measurement and risk assessments analyses are being refined.

2.2. Batteries collection and sorting systems

The final disposal of household batteries is associated with environmental management of municipal wastes, that includes different programs of battery collection and sorting systems.

A life cycle assessment (LCA) study carried out by the environmental consultant ERM on behalf on the British Government in November 2000 has confirmed that the recycling of batteries gives an environmental benefit, especially when using existing material recovery technologies such as in the steel industry. This is also valid for the recycling of other battery systems such as NiCd, NiMH, button cells and Li batteries. However, the impacts on the environment of the collection activities, mainly associated with transportation, outweigh the benefits resulting from recycling. In order to benefit the environment the task is therefore to minimize the impact associated with the collection of alkaline and zinc-carbon batteries. This would be possible by integrating the collection of these batteries with other waste streams and separate the materials afterwards for recycling in the steel industry. The objective is to minimize the collection and transportation impacts while enabling the recycling of spent batteries. This type of approach does have significant benefit for the environment and the economy since it avoids additional transportation emissions. First examples of "integrated waste management" are seen in several European countries [2]:

1. In Sweden, battery collection boxes are attached to paper collection containers. The same truck, which collects the paper, collects the batteries as well. The same approach is now being tested in Germany and Portugal.
2. In The Netherlands a project is going on to extract spent batteries from mixed household waste using magnets.
3. The collection of batteries with electrical appliances is already taking place in different countries. There would be no merit in asking consumers to separate batteries from appliances.

The collection results depend mainly on the behavior of the consumers. As batteries do not occupy much space, consequently people tend to keep the batteries in several places in their homes. Recent consumer studies in Germany, The Netherlands and Belgium show that the large majority of the population knows about the collection systems (80–90%), but only a small part of the population (30–50%) uses the systems in place. It is difficult for industry to influence the habits of consumers. Public entities are better placed to promote an effective collection system and also to help change consumers' attitudes through effective communication. It is also important that a reasonable period is allowed to achieve any collection target, taking into account the different European attitudes to recycling (certain Member States have effective systems and some do not have a framework in place at all). For primary batteries, a collection target of 50–130 g per inhabitant in all European countries is achievable, depending on the existing infrastructure and collection culture in the Member States. Producers/importers cannot be made responsible for achieving a collection target. The lifetime and consumer behavior of disposal of portable rechargeable batteries is different from that of portable primary batteries. Rechargeable batteries are incorporated in electronic equipment and will be collected in the waste electrical and electronic equipment collection systems. A collection target for non-industrial rechargeable batteries must take into account hoarding and the availability of those batteries for collection [2].

Most battery programs in the world are designed to collect all types of household batteries. After the collection, the batteries are transported to the recycling processes or final disposition, or they are previously separated. Sorting processes are associated with different manual separation steps or with different equipment designed to achieve this goal.

In the 1980s, when battery recycling discussion was beginning, the major concern was to find recycling processes that could manipulate a mixture of different kinds of batteries. With new rechargeable batteries on the market, and with the demand for efficient and less-expensive recycling processes, separation programs became more important. Batteries can be treated in a much more efficient way at recycling processes when batteries are sorted by chemical composition.

A high-speed battery-sorting machine is operating in The Netherlands. It is based on a sensor designed by Philips. The sensor induces a magnetic field on each battery and measures the response frequency. The process has 99%

accuracy, but the batteries must pass through the sensor individually. The sensor can identify one battery each 2 s. This represents a slow rate. Researches are being conducted to improve the speed and the transport method. A new sorting line was developed, based on three process steps. At the first step, mixtures of batteries pass through different sieves where the button batteries are separated. The remaining batteries pass through a magnetic separator. The non-magnetic batteries are the zinc-carbon batteries with casings of paperboard. The magnetic ones pass then through another sieve system, where the batteries are separated by shape (prismatic and cylindrical) and by size (AAA, AA, C and D). Finally, on a third step, the batteries pass through different sensors (TRI-MAG) that are able to separate different batteries according to their dimensions, mass and electromagnetic properties. An UV sensor separates batteries with a label indicating the presence of mercury [20].

In Germany, a photo recognition system was created for sorting different batteries called batteriesortierranlage (BSA). The batteries can be sorted by the information on the label as to composition, manufacturer, etc. This battery sorting system has 99% accuracy and sorts household batteries at the rate of 24 batteries/s. After a pre-selection from battery sets of the same size and shape, the batteries are send individually to the detection system. By comparing with a schematic example, the batteries can be placed automatically in the right collection box [21].

Another German system (SORBAREC) is based on sorting by X-ray images. This method is able to sort zinc-carbon, manganese-alkaline, nickel-cadmium, nickel-metal-hydride, lithium and mercury [22]. In this process, after hand and size sorting, the batteries are separated from a stock silo via different conveyor belts and fed to the X-ray sensor. The radioscopy unit consists of an X-ray tube and a sensor installed in a radiation protection cabin. The electrochemical battery type is identified in real time. The batteries fall off the conveyor belt and are pushed out of their trajectory by compressed air blasts from the side or from above. In this fashion several fractions can be reliably separated. Sorting speeds of up to 12 batteries/s are achieved with battery intervals of approximately 7 mm. The analysis ensues by computer, which likewise identifies the battery types based on the gray levels of the X-ray image. One plant of this type is in operation since 2001 [23].

The facilities to separation of batteries from EPBA/SORTBAT and from EUROBATRI use electrodynamics sensors to sort by magnetic properties, mass, size, etc. [24]. The batteries are sorted mechanically and magnetically into different fractions according to their composition, i.e. after hand sorting, during which incorrectly sorted batteries and larger batteries are removed, which are sorted by size, and the button cells are sieved out. The round cells are run across a magnetic separator. The non-magnetic batteries (paper jacket, primarily ZnC, make up approximately 10% of the round cells) are not sorted any further automatically. An electrodynamic sensor based on their "magnetic fingerprints" identifies the magnetic batteries. This process sorts the batteries at a speed of 6–8 batteries/s. The company LSI has developed a new electrodynamic sensor, which also facilitates the separation of NiCd and NiMH batteries [23].

For further recycling of the AlMn and ZnC systems it is important to separate the batteries containing mercury from the mercury-free batteries after separation into the various electrochemical systems. Since the mid-1990s, the European manufacturers have produced these batteries only in mercury-free form, but older batteries containing mercury still make their way into the waste disposal system. In order to separate these in the sorting facilities from the mercury-free batteries, for which recycling procedures already exist, the European battery manufacturers have coded their own AlMn brands and some of the ZnC batteries with a UV-sensitive varnish, so that batteries containing mercury can be separated from mercury-free batteries by means of sensors [23].

The different sorting processes result in different levels of purity in the separated fractions. Purity is nevertheless strongly dependent on the cleanliness of the battery mixture delivered for sorting (for example, heavily corroded batteries give worst results than clean). The question of which battery fractions and how many are to be sorted for depends on the sorting technology, the quality of the battery mixture, the purity required by the recycling process for which they are intended and on the costs.

2.3. Batteries recycling

As a result of new environmental regulations in different countries around the world some processes were developed to recycle batteries. To identify the chemical composition is important to promote the recycling of batteries. Unfortunately there is no relationship between the shape and size with the composition.

NiCd batteries have been collected and studies for their recycling are in course [25]. Recycling of primary batteries is a new concept, since it involves the environmental management of MSW. The separation and collection of batteries must be well established before any recycling process is organized.

Recycling processes evaluated by EPBA (European portable battery association) have proved that mercury-free manganese-alkaline and zinc-carbon batteries can be recycled in metallurgical processes, as in electric arc furnace for steel production or in zinc production in rotary furnaces. The occurrence of mercury in these batteries makes the recycling of these batteries in processes operated at high temperatures difficult [2]. In Germany recycling of mercury-free batteries is already applied at ARGE ÖKO BAT in Duisburg, ACCUREC in Mülheim an der Ruhr, DK Recycling und Roheisen GmbH in Duisburg, NIREC in Dietzenbach, NQR in Lübeck, REDUX GmbH in Dietzenbach and VARTA in Hannover. In France there are also different recycling companies as CITRON in Rogerville, SNAM in St. Quentin and VALDI in Feurs [26].

In the USA, some companies are recycling batteries: INMETCO in Pennsylvania, RMC in Ontario and Salesco Systems in Arizona. These companies recycle many kinds of batteries using different metallurgical processes [27].

2.4. Batteries recycling processes

Metallic scraps can be subject to different recycling processes, including the mineral processing techniques, pyrometallurgical or hydrometallurgical treatment. The products of the recycling process are metallic alloys or compounds, or solutions containing metal ions.

Mineral processing techniques intends to separate materials according to different properties like density, conductivity, magnetic behavior, etc. [28]. This treatment is usually applied as a pre-treatment to concentrate the metallic fraction, which will be conducted to a hydrometallurgical or a pyrometallurgical recycling process [29].

NIREC Company, in Germany, has developed a recycling process based on the materials separation by means of vacuum milling. Nickel is separated and sent as raw material to the secondary metallurgy [24]. The system places procedural emphasis on the separation, reclamation and use of the high-quality nickel content, and the potential risk of hydrogen. Due to the possibility of hydrogen being released when the NiMH batteries are pound, the processing must be performed in a vacuum environment. Using a vacuum system, the batteries are passed through a cutting chamber, which opens up the casing and releases the stored hydrogen, which is constantly drawn off by the difference in pressure. The batteries then land in a collecting container. After a stabilization period monitored by sensors, and then aeration to render it inert, the material can then be taken out. After separation of the plastic content, a usable product is obtained with a high nickel content, which can then be reused as a significant alloying component in stainless steel production [23]. To separate materials from lithium batteries the Toxco process uses cryogen embitterment [30].

Pyrometallurgical processes are usually associated with the production of steel, ferromanganese alloys or other metallic alloys. Zinc is often recovered by condensation as a dust. Pyrolysis furnaces with a controlled atmosphere are also applied as a pre-treatment step to remove mercury and organic matter such as paper, plastic, etc. [31]. The pyrometallurgical processes operated at high temperatures are usually associated with a high atmospheric emissions control, since dioxins, chloride compounds and mercury can be generated on the process.

Hydrometallurgical processes are connected to leaching steps in acid or alkaline medium and purification processes in order to dissolve the metallic fraction, in order to recover metal solutions that could be used by the chemical industry.

2.4.1. Hydrometallurgical processes

The processing of metals using hydrometallurgical techniques is becoming a well-established and efficient method for recovering metals from raw materials. In Belgium the company MMM-Sedema is developing the recycling of zinc-carbon and manganese-alkaline batteries. The batteries are mechanically processed to recover a metallic fraction (magnetic and density difference separation). The wastes generated in this process consist of a black powder composed basically of carbon, manganese and zinc. The powder is leached and a solution rich in manganese and zinc is produced. The solution is purified and manganese and zinc salts are produced [31].

In the USA, a process that has already been developed has the treatment of a mixture of dry cell batteries (zinc-carbon, manganese-alkaline, nickel-cadmium and lithium). The BATENUS process consists of many steps of mechanical treatment and hydrometallurgical processing techniques. An automatic sorting of batteries is applied and individual streams of batteries with different compositions are generated. Batteries containing mercury are separated and treated alone. The batteries become brittle after a cryogen treatment and fractions are separated by differences in size, density and magnetic characteristics. The resulting black powder is leached using sulfuric acid and the metals are recovered by electrolysis and electrodialysis [32]. Another process based on a combination of solvent extraction, ionic exchange and membrane technology has been in operation since 1997 in Germany [33].

The process AED has been developed for the recycling of lithium batteries. The process uses grinding techniques for the separation of materials and cobalt reduction reactions at room temperature [30].

Recycling processes for NiMH batteries have begun as a function of the economic value associated with nickel, cobalt and rare earths recovery. In Japan, hydrometallurgical researches have been used to recover metals [14]. Mechanical processing to recover nickel has also been evaluated [34].

2.4.2. Pyrometallurgical processes

In the case of the pyrometallurgical processes, there are two possibilities of treatment: processes of secondary metallurgy, which uses batteries as raw material, and processes created specifically for batteries.

The use of batteries as raw materials in steel production is one process among other possibilities for the recycling of batteries. In this case, metals present in the batteries, such as iron, chromium, nickel and manganese, can be used as feed materials to adjust the steel composition. Hazardous compounds, such as cadmium, copper and zinc, may be diluted in the process so that their presence should not interfere with the steel properties. Among the metallurgical problems associated with this practice are the limits in the concentration of chromium, cooper and nickel on the production of steel in the electric arc furnace. These elements may be considered contaminants and their concentrations must be controlled in the charge in order to avoid the deterioration of the steel properties. Zinc and cadmium will evaporate at the steel production temperatures. After leaving the furnace, the vapor phase reacts with oxygen and generates hazardous dusts. Mercury will cause similar problems, because this element is going to concentrate in the dusts. Chromium tends to concentrate in the slag produced, turning the slag a hazardous waste and decreasing the possibilities of use as raw material in civil construction materials [35]. Therefore, the utilization of batteries as raw material in steel production is restricted to batteries without mercury and pre-sorted. Usually this process has been applied just for zinc-carbon and manganese-alkaline batteries [2].

The imperial smelting process (ISP) in Duisburg has evaluated the recycling of zinc-carbon and zinc-air batteries on zinc production in Germany. The ISP has as a main product zinc and is already operating with different zinc concentrates as raw material [36]. Another process in Germany for batteries containing zinc is the WAELZ process, used in the recovery of metals from dusts by means of a rotary furnace. It is possible to recover Zn, Cd and Pb [37,38].

Processes created specifically to recycle batteries include different pyrometallurgical techniques [39–41]:

- Pyrolysis: Water and mercury are evaporated, separated and condensed. Organic compounds are thermally destroyed and emitted as a gas together with the water.
- Reduction: The metallic fraction that remains in the furnace after the pyrolysis is going to be treated by reduction at temperatures around 1500 °C. The reduction agent is the carbon produced by the pyrolysis step. Metallic alloys are produced.
- Incineration: The gas generated in pyrolysis is incinerated at temperatures around 1000 °C and then quenched to avoid the generation of dioxins. The sludge generated on the process contains mercury and should be treated by distillation. The wastewater from the gas rinsing process must be treated in an effluent treatment station.

RECYTEC is a Swiss process created in 1989 specifically for the recycling of battery mixtures. By pyrolysis and magnetic separation a steel scrap and a zinc dust free from mercury are obtained and sent to the specific recycling processes [42]. Nowadays it is used for the recycling of all types of batteries with the exception of NiCd batteries, as well as in the recycling of mercury lamps [43–45].

SUMIMOTO is a Japanese process totally pyrometallurgical used in the recycling of all types of batteries with the exception of NiCd batteries [45]. It is based on a pyrolysis stage, where mercury is recovered from the generated gas in a reduction stage, where zinc is recovered as a dust and a ferromanganese alloy is produced. The Swiss company BATREC did a modification of the SUMIMOTO process. The SUMIMOTO process was created for portable batteries. The BATREC process treats any waste containing heavy metals (batteries, dental wastes, thermometers, scraps, etc.) [39,40]. In France the company CITRON has developed a recycling process also based on pyrolysis and metal reduction techniques, where different materials can be treated after mechanical processing [46].

NiCd batteries are treated usually in a separate process as a function of two important reasons: the presence of cadmium that promotes some difficulties in the recovering of mercury and zinc by distillation, and the metallurgical difficulties associated with the separation of nickel and iron. Different processes were then created for NiCd battery recycling. In France it is done by the SNAM-SAVAM process [47] and Sweden uses the SAB-NIFE process [48]. Both processes use a totally closed furnace, where cadmium is distilled at a temperature between 850 and 900 °C. It is possible to obtain 99.95% pure cadmium condensate [49,50]. Nickel is recovered in electric furnaces by reduction. The production of cadmium oxides in open furnaces is not used due to safety problems.

In Germany one of the installed NiCd battery recycling processes is the ACCUREC, in Mülheim. It is based on a vacuum distillation furnace that produces cadmium and ferronickel alloys. The ACCUREC Company is also developing vacuum distillation processes for the recycling of lithium batteries [24,51]. Due to the comparatively small quantities of nickel-cadmium batteries used, about 8000 t per year, the capacities offered by the existing facilities in Germany, France and Sweden are sufficient for the recycling of all batteries in western Europe [23].

In the USA International Metal Reclamation Company (INMETCO), a subsidiary of the International Nickel Company (INCO), recycles NiCd batteries with a high-temperature process. The process was initially developed aiming at the recovery of metals from electric arc furnaces dusts. However, the process can be also applied to recover metals from other wastes and is being used to treat NiCd batteries [52]. The process used by INMETCO, as well as the SNAM-SAVAM and the SAB-NIFE, is based on cadmium distillation. Recovered nickel is used in stainless steel production. Cadmium remains in the dusts with zinc and lead and is sent out for recycling by another company [27].

Studies related to the recycling of lithium batteries have also been conducted. One of these processes is the SONY process, which recovers cobalt after an incineration step [30]. The Mülheim-based Company ACCUREC in Germany has developed the recycling through vacuum distillation (RVD) procedure for lithium manganese oxide ($LiMnO_2$) batteries. SNAM in France also offers a reprocessing procedure based on pyrolysis and magnetic separation for lithium secondary systems [23].

Acknowledgements

The authors thank CAPES-PROCAD for the financial support.

References

[1] H. Lund, The McGraw-Hill Recycling Handbook, 2nd ed., McGraw-Hill, New York, 2001.
[2] European Portable Battery Association, 2 April 2003. http://www.epba-europe.org.
[3] W. Baumann, A. Muth, Batterien—Daten und Fakten zum Umweltschutz, Springer, Berlin, 1997, 593 pp.
[4] F. Hiller, R. Giercke, H.A. Kiehne, Entsorgung von Gerätebatterien, Expert-Verlag, Hannover, 1998, 61 pp.
[5] C.C.M.B. Souza, D.C. Oliveira, J.A. Tenório, Charaterization of used alkaline batteries powder and analysis of zinc recovery by acid leaching, J. Power Sour. 103 (2001) 120–126.
[6] J.C. Bartels, How to calculate collection rates for spent batteries, in: Proceedings of the Fifth International Battery Recycling Congress, Deauville, France, 1999.
[7] N.F. Oldershausen, VFW-Rebat, a private, profit-oriented battery collection, in: Proceedings of the Fifth International Battery Recycling Congress, Deauville, France, 1999.
[8] F. Putois, Market for nickel-cadmium batteries, J. Power Sour. 57 (1995) 67–70.
[9] Choice of Battery Chemistries, 2 April 2003. http://www.cadex.com.
[10] I. Buchmann, What's the best battery? 2 April 2003. http://www.batteryuniversity.com.
[11] F. Sturn, Secondary batteries—nickel-cadmium battery, in: Comprehensive Treatise of Electrochemistry, vol. 3, Plenum, New York, 1981.
[12] H.A. Kiehne, et al., Portable Batteries, Expert-Verlag, Hannover, 1988, pp. 28–32.
[13] C. Pons, et al., Development of a hydrometallurgical process for the recycling of metals from nickel-cadmium batteries and other similar wastes, in: Proceedings of the Third ASM International Conference on the Recycling of Metals, Barcelona, 1997.
[14] P. Zhang, T. Yokoyama, O. Itabashi, Y. Wakui, T. Suzuki, K. Inoue, Recovery of metals from spent-metal hydride rechargeable batteries, J. Power Sour. 77 (1999) 116–122.
[15] W. Qunwei, L. Wenquan, P. Jai, Characterization of a commercial size cylindrical Li-ion cell with a reference electrode, J. Power Sour. 88 (2) (2000) 237–242.
[16] C. Iwakura, Y. Fukumoto, H. Inoue, S. Ohashi, S. Kobayashi, H. Tada, M. Abe, Electrochemical characterization of various metal foils as a current collector of positive electrode for rechargeable lithium batteries, J. Power Sour. 68 (2) (1997) 301–303.
[17] J.M. Chen, C.Y. Yao, S.P. Sheu, Y.C. Chiou, H.C. Shih, The study of carbon half-cell voltage in lithium-ion secondary batteries, J. Power Sour. 68 (2) (1997) 242–244.
[18] H.A. Van der Sloot, L. Heasman, Ph. Quevauviller, Harmonization of Leaching/Extraction Tests, Elsevier, Amsterdam, 1997.
[19] J.L. Means, et al., The Application of Solidication/Stabilization to Waste Materials, Lewis, USA, 1995.
[20] N. Watson, Post-consumer battery sorting, in: Proceedings of the Fifth International Battery Recycling Congress, Deauville, France, 1999.
[21] P.H. Sattler, See the label, know the type, in: Proceedings of the Fourth International Battery Recycling Congress, Hamburg, Germany, 1998.
[22] S. Rausch, Sorting of spent batteries by a fast X-ray technique in the sorbarec process, in: Proceedings of the Fourth International Battery Recycling Congress, Hamburg, Germany, 1998.
[23] J.L. Fricke, N. Knudsen, Disposal of Portable Batteries, GRS Batterien, May 2002.
[24] J.L. Fricke, Entsorgung verbrauchter Gerätebatterien, GRS Batterien, March 1999.
[25] C.J. Rydth, M. Karlström, Life cycle inventory of recycling portable nickel-cadmium batteries, Resourc. Conserv. Recycl. 34 (2002) 289–309.
[26] Gemeinsames Rücknahmesystem Batterien, GRS Batterien, 7 April 2003. http://www.grs-batterien.de.
[27] About INMETCO, 7 April 2003. http://www.inmetco.com.
[28] J.A.S. Tenório, D.C. Oliveira, A.P. Chaves, Carbon-zinc batteries treatment by ore processing methods, in: Proceedings of the Global Symposium on Recycling Waste Treatment and Clean Technology (REWAS'99), vol. II, TMS, 1999, pp. 1153–1160.
[29] J. Frenay, S. Feron, Domestic battery recycling in western Europe, in: J.H.L. Van Linden, D.L. Stewart Jr., Y. Sahai (Eds.), Proceedings of the Second International Symposium on Recycling of Metals and Engineered Materials, The Minerals, Metals and Materials Society, 1990, pp. 639–647.
[30] M. Lain, Recycling of lithium ion cells and batteries, J. Power Sour. 97/98 (2001) 736–738.
[31] A. Vassart, A chemical recycling scheme for used primary batteries, in: Proceedings of the Global Symposium on Recycling Waste Treatment and Clean Technology (REWAS'99), vol. II, TMS, 1999, pp. 1139–1146.
[32] F.P. Reinhard, A process for the recovery of raw materials from used batteries, in: E.W. Brooman (Ed.), Electrochemical Technology Applied to Environmental Problems, The Electrochemical Society, USA, 1995.
[33] L. Pietrelli, Metal recycling from exhausted batteries, in: Proceedings of the Global Symposium on Recycling Waste Treatment and Clean Technology (REWAS'99), vol. II, TMS, 1999, pp. 675–680.
[34] J.A.S. Tenório, D.C.R. Espinosa, Recovery of Ni-based alloys from spent NiMH batteries, J. Power Sour. 4707 (2002) 1–4.
[35] C.I. Helgesson, R. Lindén, Metallurgical and ecological aspects on using recycled general purpose batteries in steel making, in: Proceedings of the Fifth International Battery Recycling Congress, Deauville, France, 1999.
[36] W.D. Schneider, B. Schwab, New ways for economical and ecological battery recycling, in: Proceedings of the Fifth International Battery Recycling Congress, Deauville, France, 1999.
[37] B. Egocheaga-Garcia, Developing the Waelz process: some new possibilities for the preparations of the load in the Waelz process and ultradepuration of the volatile fraction obtained in this process, in: Proceedings of the Third International Conference on the Recycling of Metals, ASM, 1997, pp. 387–402.
[38] W.S. Moser, G.T. Mahier Jr., R.T. Knepper, M.R. Kuba, F.J. Pusateri, Metals recycling from steelmaking and foundry wastes by horsehead resource development, in: Proceedings of the International Conference on Electric Furnace, 1992, pp. 145–157.
[39] A. Krebs, Recycling of household batteries and heavy metals containing wastes, in: Proceedings of the Global Symposium on Recycling Waste Treatment and Clean Technology (REWAS'99), vol. II, TMS, 1999, pp. 1109–1116.
[40] A. Krebs, Batrec industry, in: Proceedings of the Fifth International Battery Recycling Congress, Deauville, France, 1999.
[41] R. Burri, The oxyreducer technology: a new process to recycle used batteries, in: Proceedings of the Fifth International Battery Recycling Congress, Deauville, France, 1999.
[42] J.F. Equey, Recymet: our experience in the recycling of spent batteries, in: Proceedings of the Fourth International Battery Recycling Congress, Hamburg, Germany, 1998.
[43] H. Jordi, A financing system for battery recycling in Switzerland, J. Power Sour. 57 (1995) 51–53.
[44] P. Ammann, Economic considerations of battery recycling based on recytec process, J. Power Sour. 57 (1995) 41–44.
[45] J. Frenay, Ph. Ancia, M. Preschia, Minerallurgical and metallurgical processes for the recycling of used domestic batteries, in: Proceedings of the Second International Conference on Recycling of Metals, ASM, 1994, pp. 13–20.
[46] R. Burri, The oxyreducer technology: a new process to recycle used batteries, in: Proceedings of the Fifth International Battery Recycling Congress, Deauville, France, 1999.

[47] M.E. Schweers, J.C. Onuska, R.K. Hanewald, A pyrometallurgical process for recycling cadmium containing batteries, in: Proceedings of HMC-South'92, New Orleans, 1992, pp. 333–335.
[48] T. Anulf, SAB-NIFE recycling concept for nickel-cadmium batteries—an industrialised and environmentally safe process, in: Proceedings of the Sixth International Cadmium Conference, Cadmium Association, 1990, pp. 161–163.
[49] International Metals Reclamation Company (INMETCO), 7 April 2003. http://www.rbrc.com/inmetco.htm.
[50] J. David, Nickel-cadmium battery recycling evolution in Europe, J. Power Sour. 57 (1995) 71–73.
[51] R. Sojka, Innovative recycling technologies for rechargeable batteries, in: Proceedings of the Fourth International Battery Recycling Congress, Hamburg, Germany, 1998.
[52] R.H. Hanewald, L. Schweyer, M.D. Hoffman, High temperature recovery and reuse of specialty steel pickling materials and refractors at INMETCO, in: Proceedings of the International Conference on Electric Furnace, 1991, pp. 141–146.