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An overview on the current processes for the recycling of batteries

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Abstract

The objective of this study is to describe the main battery-recycling processes currently used and those that are being developed. Technological options are presented for the recycling of lead acid, Zn–C, Zn–MnO_2, nickel metal hydride, nickel–cadmium, lithium and lithium ion batteries.

Keywords: Battery-recycling; Battery collection; Battery disposal

1. Battery-recycling

Due to new environmental legislation regulating batteries' disposal in several countries, some processes were developed for the recycling of such products.

In order to promote battery-recycling, it is necessary to know its composition. Unfortunately, there is no relation between the size or shape of batteries and their composition. Researches have occurred in several laboratories in order to develop new recycling processes for used batteries or, in certain cases, new treatments to allow a safe final disposal.

2. Lead acid batteries

Lead acid batteries are usually composed of two plates: one of a Pb alloy and the other of a PbO_2 base. During the batteries' discharge, $PbSO_4$ is formed. The PbO_2 base plate is essentially composed of a Pb alloy grate in which a PbO_2 paste is impregnated. The grates are normally composed of alloys containing low amounts of Ca, Sb and Sn. The electrolyte used is a sulfuric acid solution [1].

A polypropylene box typically contains the electrolyte and a group of six cells.

Lead acid batteries' recycling is very similar to the primary lead production process. The main differences are in material preparation before reduction, which affects plant size, since there is no need for sintering.

The recycling sequential steps normally are the separation of the plastic case (using hammers or saws), acid removal, separation of the plastic, metallic lead and paste separation, reduction, refining and casting [2].

Acid, polypropylene and lead are recovered in the recycling process. Fig. 1 shows a flowsheet of the recycling process.

Rotary furnaces, shaft furnaces and reverberatory furnaces are the most used.

Baghouse provides the treatment of the gases originated in the furnace, which means that current technologies are very conventional, both for recycling and effluent treatment.

3. Methods for battery-recycling

There are basically three methods for battery-recycling: separation of components through unity operations of mining treatment, pyrometallurgy and hydrometallurgy [3].

3.1. Separation of components through unity operations of mining treatment

This method is especially used on industrial batteries. Batteries are treated in order to separate materials of interest or to concentrate such materials for further recovering through

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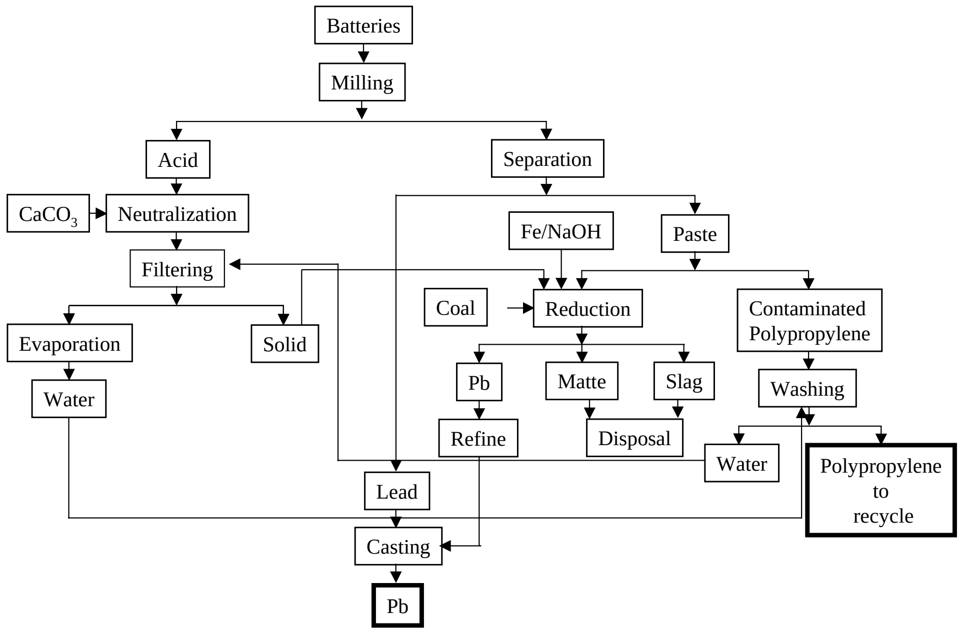

Fig. 1. Flowsheet of the pyrometallurgical recycling process of Pb–acid batteries.

other processes. This type of treatment is often the first phase of the recycling process, which means that it is the initial treatment of the scrap for a later recycling process.

Considering NiCd batteries, most of the Ni plates, more than 2 kg each, contained in industrial batteries can be recovered. A compound with a high amount of Cd can also be obtained and can be treated in a pyrometallurgical process for Cd distillation and recovery. Besides the separation of Cd electrodes, the battery case material, the electrolyte and Ni plates are also recovered [4–6].

The unity operations of mining treatment use only physical mechanisms and therefore are cheaper than any other treatment. Even though this process can have limited applications, it can lower the cost of further processing.

3.2. Hydrometallurgy

Recycling through hydrometallurgy basically consists of the acid or base leaching of scrap to put the metals in a solution. Once in a solution, metals can be recovered by precipitation, altering the pH of the solution or adding some reaction agent or by electrolysis. The solution can also be separated by solvent extraction, using an organic solvent, which binds to the metallic ion, separating the metal from the solution. The metal can then be recovered by electrolysis or by precipitation [7–9].

Cerriuti et al. [10] have studied the bio-leaching of NiCd batteries using *Thiobacillus ferrooxidans* and concluded that this technique provides results that are similar to those obtained in standard leaching process using sulfuric acid and could thus represent a cost reduction, since it does not use a concentrated acid.

Nogueira et al. [11] studied Cd, Ni and Co recovery by solvent extraction on NiCd batteries. This process basically consists of the acid leaching of batteries followed by organic solvent extraction. The solvent extraction is divided into two steps: in the first one, the Cd contained in the Ni and Co solution is separated, obtaining a second solution, which contains mainly Cd, and a third one, which contains Ni and Co. Then, another extractant is used in the third solution to separate Ni from Co. Thus, at the end of the process, three solutions are obtained, one rich in Cd, the other in Ni and the third one in Co. These metals can be recovered by precipitation or electrolysis.

Another example of hydrometallurgical process for NiCd batteries is the Toegepast-Natuurwetenschappelijk Onderzoek (TNO) [12,13]. The main advantage of using hydrometallurgical process is that it consumes less energy, but it generates wastes that must be treated afterwards.

3.3. Pyrometallurgy

This type of process essentially consists of recovering materials by using high temperatures. Pyrometallurgy can eliminate Hg contained in Zn–Mn dry batteries. After Hg decontamination, Zn may be recovered by distillation [14]. Considering NiCd batteries, cadmium can be distilled [15,16].

Presently, there are two main pyrometallurgical processes for NiCd batteries' recycling. One process evaporates cadmium in open furnace, and cadmium is recovered in the form of cadmium oxide powder. In the other process, cadmium is distilled in a closed furnace, in a controlled atmosphere, obtaining metallic cadmium powder and a high-content nickel alloy [5,12,16,17].

A third process, battery chlorination, was proposed by Cox and Fray [18], resulting in the recovering of cadmium chloride. In this process, the battery is put in contact with chlorine or hydrochloric acid and there is the formation of cadmium chloride, but Ni and Co remain stable in the initial process. The compound is then heated to 1233 K for the distillation of cadmium chloride.

Three main examples of pyrometallurgical processes presently in operation are Snam in France, Sab Nife in Sweden and Inmetco (International Metal Reclamation Company) in the United States. The advantage of this type of process in comparison with hydrometallurgical ones is in the generation of hazardous wastes, which require further treatment. The major disadvantage is energy consumption, since operating temperatures are in the range of 800–1000 °C. The energetic comparison with hydrometallurgical processes is not simple, since such processes use electrolysis for metal recovering and thus consume electrical energy.

4. Battery-recycling processes

There are several processes for battery-recycling. Sometimes, these processes are designed for specific kind of battery, but there are some in which batteries can be recycled together with other types of materials. Some of these recycling processes are described below:

- *Sumitomo*: Japanese process totally based on pyrometallurgy. Its cost is very high and it is used to recycle all types of portable batteries. It is not indicated for recycling of NiCd batteries.
- *Recytec*: Swiss process that combines pyrometallurgical, hydrometallurgical and physical treatments. It is used for recycling all types of portable batteries and also fluorescent lamps and Hg-containing tubes. This process does not recycle NiCd batteries. The investment for this process is smaller than that for the Sumitomo process, but operating costs are higher [19–21].
- *Atech*: Based on physical treatment of scrap batteries, it thus has a lower cost than hydrometallurgical or pyrometallurgical processes. It is used for recycling all portable batteries.
- *Snam–Savam*: French process for NiCd batteries' recycling, totally based on a pyrometallurgical method [22].
- *Sab Nife*: Swedish process for NiCd batteries' recycling, entirely based on pyrometallurgy [17,23].
- *Inmetco*: North American process by the International Nickel Company (INCO). Initially developed with the objective of recovering dusts from electric arc furnaces. It can also be used to recover metallic wastes from other processes, and NiCd batteries can be included as one of such wastes [24,25].
- *Waelz*: Pyrometallurgical process to recover metals from steelmaking dusts. The process uses a rotary furnace and recovers metals such as Zn, Pb and Cd from steelmaking wastes [26,27].
- *TNO*: Hydrometallurgical Dutch process for batteries' recycling. This process developed two recycling alternatives, one for Zn–C and alkaline household batteries and the other for NiCd batteries. The alternative for household batteries was not commercially implemented [12,13].
- *Accurec*: German pyrometallurgical process to recycle batteries, where NiCd batteries are treated separately [28].

In pyrometallurgical processes, NiCd batteries are recovered separately due to the presence of Cd, which inhibits Hg and Zn recovery by distillation, since Cd is also a volatile metal.

In France, Snam–Savam process is used for this type of operation, while in Sweden, the Sab Nife process is used. Both processes use a fully closed furnace in which Cd is distilled at a temperature between 850 and 900 °C, obtaining cadmium whose purity is higher than 99.95% [29]. Nickel is recovered in electric furnaces by reduction and smelting. The production of cadmium oxide in open furnaces was stopped due to extremely unhealthy working conditions.

In the United States, the company Inmetco, an INCO subsidiary, is the only company authorized to recycle NiCd batteries by using high-temperature processes. Inmetco processes, as well as Snam–Savam and Sab Nife, are all based on cadmium distillation. In these processes, Ni recovered is used by the stainless steel industry. Cadmium remains in the gases mixed with zinc and lead, and the mixture goes to another company for later separation [30].

4.1. Inmetco

Inmetco process was initially conceived to recover Fe, Zn and Pb from dusts generated at electric arc furnaces [31–36]. The process basically consists in agglomerate dusts together with a carbon-based reduction agent (self-reducing pellets). The self-reducing pellets are placed on a rotary hearth furnace, operating at temperatures up to 1350 °C. Pellets diameters are of approximately 12 mm and the load corresponds to three layers of pellets.

Due to high temperatures, the reduction of oxides occurs for up to 15 min. In the process, volatile metals such as Pb and Zn are collected by the gas treatment system. Basically, Fe–Cr metallic pellets are produced and then melted in an electric arc furnace.

The process allows the treatment of other types of wastes containing Fe, batteries included. Thus, NiCd, NiFe, NiMH, Li ion and Zn–Mn batteries free of Hg can be treated by Inmetco process [37]. Cd of the NiCd batteries is collected by the gas system together with other volatile metals. Material obtained in the gas system is sent to another company for metal recovery.

In December 1995, the company put into operation a unit for the specific treatment of NiCd batteries. Cd is recovered in a different process than the one used until that date.

Reduction using carbon occurs in a high-temperature reactor, followed by vaporization and condensation [38].

The battery treatment unit is located at Ellwood City, PA, and it is the only NiCd batteries' recycling unit in the United States.

The company receives the batteries in 50 L recipients or by mail. Initially, only NiCd batteries were received, but manual selection was used to avoid local contamination. Primarily, the process could admit other types of batteries, but load contamination by such other types of batteries could affect the purity of the products.

Before this unit started, both industrial batteries and sealed batteries were submitted to the process together with electric arc furnace dusts. Pre-treatment of industrial batteries consists of draining the electrolyte, which was used for pH control in the liquid effluents treatment station, while industrial batteries and sealed batteries are sent to the shredder and then for further treatment in the rotary hearth furnace with a carbon-based reducing agent.

After the starting of the NiCd batteries' recycling unit, some changes began to happen. Industrial batteries had their electrodes manually separated, after the removal of the electrolyte. Positive electrodes and stainless steel cases were then sent to the shredder and afterwards to the rotary hearth furnace. Negative electrodes were washed in order to remove residual quantities of electrolytes and then were treated together with sealed batteries.

Negative electrodes, pre-processed sealed batteries and a carbon-based reduction agent are fed into the chamber of the reducing furnace that operates from 12 to 14 h at 950 °C and with an atmosphere of low potential of oxygen. Cd vapor is condensed in a second chamber. The Cd-free material remaining in the first chamber is directly transferred to the electric arc furnace. Exit gasses are processed in the baghouse. Cd purity is higher than 99.95% [39].

4.2. Accurec

This process was specially developed for NiCd batteries' recycling. The first furnace was installed in 1997 and had the capacity of processing 500 tonnes per year. A second furnace started operation in 2000. The company is located in Mülheim, Germany [28].

To treat industrial batteries, the first step is the removal of the electrolyte, as in the Inmetco process. Plastic and metal cases are separated and recycled outside the unit, which only keeps parts containing Cd that are sent for distillation treatment.

Considering sealed batteries, only plastic cases are removed, to be recycled outside the unit. The rest of the material is sent for distillation treatment.

After the separation process, batteries' components go through a vacuum distillation process. The furnace is a quartz tube in which a recipient with the batteries is introduced. Stainless steel flanges seal the tube and connect it with the condensation system, which is connected to the vacuum pump. Heating of the load is obtained through an induction furnace [28].

The processing cycle is done at an operating pressure of around 10 mbar. Initially, heating goes up to 500 °C to burn the plastics and remove the water. After this first step, the load is heated to 850 °C for the distillation of Cd. Literature suggests the existence of reduction agents added, but there are no details on which are such agents or on what are their quantities [28,40].

After around 12 h processing, Cd formed in the condenser has a 99.95% purity, except if some error occurs in the separation process causing contamination of the load with other type of battery.

4.3. TNO

The Toegepast-Natuurwetenschappelijk Onderzoek process [12] was developed for the recycling of NiCd batteries, aiming the recovery of Cd, Ni and Fe and also for recycling dry and alkaline small batteries.

The NiCd batteries' recycling process is initiated by reducing the size of the scrap using knife mills. At the end of this step, the size is less than 15 mm. The material is then separated in two fractions, called fine fraction for particles inferior to 3 mm and coarse fraction for particles over 3 mm.

The coarse fraction goes to the magnetic separator, which retains approximately 50% of this fraction. The magnetic part of the coarse fraction is basically composed of steel with low Ni and Cd contamination. Both the magnetic and the non-magnetic parts are washed with 6N HCl (30–60 °C) to remove the Cd present in the material.

Ni and Cd are concentrated in the fine fraction, which contains low Fe concentration. The fine fraction is then leached in 6N HCl acid that is also used to wash the coarse fraction. Liquid/solid ratio is 10/1, and the temperature is kept at 90 °C.

Cd separation from the leaching solution is made by solvent extraction. Cd is extracted in an extraction equipment by solvents in a countercurrent piece of equipment. Organic solution used is a mixture of 75% of tributilphosfate (TBF) and 25% of Shellsol R. The stripping of Cd is obtained using a diluted solution of hydrochloric acid. Cd is recovered from the solution by electrolysis. In the aqueous solution, the next step after Cd removal is Fe precipitation, changing the Fe^{2+} ion to Fe^{3+} by adjusting the pH to 4 with the use of hydrochloric acid. Finally, the solution free of Cd and Fe is submitted to electrolysis for Ni recovery.

The patent describing the process does not discuss the presence of Co in the material [12].

The process for recycling dry and alkaline household batteries follows the same principle as the process for the recycling of NiCd batteries. In such process, household batteries are milled in the shredder and the shredded materials are screened. The coarse fraction is mainly composed of metals and is separated from the process. The fine fraction, containing C, Zn, Hg and Mn, is then leached using hydrochloric acid; the solution is oxidized with NaOCl and later filtered for the separation of plastics, graphite and MnO_2. Hg is extracted from the solution by electrolysis, and $Zn(OH)_2$ is obtained by precipitation, with the pH adjustment using NaOH.

4.4. Sab Nife

The recycling process for industrial and sealed NiCd batteries is in operation in Sweden since the 80s. It is one of the first processes for recycling NiCd batteries and it was initially developed for automotive batteries [17].

The first step of the process is the removal of the electrolyte and cleaning and drying of electrodes. The material is loaded into one single reactor, operating in three steps. In the first step, organic substances are eliminated through combustion in controlled atmosphere. In this step, the furnace operates between 400 and 500 °C for a 24 h period. A mixture of nitrogen and 3–12% oxygen is used to avoid Cd evaporation. Gases go through a second chamber at 900 °C to burn and then are washed using alkaline pH waters.

After pyrolysis, the furnace is heated to 900 °C for Cd distillation. In this second step, atmosphere changes from oxidant to reducing, which means that the gas used is a mixture of nitrogen and hydrogen. This step lasts for about 20 h, and the remaining Cd is less than 0.01%.

Cd vapor is condensed into liquid state by transferring the vapor at 900 °C to a condenser at 450 °C. Finally, the temperature is elevated to 1300 °C to obtain an Fe–Ni alloy [17].

4.5. Snam–Savam

Snam (Société Nouvelle Dáffinage dês Métaux) is operating since 1985. In 1988, Savam (Société Aveyronnaise de Valorisation dês Métaux) initiated its operation with the same technology used by Snam for NiCd batteries' recycling [13]. Presently, this process is used on both NiCd and NiMH batteries. The process begins by automatic separation of batteries, followed by a distillation process obtaining Cd vapor and an Fe–Ni alloy. The Cd produced has a 99.99% purity [41].

In the first step, industrial batteries are cut for the separation of plastic cases. The electrolyte is drained and treated for Cd recovery and then sold to battery manufacturers. The cathode and anode are separated. These materials and the household batteries are then classified in three categories:

- material containing Cd;
- material containing Ni but not containing Cd;
- material containing neither Ni nor Cd.

Material containing Cd first goes through a pyrolysis process to remove organic materials. Then, Cd distillation is performed. Cd is cooled and melted, and it is sold to NiCd batteries manufacturers or to the coating industry. Fe–Ni residue is treated through smelting together with the material containing Ni but not containing Cd. The result is an Fe–Ni alloy that is sold to steelmaking plants [13].

4.6. Eveready

This process is applicable to treatment of wastes containing Cd and was developed to recycle NiCd batteries. It is a pyrometallurgical process in which heating occurs in three steps and in the same furnace [16].

The operation temperature in the first thermal cycle is in the range of 200–300 °C and the holding time is around 1.5–2 h. The objective of this step is the elimination of moisture in the load. The second step takes approximately 2–2.5 h with temperatures ranging from 500 to 700 °C. The objective of this phase is the removal of organic material.

Finally, temperature goes up to 900–1100 °C where the Cd distillation occurs. The holding time is around 2.5–3.5 h. In this step, an inert gas (argon) is purged in the reactor. Besides the inert gas, a carbonaceous material is placed at the surface of the load to react with the oxygen that might be originated in the load; consequently, this added material diminishes the oxygen potential of the chamber.

Vapor is condensed in a chamber adjacent to where temperature ranges from 400 to 300 °C. Recovered Cd has 99.9998% purity. As occurs with TNO process, no reference is made to the Co present in NiCd batteries.

4.7. NiMH and Li ion batteries' recycling

NiMH and Li ion batteries have a more complex system than that of zinc and NiCd batteries. Besides that, the systems are in constant evolution once they are more expensive and the result of a more modern technology. Consumption of such batteries has shown a recent growth mainly caused by restrictions on the use of NiCd batteries. This increasing demand is promoting the technological development of these systems so as to improve their performance and reduce their costs.

NiMH and Li ion batteries are not included in most battery-recycling policies. Consequently, there is no obligation on establishing a collection system and on developing recycling processes.

Snam and Inmetco processes operate with NiMH batteries but since they are pyrometallurgical processes, recovery is restricted only to the Ni-rich metallic fraction. Rare earths remain in the slag and are not recovered. On the other hand, Espinosa and Tenório [42] demonstrate that a recuperation of 86% of Ni alloys is possible with the sole use of physical separation process.

Lupi et al. [43] report the development of an industrial installation in Italy to recycle NiMH batteries. In this case, hydrometallurgy is used and it also allows the recovery of rare earths. The process consists essentially of milling and separation of plastic and magnetic materials, followed by leaching in a sulfuric acid solution and finally a purification phase in multiple steps aiming at selective precipitation adjusting the pH.

Zhang et al. [44,45] have studied a very similar process. But in this case, metals were separated by solvent extraction after a sulfuric acid-leaching step. This separation occurs in two steps. In the first step, the organic phase used was DEHPA and in the second, Cyanex 272.

In the case of Li ion batteries, cobalt is the element that presents higher economic worth. But there is a tendency to substitute this material by others of a smaller worth or even to substitute this type of battery by the Li-polymer type.

According to Lain [46], the Toxco and the Sony processes are the only ones in the operation for Li ion batteries' recycling. The Toxco process is applied for each waste containing Li. In this process, the material is cooled in liquid nitrogen before going to the shredder. Fed water reacts with Li, forming hydrogen that burns immediately. The process aims at the recovery of Li metal and hydroxide. Considering Li ion batteries, Co is also recovered, but there are no descriptions of procedures.

The Sony process consists of the heating of all the materials. Plastics, lithium and hydrogenated compounds are captured in the gas treatment system, while the Co containing slag is processed by hydrometallurgical treatment.

Several other projects are being developed but all of them are still in pilot or laboratory scale [47,48].

4.8. Sumitomo

This process was planned for treating exclusively $Zn–MnO_2$ batteries. Created in the 80s, it was one of the first for household batteries' treatment. Sumitomo process is in industrial use in Wimmis, Switzerland, at the Batrec Industry. A unit was set up in 1992 to process 2000 tonnes per year of household batteries [19]. In 1995, this unit was already processing 3000 tonnes per year [49,50].

The process consists of a first step aiming to promote mercury evaporation at 750 °C, followed by reduction in electric furnace at around 1500 °C [51].

The elimination of mercury is obtained in a rotary furnace at 750 °C. Generated gas contains, besides mercury, the products of the combustion of organic materials and chlorides. The organic materials are basically plastics and papers that are present in household batteries. This material passes through an afterburner furnace because of the organic gases and also through a mercury condenser system.

The solid phase generated in the rotary furnace, free of mercury and chlorides, is placed in a reduction electric furnace, where existing carbon in the batteries acts as a reducing agent. This furnace produces Fe–Mn alloy and zinc vapor, which are condensed and cast into ingots. Each tonne of scrap fed in the process produces 360 kg of Fe–Mn, 200 kg of Zn, 1.5 kg of Hg and 20 kg of slag.

In spite of being a quite simple process, it requires about 3500 kWh/tonne of scrap batteries. Besides this, this process does not allow load contamination with other types of batteries, in particular NiCd ones.

4.9. Recytec

Another process operating in Switzerland is the Recytec process [19], located in Aclens. The installed capacity of the unity is of about 2000 tonnes per year of household batteries.

Process includes some steps that are similar to the Sumitomo process. In this case, the temperature of treatment is 650 °C. According to De Oliveira et al. [14], mercury and its chlorites, which are present in standard and alkaline household $Zn–MnO_2$ batteries, are eliminated only at 600 °C or more, this being the reason for choosing such temperature in the process.

Similar to what happens in the Sumitomo process, the generated gas is treated for mercury condensation and further treated in activated carbon filters and an afterburner furnace.

The difference between this process and the Sumitomo is that the solid fraction from the evaporation process is directed to unity operations of mining processing. Thus, the material free of mercury is then milled. The coarse fraction produced is basically composed of steel plates, zinc cups, copper contacts and graphite used in electrodes.

Steel is separated by magnetic separation. Graphite is separated from the non-magnetic fraction through an Eddy current separator. The remaining copper and zinc go through hydrometallurgical treatment [19].

After milling, manganese oxide and part of the zinc remain concentrated in the fine fraction. This material is conditioned and treated in another unit through the Waelz process.

The process can also handle the treatment of other mercury-containing wastes, such as fluorescent lamps. Nevertheless, NiCd batteries must be separated.

4.10. Waelz

Lurgi, in Germany, before the World War I, developed the Waelz process. The initial objective was to obtain zinc from oxide ores. Presently, the most common use of this process is the treatment of electric arc furnace dusts. Several units are spread around the world. In the United States, Europe and Japan, around 1 million tonne of electric arc furnace dusts is treated every year [52–58].

The process is also applicable to other zinc-containing wastes such as alkaline household batteries that do not contain Hg.

The load of wastes is mixed with coal and silica and introduced into the rotary furnace. The inclination and the rotating movement of the furnace cause the load to move inside the furnace. Operation temperature is around 1200 °C and the holding time is approximately 4 h. Pb, Zn and Cd oxides are reduced and oxidized right on the top of the load, generating a powder material that is captured in the off-gas treatment system.

The other product of the process is an Fe-rich oxide that does not contain toxic elements. This product can be used for road paving or in converters for the formation of a slag during the steelmaking process.

The product collected in the baghouse generally contains impurities such as Pb and alkalis. In many cases, Waelz process is used in two steps. A second furnace is used for the treatment of those dusts, producing a high-grade zinc oxide that can be used as raw material for primary zinc metallurgy.

In this second furnace, no reducing agent or flux is added and the load is only composed of dusts originated in the first furnace. The furnace is operated using natural gas as heating source and operation temperature is in the range of 700–1000 °C.

4.11. TERA

TERA furnaces were developed for the processing of Hg-oxide batteries of the button type and also alkaline and dry household batteries [28].

There are three units in operation: NQR since 1996 and GMR since 1998, both in Germany, and also NKC since 2000 in Japan.

The process consists of heating the load up to 350 °C under vacuum. At the exit of the vacuum chamber, oxygen injection occurs for the combustion of products originated due to the decomposition of organic materials existing in the load. This combustion is processed at 850 °C keeping the partial pressure of oxygen under control so as to avoid oxidation of Hg. Differently from the Accurec process, TERA process operates in a vertical position and total pressure is under 1 mbar [28].

The process can also provide Hg recovery from other sources such as thermometers, mercury lamps and dusts from fluorescent lamps. Holding time is approximately 24 h in order to achieve a maximum concentration of 10 ppm of Hg in the load remaining in the interior of the furnace [28].

4.12. Batenus

Batenus process treats several types of batteries through a multiple-step hydrometallurgical process.

Initially, screening separates button-type batteries that are sent to another company. Then, remaining batteries are milled in a shredder. Ferrous materials are separated in a magnetic separator, and the rest of the material is screened once more for the separation of plastics, papers and non-ferrous metals from the active fraction of the batteries, which concentrates in the fine fraction [59,60].

Fine fraction is then leached in sulfuric acid solution and filtered. Manganese oxide and carbon material remain in the cake and this mixture is sold to Fe–Mn manufacturers.

Then, a complex sequence of purification operations of the filtered solution begins. Hg is separated through ion exchange resins. In the next step, Zn is extracted from the solution using solvent extraction. The solution is stripped with diluted sulfuric acid and then Zn is recovered by electrolysis.

Cu, Ni and Cd are extracted from the solution with the use of ion exchange resins. A diluted sulfuric acid solution is used for the elution. After the elution, the sulfate solution is submitted to electrolysis.

Manganese in the solution is precipitated by the use of sodium carbonate, causing precipitation of manganese carbonate. The alkaline metals remaining in the solution are concentrated by reverse osmosis, followed by bipolar membrane electrodialysis [59,60].

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