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Economic Feasibility of a Novel Alkaline Battery Recycling Process

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Economic Feasibility of a Novel Alkaline Battery Recycling Process

A Major Qualifying Project Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree in Bachelors of Science

By

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Abstract

Spent primary alkaline batteries present an unused source of 553,500 tons of secondary metals in Europe and the US in 2009. While battery recycling programs exist, current processes are not profitable, so industry growth is difficult. A novel mechanical separation process was developed to recycle alkaline batteries at lower cost than current methods. Using a process-based cost model, the cost was determined to be $1286 per metric ton with revenue of $382 per metric ton, so supplemental funding is needed.
Acknowledgements

We would like to thank several people who were crucial to the completion of this project. Firstly, we would like to thank our advisors Professor Yang Wang and Professor Jerry Schaufeld for all of their support and guidance through this process. We are also very grateful for the input and support from Professor Apelian who contributed and continuously challenged us to accomplish more in this learning process. Your dedication and knowledge helped us be inspired through the completion of the Major Qualifying Project.

Additionally, a few other faculty members at WPI were helpful in completing our project. We would like to thank Prof. Fabienne Miller who gave us advice in creating cost models and guiding us to a realistic costing estimation. On the experimental side, we would like to thank Professor John MacDonald for training and assistance with the powder x-ray diffraction testing machine; and Professor Boquan Li for his assistance with the scanning electron microscope. Maureen Plunkett, thank you for all help with the logistics and organizing our conference calls. Barbara Furhman, thank you for your assistance in ordering and acquiring the materials needed for testing of our project.

Our complete analysis would have not been possible without the contribution for people in industry. Thanks to their knowledge and information on the equipment, and experiences with the recycling process, we were able to complete our financial analysis and adjust our process to fit a realistic model.
Executive Summary

Single use alkaline batteries dominate the battery market today, making up for at least half the mass of all batteries sold in the United States, Canada, and Europe [1, 2, 3]. But while other battery chemistries are recycled due to their toxicity and high metal value, most alkaline batteries are not recycled. Alkaline battery recycling programs have been instituted in Canada and the EU, though Canada only recycled approximately 12% of alkaline batteries in 2011, and the EU only 13.6% in 2009 [1, 3]. Recycling rates are low because alkaline batteries can be landfilled and are not considered as valuable [4, 5]. However, several life cycle analyses have shown that the recycling of alkaline batteries can be environmentally beneficial through the reduction of land fill use and energy savings from material recovery, as shown in Figure 1 [1, 6, 7]. Hence, economic reasons must be limiting the recycling of alkaline batteries.

![Figure 1: Estimated total greenhouse gas emissions associated with end-of-life recycling and disposal [2].](image)

Traditional battery recycling processes, which are either hydrometallurgical or pyrometallurgical, are not economically feasible for dedicated alkaline battery recycling. Hydrometallurgical processing uses mechanical pre-treatment, followed by several chemical-based steps to create high-purity end products. The use of chemicals adds costs so it is not economically feasible. Pyrometallurgical processing is done using existing Electric Arc Furnace metal recovery technologies. These furnaces require large capital investment and have high power usage, so pyrometallurgical recycling is also not economically feasible. Therefore, there exists a need for a different method to make dedicated alkaline battery recycling a reality. This project focused on determining the economic feasibility of a novel alkaline battery recycling process.
To keep the costs of battery recycling low, a mechanical process was developed. The goals of this process were to recover as much of the battery material as possible for reuse, to minimize process complexity, to reduce cost, and to determine desirable end products that could be sold to existing scrap industries or for other applications. Experimental research was used to verify battery composition and to determine the feasibility of separation techniques. Contact was made with many equipment manufacturers to receive technical information about separation equipment, because most of the required equipment was unavailable at WPI. Equipment cost information was also garnered from manufacturers for conducting a financial analysis of the developed recycling process.

Financial analysis was done using Technical Cost Modeling (TCM) [8] and Process Based Cost Modeling (PBCM) [9]. TCM was used to help us determine what information was needed to accurately model the process. PCBM was used because it addresses the specifics of recycling processes by separately considering process requirements, operational requirements, and the economic details. Process requirements include the specific equipment required, the flow of material through the process, and end product characterization. The operational requirements are then a detailed list of equipment specifications developed from the process requirements. This information is compiled into a financial model, detailing the various costs and the revenue of the process.

The final process, seen below in Figure 2, begins with by shredding the waste, which is then baked to dehydrate the waste and remove any mercury present in the battery waste. The shredded waste is then filtered into a coarse fraction and a fine fraction. The coarse fraction consists of scrap steel, paper, plastic, and brass. The fine fraction consists of potassium hydroxide powder, zinc and zinc oxide powder, and manganese oxide powder of various valences. These fractions are further processed to separate their components. The most valuable end products identified are brass and manganese. Brass, while composing only 2 wt% of the battery, has a very high scrap value. Manganese has comparable value to steel and zinc products, and composes 44 wt% of the battery, making it the most abundant and valuable end product. Zinc powders, scrap steel, and KOH powder have comparable value. Carbon was not separated from other products due to the additional costs this would add. Paper and plastic cannot be recycled for revenue, though they can be diverted from landfill through energy recovery at waste-to-energy facilities.
The financial assessment of this process resulted in a cost to recycle of $1286 per metric ton of alkaline batteries, plus or minus 25% since grass-roots and factored estimates were made [10]. As can be seen in Figure 3 below, most of the cost is due to equipment cost, building cost, and overhead. The end products detailed previously generate revenue of $382 per metric ton. While this is cheaper than other reported recycling processes, it is not economically feasible without supplemental funding. The low value of the end products and difficulty in improving their value limit the economic viability of alkaline battery recycling. The existence of mercury in the waste stream, which is debated in literature but verified by industry contacts, adds cost as vaporization of the mercury is required to maintain environmental standards. Without requiring the removal of mercury, our process cost would be reduced to $1236 per ton of spent batteries.

![Figure 2: Developed Recycling Process for Alkaline Battery Waste](image)

![Figure 3: Total Cost Distribution Breakdown](image)
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1. Introduction

Nearly 80% of portable batteries manufactured in the United States are alkaline batteries [6]. Additionally, 46% of all primary batteries sold in Japan and 72% of all batteries sold in Canada were alkaline batteries [11, 12]. Currently, the majority of alkaline batteries are disposed of in landfills. However, unlike other types of battery waste, alkaline batteries are generally not considered to be hazardous. Neither the electrode materials nor the alkaline electrolyte are considered as harmful to the environment by the US Environmental Protection Agency [13]. Studies also shown that zinc and manganese from battery waste does not leach out of the battery in landfills [4].

The avoidance of toxic chemicals entering into the waste stream is not the only impetus for recycling. Battery recycling can be ecologically beneficial by reducing landfill usage and recovering the materials for reuse [6, 7]. Recently, there has been an increasing amount of legislation for battery waste, such as that implemented in Europe, Canada, and California, as well as growing discussion on the environmental impacts of alkaline battery waste. These legislations have pushed for the recycling of all battery waste, including alkaline. However, there are additional environmental burdens added by recycling programs that need to be weighed against landfilling.

Consideration should also be made of the cost of recycling alkaline batteries. Traditional pyrometallurgical or hydrometallurgical battery recycling methods use high amounts of energy or large amounts of chemicals, respectively, which drive up the cost of resource recovery. For valuable materials, these problems may not be so significant, but the zinc, manganese, and iron that make up alkaline batteries are plentiful and cheap. Alkaline battery recycling must be both environmentally beneficial and economically feasible in order to be widely implemented.
The goal of this project is to develop a mechanical separation process to reduce the costs of alkaline battery recycling. Experimental work was done to help make technical decisions, and contact was made with many equipment manufacturers for their expertise and to receive price quotes. A process-based cost model was used to do a financial analysis, determining the overall costs and revenue of recycling.
2. Literature Review

The literature review is broken up into three main sections describing the alkaline battery industry, the alkaline battery recycling industry, and an overview of economic modeling methods. The alkaline battery industry information provides a basic understanding of alkaline batteries and the size of the alkaline battery market. The alkaline battery recycling industry portion describes in detail how alkaline batteries are currently recycled, how legislation impacts the recycling industry in Europe, Canada, and the United States, and the environmental benefits and concerns of alkaline battery recycling. Finally, economic modeling methods are presented to give a background on how the financial analysis was conducted given the uniqueness of the recycling industry.

2.1. Alkaline Battery Industry

Despite the increasing visibility and market share of lithium ion batteries, alkaline batteries still dominate the battery market in terms of units sold as well as mass sold in Europe, Canada, and the United States [1, 2, 3]. The following sections describe the composition and construction of alkaline batteries, which is fundamental for the understanding of recycling methods, and presents the market size of the alkaline battery industry to give a better perspective on the recycling needs.

2.1.1. Alkaline Battery Composition

Alkaline batteries are non-rechargeable battery cells which are meant to be discarded after use. Energy is created by the battery as the manganese cathode is reduced and the zinc anode oxidized. The overall cell reaction of an alkaline battery is generally accepted as:

\[ \text{Zn} + 2\text{MnO}_2 \rightarrow \text{Mn}_2\text{O}_3 + \text{ZnO} \] [13]

This reaction is simplified from what actually occurs in the battery, where many different reduced manganese oxide compositions are formed. Aside from that, not all of the active materials are
used during the discharging of the battery. This means that the electrodes in an end-of-life alkaline battery do not have a consistent chemical composition, but instead are composed of many different manganese oxides such as MnO₂, MnOOH, Mn(OH)₂, Mn₃O₄, and Mn₂O₃, and a mix of zinc and zinc oxide [6, 14, 15].

The construction of alkaline batteries is relatively simple when compared to other battery chemistries. Figure 4 below shows the typical construction of an alkaline battery. Iron is used to make the steel shell of the battery. The cathode is made of electrolytic manganese dioxide powder and carbon, and the anode is made up of very high purity zinc powder, produced by either electrowinning or distillation [3]. The anode and cathode are both saturated with a potassium hydroxide electrolyte solution for ionic conductivity. The anode current collector is a brass pin, while the iron shell acts as the cathode current collector. The overall composition of an average alkaline battery is 37% manganese dioxide powder, 23% iron, 16% zinc powder, 9% water, 5% potassium hydroxide, 4% carbon, 2% brass, and 4% other [14, 16]. The composition of the electrode powders when combined can be seen below in Table 1. The ‘other’ components include a separator composed of fabric or paper and PVC sealing washer and label.

The existence of mercury in spent battery materials is a debated topic. All batteries have natural levels of mercury, but adding mercury to batteries is now illegal in the United States, Europe, and Canada. However, batteries from before these laws and counterfeit batteries may be in the waste stream and contain added mercury. The existence of mercury has both been shown and disproven in a variety of published journal articles [3, 14, 17].
Figure 4: Construction of a typical alkaline battery [13]

Table 1: Composition of powders from alkaline and zinc-carbon batteries [3]

<table>
<thead>
<tr>
<th>Element</th>
<th>Alkaline battery powder (wt.%)</th>
<th>Alkaline battery powder (wt.%)</th>
<th>Alkaline battery powder (wt.%)</th>
<th>Alkaline battery powder (wt.%)</th>
<th>Zinc-manganese dry battery powder (wt.%)</th>
<th>Mix battery powder (wt.%)</th>
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<td>Zn</td>
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<td>12-21</td>
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<td>17.05</td>
<td>28.3</td>
<td>15.46</td>
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<tr>
<td>Mn</td>
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<td>26-33</td>
<td>31.1</td>
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<td>33.59</td>
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<td>7.25</td>
<td>4.53</td>
<td>-</td>
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<td>&lt; 0.002</td>
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<td>-</td>
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<td>41.69</td>
<td>21.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References: De Souza and Tenorio (2004), De Souza et al. (2001), Salgado et al. (2003), Veloso et al. (2005), Peng et al. (2008), De Michelis et al. (2007)
2.1.2. Alkaline Battery Market

Alkaline batteries are the most commonly purchased batteries in the US market. Alkaline batteries dominate the primary battery market because they are cheap and offer better performance than other primary battery types [13]. The United States generated a shipment of 5.4 billion units in 2010, and of that 5.4 billion, 4 billion (75%) of these were alkaline batteries [2]. An estimated 133,000 metric tons of alkaline batteries were shipped throughout the United States in 2010 [2]. The 5 major manufacturers that dominate the USA’s single use battery market are Duracell, Energizer, Spectrum, Panasonic, and Kodak [2]. Over time, the primary battery market has shifted from zinc-carbon to alkaline batteries, driving growth [18]. The demand for primary batteries is expected to continue increasing in the future as can be seen in Figure 5.

![Demand for Primary Batteries](image)

Figure 5: Demand for Primary Batteries [5]

2.2. Alkaline Battery Recycling Industry

While demand for alkaline batteries is high, recycling of alkaline batteries is low. In 2009, only 13.6% of primary batteries used in Europe were collected for recycling, and about 30,000 tons of alkaline, zinc-carbon, and zinc-air batteries were recycled [3]. A quick extrapolation shows that approximately 220,500 tons of primary batteries were disposed of in the EU in 2009. In Canada, alkaline
batteries account for 58% of the battery market by weight [1]. The metals in alkaline batteries are a currently untapped secondary source for metals that could yield hundreds of thousands of tons of metal for the market, as well as diverting these metals from landfills.

2.2.1. Existing Recycling Processes

All alkaline battery recycling processes consists of several basic steps. After spent batteries arrive at a recycling facility they are sorted by chemistry. No recycling process can handle all types of battery chemistries, so sorting is crucial in maintaining product quality. Once waste batteries have been sorted, several different recycling processes exist.

2.2.1.1. Pyrometallurgical Processes

A pyrometallurgical process usually begins by melting sorted but otherwise unprocessed batteries. Pyrometallurgical processing uses a temperature of at least 900 °C to separate metals by volatilization and melt behavior [19]. In these melts, iron and manganese remain in liquid form, while other components vaporize. Vaporized products include organics, mercury, potassium, carbon, and most notable zinc. Vaporized zinc is often recovered as an end product. Other vapors are treated to prevent toxic gasses from escaping, a costly but necessary step. Three large scale pyrometallurgical recycling processes suitable for recycling alkaline batteries are Batrec’s process in Switzerland, Citron’s process in France, and Valdi’s process also in France. Batrec’s process is described in detail below, along with an overview of the unique aspects of the other processes. Flowcharts of the other processes can be found in Appendix A [7].

Batrec is a Swiss company whose primary business is recycling batteries and other products that contain heavy metals. In Batrec’s process, the batteries are first manually sorted and then moved into a shaft furnace at temperatures up to 700 °C. The high temperature vaporizes the organic components that are then purified by washing the gasses with water, causing the vapors to solidify and separate.
Mercury vapors are produced at this stage, which are condensed and recovered via distillation. The remaining battery components are then moved into an induction furnace with a reducing environment at 1500 °C. The high temperature causes the manganese to combine with the remaining iron components, producing ferromanganese. Zinc is completely vaporized, and condensed for recovery. The Batrec process can be seen in Figure 3.

The Citron process differs from the Batrec process because it only uses one furnace. The gas effluent from this stage is treated to recover zinc, mercury and salts. Ferrous metals and manganese oxides, rather than being combined, are separated from one another and sold after the furnace treatment. The Valdi process is extremely similar to the Batrec process, but mechanical pretreatment is used to grind batteries to promote the vaporization of zinc. The Valdi process recovers zinc in the form of zinc oxide powders, rather than condensing the vapors to produce metallic zinc. A single United States based company, Inmetco, recycles alkaline batteries, and they do this through a pyrometallurgical process where the main goal is to recover iron and manganese from the batteries [1]. No company that uses pyrometallurgical methods exclusively processes alkaline batteries; they rely on other more valuable chemistries as well.

**Batrec Recycling Process**

*Figure 6: Batrec Pyrometallurgical Recycling Process [7]*
2.2.1.2. Hydrometallurgical Processes

Hydrometallurgical techniques have been used to process metals since the mid 1980’s, and over time have gained acceptance as an efficient way of recovering pure end products [3]. Hydrometallurgical processing generally involves a mechanical pretreatment step and the use of water or chemicals to separate and purify battery materials [19]. Hydrometallurgical processing is considered preferable to pyrometallurgical processes for battery recycling as hydrometallurgical processes have lower capital costs, can recover leachants used, and produce less air pollution. The chemical steps also require care so as not to create additional waste streams.

While there are many possible chemical operations for hydrometallurgical recycling processes, most begin by dissolving the electrode powders in an acidic solution. After this, metals can be separated from one another by altering pH of the solution, adding reaction agents to precipitate metallic salts, electrolysis, and liquid-liquid extraction steps [3, 20]. Processes can be categorized by how they pretreat the battery materials as well as what separation techniques are used. Figure 7 below shows the many different techniques which can be used to purify and separate metals from an acidic solution.

![Figure 7: Common Hydrometallurgical Recycling Processing Techniques [3]](image-url)
Several companies that currently recycle alkaline batteries operate hydrometallurgical processes; these include Batenus, Recupyl, Recycletec, and Revatech [20]. Other hydrometallurgical processes have been proposed in scientific journals. The most thorough example found was developed by F. Ferella, I. De Michelis, and F. Veglio of the Univeristy of L’Aquila [21]. Their study experimentally tested all the process steps and used a process cost analysis based on chemical engineering principles to determine economic feasibility. Their process is shown below in Figure 8.

![Figure 8: Process used for cost analysis in F. Ferella 2008 [21]](image)

The main products of this process are metallic zinc produced by electrolysis at a minimum purity of 99.6%, manganese oxides that can be sold as dyes for ceramics and paints or be used as raw materials for the production of other manganese compounds, and scrap steel alloys sold at €250 per ton [21]. Assuming that the process is supported by a battery surcharge of €0.5 per kilogram, and at a plant capacity of 5000 tons per year (about 1/6 of the batteries that are currently being recycled in the EU per year [3]), the return on investment was three years. The minimum possible surcharge to maintain
profitability was about €0.3 per kilogram. Perhaps most importantly, their unit cost of product was €0.72 per kilogram, or €720 per ton. This estimate does not include transportation, and when the cost is doubled to estimate transportation and collection costs, the costs is about $1800 per ton.

### 2.2.1.3. Physical Pretreatment and Separation Processes

Pretreatment steps are necessary to improve the dissolution of electrode materials into acidic solutions before hydrometallurgical processing. Pretreatments usually remove other battery materials so that they do not compromise the purity of end products. Figure 8 above details the pretreatment of batteries as well as the hydrometallurgical steps covered earlier. In most pretreatments, spent alkaline batteries are first sorted and then dismantled using a hammer-mill or industrial shredder. Screening is often used to separate electrode powders from other battery components at this point. Iron and non-ferrous materials are then separated using magnetic methods. Iron casings and electrode powders are often washed, albeit separately. During washing the potassium electrolyte is removed from solution along with soluble mercury [22]. Several options exist for separating the non-ferrous components of the battery, which include paper, plastic, graphite, and brass. Some commonly referenced methods are specific gravity separation and electrostatic separation [21, 23].

Mercury can be an environmental problem if it is not removed from batteries before any further processing and is generally not allowed in any amount in end products. Mercury can be entirely removed from battery materials by baking since it off-gasses at room temperature and completely vaporizes above 367 °C [23]. Baking at high temperatures can also burn off organics, but vaporize some of the zinc; therefore temperature selection is an important factor to consider [22].

An opportunity exists to separate anode and cathode powders based on their physical properties. Hydrometallurgical and pyrometallurgical techniques are very effective, but as shown earlier, add complexity and cost to recycling processes. One proposed method takes advantage of zinc’s low melting temperature compared to manganese, producing zinc agglomerates that can be separated from
manganese powder [22]. However, this method resulted in 70% separation or less. Physical separation of zinc and manganese oxides may be possible based on density and particle shape as well [17]. The density of metallic zinc is 7.14 g/cm$^3$, while the density of pyrolusite (MnO$_2$) is 5.03 g/cm$^3$. Hausmannite, a mineral composed of MnO$_2$ and Mn$_3$O$_4$, similar to spent cathode powders, has a density of 4.76 g/cm$^3$. Magnetic properties allow separation, as pyrolusite and hausmannite are weakly magnetic, while zinc and zinc oxide have no magnetic response [24].

Raw Materials Company (RMC), based in Ontario, Canada, has been using a primarily mechanical process to recycle alkaline as well as lithium ion battery materials for over 20 years. RMC reports that they divert from landfill 99.5% of alkaline battery materials, and recover 84.5% for reuse in various industries [1].

2.2.1.4. Current Patents on Alkaline Battery Recycling

Current patents for alkaline battery recycling were analyzed because the application for a patent represents a vested interest in the success of the process. Patents by active battery recycling companies were found, including Recupyl [25, 26], Revatech [27], and Raw Materials Company [28, 29]. Patents filed by other sponsors include the recovery of alkaline battery powders for brick coloring [30] and a hydrometallurgical process that spray dries the dissolved acidic solution to recover zinc and manganese sulfate for magnetic ferrite production [31]. It is worth noting that none of the recent patents found employed pyrometallurgical techniques and included or assumed a method to remove mercury from the battery waste. Diagrams of recycling processes retrieved from patents can be seen in Appendix A.

2.2.2. Legislation on Alkaline Battery Waste

Legislation has been the driving force behind the adoption of alkaline battery recycling in Europe and Canada. The European Union (EU) currently has the strictest legislation on alkaline batteries. EU Directive 2006/66/EC, published on September 26$^{th}$, 2006, required that all states meet a collection rate
for all batteries of 25% by September 2012 and 45% by September 2016. Additionally, this law specifies that 50% of the battery by average weight received for recycling must be made into a post-consumer form. The legislation also states that the cost of collection, recycling, and education on recycling must be covered by the battery producers themselves. Battery producers can choose how to absorb or recoup this cost. Due to this legislation, about 30,000 tons of alkaline, zinc-carbon, and zinc-air batteries were recycled in 2007 by European Battery Recycling Association (EBRA) members [32]. This number did not increase substantially in 2010. The average collection rate in 2009 was 13.6%, and while it is continually improving, many member states are well below the 2012 goal of 25% collection [3, 32]. Even under the strictest recycling laws in the world, there is still a long way to go before the majority of alkaline batteries are recycled.

Canada has also instituted an alkaline battery recycling directive. This directive has set up a network of 1,152 locations such as schools and stores where consumers can drop off batteries for recycling. The Battery Incentive Program was been introduced with the goal of recycling up to 45% of primary batteries, though this differs by province. Through the program, approved transporters are paid $1.54 per kilogram to deliver the batteries approved processors [1]. Recyclers include Inmetco and Raw Materials Company, which were discussed earlier. The Battery Incentive Program is funded through mandated industry stewardship, and companies can pass the recycling fee onto consumers or absorb the fees. The Stewardship program in Ontario has been particularly successful, collecting 1012 tons of alkaline batteries in 2011 [1]. This represents a 14% collection rate. Of these batteries, nearly all were recycled by the Raw Materials Company, recovering 12% of spent battery material in 2011 [1].

Progress towards alkaline battery recycling in the United States is not significant. California has the most progressive legislation in the country, classifying all batteries as hazardous waste. Recent studies have shown that alkaline battery recycling reduces greenhouse gas emissions compared to
landfilling, which has driven recycling legislation [2]. This act has intensified the discussion on alkaline battery recycling in the US [6].

2.2.3. Environmental and Economic Factors in Alkaline Battery Recycling

The motivation to recycle alkaline batteries is based on reducing environmental impact at end-of-life and the recovery of battery materials for reuse. The negative environmental impacts of alkaline batteries have been debated throughout the years. Alkaline batteries are considered safe for landfill by the US Environmental Protection Agency [6, 13]. It has been shown through industry experience and scientific studies in Belgium and Canada that batteries disposed alkaline batteries in municipal solid waste do not cause negative environmental impacts to aquatic or plant life [4]. In 1993 legislation was passed in the United States and Europe to prevent environmentally hazardous mercury from being added to alkaline batteries [4].

Even if alkaline batteries do not present any toxic hazards, they still contribute to an increase in the amount of land used for municipal waste which can have adverse environmental impact due to the ecosystem disruptions they cause; this impact is small compared to the impact of manufacturing [6]. Many life cycle assessments have shown that recycling programs reduce the impact of batteries at end-of-life when compared to landfilling. Studies have identified that in order to be environmentally beneficial, recycling processes must have low energy requirements, and that more than just zinc content is recovered for reuse [1, 2, 3, 6, 7, 12]. Figure 9 below exhibits one result on the environmental benefit of recycling compared with disposal of alkaline batteries. Transportation and collection of batteries represents a major challenge for recycling, as the environmental costs of travel can outweigh the benefits of recycling. Integrating battery recycling into curbside programs has been identified by many studies as the least environmentally damaging approach, and curbside pickup programs have been
instituted in countries such as Sweden [20]. Community drop-off locations have been explored, and have been instituted in Canada by several different programs [1].

![Figure 9: Estimated total greenhouse gas emissions associated with end-of-life recycling and disposal [2]](image)

Recovering valuable end products can recoup some of the costs of battery recycling. In alkaline battery recycling processes, zinc, manganese, iron, brass, and potassium hydroxide can be recovered as end products. Currently, the cost to recycle alkaline batteries is higher than the value of the end products of recycling and no company or process can sustain alkaline battery recycling without supplemental funding. Battery University estimates that it costs about $1000 to $2000 to transport and recycle one ton of batteries [5]. To make recycling sustainable solely on the value of the end products, recycling cost must be drastically reduced to become viable without added surcharges to battery prices [5].

### 2.2.4. Alkaline Battery Recycling Market

The recycling of alkaline batteries exists primarily in Canada and the European Union. Canada has a successful battery recycling programs in all of its major provinces. In 2011, 1310 tons of primary batteries were collected throughout Canada, which constitutes about 10.15% of waste primary batteries [1]. Of primary batteries, 74.5% were alkaline, so approximately 975.4 tons of alkaline batteries were
collected in Canada in 2011. Canadian batteries are either recycled by RMC in Ontario, or sent to Inmetco in Pennsylvania for pyrometallurgical processing. The only other two identified primary battery recyclers, Inmetco and Xstrata, send their alkaline batteries to either RMC or Inmetco to be processed [1].

Europe has a much larger alkaline battery recycling capacity as well as a wider variety of facilities. The European Battery Recycling Association (ERBA) members represent all of the major battery recyclers in the EU. Alkaline and Zinc Carbon recyclers reported by the ERBA include Accurec (Germany), Batrec (Switzerland), EuroDieuze (France), Paprec D3E (France), Recupyl (France, Poland, Spain), Recypilas (Spain), Redux (Germany), Revatech (Belgium), Valdi (France), and UTE Villamora (Spain) [33]. These members recycled 25,529 tons of primary zinc carbon, alkaline, and zinc air batteries in 2011, 28,175 tons in 2010, and 28031 tons in 2009 [32]. Collection rate in the EU in 2009 was 13.6%, and it is unknown if the EU has reached the 2012 goal of 25% collection rate for primary batteries [3].

The United States shipped approximately 133,000 tons of alkaline batteries in 2010, so there are thousands of tons of alkaline batteries being landfilled in the United States with not current widely used collection, sorting, or recycling infrastructure [2]. The only significant alkaline battery recycler in the United States is Inmetco, and it is unknown how many batteries they recycle from the United States, as the only information available reports that they receive batteries from Canada’s collection programs. Recupyl has a branch in the United States as well, but very little information is available. Toxco also reports that they recycling alkaline batteries. California has the most progressive legislation of any state when it comes to alkaline battery recycling, instituting a statewide recycling program called CalRecycle [2].

The cost of recycling is a limiting factor, preventing the expansion of alkaline battery recycling efforts. From literature, the overall cost for recycling one ton of alkaline batteries is at least $3,000, and
assuming about 50% of this cost is collection and transport, the cost to recycle is then about $1,500. This is similar to the Stewardship Ontario program, which charges battery producers to pay for recycling efforts, reported an average cost of $3,195 per metric ton to recycle primary batteries over the years 2009-2011 [1]. Stewardship Ontario pays for both collection and processing, so this is the ‘overall’ cost to recycling primary batteries. The program pays $1.24 per kg of batteries for recycling, compensating recyclers $1,240. And as was mentioned earlier, battery university estimates the cost to recycle batteries is about $1,000 to $2,000 per ton, while the cost for the hydrometallurgical process by F. Ferella et. al. documented above determined a cost of $1,800 dollars per ton. It can then be assumed that most existing recycling processes cost $1,500 or more per ton of batteries.

2.3. Economic Modeling of Recycling Processes

The traditional way of estimating the cost of a project for a new process or business would be to use a cost-benefit analysis (CBA). These analyses take into consideration both the cost implied in carrying out the project and the potential benefits it could bring to the business. In CBA, benefits and costs are expressed in monetary terms, and are adjusted for the time value of money so that all the flows of benefits and costs are expressed on a common basis in terms of their net present value. Unfortunately, this model is not easily applied to the manufacturing fields, where many of the constraints are based on scientific and technological boundaries.

2.3.1. Cost Estimation

When producing cost estimations there are two main classes of estimates that can be done: grass roots estimations and battery-limits estimations. Grass-roots estimates include the entire facility, starting with site preparation, buildings and structures, processing equipment, utilities, and all other the general capital costs [10]. A battery-limits estimate is one in which an imaginary boundary is drawn
around the proposed facility to be estimated. In this estimate it is assumed that all materials, utilities, and services are available in the quality and quantity required to manufacture a product [10]. The cost estimation is an important factor to consider when finding boundaries to the kind of information you want to search for in creating the cost estimate. To narrow down the estimate, there are categories for the kind of quality the estimate will achieve. The following estimates are described by Perry’s Chemical Engineer Handbook:

- **Order-of-magnitude (ratio estimate):** This estimate is based on rule-of-thumbs or in other words, based on cost data from similar-type plants are used. Accuracy: −30% to +50%

- **Study estimate (factored estimate):** This type requires knowledge of preliminary material and energy balances as well as major equipment items. Accuracy: −25% to +30%

- **Preliminary estimate (budget authorization estimate):** This estimate is more details about the process and equipment, so design of major plant items, are required. Accuracy: −20% to +25%

- **Definitive estimate (project control estimate):** The data needed for this type of estimate are more detailed than those for a preliminary estimate and include the preparation of specifications and drawings. Accuracy: −10% to +15%

- **Detailed estimate (firm estimate):** Complete specifications, drawings, and site surveys for the plant construction are required. Accuracy: −5% to +10%

### 2.3.2 Technical Cost Modeling

A more effective technique used to create an adequate estimate of costing for technical processes is known as Technical Cost Modeling (TCM). This model takes into consideration many other features of the process itself. Part of this modeling system is to be able to create algorithms that show specifications and constraints within the technical process compared to the financial viability of the overall process. This aids in the selection of the best technology from a costing perspective. To create an
accurate estimation of technologies there are many uncertainties and complexities that need to be covered. TCM helps identify the greatest commercial potential, but at the same time, the greatest technical constraints.

TCM can be defined as the process-based, “bottoms-up” approach to cost estimation, with total costs broken down into sets of individual cost elements. Each element can be estimated separately and then summed up to create the total cost. Thus, the complex process of finding an estimate is broken down to simpler algorithms that can be filled up with scientific, engineering, accounting and expertise knowledge [34]. The eight elements used to adequately describe a process are materials, labor, energy, capital equipment, tooling, building space, maintenance and time value of money. Each one of these can be derived to their cost element equation in order to process the information.

The TCM system is divided into six steps to aid in the creation of an accurate cost model [34]:

1. *Define the Process*—before anything can be done regarding costing, the process itself must be defined. This is usually accomplished by developing flow diagrams or process flows. To keep costs at the most basic level the true value added chain must be created and unnecessary complexities left aside.

2. *Background Theory*—once the process is created, the background theories of the chemical and mechanical process must be understood. This helps define the key process variables and how they depend on each other.

3. *Data Collection*—two types of data can be collected: commercial data and physical data. Commercial data is the one provided though literature and collected from experts in the field. The physical data is the one collected by testing the materials and developing the processes in house.
4. **Data analysis**—application of regression analysis and other statistical techniques that help create commercial parameters for the predicative outcomes

5. **Algorithmic Verification**—comparing the algorithms developed in the fourth step to make sure they are within statistical significance of the processes being developed.

6. **Model Verification**—with TCM the question “How accurate are the models?” becomes irrelevant and the focus is turned to “how much confidence do you have in the model?”

The TCM model proves to be more specific for manufacturing processes than a general cost benefit analysis. It is also important to note that it is coined a model and not an analysis because it is based on algorithms and attempts to model the process rather than give net present values.

### 2.3.3. Process Based Cost Modeling

Many of the decisions made during the recycling operations and much of the TCM may be used to support strategic decision making. However, de-manufacturing has certain limitations and differences that make it difficult to adapt the existing research and models. This is especially true for reoccurring operational decisions in a dynamic recycling context. The three main constraints are [9]:

- Material values are not fixed—the total outgoing value varies from production stream to production stream given that the materials and their end of life have different compositions
- Sensitivity is rarely considered—many assumptions must be made when therefore a sensitivity analysis would not provide beneficial information for the model
- Process cost is not fixed—cost depends on the processing location, equipment used, volume processed and other factors that could be assumed or scaled out

Due to these differences, the Process Base Cost Model (PBCM) was developed by the Massachusetts Institute of Technology (MIT) Material System Laboratory. The PBCM, just like the TCM, derives the operating costs by building up from the engineering realities of a process or activity and combines it
with an economic framework to map the details of products. The PBCM is divided into three elements shown in Figure 6.

![Figure 10: The Process-Based Cost Modeling elements [9]](image)

**Process Model:** The set of fundamental operations taking place that can be characterized according to scientific and engineering principles. This step resembles the first step of the TCM system and requires the key insights into cost that can be gained through a careful assessment of the ways in which engineering principles can be applied. The field of chemical engineering has probably done the most to characterize the relationship between process definition and production costs.

**Operations Model:** While the process model helps to structure the problem of cost estimation based on technical information, the operational model brings in the actual scaling of the process. This includes the physical implementation and costing for personnel, plant and chemicals. Capturing this information helps produce the operational/process parameters to characterize the entire process. A sample of the parameter list can be seen in Figure 7.

**Financial Model:** With the resource requirements and an operational model in place, the remaining piece is the completion of the costing or financial model. Classical finance models provide standard methods to distribute capital costing and analyze them to yield the desired outcomes in terms of profits and expenditures. A valuable cost model offers full transparency in this analysis so that alternative strategies can be readily incorporated.
After analyzing the steam the de-manufacturing material goes through, more accurate statements can be made about its recyclability valuation. To create a value added system, the PBCM includes the recyclability index, created by Villalba et al. [9] to reflect how much the value of the recovered material is really worth. The assumption of the index is that the material’s recyclability will be reflected by its monetary value. The basic calculation for the recyclability index is $V_p/V_m$ were both values are in ($/kg) and represented in Figure 8 below.

The unique characteristics of the de-manufacturing process of products like alkaline batteries require the use of specific models in order to calculate their process more effectively and accurately. The TCM and the PBCM are both models that accomplish the project’s goals and could be used to achieve the cost estimate for the recycling of alkaline batteries.
3. Methodology

The following section outlines the scope of the project, the initial assumptions made, the principles used when making process design decisions, experimental methods, and principles of cost modeling which were used for the financial analysis.

3.1. Project Scope

The goal of this project was to create a more economically viable, purely mechanical process to divert alkaline batteries from landfill disposal. Battery recycling creates a number of complex problems including a limited alkaline battery recycling network, high costs to transport batteries to recycling facilities, limited incentive to recycle batteries due to high processing and energy costs, environmental impacts caused by recycling, and relatively low purity, and thus low value of the recycled battery products. The various aspects of the battery life cycle which could all be separately considered by this project are shown below in Figure 13. Due to the large amount of uncertainty associated with the collecting and transporting batteries, each of which could encompass an entire project, this project chose to only focus on the economic feasibility of the recycling processing.

Figure 13: The Project Scope for this project, shown by the outline
3.2. Initial Assumptions

Many assumptions were made before and during the execution of this project in order to bring the scope of the project to a reasonable scale. These assumptions are listed below. They were also used to guide the decision making throughout the project.

1. Traditional hydrometallurgical and pyrometallurgical approaches are too expensive for dedicated alkaline battery recycling

This assumption was communicated to us by major battery recyclers. Currently, dedicated alkaline battery recycling using the traditional methods is not sustainable without supplemental funding due to high recycling costs and low value recycled products. It is for these reasons that alkaline battery recycling is not widely conducted without government initiatives. Preliminary research suggests that a purely mechanical recycling process will have lower running costs than the traditional recycling techniques.

2. Before entering into the recycling process all batteries are presorted.

Battery companies manufacture alkaline batteries in many different varieties and battery chemistries can vary slightly between different battery manufactures and different battery styles. Restricting the experimental testing to a single brand and type of battery helped in eliminate the concern of contaminating samples with new elements or other battery chemistries. It is beyond the scope of this project to validate whether other chemistries can be recycled using the developed process, and what impact this may have on end product value.

3. Batteries can be sourced for recycling without cost to the recycler.

As is described in the background on financial modeling, a battery-values estimate draws a ‘box’ around the process, so it is assumed that all materials can be sourced without cost and in as much quantity as required.

4. The quantity of the recovered material will not exceed the materials demand.
As above, the battery-values estimate made assumes that all end-products can be sold, isolating this project from having to consider market demand for end-products.

5. **It is acceptable to make some process decisions based on research**

Because not all of the equipment needed to experimentally verify every step of the process is available at WPI, we will assume that when necessary process design decisions can be made based on published literature and information obtained from speaking with people from industry.

### 3.3. Process Design Principles

To begin the design of the process, we developed several goals that we felt a recycling process should encompass. Additionally, we added several goals which we felt addressed the economic issues associated with alkaline battery recycling. The goals drove the decision making when it came to developing steps in the process, determining which operations were extraneous, and determining which end products were the most desirable. Below are several principles developed for this project. These principles came into use in several ways. As new information was received, for instance, on the existence of mercury in battery materials, new judgments were made on the process design to address the issue. We attempted to reiterate the design as we found research, conducted experiments, and spoke with industry experts.

1. **Recover as much as the battery for recycling back into use by industry**

The first point, material recovery, was taken into consideration at every stage of the process. Often it was required that materials be first separated before recovery, which drove much of the process design.

2. **If recovery is not possible, try to ensure that material is diverted from landfill**
In some cases, full recovery of a material is not possible. Many recycling processes face this issue. The goal in this situation is to still divert the material from landfill. Often this can be done by using the materials for energy recovery, assuming they are organic. It is possible that a material has no reusable value and cannot be used to generate energy, in which case it may be thrown away.

3. **Properly handle any toxic materials**

The proper handling of toxic materials is important for recycling operations for obvious reasons. Improper treatment of toxic materials can adversely affect both the environment as well as employees of the recycling operation. For alkaline batteries, the most toxic material that can be present is mercury.

4. **Design to reduce the capital as well as variable costs for recycling**

Designing to reduce the recycling costs is not necessarily a straightforward process, but in general it was intended to keep things as simple as possible. Using standardized commercially available mechanical systems reduces the price when compared to complex specialized machinery. Energy and material consumption were also an important consideration in the process design. Reducing energy and materials run hand-in-hand with reducing recycling costs. In many cases the ‘low-tech’ machines were generally the most desirable options from an economic standpoint.

5. **Attempt to increase end product value without highly increasing cost**

Increasing the end product value goes along with the financial analysis portion of this product. Increasing the value of end-products almost always occurs through additional processing, which adds costs. Financial analysis was used throughout the process design to determine if added value could be created without incurring costs that could not be recuperated.

6. **Ensure that all process steps operate effectively together**
Insuring the effective operation of the process is an obvious though important step in process design. Even though the goal was to create as simple of a process as possible, each step was always checked to ensure that it was logical. Some operations require specific morphologies, or previous separations to occur, and these requirements were worked around. In the end, there was no way to truly test all operations of the process at a large scale, but laboratory scale tests were carried out or approximated using the best available equipment.

3.4. Experimental Methods

As with every process development project, various tests needed to be conducted through process development to verify the separation techniques and material composition. At the start of this process batteries were disassembled on a small scale laboratory basis to determine the nature of the material present in the spent batteries. A copper pipe cutter was used to dissemble the battery’s steel can. After both ends of the can were removed, the powder was then pushed out of the battery and the anode and cathode were separated along with the paper and plastic materials present on the battery. After disassembly, the cathode powders were ground when necessary using a mortar and pestle to reduce the particle size of the powders. The powders were then rinsed separately to remove the potassium hydroxide electrolyte. The material was then dried using a low temperature oven. After the disassembly process, the separated materials could be used for other experiments.

When available, equipment on campus was used to gain insight on material properties. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) experiments were conducted to get a better understanding of the spent battery material composition. After characterization, various experiments were conducted on the anode and cathode powders to verify and qualitatively determine the magnetic nature of the materials. Baking experiments were conducted to verify the reduction of manganese oxides at high heat. By baking the manganese oxide powder at 400 C for 4 hours many of the manganese oxides were transformed to Mn$_3$O$_4$ which has a higher magnetic susceptibility compared to
other manganese oxides. When possible, material samples were sent to companies with separation equipment of interest to determine their feasibility. These experiments helped to design the process, and were complementary to the project scope, assumptions, and design principles shown earlier.

3.5. Cost Modeling Principles

The cost model used is one in which we included the major applicable areas of the PBCM and TCM. Namely, the elements used to adequately describe a process: materials, labor, energy, capital equipment, tooling, building space, and maintenance. Since the models incorporate the building cost as well as maintenance, the grass-root estimate was chosen. This estimate would include a larger set of data that will make the assessment of the true cost to recycling the batteries more accurate. The grass-root estimate also allowed more flexibility in the type of quality estimate chosen. Figure 14 below shows the type of requirements for the five quality estimates. After making assessments on what level of information our physical and collected data allowed, the study or factored estimate was selected. The study estimate allowed for a deeper level of processing with which a realistic accounting and financial modeling could be created.

Selecting the correct costing model was based on the grass-root factored estimate since it gave the team a clear direction of where the level of information had to fit. Although some of the concepts used in TCM are applied in the costing model, the base model used is the PCBM. The PCBM offered the most comprehensive use of the end of life recycling products. The value and sensitivity analysis were not easily achievable with the alkaline battery recycling industry which is still on its first steps.
<table>
<thead>
<tr>
<th>Estimate types</th>
<th>Site</th>
<th>Process flow</th>
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<td>Location</td>
<td>Rough sketches</td>
<td>Rough sizes and construction</td>
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<td>Preliminary flow sheets</td>
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<td>General description</td>
<td>Preliminary</td>
<td>Engineered specifications</td>
<td>Foundation sketches</td>
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<td>Site plot plan and contours</td>
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Figure 14: Required or available information for the different levels of cost estimation [10]
3.5.1. Process Model

The process model was created in collaboration with the technical team and was dependent of the mechanical steps they were following as the research permitted their process to evolve. The process flow diagram underwent several iterations as cost for machinery or equipment was updated and new alternatives for the recycling process emerged. The process model, and the subsequent models, uses as a base a 1 ton/hour average throughput in order to easily calculate costs and resources required. This reflects only a small scale operation, but it is significant enough of a sample to give us accurate data.

3.5.2. Operational Model

The requirements were gathered using the information collected in the process flow diagram shown in Figure 10 and Figure 11 from Section 2.3.3, which reflects the operational requirements used to quote the machinery. With this information, a list of equipment specifications was created.

3.5.2.1. Equipment Specification

The Equipment Specification list was determined by initially looking at existing recycling methods, which gave us a better feel for creating our own process. The next step was to figure out exactly what machines would preform certain tasks in our process. This was determined by comparing the goals of each process with technical information on equipment that was available from equipment manufacturers. Once equipment options were narrowed down to specific requirements and equipment types, manufacturers were contacted both for their expertise and for price quotes.

Contact was usually initiated through web-based forms used when asking for price quotes. With some manufacturers, it was easier to call. Effort was made to speak both with sales personel for price information as well as technical personal for their expertise, although at smaller companies these roles were often filled by a single contact. Contacts often required additional equipment specifications that we did not anticipate, and these were developed and updated for other equipment as well.
3.5.3. Financial Model

The determination of the numbers for the financial model were based on both literature and quoted information from equipment manufacturers. The cost model was then computed in a Microsoft Excel spread sheet. The spread sheet was set up to follow the TCM costing outline, in which a calculation is made for the requirements of each machine and then aggregated to get the total cost. The inclusion of certain criteria was defined based on the need of those costs to represent an accurate final cost model. The selected costs can be seen on Figure 15 below.

Figure 15: Relevant Costs for the Recycling of Alkaline Batteries

3.5.3.1. Building Cost

The building cost was estimated by square footage for a manufacturing facility in the United States of America. The resulting value is an estimate of the cost of land for the states with the largest amount of industrial production per capita. The number is average across twenty states and does not reflect preferences to any of them. This aggregate was chosen because the specific location of the de-manufacturing plant was not within scope of this project. Similarly, the construction cost is an aggregated value by square foot and includes details about the site work, masonry, plumbing, Heating Venting and Air Conditioning (HVAC), and electrical costs.
3.5.3.2. Labor Cost

The labor cost was extracted from the Bureau of Labor and their data for 2012. These costs range from the sorters, operators, sales personnel and the facilities manager. The labor cost was estimated based on annual salaries and on a regular work schedule with except status for overtime. This was decided to maintain a stable cost for the labor and not make it another variable within a complicated cost estimate.

3.5.3.3. Utility Cost

The cost for utilities was estimated based of the information gathered though literature on the average consumption of water and power of recycling plants of the same size as the one estimated in our research. We also used online calculators to determine these rates more accurately.

3.5.3.4. Material Sales Revenue

The numbers for the sale of end of process materials were all acquired though Scrap Index calculations and comparisons with current market prices. The prices were calculated in kg/year in order to keep consistency with the process flow diagram and on the calculations. The analysis also includes the calculation of the Recyclability Index, which is explained in Section 2.3.3.
4. Results

The results for this project are structured in a manner which reflects the way in which the cost model was constructed. The three main sections are then the process model, the operations model, and the financial model. The process model includes the final process, experimental information that helped to make process decisions, and end product characterization. The operations model includes the operational requirements and detailed equipment specifications. The financial model overviews the value of each end product, presents the calculated process costs, and the recyclability index for this process.

4.1. Process Model

The process model section below encompasses all information which aided the process design, including experimental results, various considered processing technologies, the final process, and end product characterizations.

4.1.1. Experimental Results

Presented below are all the experimental results that influenced the process design. Often experiments ended up not being relevant to the final result, as the project went through many changes during the course of the year, but the experience was valuable.

4.1.1.1. Battery Disassembly

Battery disassembly confirmed the battery construction which was anticipated through literature research [13, 16]. A picture of a deconstructed battery and its components is shown below in Figure 16 to Figure 21. Disassembled components were manually separated and weighed, which verified battery composition reported in the literature [21, 15, 3]. Manually separated battery components were also used for following test, specifically the electrode powders, which were used in SEM, EDS, and XRD testing.
The morphology of the battery components directly out of the battery is important to considering how the materials can be separated. Most spent batteries seem to have been dehydrated over time, though some batteries leak electrolyte during dismantling. The cathode powder is a densely compacted powder, though it is broken up into small chunks with pressure. The anode powder is clay like, and would get stuck to all the other materials without being dried. The need for drying is also reflected in the patent by the Raw Materials Company [28]. The plastics and papers are easily removed from the other materials, as they are wetted by any remaining electrolyte solution. Images of the respective battery components as they appear once removed from the battery can be seen in below.

Figure 16: Spent AA Batteries

Figure 17: Anode pin, top, and casing
Figure 18: Intact Anode Material w/ separator

Figure 19: Paper and Nylon Separator Components

Figure 20: Cathode Material
4.1.1.2. *Scanning Electron Microscope and Energy-Dispersive X-ray Spectroscopy*

SEM results agreed with other studies that characterized the composition of alkaline battery electrode powders. The SEM images themselves were not of much help, though it was determined that the electrode powders were of widely varying size even after they were baked and ground using a mortar and pestle. Figure 22 below is a 250x magnification image of battery electrode powders. More useful was the EDS results, shown in Figure 23 below, which confirmed the elemental composition of the electrode powders, in accordance with the results from published studies. These tests allowed us to continue forward knowing that the composition and morphology of battery materials agree with background literature [21, 19, 3].
4.1.1.3. **X-Ray Diffraction**

X-ray diffraction of alkaline battery powders proved to be highly difficult. Many tests were required to get results with distinguishable peaks so that the species of Manganese Oxides in the cathode material could be corroborated with background literature. First trials recovered no peaks, and
after discussion with Prof. John MacDonald, powders were grinded for 30 minutes by mortar and pestle to reduce particle size, thereby increasing the potential number of planes for X-ray diffraction. Additionally, scan time was increased from 2 sec/degree to 8 sec/degree to get more x-ray counts. After this effort, results were obtained that correlated well with established literature, identifying the existence of ZnO, MnO₂, Mn₃O₄, Mn₂O₃, as well as other potential peaks for Manganese Oxides that were not entirely agreed upon in the literature, such as Mn(OOH) [15, 21, 19]. The best X-ray diffraction result is shown below in Figure 24. The most prominent peaks were at 33.3° and 36.5°, which from literature corresponded to ZnO or Mn₂O₃ for the first peak and ZnO or Mn₃O₄ for the second peak, with both peaks being identified as alpha phase MnO₂ by Freitas et al., 2007 [15, 21, 19].

XRD was also used to try and identify the calcining of MnO₂ to Mn₃O₄ and Mn₂O₃. However, no usable results were recovered.

Figure 24: XRD of Electrode Powder
4.1.1.4. Baking of Electrode Powders

Reduction of manganese electrode powders at 400 °C for 2 hours was attempted in order to transition MnO₂ to Mn₃O₄. The motivation for this was to verify that spent battery powder could be made more magnetic through baking. Literature shows that this transition is possible and can be reliably done, though our XRD results were inconclusive [14]. This avenue of research became unimportant for the project before the reduction of MnO₂ could be verified.

Baking was also done to test the effects of drying on the battery powders. Drying of cathode powders resulted in little change of the morphology, though these powders were often dry when they were removed from the battery. Hence, the cathode powders are so compressed that even a saturated cathode will break apart easily under pressure. However, drying of the anode resulted in a drastic change. After baking, the clay-like consistency of the anode changes to a very fine powder, which is useful because it can then be easily separated along with the cathode powder and potassium hydroxide powder from the coarse fraction of brass, paper, plastic, and steel by vibratory screening.

4.1.1.5. Magnetic Characterization

Neodymium rare-earth magnets were purchased so that the magnetic susceptibility of battery powders could be characterized in a real way, as values for magnetic susceptibility in literature are hard to scale in real life applications. From the literature, we knew that Manganese Oxides should be weakly magnetic, that Mn₃O₄ should be more magnetic than MnO₂, and that metallic Zinc and Zinc Oxide should have no magnetic response. These behaviors were all observed by placing the battery powders in close proximity to the rare earth magnets. Pure Mn₃O₄ powder was also purchased to compare magnetic susceptibility of the spent powder. While Mn₃O₄ powder would stick to the magnet at up to ¼” away, spent battery cathode powder would only stick once in contact with the magnets, verifying that there are weaker magnetic materials in the spent cathode. These materials are most likely a large component
of MnO₂, though carbon, zinc, and potassium impurities would also decrease the magnetic response. Dried anode powders showed absolutely no magnetic response. These results led us to consider magnetic separation techniques for the separation of the electrode powders into Zinc and Manganese concentrates.

4.1.1.6. *External Testing*

Electrode powders were sent to a local magnetics company so that simple magnetic separation techniques could be tested on the powder materials. No dry magnetic grid or plate separators were able to achieve success. The powders were also tested using an Eddy current separator with no success. These results led us to consider other separation technologies.

Batteries were also sent to a shredding company, so that the morphology of the shredded battery materials could be analyzed. This allowed for material properties such as the bulk density of the shredded batteries could be determined reliably. However, these batteries were not returned by the company in time to affect the project, so estimates on the shredding results as well as material properties had to be made using information available in literature and patents. Additional information was gained by speaking with equipment manufacturers that helped to make decisions.

4.1.2. *Final Process*

The final process assumes a constant input stream of 1 ton per hour. Presorted batteries pass through a hammer mill where the batteries are shredded so that no particles are greater than 0.25 inches in size. The hammer mill can withstand a throughput of 1 ton of batteries per hour. After shredding, the battery material passes through a rotary drum drier to remove residual moisture from the battery material. The rotary drum drier operates between temperatures of 150 °C and 425 °C, values which were determined from documentation on the removal of mercury available in journal and patent literature. Hold time in the oven is 10 minutes. Any mercury present in the batteries will be vaporized
and captured in a carbon filter which eliminates mercury from the battery material to be recycled.

About 90 kg of water will be vaporized by the oven each hour. After passing through the rotary oven, the material passes to a vibratory screen where the coarse and fine fractions are separated through a 30 mesh screen.

The fine fraction consists of the anode and cathode powders along with the potassium hydroxide electrolyte. The fine fraction then enters a specific gravity separator at a feed rate of 650 kilograms per hour where the powders are separated according to their densities. The specific gravity separator outputs 160 kg/hour of zinc and zinc oxide powder, 440kg/hour of manganese oxides, and 50kg/hour of potassium hydroxide powders.

The coarse fraction consists of iron castings, paper, plastic brass and a small amount of agglomerated fine fraction materials. The coarse fraction is sent by conveyer belt underneath a magnetic separator at a rate of 285 kg/hour to extract the steel can from the rest of the coarse fraction. The separated steel is then passed through a wash screen at a rate of 225 kg/hour where residual powders are rinsed and separated from the steel components. The steel shreds are then passed through a briquetter where they are pressed into briquettes which are more valuable than the shredded pieces. The briquetter outputs 200kg/hour of scrap steel. The residuals are then sent back to the rotary drum dryer where they are dried again and reintroduced into the separation process.

After passing under the magnetic separator where the steel is separated from the coarse fraction, the remaining material is sent to a specific gravity separator. The specific gravity separator then separates brass, paper and plastic from other waste. The specific gravity separator outputs 20kg/hour of brass, 20 kg/hour of paper and plastic, and approximately 20 kg/hour of other waste material. The process diagram for the developed process is shown in Figure 25 below.
4.1.3. Considered Separation Techniques

Throughout the design process various separation technologies were considered and eventually ruled out due to either feasibility or cost. One of the main separation techniques considered throughout the course of this project high intensity magnetic separation as a means of separating the zinc and manganese oxide powders. Manganese oxides are slightly paramagnetic while zinc is diamagnetic. Using high intensity magnets, it was proposed that these powders could be separated from each other. A small scale lab test was conducted using strong rare earth magnets which confirmed that the spent cathode powder was slightly magnetic. Laboratory grade Mn$_3$O$_4$ was also tested and showed to be even more
magnetic than the spent cathode material which is composed of mainly MnO₂. The zinc anode material was also tested and displayed no magnetic attraction when a magnetic field was applied.

Both dry magnetic separation and wet high intensity magnetic separation (WHIMS) explored as possible separation options. Battery powder materials were prepared and sent to a local company to test the feasibility of dry magnetic separation. After the company conducted various tests on the material using the equipment in their magnetic lab, it was determined that dry magnetic separation was not a viable separation technique due to the fine particle size of the powders.

After dry magnetic separation techniques were ruled out as an option for separation, wet high intensity magnetic separation was investigated. After research and after speaking with folks from industry, it was determined that WHIMS was a feasible option for separating the powders. WHIMS is often used to separate small slightly magnetic particles. WHIMS is achieved by submerging the powders in solution. The paramagnetic particles then drift toward the magnetic screen and the diamagnetic materials is repealed away from the magnetic screen. Further research showed that WHIMS was the only feasible magnetic separation technique available to separate the battery anode and cathode powders.

Another separation technique considered was specific gravity separation. Specific gravity separation takes advantage of differences in density and particle sizes between different materials to separate the materials. By talking to industry experts, it was determined that this was a viable separation technique for the zinc and manganese oxide powders found in spent alkaline batteries. Both WHIMS and specific gravity separation were examined for the cost of separation. It was determined that specific gravity separation was a cheaper separation technique.

Various types of magnetic separators were considered for separating the steel scraps from the course fraction materials. Considered technologies included using a magnetic drum separator, overhead magnetic separator, and magnetic pulley separator. It was determined that each of these separators
were viable for the separating the steel scraps from the course fractions. An economic analysis of the three separators was conducted and it was determined that the overhead magnetic separator was the most economically viable separator for this application.

### 4.1.4. End Product Characterization

The end products of the process can be seen in Figure 9. These include paper and plastics, brass, briquetted steel scrap, zinc powder, manganese powder, and potassium hydroxide powder. The composition of each product is discussed below.

Paper and plastics end product is composed of the separator used to prevent short circuit of the anode and cathode, as well as small plastic gaskets used inside the battery. This mix includes cellulose paper, nylon, and PVC. This material can be sent to a waste-to-energy plant for energy recovery, diverting it from landfill.

Brass is recovered from the non-ferrous scrap due to its high relative density. These small brass chips, which must be under 0.25” from the shredding, are a separated scrap product after the process. These chips can be sold similar to other brass scrap, and are very similar to brass wire scrap. This is known because both brass wire and the brass pin have a fine gauge, and both are used for their good conductivity, so they will be of similar composition.

Steel end product is in the form of briquettes, after having been separated from the non-ferrous component and washed to remove any residual electrode powders or other waste. The briquetting process also removes all fluids from the steel scrap, so these do not need to be dried after being washed. Steel can be sold to existing scrap industry.

The zinc powder end product is composed both of metallic zinc as well as zinc oxide, due to the incomplete reaction of spent batteries. This powder will have a small portion of manganese, which
cannot be prevented, as well as impurities such as potassium hydroxide, which cannot be entirely removed without washing, and carbon. This zinc product can be recovered by existing zinc recycling facilities, which make use of the Waelz process in and Electric Arc Furnace. The impurities in this zinc material will not affect the purity of zinc retrieved via the Waelz process, so the zinc product is acceptable for this application.

The manganese powder is a mix of various manganese oxides, as well as impurities of zinc, potassium, and carbon. These impurities are similar in nature to the zinc powder, and cannot be removed without expensive additional processing. This manganese powder can be used to make ferromanganese or silicomanganese, and be processed similarly to how manganese ores are processed.

Potassium hydroxide product is recovered because the water in the electrolyte is removed from baking, leaving potassium hydroxide salt in the fine fraction. This potassium hydroxide powder will likely not be pure, containing zinc, manganese, and carbon contaminants in small amounts. Potassium hydroxide powder can be sold directly.

Other considered end products for the electrode powders include fertilizers, cement filler, and colorants for ceramics. The manganese product could be used to color ceramics, though this would have to be done situationally, as the resulting color is due to the specific composition of the manganese powder at that time. The value of this product was there for difficult to gauge, so it was not considered as an end product, though this end product is cited in one patent [30]. Cement filler was discarded as it would have nearly zero value. Fertilizer was a promising end product, and is cited in the Raw Materials Corporation Patent [28], but an accurate value could never be obtained. This product would not require that zinc, manganese, and KOH powders be separated, reducing cost.
4.2. Operational Model

The role of the operational model is to describe the process model in more detail. To do that we created the equipment specification list and the operational requirement tables presented in this section. Both tables represent similar information, but differ in their intended use. The equipment specification was used to describe the equipment we were looking for to the companies. The operational requirements are used to help build the financial model and the equipment specification list, since it is based on the process model.

4.2.1. Operational Requirements

The operational requirements were collected based on the requirements established during the process model and presented in Table 2 below. The costs were not added to the table until we had the information from the companies as described in the equipment specifications. The requirements include the incoming stream of materials for that machine which was computed based on the percentages of material at the end of life [35].
Table 2: Operational requirements for processing equipment

**Shredder/Hammer Mill**

<table>
<thead>
<tr>
<th>Incoming Product</th>
<th>Outgoing Product</th>
<th>Operation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Type: whole battery</td>
<td>• Destination: o Vibratory/Trommel Screen</td>
<td>• Equipment: shredder o Cost: $162,000 o Ops Rate: 1-4 ton/hr o Power: 100 HP</td>
</tr>
<tr>
<td>• Volume: 1 ton/hr</td>
<td>• Transportation: o (short) Conveyor belt</td>
<td>• Maintenance Cost: $4,950</td>
</tr>
<tr>
<td>• Composition: o Plastic—1.94% o Metals—19.9% o Paper—0.96% o Brass—1.86% o Cathode—54.66% o Anode—20.69%</td>
<td></td>
<td>• Installation Cost: $8,100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Downtime: 16 hours</td>
</tr>
</tbody>
</table>

**Rotary Drum**

<table>
<thead>
<tr>
<th>Incoming Product</th>
<th>Outgoing Product</th>
<th>Operation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Type: shredded battery</td>
<td>• Destination: o Vibratory/Trommel Screen</td>
<td>• Equipment: Rotary Drum o Cost: $198,350 o Ops Rate: 1000 kg/hr o Power: 35 HP</td>
</tr>
<tr>
<td>• Volume: 1 ton/hr</td>
<td>• Transportation: o 1 Conveyor belt</td>
<td>• Maintenance Cost: $4,959</td>
</tr>
<tr>
<td>• Composition: o Plastic—1.94% o Metals—19.9% o Paper—0.96% o Brass—1.86% o Cathode—54.66% o Anode—20.69%</td>
<td></td>
<td>• Installation Cost: $9,917</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Downtime: 16 hr</td>
</tr>
</tbody>
</table>

**Vibrator/Trommel Screen**

<table>
<thead>
<tr>
<th>Incoming Product</th>
<th>Outgoing Product</th>
<th>Operation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Type: shredded battery</td>
<td>• Destinations: o Magnetic separator o Specific gravity separator (fine particles)</td>
<td>• Equipment: Vibrator/Trommel o Cost: $12,132 o Ops Rate: 1000 kg/hr o Power: 5 HP</td>
</tr>
<tr>
<td>• Volume: 1 ton/hr</td>
<td>• Transportation: o 2 Conveyor belts</td>
<td>• Maintenance Cost: $600</td>
</tr>
<tr>
<td>• Composition: o Plastic—1.94% o Metals—19.9% o Paper—0.96% o Brass—1.86% o Cathode—54.66% o Anode—20.69%</td>
<td></td>
<td>• Installation Cost: $300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Downtime: 16 hr</td>
</tr>
</tbody>
</table>
## Magnetic Separation

<table>
<thead>
<tr>
<th>Incoming Product</th>
<th>Outgoing Product</th>
<th>Operation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: large separated particles</td>
<td>Destination:</td>
<td>Equipment: Magnetic Overhead Separator</td>
</tr>
<tr>
<td>Volume: ~300 kg/hr</td>
<td>o Ferrous: wash screen</td>
<td>o Cost: $9,408</td>
</tr>
<tr>
<td>Composition:</td>
<td>o specific gravity separator (non-ferrous)</td>
<td>o Ops Rate: 500 kg/hr</td>
</tr>
<tr>
<td>o Plastic—7.94%</td>
<td>o Transportation:</td>
<td>o Power: -</td>
</tr>
<tr>
<td>o Metals—80.69%</td>
<td>o Direct</td>
<td>Maintenance Cost: $235</td>
</tr>
<tr>
<td>o Paper—3.89%</td>
<td>o Conveyer belt</td>
<td>Installation Cost: $470</td>
</tr>
<tr>
<td>o Brass—7.54%</td>
<td></td>
<td>Downtime: 16 hrs</td>
</tr>
</tbody>
</table>

## Washer Screen

<table>
<thead>
<tr>
<th>Incoming Product</th>
<th>Outgoing Product</th>
<th>Operation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: ferrous material</td>
<td>Destination:</td>
<td>Equipment: washer screen</td>
</tr>
<tr>
<td>Volume: ~225 kg/hr</td>
<td>o Briquetter~200 kg/hr (ferrous material)</td>
<td>o Cost: $12, 130</td>
</tr>
<tr>
<td></td>
<td>o Rotary Drum~25 kg/hr (washed powder)</td>
<td>o Ops Rate: 1000 kg/hr</td>
</tr>
<tr>
<td>Composition:</td>
<td>o Transportation:</td>
<td>o Power: 5 HP</td>
</tr>
<tr>
<td>o Metals—100%</td>
<td>o 2 Conveyer belts/pipes</td>
<td>Maintenance Cost: $300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Installation Cost: $600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Downtime: 16 hrs</td>
</tr>
</tbody>
</table>

## Briquetter

<table>
<thead>
<tr>
<th>Incoming Product</th>
<th>Outgoing Product</th>
<th>Operation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: ferrous material</td>
<td>Destination:</td>
<td>Equipment: Briquetter</td>
</tr>
<tr>
<td>Volume: ~200 kg/hr</td>
<td>Collection/packing</td>
<td>o Cost: $150,600</td>
</tr>
<tr>
<td>Composition:</td>
<td>Transportation:</td>
<td>o Ops Rate: -</td>
</tr>
<tr>
<td>o Metals—100%</td>
<td>o conveyor belt</td>
<td>o Power: 33 HP</td>
</tr>
<tr>
<td></td>
<td>o sorters</td>
<td>Maintenance Cost: $2,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Installation Cost: $7,530</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Downtime: 16 hrs</td>
</tr>
</tbody>
</table>

## Specific Gravity Separation (Fine Particles)

<table>
<thead>
<tr>
<th>Incoming Product</th>
<th>Outgoing Product</th>
<th>Operation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: non-ferrous material</td>
<td>Destination:</td>
<td>Equipment: Specific Gravity Separator (Fine Particles)</td>
</tr>
<tr>
<td>Volume: 700 kg/hr</td>
<td>Collection/packing</td>
<td>o Cost: $44,552</td>
</tr>
<tr>
<td>Composition:</td>
<td>Transportation:</td>
<td>o Ops Rate: 650 kg/hr</td>
</tr>
<tr>
<td>o Zn/ZnO—30.0%</td>
<td>o Conveyer belt</td>
<td>o Power: 6 HP</td>
</tr>
<tr>
<td>o Mn—62.85%</td>
<td>o labor</td>
<td>Maintenance Cost: $1,113</td>
</tr>
<tr>
<td>o KOH—7.15%</td>
<td></td>
<td>Installation Cost: $2,227</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Downtime: 16 hrs</td>
</tr>
</tbody>
</table>
### Specific Gravity Separation (Non-Ferrous)

<table>
<thead>
<tr>
<th>Incoming Product</th>
<th>Outgoing Product</th>
<th>Operation Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Type: non-ferrous material</td>
<td>• Destination: o Collection/packing</td>
<td>• Equipment: Specific Gravity Separator (Non-Ferrous) o Cost: $27,600</td>
</tr>
<tr>
<td>• Volume: 60 kg/hr</td>
<td>• Transportation: o Conveyor belt</td>
<td>o Ops Rate: 90 kg/hr o Power: 4 HP</td>
</tr>
<tr>
<td>• Composition: o Plastic—41.12%</td>
<td>o labor</td>
<td>• Maintenance Cost: $692</td>
</tr>
<tr>
<td>o Paper—20.15%</td>
<td></td>
<td>• Installation Cost: $1,385</td>
</tr>
<tr>
<td>o Brass—39.05%</td>
<td></td>
<td>• Downtime: 16 hrs</td>
</tr>
</tbody>
</table>

### 4.2.2. Equipment Specifications

Table 3 below describes the type of equipment, specifications desired for that piece of equipment, and companies that were contacted to request price quotes based on their products meeting the defined equipment specifications.

<table>
<thead>
<tr>
<th>Machine/Equipment</th>
<th>Specifications</th>
<th>Potential Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shedder/Hammer Mill</td>
<td>Particle size after shredding is less than 0.25”, Able to operate while constantly shredding batteries (essentially shredding 1/8” steel) Low speed, high torque, often a ‘dual shaft’ model Throughput: 1 t/hr, Baseline price from BCA site: $100,000, Hydraulic vs. Electric drive for this application</td>
<td>BCA Industries, SSI</td>
</tr>
<tr>
<td>Vibratory Trommel Screen</td>
<td>Operates with constant input stream (metered feed as opposed to batch feed), 1 ton/hr, 30 mesh powders</td>
<td>BCA Industries, REMCOM, Eriez, Cleveland Vibrators</td>
</tr>
<tr>
<td>Magnetic Drum Separator</td>
<td>Separation of ferrous material for non-ferrous. Ferrous material is composed of 0.25” maximum shredded steel chips. Non-ferrous material is composed of paper, plastics, brass, and any other coarse materials. Input: 300 kg/hr coarse fraction Output: 225 kg/hr ferrous, 75 kg/hr non-ferrous</td>
<td>REMCOM, BHUPINDRA, Eriez, BCA Industries</td>
</tr>
<tr>
<td>Equipment</td>
<td>Description</td>
<td>Manufacturer(s)</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td>Rotary Drum Dryer</td>
<td>Able to operate constantly at 360-400 Celsius (just above vaporization point of mercury) Ensure safe collection of outgas to collect mercury vapors. Controlled gas flow to prevent dust issues. Throughput: 1 t/hr</td>
<td>ACE, Hi-Temp, Metco</td>
</tr>
<tr>
<td>Wash Tables</td>
<td>Able to thoroughly rinse steel scrap to remove any latent powders Powders are sufficiently washed to dissolve KOH, For Steel: Throughput: 225 kg/hr, For Powders: Throughput: 725 kg/hr</td>
<td>BCA Industries, Eriez</td>
</tr>
<tr>
<td>Briquetter</td>
<td>Condensing of steel scrap into briquettes to remove all water content after washing, improve steel scrap value Throughput: 200 kg/hr</td>
<td>ARS Inc, RUF Briquetting Systems</td>
</tr>
<tr>
<td>Specific Gravity Separator / Destoner</td>
<td>Separates non-ferrous feed into paper/plastic, brass, and other wastes Dry process should work, no need to use wet process, Input: 75 kg/hr, Output: 20 kg/hr paper and plastic, 20 kg/hr brass, 35 kg/hr of other wastes</td>
<td>Oliver Manufacturing, Buhler Group</td>
</tr>
<tr>
<td>Specific Gravity Separator</td>
<td>Separate KOH, Zinc/Zinc Oxide, and Manganese Oxide powders based on differing specific gravity Densities: KOH – 2 g/cm³, Zn/ZnO – 5.6 to 7 g/cm³, Manganese oxides – 5 g/cm³ Throughput: 700 kg/hr powder Output: 210 kg/hr Zinc powder, 440 kg/hr Manganese oxide powder, 50 kg/hr KOH powder</td>
<td>Oliver Manufacturing, Buhler Group</td>
</tr>
</tbody>
</table>

### 4.3. Financial Model

The financial model first describes how the value of end products was determined, as well as the final values. A breakdown of the process cost calculates variable costs and capital costs of the recycling process. Finally, a section on the recyclability index overviews the value of the recovered end products in comparison with the raw material value of batteries.

#### 4.3.1. End Products Value

Paper and cellulose cannot be recovered for any significant value.

Scrap brass, in dollars per pound, is actually the most valuable material recovered, and contributes to the overall revenue in a much greater proportion than its mass. The value of brass was
found from scrapindex.com. The 2012 Quarter 4 report for unsorted brass scrap can be seen in Figure 12. The average value of brass from this chart is $1.80/lb. The contribution of brass scrap to revenue is then $79.2/ton of batteries.

Steel briquettes can be sold to the existing steel scrap industry. Briquettes also increase the value of the steel scrap end-product, as briquettes are easier processed in steel melts than loose chips. The shredded steel value was found using scrapindex.com as well, and the briquetted steel value was provided by ARS Inc., the manufacturer of the briquetting equipment. As shown below, the average price for shredded steel was $0.10/lb, while briquetted steel can be sold for $0.13/lb to $0.15/lb. To remain conservative, the $0.13/lb value was used. The overall contribution of the steel scrap to recycling revenue is $57.2 per ton of batteries.
The Zinc product, because of its various impurities, would be impossible to sell at full value, but it can be sold as a scrap. The value of impure mixed zinc and zinc oxide powder scrap, shown in Figure 14 below, was found on scrapindex.com. The average value for the zinc product is about $0.18/lb, so the contribution of the zinc product to recycling revenue is $83.16 per ton of batteries.
Determining the value of the manganese product was not as simple as the others. Because no infrastructure exists that is dedicated to manganese recycling, as opposed to the recycling of manganese-steel alloys, it was difficult to find a price. A price was calculated by determining the average metallic value of manganese from ore and finished manganese products. The index for manganese ore products and ferromanganese was retrieved from steelmint.com. The average metallic value for manganese determined was $1303/ton. Then the scrap value of steel, brass, and zinc were compared to their respective pure metal values, retrieved from the London Metal Exchange. The average scrap to pure metal ratio was used to convert metallic manganese value to a scrap value of $413.4/ton, or $0.207/lb. These calculations are detailed in Appendix B. This estimate is very similar to the value for zinc. The contribution of manganese product to the recycling revenue is then $200.4 per ton of batteries. This large contribution is because manganese composes almost half of the end-product total mass.

The potassium hydroxide product cannot be sold at full value due to its impurities, but many impure potassium hydroxide powders can be found from sources such as alibaba.com. The average price of low purity potassium hydroxide seems to be about $500 per ton. The contribution of potassium hydroxide product to the recycling revenue is then $25 per ton of batteries.

The overall value for the end products per ton of is about $382. This can be compared to the value of sorted, spent alkaline batteries, which are valued at $40 per ton by scrapindex.com. The total was calculated as shown in Table 4 below.
4.3.2. Process Cost Breakdown

The creation of the cost model was based on a grass root model with a factored model estimate give us a +/- 25% accuracy in our calculations. The processes of acquiring the values used for the cost model are expressed in Table 3. Many assumptions and estimates were made through literature or calculated indexes because of the limited availability of the information. These financial assumptions are shown below in Table 5.

**Table 5: Cost Model Assumptions**

<table>
<thead>
<tr>
<th>Type</th>
<th>Assumption</th>
<th>Justification and Use</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonnage</td>
<td>1 ton/hr</td>
<td>Using the total sales of primary alkaline batteries and the 12% average collection rate, 2080 tons/year is around how much is currently being collected and could be recycled</td>
<td>[1]</td>
</tr>
<tr>
<td></td>
<td>2080 tons/year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conveyor belt price</td>
<td>$167.5 per ft.</td>
<td>Used the average price per foot of an electric conveyor belt</td>
<td>[36]</td>
</tr>
<tr>
<td>Equipment repairs</td>
<td>2-3% per year</td>
<td>Calculated it over the price of each equipment</td>
<td>[37] [38]</td>
</tr>
<tr>
<td>Land Value</td>
<td>$40 per sq. ft.</td>
<td>Using the national average per square foot of industrial land across all 50 states</td>
<td>[39] [40] [41]</td>
</tr>
<tr>
<td>Land Size</td>
<td>7,000 sq. ft.</td>
<td>A 70% of warehouses are between 5,000 and 10,000 sq. ft.</td>
<td>[42]</td>
</tr>
<tr>
<td>Land Amortization</td>
<td>30 years</td>
<td>Used 30 years based on the average mortgage rate for industrial properties being between 20-30 yrs</td>
<td>[43] [44]</td>
</tr>
</tbody>
</table>

**Table 4: Revenues after potential sales of all materials recycled**

<table>
<thead>
<tr>
<th>Product</th>
<th>Volume (kg/hr)</th>
<th>Market Price</th>
<th>Selling Price</th>
<th>Total Annual Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scrap Steel</td>
<td>200</td>
<td>$0.10</td>
<td>$0.13</td>
<td>$54,080.00</td>
</tr>
<tr>
<td>Paper</td>
<td>10</td>
<td>$</td>
<td>$</td>
<td>-</td>
</tr>
<tr>
<td>Plastic</td>
<td>10</td>
<td>$</td>
<td>$</td>
<td>-</td>
</tr>
<tr>
<td>Brass</td>
<td>20</td>
<td>$1.80</td>
<td>$1.80</td>
<td>$164,736.00</td>
</tr>
<tr>
<td>KOH</td>
<td>50</td>
<td>$0.50</td>
<td>$0.50</td>
<td>$52,000.00</td>
</tr>
<tr>
<td>Hg</td>
<td>0</td>
<td>$</td>
<td>$</td>
<td>-</td>
</tr>
<tr>
<td>Mn</td>
<td>440</td>
<td>$0.43</td>
<td>$0.43</td>
<td>$393,536.00</td>
</tr>
<tr>
<td>Zn/ZnO</td>
<td>160</td>
<td>$0.18</td>
<td>$0.18</td>
<td>$131,788.80</td>
</tr>
<tr>
<td>Other</td>
<td>20</td>
<td>0.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total Revenue</strong></td>
<td>$796,140.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Revenue/kg</strong></td>
<td>$</td>
<td></td>
<td></td>
<td>0.38</td>
</tr>
<tr>
<td><strong>Revenue/ton</strong></td>
<td>$</td>
<td></td>
<td></td>
<td>382.76</td>
</tr>
</tbody>
</table>
Based on the assumptions, we were able to calculate the total process of recycling primary alkaline batteries. The total recycling cost of a ton of alkaline batteries came to $1,286, which is significantly less than the average of $1,800-$2,000 we had originally found. Table 6 below shows the total cost analysis including the fixed costs for equipment, building, maintenance, overhead and the variable costs for materials labor and utilities.
Further breakdowns of the costs were also created based on the fixed and variable costs. These are separated based on costs for the aggregated machinery and using the assumptions made in Table 6 above. The fixed costs were calculated taking into account the totality of the plant. Since it is a grass root model, the fix costs include the cost of construction and land, as well as their annual depreciations. The cost of equipment includes a one-time 5% installation fee, as well as the annual amortization for an average of ten years. The original quotes did not include taxation, so a sales tax was added as a one-time fee too. The maintenance includes an estimated 3% of repairs per machine on an annual basis, and also the maintenance of the plant itself. Here, we include values for hiring a janitorial service for a 7,000 square foot facility and the tooling cost for the mechanics to use. Finally, the overhead costs represent the rest of the plant staff and other fixed costs like insurance, taxes and employee benefits. The estimated costs for the total capital cost and as an annual basis are shown in Table 6 for a total of about $2.13 million.

### Table 6: Total Cost Summary

<table>
<thead>
<tr>
<th>Total Cost of Recycling Alkaline Batteries</th>
<th>Fixed Cost</th>
<th>per/year</th>
<th>Total Capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Cost</td>
<td>$ 61,685.60</td>
<td>$ 731,520.27</td>
<td></td>
</tr>
<tr>
<td>Building Cost</td>
<td>$ 25,993.33</td>
<td>$ 696,500.00</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>$ -</td>
<td>$ 169,915.88</td>
<td></td>
</tr>
<tr>
<td>Overhead Labor Cost</td>
<td>$ 534,435.58</td>
<td>$ 534,435.58</td>
<td></td>
</tr>
<tr>
<td>Installation Fee</td>
<td>$</td>
<td>$ 31,261.55</td>
<td></td>
</tr>
<tr>
<td><strong>Total Fixed Cost</strong></td>
<td>$ 622,114.51</td>
<td>$ 2,132,371.73</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable Costs</th>
<th>$ 84,000.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost</td>
<td>$ 265,440.00</td>
</tr>
<tr>
<td>Direct Labor Cost</td>
<td>$ 193,609.58</td>
</tr>
<tr>
<td><strong>Total Variable Cost</strong></td>
<td>$ 543,049.58</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Process Cost</th>
<th>$ 1,165,164.10</th>
<th>$ 2,675,421.31</th>
</tr>
</thead>
<tbody>
<tr>
<td>$/kg</td>
<td>$ 0.56</td>
<td>1.29</td>
</tr>
<tr>
<td>$/ton</td>
<td>$ 560.18</td>
<td>1,286.26</td>
</tr>
</tbody>
</table>
The variable costs included the purchase of materials, in this case only the scrap price of the batteries. The tonnage processed in the plant is about 2080 tons/year and the material purchased was 2,100 tons/year in order to account for any discrepancy in the dismantling process. This still gives us a 99% recycle rate. Also included in this break down are the cost of variable labor like sorters and operators and the calculated use of water and energy by the equipment. The total amount of workers for the plant, including those represented in the fixed costs, has been outlined in a basic hierarchical structure outlined in Appendix C. All averages are presented in an annual basis.

### Table 7: Fixed Cost of the Total Process

<table>
<thead>
<tr>
<th>Equipment Cost</th>
<th>Machines</th>
<th>Annually</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shredder 1</td>
<td>1</td>
<td>$16,200.00</td>
<td>$162,000.00</td>
</tr>
<tr>
<td>Rotary Drum Dryer 1</td>
<td>1</td>
<td>$19,835.00</td>
<td>$198,350.00</td>
</tr>
<tr>
<td>Vibratory-Trommel Screen 1</td>
<td>1</td>
<td>$1,213.20</td>
<td>$12,132.00</td>
</tr>
<tr>
<td>Magnetic Separator 1</td>
<td>1</td>
<td>$940.80</td>
<td>$9,408.00</td>
</tr>
<tr>
<td>Wash Table 1</td>
<td>1</td>
<td>$1,213.20</td>
<td>$12,132.00</td>
</tr>
<tr>
<td>Briquetter 1</td>
<td>1</td>
<td>$15,062.10</td>
<td>$150,621.00</td>
</tr>
<tr>
<td>Specific Gravity Separator (Non-Ferrous) 1</td>
<td>1</td>
<td>$2,766.10</td>
<td>$27,661.00</td>
</tr>
<tr>
<td>Specific Gravity Separator (Fine Particles) 1</td>
<td>1</td>
<td>$4,455.20</td>
<td>$44,552.00</td>
</tr>
<tr>
<td>Conveyor Belts 50 (ft)</td>
<td></td>
<td>$837.50</td>
<td>$8,375.00</td>
</tr>
<tr>
<td>Installation Fee</td>
<td></td>
<td></td>
<td>$31,261.55</td>
</tr>
<tr>
<td>Machinery Tax</td>
<td></td>
<td></td>
<td>$75,027.72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Building Cost</th>
<th>SF Needed</th>
<th>Per SF</th>
<th>Annually</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Value 7,000</td>
<td>$40.00</td>
<td>$9,333.33</td>
<td>$280,000.00</td>
<td></td>
</tr>
<tr>
<td>Construction Cost 7,000</td>
<td>$59.50</td>
<td>$16,660.00</td>
<td>$416,500.00</td>
<td></td>
</tr>
</tbody>
</table>

| Maintenance Cost | | $169,915.88 |
| Repairs | $1,179.66 | $14,155.88 |
| Plant Maintenance Staff | 2 | $7,880.00 | $94,560.00 |
| Miscellaneous Tooling Cost | | $3,000.00 | $3,000.00 |
| Janitorial Services | | $210.00 | $10,920.00 |

| Overhead Labor Cost | | $534,435.58 | $534,435.58 |
| Plant Manager 1 | $7,565.83 | $90,790.00 | $90,790.00 |
| Operations Manager 1 | $5,000.00 | $60,000.00 | $60,000.00 |
| Sales Manager 1 | $4,378.33 | $52,540.00 | $52,540.00 |
| Financial Manager 1 | $5,000.00 | $60,000.00 | $60,000.00 |
| Insurance | | $2,092.50 | $2,092.50 |
| Legal and tax expenses | | $79,614.08 | $79,614.08 |
| Benefits | | $186,999.00 | $186,999.00 |
| Office Supplies | $200.00 | $2,400.00 | $2,400.00 |

| Total Fixed Cost | $622,114.51 | $2,132,371.73 |
since they are variable every year and by the amount of volume processed. The variable cost came to about $543,000 per year accounting for our current processing tonnage.

Table 8 Variable Costs for the Entire Model

<table>
<thead>
<tr>
<th>Variable Cost Breakdown</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Cost</td>
<td></td>
</tr>
<tr>
<td>Per Ton</td>
<td>$84,000.00</td>
</tr>
<tr>
<td>Disposed battery</td>
<td>$40.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Direct Labor Cost</th>
<th># Employees</th>
<th>Average Salary</th>
<th>$265,440.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorters</td>
<td>3</td>
<td>$23,200.00</td>
<td>$69,600.00</td>
</tr>
<tr>
<td>Operators</td>
<td>6</td>
<td>$32,640.00</td>
<td>$195,840.00</td>
</tr>
<tr>
<td>Benefits</td>
<td>30%</td>
<td>$16,752.00</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Utility Cost</th>
<th>$193,609.58</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity KWH daily</td>
<td>$5392.73</td>
</tr>
<tr>
<td>Water per 1000 g</td>
<td>$1.50</td>
</tr>
<tr>
<td>Chemicals</td>
<td>0</td>
</tr>
</tbody>
</table>

| Total Variable Cost     | $543,049.58 |

The aggregated values of the fixed and variable costs came from individual studies on each of the machines needed for the recycling process. Table 9 below shows a sample of the cost construction for the Briquetter. The cost for each of the equipment included the purchasing cost, depreciation cost and the potential installation fee. Labor was not calculated because it was used as an aggregate in the variable cost table. The cost also includes the maintenance and utility cost for each machine. The rest of the equipment cost can be found in Appendix D.
### 4.3.3. Recyclability Index

The recyclability index is calculated by using the value of the materials that go into the production of batteries ($V_m$) and the value of the materials at the end of the recycling process ($V_p$) [64].

From our results we know that $V_p$ is $382.76$ per ton and the $V_m$ has been calculated to be $1,601.08$ per ton. The calculation for the value of battery raw materials is shown in Appendix E. The recyclability index is calculated below.

\[
Recyclability\ Index = \frac{V_p}{V_m} = \frac{382.76}{1601.08} = 0.239
\]

The recyclability index for the alkaline battery is calculated to be 0.239. The higher the index, the better value of recycling the product has.
5. Analysis

The analysis section discusses how the information from literature, combined with the findings showcased previously, reflects on the feasibility of recycling alkaline batteries for this process in specific as well as in general. Due to the low value of the recycled materials and high process cost, current recycling processes cannot be sustained solely on the value of the recycled materials. As covered previously, no current processes report that they can profit on the end product value alone. While the developed method proposed in this research is cheaper than any reported process, it too could not be fully sustained by the value of its end products and would require additional funding to cover the costs of recycling.

5.1. Financial Analysis

The financial aspect of the recycling process does bring in some interesting conclusions for our research which could help develop future recommendations. The revenue of the material was calculated to be $0.38 per kilogram as compared to the cost of $1.29 to recycle it. This means that only a 29.2% of the investment can actually be returned, and leaves the process with a loss of $0.91 per kilogram being recycled.

Looking more in depth to the costing model, the spread of the cost was mostly dominated by the equipment cost (28%), the building cost (25%) and the overhead labor cost (20%). The amortization or depreciation of the materials and the distribution of the building cost over several years influences the results. The complete cost distribution can be seen in Figure 29. The capital investment is still an important factor since the process is not economically feasible, meaning that the equipment and land cost will not be able to pay-for-themselves over time.
The largest portion of the cost is distributed across the equipment required for the mechanical separation of the process. Although this process offers a cheaper way to process the batteries at end of life, it still suffers a substantial cost on the equipment it requires and the variable costs (such as energy) that these machines require. Figure 30 shows the breakdown of the equipment costs for the annual cost of each one of them. There is a significant spike in the use of electricity by the rotary drum drier. The spike is due to the use of higher temperatures to evaporate any potential remainders of mercury in the batteries.
Looking at the issue more closely, the analysis was also made with the use of the drum without accounting for the existence of mercury. According to the federal regulation of the EPA, the primary alkaline batteries should all be mercury free [4]. For that reason, there would be a significant impact on the model if the evaporation of mercury was not needed. The current total cost includes the evaporation of mercury in the process, and as mentioned before, is recorded at $1,286. If the batteries were clear of mercury the process could run at a lower temperature and would cause a reduction of cost to $1,236. Although this does not make the process feasible, it increases the recyclability ratio to 0.305 and revenues to a 31% of the recycling cost.

The recycling revenue can keep increasing if a study of the cost-volume analysis is made. To create Figure 31, the estimated amount of batteries sold per year was used as a base (namely 15,000 tons/year). From that, intervals were created in a regression model to the current amount being
recycled in this process (2,080 tons/year). Adjusting for variable costs and assuming that the same equipment and fixed costs are used, we can predict that the cost of recycling the batteries will decrease with an increase of volume throughput. The scaling analysis also shows that by recycling around 10,000 tons/year this process could become profitable. However, this isn’t necessarily positive news, as with the cited equipment running at full capacity with low downtime (16 hours per day, 360 days a year), only 5760 tons per year could be processed, leaving this process unfeasible at maximum uptime.

![Figure 31: Scaling Analysis with Potential Profitability](image)

### 5.2. Values of Recovered Materials

The feasibility of alkaline battery recycling is mostly limited due to the low value of the materials. This is reflected in the low recyclability index. As calculated, the value for one ton of raw materials for batteries, which include high-purity potassium hydroxide and electroplated manganese dioxide, is only $1601. Even if all battery components could somehow be converted back into these raw materials, the cost of this recycling process would be recovered by a relatively low margin. Raw material value would not even cover the costs reported by Ferella, et. al.
6. Conclusion

Overall, we have determined that dedicated alkaline battery recycling processes cannot be made economically feasible simply based on the low value of alkaline battery materials. Background research showed that all existing alkaline battery recycling processes are made economically feasible through supplemental income, be it tipping fees or government aid, in addition to revenue gained by end products. A physical separation process was developed in the attempt to reduce the cost of dedicated alkaline battery recycling, as physical separation methods should use less energy than pyrometallurgical methods and fewer chemicals than hydrometallurgical methods.

The developed process, which can be seen in Figure 25, is cheaper than any other reported recycling process. However, it is still not economically feasible. The cost of recycling alkaline batteries came to $1,286 per metric ton of batteries, while revenue from end products is only $380 per metric ton. The costs are mostly due to equipment cost, building cost, and overhead. If the presence of mercury in the battery waste was not a concern, this cost could be reduced to $1,236 per metric ton. The most important end products for revenue were brass, due to its high value, and manganese, which has decent value and constitutes the largest end product by mass. This was in contrast to many other processes, which recover zinc for high value, but it was found that scrap zinc powder has a much lower value than pure zinc. Hence, to be economically feasible an additional income of approximately $0.91 per kilogram would need to come from somewhere. This is reasonable, as in Ontario, Canada, the Battery Processing Incentives program pays $1.24 per kilogram to sort and process end-of-life batteries [1]. Most importantly, the final process diverts 98% of battery materials from landfill, recovers all metal components for reuse, and has low energy consumption compared to pyrometallurgical methods.

Despite economic challenges, alkaline battery recycling processes should be supported, as they reduce the environmental impact of alkaline batteries. Many life-cycle assessments have shown that
energy efficient recycling processes, such as hydrometallurgical and mechanical processes, are environmentally beneficial when compared to landfilling [1, 2, 12, 6], even though alkaline batteries are not generally considered toxic [4]. Also, alkaline batteries present a currently untapped source for secondary metals. Approximately 220,500 metric tons of spent alkaline batteries are landfilled each year in the EU [3]. In addition, the EPA’s *US Recycling Economic Information Study* reports that recycling industries make vital contributions to job creation and economic development in the United States [65], so there are economic incentives for promoting alkaline battery recycling.

The motivation for recycling is then clear, and further incentives are needed to promote the growth of the collection and recycling industries. It is unclear whether consumers, manufacturers, or government should be responsible for recouping the costs of alkaline battery recycling. Currently in Canada and the EU, the cost to recycle is levied on battery manufacturers by government stewardship programs, and manufacturers can choose to absorb the cost or pass it on to consumers. These systems seem to be effective, though they are not the only option. The cost of alkaline battery recycling could also be directly added to the price of a battery, absorbed by the government, or recovered by some other means. By reducing the cost of alkaline battery recycling, which is shown to be possible by this project, recyclers can better take advantage of any potential incentives.

### 6.1. Recommendations for Future Work

As a result of our project we feel that areas for additional research could include: verification of the proposed mechanical separation process, analyzing methods for supporting battery recycling, and completing a cost analysis that considers more of the battery life cycle.

Due to time constraints and the limited amount of recycling equipment available at WPI, we suggest that research be undertaken to verify the proposed separation process. Verifying the process would result in a better understanding of the end products and the costs of processing. This work would
lead to a more accurate cost estimate. Verifying the process would require significant effort because most of the equipment needed is not often readily available in the local area. Trying to determine a more accurate estimate for the value of end products could also present a challenge as battery recyclers are currently unwilling to release any information about their products or customers because of the market pressure that currently exists.

Another recommended area of research as a result of this project could be to analyze methods for supporting battery recycling. Currently different methods are used for support battery recycling worldwide in places such as Canada and Europe. Research could be conducted to determine the best method for implementing a recycling process in the United States. Some possible methods to consider could include battery surcharges where tax is added to the battery to cover recycling fees. Another way to cover the cost of recycling could be to implement a battery deposit system much like the system that is currently in place for aluminum cans. Stewardship methods, such as those in Canada, could also be used. Additional research could determine the system that could be most reasonably implemented in the United States.

Another area of research that would not only build on our research but could also build upon the research of others would be to do a more extensive cost analysis. Aspects such as collection, transportation, and sorting are important parts of recycling that must be considered when determining the overall cost of recycling alkaline batteries. Determining the added costs of some of the critical and costly components of recycling would not only lead to a better estimate of the true cost of a battery and its recycling but it could also possibly provide support for establishing a battery recycling network in the United States.
References


Appendices

Appendix A: Diagrams of Various Current Recycling Processes
The following diagrams are from Fisher et. al. [7]

Recupyl Recycling Process

Citron Recycling Process

Valdi Recycling Process

The following diagrams are from various patents, which are referenced underneath each.
Fig. 1

[26]
Figure 3
FIRST STEP: LEACHING
SAMPLE: WASTE MANGANESE BATTERY POWDER AND/OR WASTE ALKALINE BATTERY POWDER
LEACHING SOLUTION: A MIXTURE OF A SULFATE ACID SOLUTION AND A REDUCING AGENT

SECOND STEP: LEACHING
SAMPLE: WASTE MANGANESE BATTERY POWDER AND/OR WASTE ALKALINE BATTERY POWDER
LEACHING SOLUTION: LEACHED SOLUTION OBTAINED FROM THE FIRST STEP

REMOVAL OF HEAVY METALS AND ORGANIC MATERIALS

SPRAY-DRYING

DISCARD OF THE SCUM (USING ACTIVATED CARBON)

SCUM + DEFICIENT PORTION
## Appendix B: Manganese Cost Estimation

All prices for manganese ore and ferromanganese were retrieved from steelmint.com. Prices for steel billet, pure zinc, and brass were retrieved from the London Metal Exchange. Scrap values for steel, brass, and zinc were retrieved from scrapindex.com.

<table>
<thead>
<tr>
<th>Ore Grade</th>
<th>Price (USD)</th>
<th>Metal Value (USD/MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.46</td>
<td>565</td>
<td>1228.26087</td>
</tr>
<tr>
<td>0.48</td>
<td>525</td>
<td>1093.75</td>
</tr>
<tr>
<td>0.44</td>
<td>511</td>
<td>1161.363636</td>
</tr>
<tr>
<td>0.38</td>
<td>518</td>
<td>1363.157895</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FeMn Grade</th>
<th>Price (USD)</th>
<th>Metal Value (USD/MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>990</td>
<td>1414.285714</td>
</tr>
<tr>
<td>0.75</td>
<td>1030</td>
<td>1373.333333</td>
</tr>
<tr>
<td>0.78</td>
<td>1048</td>
<td>1343.589744</td>
</tr>
<tr>
<td>0.78</td>
<td>1130</td>
<td>1448.717949</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>1303.307393</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steel Value:</th>
<th>Zinc Value:</th>
<th>Brass Value:</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>2100</td>
<td>6500</td>
</tr>
</tbody>
</table>

**Scrap Steel:**

<table>
<thead>
<tr>
<th>Scrap Value Fraction:</th>
<th>Scrap value fraction:</th>
<th>Scrap Value Fraction:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.663636364</td>
<td>0.171428571</td>
<td>0.553846</td>
</tr>
<tr>
<td><strong>Average:</strong></td>
<td><strong>0.462970363</strong></td>
<td><strong>0.553846</strong></td>
</tr>
</tbody>
</table>

**Estimated Manganese Metal Scrap Value:**

603.3926966

**Assuming Powder so value more like zinc:**

223.4241244

**Average:**

in USD/ton: 413.4084105 in USD/lb: 0.206704
Appendix C: Organizational Hierarchy

The image below is the hierarchical organizational chart for the recycling plant. The numbers in parenthesis denotes the number of people hired for each of the positions.
Appendix D: Detailed Equipment Costs

The cost break down for each of the equipment that was used in the recycling process outlined.

<table>
<thead>
<tr>
<th>Shredder</th>
<th>Cost per Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Base Cost</td>
<td>$ 162,000.00</td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>$ 16,200.00</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>$ 8,100.00</td>
</tr>
<tr>
<td>Throughput Volume</td>
<td>1,000 2,080,000</td>
</tr>
<tr>
<td>Labor Cost</td>
<td>$ 32,635.20</td>
</tr>
<tr>
<td>Labors Needed</td>
<td>1</td>
</tr>
<tr>
<td>Labor Hours</td>
<td>2,080</td>
</tr>
<tr>
<td>Utility Cost</td>
<td>$ 20,359.10</td>
</tr>
<tr>
<td>Energy</td>
<td>596.56 $ 20,359.10</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>$ 4,050.00</td>
</tr>
<tr>
<td><strong>Total Annual Cost</strong></td>
<td>$ 73,244.30</td>
</tr>
<tr>
<td>$/Kg</td>
<td>$ 0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rotary Drum Dryer</th>
<th>Cost per Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Base Cost</td>
<td>$ 198,350.00</td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>$ 19,835.00</td>
</tr>
<tr>
<td>installation Cost</td>
<td>$ 9,917.50</td>
</tr>
<tr>
<td>Throughput Volume (kg/yr)</td>
<td>1,000 2,080,000</td>
</tr>
<tr>
<td>Labor Cost</td>
<td></td>
</tr>
<tr>
<td>Labors Needed</td>
<td></td>
</tr>
<tr>
<td>Labor Hours</td>
<td>2,080</td>
</tr>
<tr>
<td>Utility Cost</td>
<td>$ 152,891.20</td>
</tr>
<tr>
<td>Energy</td>
<td>4480 $ 152,891.20</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>$ 4,958.75</td>
</tr>
<tr>
<td><strong>Total Annual Cost</strong></td>
<td>$ 177,684.95</td>
</tr>
<tr>
<td>$/Kg</td>
<td>$ 0.09</td>
</tr>
<tr>
<td>Cost per Machine</td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Equipment Base Cost</td>
<td>$ 12,132.00</td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>$ 1,213.20</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>$ 606.60</td>
</tr>
<tr>
<td>Throughput Volume (kg/yr)</td>
<td>1,000</td>
</tr>
<tr>
<td></td>
<td>2,080,000</td>
</tr>
<tr>
<td>Labor Cost</td>
<td></td>
</tr>
<tr>
<td>Labors Needed</td>
<td></td>
</tr>
<tr>
<td>Labor Hours</td>
<td>2,080</td>
</tr>
<tr>
<td>Utility Cost</td>
<td>$ 1,017.96</td>
</tr>
<tr>
<td>Energy</td>
<td>29.83</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>$ 303.30</td>
</tr>
</tbody>
</table>

**Total Annual Cost**  
$ 2,534.46

$/Kg  
$ 0.001

<table>
<thead>
<tr>
<th>Cost per Machine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Base Cost</td>
<td>$ 9,408.00</td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>$ 940.80</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>$ 470.40</td>
</tr>
<tr>
<td>Throughput Volume (kg/yr)</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>624,000</td>
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<tr>
<td>Labor Cost</td>
<td></td>
</tr>
<tr>
<td>Labors Needed</td>
<td></td>
</tr>
<tr>
<td>Labor Hours</td>
<td>2,080</td>
</tr>
<tr>
<td>Utility Cost</td>
<td>-</td>
</tr>
<tr>
<td>Energy</td>
<td>0</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>$ 235.20</td>
</tr>
</tbody>
</table>

**Total Annual Cost**  
$ 1,176.00

$/Kg  
$ 3.92
### Wash Table

<table>
<thead>
<tr>
<th>Cost per Machine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Base Cost</td>
<td>$12,132.00</td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>$1,213.20</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>$606.60</td>
</tr>
<tr>
<td>Throughput Volume (kg/yr)</td>
<td>225</td>
</tr>
</tbody>
</table>

#### Labor Cost

<table>
<thead>
<tr>
<th>Labors Needed</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Hours</td>
<td>2,080</td>
</tr>
</tbody>
</table>

#### Utility Cost

<table>
<thead>
<tr>
<th>Utility</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>$1,017.96</td>
</tr>
<tr>
<td>Water</td>
<td>$0</td>
</tr>
</tbody>
</table>

#### Maintenance Cost

|       | $303.30 |

**Total Annual Cost**

|       | $2,534.46 |

$/Kg

|       | $0.01     |

### Briquetter

<table>
<thead>
<tr>
<th>Cost per Machine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Base Cost</td>
<td>$150,621.00</td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>$15,062.10</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>$7,531.05</td>
</tr>
<tr>
<td>Throughput Volume (kg/yr)</td>
<td>200</td>
</tr>
</tbody>
</table>

#### Labor Cost

<table>
<thead>
<tr>
<th>Labors Needed</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Hours</td>
<td>2,080</td>
</tr>
</tbody>
</table>

#### Utility Cost

<table>
<thead>
<tr>
<th>Utility</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>$6,718.50</td>
</tr>
<tr>
<td>Water</td>
<td>$0</td>
</tr>
</tbody>
</table>

#### Maintenance Cost

|       | $2,500.00 |

**Total Annual Cost**

|       | $24,280.60 |

$/kg

|       | $0.06     |
### Specific Gravity Separator (non-ferrous)

<table>
<thead>
<tr>
<th>Cost per Machine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Base Cost</td>
<td>$ 27,661.00</td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>$ 2,766.10</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>$ 1,383.05</td>
</tr>
<tr>
<td>Throughput Volume (kg/yr)</td>
<td>75</td>
</tr>
<tr>
<td>Labor Cost</td>
<td></td>
</tr>
<tr>
<td>Labors Needed</td>
<td></td>
</tr>
<tr>
<td>Labor Hours</td>
<td>2,080</td>
</tr>
<tr>
<td>Utility Cost</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>23.86</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>$ 691.53</td>
</tr>
<tr>
<td><strong>Total Annual Cost</strong></td>
<td>$ 4,271.99</td>
</tr>
<tr>
<td>$/kg</td>
<td>$ 0.03</td>
</tr>
</tbody>
</table>

### Specific Gravity Separator (fine particles)

<table>
<thead>
<tr>
<th>Cost per Machine</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment Base Cost</td>
<td>$ 44,552.00</td>
</tr>
<tr>
<td>Depreciation Rate</td>
<td>$ 4,455.20</td>
</tr>
<tr>
<td>Installation Cost</td>
<td>$ 2,227.60</td>
</tr>
<tr>
<td>Throughput Volume (kg/yr)</td>
<td>700</td>
</tr>
<tr>
<td>Labor Cost</td>
<td></td>
</tr>
<tr>
<td>Labors Needed</td>
<td></td>
</tr>
<tr>
<td>Labor Hours</td>
<td>2,080</td>
</tr>
<tr>
<td>Utility Cost</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>35.79</td>
</tr>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>$ 1,113.80</td>
</tr>
<tr>
<td><strong>Total Annual Cost</strong></td>
<td>$ 6,790.55</td>
</tr>
<tr>
<td>$/Kg</td>
<td>$ 0.00</td>
</tr>
</tbody>
</table>
Appendix E: Raw Material Value of Batteries

Manganese Dioxide value:

Retrieved from the US Geological Survey report on Manganese trade in October 2012 [66]:

\[
\text{Manganese Dioxide value:} \quad \frac{42,200,000}{19,600} \text{ MT} = 2153/\text{MT}
\]

Zinc Value:

From London Metal Exchange: $2,086

For metallic zinc, powdered zinc might be different

Steel value:

$550/\text{MT} \text{ from the London Metal Exchange}

Brass Value:

$6500/\text{MT} \text{ from London Metal Exchange}

KOH Value:
No price index is available for KOH, so industry trade sites were used to determine KOH value (alibaba.com, lookchem.com, guidechem.com, made-in-china.com). Highest purity (95%) KOH seems to have a value of about $1200/MT

**Graphite for batteries:**

Again, no price index for this product, so searching on industry trade sites was used (alibaba.com, made-in-china.com). Graphite powder has a wide range of values, but the top end is dominated by synthetic graphite for top-end lithium-ion batteries. Natural graphite powder (300 mesh) can be found for about $500/MT.

**Battery Composition [3]:**

Steel: 20%
MnO2: 44%
Zn: 16%
KOH: 5%
C: 4%
Brass: 2%
Water (no real value): 9%
Paper and Plastic (assuming value is low enough to be discarded): 4%

**Battery Raw Material Value:**

$1601.08/MT