April 24, 2020

Dr. Robert Counce
CBE 488
University of Tennessee

Dear Dr. Counce,
We are submitting the attached report entitled *Lithium Recovery Process from Spent Batteries*.

We hope you find this report satisfactory.

Sincerely,

Honors Design in Green Engineering, Group 3
Jordan Leith, Lacey Roberts, Nicholas Ross, and Woodi Woodland
University of Tennessee
Knoxville, TN

Enclosure: Final Report

cc:

Process Design Analysis: Lithium Recovery from Lithium-ion batteries by way of acid leaching

CBE 488: Honors Design in Green Engineering

Submitted: April 24th, 2020

Chemical and Biomolecular Engineering Department University of Tennessee 1331 Circle Park Drive SW, Knoxville, TN, 37916

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1.0 Introduction

The principal objective of the project was to utilize extant models of lithium recovery processes and create a conceptual industrial scale process utilizing spent lithium-ion batteries to salvage lithium, cobalt, and manganese. With this memorandum we propose an industrial process to recover lithium and other valuable metals from spent lithium batteries. The memorandum contains synthesis information, process design outline, optimization methodology, results summary, a discussion of the results, conclusion, and recommendations.

Lithium-ion batteries have been utilized for their high energy density for many portable applications such as mobile devices, computers, and pacemakers. With these devices and electric vehicles becoming more prevalent, Li-ion batteries are becoming increasingly attractive. To minimize the ecological impacts from lithium mining as well as reducing the costs of raw materials in making Li-ion batteries, recycling lithium from spent Li-ion batteries is imperative. Common Li-ion batteries include cathode materials of $LiMn_2O_4$ and $LiCoO_2$. We will focus on the process of recycling Lithium optimized from previous processes. The ChE index used is 599.5 from October 2019. The process described starts with 1000 kg/hr feed of spent Li-ion batteries and ends with purified lithium, cobalt, and managense.

This paper incorporates results from the 2020 capstone project from the Honors Design Internship in Green and Biomolecular Engineering. Senior students in the Chemical Engineering department at the University of Tennessee, Knoxville (UTK) campus focused on the development of an industrially scaled recycling process of Lithium. The motivation for this process stems from the gross incorporation of lithium batteries in modern apparatuses as well as the importance of proper disposal of such resources. The students worked with contacts at the

University of Tennessee Knoxville, Drs. R.M. Counce and J.S. Watson, who served as liaisons and were serviced with contributions by the JSW Fund for Undergraduate and Graduate Research at the University of Tennessee, Oak Ridge National Laboratory, and the Lithium Ion Industry.

Flow sheets, capital costs, and intermediate operating costs were conducted for such a process while ensuring that product purity specifications were met, i.e. nearly 100% lithium, 100% cobalt, 100% manganese and minimal radiological waste. The economic analysis outlining annual earnings of the lithium recovery process was conducted in 2020 dollars and included considerations for process optimization. Also, of central importance were safeguards to protect workers, communities, and the environment.

Recent reviews of lithium recycling have been conducted and summarized by Castillo et al. (2002), Zheng et al. (2014), Wang et al. (2009), and Xu et al. (2008). Leading lab-scale processes include washing of the batteries to discharge the batteries followed by a crushing method and subsequent separation. Next, leaching, precipitation, and filtration is required in order for final obtainment. The process proposed follows a similar pathway, as well as includes adjustments as needed to better allow for an industrial over lab-scale process.

2.0 Synthesis Information for Processes

2.1 Overall Process Design

The process as seen in Figure 1 starts with a feedstock of mixture 50% $LiMn_2O_4$ batteries and 50% $LiCoO_2$. The compositions of these batteries were found in previous literature, Tables 1 and 2, and the mixture was calculated to give the flow rates of the cathodic materials, Table 3.

Table 1. Battery composition of $LiCoO_2$ batteries [3].

Component	wt. %
$LiCoO_2$	27.5000
Li	3.9868
Co	5.1300
O	18.3831
Steel/Ni	24.5000
Cu/Al	14.5000
Carbon	16.0000
Electrolyte	3.5000
Polymer	14.0000

Table 2. Battery composition of $LiMnO_2$ batteries [2].

Component	wt. %
Li	1.5
Mn	9.6
Co	0.1
Fe	5.4
Cr	9.6
Mo	0.8

Table 3. Cathodic materials flow rates.

Component	Flow rate (kg/hr)
Li	27.43
Co	25.65
Mn	48.00

The batteries start with a salt washing to fully discharge the batteries to prevent fires and explosions [1]. The batteries are dried, and then sent to a shredder to dismantle the battery

components. A magnetic separator then extracts the steel encasing of the batteries to simplify the chemical separation. Lithium, cobalt, and manganese are extracted from the rest of the materials and closely follows the process given by Wang et. al [4].

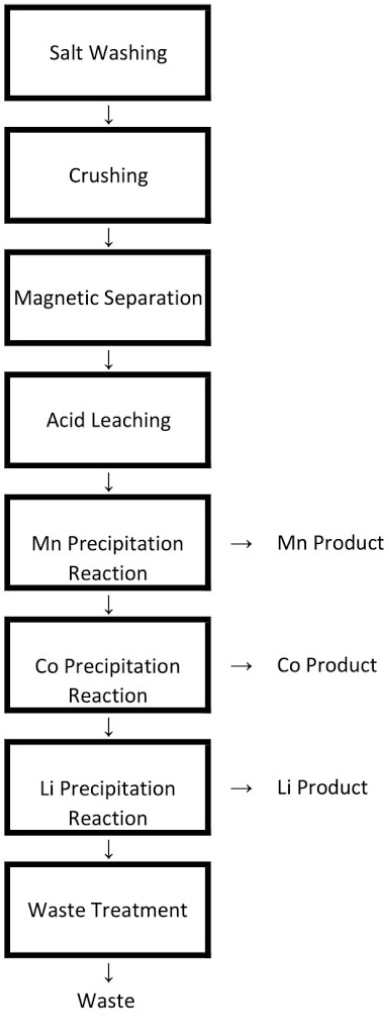


Figure 1. Block flow diagram of the proposed process.

2.2 Process Chemistry

The addition of 4 M hydrochloric acid to the battery components forms a solution with lithium, manganese, and cobalt. Hydrogen gas is also formed which is collected.

$$2Li(s) + 2HCl(aq) \rightarrow 2Li^{+}(aq) + 2Cl^{-}(aq) + H_2(g) \quad (1)$$

$$Mn(s) + 2HCl(aq) \rightarrow Mn^{2+}(aq) + 2Cl^{-}(aq) + H_2(g) \quad (2)$$

$$Co(s) + 2HCl(aq) \rightarrow Co^{2+}(aq) + 2Cl^{-}(aq) + H_2(g) \quad (3)$$

Following the Wang process to precipitate out the cathodic materials, manganese is first precipitated by changing the pH to 3, and then the addition of potassium permanganate. Wang states that the precipitation of manganese oxide, Equation 4, is the major reaction and the precipitation of manganese hydroxide, Equation 5, is minor. When modeling this system in OLI, manganese oxide is not an available chemical. For purposes of modeling this system, Equation 5 was used at the major reaction, and the manganese product is in the form of manganese hydroxide. For modeling in OLI, a composition splitter was also needed to separate the manganese hydroxide, as it was still in its aqueous form. We predict that if manganese oxide is able to precipitate, the composition splitter will not be needed.

$$3Mn^{2+}(aq) + 2MnO_4^{-} + 2H_2O \rightarrow 5MnO_2 + 4H^{+} \quad (4)$$

$$Mn^{2+}(aq) + 2NaOH \rightarrow Mn(OH)_2 + 2Na^{+} \quad (5)$$

Following the precipitation of manganese, the pH is adjusted to 0 to begin the precipitation of cobalt hydroxide. Sodium hydroxide is added to the solution of pH=0, and cobalt hydroxide precipitates out, as in Equation 6. A solid liquid separator was then used to model the filtration in OLI.

$$Co^{2+}(aq) + 2NaOH(s) \rightarrow Co(OH)_2(s) + 2Na^{+}(aq) \quad (6)$$

The lithium product is precipitated last. Sodium carbonate is added to the remaining solution, and lithium carbonate is precipitated, as in Equation 7. A solid liquid separator was also used to model the filtration of the solid product in OLI.

$$2Li^{+}\,(aq) + Na_2CO_3(aq) \rightarrow Li_2CO_3(s) + 2Na^{+}\,(aq) \quad (7)$$

The remainder of the solution was neutralized with hydrochloric acid to reach a pH of 7 and sent to further waste treatment processing.

2.3 Literature Summary

Although lithium primary cells were introduced to the market first, lithium secondary batteries, known as Lithium ion batteries, have become the defacto standard. They are favored due to their high energy density, high cell voltage, long storage life, low self-discharge rate, and large temperature range. These favorable characteristics are derived from several modifications of the the lithium primary cell including the utilization of a polymer electrolyte, changing the composition of the negative electrode from lithium metal to a lithium-storing material, and using a lithium-containing compound in the positive electrode like $LiCoO_2$ or $LiMnO_2$.

Lithium ion batteries have become ubiquitous. They are used as portable electrochemical power sources in a wide range of products including, but not limited to, mobile phones, laptops, headphones, and even medical implants. However, the lifespan of these devices is finite. They are often disposed of after a few years of use. This places a large burden on the waste storage industry because these batteries contribute to metal-containing hazardous waste which requires special storage capacity and special dump sites. As a result, disposal costs of lithium ion batteries are relatively high. Recycling spent lithium ion batteries has been identified as a way to reduce

the cost of disposal as well as mitigate the environmental risks associated with metal-containing hazardous waste.

The process of recycling spent lithium ion batteries is currently limited to the laboratory scale. Lithium is highly reactive at moderate temperatures and in the presence of moisture. This poses a design challenge in order to maintain the safety of workers and the environment. Most of the studied recycling processes are hydrometallurgical in nature and involve some sort of physical separation followed by acid leaching or another form of selective precipitation. These laboratory scale processes are a proof of concept to indicate the recovery of metals from the positive cathode is possible. Scale-up of these processes to the industrial level is the next logical step.

2.4 Basic Process Economics

The primary aim of this study was to design a process for the recycling of spent lithium ion batteries and to evaluate whether it was economically viable. There were many different processes that focused on processing lithium ion batteries to recover a single product. However, the process we chose to scale up to the industrial level focused on recovering each component of the lithium ion battery. Our economic analysis utilized the following variables: the overall conversion of lithium ion batteries to metal oxides (our final products), raw material and reagents costs, the capital and operating costs of individual pieces of equipment (based upon sizing and parameters from OLI), and the price of our viable products.

3.0 Method of Approach

One thousand kilograms per hour of active cathode material will be separated into constituent components through mechanical separation followed by selective precipitation. First,

the active cathode material will undergo crushing and sieving in order to recover the larger portions of the battery casings such as iron, aluminum, copper, and plastic. A magnetic separator, fine crushing, and additional sieving will allow remaining portions of the casing such as iron and aluminum to be recovered. Remaining internal components of the cathode will then proceed into CSTR 1 via a conveyor belt for selective precipitation. Twenty liters of 4M hydrochloric acid (.02 kg/L ratio) will then be added to CSTR 1. The temperature and stir rate of CSTR 1 will be set at 80 º C and 300 rpm, respectively. The reactor contents will be allowed to leach for one hour. When the hour is complete, the resulting leach liquor will be pumped to CSTR 2. Sodium hydroxide will then be added to the contents of CSTR 2 drop by drop until a pH of 3 is reached. Potassium permanganate will be added to CSTR 2. The amount of potassium permanganate added will be two times the expected moles of manganese present in the active cathode material. The temperature will be set in the range of 40-50 º C. Fluctuations between these values are negligible. The precipitation reaction will be allowed to proceed for ten minutes. The contents of the reactor will then be separated based upon state. The precipitate, manganese oxide, will be collected and sent to a storage tank. The remaining leach liquor will be sent to CSTR 3. The leach liquor from CSTR 3 is then sent to mixing vessel 1. Here, 4M hydrochloric acid and 1M sodium hydroxide will be added consecutively causing the pH to drop to 0 then rise to 11. As a result, cobalt hydroxide will precipitate out and be separated from the leach liquor containing lithium. This leach liquor will be sent to CSTR 4, treated with a saturated solution of sodium carbonate, and maintained at a steady temperature of 100 º C. Lithium carbonate will precipitate. Finally, it will be recovered and washed. The remaining leach liquor will consist of sodium ions and be disposed of as waste. Figure 2 shows the OLI model of our process. Note that some

Reactors might not be needed in practice, such as the manganese composition splitter. pH systems were not effective in OLI, but we assume that they would be needed in practice.

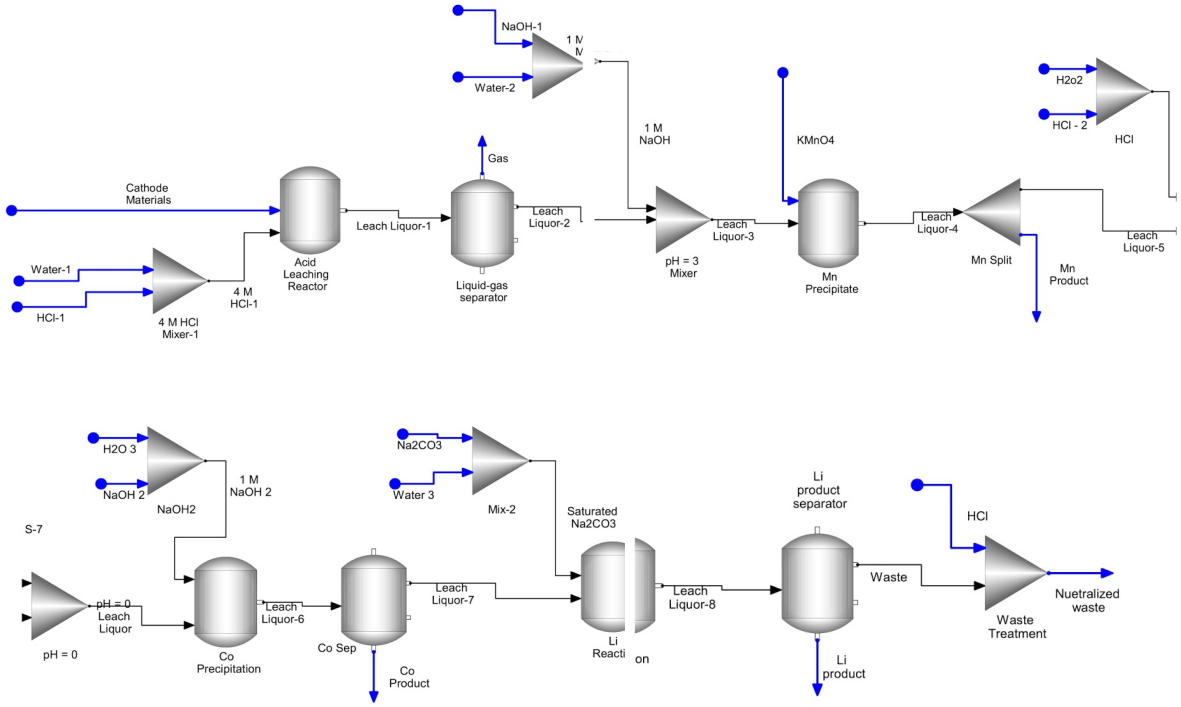


Figure 2. OLI model of process.

3.1 Sustainability, Environment, and Worker Safety

The process was designed to be sustainable while also minimizing the environmental impact and potential hazards to workers. We expect the overall process to be sustainable because we assumed our plant would receive the primary raw material, lithium ion batteries, from disposal sites that have no use for them. We would be acquiring the lithium ion batteries at a price that is a fraction of both their market price and the price of their individual components. Thus, as long as lithium ion batteries are being disposed of and we are able to acquire them at a small cost, we believe the process will continue to be sustainable. Most of the streams exiting the process consist of desirable products that have precipitated from the leach liquor; however, there

are a few waste streams. Although these waste streams are present, we do not anticipate there to be a large environmental impact. The stream of primary concern contains hydrochloric gas. This gas will be condensed and neutralized with an aqueous base and then proceed to wastewater treatment. Another of these waste streams is composed of hydrogen gas which will be burned off through solubilization in a flare. The remaining two waste streams are composed of the remnants of the leach liquor. As such, they will contain aqueous metal cations which can be disposed of through sanitary sewer systems that end in wastewater treatment. For this reason, these waste streams will be sent to a tank and tested for composition. If the tank composition is nontoxic, it will be emptied via a sanitary sewer line. As long as the effluent from these streams is not allowed to contaminate surface water, the environmental impact should be minimal.

Key considerations when designing the plant to maximize worker safety include understanding the reactivity of lithium and the reagents used to selectively precipitate the desired products. Lithium is highly reactive when exposed to high temperatures and moisture. Thus, it is susceptible to undesired reactions during the mechanical separation phase that occurs before selective precipitation. It would be prudent to install a strict temperature feedback system that shuts down operation if the temperature exceeds a predetermined threshold. A similar system should be implemented to manage the humidity surrounding this portion of the process. Finally, one of the waste streams and many of the reagents used in this process are highly caustic. It would benefit operators to have a brief course when they are hired on handling such caustic chemicals including first-aid with respect to chemical burns. Additionally, eye washers and chemical showers should be prevalent.

3.3 Product Quality

The final design consideration is product quality. Maintaining high quality products is imperative. As the quality of a product increases, the closer we will come to being able to sell the products at the desired selling price. Our initial goal is to set the product quality to at least 85% by weight of each desired product. Because there are no explicit product quality requirements, this process allows for optimization. Increasing the quality of one product might lead to a decrease in quality of another product. Thus, this can be optimized economically so that the quality of the highest priced products is prioritized over the quality of the lower priced products. This will require future process testing. In order for the initial target of at least 85% by weight of each product, the equipment was designed for specific precipitations taking into account sizing and costing.

4.0 Results

4.1 Capital Cost Estimates

A complete detailed breakdown of all capital cost estimates are listed in Table 5 in Appendix A. The list of equipment is extensive, but the main components were a solid conveyor, storage tanks, fine crusher, pH sensor, discharge reactor, magnetic separator, vibratory screen, and pumps and pipes accordingly. For every component it was necessary to make assumptions and justifications of use, which are detailed below. The total capital cost was calculated and determined to be a final estimate of $15,539,145.83. Sample calculations are listed in Appendix B.

4.2 Manufacturing Cost Estimates

Manufacturing costs can be seen in Table 4 below. Our process has a capacity of 1,000 kg of batteries per hour, or 8,760,000 kg batteries per year. Since an industrial scale lithium recovery process does not exist, we would suggest making a pilot plant and re-analyzing the manufacturing costs. There could possibly be unforeseen specialized equipment or other expenses. Our estimates suggest that there is potential for this process to be profitable.

Table 4. Manufacturing Cost Summary

MANUFACTURING COST SUMMARY		
Job Title Lithium recovery from lithium-ion batteries		
Location Tennessee Annual Capacity (kg/yr) 8,760,000 used li-ion batteries		
Effective Date to Which Estimate Applies 2020 Cost Index Type CE Plant Cost Index		
Cost Index Value 596.2		
Capital		
Fixed Capital, CFC	$15,593,145.83	
Working Capital (10-20% of fixed capital), CWC	$1,559,314.58	
Total Capital Investment, CTC	$17,152,460.41	
Manufacturing Expenses	Annual cost	
Direct	$/yr	$/yr
Raw Materials	$5,426,834.26	
Operating Labor	$301,479.41	
Supervisory and clerical labor (10-30% of operating labor)	$30,147.94	
Utilities		
Electricity 1,158,000,000kWh @ 0.09$/kWh	$267,000.00	
Process Water 370,328,000m^3 @ 1.1/m^3	$443,000.00	
Waste disposal 386,995,200 m^3 @ 1.22$/m^3	$472,134.14	
Maintenance and repairs (6% of fixed capital)	$935,588.75	
Operating Supplies (15% of maint. & repairs)	$140,338.31	

Laboratory charges (15% of operating labor)	$45,221.91	
Patents and royalties (3% of total expense)	$28,067.66	
Total, *ADME*	**$8,089,812.39**	**$8,089,812.39**
Indirect		
Overhead (payroll and plant), packaging, storage (60% of op. labor, supervision, and maintenance)	$760,329.66	
Local Taxes (1.5% of fixed capital)	$233,897.19	
Insurance (1.5% of fixed capital)	$233,897.19	
Total, AIME	**$1,228,124.03**	**$1,228,124.03**
Total manufacturing expense, AME=ADME+AIME	**$9,317,936.43**	**$9,317,936.43**
General Expenses		
Administrative cost (25% overhead)	$190,082.41	
Distribution and selling (10% of total expense)	$931,793.64	
Research and development (5% of total expense)	$465,896.82	
***Total general expense, A*GE**	**$1,587,772.88**	**$1,587,772.88**
Depreciation (approx. 10% of fixed capital, ABD	$1,559,314.58	
***Total expenses*, ATE**	**$12,465,023.89**	**$12,465,023.89**
Revenue from sales (4,300,327 kg/yr @ $4.94/kg), As		$21,248,583.00
Net annual profit, ANP		$8,783,559.11
Income taxes (net annual profit x tax rate), AIT		$2,986,410.10
Net annual profit after taxes (ANP-AIT), ANNP		$5,797,149.01
After tax of return, i=(1.5ANNP/CTC)*100	**50.70%**	

4.3 Product Composition

It was desired to obtain purified concentration of manganese, cobalt, and lithium as our products. Based on the proposed process, each was able to be separated out with a purity of 100%. The beginning molar flow rates of manganese, cobalt, and lithium were 873, 2872, and 3953 mol/hr, respectively. Manganese was able to be fully recovered and purified with no loss to waste. 99.99% of the beginning cobalt stream was recovered, so assumed loss was negligible and 100% purified and recovered. 100% of the starting lithium was recovered with a purity of 100%

in the product stream. Because our analysis is from an idealized model, our analysis suggests that the product recovery and purity is 100%. We suggest a pilot plant would give a better estimate for product recovery, though we believe it should be at least 90% for all products.

5.0 Discussion of Results

5.1 Equipment

Storage Tanks

It was necessary to break storage tanks into their perspective types- bullets and bins for liquid and solid storage, respectively. Glass-lined tanks were used for storage bullets and liquid storage, while rubber-lined tanks were used for the solid storage bins. Both of these materials were chosen to prevent corrosion from residual HCl. For the implementation of these tanks, no extra storage was required because working under the impression that NaCl was conveyed into the reactor directly from its bulk packaging. The storage tanks were also optimized to carry 48 hours of storage. In total 5 storage bins and 4 storage bullets were required.

Reactors

Two types of reactors were needed due to the accumulation of HCl and the need for a corrosive resistant reactor. For the discharge reactor, which is early in the pathway and before the accumulation of HCl, a carbon steel-lined reactor was used. Later in the pathway, a glass-lined reactor was used. Only 1 discharge reactor was included in the process, and 4 glass-lined reactors were used in the process. The reactors were run for one hour based on recommendations from the literature. Each battery was taken to have a density of 2 grams and believed to discharge in 1 liter of water. To simplify calculations, the density of HCl was approximated to that of the

density of the solution being processed in the reactor. Lastly, the reactor used for solubilization was priced for a jacketed CSTR in order to account for the subsequent production of gas.

Pumps and Piping

12 pumps plated with titanium to prevent HCl corrosion were used in total. Centrifugal pumps starting on the production floor, pumping to a height of 5 meters, were modeled for processing. An efficiency of 85% was assumed to be maintained. This number was based on similar processes found in the literature. CPVC piping was used as a resistance measure to corrosion. 12 sections of 30 meters were necessary. The relatively small flow rates led to the use of 5 cm pipes. Each pipe was spaced 30 meters apart, requiring 30 meters of piping.

Crushers and Conveyors

1 crusher and fine crusher with kg/s parameters were used in the process. A jaw crusher was used and the flow rates were taken from the accompanying OLI flowsheet. 10 belt conveyors were used and assumed to have a 0.5 meter belt width and 30 meters in length as to provide adequate spacing between all pieces of equipment.

Vibratory Screen

One carbon steel vibratory screen reference was used with an area of 100 m^2. This size was chosen in order to accomodate all of the crushed battery material. The particle diameters were assumed to be 250 micrometers based on the requirements for material separation. The particles had an average density of 5000 kg/m^3.

Decanter, Magnetic Separator, and pH sensor

4 decanters plated with titanium were used. One magnetic separator and pH sensor were needed each.

5.2 Product Composition

The recycling process of spent lithium proved to be successful. The desired products of manganese, cobalt, and lithium were all able to be purified from fractured batteries and subsequently be used in a new process. Manganese, cobalt, and lithium were able to be fully recovered with negligible losses.

All pursuits and models for the recycling of lithium have been lab-scale to date, a successful model for an industrial procedure has been proposed. The capital cost of roughly $15.5 million includes the start-up costs. This cost can only be assumed to go down as the process is more established and transitions into a period of upkeep versus acquisition and startup. Also, since the products were able to be purified with no losses in recovery, the products are viable to be sold. This is an essential process to be maintained and implemented. The increasing use of lithium in mainstream applications calls for a need to be able to be able to retrieve spent lithium and be able to recycle and reuse it. Tainted lithium is highly reactive if left untreated and has a negative impact left unpurified. Cobalt and manganese are also an essential acquiesced product. They can be sold to other processes to make other necessary goods. Cobalt can be used to make magnets or further used and recycled in the battery industry as well. Manganese can be sold and set aside for steel production or for aluminum alloy production. While this model was able to ideally achieve a purity of 100%, there is more than likely a loss of purity throughout the process. It is not projected to be any less than 10%, but is something to note. While it is hoped 100% could be recovered, a more realistic projection for industry would be roughly around 90%. It is hoped that within a 5 year time frame the investment would be recovered.

6.0 Conclusions

A proposed industrial scale process for the recycling of lithium from batteries was presented. With access to the literature and lab scale processes, an industry process was able to be modeled with hopeful implementation in large scale production. The process proved to be successful. Lithium was able to be recovered with a purity and recovery of 100%. Cobalt and manganese were also obtained as products and able to be wholly purified with negligible losses. This scaleup from a lab scale process is a needed model for the industry today. Batteries are used in copious amounts of modern technology. However, when these devices are no longer needed or in use, the battery is leftover and neglected. The problem is these batteries are highly reactive and will not break down on their own accord. Models are needed to recycle the elements in these batteries to continue the use of these materials and recycled in a later process. The need of this process justifies the cost. This industry, as it now stands, would garner use for the next generations to come and would remain a needed industry.

7.0 Recommendations

Because the recycling of spent Lithium ion batteries to recover desirable products has been conducted predominantly at the laboratory scale, the scaled-up industrial process we have designed represents a “base-case”. It was designed as a proof of concept that would achieve the minimum design goals. As such, there are many improvements that could be made to process in order to enhance the process and mitigate costs.

Before the batteries can undergo mechanical separation via crushing, they must be discharged. The discharge of these batteries requires a discharge reactor which incurs an additional capital cost. This capital cost can be mitigated by purchasing spent Lithium-ion

batteries that have already been discharged. Many companies recycle their own electronics to salvage usable parts and discharge used lithium-ion batteries. If the process we designed is implemented, we suggest that discharged batteries, our raw material, be purchased from such companies. We estimate that this would cut down capital costs by $500,000 and only increase operating costs slightly.

We also identified that there is a high capital cost associated with storage tanks. Our process currently contains two HCl storage tanks and two NaOH storage tanks. Each feeds into a different reactor for selective precipitation. To reduce the capital costs the two HCl tanks could be consolidated into a single tank. The same could be done for the two NaOH storage tanks. The joint capital cost savings from consolidating the four storage tanks into two tanks is estimated at $1,500,000. Additionally, there is an effluent storage tank at the end of the process that contains process waste. This tank could be eliminated and waste could be continuously discharged into a sanitary sewer line. The elimination of this effluent tank would save approximately $1,500,000.

Currently, our process is designed with reagent storage tanks that contain enough HCl and NaOH for the plant to operate for 48 hours without being refilled. Thus, shipments of the reagents would arrive approximately every two days. If the storage requirements of the reagent tanks were lowered, the size of the tanks would be reduced as would the associated capital costs. Thus, we propose that the storage requirements of the reagent tanks be lowered so the plant could operate for 24 hours without being refilled. This would necessitate daily shipments of reagents; however the capital cost of the tanks could be reduced by $1,500,000.

Because we are trying to minimize the environmental impact of the process, it would be prudent to utilize as many waste streams as possible. The current process emits hydrogen gas as

a waste product which is solubilized by a flare. We think this hydrogen gas could be put to better use. The emitted gas could instead be burned and used to partially heat the reactors in the process. If the hydrogen gas was purified, hydrogen fuel cells could also be used to power the process. If this is not feasible, it could also be stored and sold since it is a commodity in industries that utilize the Haber-Bosch reaction. To further minimize the environmental impact we also suggest the renewable energy be utilized to power the plant as much as possible. This could be in the form of solar, wind, or geothermal power, depending on where the processing plant is located.

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Appendices

Appendix A: Capital Cost Summary Table

Table 5. Capital Cost Summary

	CAPITAL COST SUMMARY			Date to which estimate applies 2020			
Job Title: Lithium-ion Battery Recycling Plant			Location: Tennessee				
			Cost Index Type: CE Plant Cost Index			Cost Index Value: 596.2	
			(base material)		Actual Bare Module Factor, FBM	Actual Bare Modual Cost, CBM	Total
Equipment Identification	Number	Capacity or Size specifications	Year 2004	Year 2020			
Crushers							
Crusher	C-110	0.278 (kg/s)	$5,000.00	$7,452.50	2.1	$15,650.25	$15,650.25
Fine Crusher	C-210	0.694 (kg/s)	$10,000.00	$14,905.00	2.1	$31,300.50	$31,300.50
Total Crushers							$46,950.75
Conveyors							
Solid Conveyor (Unopened Batteries)	B-110	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430

NaCl Conveyor	B-210	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Solid Conveyor (Spent Batteries)	B-120	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Solid Conveyor (Crushed Batteries)	B-130	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Solid Conveyor (Spent Batteries)	B-140	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Solid Conveyor (Crushed, Magnetized Batteries)	B-150	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Conveyor Belt	B-220	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Solid Conveyor(MnO2)	B-230	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Solid Conveyor (CoOH)	B-240	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Solid Conveyor (Na2CO3)	B-250	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430
Solid Conveyor (Li2CO3)	B-260	30 (m)	$25,000	$37,263	2.4	$89,430	$89,430

Total Conveyors							**$983,730**
Reactors							
Discharge Reactor	**R-110**	**500 (m3)**	**$175,000**	**$260,838**	**3**	**$782,513**	**$782,513**
CSTR 1 (with ventilation for all)	**R-310**	**5.8 (m^3)**	**$10,000**	**$14,905**	**7.5**	**$111,788**	**$111,788**
CSTR 2	**R-210**	**14.0 (m^3)**	**$9,000**	**$13,415**	**7.5**	**$100,609**	**$100,609**
CSTR 3	**R-220**	**45 (m^3)**	**$17,000**	**$25,339**	**7.5**	**$190,039**	**$190,039**
CSTR 4	**R-230**	**320 (m3)**	**$45,000**	**$67,073**	**7.5**	**$503,044**	**$503,044**
Total Reactors							**$1,687,991**
Storage Tanks							
Storage Tank (HCl)	**T-110**	**243 (m^3)**	**$100,000.00**	**$149,050.00**	**5.7**	**$849,585.00**	**$849,585.00**
Storage Tank (Carbon and Binder)	**S-110**	**1.48 (m^3)**	**$100.00**	**$149.05**	**2.7**	**$402.44**	**$402.44**
Storage Tank (1M NaOH)	**T-120**	**420.5 (m^3)**	**$200,000.00**	**$298,100.00**	**2.1**	**$626,010.00**	**$626,010.00**
Storage Tank (MnO2)	**S-120**	**0.58 (m^3)**	**$100.00**	**$149.05**	**2.7**	**$402.44**	**$402.44**

Storage Tank (1M NaOH) (24 hr storage)	**T-130**	**610 (m^3)**	**$250,000.00**	**$372,625.00**	**2.1**	**$782,512.50**	**$782,512.50**
Storage Tank (4M HCl)	**T-140**	**210.3 (m^3)**	**$100,000.00**	**$149,050.00**	**5.7**	**$849,585.00**	**$849,585.00**
Storage Tank (CoOH)	**S-130**	**0.82 (m^3)**	**$100.00**	**$149.05**	**2.7**	**$402.44**	**$402.44**
Storage Tank (Na2CO3)	**S-140**	**~1 (m^3)**	**$128.57**	**$191.64**	**2.7**	**$517.42**	**$517.42**
Storage Tank (Li2CO3)	**S-150**	**1.39 (m^3)**	**$100.00**	**$149.05**	**2.7**	**$402.44**	**$402.44**
Storage Tank (Effluent) (8hr storage)	**T-150**	**387 (m^3)**	**$180,000.00**	**$268,290.00**	**5.7**	**$1,529,253.00**	**$1,529,253.00**
Total Storage Tanks							**$4,639,072.66**
Screens, Separators, and Filters							
Vibratory Screen	**V-110**	**50 (kW)**	**$5,000.00**	**$7,452.50**	**2.8**	**$20,867.00**	**$20,867.00**
Magnetic Seperator	**M-110**		**$5,000.00**	**$7,452.50**	**1**	**$7,452.50**	**$7,452.50**

Filter 1	D-110	0.051 (kg/s)	$55,000.00	$81,977.50	7.5	$614,831.25	$614,831.25
Filter 2	D-120	0.051 (kg/s)	$55,000.00	$81,977.50	7.5	$614,831.25	$614,831.25
Filter 3	D-130	0.051 (kg/s)	$55,000.00	$81,977.50	7.5	$614,831.25	$614,831.25
Filter 4	D-140	0.051 (kg/s)	$55,000.00	$81,977.50	7.5	$614,831.25	$614,831.25
Total Screens, Separators, and Filters							$2,487,644.50
Pumps and Piping							
Pump 1	L-110	0.0928 (kW)	$2,000.00	$2,981.00	5.7	$16,991.70	$16,991.70
Piping 1	P-110	30 (m)	$382.69	$570.40	3.9	$2,224.57	$2,224.57
Pump 2	L-120	0.0964 (kW)	$2,000.00	$2,981.00	5.7	$16,991.70	$16,991.70
Piping 2	P-120	30 (m)	$382.69	$570.40	3.9	$2,224.57	$2,224.57
Pump 3	L-130	0.0964 (kW)	$2,000.00	$2,981.00	5.7	$16,991.70	$16,991.70
Piping 3	P-130	30 (m)	$382.69	$570.40	3.9	$2,224.57	$2,224.57
Pump 4	L-140	0.145 (kW)	$666.67	$993.67	5.7	$5,663.90	$5,663.90
Piping 4	P-140	30 (m)	$382.69	$570.40	3.9	$2,224.57	$2,224.57
Pump 5	L-150	0.24 (kW)	$2,500.00	$3,726.25	5.7	$21,239.63	$21,239.63
Piping 5	P-150	30 (m)	$382.69	$570.40	3.9	$2,224.57	$2,224.57

Pump 6	**L-160**	**0.24 (kW)**	**$2,500.00**	**$3,726.25**	**5.7**	**$21,239.63**	**$21,239.63**
Piping 6	**P-160**	**30 (m)**	**$382.69**	**$570.40**	**3.9**	**$2,224.57**	**$2,224.57**
Pump 7	**L-170**	**0.422992 (kW)**	**$3,000.00**	**$4,471.50**	**5.7**	**$25,487.55**	**$25,487.55**
Piping 7	**P-170**	**30 (m)**	**$382.69**	**$570.40**	**3.9**	**$2,224.57**	**$2,224.57**
Pump 8	**L-180**	**0.080256 (kW)**	**$1,070.18**	**$1,595.10**	**5.7**	**$9,092.05**	**$9,092.05**
Piping 8	**P-180**	**30 (m)**	**$382.69**	**$570.40**	**3.9**	**$2,224.57**	**$2,224.57**
Pump 9	**L-190**	**0.743472 (kW)**	**$3,500.00**	**$5,216.75**	**5.7**	**$29,735.48**	**$29,735.48**
Piping 9	**P-190**	**30 (m)**	**$382.69**	**$570.40**	**3.9**	**$2,224.57**	**$2,224.57**
Pump 10	**L-210**	**0.743472 (kW)**	**$3,500.00**	**$5,216.75**	**5.7**	**$29,735.48**	**$29,735.48**
Piping 10	**P-210**	**30 (m)**	**$382.69**	**$570.40**	**3.9**	**$2,224.57**	**$2,224.57**
Pump 11	**L-220**	**0.795088 (kW)**	**$3,800.00**	**$5,663.90**	**5.7**	**$32,284.23**	**$32,284.23**
Piping 11	**P-220**	**30 (m)**	**$382.69**	**$570.40**	**3.9**	**$2,224.57**	**$2,224.57**
Pump 12	**L-230**	**0.795088 (kW)**	**$3,800.00**	**$5,663.90**	**5.7**	**$32,284.23**	**$32,284.23**
Piping 12	**P-230**	**30 (m)**	**$382.69**	**$570.40**	**3.9**	**$2,224.57**	**$2,224.57**
Total Pumps and Piping							**$284,432.12**
pH Sensors							
pH Sensor 1	**G-110**		**$5,000.00**	**$7,452.50**	**1**	**$7,452.50**	**$7,452.50**
pH Sensor 2	**G-120**		**$5,000.00**	**$7,452.50**	**1**	**$7,452.50**	**$7,452.50**
Total pH Sensors							**$14,905.00**

Total bare module cost							**$10,129,821.27**
Contingency Allowance							**$1,519,473.19**
Contractor Fee							**$303,894.64**
Total module cost							**$11,953,189.10**
Site Development							**$597,659.46**
Auxiliary Buildings							**$478,127.56**
Off-site Facilities							**$2,510,169.71**
Grass Roots capital							**$15,539,145.83**

Appendix B: Sample Calculations for Equipment

Vibratory Screen

Specification equation:

$$P = 5 * 10^{-6} * \rho_s{}^2 * \frac{A}{D_p}$$

Assumed to have an area of 100 m^2, witha diamter of 250 micrometers and average density of 5000 kg/m^3.

$$P\ (kW)\ =\ 5 * 10^{-6} * 5000\ (kg/m^3)^2 * \frac{100\ (m^2)}{250\ (\mu m)}$$

Storage Tank

Specification Equation:

$$V = m\ *\ t\ *\ \frac{1}{MW} * \frac{1}{\rho}$$

With a carrying capacity of 48 hours.

$$HCKV\ (m^3)\ =\ 5.8 * 10^6\ (g/hr)\ *\ \frac{1\ (m^3)}{1.145 * 10^6 (g)} * 48\ (hrs)$$

Reactor

Specification Equation:

$$V = \Sigma(m_i + \frac{1}{MW_i} * \frac{1}{\rho_i}) * t\ (reaction\ time)$$

Each battery assumed to be 2 grams and discharged 1 L of water.

Pump

Specification Equations:

$$W_s = \frac{q \cdot * \Delta P}{\epsilon} \;\; ; \;\; \Delta P = \rho * g * \Delta h \;\; ; \;\; q \cdot = m \cdot * \frac{1}{\rho}$$

Efficiency of 85% was achieved with a pump height of 5 meters.

$$W_s\,(kW) = \frac{5.8*10^6\,(g/hr) * \frac{1\,(hr)}{3600\,(sec)} * \frac{1}{\rho} * \frac{1\,(kg)}{1000\,(g)} * \rho * 9.8\,(m/s^2) * 5\,(m)}{0.85} * \frac{1\,(kW)}{1000\,(W)}$$