Development, Implementation and Analysis of the First Recycling Process for Alkaline Liquid Metal Batteries

by

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B.Sc. Mechanical Engineering (2013)
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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

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Abstract

Increasing energy prices, new environmental laws and geopolitical interests demand for new, more efficient and cheaper grid level energy storage solutions. Grid level energy storage refers to large scale energy storage applications that are connected to the power grid. Ambri Inc. is a MIT startup that develops liquid metal batteries for grid level energy storage. Their liquid metal battery operates at elevated temperatures and uses molten metals as electrodes thereby exhibiting a very low fade rate over hundreds of charging and discharging cycles. Ambri cooperated with MIT to develop a new recycling process for their unique battery chemistry to implement a sustainable end of life management for their product.

This thesis describes the process development, implementation and analysis of a hydrometallurgical recycling process for a liquid metal battery. According to jointly developed process requirements, the MIT team build a process that is capable of recycling 5 liquid metal batteries per batch with an estimated processing time of 60 minutes. This will increase Ambri's profit by several hundred thousands of dollars even during the first year of production. The performed analysis of the process investigated safe and stable operating conditions, cost efficiency and scalability. The MIT team concluded that the newly developed recycling process best accommodates for Ambri's current needs and future growth compared to the only competing process, the full cell incineration with following hazardous waste landfill deposition.

Thesis Supervisor: Dr. Timothy G. Gutowski
Title: Professor of Mechanical Engineering

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Table of Contents

List of Figures

List of Tables

1. Introduction

The introduction of this thesis provides an overview over the battery industry, classifies Ambri's liquid metal battery and explains the task of designing a new battery recycling process.

The chapter starts with an *Overview of the U.S. Battery Industry* which provides background information of the U.S. battery market and industry. The second part *Ambri and the Liquid Metal Battery* introduces the company and its product for which the recycling process described in this thesis was developed. With the thereby provided company and project background, the *Research Motivation* is explained and the *Problem Statement* derived. The chapter closes with an overview of the *Thesis Structure* and the causal link between the chapters.

1.1 Overview of the U.S. Battery Industry

The first part of the following chapter provides an overview of the U.S. battery industry and market. The second part differentiates between different product categories and explains their main applications. The third and last part introduces the battery recycling industry, from well-established technologies to embryonic process development.

1.1.1 The Market

The U.S. battery industry supplies a highly technology driven, globalized market with an estimated revenue of about $12.9 billion and a profit of $554 million for U.S. companies in 2014. The annual growth between 2009 and 2014 was 5.3% with a projected growth for the following 5 years until 2019 of 1.8%. The 6 market leaders of the U.S. battery industry are: [1]

- The Proctor & Gamble Company (20.7% market share)
- Johnson Controls Inc. (20.1% market share)
- East Penn Manufacturing Co. Inc. (11.3% market share)
- EnerSys Inc. (9.2% market share)
- Exide Technologies (8.9% market share)
- Energizer Holdings Inc. (7.2% market share)

They alone account for more than ¾ of the whole market, which sets the barriers of entry for new competitors high.

A major problem for operators in the industry is developing a sustainable business model by projecting and managing the operating costs due to the high volatility of input material prices. Industry reports state that nonferrous metal prices e.g. dropped by 14.2% in 2009 just to increase by as much as 38.6%

in 2010. The cost of this uncertainty and the average annual increase of 8.0% between 2009 and 2014 could only be partially passed towards customers as low cost imports even out consumer prices. This development reduced the industry profit from 4.6% of the revenue in 2009 to 4.3% in 2014 with a similar outlook for the following years. [1]

Besides the already mentioned cost uncertainty other factors increase the difficulty of developing a sustainable business model in the market as well. A recent example is the former MIT startup A123, a manufacturer of lithium ion batteries for the electric car industry. The company had to file for bankruptcy in 2012 and was bought by a Chinese conglomerate. [2] A123 overestimated the projected sales and underestimated the complexity of producing innovative lithium-ion batteries.

Despite these recent setbacks, demand is expected to rise especially in the field of rechargeable batteries. Due to increasing oil prices the sales of electric cars will continue to increase, reaching approximately 3.8 million sales worldwide in 2020. [3]

Besides the already established market segments, the implementation of an increasing amount of renewable energy sources provide growth opportunities for the right rechargeable battery technology. Over 61,108MW of wind energy are installed in the United States alone. So called interrupted renewable energies like photovoltaic, thermal solar energy or wind power account for more than 15% of the renewable energy electricity generation. A major disadvantage of these technologies is the fact that they provide overcapacity when the sun shines or wind blows and no capacity under reverse conditions. [4] To further expand power production from renewable sources, a method needs to be developed to store large amounts of electricity during overcapacity time periods and release them into the grid when needed. Such a technology must not only provide the possibility to store a vast amount of energy, it must also only require a minimal amount of maintenance while having a long lifetime.

To position itself in this competitive, global scale market, the U.S. battery industry has to increase its research and development expenditures over the following years to further supply the market with innovative premium products.

1.1.2 Products and Applications

The probably most important and general distinction of the battery market is the difference between primary and secondary batteries. Linden's Handbook of batteries defines primary batteries as accumulators "that do not recharge and after use, that is, discharge can be recycled or disposed of as waste" while "secondary batteries include various types of batteries that after discharge can be recharged or expanded. Secondary batteries are the following types: nickel metal hydride, lithium ion batteries (eg mobile phones) and lead acid batteries." [5]

Since Ambri's liquid metal battery is a secondary battery with important similarities to lead-acid and lithium ion accumulators, the literature research of this thesis is focused on these two types of accumulators.

Nevertheless, primary batteries like alkaline accumulators (with a total market share of 20.7%) still play an important role in the industry as shown in figure 1. [1]

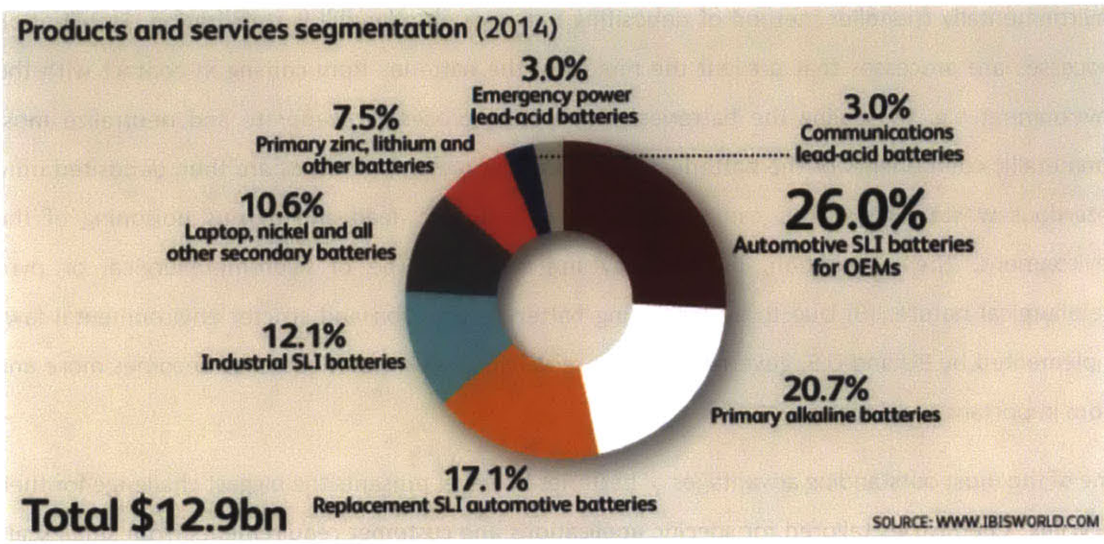


Figure 1: Products and Service Segmentations [1]

The biggest single market share have the so called starting, lighting and ignition (SLI) batteries with over 50 percent (or more than $7 billion revenue in the U.S. alone). A vast majority of SLI batteries are lead-acid type accumulators. [1]

A constantly growing sector are the consumer electronic batteries with a market share of more than 10% in the U.S. in 2014. This sector is dominated by lithium ion batteries as the power source of choice for electronic devices like laptops or smartphones with energy consuming high performance processors. [1]

As battery technology evolves and emerging sectors like grid level storage of renewable energies, electric vehicles and new areas of applications are explored, the market share breakdown can and has changed significantly over short periods of time (e.g. market introduction of the lithium ion battery in 1991 or the introduction of the iPhone as a gateway for the smartphone revolution in 2007).

1.1.3 Battery Recycling

At the end of their life cycle all batteries have to be disposed of. This can generally happen in four different ways: [6]

- Deposition on a landfill
- Stabilization
- Incineration
- Recycling

Most household, especially primary batteries are currently disposed of on a landfill. A high cost yet environmentally friendlier method of depositing batteries on a landfill is stabilization. Stabilization processes are processes that prevent the metals of the batteries from coming in contact with the environment e.g. by sealing the batteries. Incineration processes evaporate and neutralize most nonmetallic components of the batteries. The remaining metals and ashes are then deposited on a hazardous waste landfill. This can cause mercury, cadmium, lead and dioxins poisoning of the environment. The last option, battery recycling can either be of hydrometallurgical or pyro metallurgical nature. [6] Due to an increasing battery production and stricter environmental laws implemented by EU and U.S. governments, the recycling of all kinds of batteries becomes more and more important and necessary.

One of the most outstanding advantages of batteries however presents the biggest challenge for their recycling: Chemistries tailored for specific applications and customer requirements from small scale mobile phone batteries to back up power supplies for hospitals and batteries capable of powering entire submarines. One of the best example for this challenge is the well-established, highly efficient recycling of lead acid batteries compared to the different, non-established, mostly experimental scale recycling processes for lithium ion batteries. (Both discussed in the next chapter *Literature Review*).

The industry has to increase their R&D budget to develop more advanced and flexible battery recycling methods to accommodate for the increasing battery production and the variety of chemistries. If the improvements of recycling technics remain slow, one of the capacity limiting factors for ambitious plans like the Tesla lithium ion Gigafactory or Ambri's grid level storage could in fact become the end of life management of the batteries.

1.2 Ambri and the Liquid Metal Battery

The following chapter introduces Ambri and provides a brief overview of the company history and the current team. The second part explains the general concept of a liquid metal battery with its constituting properties.

1.2.1 The Company

Ambri (formerly Liquid Metal Battery Corporation) was founded by Donald Sadoway, David Bradwell and Luis Ortiz in 2010. Prof. Sadoway's group at the Massachusetts Institute of Technology (MIT) invented the liquid metal battery at the Department of Material Science and Engineering (DMSE). Ambri's goal is the development of "an electricity storage solution that will change the way electric grids are operated worldwide. Ambri will enable the more widespread use of renewable generation like wind and solar, reduce power prices and increase system reliability." [7]

To accomplish these goals, Ambri has assembled a team of more than 40 employees (as of June 2014) consisting of experts in the fields of mechanical, material, chemical and electronic engineering. The team is led by Phil Giudice, Chief Executive Officer (CEO), president and board member. Co-founder and MIT graduate Dr. David Bradwell serves as CTO of the company while Co-founder Dr. Donald Sadoway is a member of the board and Ambri's chief scientific adviser. The manufacturing division is led by Shazad Butt, a former Ford and A123 manager. Kristin Brief serves as the VP of corporate development and treasurer with over ten years of experience in the energy industry.

The circle of Ambri's investors includes Khosla Ventures, Bill Gates and the energy company Total. The company recently ended its third round of funding to start its production and first product delivery at the beginning of 2015.

1.2.2 The Liquid Metal Battery Technology

Ambri's liquid metal battery technology is a completely new approach on the energy storage market: "Each cell consists of three self-separating liquid layers — two metals and a salt mixture — that float on top of each other based on density differences and immiscibility. The system operates at elevated temperature maintained by self-heating during charging and discharging. The result is a low-cost and efficient storage system." [8] This general principle is shown with Ambri's initial chemistry in figure 2 below:

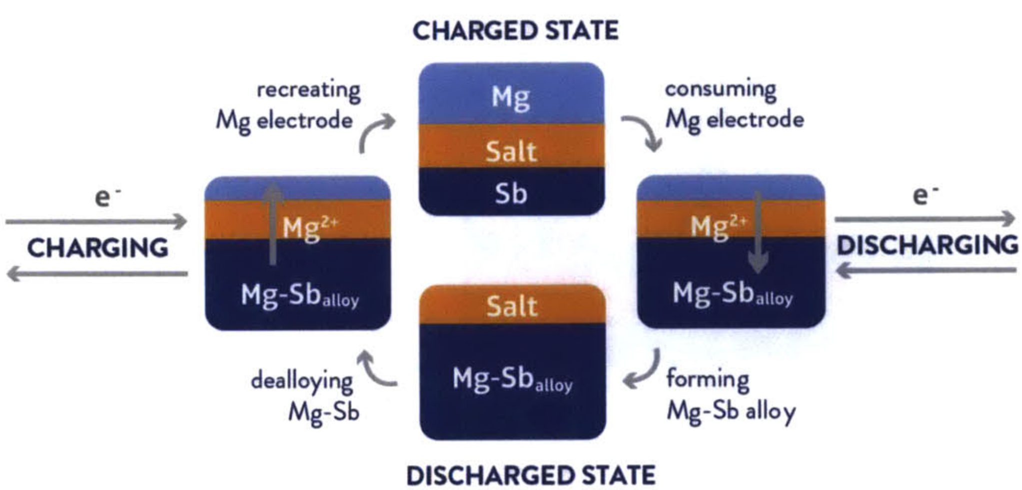


Figure 2: Liquid Metal Battery Concept [9]

In the charged state, elementary, liquid antimony (Sb) is on the bottom of the cell, while the liquid electrolyte (salt) and magnesium (Mg) float on top. During the discharge, the magnesium loses 2 electrons and the remaining ion migrates through the electrolyte into the antimony where it forms an Mg-Sb alloy. This process continues until all elementary magnesium is consumed. At this state the battery is completely discharged and the salt floats on the liquid Mg-Sb alloy. During the charging process the reaction is reversed and magnesium ions migrate through the electrolyte to the top of the battery were they gain 2 electrons to form elementary magnesium. [10]

The active material of the battery is contained in a rigid 3.2mm thick stamped 304 stainless steel casing with welded top. The current collector of the anode is the casing itself while the current collector of the cathode is the cylindrical stem on top of the battery that reaches in to the active material. The battery is sealed with a ceramic seal that connects the stem with the battery casing, thereby electrically isolating the current collectors from one another. Figure 3 is a schematic of the, for the recycling process important features and doesn't picture all design elements of the battery due to NDA restrictions.

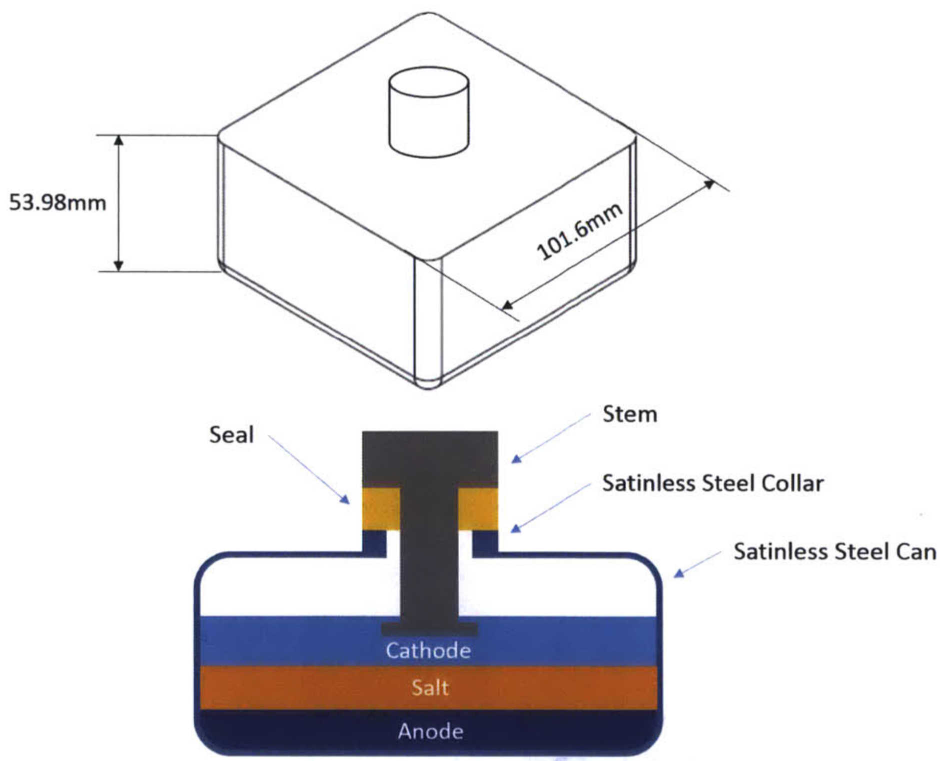


Figure 3: Ambri's Cell Design

Ambri's battery thereby combines the following advantages due to this unique, patented technology and design: [8], [9]

- Low Cost
- Flexible Application
- Long Lifespan
- Easy to Permit
- Easy to Deploy
- Reliable
- Robust

Low cost is achieved by using earth-abundant materials as well as conventional manufacturing processes to assemble the battery. The flexibility of the liquid metal battery is inherent to its design: „It can respond to regulation signals in milliseconds and it can store up to twelve hours of energy and discharge it slowly over time." The long lifespan is achieved by avoiding common failure mechanisms of conventional batteries (e.g. particle cracking of the active material of the electrodes with permanent disconnection from the current collector). This is because the all-liquid design reconstitutes the electrodes with each charge. Ambri's product is additionally easy to permit and deploy since it has no moving parts, operates emission free and silently. Lastly, the liquid metal battery is constructed with a robust architecture to further increase its reliability. [8], [9]

While the principles of Ambri's current liquid metal battery remain the same, the chemical composition differs and is considered one of Ambri's technology secrets.

1.3 Research motivation

Like most batteries, Ambri's product is composed out of materials that cannot just follow the normal garbage disposal process stream and be safely deposited on a landfill after it reached the end of its life. Complete incineration of the product, as an approach often used for special or toxic waste though is too expensive and does not comply with Ambri's fundamental understanding of sustainable life cycle management.

Another important consideration for the new recycling process design is of legal nature: In order to be able to dissect their own cells for e.g. process and quality control purposes, Ambri is required by law to have a fully functional recycling process to dispose safely and environmental friendly of the battery remains.

Due to its design and innovative chemical composition no currently existing recycling process can be copied and applied to the liquid metal battery. The robust architecture of the product that increases its reliability and resistance to environmental influences imposes an additional challenge for an inexpensive, repeatable and scalable recycling process.

The last important consideration is the fact that Ambri is a startup company that is developing a completely new product. The recycling process must therefore be stable and general enough to manage changes in the design of the battery itself, its architecture and materials. Besides that, the development and purchasing cost of the new process must be kept low.

1.4 Problem Statement

All of the above mentioned considerations lead to the problem statement that was iteratively developed during the initial technology research and later refined due to new financial capabilities of the company.

The following is the original problem statement under which the general process flow and the function of all process steps were defined and developed:

"The objective is to develop and implement a recycling process in accordance with Ambri's rigorous safety policies and the criteria for a recycling permit that is able to recycle 5 cells per day for the current production cells with a budget of $20,000."

After an iterative development process spanning from mid-March 2014 to the beginning of June 2014, ending with the third round of funding, the focus shifted: The new objectives were to not only implement a cost efficient short term solution but also a process that can readily be automated and enhanced in its functionality by further process development.

Ambri's new requirements for a successful recycling method were that the process:

- Is safe and cost efficient
- Can be permitted as a production process
- Can be implemented in one month
- Has integrated safety measures
- Provides for the possibility of process automation not included in its initial design
- Provides for the possibility of full process containment
- Provides for process and quality control measures
- Can incorporate further process steps for added functionality
- Can accommodate for the anticipated throughput during the first year of production
- Separates the operator as much as possible from the process steps and their in- and outputs
- Provides the operator with as much information about the process as possible
- Is safely to operate with one designated and trained operator without assistants
- Is ergonomically designed in all machines and functional parts

The new budget was not exactly specified but was supposed to not exceed the anticipated first budget of $20,000 by more than ca. 40%.

Due to the team's anticipation of a changing financial situation the focus until the final requirements were found was to develop a process flow that can be implement as a cost efficient R&D process or a high throughput production process solely dependent on the machines used for the different process steps.

This thesis describes the approach to design, implement and analyze this battery recycling process.

1.5 Thesis Structure

This thesis is structured in six main chapters. The introduction defines the terminology used in the thesis, and provides background information about the U.S. battery industry. It explains Ambri's technology and their battery design. The chapter ends by describing the research motivation of the liquid metal battery recycling project and deriving the problem statement.

The second chapter *Literature Review* provides an overview of the research performed for this project in order to find and evaluate different battery recycling processes. The chapter is divided in to a section concerning lead acid batteries and a section about lithium ion batteries as their recycling process relevant properties are similar to Ambri's liquid metal battery.

The third chapter *Current Recycling/ Disposal Processes for the Liquid Metal Battery* discusses the two currently used approaches to dispose of Ambri's liquid metal battery. The first option is complete cell incineration with following disposal on a hazardous waste landfill. The second option is Ambri's currently used laboratory scale cell dissection process with following incineration. Both process are evaluated according to Ambri's most relevant criteria to compare them in the end with the newly developed process.

Chapter four *The New Recycling Process* describes the newly developed process based on the performed research. After a brief explanation of the process development approach, timeline and requirements, the new process flow is presented and summarized. The second half of the chapter is an in depth description of every process step, its design considerations and implementation.

The fifth chapter Analysis of the New Recycling Process starts with a partial process characterization. The second half consists of safety, costs and scalability analyses. The newly developed recycling process is then compared to the currently used methods illustrating the increase in safety and efficiency while significantly decreasing costs.

The last main chapter Recommendations, Future Work and Conclusion provides Ambri first with recommendations that are necessary to safely operate the process in the future by understanding its properties. Further recommendations can be implemented to enhance the process functions to aim towards closed loop recycling. In the future work sections, general directions of process development are discussed to accommodate for Ambri's anticipated future needs. The chapter then ends with a conclusion of the liquid metal battery recycling project.

2. Literature Review

This chapter summarizes market, technology and recycling background information of Ambri's most relevant technology competitors: *Lead-Acid Batteries* and *Lithium-ion Batteries*. By explaining their characteristics and functionality, it provides the two most important case studies of batteries with similar recycling hazards and properties as Ambri's liquid metal battery. The considerations derived from this research combined with the information from Ambri's current disposal processes were the direct basis for the development of the new recycling process.

2.1 Lead-Acid Batteries

The following chapter focuses on lead-acid batteries as a case study of a battery with toxic and corrosive contents similar to the first two major hazards of Ambri's liquid metal battery. By understanding the battery, its design, chemistry and well established recycling process stream, the team gained first insides in to battery recycling and valuable information directly applicable for the later process development. The first part *Lead-Acid Battery Overview* starts with a brief overview of the history, the current market and industry situation as well as the most common applications. The following part *Lead-Acid Battery Chemistry Fundamentals* provides insides into the design of current lead-acid batteries as well as the necessary chemistry background. The last part *Lead-Acid battery Recycling* explains the well-established and efficient recycling process for the lead acid battery technology.

2.1.1 Lead-Acid Battery Overview

The lead-acid battery was invented more than 150 years ago by Raymond Gaston Planté in 1860 and is therefore the oldest type of battery. [5], [11] It is the by far most important class of secondary batteries: Lead-acid accumulators represent the largest segment of the battery market in the world. [5] In the United States, lead-acid batteries alone are expected to account for almost 90% of the complete production volume of secondary batteries in 2014. [1]

Their success is mainly due to their low cost and long cycle life characteristics that make up for their low specific energy and energy density. If only discharged to a certain percentage (conventionally not below 70% of the full capacity) [12], lead-acid batteries suffer very little from chemical degradation due to side reactions. This property makes their charge/discharge process essentially reversible. [5] In recent years lead-acid batteries started to get replaced in certain sectors like the electric car industry by competing technologies (mainly lithium-ion batteries). Lead-acid batteries are nevertheless expected to keep playing an important role in the energy storage market. [13] As a result, only in 2009

East Penn Manufacturing Company received a $32.5 million grant by the U.S. government to increase its lead acid battery production. [1]

Lead-acid batteries are produced in a wide variety of configurations ranging from cells with a capacity of 1Ah to 12,000Ah for several different application as listed in the table 1. [5]

Table 1: Types and applications of lead-acid batteries [5]

Type	Typical applications
• SLI (starting, lighting, ignition)	• Automotive, marine, aircraft, diesel engines in vehicles and for stationary power
• Stationary (including energy storage types such as charge retention, solar photovoltaic, load leveling	• Standby emergency power: telephone exchange uninterruptible power supply (UPS), load leveling, signaling
• Traction	• Industrial trucks (material handling)
• Vehicular propulsion	• Electric vehicles, golf carts, hybrid vehicles, mine cars, personal carriers
• Submarine	• Submarine
• Portable	• Consumer and instrument applications: portable tools, appliances, lighting, emergency lighting, radio, TV, alarm systems

The oldest as well as largest commercial application for lead acid batteries is starting cars and other engine powered vehicles. These so called SLI batteries (starting, lighting & ignition) perform different functions. Besides just starting, the lead-acid power unit can be responsible for powering the electrics and electronics in automotive, marine and submarine vehicles as well as other engine powered vehicles. SLI batteries can be used furthermore to smooth out electrical spikes that otherwise could potentially harm the electrical circuitry. [12]

The automotive industry is the key sector for SLI lead-acid battery applications. More than 94.3 percent of the SLI lead-acid battery revenue is generated in this industry. While the demand in Europe and the United States is stable but stagnating, the growing eastern European, Pacific Rim and especially Asian market account for an expected market growth at a CAGR of 4.3 percent (Compound Annual Growth Rate) between 2007 and 2014. The two countries that account for most of this projected growth are China and India. [13] China is as of 2008 the largest unit manufacturer of cars when it first exceeded the U.S. automobile production of 657,000 cars by 133,000 units with 790,000 cars. [14] Both, China and India benefit in particular from heavy investments by the major automotive companies such as Daimler AG, General Motors, BMW or Ford Motor Company. [13], [15]

Another noticeable and evolving application of lead-acid batteries are utility and grid level energy storage systems. [5] These large stationary lead-acid batteries (SLA) are used for "backup power, emergency lighting, alarm, ... telecommunication, uninterruptible power supplies (UPS)/data communication, utility, emergency lighting, security system, cable television/broadcasting, oil and gas exploration, renewable energy, signaling systems, and other applications." [16] Due to the increasing concern about global warming and air pollution, the focus in recent years shifted towards renewable energies. Lead-acid batteries are used in this sector to store the energy of renewable yet interrupted energy sources like solar or wind energy. The near term goal is to provide the industry with large batteries (50MWh and 1000V) that equalize main power fluctuations in excess of 2000 cycles (equivalent of ca. 10 years of operation) at costs of about $90 per kWh. [5], [16] This makes SLA batteries a direct competitor for Ambri's liquid metal battery.

The stationary lead acid battery market generated $3.48 billion in revenues in 2008 worldwide. With a compound annual growth rate of 7.6 percent, the market is anticipated to generate around $5.79 billion sales revenues in 2015. [16]

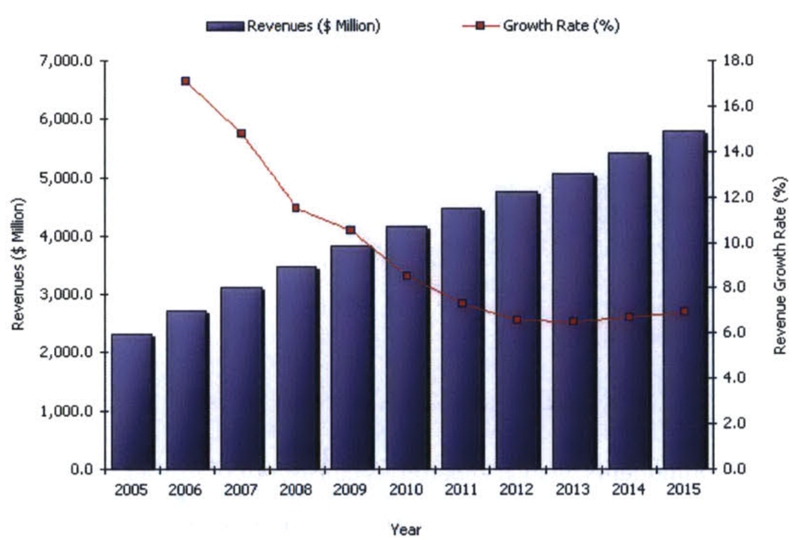


Figure 4: Stationary Lead-Acid Battery Market: Revenue Forecast (World), 2005-2015 (Frost&Sullivan 2008) [16]

The SLA market for renewable energies with an expected average revenue growth rate between 2005 and 2015 of over 20 percent will be one of the fastest growing segments in this sector. In 2015 it is expected to generate a revenue in excess of $200 million. [16]

2.1.2 Lead-Acid Battery Design and Chemistry

2.1.2.1 Lead-Acid Battery Design

The design of lead-acid batteries hasn't changed much over the last decades. The cell components are contained within a polypropylene casing which combines light weight with chemical and mechanical resistance. The (charged) cell consists out of a Pb anode which is usually separated from the PbO_2 cathode by a micro-porous polyethylene synthetic material and aqueous H_2SO_4 solution that serves as the electrolyte. The anodes and cathodes are connected by a current collector to form the minus and plus pole of the battery respectively. The figure below shows the idealized cross section of a simple lead acid SLI battery: [17]

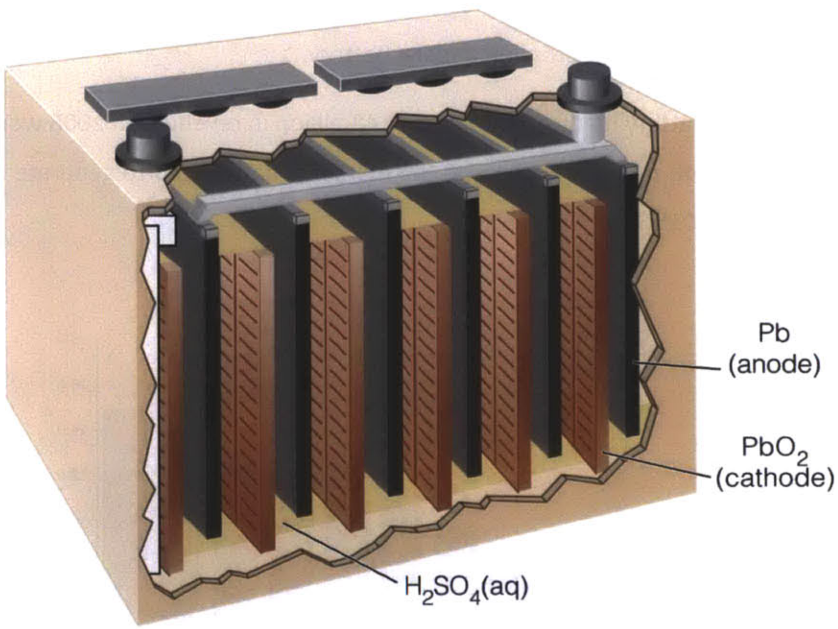


Figure 5: SLI Lead-Acid Battery Design [18]

Besides these major components, lead acid batteries consist out of further functional parts (common parts for SLI batteries are listed below. Batteries for other applications have analogous components): [5]

- Reinforced case end wall (for added rigidity)
- Molded symbols (permanently identifying terminal polarity)
- Liquid-gas separator on top (returns any liquid to reservoir)
- Bottom hold down ramp (for secure mount)
- Built-in hydrometer (for fast checking)

- Built-in flame arrester vent
- Separator envelopes (encapsulate plates to prevent shorting and vibration damage)

2.1.2.2 Lead-Acid Battery Chemistry

The charge-discharge mechanism of a lead-acid battery is called a double-sulfate reaction. The electrode processes involve a dissolution-precipitation mechanism and not a solid-state ion transport or film formation mechanism as in competing technologies (e.g. lithium-ion). The complete charge and discharge processes with the ionization step and the actual current producing reaction are shown in figure 6: [5]

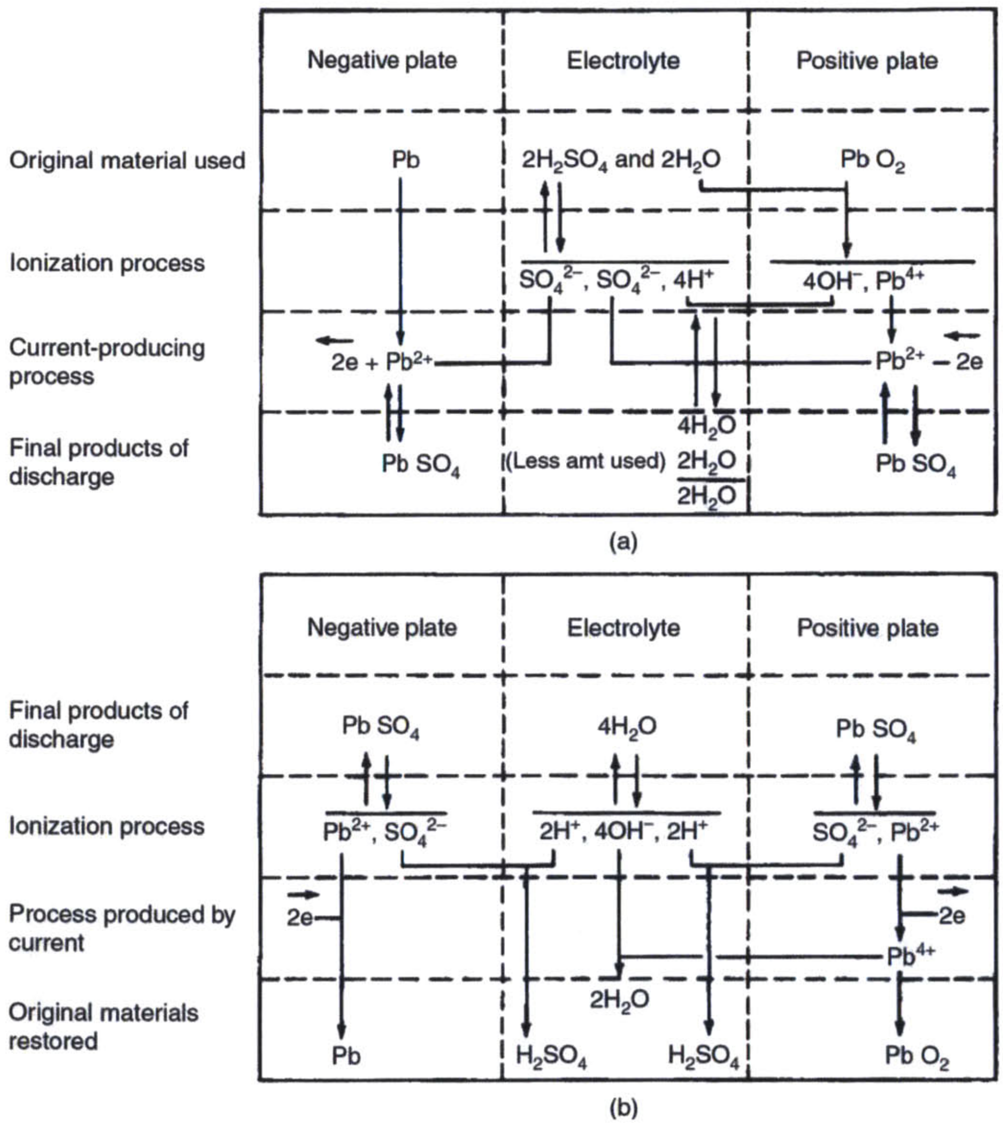


Figure 6: Lead-Acid Cell (a)Discharge- (b)Charge Mechanism (also known as double-sulfate reaction) [5]

The lead-acid battery uses PbO_2 as the active material of the cathode (positive electrode) and Pb as anode material (negative electrode). The electrolyte in a conventional lead acid battery is a sulfuric acid solution, H_2SO_4 (ca. 37% acid by weight when fully charged). Since the sulfuric acid itself is part of the reaction, it is considered an active material (which is in some lead-acid battery designs even the capacity-limiting factor). [5]

During the discharge process, both electrodes are converted to lead sulfate ($PbSO_4$):

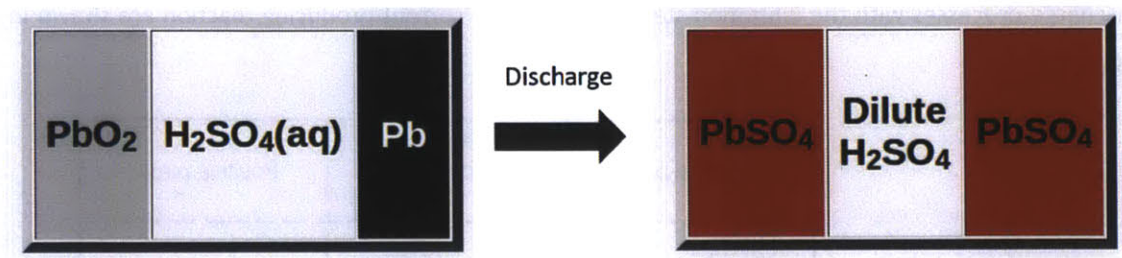


Figure 7: Lead-Acid Battery Discharge[1]

As shown in figure 6a, the lead loses 2 electrons per atom to form $PbSO_4$ during the discharge reaction, thereby inducing the current. The discharge reaction is shown in equation 1.

$$Pb(s) + PBO_2(s) + 2H_2SO_4(aq) \longrightarrow 2PbSO_4(s) + 2H_2O(l) \qquad (1)$$

The charging operation reverses this reaction. This time the Pb^{2+} ion of the PbSO4 in the anode gains 2 electrons to form metallic lead while the Pb^{2+} ion in the cathode gives up 2 electrons to form the initial lead oxide (PbO2) again (shown in figure 6b).

Due to these chemical reactions, certain risks are associated with lead-acid batteries that dictate precaution during production, use and recycling of this type of battery:

The first major risk is the so called overcharge gassing. As soon as a majority of the $PbSO_4$ is converted to metallic lead or lead dioxide again, the charging voltage can become higher than the so called gassing voltage which is about 2.39V per single cell. If this happens, the following reaction takes place additionally to the $PbSO_4$ transformation, producing explosive hydrogen and oxygen gas: [5]

$$Negative\ electrode:\quad 2H^+ + 2e \longrightarrow H_2 \qquad (2)$$

$$Positive\ electrode:\quad H_2O - 2e \longrightarrow \tfrac{1}{2}O_2 + 2H^+ \qquad (3)$$

$$Overall\ reaction:\quad H_2O \longrightarrow H_2 + \tfrac{1}{2}O_2 \qquad (4)$$

[1] Based on figures from Wikipedia, Riventree (http://en.wikipedia.org/wiki/File:Discharged.gif and http://en.wikipedia.org/wiki/File:Recharged.gif)

The production of gaseous hydrogen in this context is not only a fire and explosion risk but also a toxic concern, yielding the second major risk: The production of stibine gas.

Even in small concentrations, the introduction of antimony into the active material (positive or negative electrode) can increase the cycling performance of lead-acid batteries. If, e.g. during overcharge, the antimony (Sb) comes in contact with H_2 an essentially odorless and colorless gas called stibine (SbH_3) is formed. Stibine, which is used in the semiconductor industry to dope silicon is a highly toxic gas. The OSHA limit is 0.1 ppm (0.5 mg/m^3 TWA) while the immediately dangerous to life or health concentration (IDLH) lies at only 5 ppm. The possible production of a highly toxic gas is the reason why these performance enhanced batteries cannot be used in sensible application like submarines. [5], [19], [20], [21]

2.1.3 Lead-Acid Battery Recycling

The recycling process of lead-acid batteries is amongst the most established, efficient and well-known recycling processes of the whole battery industry: "Ninety-six percent of all lead-acid batteries are recycled. Almost any retailer that sells lead-acid batteries collects used batteries for recycling, as required by most state laws." [22] That makes lead-acid batteries the most recycled consumer product in the United States, before aluminum cans (49% recycling), paper (45% recycling) or glass (21% recycling). New lead-acid automotive batteries can therefore be made out of 80% recycled materials, while 99% of the material of those batteries is recyclable. [23]

The recycling process for lead acid batteries must therefore be an efficient process that also accounts for the hazards described in the *Lead-Acid Battery Chemistry* section. A general process flow chart of the (in different variations) commercially used processes is shown in figure 8:

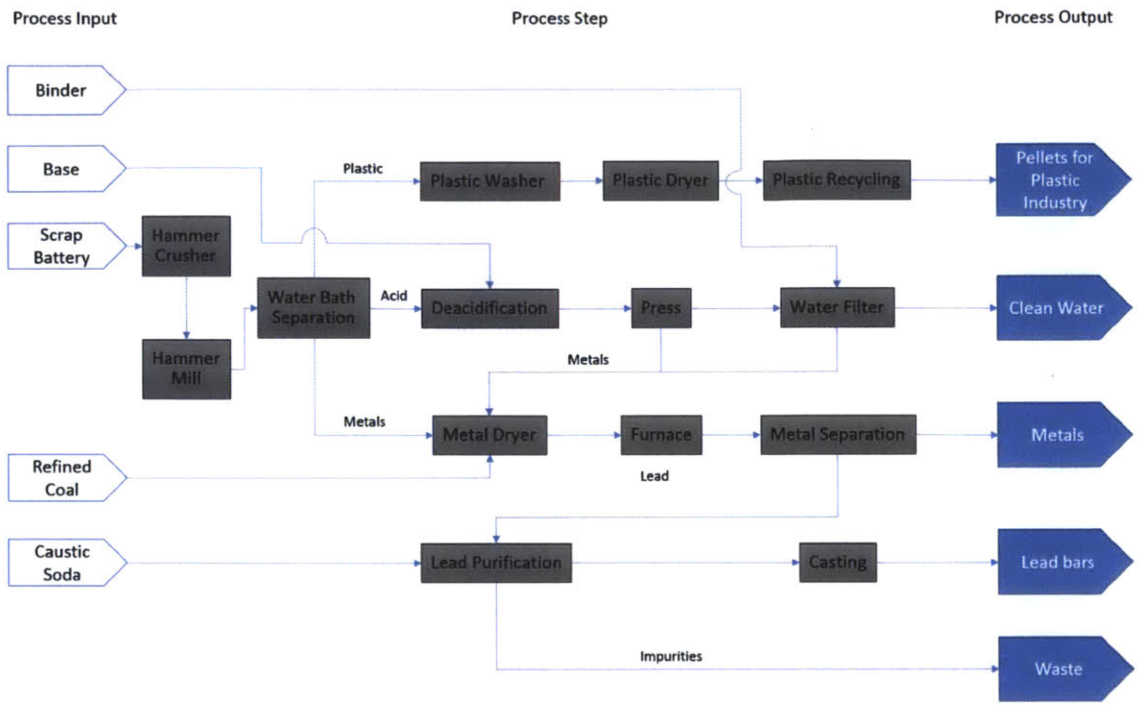


Figure 8: Lead-Acid Battery Recycling Process Flow

The first process step is to mechanically crush the batteries in to pieces. [24], [25] To achieve that, the spent batteries are delivered by a conveyer system to e.g. a hammer mill. Some companies add a hammer crusher step first to decrease the wear of the hammer mill and separate a portion of the electrolyte before the washing step. The pieces then fall in to a water bath. The shredded plastic floats on top, the metals sink while the H_2SO_4 and microscopic particles are washed away with the water. Each of the separated materials will then be subject to a different recycling stream. [26]

The plastic is scooped from the surface of the water bath, cleaned and dried. [25] After this treatment, the plastic confirms to the standards to undergo the normal plastic recycling process. It is heated and then extruded into uniform pellets. [26]

The sulfuric acid can be dealt with in two different ways. The first possibility is to neutralize it with a base (e.g. calcium carbonate - $CaCO_3$ or calcium hydroxide - $CaOH_2$) to turn it into water. [27] After that, the water still contains small particles due to the crushing step and residuals that were precipitated out during the deacidification. These particles are filtered out mechanically and chemically in a press and a bath respectively. The solid particles are added to the pile of lead and other metals, while the water is clean enough to be poured down the drain. [26] The other possibility is to convert H_2SO_4 into sodium sulfate (Na_2SO_4) which can be used e.g. in the textile industry. [26]

The lead and other metals that sunk to the bottom of the water bath [25] and the smaller particles that were filtered out of the deacidized solution during the pressing and chemical filtering step are then mixed with refined coal. The mixture is dried to extract remaining moisture. The dried material is then poured in to a furnace. The temperature is set above 327°C to melt the lead but far below the melting temperature of the other metal components that were in the battery (e.g. screws, electric connections and so forth). Due to the high density of the lead, the other metals float on top and can easily be removed and serve as input material for further metal recycling processes. The molten lead is filled into ingot molds to produce lead bars for the industry. [26]

Due to the involved metals, acids and bases, several precautions are in place every time a worker has to interact with the process directly (e.g. while performing process control measurements). Lead and sulfuric acid are toxic chemicals that can cause severe short and long term effects and death. [28] Personal protective equipment (PPE) including a respirator, acid resistant polymer coats, glasses and gloves are necessary. Although gases like stibine are not produced in significant amounts due to a lag of excess hydrogen, good ventilation, air filtration and masks are standard equipment for every lead-acid recycling plant.

2.2 Lithium Ion Batteries

The following section focuses on lithium-ion batteries as a case study for the recycling of batteries with flammable contents similar to the third major hazard of Ambri's liquid metal battery. By understanding the battery, its design, chemistry, currently used and recently developed recycling processes, the team gained information directly applicable for the later process development. The first part *Lithium Ion Battery Overview* starts with a brief overview of the history, the current market and industry situation as well as the most common applications. The following part *Lithium Ion Battery Design and Chemistry* provides insides into the design of current lithium ion batteries as well as the, for this thesis necessary chemistry background of the product. The last part *Lithium Ion battery Recycling* explains the different approaches for commercial lithium-ion battery recycling.

2.2.1 Lithium Ion Battery Overview

Lithium ion batteries are a new technology. First work concerning alkali metal ion intercalation in carbon anodes and oxidized cathodes was performed at TU Munich during the 1970's. In 1980, the first working lithium-ion battery was the lithium-cobaltdioxide accumulator build by John B. Goodenough's group at the University of Oxford. But even after these initial positive results it took another 11 years until the first commercial lithium-ion battery, used in a Hi8 video camera, was sold by Sony in 1991. [5]

Compared to other battery technologies (e.g. lead-acid) lithium-ion batteries have distinct advantages and disadvantages as listed below: [5]

Advantages

- Sealed cells; no maintenance required
- High specific energy and energy density
- Broad temperature range of operation
- Long shelf life
- Low self-discharge rate
- Rapid charge capability
- High-rate and high-power discharge capability
- High coulombic and energy efficiency
- No memory effect
- Wide variety of chemistries offer design flexibility

Disadvantages

- Moderate to high cost
- Degrades at high temperature
- Capacity fade over cycle life
- Need for protective circuitry
- Capacity loss and potential for thermal runaway when overcharged
- Possible venting and possible thermal runaway when crushed
- May become unsafe if rapidly charged at low temperatures (<0°C)

These advantages and disadvantages lead to the following main fields of application of secondary lithium-ion batteries:

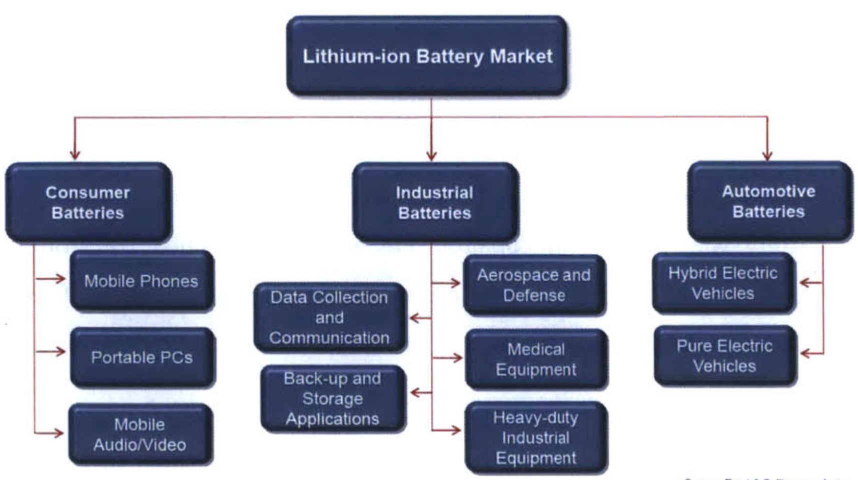


Figure 9: Secondary Lithium-Ion Battery Applications [29]

The high energy density (and therefore compact design) as well as the ability to be quickly charged and discharged at high rates makes lithium-ion batteries the power source of choice for consumer electronics and power sources for electric vehicles. The essential absence of a memory effect or maintenance requirements are attractive for the aerospace industry and back-up applications. [29] But cases like the burning lithium-ion batteries in Boeing airplanes of the type 787 and similar incidences with electric cars force the industry to rethink possible safety issues with lithium accumulators that are mainly composed out of flammable lithium and carbon. [30]

To this point though, these possible hazards did not stop the rapid growth of the lithium-ion market: "The global market was USD 11.70 billion in 2012 and is expected to reach USD 33.11 billion in 2019, growing at a CAGR of 14.4% from 2013 to 2019." [31]

Two major reasons for this growth are the increasing sales of consumer electronics with high-performance processors (and therefore high energy consumption) and the rising fuel cost: "The popularity of Electric Vehicles and Hybrid Electric Vehicles (HEVs) has increased over the past couple of years. These vehicles are powered by lithium ion batteries. In addition, stringent government regulations to regulate the carbon emission in many countries in Europe and North America are supporting the adoption of lithium ion batteries in vehicles." [31]

Elon Musk, founder of electric car forerunner Tesla Motors plans to attack the problem of high cost which is one of the few remaining reasons for low sales of electric vehicles. The company revealed on Feb. 26 2014, their plans for the so called Gigafactory: "A massive facility that will be designed to produce more lithium-ion batteries annually by 2020 than were made worldwide in 2013. At 10 million square feet, Tesla estimates that the plant will have the capacity to produce 50 gigawatt hours of battery packs a year. The batteries will be used for Tesla's Model S luxury sedan and a cheaper third-generation vehicle intended for the mass market. By 2020, Tesla estimates the facility will be able to make enough batteries to supply 500,000 vehicles a year." [32]

Tesla aims to reduce the cost of lithium-ion battery packs by more than 30% by the end of the first year of volume production: "As we at Tesla reach for our goal of producing a mass market electric car in approximately three years, we have an opportunity to leverage our projected demand for lithium ion batteries to reduce their cost faster than previously thought possible." [33]

Developments like this will further leverage the impact of lithium ion batteries. They are likely to force the federal government and the industry to further develop a sustainable product life cycle management that includes the development and establishment of advanced recycling processes.

2.2.2 Lithium-Ion Battery Design and Chemistry

2.2.2.1 Lithium-Ion Battery Design

In contrast to the lead-acid battery, the anodes and cathodes of a lithium ion battery are much thinner. This assures and efficient and fast ion exchange due to a large surface area. Figure 10 shows the general design of a round lithium ion battery, as it is most common for many applications.

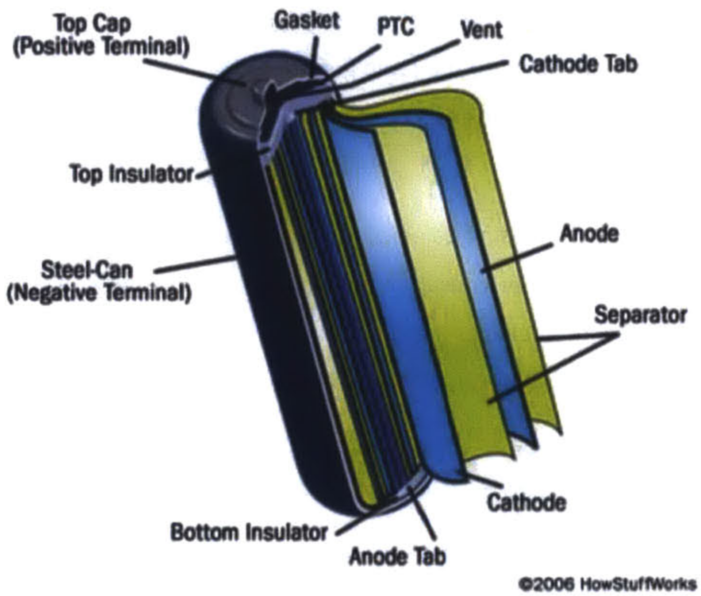


Figure 10: Lithium-Ion Battery Design [34]

The anode and cathode are separated by a micro porous foil that contains the electrolyte. This separator has a thickness of about 16 to 25 microns (dependent on the battery design) and can become the capacity limiting factor as well as the largest part of the material cost breakdown. [5] The active material of the anode is deposited on an 8 to 15 microns thick copper foil resulting in a total height between 100 and 250 microns. The active material of the cathode, with a total height of 100 to 250 microns as well, is deposited on a 10 to 20 micron thick aluminum foil. [5] This leads, considering the respective material densities to the following weight breakdown of a modern lithium ion battery:

Table 2: Lithium Ion Battery Weight Breakdown [35]

Battery component	Wt%
Casing	25
Cathode material	25
Anode material	14
Electrolyte	10
Copper electrolyte foil	8
Aluminium electrolyte foil	5
Separator	4
Other	6

The active sheets are pressed together and then folded in to the desired shape. They are contained inside a metal casing that serves as the negative pole. Insulating caps on the bottom and top, as well as an extra separator layer between the outer electrode and the casing prevent a short circuit. The cathode is therefore only connected with the positive pole on the top but not the negative casing. [34]

The vent as well as the Positive Temperature Coefficient (PTC) switch are safety measures to prevent an explosion in case of a gas build up. [34] Researchers at the Samsung SDI Co. corporate R&D center have shown that lithium-ion batteries operated at high temperatures (85-90°C) can produce significant amounts of CO_2, CO, C_2H_4, CH_4 and H2. [36] Without a safety vent, this pressure build-up can cause a rupture of the metal casing and in the presence of moisture the ignition of lithium inside the cell.

It is therefore apparent that the design and operation of lithium ion batteries requires special care and build-in safety measures.

2.2.2.2 Lithium-Ion Battery Chemistry

A normal lithium ion battery cell consists of an anode that is made from carbon and polyvinylidene fluoride (PVDF) binder on the one side and a lithium metal oxide (e.g. $LiCoO_2$) as cathode on the other side. [35] Both electrodes are separated by a polypropylene (PP) or polyethylene (PE) separator containing the electrolyte e.g. lithium hexaflourophospate (LiPF6) with an organic solvent [35] as shown in figure 11:

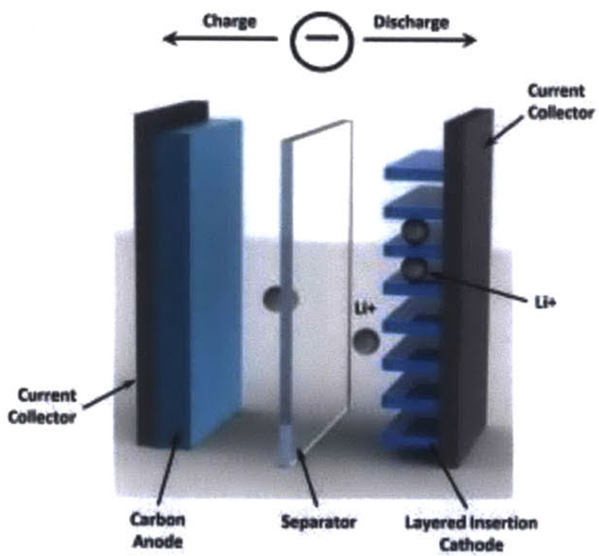


Figure 11: Lithium-Ion Single Cell [37]

During the charging process, lithium ions are released out of the metal oxide grid due to the applied voltage (4.2V for $LiCoO_2$ cell with graphite anode). [38] To accelerate this process, modern cathodes have either a layered or tunneled structure to provide a large surface area that allows for a fast ion exchange. The ions then travel through the electrolyte to the amorphous graphite anode which supports a fast ion exchange as well. At the anode, the lithium forms chemical compounds with the carbon (especially Li_xC_6 with $0 \leq x \leq 1$). The charge reaction of this process on the positive electrode is therefore: [5]

$$LiMO_2 \longrightarrow Li_{1-x}MO_2 + xLi^+ + xe^- \tag{5}$$

While on the negative electrode:

$$C + yLi^+ + ye^- \longrightarrow Li_yC \tag{6}$$

This gives the overall reaction:

$$LiMO_2 + \frac{x}{y}C \longrightarrow \frac{x}{y}Li_yC + Li_{1-x}MO_2 \tag{7}$$

With MO_2 as the metal oxide (e.g. CoO_2). The discharge process just reverses these reactions as it reverses the polarity.

The crucial takeaways from this battery chemistry are the usage of a metal component that produces flammable gas when it comes in contact with H_2O and can exhibit uncontrolled reactions at high temperatures. These hazards significantly affect possible recycling process solutions.

2.2.3 Lithium-Ion Battery Recycling

As of 2014 no feasible, widespread process for lithium ion battery recycling has been established. [35] Figure 12: Lithium Ion Battery Waste Cost Breakdown [35]shows the material cost breakdown of one ton of current lithium ion battery waste. The cost were calculated by Gratz et al. using the lithium ion battery weight breakdown shown in table 2, material cost by Gaines et al. and the forecasted 2012 Li-ion battery cathode chemistry makeup by the YANO research institute:

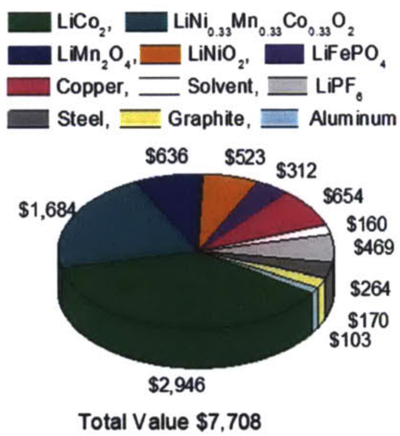


Figure 12: Lithium Ion Battery Waste Cost Breakdown [35]

As can be seen in figure 12, lithium cobalt dioxide ($LiCoO_2$) makes up more than 38% of the total value. It is currently the most commonly used cathode for lithium ion batteries as it is the active material in ca. 37.2% of all lithium ion batteries. This is why the majority of commercial lithium ion battery recycling processes focuses on recovering cobalt from the cathode. [35]

With a growing industry focus on cost and safety new chemistries like $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (used in ca. 29% of all lithium ion batteries) or $LiMn_2O_4$ (used in ca. 21.4% of all lithium ion batteries) are rapidly gaining market share. [35]

This increasing variety of applied chemistries imposes an enormous challenge for a future recycling process. The requirements for such a process are the abilities to safely and cost efficiently recycle a wide variety of batteries with different chemistries.

Different approaches are under development to comply with these requirements. In their review of processes and technologies for the recycling of lithium-ion secondary batteries, J. Xu et al. divide those approaches into the following two major categories with their respective under categories: [39]

- Physical Processes
  - Mechanical Processes

    - Thermal Treatments
    - Mechanochemical Processes
    - Dissolution Processes
- Chemical Processes
    - Acid Leaching
    - Bioleaching
    - Solvent Extraction
    - Chemical Precipitation
    - Electrochemical Processes

Mechanical processes include crushing, sieving, magnetic separation, fine crushing and classification. Those mechanical separation processes are normally used in the first stages of the recycling process to separate metal from nonmetal parts. The step serves therefore as a preparation for following hydrometallurgical and/ or pyrometallurgical process steps. [39]

Thermal treatments usually act as a further purification of the metal content of the waste stream by eliminating organic compounds. They can also be used as a separation between metals of different melting points and/ or densities. [39]

Mechanochemical processes are processes that use a mechanical component like grinding to increase the yield of a chemical reaction e.g. by increasing the surface area. Experiments showed that processes of this category can increase the recovery of Co and Li to "over 90% and nearly 100% respectively". [39]

Dissolution processes are highly effective to recover LiCoO2 without separating anode and cathodes with complex mechanical, mechanochemical or e.g. pyrometallurgical processes. Due to the high prices of currently available solvents which are able to dissolve the chemically stable PVDF and other binders used in the battery, those processes need further development to be scaled. [39]

Acid leaching processes have the primary goal to further separate the metals from other nonmetallic content after an initial rough e.g. mechanical separation step. The leaching agents that are primarily used to transfer metals to an aqueous solution are inorganic acids like "H_2SO_4, HCL and HNO_3". [39]

Bio leaching processes are using bacteria to help dissolve metals. The bacteria metabolize certain parts of the battery like sulfur and ferrous ions in to acidic leaching agents like sulfuric acids. Even though bio leaching processes are still in their research stage, their potential impact on the battery recycling industry is huge due to "their higher efficiency, lower costs and few industrial requirements". [39]

Solvent extraction processes can be used in hydrometallurgical plants to extract Co, Li and Cu with acidic agents like phosphoric acids phosphinic acids. [39]

Chemical precipitation processes use chemical precipitation agents to form compounds with the metals of interests. Cobalt in hydrochloric solution e.g. forms Co(OH)2 which precipitates out and can easily be recovered with a simple filtration step for further purification and/ or recycling. Chemical precipitation can replace solvent extraction processes as it is a simpler method that produces higher yields of recyclable material. [39]

Electrochemical processes use current but no other substances to separate e.g. Co from spent batteries thus reducing impurities. By introducing titanium electrodes and appropriate pH conditions in a solution of waste $LiCoO_2$, cobalt hydroxide forms on the electrodes which can then undergo heat treatment to form cobalt oxide for further recycling. The advantages of high efficiency (Co recovery of more than 93%) and high purity output comes with the disadvantage of high electricity costs. [39]

The table below summarizes which process are most suitable to recycle the different lithium ion battery components.

Table 3: Recycling Process Steps for Lithium Ion Battery Components [39]

Components	Elements	Recycling processes
Shells	Fe	Mechanical processes; thermal treatment
	Plastics	Mechanical processes
Aluminum foil	Al	Mechanical processes; acid leaching; chemical precipitation
Anode	Cu	Mechanical processes
	C (graphite)	Mechanical processes; thermal treatment
Adhesive agent	PVDF binder	Thermal treatment
Electrolyte (organic liquid—$LiPF_6$, $LiBF_6$, $LiClO_4$)		Thermal treatment; solvent extraction
Cathode ($LiCoO_2$, $LiNiO_2$, $LiMnO_4$)	Co	Mechanochemical process; dissolution process; thermal treatment; acid leaching; bioleaching; solvent extraction; chemical precipitation; electrochemical process
	Li	Mechanochemical process; thermal treatment; dissolution process; acid leaching; bioleaching; Solvent extraction
	Ni	Mechanochemical process; chemical precipitation; electrochemical process
	Mn	Chemical precipitation

Due to the complexity of the task, only very few companies are currently able to recycle lithium ion batteries commercially. Providers of lithium ion battery recycling include Sony/Sumitomo, Umicore, Toxco Inc. and Recupyl Battery Solutions. While Sony/Sumitomo and Umicore primarily use high temperature processes and Toxco Inc. a cryogenic processes, Recupyl Battery Solutions is the only provider for a room temperature recycling application in this list.

A high temperature lithium ion battery recycling process used by Sony/Sumitomo and Umicore in different variants aims to recover metallic components of the battery. While the Sony-Sumitomo process was specifically intended to recover only cobalt oxide from spent lithium-Ion batteries and cannot be applied to the lithium metal solid and gel polymer technology [40], the Umicore process can not only recycle spent lithium ion cells but also NiMH batteries. [41] As it can therefore be considered the more flexible and advanced process, the Umicore high temperature recycling process is shown in figure 13.

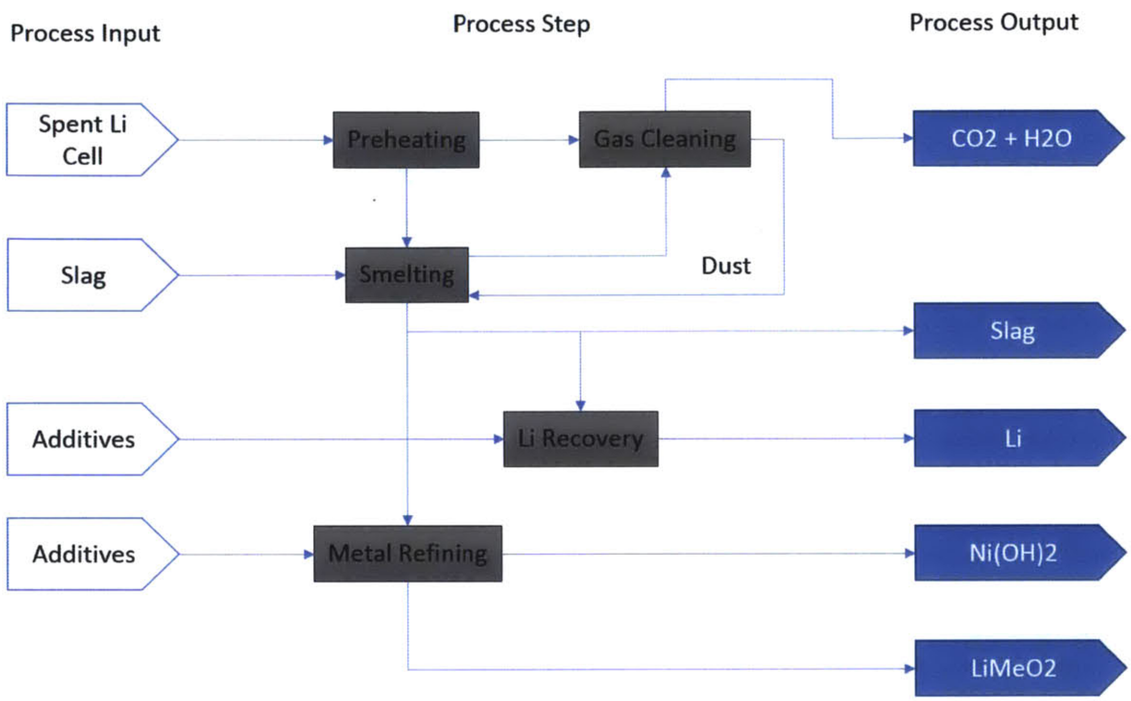


Figure 13: Umicore Lithium Ion Recycling Process [41], [42]

The first step that the spent batteries undergo is a preheating process at 500°C to evaporate the electrolyte. If the batteries would undergo the smelting operation at 1450°C directly, they could explode due to the instantaneous evaporation of the electrolyte [42] and other non-metallic parts. After the preheating, the batteries are conveyed in to a furnace with a temperature of 1450°C. The charge is added with slag either from the steel industry (containing 40 w. % CaO, 34 wt. % SiO_2 and 11 wt. % Al_2O_3, limestone and cokes) or the Pb industry (containing 1.5 wt. % Pb, 26 wt. % Fe, 18 wt. % SiO_2, 27 wt. % CaO, 5 wt. % Al_2O_3, limestone and cokes). [42] The gases from the preheating and smelting are passed through a filter. CO2 and H2O are released in to the environment while remaining dust is collected and fed back in to the furnace. Additionally, the fluorine from the electrolyte can be collected in the filtration system for further recycling. [41]

The other two fractions obtained from the smelting operation are slag and metal fraction that contains Co, Ni, Mn and other metals dependent on the battery chemistry. The slag can either be converted in to concrete with 30 wt. % slag and 10 wt. % cement [42] or undergo further refinement to recover lithium and other valuable components. The metal fraction undergoes further refining steps as well to be converted to $Ni(OH)_2$ or $LiMeO_2$ (with Me as either Co, Ni or Mn). All of those compounds are new cathode materials that close the loop of the Umicore recycling process. [41]

The hydrometallurgical lithium ion battery recycling process patented by Toxco Inc. is shown in figure 14 according to United States patent 5,888,463. [43]

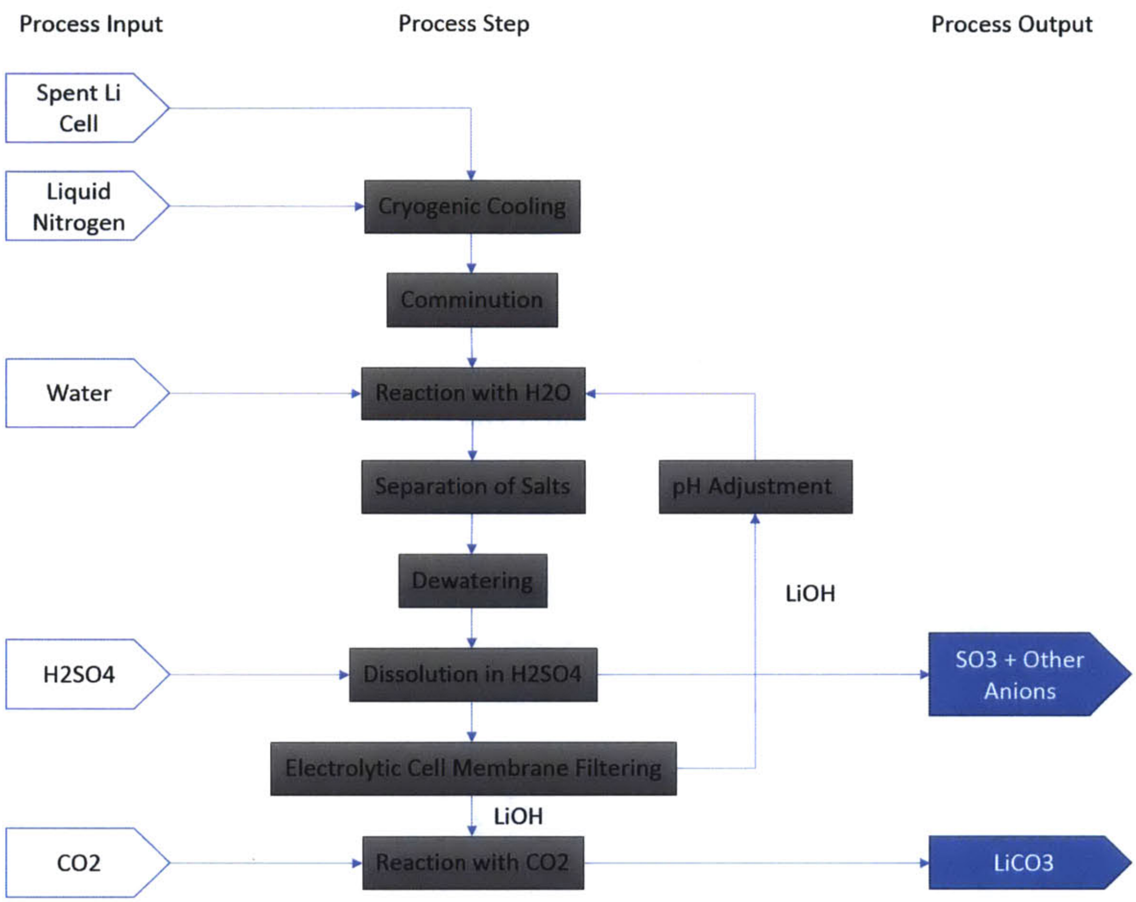


Figure 14: Toxco Inc. Lithium-Ion Battery Recycling Process [43]

The Toxco Inc. process starts with cryogenic cooling in liquid nitrogen. The cooling time for different batteries is not uniform and can vary between minutes and 8 hours dependent on the battery size. The batteries are cooled to -195.6°C to reduce the reactivity of the lithium content by 5 to 6 orders of magnitude. [43]

After this initial energy intensive cooling step that requires the replenishment of liquid nitrogen during production, the batteries are conveyed to a mechanical comminution step. Toxco Inc. uses hammer mills and/ or shredders to produce a homogeneous output of battery scrap with a diameter of ca. 1". This crushing operation serves to expose the content of the encapsulated cells and increase the surface area for the following chemical reaction. [43]

The produced battery scrap mass is then reacted with an aqueous LiOH solution in a reactor. The LiOH is added as a safety measure to raise the pH value of the solution to at least 10 in order to prevent the formation of hazardous H_2S. The H_2 that forms during the reaction is ignited over the water. The LiOH itself is obtained from a later process step. During the wash and dependent on the type of battery, different lithium salts form. After the solution is saturated those salts precipitate out. Aqueous solution that contains those precipitates is pumped out of the reactor and pressed through a filter. [43]

The dewatered mass is conveyed in a hybrid electrolytic cell where sulfuric acid is introduced in to the system. The sulfuric acids separates the Li^+ ions which can pass through a membrane filter. The ions are then reacted with CO_2 to the salable end product $LiCO_3$. SO_3 and other anions can't pass the membrane and are the second major output of the system. [43]

The Toxco Inc. process is thereby capable of recovering ca. 97% of the lithium ions from spent batteries. While this is a major advantage of the process, disadvantages include the expensive cooling system, significantly different cooling times for different battery sizes and the necessity of a controlled ignition of H_2. [43]

Farouk Tedjar the founder and scientific director of Recupyl Battery Solutions and Jean-Claude Foudraz patented a room temperature hydrometallurgical process for all types of lithium anode cells and batteries in 2005 which was issued as US patent US 7,820,317 B2 on October 26, 2010. [44]

The process flow is shown in figure 15:

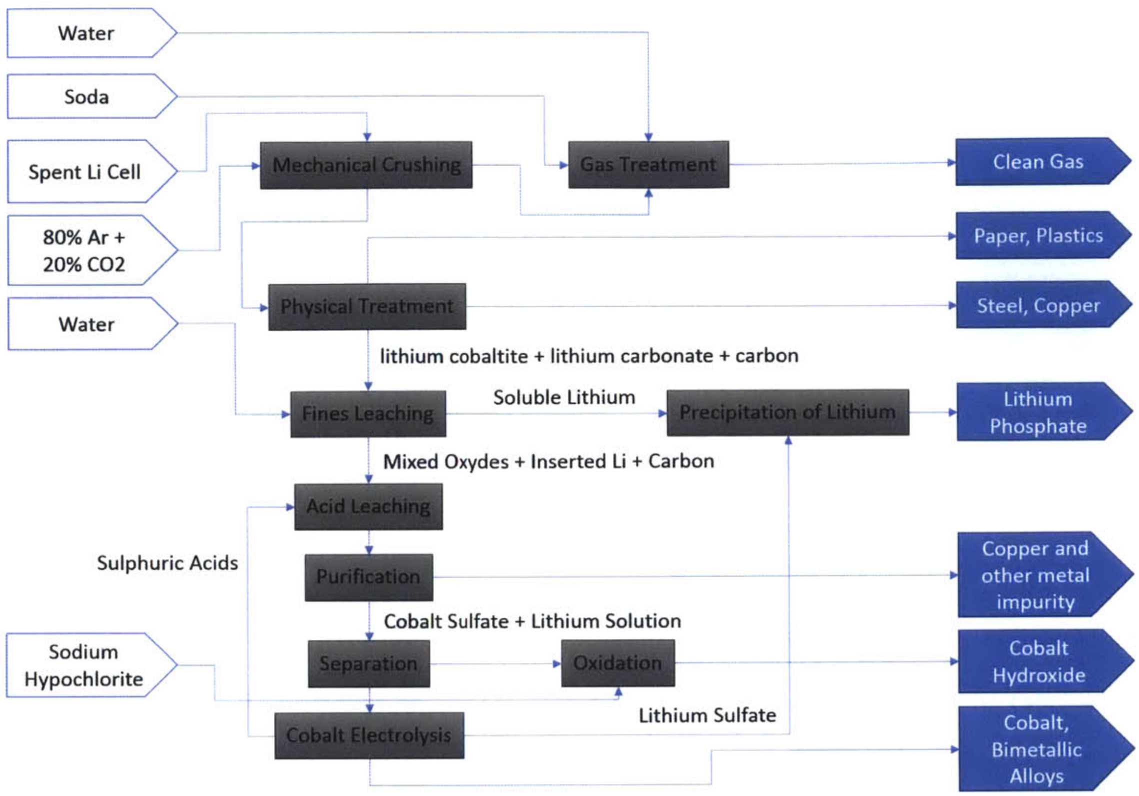


Figure 15: Recupyl Battery Solutions Lithium-Ion Battery Recycling Process [44]

The battery recycling starts with a mechanical process. Two mills arranged in series crush the lithium batteries in an inert atmosphere. The continuous input of scrap batteries and homogenate output is accomplished by a conveying system with double air-lock on both sides. The gaseous output of the first process step is treated with water and soda to be safely released in the environment. [44]

After this initial treatment of the cells, the crunched mass undergoes a physical partition by density high induction magnetic separation. This way the three charges of Steel + Copper, light nonmetallic components and lithium cobaltite + lithium carbonate + carbon are obtained. While the first two charges can directly undergo their well-established respective recycling process, the third charge undergoes further treatment in the battery recycling plant. [44]

First the lithium cobaltite, lithium carbonate and carbon are subject to a water leaching step to recover the soluble lithium components. These components are then in a further step precipitated out of the solution to obtain salable lithium phosphate. The remaining mixed oxides, inserted lithium and carbon undergo a further, acidic leaching process. Sulfuric acid, obtained in a later process step is added to the material to dissolute lithium cobaltite. The solution is then filtered and purified to separate cobalt containing components from carbon, copper and other metallic impurities. [44]

The remaining cobalt sulphate and lithium solution then undergoes to separate processes. The first part is oxidized with sodium hypochlorite added to the process to produce the end product cobalt hydroxide. The second part undergoes an electrolytic process in which three fractions are obtained: Sulphuric acid which is used as an input for the acidic wash, lithium sulfate that is pumped to the lithium precipitation step and new cobalt cathode material for use in new lithium ion batteries. [44]

The patented process is able to recycle 98% of the metals in the spent lithium ion batteries. One metric ton of input material can thus be converted into: [45]

- 130 kg of cobalt
- 290 kg of stainless steel
- 80 kg of copper
- 240 kg of paper and plastic waste

An estimation of the current market value of these materials is: [46], [47], [48]

- $32.50/kg for cobalt
- $1.61/kg for 304 stainless steel
- $7.04/kg for copper

Even with no further recycling of plastic and paper waste, the value of recovered material from 1 metric ton of lithium ion battery waste is therefore ca. $5,255.

Another main advantage of the Recupyl process is the absence of extreme cooling or heating of the cells. The complete process operates near room temperature without additional, complex and expensive energy consuming cooling or heating apparatuses. Safety is granted nevertheless by performing the mechanical crunching where lithium is exposed under an inert atmosphere. [44]

The main conclusions for the development of the new process derived from this research were:

- Mechanical battery opening necessary
- Extreme temperature processes too complex, expensive and/ or risky
- Alkaline solution reduces reactivity of active material
- Argon and/ or CO_2 atmosphere significantly increase process safety when working with reactive material
- Focus on near room temperature process due to simplicity and possible recovery of various valuable elements and compounds

3. Current Recycling/ Disposal Processes for the Liquid Metal Battery

This chapter provides information about Ambri's currently used disposal processes: Complete cell incineration and the R&D disposal process. It explains the technology of these processes and evaluates them according to safety, economic and scalability aspects. It thereby provides two important case studies of the only disposal/ recycling processes that are proven to work for the liquid metal battery technology so far. The considerations derived from evaluating these processes combined with the research performed on lead acid and lithium ion battery recycling was the basis for the technical development of the new process.

3.1 Complete Cell Incineration

The first part of the chapter describes the first process used by Ambri to dispose of their scrap batteries: Full cell incineration. The chapter first explains the process with its in- and outputs while the second part evaluates the process according to economic considerations and scalability aspects.

3.1.1 Process Description

The process flow of the complete cell incineration is requires the smallest possible amount of operations at Ambri with the disadvantage of high cost. The process is as follows:

The spent liquid metal batteries are accumulated in a waste storage area at the Ambri Cambridge facility. There they are packed in units of 5 in to a 5 gal waste drums. The drums are sealed and provided with a waste product service number which unequivocally defines the content of the drum. The next step is the transport of a third party waste management provider to a storage facility. The transport and waste storage is approved and monitored by the Environmental Protection Agency (EPA), the Department of Transportation (DOT) and the Occupational Safety and Health Administration (OSHA). [49] Dependent on the content (which cannot be disclosed due to NDA restriction) the drum can be stored for a certain amount of days in the storage facility. During the permitted storage time, the drums are loaded on to trucks for a second approved transport to a third party waste incineration provider. The incineration takes place at a temperature below the melting point of the stainless steel can. No component of the waste is recovered for further used. All remainders including metal, ashes and unburned materials are deposited on a hazardous waste landfill. The corresponding process flow diagram is shown in figure 16.

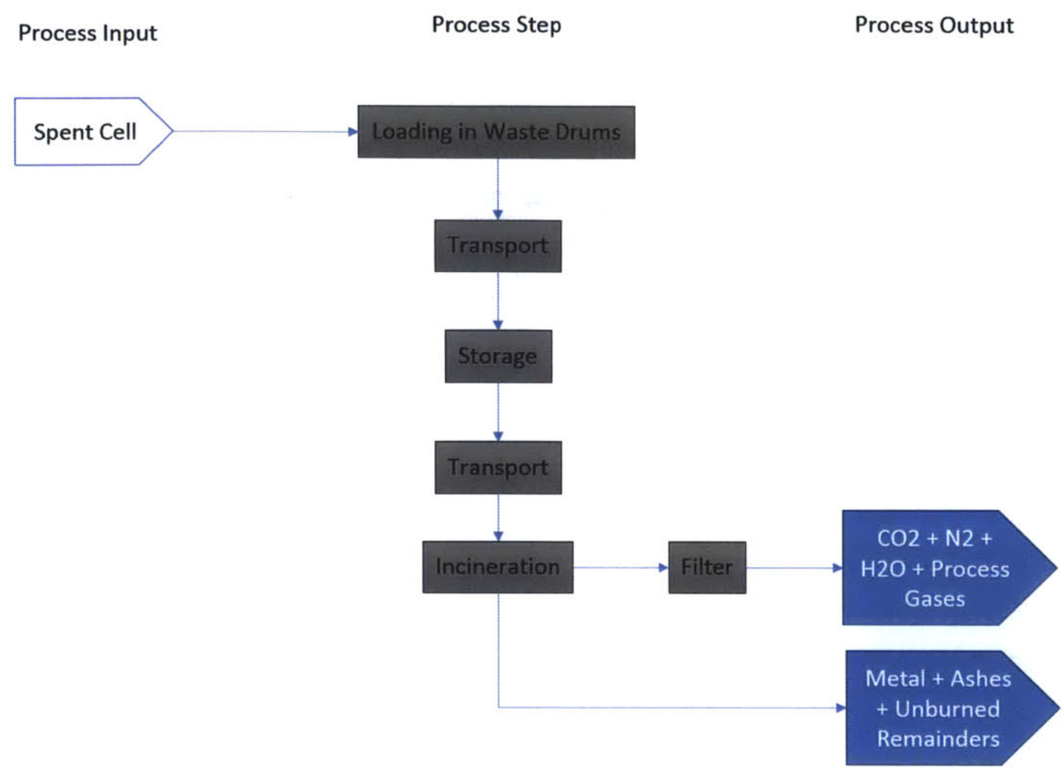


Figure 16: Complete Cell Incineration Process Flow

As the process flow is monitored and regulated by the EPA, DOT and OSHA as well as certified to the ISO 14001:2004 standard and proven to work with Ambri's as well as more hazardous waste from other clients, it can be considered safe.

3.1.2 Economic Evaluation

Accounting typically divides the total cost of a potential solution in to capital expenditures (CAPEX) and operating expenses (OPEX) to evaluate the economic aspect efficiently.

Capital expenditures or CAPEX, are constituted as expenses that occur when a company buys a fixed asset. A main property is therefore that CAPEX are not directly bound the produced product quantity. A typical example for a CAPEX item in the yearly balance is the acquisition of a building.

Operating expenses or OPEX, on the other hand are the cost to turn inventory in to throughput. In this case we view the operating expenses as cost directly associated with the product quantity. A typical example for an OPEX item are the cost for the materials that a product is made out of.

In Ambri's specific case machines are therefore CAPEX items while the waste, supplies such as PPE, buckets or saw blades can be viewed as OPEX. This clear differentiation cannot be applied for every item. Labor cost e.g. can be OPEX or CAPEX, dependent on their nature. In case of the complete cell incineration where the time of the recycling process operator is almost exclusively spent on paper work with the same work for 5 or 1000 cells, these expenses can be considered a CAPEX item. The calculation furthermore assumes that enough storage space, illumination of the area and so forth are provided and therefore does not include rent, electricity etc.

These assumptions combined with the disposal prices of Ambri's contractor lead to the following cost breakdown per cell for the complete cell incineration as follows: OPEX only consists of incineration cost between $75 and $200 per cell and Capex only consisting of labor. The labor is assumed to be only part time and therefore estimated with $5,000 per year. This cost breakdown is altered and simplified due to NDA requirements without changing the general meaning. Assuming a yearly recycling volume of 10,000 cells leads then to a total cost of recycling between $705,000 and $2,005,000.

3.1.3 Evaluation of Scalability

In order to evaluate the feasibility of using the full cell incineration as the recycling process for Ambri's commercial battery production, the findings from the safety and economic evaluation as well as considerations derived from regulations and the process complexity and requirements are taken in to account.

In order to quantify those findings for easy comparison between options, numbers were assigned for the different criteria according to the evaluation scheme shown for the incineration below.

Table 4: Complete Cell Incineration Scalability

Regualtions	Impossible to permit	Hard to permit	Medium hard to permit	Easy to permit	Already permitted
	1	2	3	4	5
					X
Safety	Unsafe				Safe
	1	2	3	4	5
					X
Cost	High				Low
	1	2	3	4	5
	X				
Complexity	High				Low
	1	2	3	4	5
					X
Throughput	Low				High
	1	2	3	4	5
					X
Process Control	Impossible				Possible
	1				5
	X				
Scalabilty	22				

As the process is already permitted and thereby in accordance to EPA, DOT and OSHA standards as well as ISO 14001:2004 certified, the value assigned for this criterion was therefore a 5.

Concerning the safety aspect, as described in the corresponding section the incineration process executed by waste management professionals can be considered safe. The handling of the unopened spent batteries at Ambri can also be considered safe as Ambri's expertise lies in the manufacturing, testing and general handling of their cells. The value assigned for this criterion was therefore a 5 as well.

As outlined in the economic evaluation, the cost of the complete cell incineration lies somewhere between \$755,000 and \$2,005,000 for one year of recycling. The cost associated with this process are not acceptable for Ambri. The value assigned for this criterion was therefore a 1.

The complexity associated with the complete cell incineration is the lowest of all possible disposal/ recycling options for Ambri, as the responsible recycling operator just needs to schedule a waste collection. The value assigned for this criterion was therefore a 5.

A process control i.e. disassembling the battery for further analysis e.g. of the interior, the chemicals, the seal and so forth is not possible with this option. The value assigned for this criterion was therefore a 1.

The maximum throughput of this option can be set as high as desired. The waste management contractor can collect as much waste as often as desired as it is one of the largest waste disposal companies in the U.S. The value assigned for this criterion was therefore a 5.

The calculated scalability is the sum of the individual points assigned to each criterion. The scalability value for the complete cell incineration is therefore 22. This leads to the conclusion that the complete cell incineration process is a proven, convenient and easy to manage disposal operation. It on the other hand does not confirm with Ambri's understanding of sustainability and life cycle management, doesn't provide the possibility of process control or end of life analysis and causes significant disposal costs.

3.2 R&D Disposal Process

This chapter explains the current R&D disposal process used by Ambri for the liquid metal battery. The process was established because of the need to open cells for the ongoing research for the battery itself and the high cost of the complete cell incineration. The first part of the chapter describes the process with its in- and outputs while the second part evaluates the process according to safety, economic and scalability aspects. The chapter ends with a summarizing evaluation of scalability that takes all analyzed factors in to account to derive a scalability factor that serves as a mean of comparison between the given and newly developed recycling and disposal options.

3.2.1 Process Description

The R&D disposal process is implemented at Ambri's headquarter and research facility in Cambridge, Massachusetts. The process was developed after Ambri reached out to their active material suppliers and manufacturers to understand how they dispose of contaminated parts. The key information obtained were that a reaction with water leaches all reactive content away while covering the reactive materials with oil while handling them significantly increases the process safety by reducing the reactivity.

The process flow and layout are shown in figures 17 and 18:

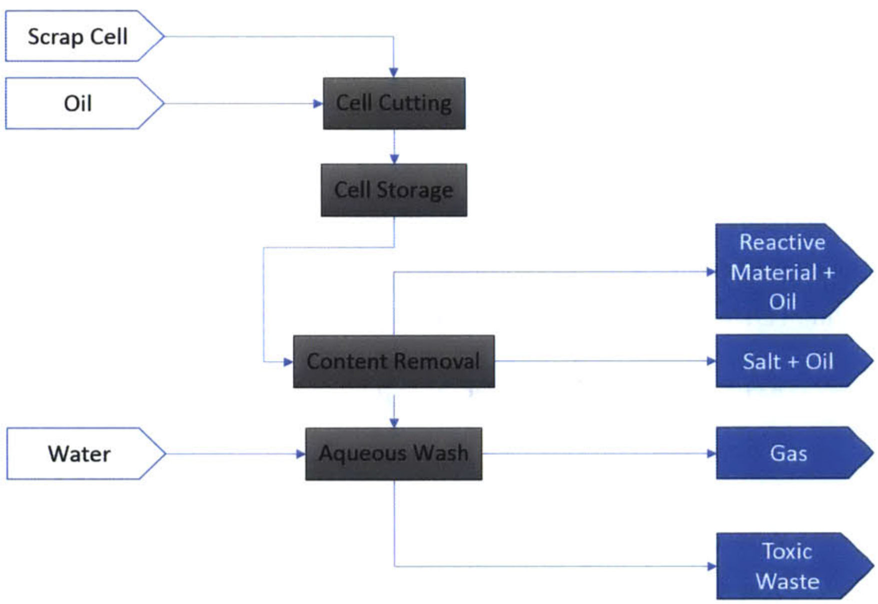


Figure 17: Ambri's Current Liquid Metal Battery Recycling Process Flow

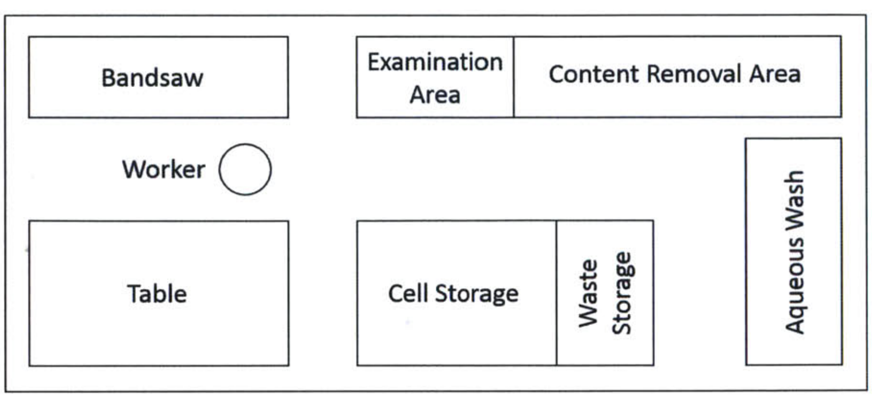


Figure 18: Ambri's Current Disposal Process Layout

The first process step is a band saw cutting operation with excess oil to cover all the material inside the cell. The cell is cut diagonally but not through the seal. This results in two cell halves, a big one with seal and a small one without seal. This partition will result in a significant problem for the content removal operation later on in the process. The in- and output of the first process step are shown in the figure below:

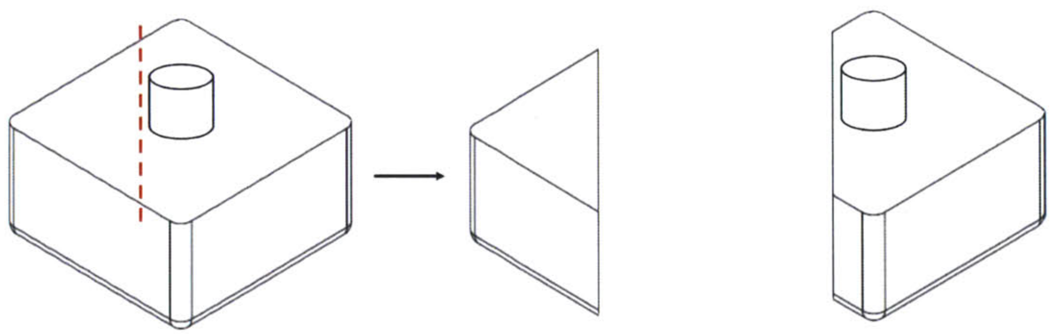


Figure 19: Current Band Saw Cell Cutting

The saw used for this operation is a KC812W band saw by Clausing Industrial. The cutting parameters were early on optimized for long blade life by the MIT consultants with the kind help and cooperation of the saw blade manufacturer LENOX. The blade parameters and cutting settings are listed below.

- Blade: RX+ X 13'6" X 1 X 0.035 X 5/8
- Blade Type: RX+
- Width: 1"
- Thickness: 0.0350"
- Length: 13ft 6in
- Material Number: 93232RPB134115
- Band Speed: 18 m/min
- Feed Rate 1 in/min

The cut and oil covered cell halves are then packed in to two thick plastic backs to decrease the chance of burrs cutting through the containment. Those plastic bags are placed in a plastic bucket which is then stored in a steel cabinet made for flammable content. The cells stay in this storage until ca. 40-70 cells have accumulated and a content removal and aqueous wash operation are scheduled.

If the cells are research relevant, they are photographed and catalogued after the cutting. This operation takes place in the examination area which provides a camera with a small photo booth and a computer. After that they are packed in to plastic bags and a bucket and stored in the cabinet as well.

The following content removal operation takes place on an easy to clean metal table with raised edges with a cutout for the press. The hydraulic press is capable of applying 267kN of force and can be actuated by hand with a lever that opens and shuts a hydraulic valve.

The current process does not use a special fixture or stamp for the operation. The parts are placed on a metal plate and are deformed by a stamp with a diameter of 10mm. The points of attack that are most commonly used by the recycling personal are marked with red arrows in figure 20.

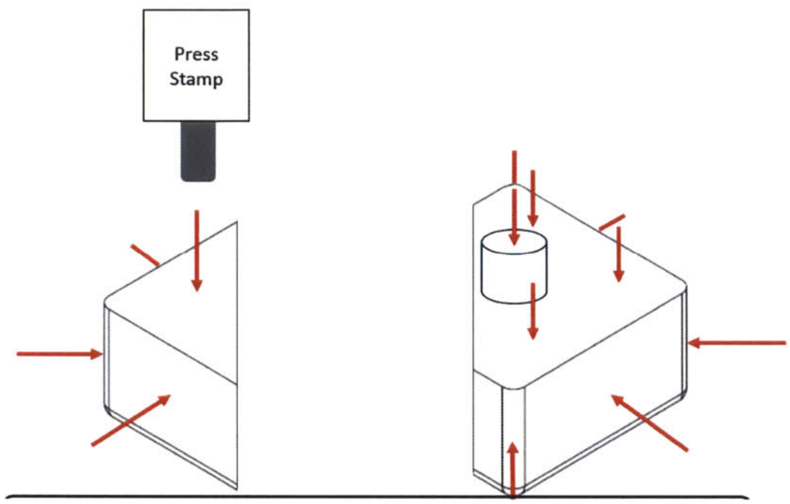


Figure 20: Current Content Removal with Press

As mentioned earlier, the location of the cut imposes a challenge for the operator of the recycling process. While the content of the small half of the cell is usually easy to remove, the content of the larger half is stuck inside the cell. The figure below marks the three problem areas in red while the location of the content inside is indicated with the dashed blue lines:

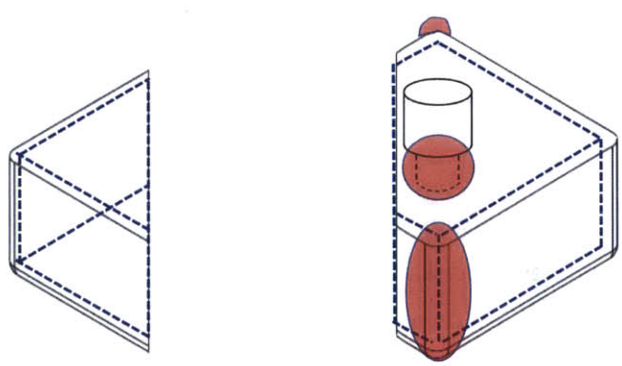


Figure 21: Problem Areas during Content Removal

The two corners of the larger half are undercuts filled with solid material and act therefore as an anchor for the content. Furthermore, the part of the seal stem that is inside of the cell reaches in to the content which solidified around it.

These features make the content removal process unpredictable and impose a risk for the recycling personal. In order to remove the content of the larger half, the worker usually first applies pressure on the seal stem to loosen the solid cell content around it. The recycling personal then proceeds to apply pressure on the flat top and bottom of the cell half to break the solid content inside. If this method cannot remove the material, the operator applies pressure on the edges of the can as shown in figure 22.

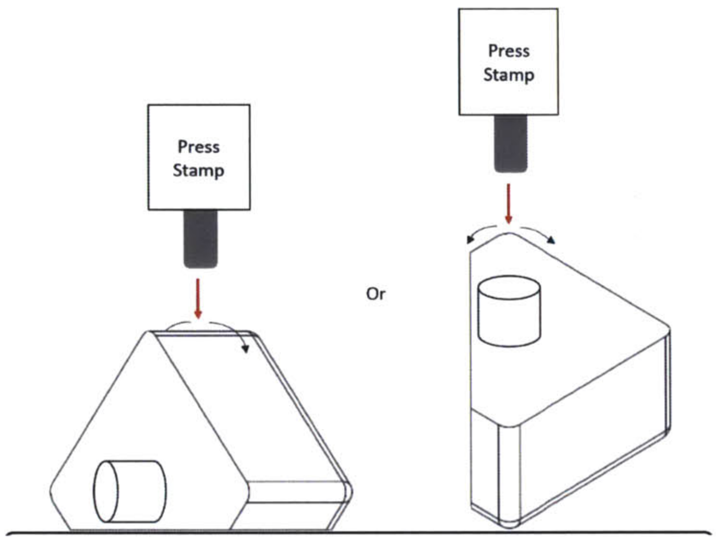


Figure 22: Pressing of Cell Corners

This method bears the risk of flipping the cell to the side while applying pressure as indicated by the black arrows. This can occur since the attack point of the press stamp is not a flat surface but a curvature with a steeply sloping contour on each side. The second option shown in the right part of the figure as furthermore no stable interface to the metal plate so that the operator has to hold the cell while applying pressure.

Once the content is removed, it is put in to steel cans. Those steel cans are then placed in to a 5 gallon drum which is sealed with the top and then stored in the waste storage area. When the waste storage area is full, a contractor is called to collect the drums. The contractor then transports the drums to a storage facility. After a short waiting time caused by logistics, the drums are transporting to an incineration facility where they are incinerated. Remaining ashes, metal and unburned remainders are then brought to a hazardous waste landfill.

The emptied cell cans on the other hand do not follow the incineration waste stream. Instead they undergo an aqueous washing process to clean them from any remaining hazardous content.

After the content removal the cans are placed in to a metal box that has a capacity for roughly 70 cells. The metal box is permanently placed in a secondary containment that is sealed nearly airtight when its doors are closed. A ventilated exhaust is connected to the containment in order to prevent hazardous gases from exiting it. The aqueous wash setup as described above is shown in the figure below.

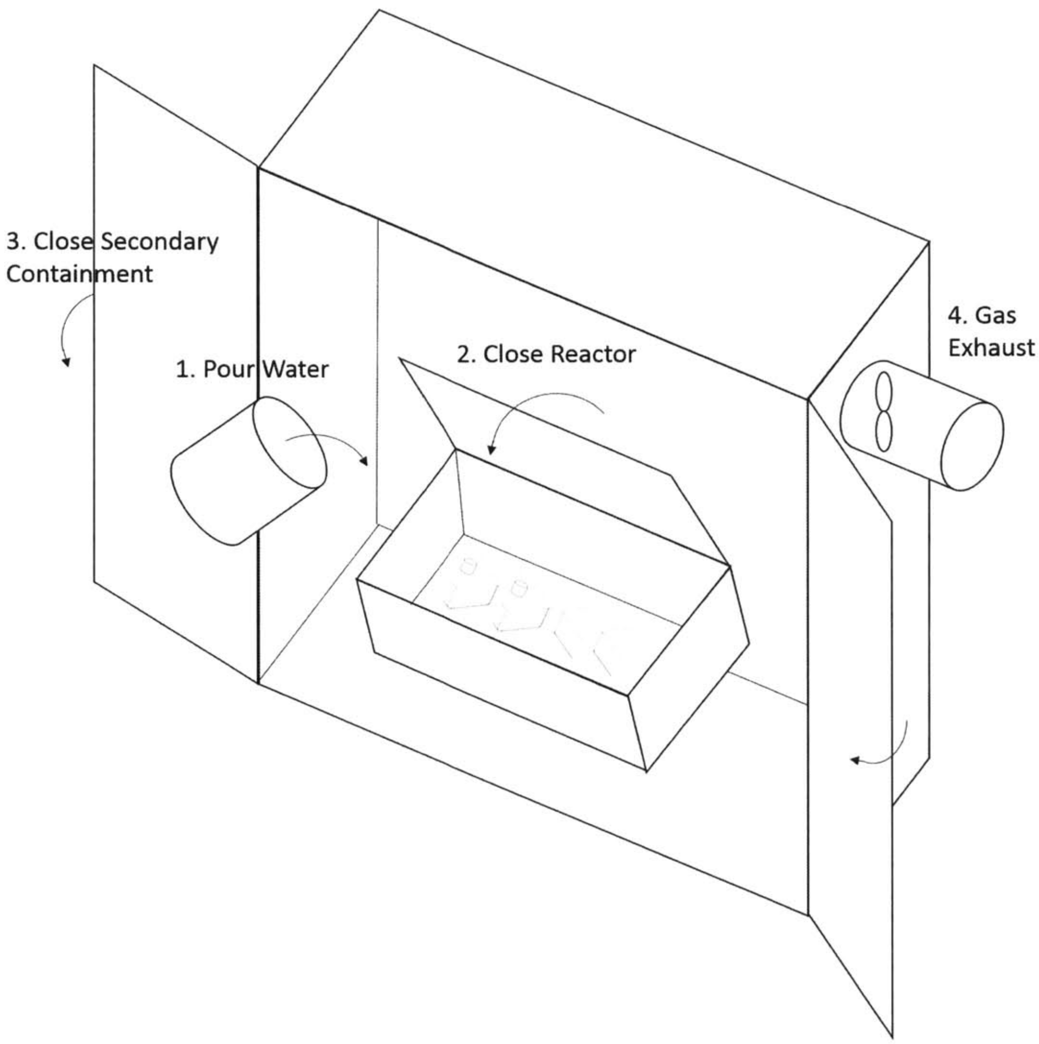


Figure 23: Ambri's current Aqueous Wash

When all cans are placed inside the metal box reactor, the operator in charge of the recycling process switches on the exhaust system and calls for three assistants. The first assistant places his hands on the top of the reactor while the two further assistants place themselves at the doors of the secondary containment. The operator in charge of the recycling then fills a 5 gallon bucket with water and pours in in the reactor box. As soon as he finishes pouring the water, the first assistant closes the reactor while the two further assistants close the doors of the secondary containment as fast as the operator and first assistant finished their tasks and got out of the way.

The reaction then takes place over an unknown amount of time and produces flammable H_2 and due to this excess of hydrogen a toxic gas. The earliest time the operator is allowed to open the secondary containment and reactor is 24 hours after he started the reaction by pouring water over the cans. The 24 hours include a safety time buffer. The reaction of the remaining hazardous content is from experience considered to be a lot faster. But since the water in the reactor is not agitated to accelerate the reaction and the amount of remaining content in the cells is not specified, no risks are taken.

After the 24 hour waiting time, the operator then opens the secondary containment and reactor, removes the cells and places them in to a 55 gallon drum. These drums are considered toxic but recyclable waste and are accumulated in the waste storage area as well. Once the waste storage area is full, a contractor is called to collect the drums and transport them to a metal recycling company.

3.2.2 Process Safety Evaluation

The current disposal process is a R&D process. The high standards set for shop floor production processes therefore do not apply. Ambri strives nevertheless to design and execute the process as safe as possible. A few of Ambri's safety measures are listed below:

- Implemented SOP
- Personal protection equipment required during the complete process
  - Nitrile gloves
  - Apron
  - Rubber sleeves
  - Safety glasses and face shield
- Designated and trained operator is in charge of every recycling process step, every time
- Safety time buffer for reaction
- Coverage of reactive and hazardous material with oil

A so called process failure mode and effect analysis (P-FMEA) was performed to access the safety of the process efficiently and evaluate which process steps must be improved if they are used in the new recycling process as well.

The failure mode and effects analysis (FMEA) was developed in the 1960s as a design tool for the aerospace industry to prevent errors from reaching the customer. Since then it has been used in several fields of industry including: "aerospace, automotive, nuclear, electronics, chemical, mechanical and medical technologies". [50] A major advantage is the easy to use framework that is not bound to any single step of a development process that can be used to quantitatively record the impact of new safety measures. [50]

The process FMEA used by Ambri is adapted from the automotive industry. The goal is to calculate the so called risk priority number or RPN. The risk priority number is an indicator of the process safety. The lower the number the safer the process. The RPN is the product of its three multipliers SEV, OCC and DET. SEV stand for severity factor, OCC is the occurrence value and DET is the detection number. The severity factor indicates the severity of the effects that a potential failure mode can have. The Occurrence value is an estimate for how often this failure mode is going to occur while the detection number evaluates the probability of detecting the error before it causes harm/ reaches the customer.

Once the RPN for every process step is calculated, the process steps are ranked according to the RPN value. It should be noted that not the absolute value of the RPN is the crucial factor. The values are calculated to help with the decision which process steps need the most improvement. This way the process development team can focuses on the important issues.

The first step of the P-FMEA is to define the scope. In this case the scope was to evaluate the risk potential of Ambri's currently used disposal/ recycling process in their R&D facility in Cambridge, MA.

The second step is to assemble a cross functional team. The team to evaluate the given process consisted out of the two MIT consultants Dale A. Thomas, B.Sc. in marine systems engineering and Martin C. Feldmann, B.Sc. in mechanical/ production engineering as well as Ambri employee Isha Gujarati, M.S. in chemical and biochemical engineering.

The next task is to dissect the process in to all required process steps that can be considered a single action. Ambri's disposal/ recycling process has 28 operator process steps as listed in table 5:

Table 5: Current Recycling Process Steps

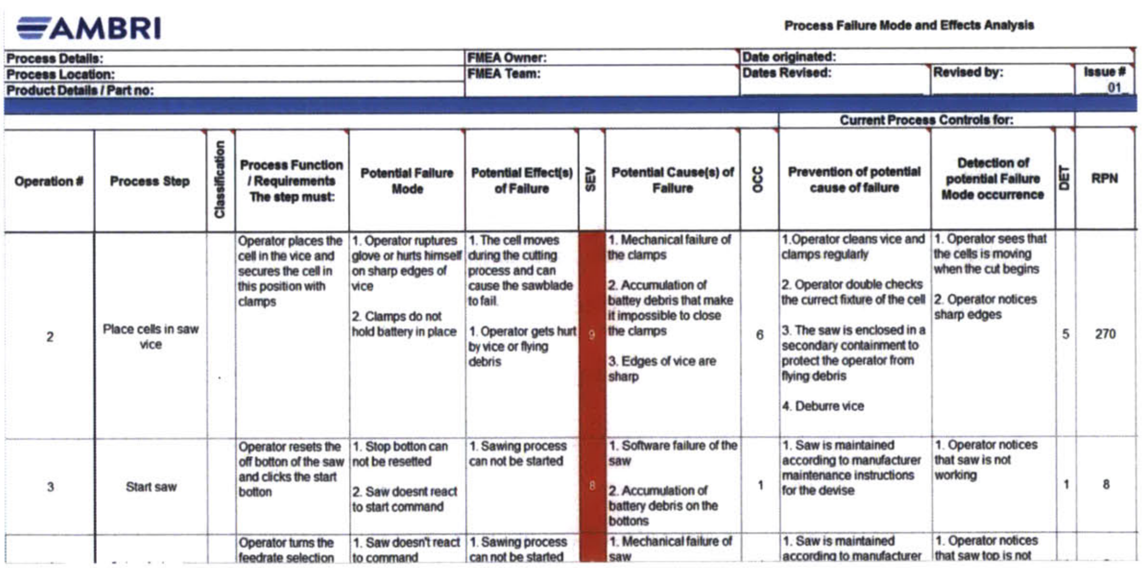
Operation	Process Step	Operation	Process Step
1	Lift saw blade up	15	Open reactor
2	Place cells in saw vise	16	Place cell cans in reactor
3	Start saw	17	Pour water over cans
4	Select federate	18	Close reactor
5	Cut cell	19	Close secondary containment
6	Stop saw	20	Main reaction
7	Lift saw blade up	21	Open secondary containment
8	Remove cell parts from vise	22	Draining of aqueous solution
9	Cell Storage	23	Close secondary containment
10	Oil Draining	24	Content drying

11	Press seal stem in	25	Open secondary containment of aqueous wash
12	Remove foam	26	Open reactor
13	Remaining content removal	27	Remove cell cans
14	Open secondary containment of aqueous wash	28	Store Waste

Afterwards the function of each process step is described, all possible failure modes that can occur and the effects that those failures would cause are found. With these information, the severity ranking SEV can be estimated. Is the severity ranking determined, the potential causes of each possible failure are found and the occurrence of these causes is evaluated to estimate the occurrence value. After the OCC ranking, possible prevention and detection mechanisms are evaluated to determine the detection estimate DET.

With the obtained values for SEV, OCC and DET, the risk priority number can be calculated and the process steps can be ranked according to the risk they impose.

A screenshot of Ambri's Process FMEA template is shown in figure 24:



AMBRI

Process Failure Mode and Effects Analysis

Process Details:	FMEA Owner:	Date originated:		
Process Location:	FMEA Team:	Dates Revised:	Revised by:	Issue # 01
Product Details / Part no:				

Operation #	Process Step	Classification	Process Function / Requirements The step must:	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	Current Process Controls for: Prevention of potential cause of failure	Detection of potential Failure Mode occurrence	DET	RPN
2	Place cells in saw vice		Operator places the cell in the vice and secures the cell in this position with clamps	1. Operator ruptures glove or hurts himself on sharp edges of vice 2. Clamps do not hold battery in place	1. The cell moves during the cutting process and can cause the sawblade to fail. 1. Operator gets hurt by vice or flying debris	9	1. Mechanical failure of the clamps 2. Accumulation of battey debris that make it impossible to close the clamps 3. Edges of vice are sharp	6	1.Operator cleans vice and clamps regularly 2. Operator double checks the currect fixture of the cell 3. The saw is enclosed in a secondary containment to protect the operator from flying debris 4. Deburre vice	1. Operator sees that the cells is moving when the cut begins 2. Operator notices sharp edges	5	270
3	Start saw		Operator resets the off botton of the saw and clicks the start botton	1. Stop botton can not be resetted 2. Saw doesnt react to start command	1. Sawing process can not be started	8	1. Software failure of the saw 2. Accumulation of battery debris on the bottons	1	1. Saw is maintained according to manufacturer maintenance instructions for the devise	1. Operator notices that saw is not working	1	8
			Operator turns the feedrate selection	1. Saw doesn't react to command	1. Sawing process can not be started		1. Mechanical failure of saw		1. Saw is maintained according to manufacturer	1. Operator notices that saw top is not		

Figure 24: Ambri Process FMEA Template

The P-FMEA of the R&D process lead to the following ranking (table 6) of operations that need to be improved if implemented as an industrial scale recycling process:

Table 6: Process FMEA Results

RPN Ranking (high to low)	Operation	Process Step	RPN
1	11	Pressing seal and stem in	1000
2	13	Remaining content removal	1000

3	21	Open secondary containment	800
4	5	Cut cell	600
5	16	Place cell cans in reactor	600
6	17	Pour water over it	600
7	18	Close reactor	600
8	19	Close secondary containment	600
9	9	Cell storage	378
10	10	Oil draining	360
11	24	Content drying	360
12	27	Remove cell cans	360
13	2	Place cells in saw vise	270
14	8	Remove cell parts from vise	270
15	20	Main reaction	200
16	22	Draining of aqueous solution	135

As can be seen, the operations associated with the press (operations 11, 13, 10) have the highest risk associated with them. This is because even with personal protective equipment, the operator needs to interface directly with the press and the cell during the content removal operation. The risks associated with flying debris, slippery oil covered surfaces on the cans and press as well as not standard procedure to remove the active material from the cell halves increase the RPN.

The second process part generally associated with an elevated risk is the aqueous was (operations 21, 16, 17, 18, 19, 24, 27, 20, 22). This is foremost due to the fact that with the current system, the operator has no remote control to start and end the process. The operator furthermore has no means to know how long the reaction takes and when it is safe to remove the content. The first steps of the process present hereby the highest risk. The operator and his assistants place the cans inside the reactor, pour water over it and then closes reactor and secondary containment. Doing this the involved workers can get in contact with splashing hazardous aqueous solution or flammable and/ or hazardous gas that escapes the secondary containment before it can be closed.

The remaining operations with an increased RPN value are: Cell cutting, cell storage, oil draining and placing the cells in the saw vise. This is mainly due to the risks associated with contamination with active material and oil as well as machines, vises and storage containments not designed for a high throughput production process.

The overall lessons learned from the performed process FMEA were therefore to:

1. Completely redesign the content removal step for the new process with the objectives to significantly reduce the forces involved and decrease the process variation
2. Remotely control the start and end of the aqueous was reaction
3. Deeper understanding of the reaction itself

4. General machine design primarily oriented on safety and easy to use considerations

The complete process FMEA cannot be disclosed due to NDA requirements.

3.2.3 Economic Evaluation

The economic evaluation of the process is again divided in to capital expenditures (CAPEX) and operating expenses (OPEX) as described earlier.

The CAPEX expenditures include the machines with all functioning parts, enclosures and installed safety measures with a total cost of roughly $8,000. The calculation furthermore assumes an installed exhaust system for ca. $12,000 and enough space to be provided for the machines. The capital expenditures are therefore $20,000. This CAPEX breakdown is altered and simplified due to NDA requirements without changing the general meaning.

The operating expenses are divided in to the consumable material costs, costs for disposal of the end products and labor. The OPEX breakdown without labor cost of the current process only consists out of the waste incineration cost between $40 and $80 per cell as well as PPE that can be estimated with $0.10 per cell. The observed high variance of the time spent for especially the content removal made it appear to be necessary to perform a time study for the process to get an accurate estimate of the labor cost. The three process steps that actively involve the recycling personal as shown in the process flow are listed with their average process times and standard deviations for 65 cells in table 7.

Table 7: Process Times R&D Disposal Process

	Average Time	Standard Deviation
Cell Cutting	5:00h	0:20h
Content Removal	4:00h	2:13h
Aqueous Wash	23:00h	00:00h

As expected, the standard deviation of the least stable process step, the content removal is abnormally high. The process run charts of this operation (figures 25 and 26) illustrate this problem:

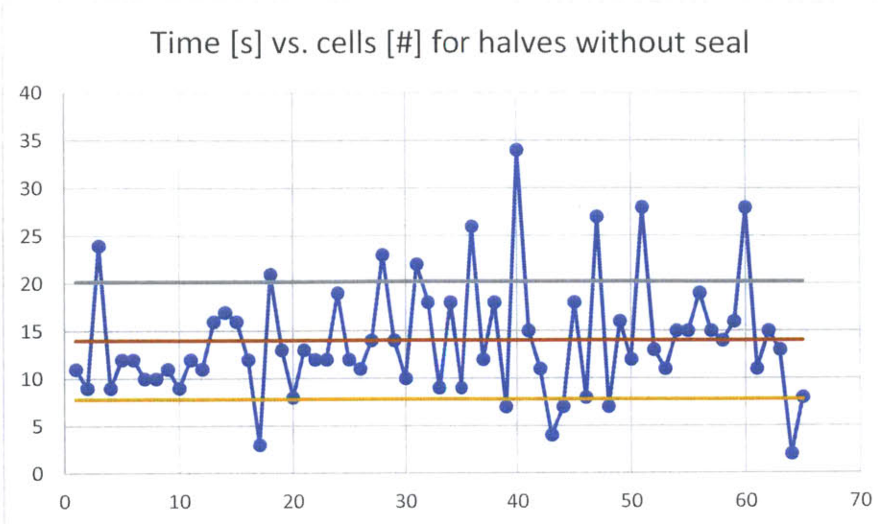


Figure 25: Run Chart Press: Cells without Seal

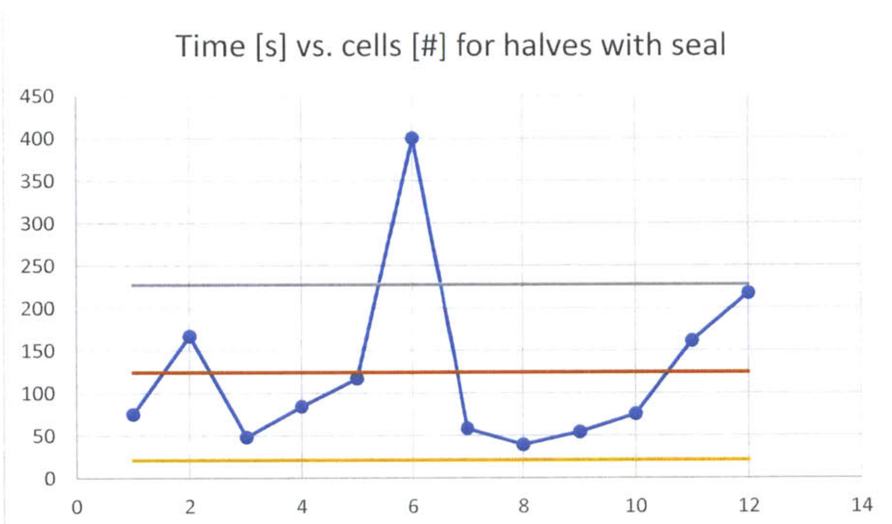


Figure 26: Run Chart Press: Cells with Seal

The orange line indicates the average while the yellow and grey line represent the average minus and plus one standard deviation respectively. The average time for cells without seal is 14 sec. while its standard deviation is 6.2 sec. The average process time for cells with seal is 124.6 sec. while its standard deviation is 103.0 sec., almost 83% of the average. The complete time study with all information can be found in the appendix of this thesis.

Assuming a salary of $26.09/h for a mechanical engineering technician (according to the U.S. bureau of Labor Statistics May 2013) and adding the non-labor OPEX gives an estimation of $52.94 -$92.94 with a standard deviation of ca. $1 per cell.

This shows that measures of risk reduction applied to increase the process stability to provide for a safe process can also decrease the production cost significantly by doing just that.

Assuming a yearly recycling volume of 10,000 cells and a remaining machine value of 70% after one year of operation, the total cost of recycling are therefore between $535,400 and $935,400.

3.2.4 Evaluation of Scalability

In order to evaluate the feasibility of using the current R&D disposal method as the recycling process for Ambri's commercial battery production, the findings from the safety and economic evaluation as well as considerations derived from regulations and the process complexity and requirements are again evaluated according to the presented scheme. These evaluation lead to the following result (as shown in table 8):

Table 8: Current R&D Disposal Process Scalability

Regualtions	Impossible to permit	Hard to permit	Medium hard to permit	Easy to permit	Already permitted
	1	2	3	4	5
		X			
Safety	Unsafe				Safe
	1	2	3	4	5
	X				
Cost	High				Low
	1	2	3	4	5
		X			
Complexity	High				Low
	1	2	3	4	5
				X	
Throughput	Low				High
	1	2	3	4	5
	X				
Process Control	Impossible				Possible
	1				5
					X
Scalabilty	16				

The transport and waste disposal of the current option is still handled by a third party waste management provider that operates in accordance to EPA, DOT and OSHA standards and is ISO 14001:2004 certified. The cell opening, content removal and aqueous wash step at Ambri however are laboratory grade research processes. Preliminary research performed by Ambri experts showed that these processes would need extensive improvements to be performed on a shop floor at an industrial scale. The value assigned for this criterion was therefore a 2 indicating that the process is hard to permit.

The process safety was assessed with the P-FMEA discussed in the corresponding chapter. The result of this analysis was that the process cannot be safely applied as a high throughput production process in a shop floor environment. The value assigned for this criterion was therefore a 1.

The cost were estimated to be between $535,400 and $935,400 for 10,000 cells during one year of operation with a depreciation of 30%. As the cost are lower than for complete cell incineration but still unacceptably high for high throughput production, the value assigned for this criterion is a 2.

The complexity of the current recycling process as described in this chapter is not very high. Besides being trained in working in a lab environment, the operator who is responsible for the recycling process must be capable of operating and maintaining a regular manual band saw and hydraulic press as well as using an HVAC system. The value assigned for this criterion was therefore a 4. It is important to note at this point that this assessment of the process complexity is not making a statement about the safety and/ or stability of the process.

The process throughput can be easily estimated with the performed time study. Assuming 32 hours for process steps, the maximum yearly throughput of one full time operator with two half time assistants is:

$$65\ cells * \frac{251\ working\ days\ per\ year}{4\ working\ days\ per\ 65\ cells} < 4079\ cells\ per\ year \tag{8}$$

This is not even half of Ambri's requirement of 10,000 cells per year even under the assumption of no downtime over one full year. The value assigned for this criterion was therefore a 1.

Since Ambri can open and analyze the cells with its current method, the process control is possible. The value assigned for this criterion was therefore a 5.

These considerations lead to a scalability factor of 15. The conclusions derived from the overall evaluation of scalability is that Ambri's current R&D disposal process is a simple disposal solution for research purposes. As described, in order to use it further and/ or on a larger scale, certain risk decreasing improvements would need to be made. However this process cannot be implemented on a commercial scale without significant changes. The reasons lie not only in the needed separation of operator and process but also in the fact that this option only produces hazardous output that needs to be disposed of for a considerable amount of money. The process furthermore needs up to 3 operators and can only handle the currently required research throughput.

4. The New Recycling Process

This chapter describes the development and implementation of the new recycling process for Ambri's liquid metal battery. The chapter starts with a summary of the requirements, objectives and specifications for the final process design. The chapter continues with a description of the evaluation of process alternatives and the following process development of the new recycling process. The chapter ends with an overview of the new recycling process and a thorough discussion of every process step.

4.1 Requirements, Objectives and Specifications

4.1.1 Requirements and Objectives

As described in the problem statement of the introduction, the development of the recycling process requirements were an iterative process spanning from mid-March 2014 to the beginning of June 2014, ending with the third round of funding. Ambri's final requirements for a successful recycling method were that the process:

- Is safe and cost efficient
- Can be permitted as a production process
- Can be implemented in one month
- Has integrated safety measures
- Provides for the possibility of process automation not included in its initial design
- Provides for the possibility of full process containment
- Provides for process and quality control measures
- Can incorporate further process steps for added functionality
- Can accommodate for the anticipated throughput during the first year of production
- Separates the operator as much as possible from the process steps and their in- and outputs
- Provides the operator with as much information about the process as possible
- Is safely to operate with one designated and trained operator without assistants
- Is ergonomically designed in all machines and functional parts

The new budget was not exactly specified but was supposed to not exceed the anticipated first budget of $20,000 by more than roughly 40% leading to a maximal amount of $28,000.

4.1.2 Process Development Specifications

The specifications derived from the discussed and listed process requirements and objectives in the previous section were as follows:

Concerning the general process and process safety requirements necessary for a permission, the team agreed upon consulting with Ambri's in-house safety experts as well as a third party waste management consultant to ensure adequate process safety.

The cost limit was internally set by the MIT consultants at $25,000 to be able to accommodate for minor changes that could become necessary during the final assembly or testing.

The timeline for the process implementation was set to accommodate for the narrow time frame as follows:

- Week 1: Final part sourcing and process assembly
- Week 2: Physical and chemical process characterization
- Week 3: Interpretation of the results and derivation of final design changes
- Week 4: Final assembly of adjusted process and job #1

In order to further accelerate the process, the team decided to only purchase equipment from within the United States.

To comply with the requirements of integrated safety measures and process containment, the team agreed upon the following four design guidelines:

- Full containment of every process step
- Ability to flush every containment with inert gas
- Ability to actively control chemical process steps
- Automation of most critical safety measures

To provide for the possibility of future process enhancement, process and quality control as well as automation, the team decided to comply with the following design guidelines:

- Only standard connections
- Modular design of separated process steps
- Possibility of full disassembly with easy accessibility of every part
- Cost of custom parts below $3,000

To accommodate for the anticipated throughput during the first year of production and recycling the team assumed a yearly volume of 10,000 cells after consulting with Ambri's vice president of manufacturing. The requirement for the process is therefore a yearly throughput of 10,000 cells and the capability of maintaining this throughput for one year without unforeseeable process equipment failures.

4.2 Process Development and Evaluation

This section describes the process development with its evaluations to design Ambri's new recycling process for the liquid metal battery.

The final recycling process was developed under the consideration of all information gathered during the initial literature review, the analysis of Ambri's currently used disposal processes and the process specifications jointly developed by the MIT consultants and Ambri's vice president of manufacturing. During the development process, the team used the process failure mode and effects analysis iteratively to compare the anticipated safety and stability of potential variants. The obtained findings were another major factor for the evaluation of different options. The main process development took place between mid-March 2014 and mid-June of the same year and is described below.

The first major decision made in March after an initial literature review was that the new recycling method has to be a process that operates at or near room temperature. The complexity, cost and regulatory issues associated with extreme temperature processes were considered to be too high to provide Ambri with an efficiently working recycling operation by the end of July 2014. Since pyrometallurgy was therefore not considered to be a feasible option it was decided to develop a hydrometallurgical room temperature processes. To nevertheless design a process that is capable of handling the reactive material safely, the additional decisions were made to use inert atmospheres wherever required (according to Recupyl's process) and to reduce the reactivity during the chemical reactions (According to Toxco's process).

After actively participating in the R&D process in April, the team decided furthermore to not use any method of battery opening or content removal that requires forces high enough to deform and destroy the stainless steel can as it is regarded as too risky and unstable for a commercial production process.

After further research on materials for usage in caustic environments such as ceramics and polymers, the team decided in May to only use processes at or near ambient pressure. This consideration was derived from the brittle and/ or weak nature of the materials that can be used while not significantly exceeding the budget by e.g. using advanced coating technologies on process equipment. With this decision the process additionally increased its safety level as no material failure could cause an explosion.

The last major decision made in the beginning of June before the process design had to be finalized to source and order the parts in time to finish the project was that the process flow will be executed as a pull system closely related to a Toyota Production Cell. One operator has to be able to manage the whole process with every machine. The process steps need to be therefore easy to operate and efficiently coordinated time wise.

4.3 Final Process Flow

The final process flow developed after a total of 4 months of continuous research and evaluation is shown in the figure below.

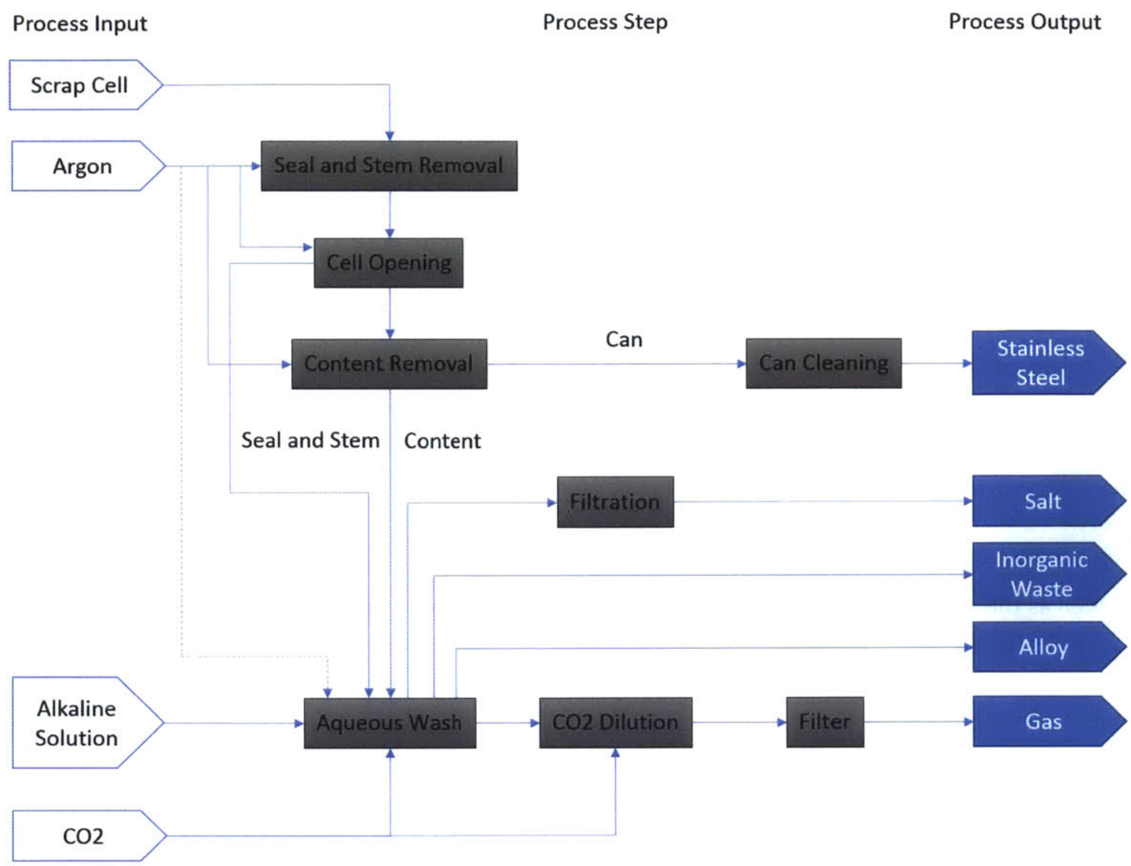


Figure 27: New Recycling Process Flow

The first operation performed on the scrap cell is the removal of the seal and the stem:

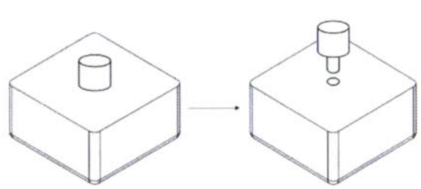


Figure 28: Schematic of Seal and Stem Removal

This way the cell can be flushed with argon inert gas during the cell opening shown below:

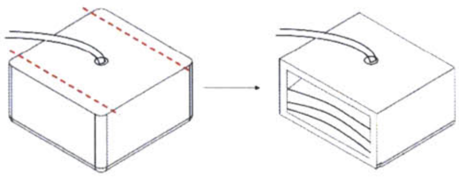


Figure 29: Schematic of Cell Opening

After the cell is opened, the content and can are separated in the content removal operations:

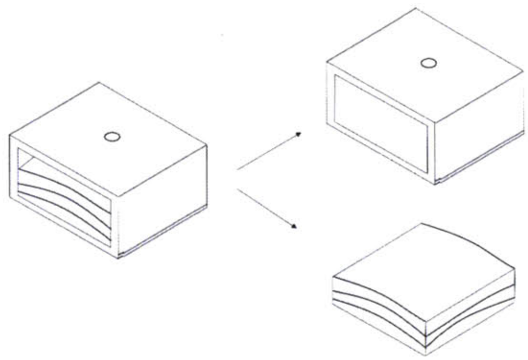


Figure 30: Schematic of Content Removal

The empty can undergoes a cleaning procedure and can be sold as stainless steel scrap. The content as well as the remaining seal and stem then undergo and aqueous wash.

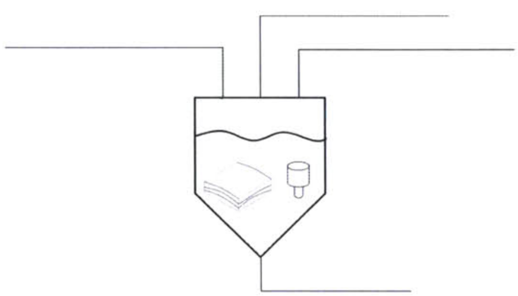


Figure 31: Schematic of Aqueous Wash

The outputs of the aqueous wash are salable salts, a salable metal alloy, inorganic waste and a gases. The gases are directed through a filter and safely released to the environment.

The following chapters will explain every process step, its specifications as well as its physical implementation in chronological order of their development in detail.

4.4 Content Removal

The first process step to be developed was the content removal operation. This step separates the active material of the battery from the stainless steel can. The separation provides access to the battery content for further reaction in to reusable or easy disposable outputs and enables efficient recycling of the stainless steel container. The content removal method was developed first since it is the central process step of the recycling system. It determines how the cell has to be opened at the beginning and what material is accessible for further hydrometallurgical operations at the end.

The chapter is structured in an initial description of the specification developed for this process step, the following evaluation of process alternatives and the design of the final solution.

4.4.1 Specifications and Requirements

As mentioned in the analysis of the current process, the main focus during the development of the new removal operation was to find a secure and stable way of removing the active material from the can. To ensure this and compliance to Ambri's further requirements, the team developed the following specifications for the new content removal operation:

- Complete separation between operator and cell during the content removal
- One single removal operation of the complete content
- Pressures below the yield strength of the stainless steel can
- Process provides for a capacity of at least 5 cells/day
- Process provides for easy automation
- Process budget ca. $5,000

4.4.2 Evaluation of Alternatives

The research showed that commercial battery recycling processes use some kind of crushing operation at the beginning to shred the batteries in to geometrically undefined pieces. This operation is necessary to expose the content and increase its surface area to enable the chemical reactions in further steps. The rigid design of Ambri's battery with its solidified metal enclosed in a 3.2mm thick stainless steel can would impose a challenge even for larger hammer mills as the task is not only to deform of crack the containment but to evenly expose all of the active material inside.

A further consideration was that a geometrically undefined shredding of the cells could cause instability of downstream processes. Deformed stainless steel from the can could e.g. enclose active material in a way that the aqueous wash cannot react all of the content in the specified time. This could lead to a process failure mode where the shop floor or even an operator is exposed to hazardous material before it is transformation in to not or significantly less hazardous end products.

Lastly, the purchase and gas tight enclosure of e.g. a complete hammer mill would have not complied with the budget restrictions.

Due to these considerations it became apparent that only a geometrically defined removal could guaranty safety and repeatability while not exceeding the budget. The adhesion between the solidified content and the can furthermore restricted the alternatives to options that are able to apply a sufficient amount of pressure. The process therefore needed to incorporate some type of press. The most cost efficient way to accomplish that while also providing for automation is a simple hydraulic H-frame press as produced in many variants by several manufacturers.

In order to evaluate the feasibility of using such a press, a procedure had to be found that allows for the removal of all of the content while only using the vertical stroke that the press provides. A natural idea was therefore to remove two complementary sides or top and bottom and then push the content out of the hull with a stamp:

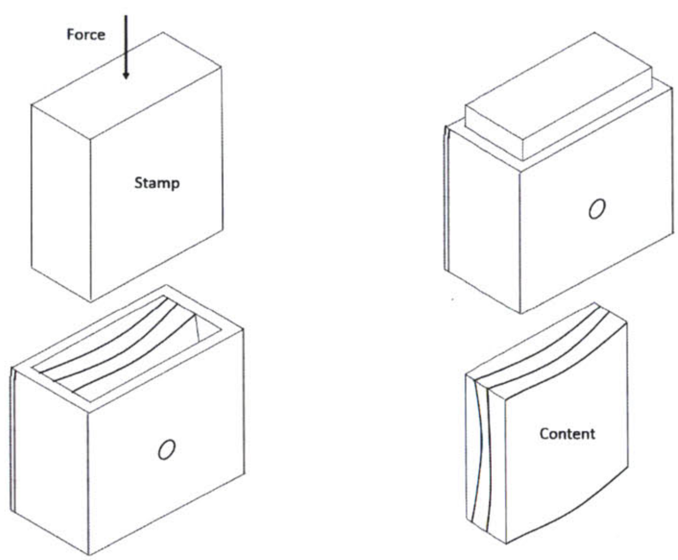


Figure 32: One Directional Content Removal with Stamp

The theory of a safe, simple, repeatable and cost efficient way to remove the content of several cells per hour was thereby developed and ready to be tested with actual process equipment.

4.4.3 Design and Implementation

In order to implement and test the content removal operation, the team had to execute the following tasks:

- Develop specifications for and purchase a press
- Design and purchase a vise to hold the cell during the removal
- Design a containment for the press

4.4.3.1 The Press

Since the purchase of the press could potentially have a long lead time dependent on the requirements to be developed, the first step was to specify what kind of press was needed. The developed specification were that the press had to have:

- A stroke that is longer than the cell
- Enough force to remove the content
- An easy to operate and automate design
- The ability to move the stamp up and down to separate the stamp and can after the removal
- Longevity to operate for at least one year without complete replacement

In order source and acquire a machine, those specifications were quantified as follows:

Dependent on the removal direction, the stroke has to be either at least 53.98mm long or 101.6mm long as shown in figure 33.

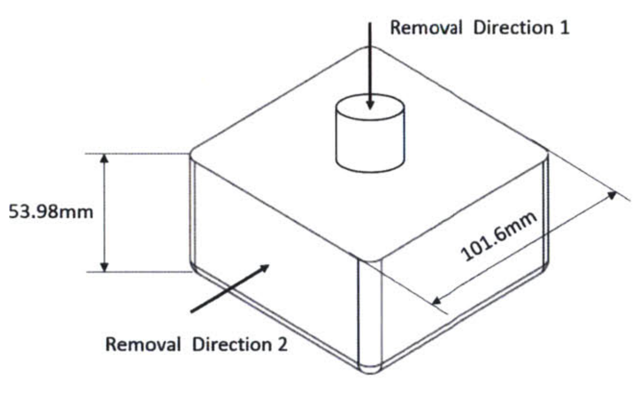


Figure 33: Removal Directions

The team decided to reserve the possibility to do either as it was too early to make a decision without testing and further process development. The minimum stroke was therefore set to 101.6mm.

In order to estimate the required maximum force that the press needs to be able to apply, the team assumed worst case conditions. The worst case was calculated by assuming a complete coverage and perfect wetting of the metal content on the bottom (or top) and the two remaining sides of the can. This area multiplied with the ultimate shear strength of the metal component results in the force requirement:

$$(92.25^2mm^2 + 50.8mm * 92.25mm * 2) * Metal\_Shear\_Strength < 220{,}000N \quad (9)$$

This estimate can be considered as the worst case since gravity and the limited total amount of content inside the cell prevent the complete coverage of all three sides used in the formula. Furthermore only ca. 50% of the content by volume is metallic. (Numbers altered due to NDA requirements without changing the general meaning). The salt used as electrolyte breaks readily long before the ultimate shear strength of the metal is reached. Finally the team does not expect the material failure mode to be complete shearing of the metallic content. Observations with the currently used disposal process showed that forces well under 17,000N were sufficient to cleanly separate the can from the content every time the separation line was actually accessible for the press.

The requirements for an easy to operate and automate design were met by deciding to purchase a hydraulic press powered by an electric motor. This way the operator can adjust the height of the stamp with a three position lever to control advancement and return of the stamp. The press can furthermore be automated by replacing the lever/ valve mechanism with a solenoid valve. The solenoid valve can then be remotely controlled by the operator or actuated by a process control unit dependent on the level of automation.

In order to be able to accurately adjust not only the advancement of the stamp but also the return, the press needs to have a double acting hydraulic cylinder. Those cylinders differ from normal single acting cylinders as they can also apply hydraulic pressure to retrieve the stamp. In a single acting system this task is normally performed by a spring mechanism that brings the stamp back to its upper default position without further operator control.

To account for a sufficient life time of the press and its parts, potential suppliers were called to assure the purchase of a press that could handle 10,000 operations.

The press that fulfilled all these requirements and was with a price of approximately $3,300 a very cost efficient quality model, was the "Dake Force 25DA Double Acting, Electrically-Operated Hydraulic Press", that was therefore immediately purchased. The press data sheet can be found in the appendix of this thesis.

4.4.3.2 The Vise

The next important task was to design and purchase a vise that holds the cell during the removal operation. The team anticipated to go through one or two design iterations and therefore decided to develop two vises. The first vise was designed to test the concept in a cheap and flexible way before the vise for the final process could be produced with further input from those tests. The basic specifications for the proof of concept vise were:

- The vise needs to safely hold the cell during the content removal
- The vise needs to be flexible enough for iterative process development
- The vise needs to be rigidly connected to the press, yet adjustable for different tests

According to the first bullet point, the main function of the vise is to fixate the cell in a position so that pressure can be safely applied from the top to push the content out. This can be accomplished in two general ways, either with a frictional or a positive connection as shown in figure 34 a) and b).

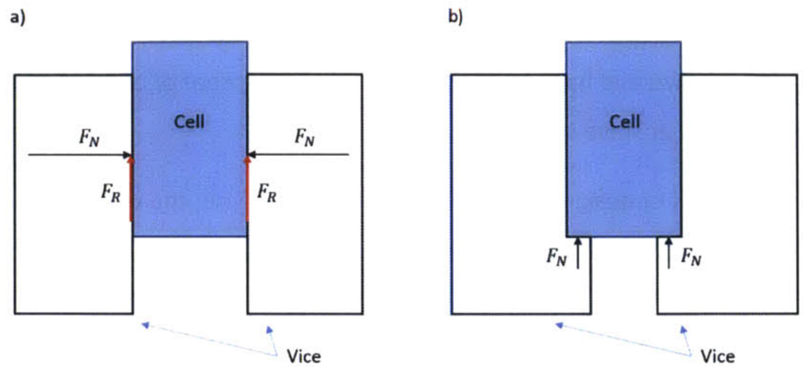


Figure 34: a) Frictional Connection b) Positive Connection

The main disadvantage of a positive connection is the small wall thickness of the can combined with the design restriction that no part of the vise can spatially interfere with the stamp or content during the removal. The edges that hold the cell in place could therefore only be very small as pictured in figure 35. This design however makes the edges vulnerable to wear.

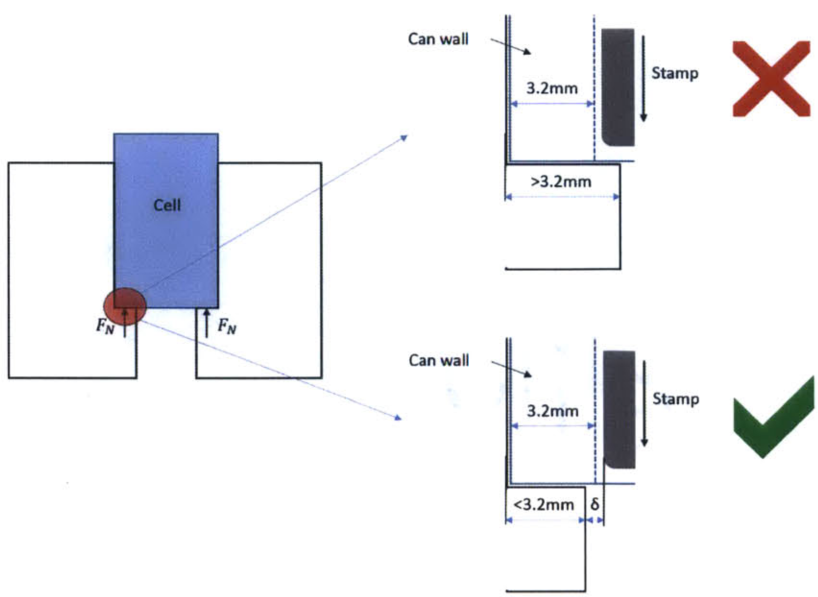


Figure 35: Holding Edge Design

Yet, the second option of securing the can position through friction would require a very rigid and heavy design of the vise that needs to include a mechanism to apply the necessary pressure to account for a friction force as high as the calculated maximum press force of ca. 220,000N. This would mean that the mechanism has to apply a force of:

$$Minimum\_Vise\_Press\_Force = \frac{220{,}000N}{\mu_{Steel\ vs.\ Steel}} \tag{10}$$

With a minimum estimate of the friction coefficient between two dry and hard steel parts of $\mu_{Steel\ vs.\ Steel} = 0.74$ [51], the force must therefore exceed 297,000N. This option was ruled out as such a mechanism would be too expensive and have a too long lead time for a proof of concept vise. The final decision was therefore to use a positive connection.

In order to account for the requirements of designing a flexible and adjustable vise, the decision was made to also include two further edges in the design to be also able to hold an object down while pulling and make the relative position of the two blocks adjustable with screws on the bottom. The rigid connection to the press was accomplished with an upper and a lower plate connected with 4 bolts to secure the vise around the U channel profiles of the press.

The final design of the test vise is shown in figure 36:

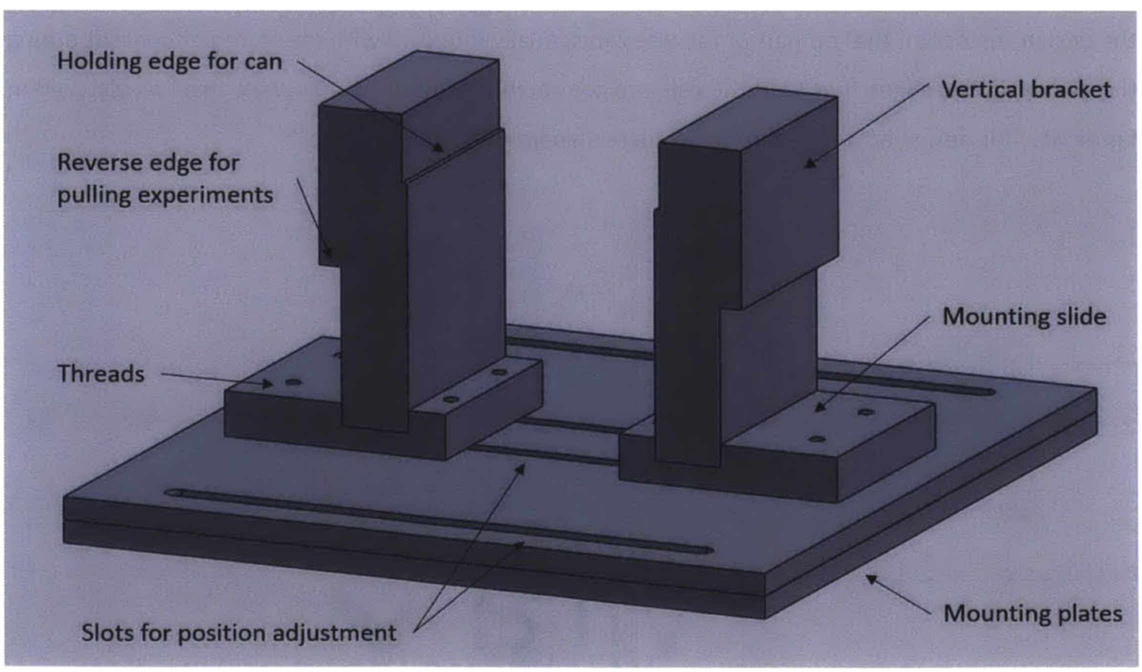


Figure 36: Content Removal Test Vise

Tests with the acquired vise showed that the process works repeatable without malfunctions. The most secure and rigid way to position the cell in the vise was discovered to be the vertical alignment as shown in figure 32. Due to the complete success of the test vise, the team only suggested three design changes for the final vise to be used in the actual recycling process:

- A hole in the middle of the mounting
- Carbide insert plates on top of the edges
- Detachable instead of welded vertical vise brackets

The hole in the middle of the mounting plates was added to achieve a more efficient content removal with less human interaction. After the stamp pushed the content now out of the battery, the content can fall through the vise and be accumulated in a bucket underneath.

The carbide insert plates are pressed in to the two vertical brackets of the vise in order to reduce wear and thereby prohibiting a vise malfunction during which cell is pressed in to the vise.

The last change was to not connect the vertical brackets of the vise by welding with their mounting plates but with a bolt connection. This change enables easier maintenance and cheaper repairs.

4.4.3.3 The Content Removal Stamp

The stamp for the content removal operation was designed according to the following list of basic requirements defined by the MIT consultants.

- Quick connection to the press for fast maintenance
- Rigid design for long lifetime
- Modular design for cost efficient part replacement
- Design that can accommodate for vast tolerances of the cell cans
- Integrated quality control system

To guarantee a quick connection to the press, the team decided to design the stamp with an internal thread that directly fits on the threaded end of the hydraulic piston of the press

A rigid and modular design was accomplished by building the stamp out of five tool steel segments that can be separately replaced and are connected by two long bolts.

In order to accommodate for the tolerances of the stainless steel cans, the team decided to incorporate a 45° phase on the first segment of the stamp to enable self-alignment.

A quality control that allows conclusions about the seal and wetting quality was integrated by incorporating a Mark 10 force measurement gauge in to the stamp that can directly be connected to a computer.

The design of the final stamp is shown in figure 37.

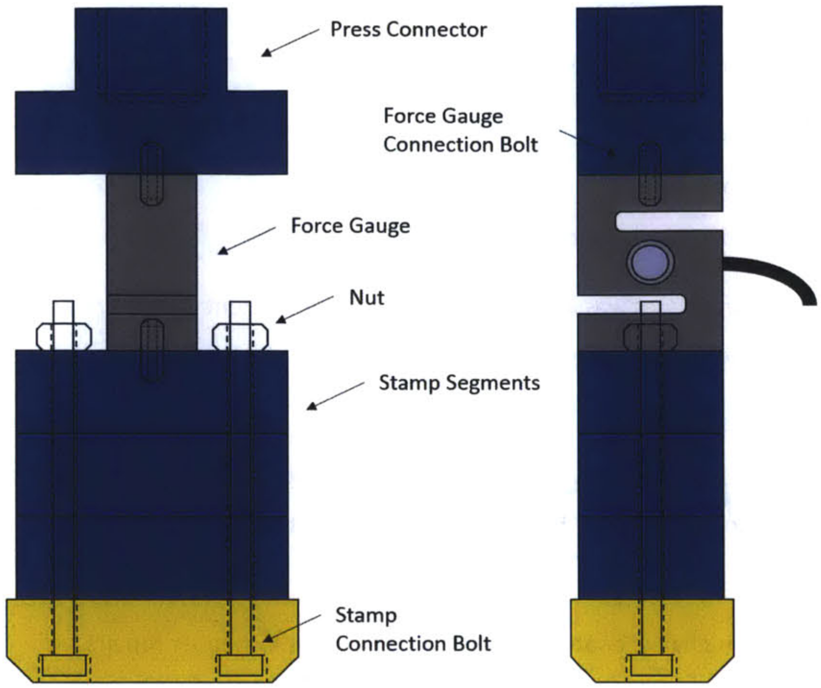


Figure 37: Content Removal Stamp

4.4.3.4 The Containment

As stated in the basic process requirements for the overall recycling task, the process steps need to separate the operator as much as possible from all moving parts and the content of the battery. The press therefore needed a secondary containment to protect the operator and prevent the shop floor to be contaminated. The team developed the following requirements for this press containment:

- Complete containment of all moving parts and battery content
- Maximal accessibility of press parts for operation and maintenance
- Ability to open the vise area separately from the content collection container area
- Ability to purge the containment with inert gas if necessary

In order to comply with the first two bullet points and provide a maximum of safety and accessibility, it was decided to design a containment for the area inside the two vertical U-profiles of the H-frame that spans from the ground to the upper horizontal U-profile of the press. This way, all hydraulic and electric parts are outside of the containment and therefore not subject to the corrosive environment inside and are easy to operate and maintain.

To provide for fast and separate access to the storage container and the vise area, two doors were designed. One was placed below the removal area and the other one above. This ensures that when a new cell is placed inside to be processed, only a small area of the containment needs to be opened thus not allowing for battery debris to fall out and contaminate the shop floor. The lower and larger door only needs to be opened once all batteries are processed and the content can proceed to the aqueous wash.

A cheap, flexible and easy to build solution was to design the containment out of polycarbonate sheets and profiles from the 80/20 framing system. The final design of the containment around the press frame is shown in figure 38.

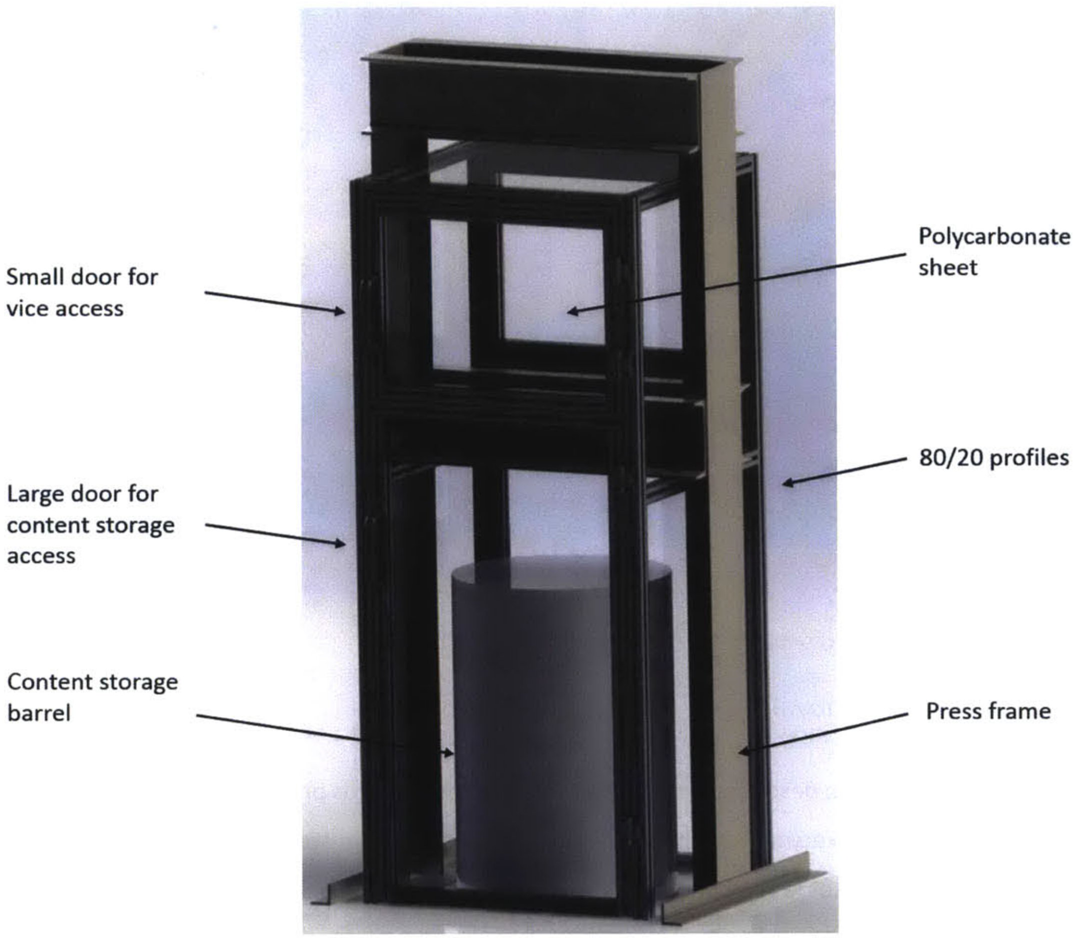


Figure 38: Final Press Containment

Lastly, in order to account for a possible purging of the volume inside the containment, the sheets and profiles were sealed with a rubber seal that is also sold by 80/20 Inc. for their system.

A photo of the almost finished content removal press setup (without bucket and polycarbonate sheets) is shown in figure 39.

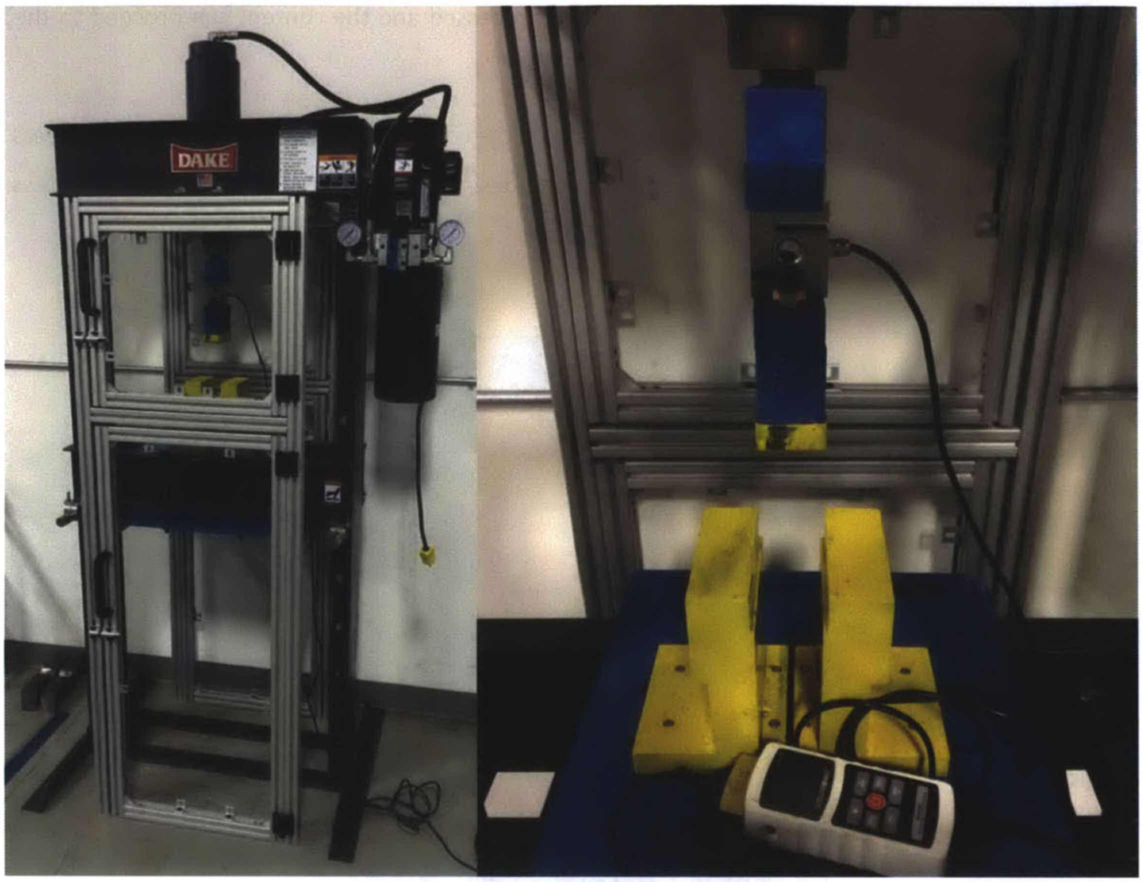


Figure 39: Content Removal Press Setup

4.5 Seal and Stem Removal

The in the previous section described content removal operation needs prior preparation of the spent battery before it can be executed. As shown in figure 32, the seal with stem and two complementary sides of the battery have to be removed.

This section describes the seal and stem removal operation. This process step serves two purposes: It firstly provides the ability to purge the cell through a hose with argon during the side removal to ensure a non-reactive environment for the content. It secondly removes the part of the stem that reaches inside of the battery. This is important as the stem is made out of stainless steel which would need to be sheared by the stamp on its way through the can during the removal. This however would be in conflict with the safety requirement to not apply pressures high enough to shear or crack rigid steel parts.

This section is structured in an initial description of the specification developed for this process step, the following evaluation of process alternatives and the team's recommendations for the future implementation.

4.5.1 Specifications and Requirements

Besides the general requirements for all recycling process steps, four further specifications were developed for the seal and stem removal operation:

- Minimal disturbance of battery content during removal
- Process with minimal heat, spark and fire hazard
- Possibility of inert gas environment
- Minimal additional equipment purchase

The main goal was to find a removal method that imposes minimal safety risks. The battery is opened for the first time. The inside can therefore not be purged with inert gas during the removal operation. The team thus decided to develop a method that minimizes mechanical and thermo dynamical disturbance of the content. To further reduce the risk of uncontrolled reactions and contamination, it was decided to operate the process within a containment that can be purged with inert gas alike the press containment of the content removal process. Finally, to minimize the capital expenditures of the recycling process, it was decided that for the proof of concept no further major equipment parts should be purchased. The press and the bandsaw were therefore the only two machines that could potentially be used for the seal and stem removal.

4.5.2 Evaluation of Alternatives

The main challenge of the seal and stem removal is the double positive connection of the stem as shown in figure 40.

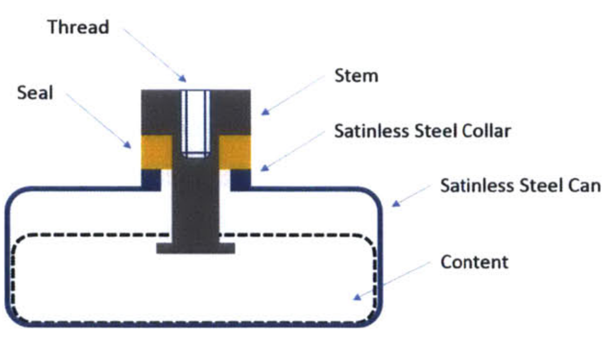


Figure 40: Seal and Stem Design

The two removal options were therefore either to cut the stem between seal and cell and push the remaining part further inside or to pull the complete stem out by breaking the seal and deforming the plate inside the battery. The alternatives are shown in figure 41 a) and b) respectively.

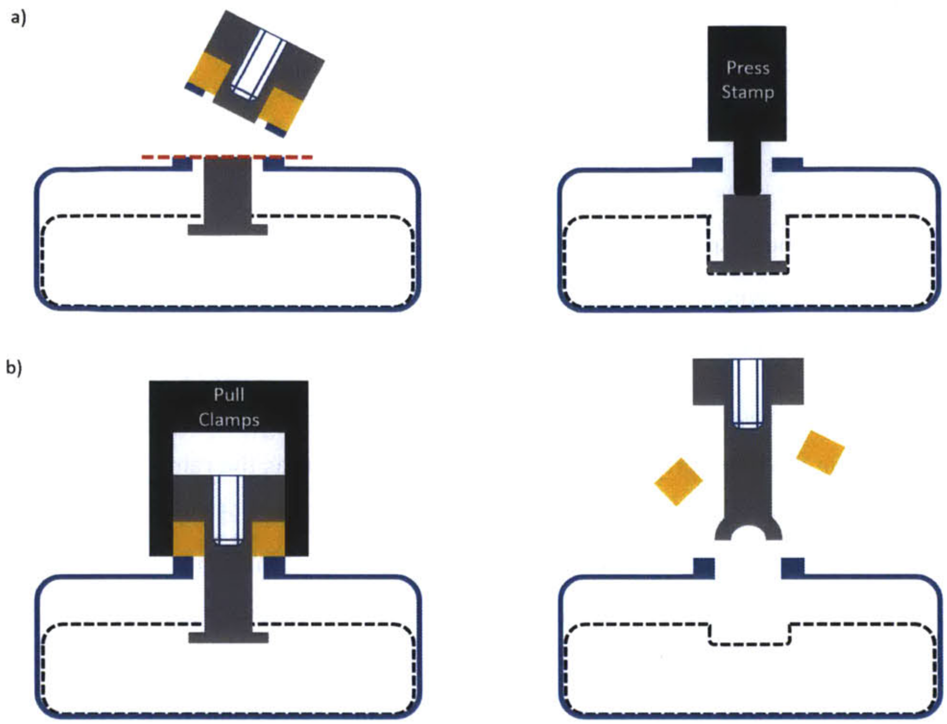


Figure 41: Seal and Stem Removal Alternatives

The main disadvantages of option a) are the heating of the can by cutting the stem as well as the greater battery content disturbance while pushing the remaining stem inside. Additionally, removal method a) needs to use two machines consecutively: saw and press. It was therefore decided to pursue option b) even though it requires bending of a steel part. But as the steel plate is only 0.7mm thick and has a ca. 0.25mm larger radius than the hole in the can, the pulling forces were expected to be low.

4.5.3 Design and Implementation

Alike the content removal operation, the feasibility of this process step needed to be proven before further major purchases could be made. Since no hydraulic clamps were available to pull the stem, the thread in the stem was used to connect the stem to a pulling stamp with a bold sticking out of it. The test setup is shown in figure 42.

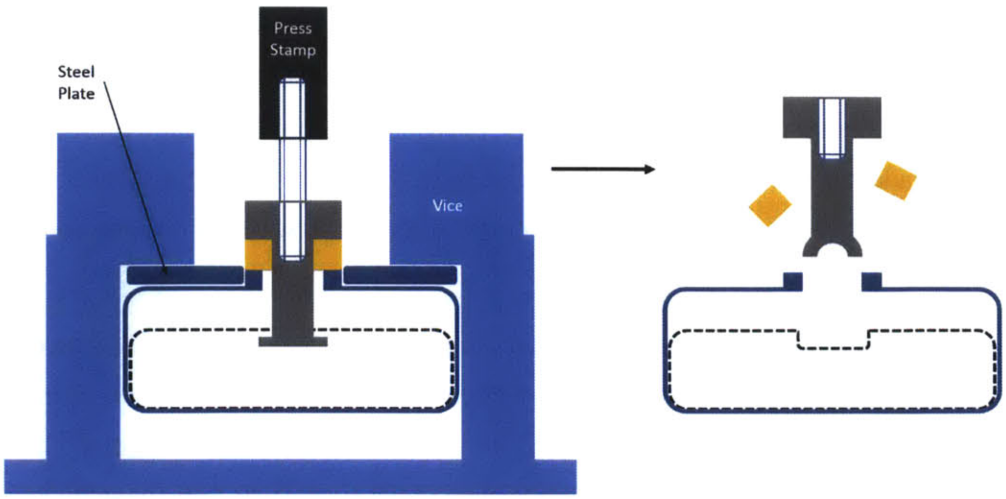


Figure 42: Proof of Concept Setup

Since the already purchased test vise blocks just needed to be turned around to provide an edge to hold the cell down, the only new parts needed were the cell-stem-connection bolt, a stamp segment with a cutout and a thick steel plate with a hole in the middle to provide structural support for the cell during the removal. The stamp design used for the test is shown in figure 43.

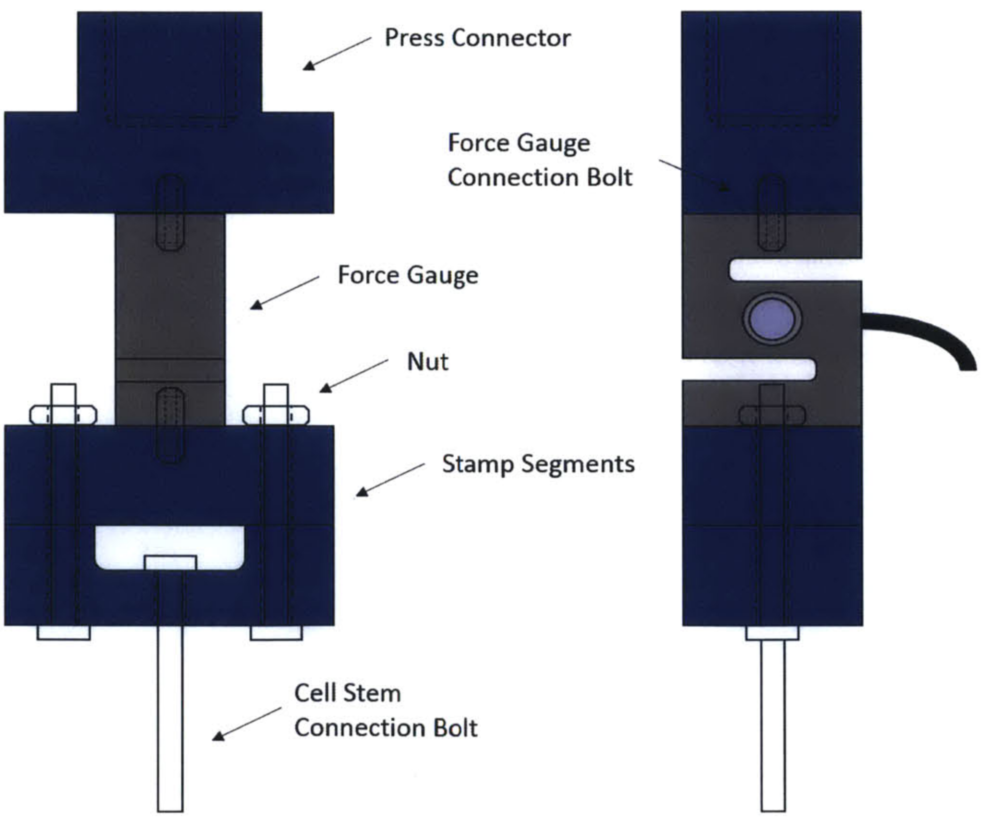


Figure 43: Seal and Stem Removal Stamp

In order to validate the safety and technical feasibility of this design before performing experiments, the maximal pulling force was calculated to determine if the threaded rod could be used for the test. Since the deformation of the stainless steel part inside the can is minimal, the potentially biggest force in a worst case scenario must be applied to break the ceramic seal. The force to destroy the ceramic seal under the assumption of perfect wetting of the ceramic to the stainless steel stem was already calculated in equation 9 as to be below 220,000N.

In order to estimate the maximal force that the bolt can withstand its likely failure mechanism has to be determined. The fact that the bolt can be threaded 3-5 times its own diameter in to the battery stem thus assuring proper thread engagement leads to the conclusion that tensile failure of the bolt and not shearing of the thread is the likely failure mechanism of this connection. [52] The maximum force that can be applied can therefore be calculated with equation 11.

$$Maximum\_Force = \frac{\pi}{4} * Bolt\_Diameter^2 * Bolt\_Tensile\_Strength \qquad (11)$$

The diameter of the bolt cannot be revealed due to NDA restrictions but even with grade 5 or 8 quenched and tempered bolts, the calculated force that the bolt can withstand is lower than the force necessary to break a perfect ceramic seal. This finding lead to a discussion with Ambri's lab personal and recycling experts about their experiences with the current disposal process. Their observations was that the brittle ceramic readily breaks under small pressure or tension applied by the currently used hydraulic press. It was therefore expected that the threaded rod would be strong enough to break the seal and pull the stem out.

With this information four experiments with the described setup (figure 44) were carried out proving that the seal can be broken and stem be removed without problems. A more detailed description of the test results can be found in chapter 5 *Analysis of the New Recycling Process*.

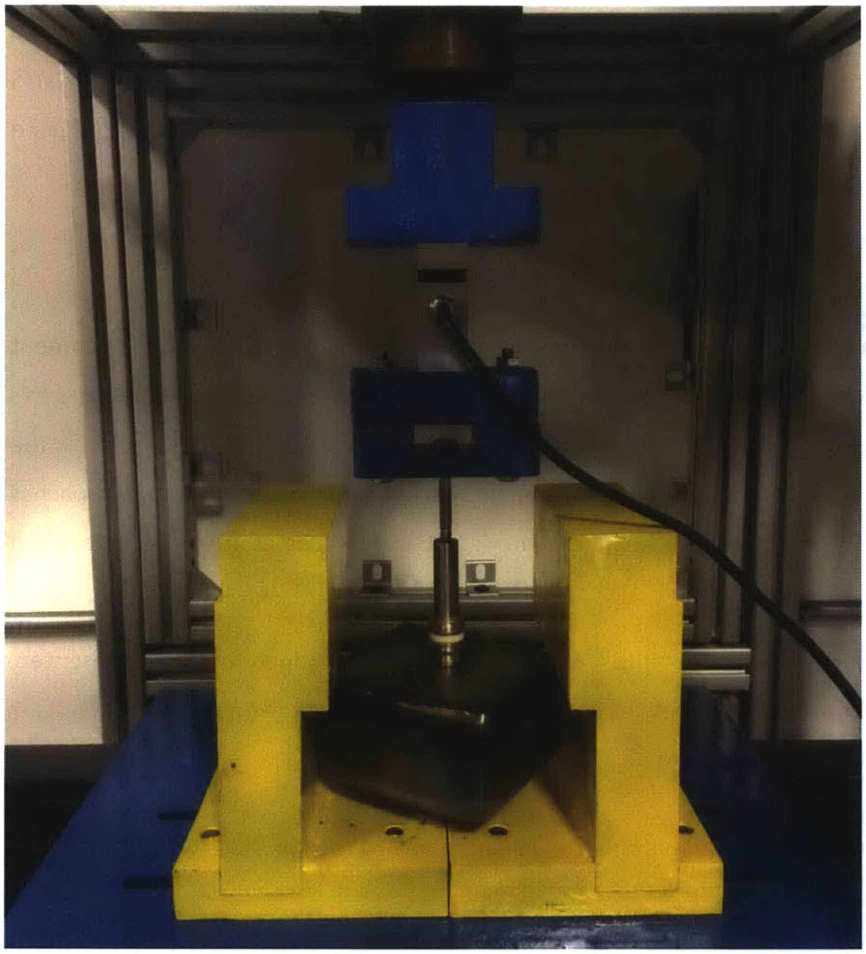


Figure 44: Seal and Stem Removal Setup

The feasibility was therefore proven. The test determined furthermore that even with the current setup consisting of the test vise and the modified stamp, one operator is capable of removing seal and stem of one cell per minute. As this rate is more than 400 times faster than Ambri's required recycling rate of only 5 cells per day, the team suggested to use the test vise and test stamp as the actual recycling equipment for as long as the cell stem as the internal thread.

In order to run the seal and stem removal process simultaneously with the content removal process to increase efficiency, it was decided to purchase the same press model which was already used for the content removal step again. No negative experience with the Dake Force 25DA were made until this point and with two identical presses future repairs and spare part orders could be executed cheaper and easier. Furthermore, a containment was already designed for the press and could just be duplicated.

In case a new production series of batteries does not include the thread inside the stem anymore, the team suggested to use hydraulic wedge grips for the seal breaking operation. Hydraulic grips for round specimen can be purchased in a price range of $5,000-$15,000 depending on the model and provide furthermore for easy process automation. The 647 series of side-loading hydraulic wedge grips by MTS (as can be seen in the appendix of this thesis) could be an efficient yet flexible solution even for future design and material changes of the seal and stem.

4.6 Cell Opening

This chapter describes the cell opening process step. This operation prepares the cell for the content removal by cutting the sides off, thereby providing a free path for the stamp. The cell that enters this process is prepared by having the seal and stem removed according to the process description in the previous section. The main part of the process development was to compare the different approaches and machines due to the wide range of cutting and material removal processes as well as safety and efficiency requirements.

This chapter is structured in an initial description of the specification developed for this process step, the following evaluation of process alternatives and the implementation of the final solution.

4.6.1 Specifications and Requirements

The main focus of this task was to find a machine capable of removing the two sides while:

- Not imposing the risk of an uncontrolled reaction of the active battery material
- Having primarily low operating expenditures and secondarily low capital expenses
- Providing for easy containment of all process substances and battery debris

Ambri's and the team's main requirements for this process step were to be able to cut the cells safely and efficiently. The capital expenditures (CAPEX) were of secondary concern as an improper execution of this critical process step could result in severe safety problems.

4.6.2 Evaluation of Alternatives

As the cell opening process was therefore allowed to exceed the budget if necessary, a wide variety of different cutting and material removal methods could be considered and compared to each other. In order to efficiently assess which option or options best suited, the team developed an evaluation according to the following criteria:

- Difficulty of providing for safety
- Difficulty of containing the process
- Difficulty of automating the process
- Cell opening cycle time

- Amount of cell openings per maintenance cycle
- Use of process chemicals
- Amortized cost per cell over one year of operation
- Consumer grade or industrial grade solution
- Scalability
- CAPEX

After the evaluation criteria were set, the research focused on finding different cell opening options. The following options past a general assessment of their ability to open the cell and the feasibility and degree of difficulty of using such a machine on a shop floor:

- Cold saw
- Band saw
- Water jet
- CNC machine
- Plasma cutter
- Laser

Shearing was a seventh alternative considered in the beginning but ruled out after 6 suppliers for shearing machines and equipment confirmed that due do the can geometry and wall thickness no stable opening process could be guaranteed. Cells would instead likely be deformed or crushed completely. The remaining options were then numerically graded according to their degree of performance in each of the criteria on a scale from 1 to 5 with one being the lowest and 5 being the highest grade. The results are listed in table 10.

Table 10: Cell Opening Machine Evaluation

	Cold saw	Band saw	Water jet	CNC machine	Plasma cutter	Laser
Difficulty of providing for safety	1	5	1	3	1	1
Difficulty of containing the process	3	4	1	3	2	1
Difficulty of automating the process	1	3	5	5	3	5
Cell opening cycle time	2	2	3	3	4	5
Amount of cell openings per maintenance cycle	2	2	4	3	4	5
Use of process chemicals	5	5	1	3	2	5

Amortized cost per cell over one year of operation	5	5	1	2	2	1
Consumer grade or industrial grade solution	1	3	5	5	3	5
Scalability	1	4	2	2	4	4
CAPEX	5	5	1	2	3	1
SUM	26	38	24	31	28	33

The numbers are based on tests, manufacturer specifications and expert estimates from suppliers and manufacturing professionals as well as thorough analysis of the MIT consultants. The acquired quotes, specification sheets and test results can be found in the appendix of this thesis.

4.6.3 Recommendation

As can be seen in table 10, the band saw option scored highest of all evaluated methods to open the cell. This is mostly because a band saw can be operated without process chemicals, can be easily contained with a 80/20 and polycarbonate containment like the hydraulic press, is easy to maintain while not being too expensive or disturbing the battery content mechanically or thermally like a LASER or plasma cutter, water jet or cold saw.

The team therefore recommended the purchase of a semi-automated band saw. Semi-automated band saws like the Jet J-7060-4 for ca. $10,000, the Wellsaw Model 1318-SA for ca. $12,000 or the Baileigh Industrial Bs-260sa for ca. $7,500 are recommended to be considered in Ambri's future process development. As discussion concerning the future direction of the recycling process was still evolving when the project ended, the cell opening process step wasn't implemented by the MIT consultants.

4.7 Aqueous Wash

This chapter describes the aqueous washing process. The aqueous wash is the hydrometallurgical core of the recycling process and responsible for the content neutralization and transformation in to different compounds. The main goal was to design a process capable of safely reacting all active and hazardous materials and convert as much as possible in to reusable and/ or salable chemicals.

This chapter is structured in an initial description of the specifications and requirements developed for this process step, the evaluation of process alternatives and the implementation of the final solution.

4.7.1 Specifications, Requirements and Evaluation

Besides the main requirements for the complete recycling task, the team and Ambri developed the following list of demands specific for the material transformation process:

- No extreme temperatures
- Process at or near atmospheric pressure
- Ability to start and stop the reaction without interaction with the battery content
- Flexibility to incorporate future changes and added functionality
- Maximal reuse of material
- Providing for automation were feasible

As described earlier only a hydrometallurgical process is able to comply with all requirements. A pyro metallurgical process requires high temperatures and expensive equipment. As chemicals inside the liquid metal battery furthermore present a fire hazard under certain conditions, a pyro metallurgical process was additionally not considered safe enough if developed with the given time restrictions of the project.

The no extreme temperature requirement not only rules out pyro metallurgy but also super cooling with e.g. liquid nitrogen. A method used by e.g. Toxco to lower the reactivity of active material to prevent uncontrolled process states. The only feasible methods of lowering the reactivity were therefore the usage of alkaline solutions and moderate cooling.

The near atmospheric pressure requirement was set in place as a pressure build up with flammable and possibly toxic gases during the process was considered to be too unsafe in the event of failing process equipment.

The study of the current disposal process and commercial battery recycling processes showed furthermore the necessity of having the ability to stop chemical reactions in case of uncontrolled process conditions. This is required as the possibility of human or machine error during the production or the recycling setup could lead to non-standard material input in to the system and therefore unexpected reaction kinetics.

Besides these safety requirements the team focused on developing a process that is capable of recycling as much material as possible and flexible enough to incorporate added functionality of future process development.

4.7.2 Design and Implementation

The design considerations were derived directly from the process requirements and the properties of the liquid metal battery. This lead to the following list of sub-systems that the aqueous washing process needed to include:

- A separate reactor and tank so that the aqueous solution can be transferred from one to the other vessel to start and stop chemical reactions.
- A cooling system to lower the reactivity.
- A filter system to protect pumps, hoses and connections from clocking by battery debris accumulation.
- A safe filling and emptying method for the aqueous solution into the system and out of the system.
- Valve banks that can be operated manually and automatically
- Exclusive use of parts that can withstand the caustic environment
- Safe exhaust and gas dilution
- Secondary containment for additional process safety

Figure 45 shows the circuit diagram of the aqueous wash that was developed to comply with the listed design considerations and requirements.

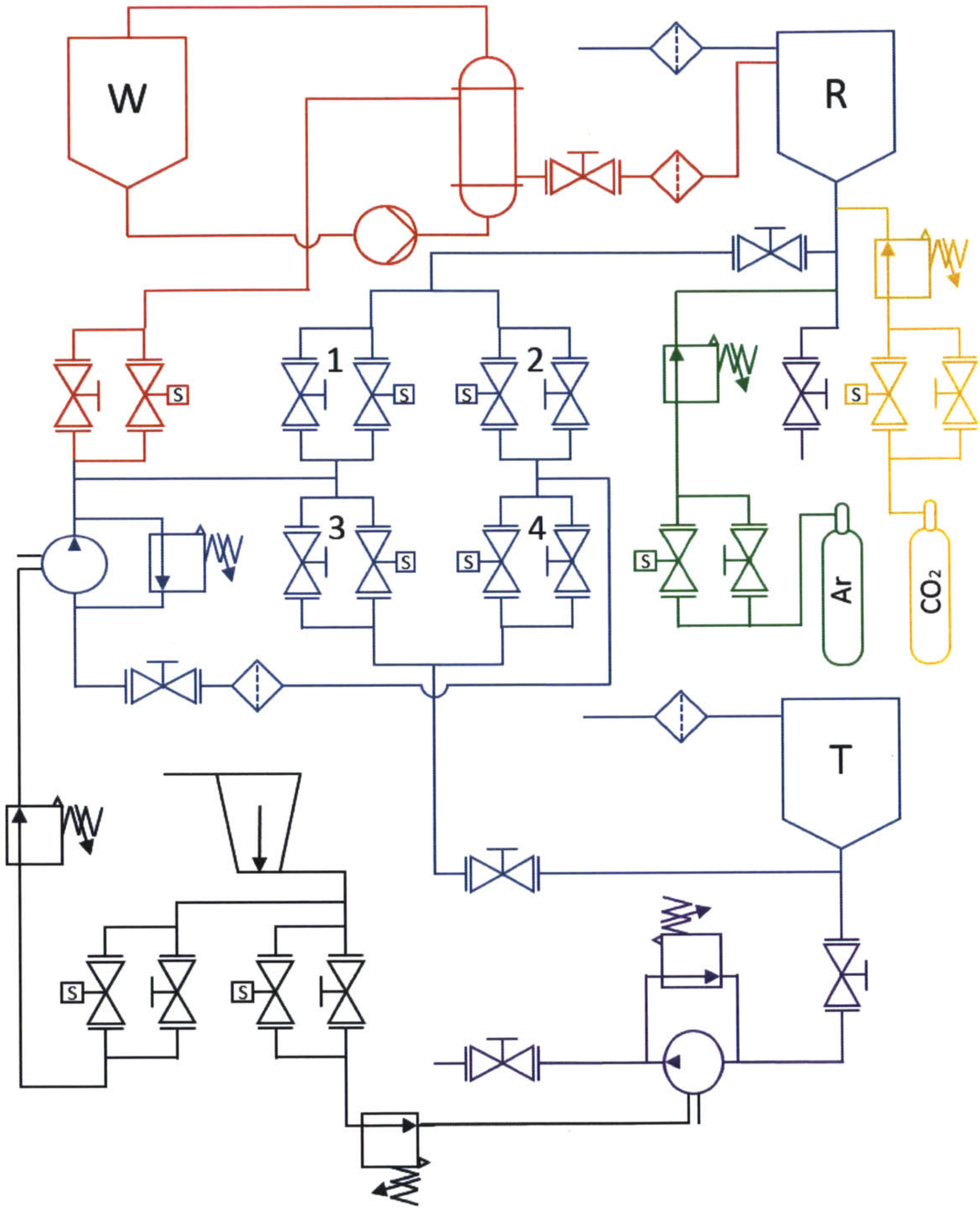


Figure 45: Aqueous Wash Circuit Diagram

Figure 46 provides the list of the used symbols and colors.

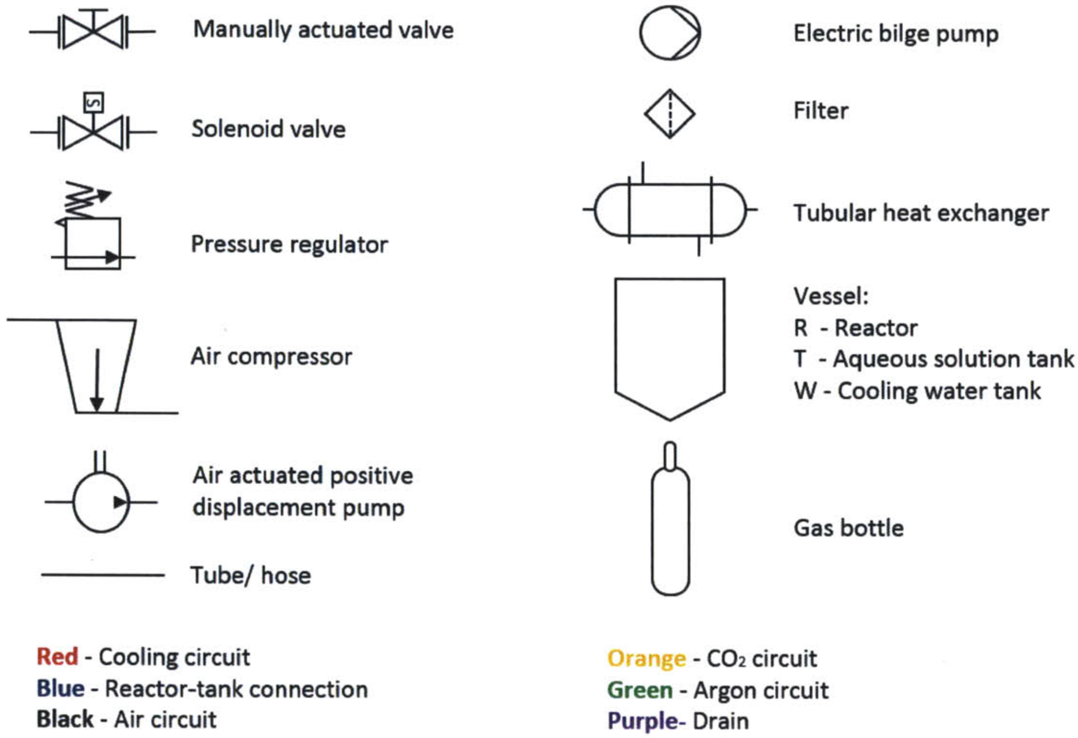


Figure 46: Aqueous Wash - Symbol and Color Coding

4.7.2.1 Reactor-Tank Connection

The reactor tank connection (blue circuit) is a sub-system consisting out of 7 manual valves, 4 solenoid valves, 3 filters, 2 vessels and a pump with pressure regulator. It connects the reactor vessel "R" with the aqueous solution storage tank "T". The sub-system is powered by an air actuated positive displacement pump. The main valve bank with the four manual/ solenoid double valve systems (numbered 1-4 in the diagram) is used to fill and empty the reactor, while all other valves are default open and can be closed for maintenance activities.

The sub-system is connected with ½" PFA hose and stainless steel tubing. The reactors and tank are conical vessels made out of HDPE to withstand the caustic environment. The top of the reactor is sealed with a synthetic seal and fixated with 4 clamps with a holding capacity of 50lbs each. The diluted reaction gases leave the reactor through a charcoal filter that binds all remaining hazardous compounds before releasing the remaining gases safely in to the environment. It is therefore also guaranteed that the system operates near atmospheric pressure as the maximum pressure build up inside tank and reactor is the pressure drop through the charcoal filters which is expected to be not more than 5 psi. Before the aqueous solution enters the pump, it flows through a porous filter that removes particles with a diameter greater than 100 microns. The pump itself has a safety pressure relief circuit. In case of a pressure build up, the regulator set to INSERT psi opens thereby connecting pump in- and output preventing component failures and system leaks.

4.7.2.2 Cooling Circuit

The cooling circuit (red circuit) connects the reactor "R" and the cooling water tank "W" with their respective connections on the heat exchanger. The sub-system consist out of 2 manual valves, 1 solenoid valve, 1 filter, 1 pump, 1 heat exchanger and 1 vessel. In order to reduce the amount of parts and connections that can potentially fail as well as cost considerations, the aqueous solution part of the cooling circuit is powered by the same pump as the reactor-tank connection. The cooling water part uses an electric bilge pump. The circuit is controlled by one manual/ solenoid double valve system while the other manual valve is default open and can be closed for maintenance activities. The aqueous part of the sub-system is connected with ½" PFA hose and stainless steel tubing while the cooling water part is connected with 1" hose.

4.7.2.3 Drain

The draining sub-system was designed to safely empty the complete system to replace the aqueous solution when necessary. It consists out of 3 default closed manual valves and 1 pump with pressure regulator. The standard way to empty the system is to pump the aqueous solution back in to the tank with the reactor-tank connection circuit and then slowly drain the tank with a small positive displacement pump through ¼" PFA hose and stainless steel tubing without the danger of splashing solution. The reactor nevertheless also possess a manual gravity actuated drain that can be opened for maintenance.

4.7.2.4 Air circuit

The air circuit connects the two air actuated pumps with the compressor. It consists out of 2 manual valves, 2 solenoid valves, 2 pressure regulators and an air compressor. The system is connected with ¼" PFA hose and stainless steel tubing and controlled with two manual/ solenoid double valve systems.

4.7.2.5 CO_2 Circuit

The CO_2 circuit connects the lower end of the reactor with a CO_2 gas bottle. The CO_2 gas is bubbled through the solution during the main reaction to dilute and control the conditions as explained in the next section Aqueous Wash Process Control. The sub-system consist out of the CO_2 gas bottle, 1 manual and 1 solenoid valve as well as 1 pressure regulator. The system is actuated by the manual/ solenoid double valve system.

4.7.2.6 Argon Circuit

The argon circuit connects the lower end of the reactor with an argon gas bottle. The reactor can be purged with argon gas in case of an uncontrolled reaction or thermal runaway to provide an inert environment as explained in the next section Aqueous Wash Process Control. The sub-system consist out of the argon gas bottle, 1 manual and 1 solenoid valve as well as 1 pressure regulator. The system is actuated by the manual/ solenoid double valve system.

4.7.2.7 Secondary Containment

The secondary containment prevents contamination of the shop floor in the event of a failing system components or an uncontrolled reaction. The designed aluminum profile/ polycarbonate sheet containment encloses the complete system except for the compressor, the cooling water tank and the bilge pump as there is no need for enclosure of those parts. In case of the cooling water tank and bilge pump, it is not only unnecessary but safer to place the components outside of the secondary containment as the therefore uncontaminated cooling water can be disposed of normally.

The secondary containment is furthermore modified to act as a fume hood. An exhaust system connected to the assembly continually pumps air out of the system and filters it before releasing it in to the environment.

4.7.2.8 Implemented System

The aqueous wash system was besides the already mentioned components mainly build with Swagelok tubes, hoses and connectors as well as corrosive resistant valves and structural components like 8020 aluminum profiles and HDPE plates e.g. for the valve banks and the pump stand. Figure 47 shows a photo of the implemented system without secondary containment on the shop floor. The secondary containment will be added after the project.

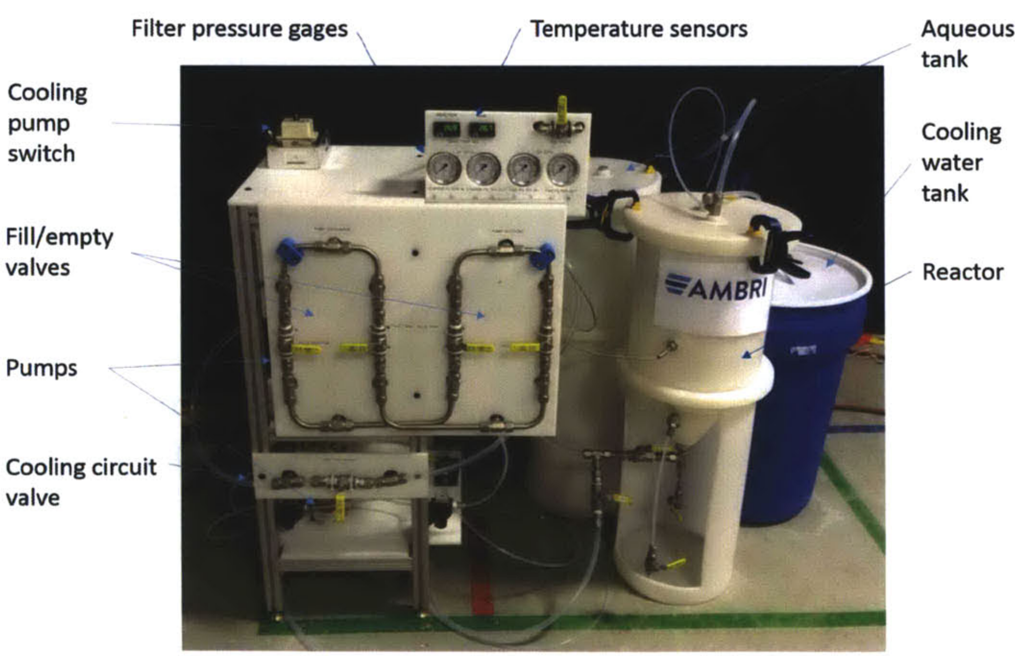


Figure 47: Aqueous Wash Final Assembly

4.7.3 Aqueous Wash Process and Control

When a new batch of battery content of 5 spent batteries is prepared to enter the aqueous wash system, the first step is to fill the tank "T" with an alkaline aqueous solution by mixing a hydroxide salt with clear room temperature water in the tank. The cooling system is prepared by filling the cooling water tank with water of approximately 15°C.

The next step is to fill a porous bucket with the battery debris, place it in the reactor and close the reactor with the reactor top and the clamps as shown in figure 48.

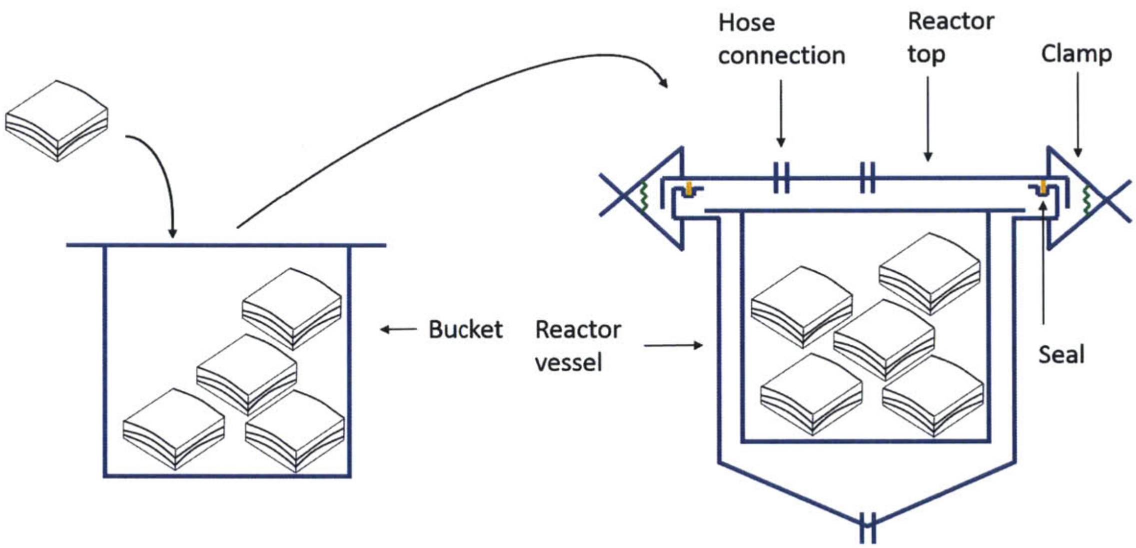


Figure 48: Reactor Filling

When the system is therefore filled with all necessary components the reaction is started by filling the reactor. This task can be executed either manually or automatically:

If the process is operated manually, all manual and solenoid valves are default closed. The operator first opens the manual air valve to activate the main pump. The operator then opens manual valve 1 and 4 to start filling the reactor. The reactor is filled after approximately 180 seconds. When the reactor is filled, the operator closes valve 1 and 4 and opens valve 2 and the manual valve of the cooling and CO_2 system to start the active system cooling as well as the CO_2 intake. If the process is operated remotely, all valves are default closed. The control unit then opens the corresponding solenoid valves according to the manual description above.

The now following calculations are examples how the MIT team estimated secure operating conditions of the aqueous wash process. THE NUMBERS ARE ALTERED DUE TO NDA REQUIREMENTS AND CANNOT BE USED TO SAFELY OPERATE THE PROCESS!

The main reactions inside the reactor are the dissolution of the salts of the batteries electrolyte and the reaction of the alkaline content with the aqueous solution. Both reactions are exothermic with a total released energy of approximately 6660 kJ. With a total of ca. 30 liters in the aqueous solution system the total temperature increase without active cooling is therefore calculated with equation 12.

$$Temperature\_Increase = Excess\_Energy/(Water\_Mass * Heat\_Capacity\_Water) \quad (12)$$

The anticipated temperature increase is therefore approximately 46°C. In order to not damage system components, resulting in material failure, only components were bought that can continually operate at a temperature of 75°C. The system would in this example therefore not be expected to critically fail even with a total loss of the cooling circuit and a shop floor temperature of 25°C. The displayed numbers are altered due to NDA requirements and cannot be used to safely operate the process!

As more and more salts are dissolved and alkaline content reacted, the reaction is anticipated to decelerate as the molarity of the hydroxide solution increases. To nevertheless be able to dissolve all the salt and react all the alkaline content, CO_2 is introduced in to the system. The CO_2 and the hydroxides in the aqueous solution form a carbonate according to the following example of a sodium compound reaction:

$$2NaOH + CO_2 \longrightarrow Na_2CO_3 + H_2O \quad (13)$$

This reaction therefore controls the hydroxide molarity by transforming excess hydroxides in to a carbonate compound.

The CO_2 has furthermore and important role for the system safety. Due to the production of hydrogen, the direct output of the main reaction would be flammable with excess oxygen. The CO_2 reduces the percentage of hydrogen in the gaseous output, thereby reducing the fire hazard.

The process is controlled by a temperature sensors inside the reactor and the cooling water tank as well as a pH meter inside the reactor. The pH meter is used to monitor the reaction and provide information about the saturation of the aqueous solution. The temperature sensors are implemented as a safety mechanism. If the sensors inside the reactor or the cooling water tank indicate temperatures in excess of 50°C or 25°C respectively, the process has to be stopped with the following emergency procedure:

The emergency stop consists out of opening valve 3 and the argon valve as well as closing the cooling circuit and CO_2 valve. The aqueous solution is pumped back in to the tank while the reactor is purged with inert argon thereby inhibiting further reactions.

Possible causes for an unexpected temperature increase can be batteries falsely produced with too much reactive content or an operator error of filling the system with more than 5 cells.

In case of a normal operating process, the salts are dissolved and the alkaline content completely reacted with the aqueous solution. The system is then stopped by opening valve 3 as well as closing the cooling circuit valve. The CO2 is flushed for approximately 10 more minutes to dry the battery debris and displace remaining hazardous or flammable gases before opening the reactor.

4.8 Process Output Treatment

This section describes Ambri's different options of using, selling or safely disposing of the recycling process outputs. It discusses these options by analyzing the required internal processes at Ambri as a part of chapter 4 *The New Recycling Process*. The economic evaluation of these options is like all other parts of the process analysis described in chapter 5 *Analysis of the New Recycling Process*.

After the active battery content and the electrolyte are reacted out and the aqueous washing process ended, only the insoluble parts of the battery debris remain in the reactor bucket. They consist of a nonmetallic material and, depended on the initial charging state of the battery before it entered the recycling process, one or two hazardous alloys. The stainless steel can, the solid aqueous wash remainders and the salts dissolved in the aqueous solution are therefore the recycling process outputs. Ambri has different options of recycling, further processing or disposing these materials. The following 3 sections describe 3 general options.

Option 1 is the easiest option requiring no further output treatments or other major processes. The recycling operator fills all solid remainders of the aqueous wash in to a hazardous waste drum and places it in to a storage area. The operator then drains the aqueous solution tank and fills the solution in to liquid waste drum. As soon as the storage area and the liquid waste drum are filled, a waste management company is contracted to dispose of the waste. The stainless steel cell can and its two separated sides on the other hand are send to a metal recycling company.

Option 2 is an intermediate option requiring very little further process development by significantly reducing the waste. Like option 1, the recycling operator fills all solid remainders of the aqueous wash in to a hazardous waste drum and places it in to a storage area. As soon as the storage area is filled, a waste management company is contracted to dispose of the drums. The stainless steel cell can and the two separated sides are again send to a metal recycling company. The difference lies within the treatment of the aqueous solution. Due to the dissolving salts and the active battery material, the aqueous solution becomes saturated and cannot react more battery content. Further process tests need to be performed to evaluate how many batteries can be recycled before the solution must be changed.

Due to the different solubility of the hydroxide and carbonate salts at different temperatures, the aqueous solution can be heat treated in order to separate these contents. The process is to increase the temperature until the carbonate precipitates out of the solution while the hydroxide still remains mainly dissolved. The temperatures are well below the boiling temperature of water but cannot be disclosed as they are highly compound specific. The precipitated carbonate can then be removed from the restored remaining aqueous solution by e.g. a cyclonic filter. The obtained carbonate can then be sold like the stainless steel can. A salt precipitation circuit that can be directly integrated in the existing aqueous wash is discussed in chapter 6.

Option 3 is a near-closed-loop recycling solution that can be implemented with the current process with the addition of the salt precipitation circuit described in option 2 and a further metal recycling step. The only waste produced by option 2 are the insoluble remains of the aqueous wash consisting of a non-metallic and one or two metallic components as mentioned in the beginning. By implementing a smelting oven operating under an inert atmosphere, the metals could be molten while the still solid non-metallic component would swim on top of the liquid where it can be skimmed off. The metals can then be separated by density differences as well and directly reused in new liquid metal batteries. Design and safety consideration for such a smelter are derived in more detail chapter 6.

5. Analysis of the New Recycling Process

This chapter provides an analysis of the newly developed recycling process for Ambri's liquid metal battery. The process is first characterized by discussing the gained in situ data of test runs. With these information as well as its design characteristics and operating procedures, the process safety is evaluated. The following third section of the chapter completes the fundamental analysis by performing an economic evaluation of the process. The chapter ends with summary of all information compiled in an evaluation of the scalability of the new recycling process. This final evaluation illustrates that a systematically executed recycling process is not only cheaper than all other options but provides Ambri furthermore with additional information about their product and plays a key role for increasing the liquid metal battery production.

5.1 Process Characterization

5.1.1 Seal and Stem Removal

The first step of the recycling process, the seal and stem removal operation was tested by measuring the required forces and estimating the processing time based on handling tests. These tests served as validation of the integrated process and quality control force gage and the process throughput and efficiency.

The process forces were measured with the already described press-stamp-vise pull setup. A characteristic force measurement obtained during one of the tests is shown in figure 49. (The actual numeric values of the forces are not shown due to NDA requirements.)

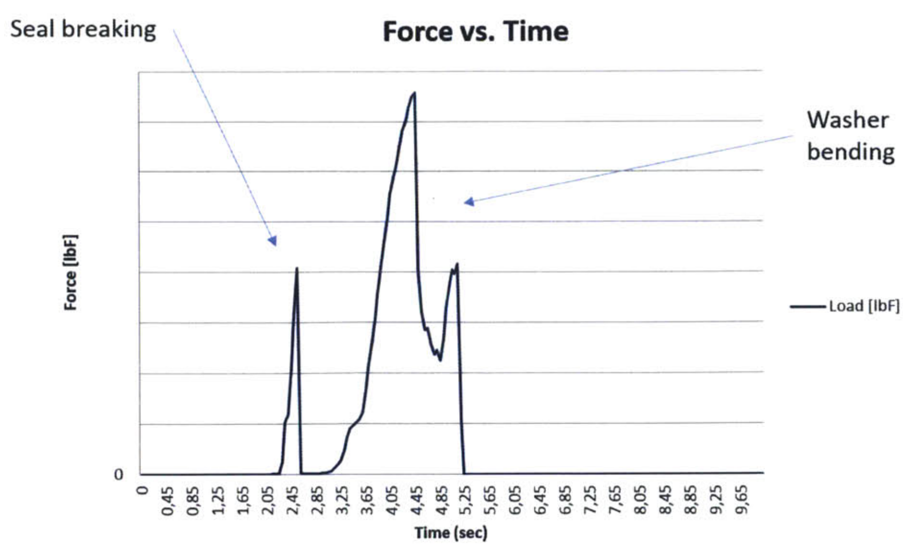


Figure 49: Seal and Stem Removal Force Measurement

To be increase the accuracy of the results, the time set the sampling rate of the force gage to one measurement every 0.05 seconds. A high sampling rate was considered to be necessary as especially ceramic force vs. time graphs exhibit steep slopes during destructive tests. As can be seen, the seal broke as expected at much lower forces than the theoretical ultimate tensile strength of the ceramic. The forces for the seal breaking are indeed so low that the second peak in the figure that indicates the force necessary to bend the washer through the hole in the can are almost twice as high. Both of the forces however are more than one order of magnitude below the press capability.

Repeated tests seem to indicate furthermore that the force peaks only fluctuate in a narrow margin. The small amount of tests and the fact that all used cells were produced in different batches and not stored under controlled test conditions prior to the measurements do however not allow definitive statements bout repeatability and process control.

The second test performed was a handling test. The team simulated repeated seal and stem removals with two test cells. The performed operation steps were:

- Taking test cell off of table right to the press
- Inserting cell in to the vise
- Fastening bolt
- Closing press containment
- Activating press
- Stopping press
- Opening press containment
- Unfastening bolt
- Remove cell from vise
- Place cell on second table on the left of the machine

The full procedure took on average 53 seconds with a standard deviation of 5 seconds. The cell handling operation can therefore be considered stable and highly repeatable.

5.1.2 Content Removal

The third step of the recycling process, the content removal operation was tested by measuring the required forces and estimating the processing time based on handling tests. These tests served as validation of the integrated process and quality control force gage and the process throughput and efficiency.

The process forces were measured with the already described press-stamp-vise push setup. A characteristic force measurement obtained during one of the tests is shown in figure 50. (The actual numeric values of the forces and in this case the time as well are not shown due to NDA requirements.)

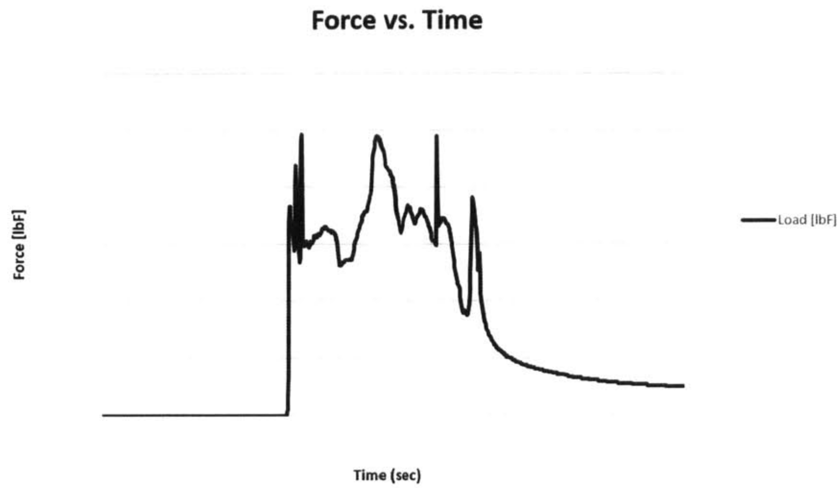


Figure 50: Content Removal Measurement

The maximum force needed to push the content out of the cell was 3 orders of magnitude lower than the calculated theoretical maximum. The explanation for this behavior was found during the visual analysis of the removed content and the cell: The metallic content did not actually shear. The content and cell separated cleanly. This behavior is expected to not necessarily apply to actually used batteries as the number of heat cycles can be expected to increase the bonding strength between content and can. The forces might therefore be higher during actual recycling. But as described in the previous chapter, the press is theoretically capable of removing the content even under the assumption of perfect wetting.

The second test performed was again a handling test. The team simulated repeated content removals with two test cells. The performed operation steps were:

- Taking test cell off of table right to the press
- Inserting cell in to the vise
- Closing press containment
- Activating press
- Stopping press
- Opening press containment
- Remove cell from vise
- Place cell on second table on the left of the machine

The full procedure took on average 44 seconds with a standard deviation of 7 seconds. The cell handling operation can therefore be considered stable and repeatable as well.

5.1.3 Aqueous Wash

The fourth step of the recycling process, the aqueous wash operation was analyzed with two different tests so far. The first test was a general test of the cooling circuit efficiency without chemical reaction. The second test performed was a test of the systems capability to safely dissolve the highly reactive parts of the battery content.

The first test setup was a filled cooling water tank with a due to NDA reasons not disclosed amount of water with an initial temperature of 13.2°C and a filled aqueous solution tank with a temperature of 25.2°C. The ambient temperature on the shop floor was 27.6°C at the beginning of the test and 27.8 at the end of the test and stable throughout the experiment. The test was started by activating the water cooling circuit, then pumping the aqueous solution inside the reactor and then starting the aqueous part of the cooling circuit. The temperature of the cooling water in the cooling water tank and the temperature of the aqueous solution inside the reactor were measured every minute. The resulting temperature/ time graphs are shown in figure 51.

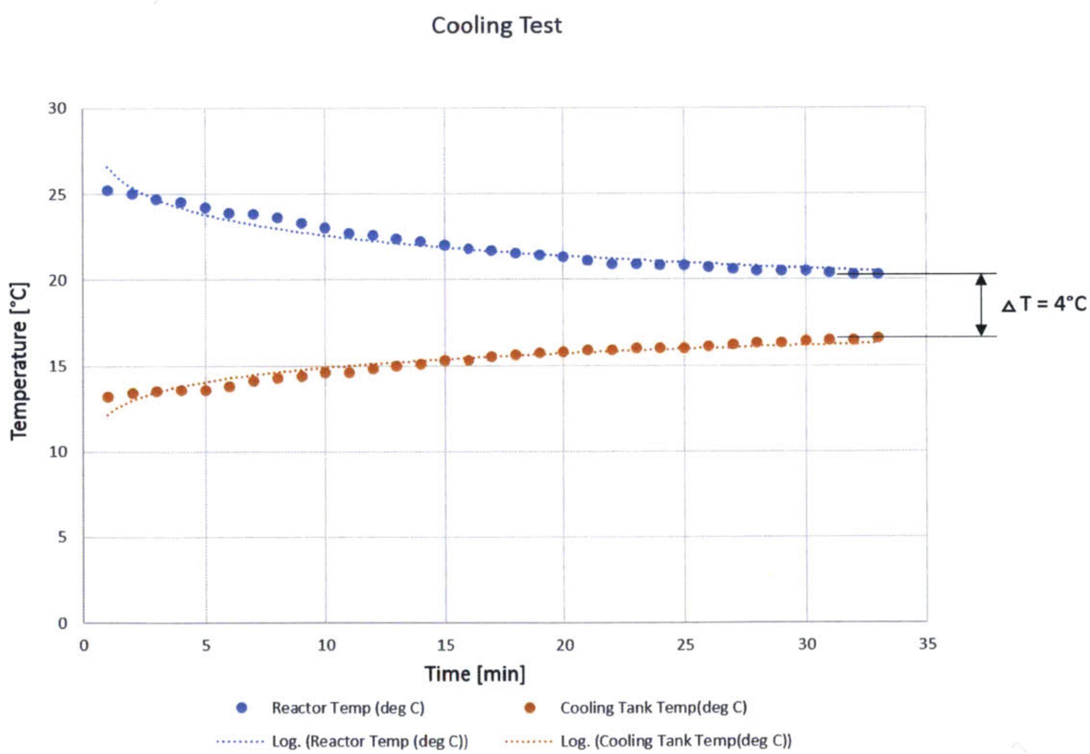


Figure 51: Cooling Test

As can be seen, without any internal source of energy, the temperatures of the cooling water and the aqueous solution approach each other almost logarithmically. The active cooling stopped after approximately 33 minutes at a temperature difference of 4°C between cooling water and aqueous solution. An important finding was the unexpectedly high heat increase of the cooling water solution by approximately 3.4°C. With a given total amount of cooling water this energy increase can be calculated with equation 14:

$$Energy\_Increase = 4.179 \frac{J}{g*°C} * 3.4°C * Amount\_of\_Water\_in\_g \quad (14)$$

While the energy decrease of the aqueous solution inside the reactor can be calculated with equation 15:

$$Energy\_Decrease = 4.179 \frac{J}{g*°C} * 4.9°C * Amount\_of\_Water\_in\_g \quad (15)$$

The delta between the decrease and increase can be explained by the high ambient temperature on the shop floor of ca. 28°C and therefore a high energy transfer by confection throughout the system. The team therefore recommends a climate control for the shop floor and extensive tests to determine up to which ambient temperature and starting temperature of the cooling water and aqueous solution the system can safely operate.

The second test performed was an experiment with highly reactive battery content. The amount of highly reactive content cannot be disclosed due to NDA requirements but was the equivalent of five spent batteries. It is important to mention that only the highly reactive material was used during this experiment as it actively reacts with the aqueous solution forming another compound thereby undergoing a significant enthalpy change. The other components of the content that only produce a certain amount of heat due to their energy of dissolution were not included in the experiment setup. This was decided as no elaborate but only an experimental exhaust system was installed at the time of the experiment. The MIT team and Ambri concluded that before such a system is installed and extensive tests on the gaseous output of the reaction are performed, such a test cannot be considered safe.

The first step was to fill the cooling water tank with water with an initial temperature of 17.8 °C. The aqueous solution tank was filled with an alkaline solution with an initial pH value between 9 and 12 (actual value is not disclosed due to NDA requirements) with a temperature of 28.4°C. The ambient temperature on the shop floor was 27.8°C at the beginning of the test and 27.8 at the end of the test and stable throughout the experiment. The reaction was started by activating the water cooling circuit, then pumping the aqueous solution inside the reactor and then starting the aqueous part of the cooling circuit. The temperature graphs of the cooling water in the cooling water tank and of the aqueous solution inside the reactor were measured every minute. The resulting temperature/ time graphs are shown in figure 52. (This time due to NDA requirements without the actual value of the temperature.)

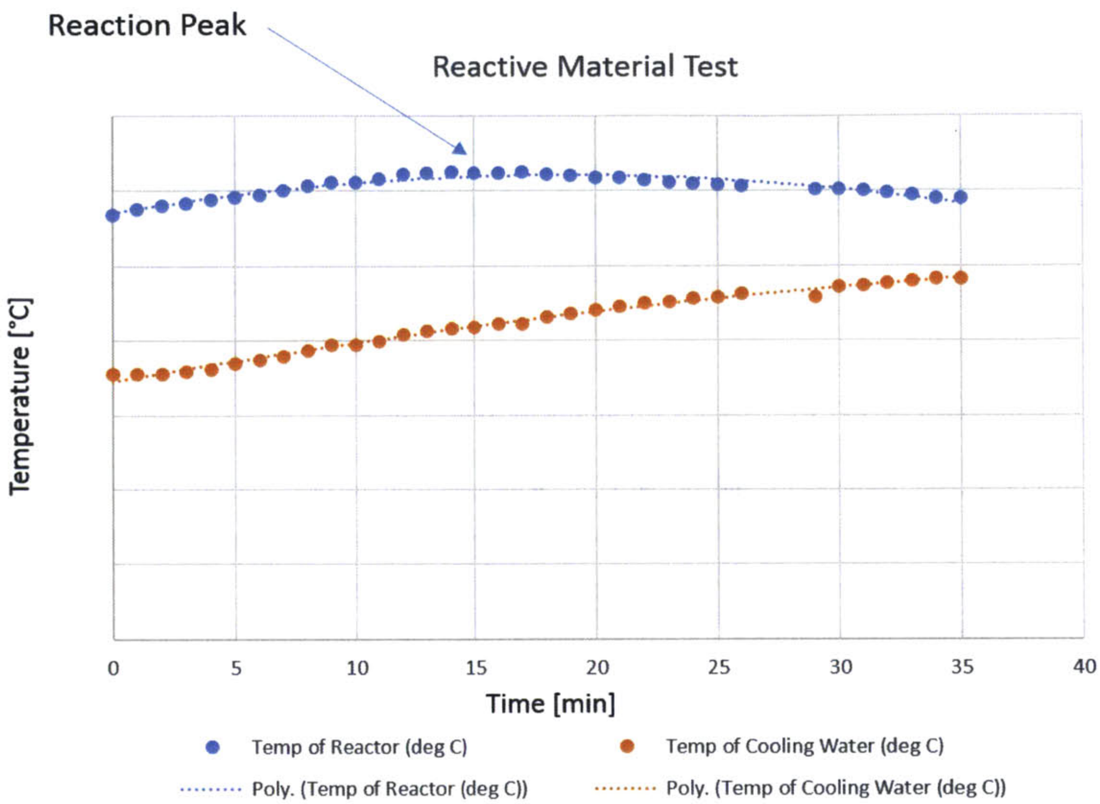


Figure 52: Reactive Material Test

As can be seen, with internal energy source the temperature of the cooling water increases almost lineally while the aqueous solution temperature exhibits a rather parabolic behavior with a maximum between 25-37°C at around 15 minutes. After this point the temperature in the reactor decreases again.

An interesting observation was that the slope of the cooling water tank temperature does not flatten after the peak of the reaction. This could be explained with a still high production of heat combined with an efficient energy exchange between the two liquids in the heat exchanger as long as delta T is above 4-5°C. The latter thesis was already confirmed by the fist experiment while the first was confirmed in minute 27-28 of this experiment when the team visually confirmed that the reaction was still ongoing.

The reaction stopped after approximately 34 minutes. The total energy increase of the system was again also effected by heat gains through confection and not only determined by the heat generated by the reaction.

The experiment therefore confirmed that the developed hydrometallurgical recycling process can safely react the highly reactive content equivalent of 5 spent batteries. Further experiments need to be carried out however to confirm the process capability of dissolving the complete content of 5 spent batteries. A more detailed recommendation can be found in chapter 6 *Recommendations, Future Work and Conclusion*.

5.2 Process Safety Evaluation

The process safety evaluation of the new recycling process was performed with the same failure mode and effects analysis tool (Process FMEA) as the process safety evaluation of the currently used disposal process. The goal is to calculate the risk priority number (RPN) as a product of the three multipliers severity factor (SEV), occurrence value (OCC) and detection number (DET).

The first step was again to define the P-FMEA scope. In this case the scope was to evaluate the risk potential of Ambri's new recycling process in their manufacturing facility in Marlborough, MA. The evaluation team consisted of the same three members as for the first FMEA: The MIT consultants Dale A. Thomas and Martin C. Feldmann as well as Ambri Inc. employee Isha Gujarati.

The list of all process steps necessary for the new process is listed in table 9.

Table 9: New Recycling Process Steps

1	Take cell off of table	18	Set feedrate to zero	35	Close secondary containment
2	Insert cell in to the vise	19	Remove cell parts from vise	36	Start CO_2
3	Fastening bolt	20	Take cell off of table	37	Start reactor filling
4	Close press containment	21	Insert cell in to the vise	38	Stop reactor filling
5	Activate press	22	Close press containment	39	Start cooling circuit
6	Stop press	23	Activate press	40	Main reaction
7	Open press containment	24	Stop press	41	Stop cooling circuit
8	Unfastening bolt	25	Open press containment	42	Start reactor emptying
9	Remove cell from vise	26	Remove cell from vise	43	Stop reactor emptying
10	Place cell on second table	27	Place cell on second table	44	Stop CO2
11	Lift saw blade up	28	Temperature, valves and pump check	45	Open secondary containment

12	Place cells in saw vise	29	Open secondary containment	46	Open reactor
13	Start saw	30	Open reactor	47	Remove bucket
14	Select feed rate	31	Remove bucket	48	Fill recycling container
15	Cutting	32	Fill bucket	49	Insert bucket
16	Stop saw	33	Insert bucket	50	Close reactor
17	Lift saw blade up	34	Close reactor	51	Close secondary containment

The complete FMEA with process and failure description cannot be disclosed as it is based on NDA protected, proprietary content. The results of the FMEA lead to the list with the process steps ranked according to their risk priority number below. (Only highest ranking steps are shown).

1. Open reactor
2. Open secondary containment
3. Main reaction (aqueous wash)
4. Fill recycling container
5. Remove cell parts from vise (saw)
6. Remove cell from vise (press)
7. Unfastening bolt
8. Temperature, valves and pump check
9. Activate press

As can be seen, the operations associated with direct interaction and handling of the battery content (1, 2, 4, 5 and 6) are the operations associated with the highest risk. In order to minimize this risk, the reactor is purged with CO2 after the aqueous solution was pumped back into the tank to minimize the risk of hazardous gases being present when the operator opens the secondary containment and the reactor. The operator furthermore has to wear sufficient PPE (according to the MSDS's) - at least including a chemical apron, sleeves, chemical and working gloves as well as safety goggles and a face shield. This prevents plashes of alkaline solution from the aqueous wash and any kind of hazardous battery content to come in contact with the operator. Thick gloves furthermore prevent the operator from being cut by burrs of the stainless steel can during the removal of parts from the vises. To protect the operator from flying debris during the seal and stem as well as content removal (9. Activate press) the aluminum/ polycarbonate containment was designed for the presses. Lastly, the operator has to check all valves and pump before starting the hydrometallurgical process to minimize chances of a thermal runaway. He furthermore has to monitor the process parameters throughout the reaction to activate the emergency shutdown procedure if necessary.

None of the process steps had an RPN ranking over 150, even under the consideration of highly unlikely events that can only happen by disregarding SOP or severe and unexpected material failure.

5.3 Economic Evaluation

According to the already established scheme, the process cost are again divided in to capital expenditures (CAPEX) and operating expenses (OPEX). The numbers in this calculation are altered and simplified due to NDA requirements without changing the general meaning.

The CAPEX expenditures include again all the machines with all functioning parts, enclosures and installed safety measures as already described in the previous chapter. The breakdown again assumes an installed exhaust system and enough space provided for the machines which are therefore not listed as expenditures. The total CAPEX basis for this calculation is therefore the project budget of approximately $28,000 as stated in the problem statement.

The operating expenses are again divided in to the consumable material costs, costs for disposal/ recycling of the end products and labor. The OPEX for the newly implemented system as it can be used right now (without labor) are assumed to be between $5 and $12 per cell.

The performed initial time studies as discussed in the previous chapter provide enough information to estimate the labor cost. By assuming the estimated 2*270 seconds sawing time (information provided by saw blade manufacturer LENOX after tests with actual cell cans), 53 seconds for the seal breaking, 44 seconds for the content removal and ca. 60 minutes for the aqueous wash of 5 cells, the cost of labor per cell are between $3 and $13. (Assuming again an average salary of $26.09/h for a mechanical engineering technician according to the U.S. bureau of Labor Statistics, May 2013).

Assuming a yearly recycling volume of 10,000 cells and a remaining machine value of 80% after one year of operation, the total cost of recycling are therefore between $85,600 and $255,600. Compared to the $705,000 - $2,005,000 for cell incineration as the only industrial grade alternative, the cost were lowered by $619,400 - $1,749,400 with the first now implemented recycling process iteration.

5.4 Evaluation of Scalability

In order to evaluate the feasibility of using the newly developed recycling process for Ambri's commercial battery production, the findings from the safety and economic evaluation as well as considerations derived from regulations and the process complexity and requirements are again evaluated according to the presented scheme. These evaluation lead to the following result:

Table 10: Current R&D Disposal Process Scalability

Regualtions	Impossible to permit	Hard to permit	Medium hard to permit	Easy to permit	Already permitted
	1	2	3	4	5
				X	
Safety	Unsafe				Safe
	1	2	3	4	5
				X	
Cost	High				Low
	1	2	3	4	5
					X
Complexity	High				Low
	1	2	3	4	5
				X	
Throughput	Low				High
	1	2	3	4	5
				X	
Process Control	Impossible				Possible
	1				5
					X
Scalabilty	26				

Concerning the regulations: While the process wasn't officially approved by a third party as of the end of the project, it was developed with iterative PFMEA, input from Ambri's process safety professionals and third party waste management consultants. After the implementation of all suggested process containments and an extensive process analysis described in chapter 6 *Recommendations, Future Work and Conclusion*, the process is expected to be permitted without difficulties.

As mentioned, the process safety was assessed with iterative PFMEA. The result of this analysis was that the process can, after further tests, be safely applied as a high throughput production process on a shop floor environment. While all performed tests so far indicate safe and stable operating conditions, further tests have to be performed to fully access the process and its properties to finally evaluate its safety. As only partial testing could be performed due to the project deadline, the value assigned for this criterion was a 4.

The cost were estimated to be between \$85,600 and \$255,600 for 10,000 cells during one year of operation saving between \$619,400 and \$1,749,400 compared to the only viable alternative of full cell incineration. The value assigned for this criterion is therefore a 5.

The complexity of the newly developed recycling process as described in the previous chapter is not high. The process was designed to be operated by one trained operator. The value assigned for this criterion was therefore a 5. It is important to note at this point that this assessment of the process complexity is not making a statement about the safety and/ or stability of the process.

The process throughput can be easily estimated with the performed acquired and the estimated processing time data as described in the calculation of the labor cost. Assuming 1 hour to process 5 cells, the maximum yearly throughput of one full time operator is:

$$40\ cells * \frac{251\ working\ days\ per\ year}{1\ working\ days\ per\ 40\ cells} = 10{,}040\ cells\ per\ year \tag{16}$$

The process is therefore capable of recycling Ambri's anticipated throughput of 10,000 cells per year. The value assigned for this criterion was therefore a 4.

Since Ambri can open and analyze the cells with this process, the process and quality control of their batteries are possible. The value assigned for this criterion was therefore a 5.

These considerations lead to a scalability factor of 26. The process is therefore the most feasible method to recycle/ dispose of spent batteries. The conclusions derived from the overall evaluation of scalability is that the newly developed recycling process is easy to permit and with further tests and characterizations safe to operate. The process additionally provides for integrated process and quality control measures and can accommodate for the anticipated throughput. The requirement of recycling 5 cells per day was surpassed 8 times as the anticipated recycling capacity is 40 cells per day. The overall scaling and the incorporation of further process functionality are accomplishable due to the flexible and modular design achieved with low CAPEX machines and parts.

6. Recommendations, Future Work and Conclusion

This last chapter ends the thesis with short term recommendations, future work suggestions and a project conclusion. The first part *Recommendations* discusses steps that need to be taken to understand and safely operate the process as well as process enhancements that can readily be incorporated to save money, become more environmental friendly and aim towards closed loop recycling. The second part *Future Work* discusses more extensive process enhancements that can be implemented in the future to accommodate for Ambri's growth. The chapter then ends with a conclusion of the liquid metal battery recycling project at Ambri Inc.

6.1 Recommendations

6.1.1 Process Testing

Before the new recycling process can be safely operated, its properties and behavior with different ambient conditions and inputs have to be thoroughly analyzed. The following list of proposed tests does not claim to be complete but can serve as a connection between the partial process characterization already performed and future testing. The suggested tests are:

- ICP MS
- GC ICP MS (before and after gas filter)
- Dissolving tests
- Tests with different process gas mixtures
- Continuous temperature monitoring
- Continuous pH monitoring

The team suggests an inductively coupled plasma mass spectrometry (ICP MS) to be performed on the aqueous solution during reactions with different amounts of battery content. The solution, its composition, the change and rate of change can thereby be measured and analyzed to infer safe operation settings and process stability.

An additional GC ICP MS is suggested to be performed on the gaseous output of the reaction. If performed in front and after the gas filtration the results can show if hazardous gases are produced and actively filtered out.

It is furthermore advised to do process tests with the complete content of a single battery before recycling the proposed 5 cells at a time. If the tests are successful, the amount can steadily be increased until the safe maximum of battery content that can be dissolved at a time is found.

The tests should also be performed with different CO_2 and Ar process gas mixtures to understand their influence on the reaction.

It is advised to record the temperature of the cooling water tank and the temperature and pH values of the aqueous solution during all performed tests. An analysis of the numeric differences between test setups and the slopes of the graphs will provide important information about the process control and stability.

6.1.2 Automation

The new developed and implemented process provides for a total of four different easy to implement automation opportunities in three different process steps. The first two process steps in the process flow that can readily be automated are the seal breaking and content removal performed with the hydraulic presses. The manual three position lever that currently controls the up and down movement of the press actuates a valve. This lever and its valve can be replaced with a solenoid valve so that the hydraulic flow that operates the press can be controlled remotely by an operator or in the future by a fully automated process control unit. To increase the process safety the team suggests furthermore that the electrical connection to control the solenoid valve is disconnected when the door of the press containment is opened. This can be done by installing an electrical switch or two electrical contacts on the door and the stationary frame respectively to open the circuit when the door is not closed.

The next two immediate automation opportunities can be implemented in the aqueous wash process step. Right now the valves to fill and empty the reactor, start and stop the airflow to the pumps and operate the cooling cycle, CO2 and argon are operated manually. For easy automation without the necessity of disassembling the process, the team already implemented the discussed manual/ solenoid valve systems for these connections. As soon as the solenoid valves are connected to an electrical switch, the manual valves can be permanently closed and the process can be operated remotely by an operator or directly by an automated process control unit.

To further increase the safety, the temperature sensors in the reactor and the cooling water tank should be connected to the control unit so that the emergency stop due to a temperature runaway is executed automatically.

Lastly, in order to override false manual input in case of an emergency, the currently implemented parallel connections of the manual/ solenoid valve systems can be switched to an integrated serial/ parallel connections as shown in figure 53.

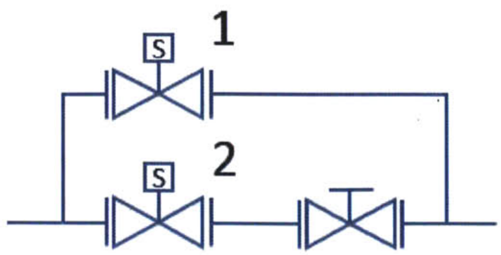


Figure 53: Two Stages Solenoid/ Manual System

During a manual operation the solenoid parallel to the manual valve (solenoid valve 1) would be default closed while the solenoid in series to the manual valve (solenoid valve 2) would be default opened. In case the automatic control needs to override any manual input it can close solenoid valve 2 and then control the flow with solenoid valve 1 as if no manual valve is implemented in the line.

6.1.3 Salt Precipitation Circuit

As explained in the different methods discussing how to treat the process output streams, the main source of waste (and cost) is currently the aqueous solution. Once the aqueous solution is saturated with salts, no more battery content can dissolve in it. Before this happens the solution must be replaced so that every reaction can be completed. The team suggested for safety reasons to replace the solution after every reaction of 5 cells as long as no extensive process analysis is performed to determine the content of how many batteries exactly can be reacted with one fill of new solution. One method to recycle the solution for longer usage by removing alkaline salts is shown in figure 54.

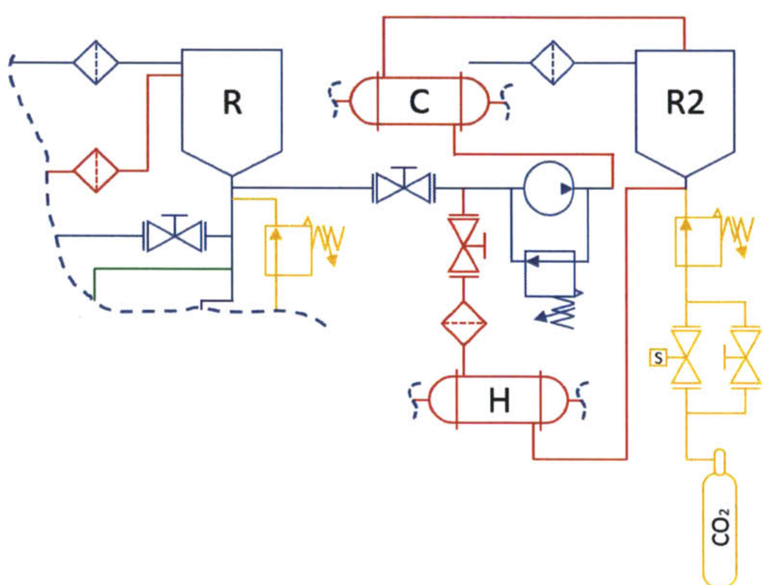


Figure 54: Precipitation Circuit

While the solubility of all other dissolved salts in water increases with higher solution temperature, the solubility of the carbonate decreases. The idea is therefore to first saturate the cold solution with carbonate salt by feeding the reactor vessel R2 with a constant flow of CO_2. The next step is to heat the carbonate saturated solution in heat exchanger H and pump it through a filter. The carbonate precipitates out and accumulates in the filter. By using e.g. a cyclone filter, the carbonate can be periodically removed, dried and stored. After the solution passed the filter it is cooled in heat exchanger C and reenters the reactor.

In order to evaluate the long term economic feasibility of this method, equation 17 must be solved.

$$Price\_of\_Salt * Amount\_of\_Salt + Cost\_of\_Solution\_Disposal - Process\_Cost \tag{17}$$

The selling price of the carbonate salt multiplied by the produced amount gives the gain of producing and selling carbonate salt. The cost of aqueous solution disposal takes the saved cost in to account that must not be spent since the aqueous solution is now reused. Subtracted from this sum are the cost of the process (e.g. electricity and CO_2 cost). Is the outcome of the equation greater than zero, the described aqueous solution recycling is economically feasible.

Another way of prolonging the time of usage of the aqueous solution that is potentially more efficient but also riskier is using the temperature increasing solubilities of the electrolyte salts during and directly after the battery content reaction. The water solubilities of the alkaline salts in the battery electrolyte can exhibit an increase of up to 60% when the temperature increases by 40°C (numbers altered due to NDA requirements without changing the theory behind the process). The idea behind that method is to react the battery content at an elevated but constant temperature until saturation is almost reached. The solution is cooled down after the reaction of all battery content. The salts thereby precipitate out and can be collected in a filter for further usage. Due to the fact that the reactivity of the battery content increases by orders of magnitude with increasing aqueous solution temperature, extensive and thorough process evaluations and calculations need to be performed before data collected by performing small scale experiments can be used to evaluate the process safety and technical feasibility.

6.1.4 Metal Recycling Process

With the recovery of the stainless steel, salts and reuse of the aqueous solution, the only waste produced by the new recycling process are the insoluble solids remaining after the aqueous wash. They consist of a nonmetallic material and, depended on the initial charging state of the battery before it entered the recycling process, one or two hazardous alloys. The metallic components could enter a metal smelter that operates under an inert atmosphere. The smelter would liquefy the metallic components which would then separate because of density differences. The separated metals can then be poured in to bars and reenter the battery production process. A schematic of such a smelter operating under inert atmosphere is shown in figure 55.

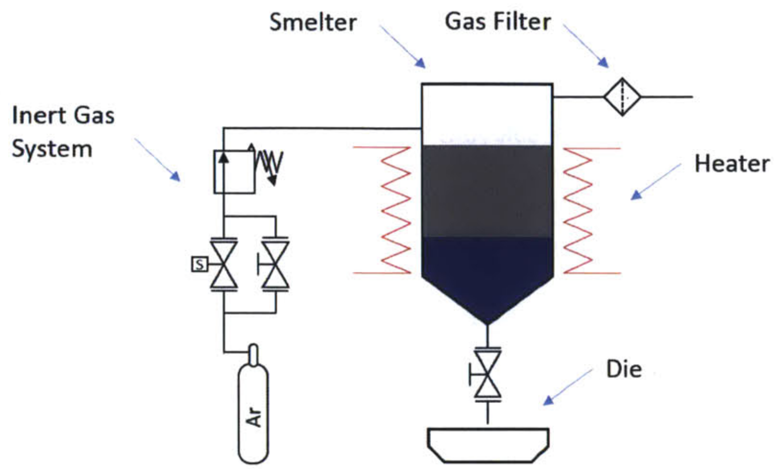


Figure 55: Metal Recycling Smelter

One of the two alloys that can be found in the solid remainders of the aqueous wash consists of a highly reactive component. This metal however did not react during the aqueous wash due to its alloy bond. Although Ambri already possesses the capability of melting and handling this component as a liquid, it is highly advised to perform extensive safety evaluation and confirm the technical feasibility with small scale experiments before implementing such a smelting process for metal recovery.

6.2 Future Work

This section focuses on steps to be taken after the immediate follow up on the MIT/ Ambri process development cooperation. It is divided in to three parts. The first suggestion is to automate the complete process flow for high volume cell recycling. The second part discusses a process scaling for larger throughput per batch. The section ends with a brief discussion of the idea of mobile recycling.

6.2.1 Fully Automated Recycling

The last stage of full process automation is an automated transfer system from process step to process step. Due to the handling complexity caused by shape change of the process flow material (e.g. during cell opening and content removal) or alignment operations (e.g. fixating with vise) and the close proximity in which all machines are placed, a robot arm can be effectively used for material transfer.

Robot arms like the 6 axis KUKA KR 16 L6-2 with a maximum payload of 6kg and a maximum reach of 1.9 meters or model KR 30 L16-2 with the same properties but a reach of 3.1 meters can be used as a cost efficient way to operate the process like an automated Toyota production cell. In order to provide for easy integration of a robot arm, the team would furthermore suggest a process layout close to the one shown in figure 56.

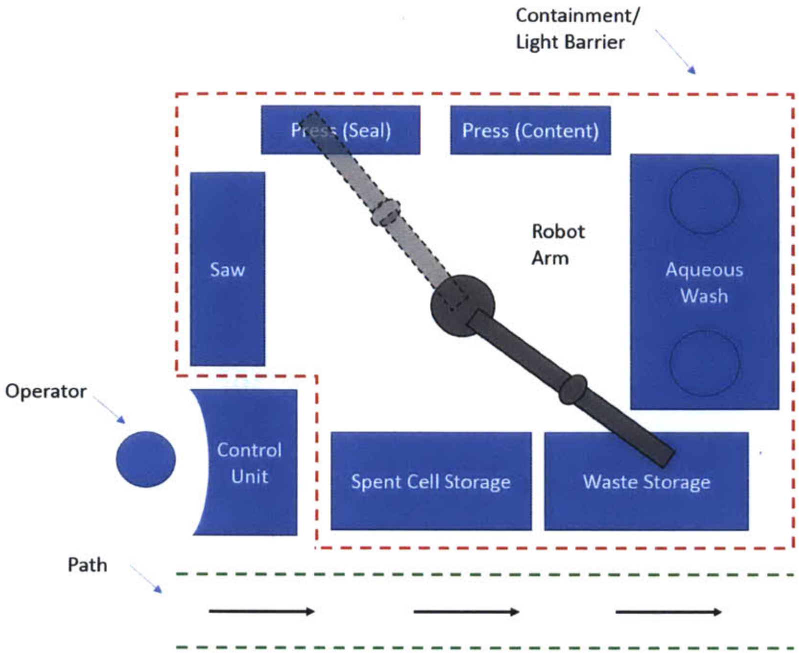


Figure 56: Automated Process Layout

The key points of the layout are that every machine must be in reach of the robot arm while the operator of the process must be physically out of reach of the arm to increase the process safety. Besides reorienting the machines of each process step, additional actions have to be taken for a robot arm operated system. Initial action points are e.g.:

- Light barrier and closed containment around robot accessible area
- Robot arm compatible connections on the process equipment
- Automation of support functions (e.g. containment opening and closing, argon purging)

6.2.2 Scaling

While the press and saw related process steps with cycle times of 1 to 9 minutes of the new recycling process are capable of accommodating for very high throughput, the capacity limiting factor is currently the aqueous washing process with an estimated cycle time of ca. 60 minutes. The reaction of the battery content with the aqueous solution should not be accelerated due to safety concerns. The two possibilities for Ambri to increase the recycling throughput is therefore to either increase the capacity of one aqueous wash machine or implement multiple aqueous washing systems. Both alternatives need to be evaluated regarding their safety and costs.

If the capacity of one reactor is increased, Ambri is advised to also implement the following system changes:

- New aqueous solution vessels
- Enhanced active cooling
- Larger pumps
- Use of large diameter corrosion resistant metal tubing

New storage and reaction vessels are necessary to ensure gas tight enclosure and heat resistance. Initial research performed lead to the conclusion that PTFE coated stainless steel vessels are a feasible and cost efficient option that should be explored. A new active cooling circuit with a higher flow rate and larger temperature gradient is also recommended to increase process safety. To accommodate for higher flow rates in the cooling circuit as well as the filling and emptying circuit, larger pumps and tubing are expected to be necessary. Initial research showed that tubes and pump parts made of Hastelloy are a cost efficient option to ensure corrosion resistance and process safety.

6.2.3 Mobile recycling

Another important area for Ambri to research is the possibility of mobile recycling. Ambri's battery is a stainless steel enclosed pug of metals and salt. This inherently makes it heavy - like other large scale batteries. Ambri furthermore aims to provide customers across the U.S. and in the future across the world with their grid level storage batteries. Sending spent liquid metal batteries across the United States or even across continents just to dispose of them would however be an expensive operation.

The team suggests therefore that Ambri considers the possibility of mobile recycling. The current recycling process is installed on an area of approximately 5 by 3 meters. The whole process would therefore fit without problems in to a truck (even with larger reaction vessels and a bigger waste storage area). Such a truck could be strategically placed in the proximity of customers and be send out for maintenance operations. The spent batteries would be recycled on side without the need of transporting hazardous waste through different states or countries. The salable end products of the recycling process could be sold to regional recycling centers.

Some of the important key aspects to consider for mobile recycling are:

- Federal regulations such as EPA requirements
- Relevant state laws
- Department of Transportation (DOT) requirements for a mobile recycling process
- Fail safe exhaust system for mobile applications
- Fail safe cooling system for mobile applications

6.3 Conclusion

The MIT team in cooperation with Ambri Inc. was able to develop and implement the vast majority of Ambri's new liquid metal battery recycling process. The process was implemented at Ambri's manufacturing facility in Marlborough, MA.

The performed research concluded that a hydrometallurgical main process that reacts the battery content to form less reactive, salable compounds is the most feasible, safe and cost efficient option to recycle the liquid metal battery. To enable such reaction, three mechanical battery dissection process steps were implemented to separate the battery content from its rigid, stainless steel can.

Process tests with the assembled equipment suggest that the process steps can be operated stable and repeatable to recycle an estimated amount of 40 cells per day. This enables Ambri to recycle more than 10,000 during their first year of production, increasing the company's profit by several hundred thousands of Dollars.

The team furthermore conducted research and performed experiments to determine promising future process development opportunities. The results demonstrated that the newly developed process can readily be enhanced to provide for automated, near closed loop recycling of Ambri's liquid metal battery. Future opportunities include furthermore scaling of the process and a mobile recycling strategy.

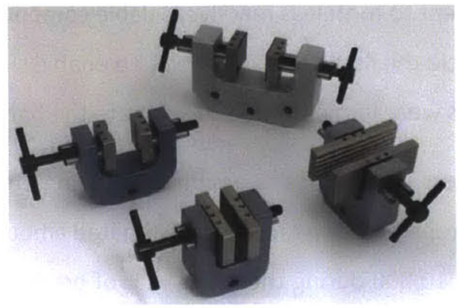
Appendix

TESTRESOURCES

G240k Family

Vice Grip

G240k-2.5-10	
Tensile force	2.5 kN (560 lbs)
Opening	0 – 10 mm (0.4") dependent on jaw
Weight	0.29 kg (0.6 lbs) each without jaws
G240k-1-20	
Tensile force	1 kN (225 lbs)
Opening	0 – 20 mm (0.8") dependent on jaw
Weight	0.33 kg (0.7 lbs) each without jaws
G240k-1-30	
Tensile force	1 kN (225 lbs)
Opening	0 – 30 mm (1.2") dependent on jaw
Weight	0.32 kg (0.7 lbs) each without jaws
G240k-1-50	
Tensile force	1 kN (225 lbs)
Opening	0 – 50 mm (2") dependent on jaw
Weight	0.57 kg (1.25 lbs) each without jaws
G240k-2.5-10, G240k-1-20, G240k-1-30, G240k-1-50	
Temperature range	0°C – 180°C (32° – 356°F)
Body	aluminum



Interchangeable Jaws or Faces

Jaw	Description
J240-B	Blank jaws, 30 x 30 mm
J240-BG	Rubber jaws, 30 x 30 mm
J240-BP	Pyramid jaws, 30 x 30 mm
J240-BV2	V-jaws, 30 x 30 mm
J240-BV3	V-jaws, 30 x 30 mm
J240-BW	Wave jaws, 30 x 30 mm
J240-BD	Diamond jaws, 30 x 30 mm
J240-B50	Blank jaws, 30 x 50 mm
J240-BG50	Rubber jaws, 30 x 50 mm
J240-BP50	Pyramid jaws, 30 x 50 mm
J240-BW50	Wave jaws, 30 x 50 mm
J240-BD50	Diamond jaws, 30 x 50 mm
J240-B80	Blank jaws, 30 x 80 mm
J240-BG80	Rubber jaws, 30 x 80 mm
J240-BP80	Pyramid jaws, 30 x 80 mm
J240-BW80	Wave jaws, 30 x 80 mm
J240-BD80	Diamond jaws, 30 x 80 mm

Jaw	Description
J240-B100	Blank jaws, 30 x 100 mm
J240-BG100	Rubber jaws, 30 x 100 mm
J240-BP100	Pyramid jaws, 30 x 100 mm
J240-BW100	Wave jaws, 30 x 100 mm
J240-BD100	Diamond jaws, 30 x 100 mm

Specimen for V-jaws

	G240k-BV2	G240k-BV3
G240k-2.5-8	Ø 2 – 9 mm (0.08" – 0.35")	Ø 3 – 9 mm (0.12" – 0.35")
G240k-1-20	Ø 2 – 20 mm (0.08" – 0.8")	Ø 3 – 20 mm (0.12" – 0.8")
G240k-1-30	Ø 2 – 30 mm (0.08" – 1.2")	Ø 3 – 30 mm (0.12" – 1.2")
G240k-1-50	Ø 2 – 50 mm (0.08" – 2")	Ø 3 – 50 mm (0.12" – 2")

TestResources Inc – 701 Canterbury Road – Shakopee MN USA 55379
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Data Sheet

32-1127 REV 2

The M5-1000 and M5-2000 advanced digital force gauges are designed for tension and compression force testing in numerous applications across virtually every industry, with high capacities of 1,000 lbF (5,000 N) and 2,000 lbF (10,000 N), respectively. The gauges features an industry-leading sampling rate of 7,000 Hz, producing accurate results even for quick-action tests. Accuracy is ±0.1% of full scale ±1 digit, and resolution is 1/5,000. A large, backlit graphics LCD displays large, legible characters, while the simple menu navigation allows for quick access to the gauges' many features and configurable parameters. Data can be transferred via USB, RS-232, Mitutoyo (Digimatic), or analog outputs.

Shown with a TSF test stand in a spring testing application

On-board data memory for up to 1,000 readings is included, as are statistical calculations with output to a PC. Integrated set points with indicators and outputs are ideal for pass-fail testing and for triggering external devices such as an alarm, relay, or test stand. The gauges are overload protected to 150% of capacity, and an analog load bar is shown on the display for graphical representation of applied force.

The gauges' averaging mode addresses the need to record the average force over time, useful in applications such as peel testing, while external trigger mode makes switch activation testing simple and accurate. An ergonomic, reversible aluminum design allows for hand held use or test stand mounting for more sophisticated testing requirements. The force gauges are directly compatible with high capacity Mark-10 test stands, grips, and software.

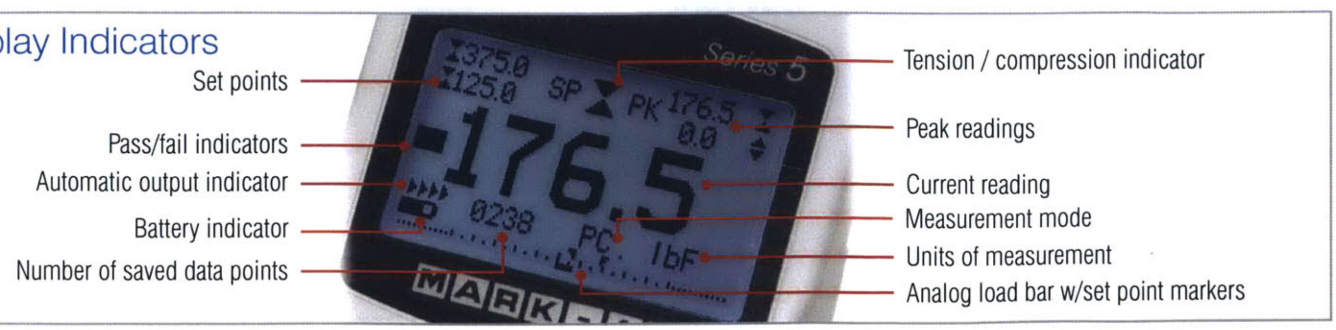
MESUR™ Lite data acquisition software is included with the gauges

The gauge include MESUR™ Lite data acquisition software. MESUR™ Lite tabulates continuous or single point data. Data saved in the gauge's memory can also be downloaded in bulk. One-click export to Excel easily allows for further data manipulation.

Features

- **High-speed 7,000 Hz sampling rate**
- **USB, RS-232, Mitutoyo, and analog outputs**
- **Large backlit graphic display**
- **1,000-point data memory with statistics and outputs**
- **Live load bar graph with set point markers**
- **Programmable set points, with indicators and outputs**
- **Peak readings and set points always displayed**
- **Averaging mode - calculates average readings over time**
- **External trigger mode - for switch contact testing or remotely stopping display update**
- **Automatic data output via USB/RS-232**
- **5 selectable units of measurement**
- **Configurable audio alarms and key tones**
- **Password protection, configurable for individual keys and calibration**

Display Indicators



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3 YEAR WARRANTY

Digital Force Gauges M5-1000 / M5-2000

32-1127 REV 2

Focus on Engineering: Reversible Housing

Housing separates into reversible halves, electrically connected by gold-plated spring contacts.

Reversible housing allows the gauge to be used in different orientations.

The display and keypad remain upright.

Specifications

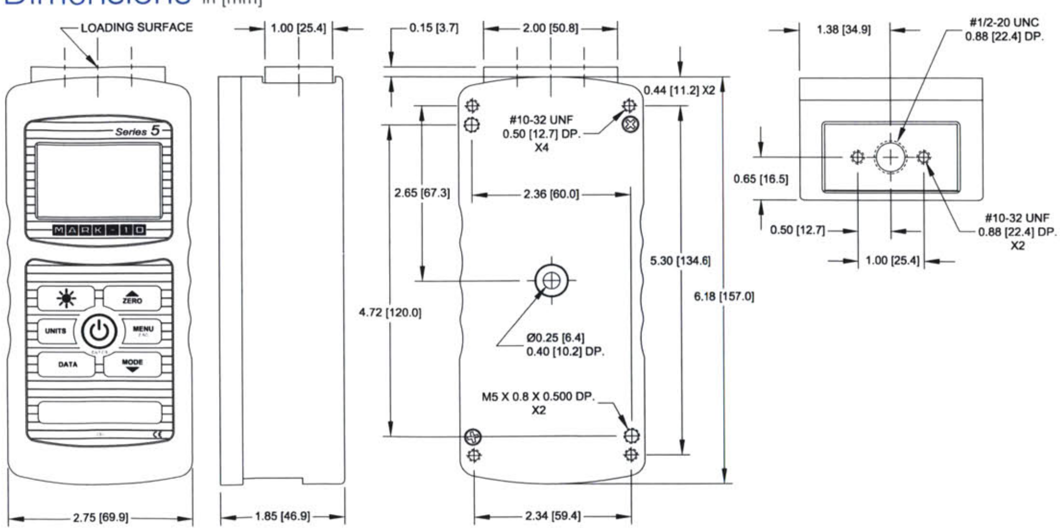
Capacity x Resolution:	**M5-1000:** 1000 x 0.5 lbF, 16000 x 5 ozF, 500 x 0.2 kgF, 5000 x 2 N, 5 x 0.002 kN **M5-2000:** 2000 x 1 lbF, 32000 x 20 ozF, 1000 x 0.5 kgF, 10000 x 5 N, 10 x 0.005 kN
Accuracy:	±0.1% of full scale
Sampling Rate:	7,000 Hz
Power:	AC or rechargeable battery. Multi-step low battery indicator is displayed, gauge shuts off automatically when power is too low.
Battery life:	**Backlight on:** up to 7 hours of continuous use / **Backlight off:** up to 24 hours of continuous use
Outputs:	**USB / RS-232:** Configurable up to 115,200 baud. Includes Gauge Control Language 2 for full computer control. **Mitutoyo (Digimatic):** Serial BCD suitable for all Mitutoyo SPC-compatible devices. **Analog:** ±1 VCD, ±0.25% of full scale at capacity. **General purpose:** Three open drain outputs, one input. **Set points:** Three open drain lines.
Configurable settings:	Digital filters, outputs, automatic output (via USB/RS-232), automatic shutoff, default settings, averaging mode, external trigger, passwords, key tones, audio alarms, backlight, calibration
Safe overload:	150% of full scale (display shows "OVER" at 110% and above)
Weight:	1.8 lb [0.82 kg]
Load cell deflection:	0.015 [0.38] at full scale
Environmental requirements:	40 - 100°F, max. 96% humidity, non-condensating
Included items:	Carrying case with chisel, cone, V-groove, hook (M5-1000 only), flat, extension rod, universal voltage AC adapter, battery, quick-start guide, USB cable, resource CD (USB driver, MESUR™ Lite software, MESUR™gauge DEMO software, and user's guide), and NIST-traceable certificate of calibration with data.
Warranty:	3 years (see individual statement for further details)

The gauges include a 110V AC adapter.

Specify suffix 'E' for euro plug (220V), 'U' for UK plug (220V), or 'A' for Australian plug (220V).

Ex:
M5-1000E, M5-2000A

Dimensions in [mm]



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- **RS232 and RS485 Serial Communications Optional**
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- **Ratiometric Mode for Strain Gages**
- **Programmable Digital Filter**

The OMEGA® iSeries is a family of microprocessor-based instruments offered in three true DIN sizes with NEMA 4 (IP65) rated front bezels. All of the instruments share the same set-up and configuration menu and method of operation, a tremendous time saver for integration of a large system. The iSeries family includes extremely accurate digital panel meters "DPi" and single loop PID controllers "CNi" that are simple to configure and use, while providing tremendous versatility and a wealth of powerful features.

The DPi Series covers a broad selection of transducer and transmitter inputs with 2 input models.

The Universal temperature and process instrument (DPi models) handles 10 common types of thermocouples, multiple RTDs and several process (DC) voltage and current ranges. This model also features built-in excitation, 24 Vdc @ 25 mA. With its wide choice of signal inputs, this model is an excellent choice for measuring or controlling temperature with a thermocouple, RTD, or 4 to 20 mA transmitter.

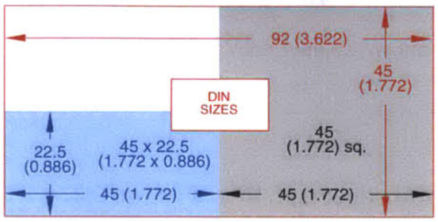
The strain and process instruments (DPiS models) measure inputs from load cells, pressure transducers, and most any strain gage sensor as well as process voltage and current ranges. The DPiS has built-in 5 or 10 Vdc excitation for bridge transducers, 5 Vdc @ 40 mA or 10 Vdc @ 60 mA (any excitation voltage between 5 and 24 Vdc is available by special order). This DPiS model supports 4- and 6-wire bridge communications, ratiometric measurements. The DPiS features fast and easy "in process" calibration/scaling of the signal inputs to any engineering units. This model also features 10-point linearization which allows the user to linearize the signal input from extremely nonlinear transducers of all kinds.

Programmable Color Display

The DPi Series are ⅛, 1⁄16 and 1⁄32 DIN digital panel meter featuring the big iSeries color-changing display. The digits are twice the size of typical ⅛ DIN panel meters. The iSeries meters feature the only LED displays that can be programmed to change color between **GREEN**, **AMBER**, and **RED**.

Embedded internet and serial communications featuring optional "embedded Internet" (specify "-EIT" option) the iSeries are the first instruments of their kind that connect directly to an Ethernet network and transmit data in standard TCP/IP packets, or even serve Web pages over a LAN or the Internet. The iSeries are also available with serial communications. With the "-C24" option, the user can select from the pushbutton menu between RS232, RS422, and RS485, with straightforward ASCII commands or MODBUS.

Dimensions: mm (inch)



Options

Ordering Suffix	Description
Network Options	
-EIT	Ethernet with embedded internet
-C24	Isolated RS232 and RS485, 300 to 19.2 KB
-C4EIT	Ethernet with embedded Web server + isolated RS485/422 hub for up to 31 devices
-DC	12 to 36 Vdc*, 24 Vac (standard power input: 90 to 240 Vac/dc, 50 to 400 Hz)
Factory Setup	
-FS	Factory setup and configuration
-FS(RTD-1N)	Customized DPiS model for MIL-T-7990B nickel RTD input, 0 to 200°C (32 to 392°F)
-FS(RTD-2N)	Customized DPiS for MIL-T-7990B nickel RTD input, -40 to 300°C (-40 to 572°F)
Software (Requires Network Option)	
OPC-SERVER LICENSE	OPC server/driver software license

***Note:** "**-DC**", "**-C24**" and "**-C4EIT**" not available with excitation. Models "**-EIT**" and "**-C4EIT**" are only offered on DPi8 and DPiS8 models.*
** 20 to 36 Vdc for DPi8A, DPi16A, -C4EIT or -EIT.*

***Ordering Examples:** **DPi8A**, ⅛ DIN meter with isolated scalable analog retransmission of process value. **DPi8C**, ⅛ DIN temp/process meter in compact case, **DPi32**, 1⁄32 DIN temp/process monitor.*

iSeries Controllers Also Available!

CNi Series Models with Control and Alarm Outputs, Visit omega.com

CNi16D, shown actual size.
Visit omega.com/cni16_series

Input Type		Range	Accuracy
Universal Strain/Process Input Models			
Process Voltage		0 to 100 mV, 0 to 1V, ±100 mV, 0 to 10V	0.03% rdg
Process Current		0 to 20 mA (4 to 20 mA)	0.03% rdg
Universal Temperature/Process Input Models			
J	Iron-Constantan	-210 to 760°C (-346 to 1400°F)	0.4°C (0.7°F)
K	CHROMEGA®-ALOMEGA®	-270 to -160°C (-454 to -256°F) -160 to 1372°C (-256 to 2502°F)	1.0°C (1.8°F) 0.4°C (0.7°F)
T	Copper-Constantan	-270 to -190°C (-454 to -310°F) -190 to 400°C (-310 to 752°F)	1.0°C (1.8°F) 0.4°C (0.7°F)
E	CHROMEGA®-Constantan	-270 to -220°C (-454 to -364°F) -220 to 1000°C (-364 to 1832°F)	1.0°C (1.8°F) 0.4°C (0.7°F)
R	Pt - Pt/13%Rh	-50 to 40°C (-58 to 104°F) 40 to 1768°C (104 to 3214°F)	1.0°C (1.8°F) 0.5°C (0.9°F)
S	Pt - Pt/10%Rh	-50 to 100°C (-58 to 212°F) 100 to 1768°C (212 to 3214°F)	1.0°C (1.8°F) 0.5°C (0.9°F)
B	Pt/30%Rh - Pt6%Rh	100 to 640°C (212 to 1184°F) 640 to 1820°C (1184 to 3308°F)	1.0°C (1.8°F) 0.5°C (0.9°F)
C	W/5%Re - W/26%Re	0 to 2320°C (32 to 4208°F)	0.4°C (0.7°F)
N	OMEGALLOY® Nicrosil-Nisil	-250 to -100°C (-418 to -148°F) -100 to 1300°C (-148 to 2372°F)	1.0°C (1.8°F) 0.4°C (0.7°F)
L	J DIN	-200 to 900°C (-328 to 1652°F)	0.4°C (0.7°F)
RTD	Pt, 0.00385, 100, 500, 1000 Ω	-200 to 900°C (-328 to 1652°F)	0.4°C (0.7°F)
RTD	Pt, 0.00392, 100, 500, 1000 Ω	-200 to 850°C (-328 to 1562°F)	0.4°C (0.7°F)
RTD-1N	(Nickel MIL-T-7990B) (FS required)	0 to 200°C (32 to 392°F)	0.1°C (0.2°F)
RTD-2N	(Nickel MIL-T-7990B) (FS required)	-40 to 300°C (-40 to 572°F)	0.3°C (0.5°F)
Process Voltage		0 to 100 mV, 0 to 1V, 0 to 10V	0.03% rdg
Process Current		0 to 20 mA (4 to 20 mA)	0.03% rdg

To Order *Visit omega.com/dpi_series for Pricing and Details*

Model No.	Size/Cutout	Input Type	Other Features
DPi8	⅛ DIN	Temperature/process	—
DPi8A	⅛ DIN	Temperature/process	Analog output
DPiS8	⅛ DIN	Strain/process	—
DPi16	1⁄16 DIN	Temperature/process	—
DPi16A	1⁄16 DIN	Temperature/process	Analog output
DPiS16	1⁄16 DIN	Strain/process	—
DPi32	1⁄32 DIN	Temperature/process	—
DPiS32	1⁄32 DIN	Strain/process	—
DPi8C	⅛ DIN	Temperature/process	Compact depth
DPiS8C	⅛ DIN	Strain/process	Compact depth

Comes complete with operator's manual.

Accessory

Model No.	Description
DPP-5	⅛ DIN panel punch

iSeries Common Specifications (All i/8, i/16, i/32 DIN)

Universal Temperature and Process Input (DPi/CNi Models)

Accuracy: ±0.5°C temp; 0.03% rdg
Resolution: 1°/0.1°; 10 µV process
Temperature Stability:
RTD: 0.04°C/°C
TC @ 25°C (77°F): 0.05°C/°C
Cold Junction Compensation
Process: 50 ppm/°C
NMRR: 60 dB
CMRR: 120 dB
A/D Conversion: Dual slope
Reading Rate: 3 samples/s
Digital Filter: Programmable
Display: 4-digit 9-segment LED 10.2 mm (0.40"); i32, i16, i16D, i8DV 21 mm (0.83"); i8 10.2 mm (0.40") and 21 mm (0.83"); i8DH RED, GREEN, and AMBER programmable colors for process variable, setpoint and temperature units
Input Types: Thermocouple, RTD, analog voltage, analog current
Thermocouple Lead Resistance: 100 Ω max
Thermocouple Types (ITS 90): J, K, T, E, R, S, B, C, N, L (J DIN)
RTD Input (ITS 68): 100/500/1000 Ω Pt sensor, 2-, 3- or 4-wire; 0.00385 or 0.00392 curve
Voltage Input: 0 to 100 mV, 0 to 1V, 0 to 10 Vdc
Input Impedance: 10 MΩ for 100 mV 1 MΩ for 1 or 10 Vdc
Current Input: 0 to 20 mA (5 Ω load)
Configuration: Single-ended
Polarity: Unipolar
Step Response: 0.7 sec for 99.9%
Decimal Selection:
Temperature: None, 0.1
Process: None, 0.1, 0.01 or 0.001
Setpoint Adjustment: -1999 to 9999 counts
Span Adjustment: 0.001 to 9999 counts
Offset Adjustment: -1999 to 9999
Excitation (Not Included with Communication): 24 Vdc @ 25 mA (not available for low-power option)

Universal Strain and Process Input (DPiS/CNiS Models)

Accuracy: 0.03% reading
Resolution: 10/1µV
Temperature Stability: 50 ppm/°C
NMRR: 60 dB
CMRR: 120 dB
A/D Conversion: Dual slope
Reading Rate: 3 samples/s
Digital Filter: Programmable
Input Types: Analog voltage and current
Voltage Input: 0 to 100 mVdc, -100 mVdc to 1 Vdc, 0 to 10 Vdc
Input Impedance: 10 MΩ for 100 mV; 1 MΩ for 1V or 10 Vdc
Current Input: 0 to 20 mA (5 Ω load)
Linearization Points: Up to 10
Configuration: Single-ended
Polarity: Unipolar
Step Response: 0.7 sec for 99.9%
Decimal Selection: None, 0.1, 0.01 or 0.001
Setpoint Adjustment: -1999 to 9999 counts
Span Adjustment: 0.001 to 9999 counts
Offset Adjustment: -1999 to 9999
Excitation (Optional In Place Of Communication): 5 Vdc @ 40 mA; 10 Vdc @ 60 mA

Control

Action: Reverse (heat) or direct (cool)
Modes: Time and amplitude proportional control; selectable manual or auto PID, proportional, proportional with integral, proportional with derivative and anti-reset Windup, and on/off
Rate: 0 to 399.9 s
Reset: 0 to 3999 s
Cycle Time: 1 to 199 s; set to 0 for on/off
Gain: 0.5 to 100% of span; setpoints 1 or 2
Damping: 0000 to 0008
Soak: 00.00 to 99.59 (HH:MM), or OFF
Ramp to Setpoint: 00.00 to 99.59 (HH:MM), or OFF
Auto Tune: Operator initiated from front panel

Control Output 1 and 2

Relay: 250 Vac or 30 Vdc @ 3 A (resistive load); configurable for on/off, PID and ramp and soak
Output 1: SPDT, can be configured as alarm 1 output
Output 2: SPDT, can be configured as alarm 2 output
SSR: 20 to 265 Vac @ 0.05 to 0.5 A (resistive load); continuous
DC Pulse: Non-isolated; 10 Vdc @ 20 mA
Analog Output (Output 1 Only): Non-isolated, proportional 0 to 10 Vdc or 0 to 20 mA; 500 Ω max

Output 3 Retransmission

Isolated Analog Voltage and Current
Current: 10 V max @ 20 mA output
Voltage: 20 mA max for 0 to 10 V output

Network and Communications

Ethernet: Standards compliance IEEE 802.3 10 Base-T
Supported Protocols: TCP/IP, ARP, HTTPGET
RS232/RS422/RS485: Selectable from menu; both ASCII and MODBUS protocol selectable from menu; programmable 300 to 19.2 Kb; complete programmable setup capability; program to transmit current display, alarm status, min/max, actual measured input value and status
RS485: Addressable from 0 to 199
Connection: Screw terminals

Alarm 1 and 2 (Programmable)

Type: Same as output 1 and 2
Operation: High/low, above/below, band, latch/unlatch, normally open/ normally closed and process/deviation; front panel configurations
Analog Output (Programmable): Non-isolated, retransmission 0 to 10 Vdc or 0 to 20 mA, 500 Ω max (output 1 only); accuracy is ± 1% of FS when following conditions are satisfied: input is not scaled below 1% of input FS, analog output is not scaled below 3% of output FS

General

Power: 90 to 240 Vac ±10%, 50 to 400 Hz*, 110 to 375 Vdc, equivalent voltage
Low Voltage Power Option: 24 Vac**, 12 to 36 Vdc for DPi/CNi/DPiS/CNiS; 20 to 36 Vdc for dual display, ethernet and isolated analog output from qualified safety approved source

Isolation

Power to Input/Output: 2300 Vac per 1 minute test
For Low Voltage Power Option: 1500 Vac per 1 minute test
Power to Relay/SSR Output: 2300 Vac per 1 minute test
Relay/SSR to Relay/SSR Output: 2300 Vac per 1 minute test
RS232/485 to Input/Output: 500 Vac per 1 minute test
Environmental Conditions:
All Models: 0 to 55°C (32 to 131°F) 90% RH non-condensing
Dual Display Models: 0 to 50°C (32 to 122°F), 90% RH non-condensing (for UL only)
Protection:
DPi/CNi/DPiS/CNiS32, i16, i16D, i8C: NEMA 4X/Type 4 (IP65) front bezel
DPi/CNi8, CNi8DH, i8DV: NEMA 1/Type 1 front bezel
Approvals: UL, C-UL, CE per EN61010- 1:2001, FM (temperature units only)
Dimensions
i/8 Series: 48 H x 96 W x 127 mm D (1.89 x 3.78 x 5")
i/16 Series: 48 H x 48 W x 127 mm D (1.89 x 1.89 x 5")
i/32 Series: 25.4 H x 48 W x 127 mm D (1.0 x 1.89 x 5")
Panel Cutout
i/8 Series: 45 H x 92 mm W (1.772 x 3.622"), ⅛ DIN
i/16 Series: 45 mm (1.772") square, 1/16 DIN
i/32 Series: 22.5 H x 45 mm W (0.886 x 1.772"), 1/32 DIN
Weight
i/8 Series: 295 g (0.65 lb)
i/16 Series: 159 g (0.35 lb)
i/32 Series: 127 g (0.28 lb)

** No CE compliance above 60 Hz.*
*** Units can be powered safely with 24 Vac power, but no certification for CE/UL are claimed.*

DAKE

INSTRUCTIONS AND PARTS LIST FOR MODEL FORCE 10DA and FORCE 25DA

(Double Acting, Electrically-Operated Hydraulic Press)

Thank you for buying Dake !!!!

We hope you enjoy many years of using your new Dake hydraulic press. We hope you find these instructions helpful, if you have any questions please give us a call, or just stop by for a factory tour.

724 Robbins Road
Grand Haven, MI 49417

Phone: 616-842-7110 800-937-3253

Ordering information

Please order all parts by part number and name; also mention model number as shown on plate attached to the frame of the press.

Note: This press is not intended for stripping operations! Personal injury or machine damage can result.

Press set-up
Installation Instructions

Your new Dake Press has been packaged in a manner to prevent damage to any critical components; some assembly may be required. All parts in the accessory box are critical to the function of your press. Some presses may come completely assembled.

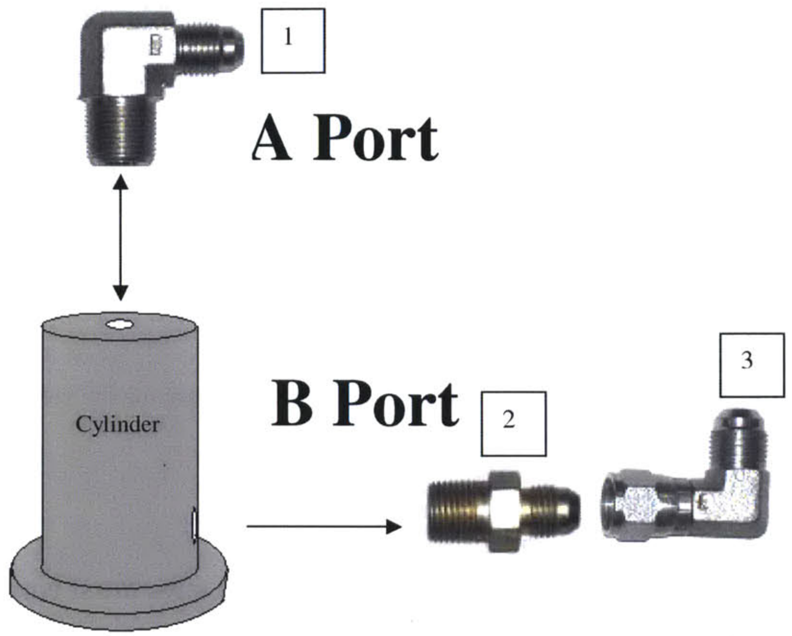
NOTE: FOR EASE OF ASSEMBLY LEAVE THE PRESS FRAME MOUNTED ON THE SHIPPING SKID

1. **Remove plastic from the machine.**
2. **Open the box and you will see a pumping unit, with the press still laying on its side. Locate the four holes on the side of the press facing up.**
3. **Place the pumping unit on the side of the press with the mounting bracket facing down, making sure the holes all line up.**
4. **There are four bolts, washers and nuts in a bag, in the box. Put the bolts in the holes using the washers and nuts. Make sure all nuts and bolts are tight.**
5. **With the press lying on its side fill the reservoir with DTE 24 Mobile oil or equivalent with 2 gallons of oil.**

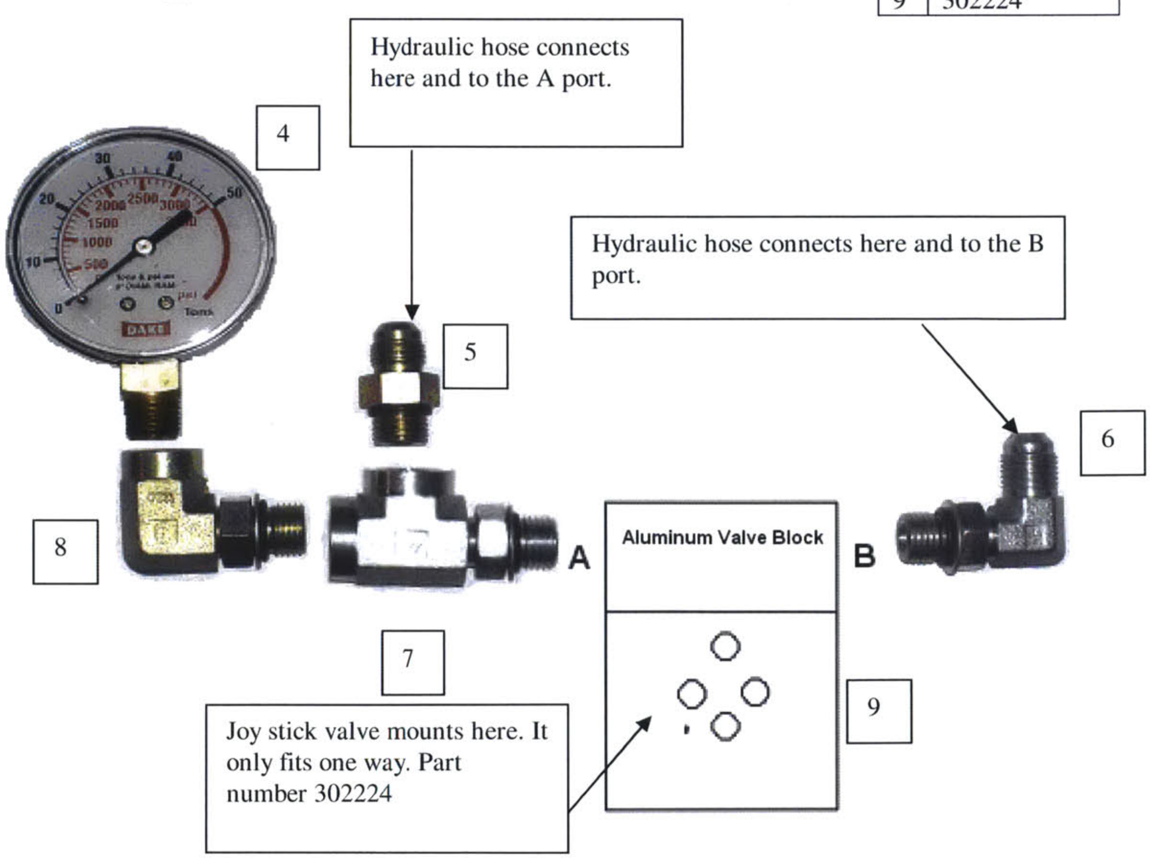
WARNING!!!!

Be sure all bolts and fittings are tight before operating this pumping unit, personal injury could result.

How to install the fittings on your new hydraulic press



1	72050
2	73425
3	72047
4	10 ton 301315 25 ton 301316 50 ton 302179
5	69671
6	72402
7	302183
8	302061
9	302224



WARNING!!!

Be sure all fittings and bolts are tight.
Do not over tighten fittings or bolts.

Wiring Instructions

WARNING!!!!
A licensed qualified electrician that follows all state and local laws must wire and install the electrics on this machine.

110 Volt

1. For 110 volts this machine is ready to plug in. The machine can be wired 220 volt single phase. Always follow the wiring diagram provided in the motor cover when converting to 220 volt single phase. A cord and plug that is rated for the specified voltage and amperage must be used. This rating is located on the motor.

WARNING!!!!
It is the responsibility of the installer to make sure the motor is wired correctly for the voltage needed. Damage to motor could result.

220 Volt single phases

WARNING!!!!
A licensed qualified electrician that follows all state and local laws must wire and install the electrics on this machine.

WARNING!!!!!
This Machine new is shipped out as a 110 volt machine. If the wiring must be changed to suit 220 volts single phase.

1. The leads on the motor must be changed to fit 220 volts, follow the diagram on the motor.
2. Install plug and wire that fits the rating on the motor, this plug and wire must be rated for the voltage and amperage listed on the motor.

Operation

1. Fill the reservoir with 2 gallons of Mobil DTE 24 hydraulic fluid or its equivalent AW 32.

2. Turn the on / off power switch (toggle switch) to the “on” position (up).

3. Move the control lever down, this will advance the ram in the downward position.

4. Release the control lever and the ram will stop moving.

5. Move the control lever handle to the up position and the ram will move up.

6. When the press is new be sure to move the ram up and down to work out any air that may be in the system.

Lubrication

Keep all working parts of the press well oiled for easier operation. Also, keep a light film of oil over the entire surface of the ram to prevent rust.

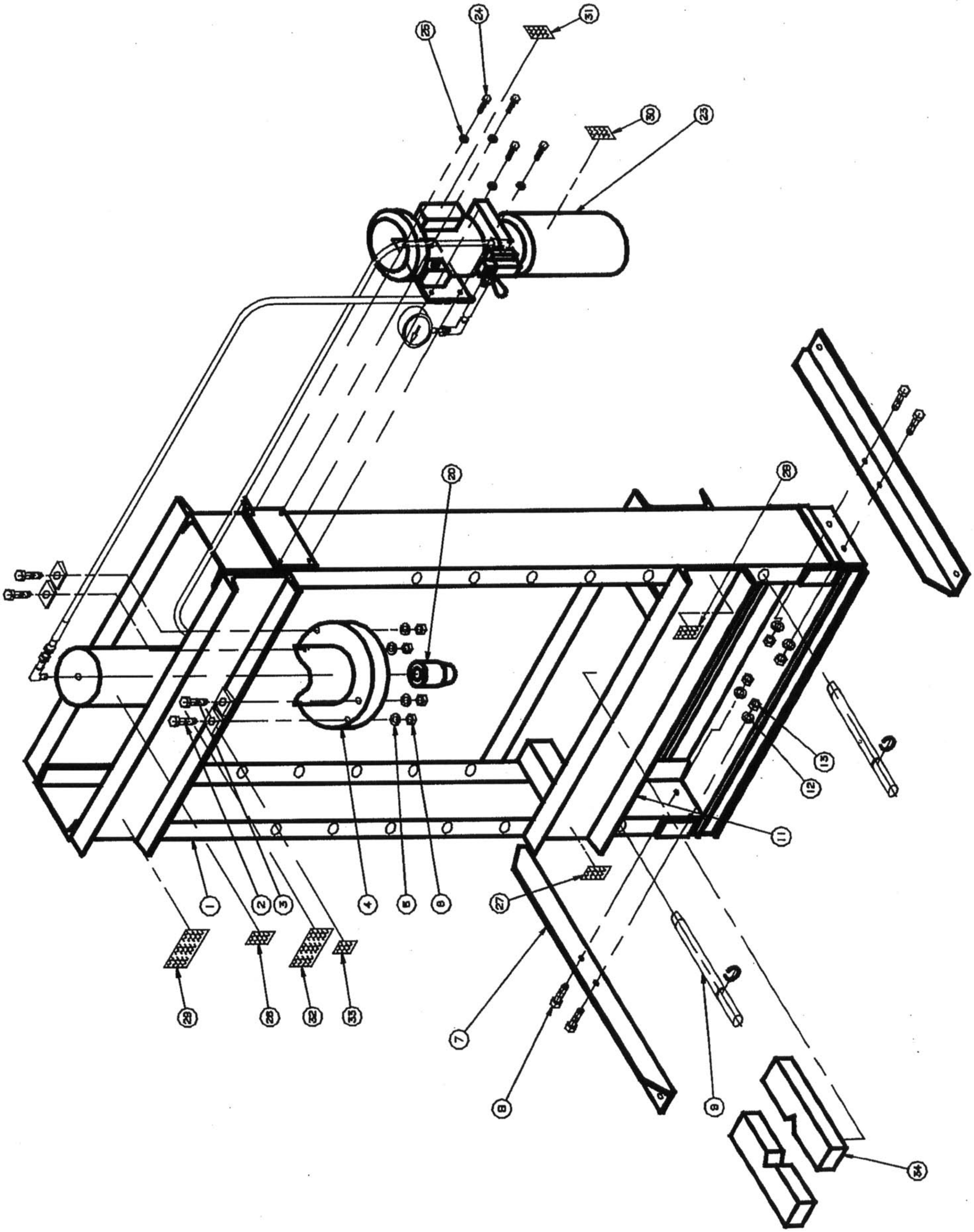
WARNING!!!!

This press is not intended for stripping operations! Personal injury or machine damage can result.

WARNING!!!!

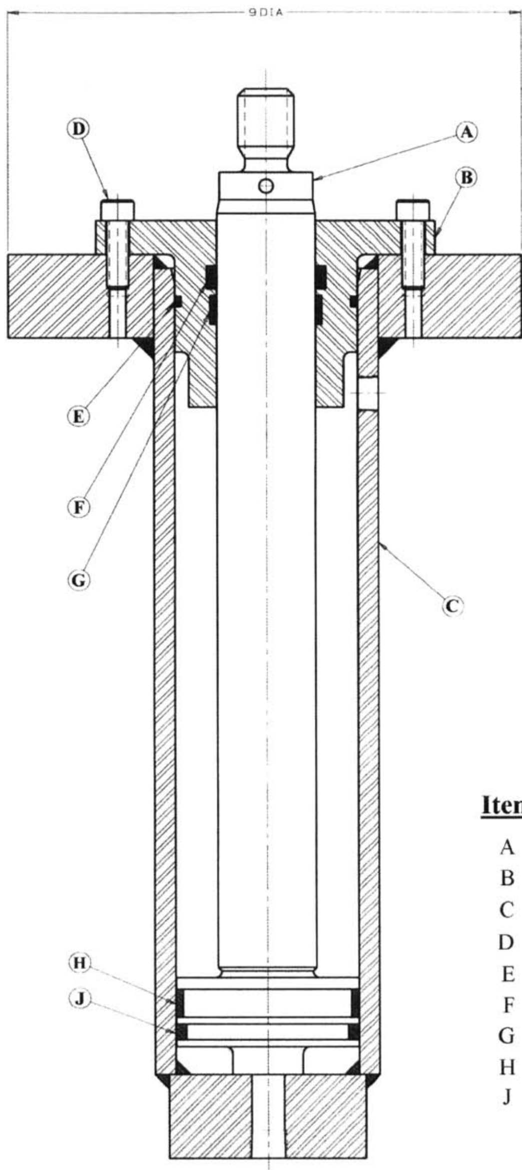
Only use Hydraulic oil in this machine DTE 24 hydraulic oil is recommended.
Do not use transmission fluid in this press, the warranty will be void and this fluid will damage the seals.

PROBLEM & SOLUTIONS		
Ram moves in the neutral position	4-way valve is not functioning correctly	Test 4 way valve for proper function
Ram runs jerky while moving up and down	Air in the system	Self-bleeding system. Continue to run ram up & down aprox. 15 times.
Machine will not build desired pressure	Relief valve needs to be reset Hydraulic hoses connected incorrectly or in reverse	Remove octagon cap from back of manifold and adjust set screw to correct pressure. WARNING – Do not exceed 2413 PSI for 10 tons and 3145 psi for 25 tons. Make sure the hose on top of the cylinder is connected on the left side of the valve by the gauge.
Pins are shearing or bending	Relief valve needs to be reset	Remove octagon cap from back of manifold and adjust set screw to correct pressure. WARNING – Do not exceed 2413 PSI 10 tons and 3145 psi for 25 tons
Oil leaks around the ram	Cylinder seals need replacing	Replace cylinder seals
Oil leaks around holes other than the ram	Bolts need to be tightened.	Tighten bolts around the ram.
Ram will not extend the full 10 inches.	Oil level is too low.	Re-fill the reservoir with oil or add oil up to the fill hole with the elbow removed.
Hydraulic gauge will not read pressure	Hydraulic gauge is bad Hydraulic hoses connected in reverse	Replace the hydraulic gauge Switch the hydraulic lines
Motor will not start	No power to it, Power switch is bad	Double check the electrical cord. Trouble shoot power switch
Motor overheats and shuts down	Duty cycle time is exceeded Too long of extension cord is being used.	Check the duty cycle time on the motor. Extension cord will lower the Amps and will cause overheating of the motor. Remove cord.
Motor runs but ram will not move	Motor runs in reverse rotation	Check motor wiring diagram on motor and correct motor rotation with the yellow arrow on the motor



ITEM	DESCRIPTION	QTY	10DA Part No.	25DA Part No.	REMARKS
1	Frame	1	86517	86684	
2	1/2" - 13NC x 2 3/4"	4	43355	43355	LG. Hex Cap Screw
3	1/2" Channel Washer	4	43657	43657	
4	Workhead Assembly	1	716514	716640	
5	1/2" Lock Washer	4	43647	43647	
6	1/2" - 13 Hex Nut	4	43916	43916	
7	Base Angle	2	85189	978	
8	1/2" - 13NC LG.	4	43349	43347	Hex Cap Screw
9	Table Pin	2	86520	85407	
9A	Retaining Ring	2	43975	76818	
11	Table Channel	1	86692	86682	
12	1/2" Lock Washer	4	43647	43644	
13	1/2" - 13 Hex Nut	4	43916	43916	
20	Nose Piece	1	86691	86683	
23	Hydraulic Power Unit	1	300266PU	300265PU	does not include Gauge, Fittings, Hoses and Valve
	Gauge, Fittings, Hoses and Valve	1	300266KIT	300265KIT	Gauge, Fittings, Hoses and Valve
24	5/16" - 18NC x ½"	4	43313	43313	LG. Hex Cap Screw
25	5/16" Flat Washer	4	43632	43631	
27	Warning Label	1	84487	84487	(See Page 10)
28	Warning Label	1	84399	84399	(See Page 10)
29	3-IN-1 Warning Label	1	300168	300168	(See Page 10)
30	Safety Instructions	1	76462	76462	(See Page 10)
31	Warning Label	1	84395	84395	(See Page 10)
32	DAKE Name Plate	1	86533	86534	(See Page 10)
33	Made In USA Plate	1	76936	76936	(See Page 10)
34	Table Plates	2	85427	85508	
	Conversion tons to psi Label	1	79955	79964	CONVERSION CHART LABEL
	PARTS NOT ILLUSTRATED				
	Breather Vent and elbow	1	300267	300267	Reservoir fill port
	Eyebolts	2	N/A	300284	
	Triangular Snap Hooks	4	N/A	300285	
	Coil Chain	2	N/A	78477	
	Gauge	1	301315	301316	Reads in tons / psi
	Gauge	1	301315	300268	Reads in bar / psi
	Reservoir	1	300269	300269	2 gallon
	Optional check valve	1	302071	302071	Check valve
	Optional relief valve	1	301949	301949	290-3625 psi or 20-250 bar
	Optional relief valve	1	302197	302197	43.5-435 psi or 3-30 bar
	Bolts	4	43401	43401	Mounting bolts for valve only
	Bolts	4	76749	76749	Mounting bolts for valve and relief valve or check valve
	Bolts	4	302221	302221	Mounting bolts for valve, check valve and relief valve.

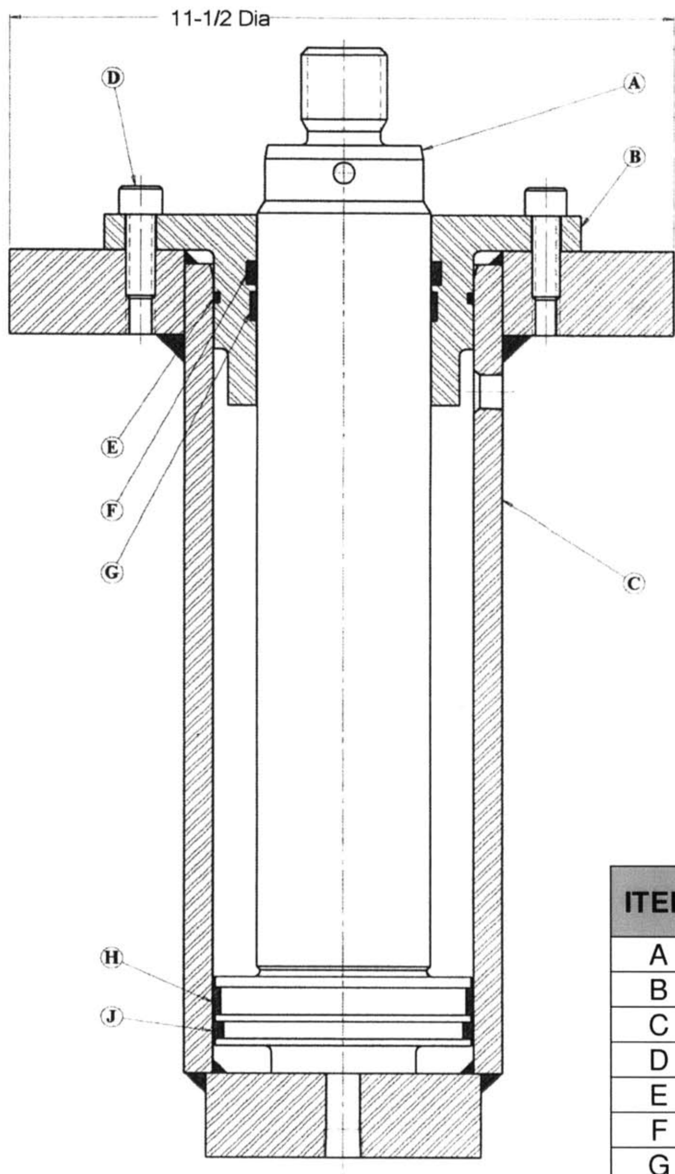
Force 10DA Workhead



10 ton workhead
3-1/4" Dia. Bore
1-3/4" Dia. Rod
10-1/4" Actual Stroke
10" Rated Stroke
Total Wt. = 66#

Item	Description	Part No.
A	Piston	86690
B	Cylinder Flange	86689
C	Cylinder	86688
D	Socket Head Cap Screw	43450
E	O-Ring	78483
F	Seal	78484
G	Wear Ring	78485
H	Wear Ring	78486
J	O-ring seal	78487

Force 25DA Workhead

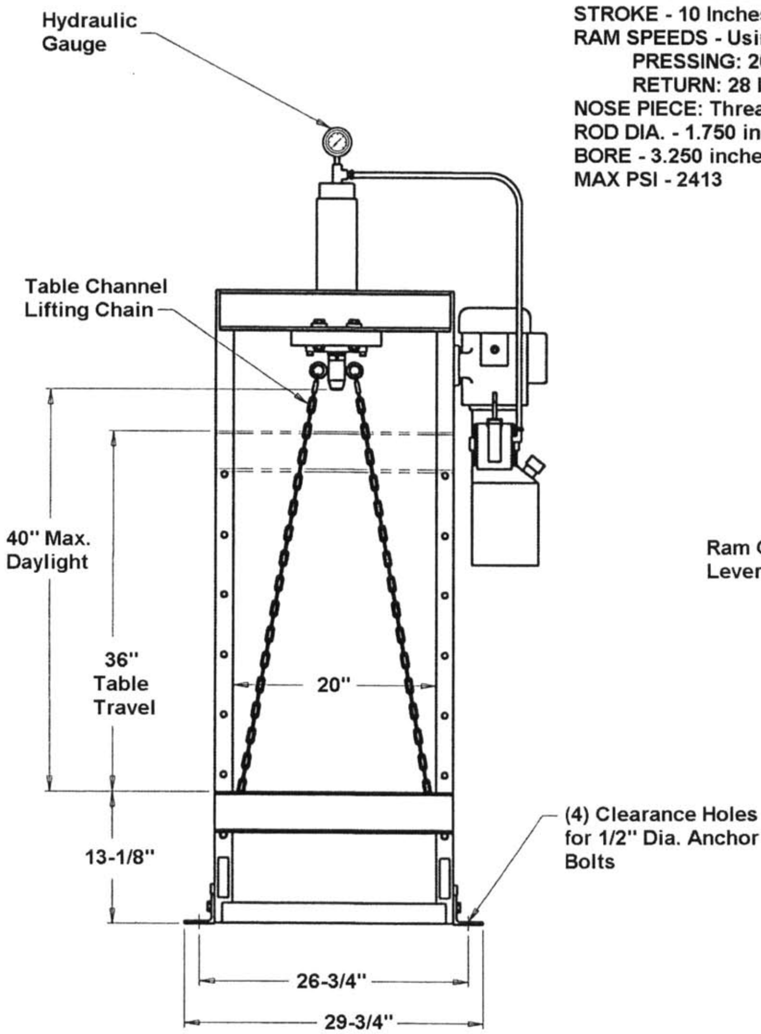


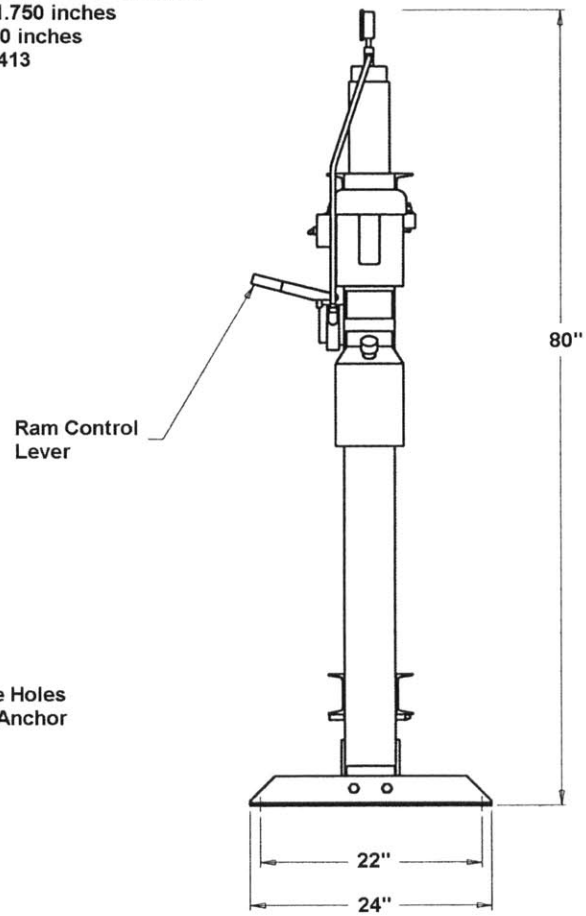
25 ton Workhead
4-1/2" Dia. Bore
3" Dia. Rod
10-1/4" Actual Stroke
10" Rated Stroke
Total Wt. = 127#

ITEM	DESCRIPTION	PART NO.
A	Piston	86463
B	Cylinder Flange	86462
C	Cylinder	86461
D	Socket Head Cap Screw	43471
E	O-Ring	79881
F	Seal	79880
G	Wear Ring	78486
H	Wear Ring	79840
J	O-Ring	79882
Complete Workhead Assembly		716640
Cylinder Repair Kit (Includes items E, F, G, H, J)		716698

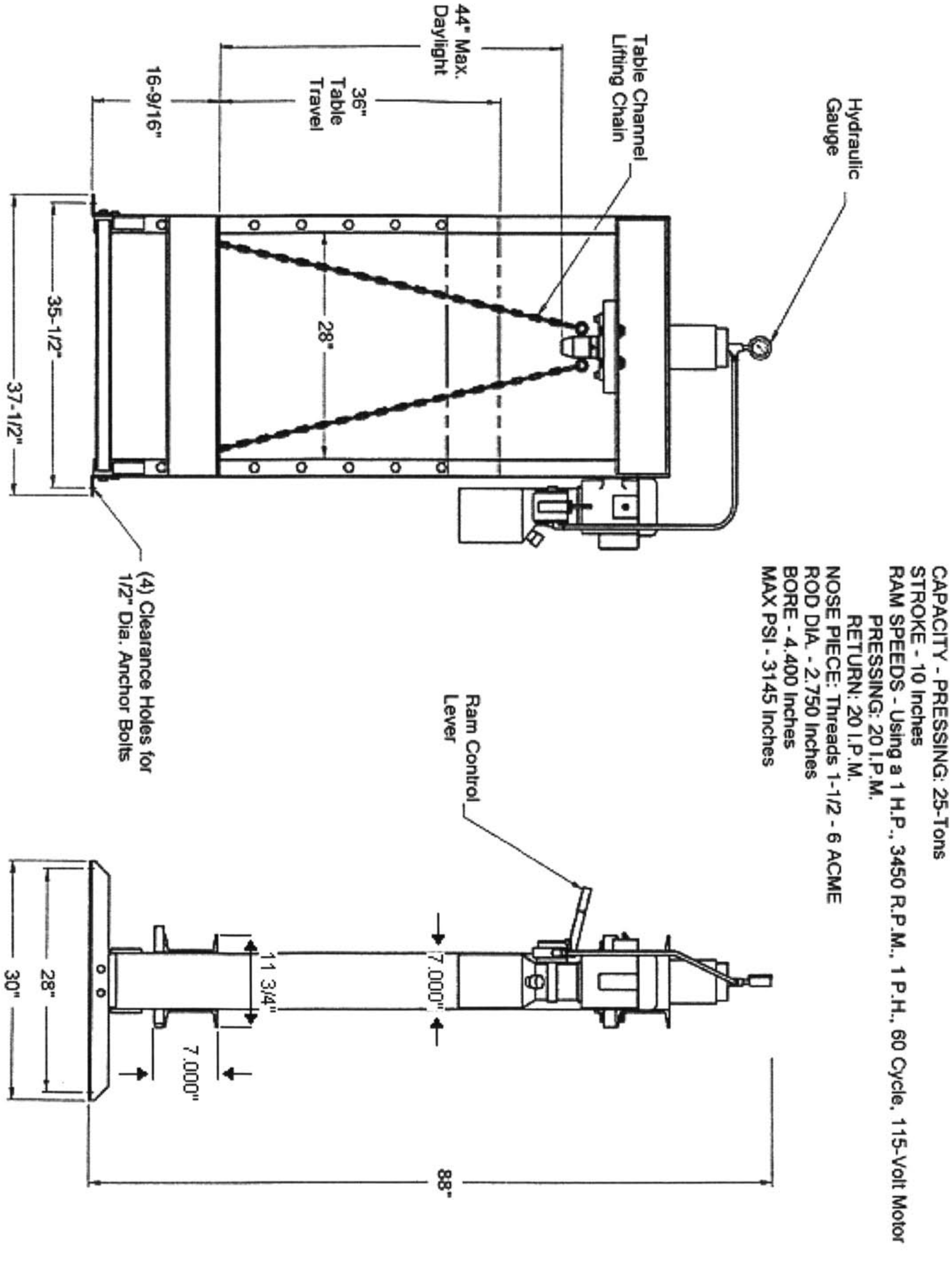
FORCE 10DA - Specifications

CAPACITY - PRESSING: 10-Tons
STROKE - 10 Inches
RAM SPEEDS - Using a 1 H.P., 1725 R.P.M., 1 P.H., 60 Cycle, 115-Volt Moto
PRESSING: 20 I.P.M.
RETURN: 28 I.P.M.
NOSE PIECE: Threads 1-8 Acme
ROD DIA. - 1.750 inches
BORE - 3.250 inches
MAX PSI - 2413





FORCE 25DA - Specifications



Safety

This is the safety alert symbol; follow recommended precautions and safe operating practices. When you see this symbol on your press be alert to the potential for personal injury.

Carefully read all safety messages in these instructions and on your press safety signs.

Keep safety labels in good condition. Replace missing or damaged safety labels

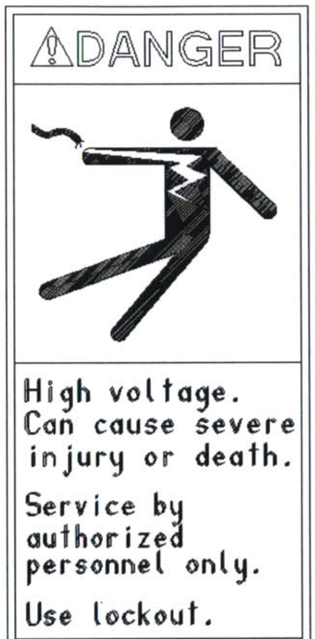
This machine is intended to be operated by one person. This person should be conscious of the press ram movement not only for himself but also for persons in the immediate area of the machine.

Part No: 76462

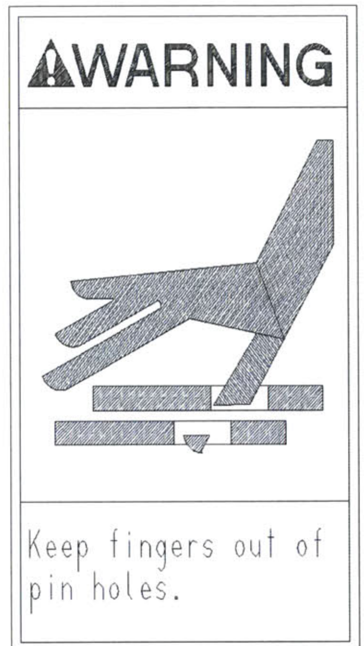
SAFETY INSTRUCTIONS

LOCKOUT PROCEDURE

1. Announce lockout to other employees.
2. Turn power off at main panel.
3. Lockout power in off position.
4. Put key in pocket.
5. Clear machine of all personnel.
6. Test lockout by hitting run button.
7. Block, chain or release stored energy sources.
8. Clear machine of personnel before restarting machine.



Part No: 84395



Part No: 84399

CAUTION

ALL pins must be inserted before applying any pressure.

Read instructions.

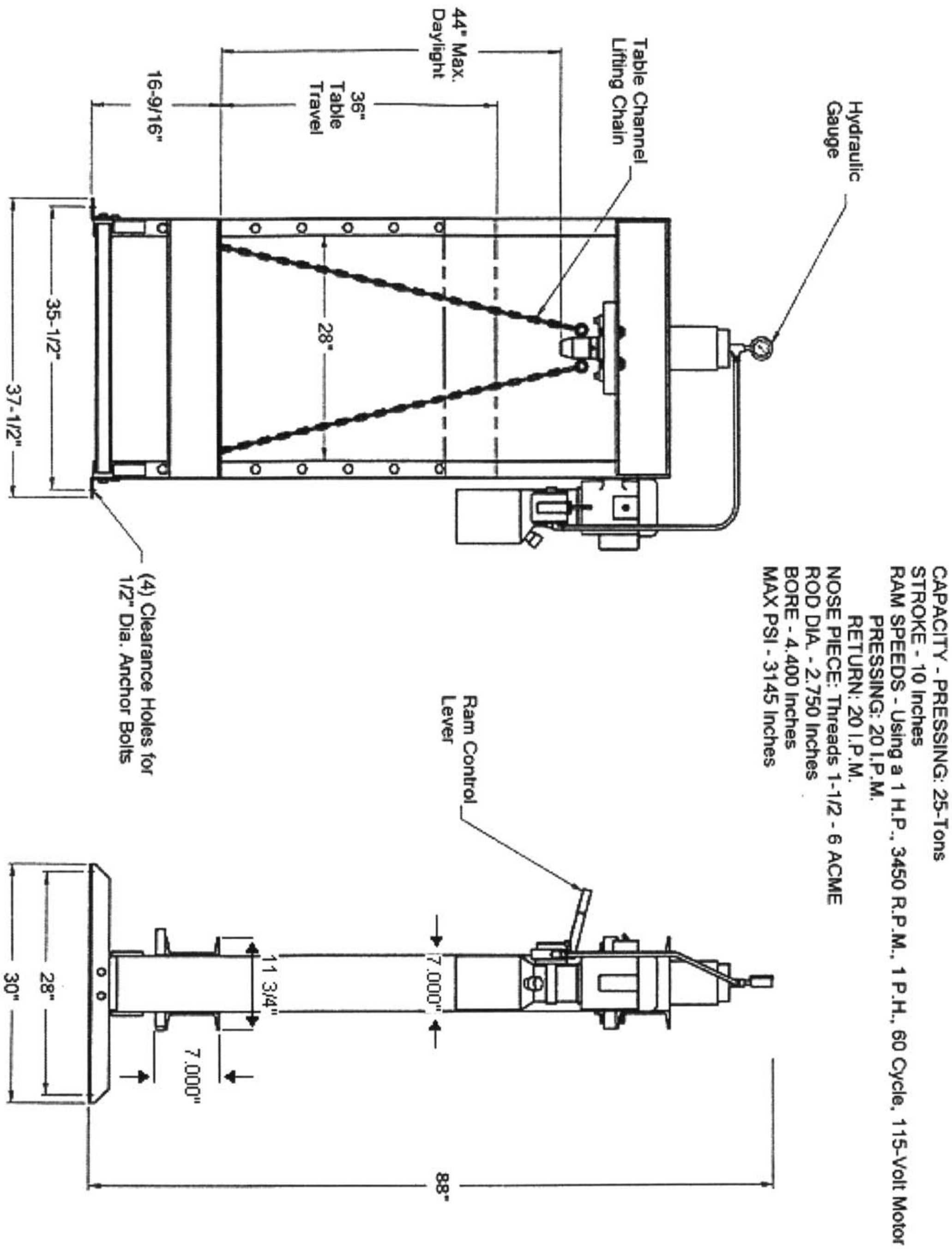
Part No: 84487

This machine is not designed for stripping operations. Personal injury or machine damage can result.

Please contact factory for current prices.

724 Robbins Road
Grand Haven, MI 49417
Phone: 616-842-7110 800-937-3253
Fax: 616-842-0859 800-846-3253
Web: www.dakecorp.com
E-mail: customerservice@dakecorp.com
technicalservice@dakecorp.com

FORCE 25DA - Specifications



INPUTS

MACHINE	**DAITO GA-330**
MATERIAL	**409**
DIMENSIONS	**RECTANGLETUBE**
A - (in)	4
B - (in)	4
C - (in)	0.125
VISING	**SINGLE**
#Total	1
# High (rows)	1
# Wide (Pieces-bottom row)	1
CONDITIONS	**LIFE, DRY**

RECOMMENDATIONS

BLADE	**RX+ X 13'6" X 1-1/4 X 0.042 X 5/8**
BLADE TYPE	RX+
WIDTH	1-1/4
THICKNESS	0.0420
TPI	5/8
LENGTH	13ft 6in
Material Number	93031RPB134115
BAND SPEED	**70**
FEED RATE	**1.06**
AVERAGE CHIP LOAD	0.00021
CUTTING RATE	0.46 in²/min.
CUT TIME	**00:04:14**

NOTES

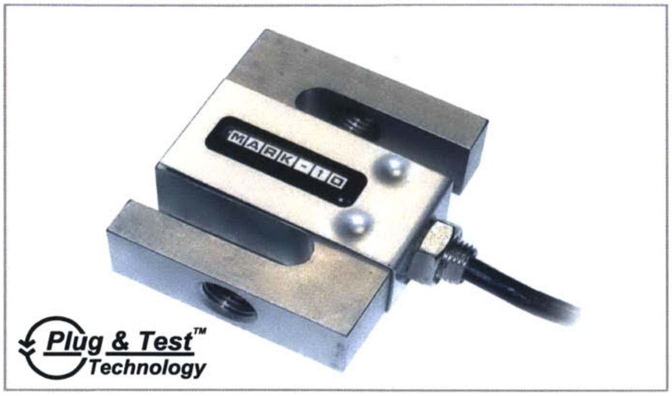
Material entered as 45 HRc.

All calculations are based on sawblade potential and results may vary with actual conditions

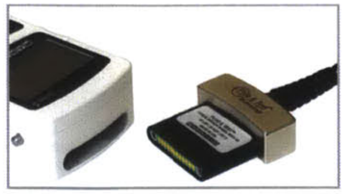
SAWCALC Version 1.0 Web

Data Sheet Plug and Test™ Force Sensors **Series R01**

32-1130 REV 2



Series R01 rugged smart sensors are designed for measuring tension and compression force, with applications in virtually every industry. Durable S-Beam design with threaded holes on two sides allows for many configurations. The sensor can be integrated into an existing system or mounted to a Mark-10 test stand. A shortened cable is available for mounting to an ESM1500LC test stand*. Capacities available from 50 to 10,000 lbF [250 N to 50 kN]. Compatible with Mark-10 indicators (sold separately) through unique Plug & Test™ technology.



< Unique Plug & Test™ technology allows for interchangeable sensors to be used with any Mark-10 indicator. All calibration and configuration data is saved in the smart connector.

< The Plug & Test™ connector locks into the receptacle in the indicator when fully inserted. Dual buttons on the indicator housing release the connector for easy removal. Gold plated spring contacts ensure long lasting and reliable connection.

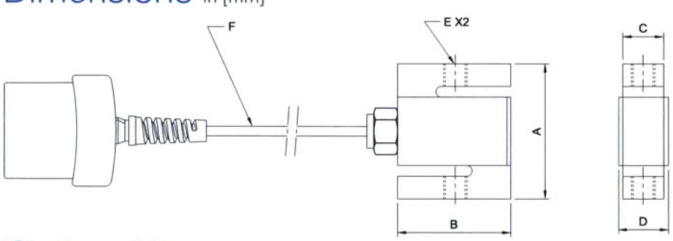
^ Optional AC1018 mounting kit adapts a Series R01 sensor to a Mark-10 test stand.

^ Series R01 sensor with shortened cable is shown mounted to an ESM1500LC test stand.*

Specifications

Accuracy:	±0.15% of full scale + indicator
Safe Overload:	150% of full scale
Weight:	1.9 to 3.0 lb [0.9 to 1.4 kg], depending on model

Dimensions in [mm]



Model No.	A	B	C	D	E	F
MR01-50*						
MR01-100*			0.46 [11.7]	0.65 [16.5]	1/4-28 UNF	
MR01-200*	2.40 [61.0]	2.00 [50.8]				MR01-XXXXX: 20 ft [6 m]
MR01-500*			0.71 [18.0]	0.90 [22.9]		
MR01-1000*					1/2-20 UNF	MR01-XXXX-1* 7.5 in [191 mm]*
MR01-2000*			0.96 [24.4]	1.15 [29.2]		
MR01-5000	3.90 [99.1]	3.00 [76.2]			3/4-16 UNF	
MR01-10000						

Optional Items

AC1018	Mounting kit, Series R01/R03 to test stand (not required for ESM1500)

Capacity x Resolution

Model No.	With Models 7i & 5i indicators						With Model 3i indicator			
	lbF	ozF	gF	kgF	N	kN	lbF	kgF	N	kN
MR01-50*	50 x 0.02	800 x 0.5	25000 x 10	25 x 0.01	250 x 0.1	-	50 x 0.05	25 x 0.02	250 x 0.2	-
MR01-100*	100 x 0.05	1600 x 1	50000 x 20	50 x 0.02	500 x 0.2	-	100 x 0.1	50 x 0.05	500 x 0.5	-
MR01-200*	200 x 0.1	3200 x 2	-	100 x 0.05	1000 x 0.5	1 x 0.0005	200 x 0.2	100 x 0.1	1000 x 1	-
MR01-500*	500 x 0.2	8000 x 5	-	250 x 0.1	2500 x 1	2.5 x 0.001	500 x 0.5	250 x 0.2	2500 x 2	-
MR01-1000*	1000 x 0.5	16000 x 10	-	500 x 0.2	5000 x 2	5 x 0.002	1000 x 1	500 x 0.5	5000 x 5	-
MR01-2000*	2000 x 1	32000 x 20	-	1000 x 0.5	10000 x 5	10 x 0.005	2000 x 2	1000 x 1	10000 x 10	-
MR01-5000	5000 x 2	-	-	2500 x 1	25000 x 10	25 x 0.01	5000 x 5	2500 x 2	-	25 x 0.02
MR01-10000	10000 x 5	-	-	5000 x 2	50000 x 25	50 x 0.02	10000 x 10	5000 x 5	-	50 x 0.05

* Add suffix "-1" for shortened cable, for use on the ESM1500LC test stand. Ex: MR01-1000-1. "-1" sensors include hardware for mounting to the ESM1500LC's crosshead.

MARK-10

Mark-10 Corporation ■ www.mark-10.com ■ info@mark-10.com
Toll-free: 888-MARK-TEN ■ Tel: 631-842-9200 ■ Fax: 631-842-9201

3 YEAR WARRANTY

Specifications subject to change without prior notice

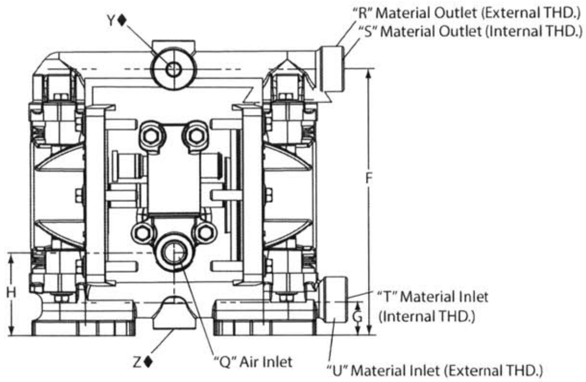
SALES & ENGINEERING DATA

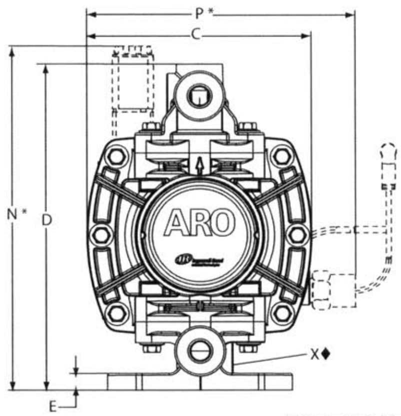
RATIO SERIES:	1:1
FLUID PSIG RANGE:	10 - 125

PX01X-XXX-XXX-AXXX
1/4" DIAPHRAGM PUMP

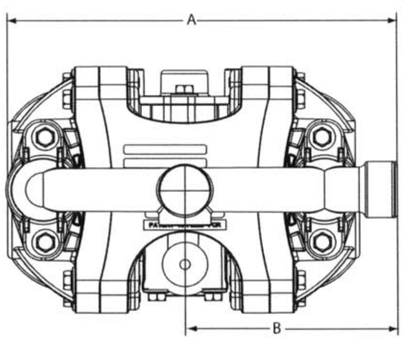
RELEASED: 3-7-13
REVISED: 7-14-14
(REV. C)

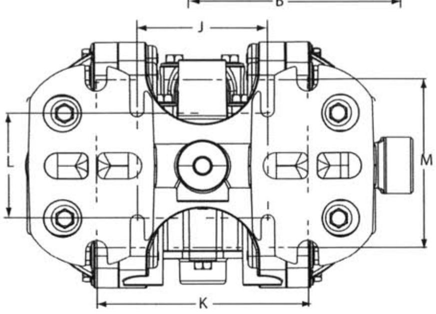
DIMENSIONAL DATA





* Dimensions N & P are for models PE01X only.
Dotted lines show options for PE01X pumps.





♦ X, Y, Z are for multiport models (HEX, HLX, HRX) only.

SPECIFICATIONS

Model Series PD01X-XXX-XXX-AXXXX, PE01X-XXX-XXX-AXXX
Pump Type. . Non-Metallic Air Operated Double Diaphragm
Ratio. 1:1
Air Inlet. . . . . Q - 1/4 - 18 PTF SAE Short
Weight. . . . . . Polypropylene. . . . . 2.86 lbs (1.30 kgs)
PVDF. . . . . 3.88 lbs (1.76 kgs)
Acetal. . . . . 3.52 lbs (1.60 kgs)

PERFORMANCE

Maximum Air Inlet Pressure . . . . 125 psig (8.6 bar)
Minimum Air Inlet Pressure. . . . . 10 psig (0.69 bar)
Maximum Outlet Pressure. . . . . 125 psig (8.6 bar)
Maximum Flow Rate. . . . . 5.3 gpm (20 lpm)
Maximum Material Inlet Pressure. . . . 10 psig (0.69 bar)
Displacement / Cycle @ 125 psig. . . . 0.019 gal / 0.072 ltrs
Maximum Particle Size . . . . 1/16" dia.(1.6 mm)
Maximum Temperature Limits (diaphragm / ball / seat material)

Acetal. 10° to 180° F (-12° to 82° C)
E.P.R. / EPDM. . . . . -60° to 280° F (-51° to 138° C)
Kynar® PVDF. . . . . 10° to 200° F (-12° to 93° C)
Hytrel® . . . . -20° to 150° F (-29° to 66° C)
Neoprene . . . . 0° to 200° F (-18° to 93° C)
Nitrile® . . . . 10° to 180° F (-12° to 82° C)
Polypropylene. . . . . 35° to 175° F (2° to 79° C)
Viton® . . . . -40° to 350° F (-40° to 177° C)
Santoprene®. . . . . -40° to 225° F (-40° to 107° C)
PTFE. . . . . 40° to 225° F (4° to 107° C)

Noise Level @ 70 psig, 60 cpm. . . . . 62.3 dB(A)①

① The pump sound pressure levels published here have been updated to an Equivalent Continuous Sound Level (L_{Aeq}) to meet the intent of ANSI S1.13-2005, CAGI-PNEUROP S5.1.

Mounting Adapter Plate Optional Accessory Kit (24123879) available. Please contact your nearest **ARO / Ingersoll Rand** customer service or distributor for details.

DIMENSIONS

Dimensions shown are for reference only, they are displayed in inches and millimeters (mm).

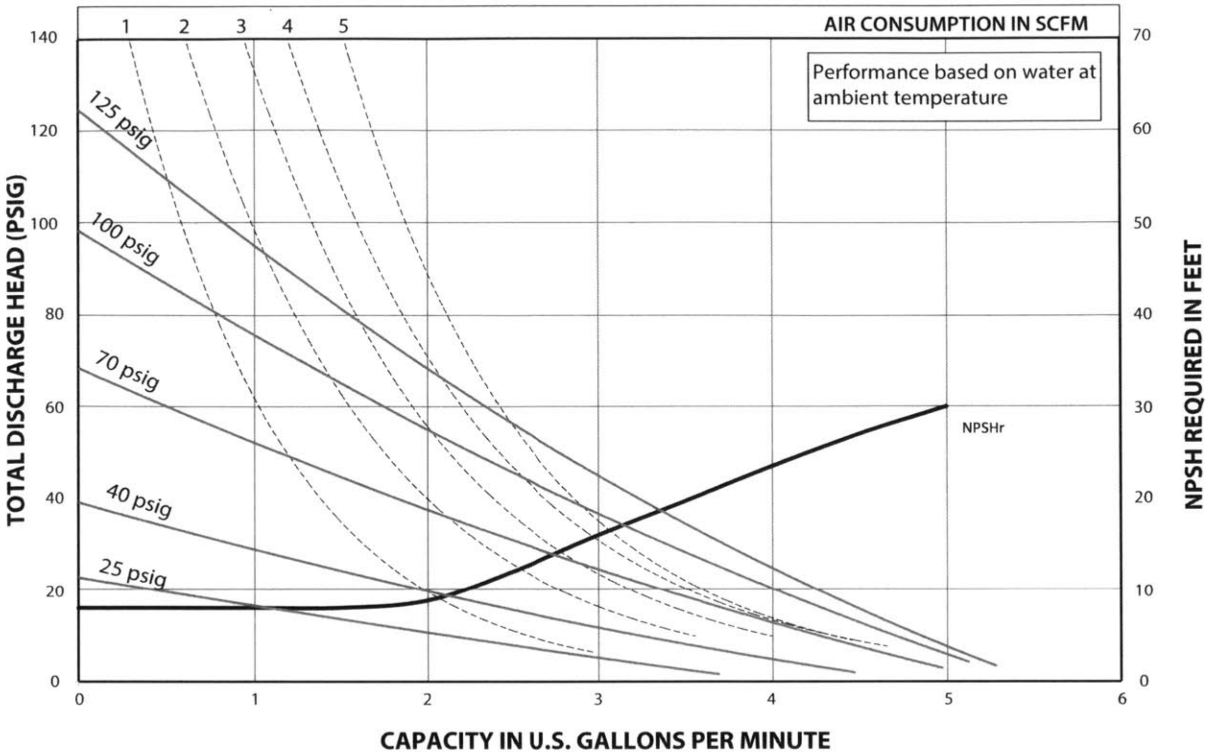
A - 7.2" (182 mm)	H - 1.9" (48.6 mm)	Q - 1/4 - 18 PTF SAE Short	Z - 1/4 - 18 PTF SAE Short
B - 3.9" (100.0 mm)	J - 2.4" (61 mm)	R - 3/4-14 NPTF	
C - 4.6" (117.0 mm)	K - 3.9" (99 mm)	S - 1/4 NPTF / BSPT Hybrid*	
D - 6.8" (173.0 mm)	L - 2.1" (53 mm)	T - 1/4 NPTF / BSPT Hybrid*	
E - 0.3" (8.8 mm)	M - 3.2" (81 mm)	U - 3/4-14 NPTF	
F - 6.1 " (156 mm)	N - 7.2" (184 mm)	X - 1/4-18 NPTF / BSPT Hybrid	
G - 0.8" (20.7 mm)	P - 5.6" (142.2 mm)	Y - 1/4 NPTF / BSPT Hybrid	

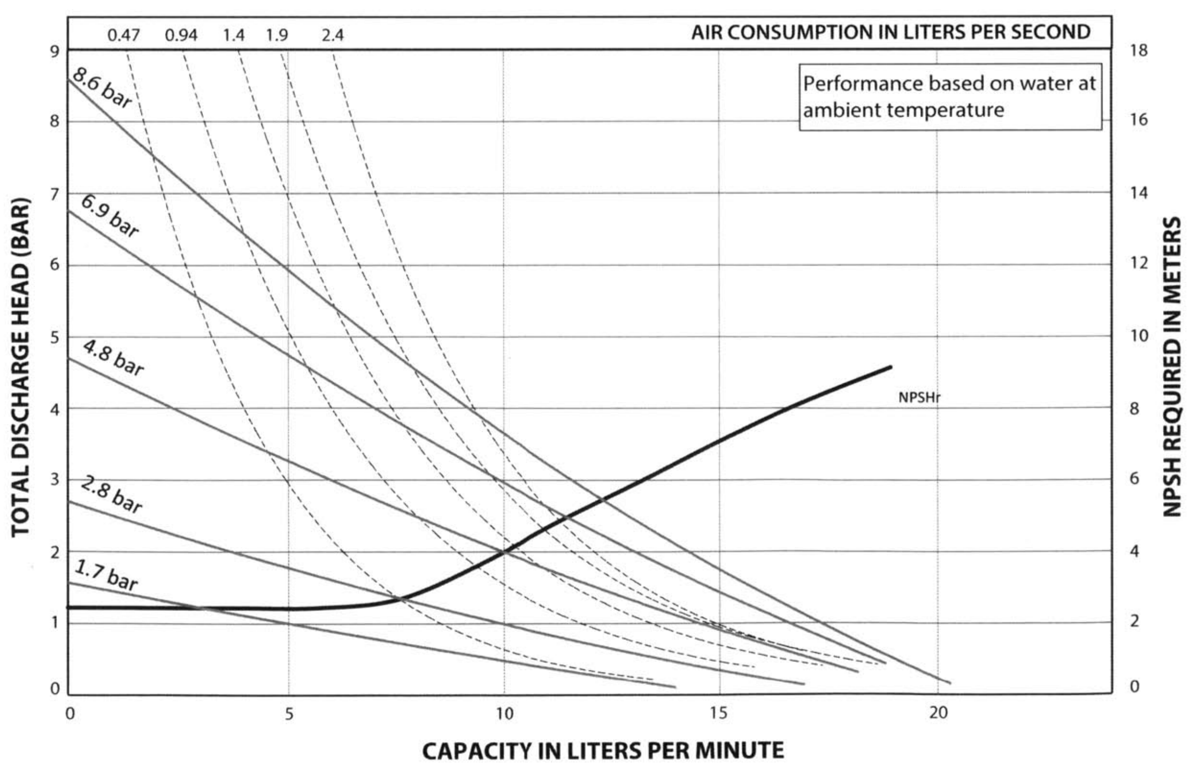
* Multiport Options Discharge Manifold has (2) and Inlet Manifold has (3).

INGERSOLL RAND COMPANY LTD
209 NORTH MAIN STREET – BRYAN, OHIO 43506
(800) 495-0276 • FAX (800) 892-6276
ingersollrandproducts.com

ARO Ingersoll Rand

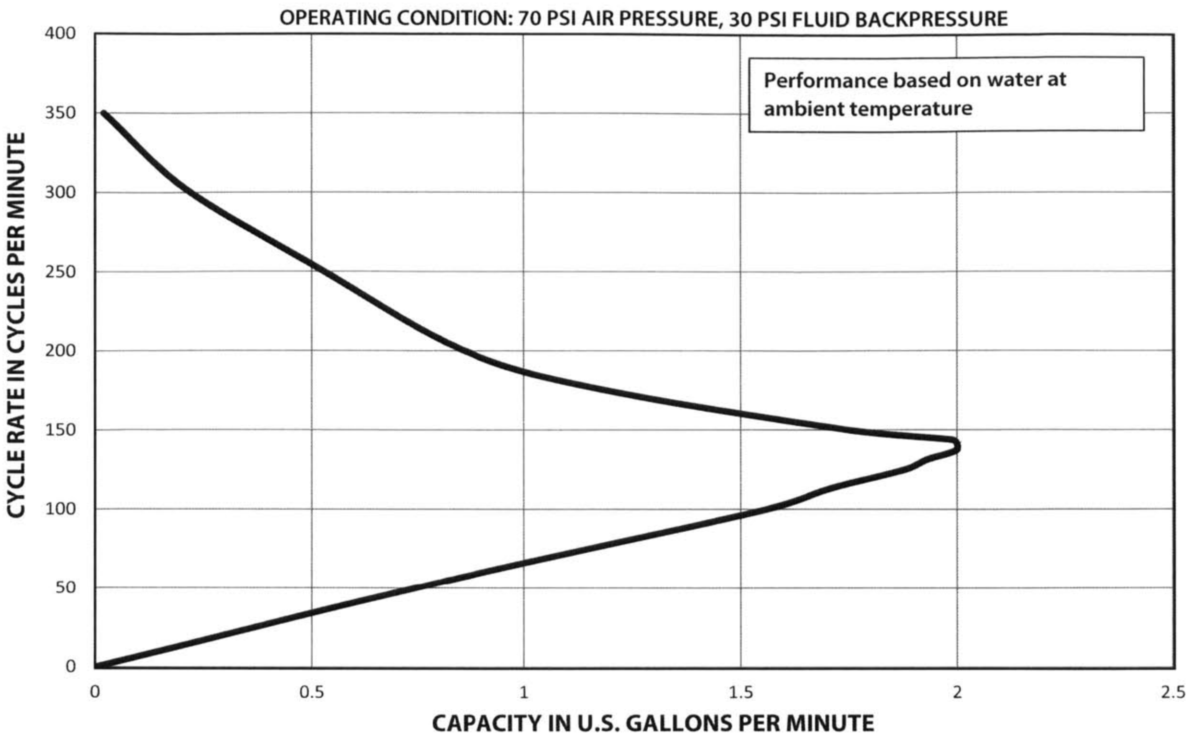
PD01P-XXS-XXX 1/4" NON-METALLIC DIAPHRAGM PUMP

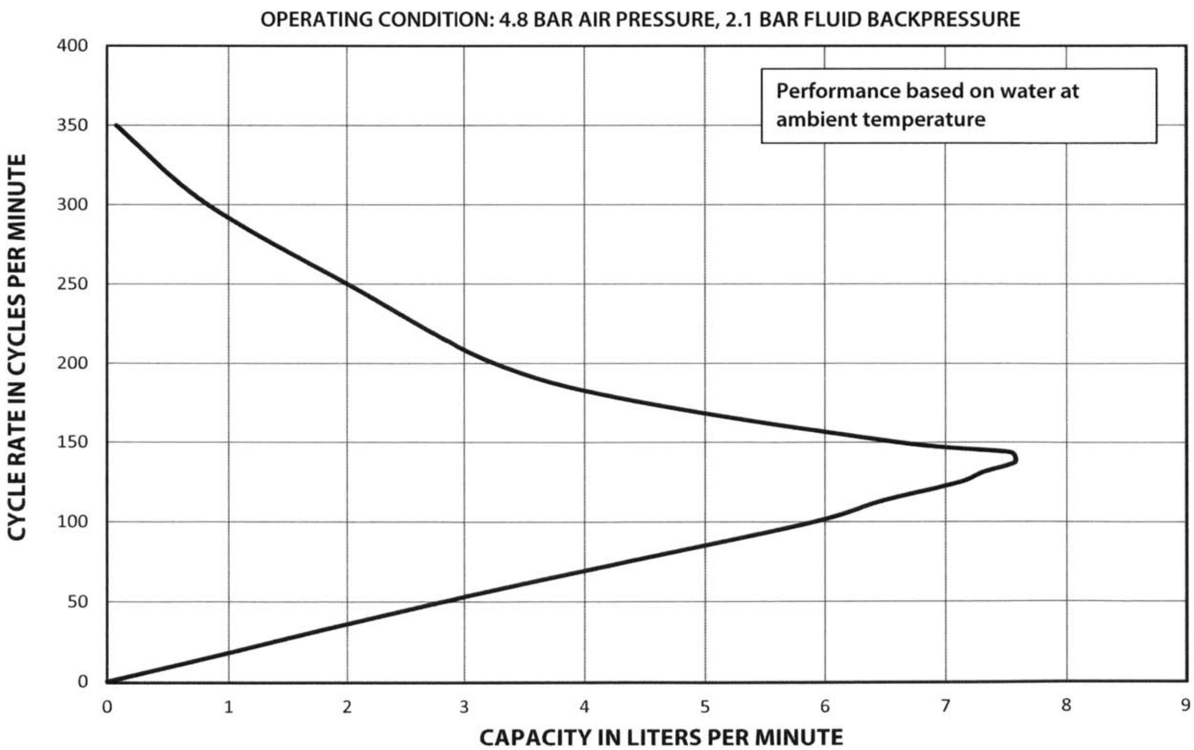




PERFORMANCE CURVES

PE01X-XXX-XXX SOLENOID-CONTROLLED TIME-BASED FLOW RATE





SFN Series
Single Filter Housings
Bolt and Nut Closure

neo•PURE™

Residential / Commercial / Industrial Filtration Applications

Standard Features

- Manufactured in USA
- Designed for commercial or industrial filter applications
- Heavy-duty 304L or 316L stainless steel construction for maximum durability and corrosion resistance
- Bolt and nut closure allow for quick cartridge change-outs (T-handle optional) and inline connections for easy installation
- Uses double open-end (DOE) cartridges
- Available with 1/4", 3/8", 1/2", 3/4", and 1" connections
- Both ends of cartridge have knife-edge seals to help eliminate potential bypass

Applications

- Water
- Food and Beverage
- Electronics
- Coolants
- Oil / Gas
- Paints / Inks / Coatings
- Paper and Pulp
- Chemicals
- Desalination Prefiltration
- Cooling Tower Filtration

USA MADE

Specifications, Operating Parameters and Options

Maximum Operating Pressure
250 psig (17 bar) @ 275°F (135°C)

Connections
Inlet/Outlet: 1/2", 3/4", or 1" FNPT
Optional: 1" RF flange, BSP or 1" sanitary ferrules
Drain Ports: 1/8" FNPT

Materials of Construction
Head: 304L, 316L or Brass Nickel-Plated
Shell/Connections: 304L or 316L stainless steel
Drain: Stainless steel plug

Gaskets
Standard: Buna N (FDA grade)
Optional: EPR, silicone, Teflon, Viton, neoprene, vellumoid

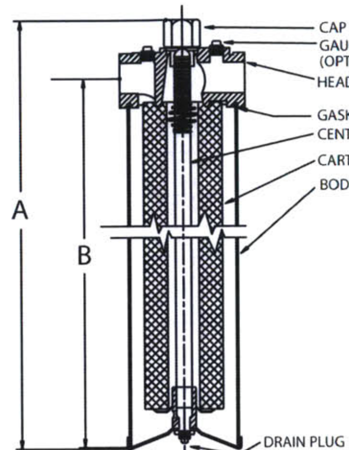
Finish
Polycoat on exterior surfaces

Options
1/4" gauge ports In/Out
Tee handle
Variable seal (spring loaded)
Vent screw outlet

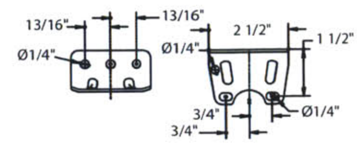
MODEL	QUANTITY (LENGTH) OF CARTRIDGES	RATED FLOW CAPACITY* GPM (LPM)	MAXIMUM DIAMETER CARTRIDGE	DRAIN SIZE	STANDARD		SPRING LOADED	
					A	B	A	B
SFN-x	1 (4-7/8")	3.5 (132)	2-3/4"	1/8"	8-7/8" (22.5)	6-15/16" (17.6)	9-1/2" (24.1)	7-9/16" (19.2)
SFN-1	1 (9-3/4")	7 (26.5)	2-3/4"	1/8"	13-3/4" (34.9)	11-13/16" (33.0)	14-3/8" (36.5)	12-7/16" (31.6)
SFN-2	1 (20")	14 (53.0)	2-3/4"	1/8"	23-7/8" (60.6)	21-15/16" (55.7)	24-1/2" (62.2)	22-9/16" (57.3)
SFN-3	1 (30")	21 (79.5)	2-3/4"	1/8"	33-7/8" (86.0)	31-15/16" (81.1)	34-1/2" (87.6)	32-9/16" (82.7)

* Based upon 7 gpm per 10" length with a 25 micron wound cartridge at 2 PSID clean and viscosity of 1 cps. Flow rates are approximate. Actual flow rates are based upon fluid, viscosity, cartridge type, micron ratings and other factors.

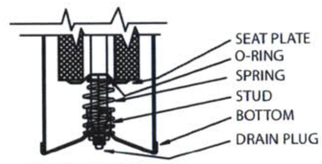
Dimensions



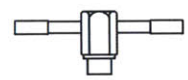
STANDARD STYLE



MOUNTING BRACKET



SPRING LOADED STYLE



TEE HANDLE CAP NUT

Ordering Guide (Example: SFN-1B-316L4-FL-T-S)

SFN –	1B –	316L	4 –	FL –	T –	S
MODEL	**CARTRIDGE LENGTH**	**MATERIAL**	**INLET/ OUTLET SIZE**	**CONNECTION TYPE**	**OPTIONS**	**GASKET**
SFN = 304L Stainless Steel Head Nut Double Open End SFBH = Brass Nickel-Plated Head Nut Double Open End	1 = 9-3/4" 1B = 10" (9-7/8" MB and SV) 2 = 20" 2B = 19-1/2" 3 = 30" 3B = 29-1/4" x = 4-7/8" available	Blank = 304L (standard) 316L = 316L	4 = 1/2" 6 = 3/4" 8 = 1"	Blank = FNPT (standard) FL = Flange 1" only BP = BSP TC = Ferrules 1" only	Blank = None (standard) GP = 1/4" gauge ports IN/OUT T = Tee handle DSG = Variable seal (spring loaded) V = Vent screw outlet	Blank = Buna N (standard) E = EPR S = Silicone T = Teflon N = Neoprene Vell = Vellumoid

Cartridge Options

Available in 9-3/4", 20" and 30" Lengths

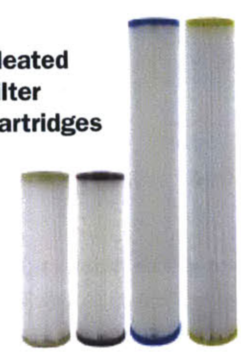
Meltblown Sediment Cartridges

For more information, see **MB Series Brochure**

String Wound Cartridges

For more information, see **WPP Series Brochure**

Pleated Filter Cartridges



NeoLogic SOLUTIONS Filtration Division

9450 SW Gemini Dr, ECM #83358, Beaverton, OR 97008
Tel 855-896-3525 | Fax 866-409-9622
www.neologicsolutions.com
email: info@neologicsolutions.com
STUART, FL | BEAVERTON, OR | GREENVILLE, SC | SAN DIEGO, CA

Questions? Ask one of our Service Representatives: Mon-Fri 8a-8p, Sat 8:30a-4:30p EST

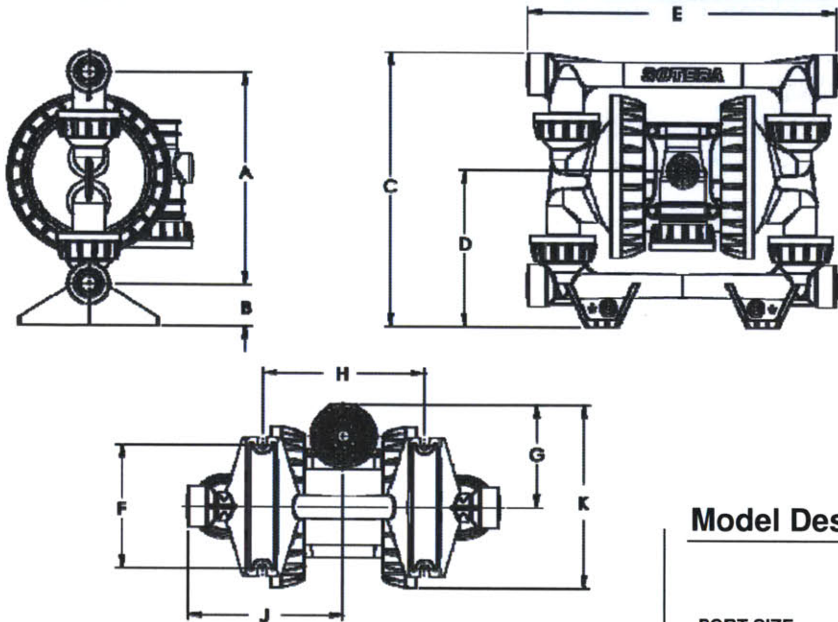
We ship 6 days a week! FedEx

10008A022814

SOTERA SYSTEMS

1/2" Air Operated Diaphragm Pump S & E Data Sheet

Model SP100-05X-XX-XXX-X



Dimension	Inches	Metric
A	8.245"	209.42 mm
B	1.625"	41.28 mm
C	10.70"	271.78 mm
D	6.123"	155.524 mm
E	12.000"	304.80 mm
F	4.875"	123.825 mm
G	4.031"	102.387 mm
H	6.250"	158.75 mm
J	6.000"	152.40 mm
K	7.206"	183.032 mm

Pump Technical Data

Pump Type: Non-Metallic Air Operated Double Diaphragm

Models: See Model Description Chart for "-XXX"

Construction Materials: See Model Description Charts

Maximum Air Inlet Pressure: 100 p.s.i.g. (6.9 bar)

Maximum Material Inlet Pressure: 10 p.s.i.g. (.69 bar)

Maximum Outlet Pressure: 100 p.s.i.g. (6.9 bar)

Air Consumption (@ 40p.s.i): 0.65 c.f.m. / gallon (approx.)

Maximum Flow Rate (flooded inlet): 17.5 g.p.m. (66.23 l.p.m.)

Displacement / Cycle @ 100p.s.i.g.: 0.036 gal. (0.14 lit.)

Maximum Particle Size: 3/32" dia. (2.4 mm)

Maximum Temperature Limits (diaphragm / ball / seat material):

Acetal .... 10° to 180° F (-12° to 82° C)

Hytrel® .... -20° to 150° F (-29° to 66° C)

PVDF .... 10° to 200° F (-12° to 93° C)

Polypropylene.................... 35° to 175° F (2° to 79° C)

Santoprene®..................... -40° to 225° F (-40° to 107° C)

PTFE............................. 40° to 225° F (4° to 107° C)

Dimensional Data (box): 11-3/4"(H) x 14-1/4" (W) x 9-1/8" (D)

Noise Level: 75.0 db (A) (@ 70 p.s.i., 60 c.p.m.)

Weight Information:

Pump Material	Pump Weight lbs	Pump Weight Kg	Shipping Weight lbs	Shipping Weight Kg
Polypropylene	5.7	2.6	7.2	3.3
PVDF	7.2	3.3	8.7	4.0
Groundable Acetal	6.8	3.1	8.3	3.8

Model Description Information

SP100 - 05 X - X X - X X X - X

PORT SIZE

FLUID CONNECTION
- N - 1/2-14 NPTF-1
- B - Rp 1/2 (BSPP)

DRIVE MATERIAL OF CONSTRUCTION
- P- POLYPROPYLENE
- C - GROUNDABLE NYLON

WET-END MATERIAL OF CONSTRUCTION
- P - POLYPROPYLENE
- D - GROUNDABLE ACETAL
- F - PVDF

DIAPHRAGM
- S - SANTOPRENE®
- H - HYTREL®
- T - PTFE WITH SANTOPRENE® BACKER

BALLS
- S - SANTOPRENE®
- H - HYTREL®
- T - PTFE

SEATS
- S - SANTOPRENE®
- H - HYTREL®
- P - PP (w/PTFE seal)
- F-PVDF (w/PTFE seal)

OPTIONS

KIT

S05 X X X

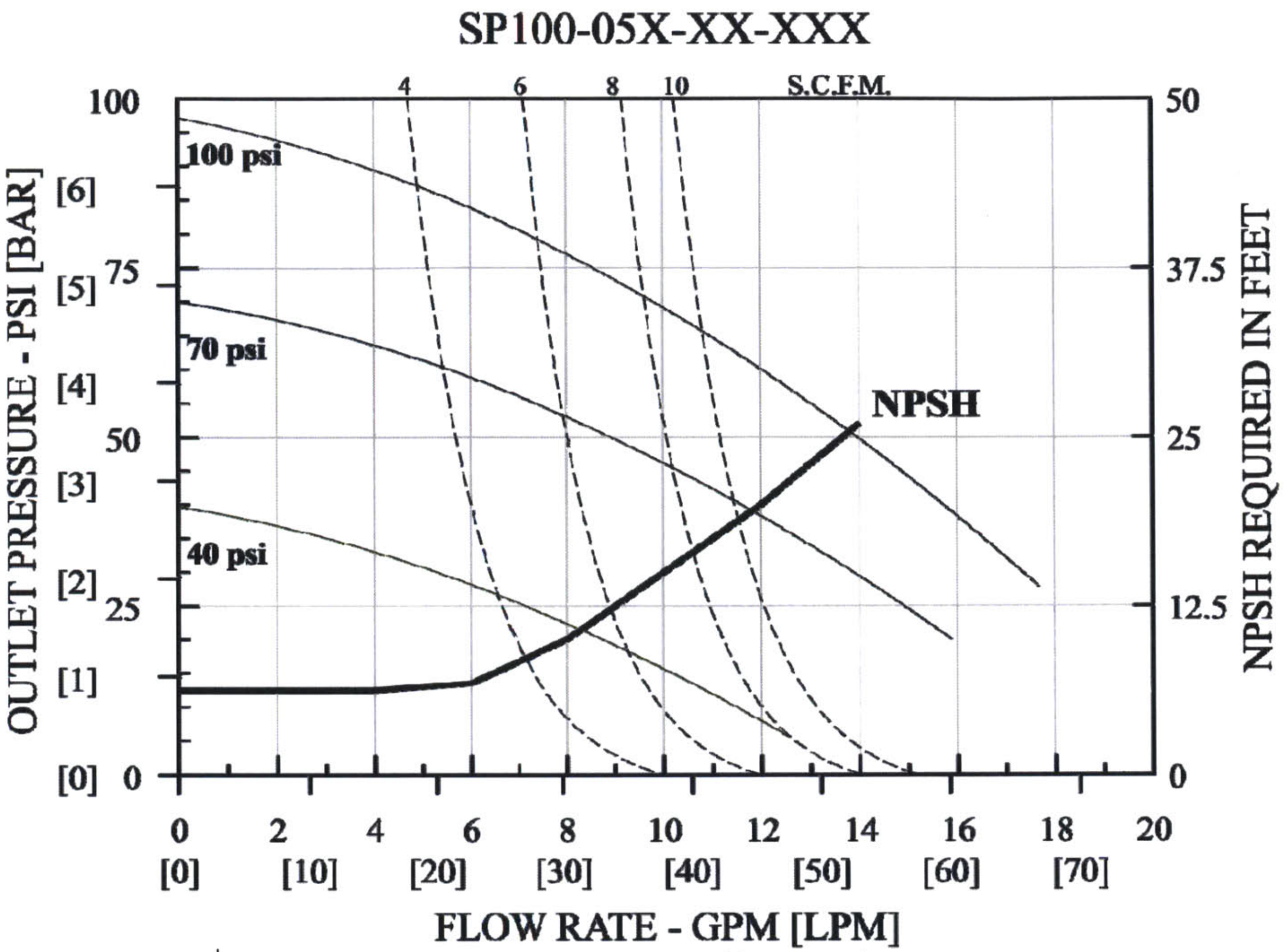
FLUID SECTION SERVICE KIT

DIAPHRAGM

BALLS

SEATS

Tuthill
Tuthill Transfer Systems
Fort Wayne, Indiana
(800) 634-2695
www.tuthill.com



(Performance based on water at ambient temperature)

ACCESSORIES

The following accessories are available to customize your SP100 AOD Pump.

Contact your Sotera Representative if you have questions, or would like to order any of the accessories listed below.

Part #	Accessory	Description
KITS05WMA	Wall Mount Bracket	Stainless steel bracket for wall mount applications of the SP100 AOD Pump.
KITS05FRH	Filter / Regulator Kit	Air line filter, regulator, and hose
KITS05MUF	Muffler	Muffler for air exhaust
KITS05WCH	Assembly Wrench	Special service tool for use on manifold and fluid retainer rings
KIT180MAMPS	Tote Plate (for IBC tote)	Tote plate, attaching hardware

Visit us on the web at:

www.sotera.com

Learn more about Tuthill Corporation and our family of high quality, value minded products at:

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SOTERA SYSTEMS
Sotera Systems
8825 Aviation Drive
Fort Wayne, IN 46809
1-800-834-2695

Tuthill

724 Robbins Road
Grand Haven, Michigan 49417
Web: www.dakecorp.com

Phone 616-842-7110 800-937-3253
Fax 616-842-0859 800-846-3253
E-mail : customerservice@dakecorp.com

July 29, 2014

Quote File # [Click **here** and type Quote No]

[Click **here** and type Company Name]
[Click **here** and type Address]
[Click **here** and type City, State & Zip]
Attn: [Click **here** and type Name]

Dear: [Click **here** and type Name]

Subject: Dake/Johnson Horizontal Bandsaws – Made in the U.S.A.

In response to your recent request, we are pleased to submit the following quotation.

Model No.	Model Name	Voltage (Please Specify)	Price US	Delivery (F.O.B. Factory)
85017	JH10W1	120 or 220 1 ph	$5,895	[Click **here** to enter]
85018	JH10W3	220 or 440 3 ph	$5,895	[Click **here** to enter]

Terms: [Click **here** and type terms]

Installation: Installation is the responsibility of the Purchaser. One instruction manual, including operating instructions, is provided at time of shipment. Additional assistance may be obtained from Dake via telephone. If a Service Technician is requested for on-site installation supervision, additional charges will be incurred. These charges will be quoted separately.

Please review the enclosed Dake Standard Terms & Conditions of Sale.

We would like to take this opportunity to thank you for your interest in Dake and want to assure you we are looking forward to entering your purchase order for the earliest possible delivery.

Sincerely,

[Click **here** and type Name]

SPECIFICATIONS

Machine type	Manual horizontal band saw
Blade length	11 foot x 5 inches or (137 inches)
Blade width	1 inch
Wheel diameters	16 inches
Blade speeds	V-belt 4 speed
Minimum/Maximum FPM	50 FPM / 90 FPM / 160 FPM / 270 FPM
Head feed	Hydraulic controlled gravity feed
Vise	Manual screw with quick release
Blade tension	Manual handwheel
Coolant pump	Submersible electric
Bed work area	11 inches x 18 inches
Miter cutting capabilities	45°
Controls	Magnetic starter
Horsepower	1 h.p. Maximum
Weight	935 lbs.
Overall height	75 inches
Base width	30 inches
Depth	65 inches
Lubricant	Wet models use a flood type unit built into the machine (Electric)
Voltage	• Available 120 or 220-volt single phase • Available 220 or 460-volt three phase **Machine should be wired to main service by a qualified Electrician.**
AMP	• 20-amp service for 120/220-volt machine • 16-amp service for 460-volt machine
Compressed Air	Not Available
Operating Temperature	No special operating temperature level

CUTTING CAPACITIES

Degree	Round	Flat
90°	10 inches	5 inches x 18 inches
45°	7 inches	4 inches x 10 inches

OPTIONS

Part Number	Description	Price
20000-00	Caster (Set of 3)	$95.00
20200-00	Stock Stand	$600.00
10590-00	24” Discharge Table (attaches to machine)	$285.00

FEATURES

- Heavy duty, American made medium production saw, comes with one standard Bi-metal blade.
- Hydraulic controlled, gravity head feed, for hands free cutting. Hydraulically variable head feed control for regulation of head feeding rate. Machine automatically shuts off after cut is complete.
- Cast two piece head frame and large pivot bar, for extreme rigidity and long life.
- Counter balanced head for easy one hand lifting.
- Gear box uses only the highest quality bronze and steel gears.
- Gear box is driven via "V" belt and step pulleys for fast speed changes.
- Low voltage switches. Thermo over load protection, Magnetic starter switch low voltage protection.
- Miters up to 45°
- Vise has quick release for quick change over of material sizes. Bronze half nut retracts to allow free travel of the vise. By turning a lever, the vise locks into place ready for clamping.
- Vertically mounted guide arms for more rigidity and straightest cuts. Guides are rollers that are fully adjustable and replaceable.
- Chip brush keeps the gullets of the blade clean.
- Table bed is cast and precision machined for rigidity and quality cutting.
- Cast legs are of a point design. This unique design lets the machine sit flat, even on uneven floor surfaces.
- The wet model machines, incorporate and 120-volt submersible coolant pump with on/off switch. This allows coolant flow to be shut off when cutting dry applications.
- The saw is fully guarded for operator safety.

DAKE STANDARD TERMS & CONDITIONS OF SALE

All proposals and quotations for the original sale of our products are subject to the following terms and conditions:

ACCEPTANCE OF ORDER: All orders are subject to acceptance by Dake at its main office in Grand Haven, Michigan.

PRICES: Unless otherwise agreed to in writing, all prices are F.O.B. our plant in Grand Haven, Michigan. In any event, the quoted prices become invalid sixty (60) days after date of quotation. Unless otherwise specified in Dake's quotation, installation services and final on-site adjustments are not included in the quotation.

TERMS OF PAYMENT: Terms of payment are as stated in Dake's quotation subject to credit approval by our home office. Dake will invoice Purchaser when the equipment is completed and ready for shipment. Payment terms run from invoice date.

TAXES: Prices do not include taxes. If any sales, use or similar tax is payable to Dake in connection with any transaction or part thereof between the Purchaser and Dake with respect to goods delivered, the Purchaser will, upon demand, pay to Dake the amount of any such tax.

DELIVERY: The proposed shipment date is an estimate and is contingent upon causes beyond Dake's control. Under no circumstances shall Dake have any liability whatsoever for loss of use or for any direct or consequential damages resulting from delay.

PERMITS AND COMPLIANCE: Dake shall not be responsible for obtaining any permits, inspections, certifications, or licenses required for the installation or use of the equipment. Dake makes no promise or representation that the equipment or any services to be furnished by Dake will conform to any federal, state or local laws, ordinances, regulations, codes or standards.

CANCELLATION: We shall have the right to cancel and refuse to complete your order if, in our opinion, you have not established credit to promptly meet the payment terms of your order.

WARRANTY: If, within a period of one (1) year from date of shipment, any part of any equipment sold by Dake is defective in material or workmanship and is so found after inspection by Dake, it will be replaced or repaired at the option of Dake, providing the equipment has been given normal and proper usage and is still the property of the original Purchaser. Purchased components such as Micro Drop mist system or the like, installed as a part of Dake equipment are warranted only to the extent of the original Manufacturer's warranty. Dake is not responsible for any service work performed unless authorized in advance.

THE FOREGOING WARRANTY IS EXCLUSIVE AND IN LIEU OF ALL OTHER WARRANTIES WHETHER WRITTEN, ORAL OR IMPLIED (INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR PARTICULAR PURPOSE). UNDER NO CIRCUMSTANCES SHALL DAKE BE LIABLE FOR ANY INCIDENTAL OR CONSEQUENTIAL DAMAGES.

APPLICABLE LAWS: This quotation or acceptance shall be governed in all respects by the laws of the State of Michigan.

Quote

BAILEIGH INDUSTRIAL

021035

1625 Dufek Drive
PO Box 531
Manitowoc, WI 54221-0531
Phone: (920) 684-4990
Fax: (920) 684-3944
Email: sales@baileighindustrial.com
Website: www.baileighindustrial.com

BILL TO:

DT3
DALE THOMAS
143 ALBANY ST APT 210
CAMBRIDGE, MA 02139

SHIP TO:

DT3
DALE THOMAS
143 ALBANY ST APT 210
CAMBRIDGE, MA 02139

Notes

Customer MUST have Fork Lift & Loading Dock to get off truck
Customer must be delivering to Commercial/Business Address
-PLEASE notify us if we need to change & get new freight rate

Sales Rep	Payment Terms	FOB Point	Shipping Terms	Carrier	Date
EBRESKE	PREPAYMENT	Origin	Prepaid & Billed	FEDEX FRT PRIO	07/30/2014 (VALID FOR 30 DAYS)

QTY	Unit Price	Part Number	Description	B.C.D	Ext. Price
1	$7,395.00	BS-260SA	220 Volt Single Phase Dual Mitering Semi-Automatic Metal Cutting Band Saw. 1" Blade Width. *IN STOCK*		$7,395.00

Authorization ______________________ Date: ________________
By signing this document or providing payment, signee accepts all Baileigh Industrial Inc. terms and conditions, see attached or http://metal.baileighindustrial.com/terms-ofsale/

Subtotal	$7,395.00
Shipping & Handling	$406.00
Misc.	$0.00
T/D	<$0.00>
Sales Tax	$0.00
TOTAL	$7,801.00

The world comes to Boyd for coatings.

Boyd COATINGS RESEARCH CO., INC.

Boyd Coatings Research Co.,Inc
51 Parmenter Road
Hudson, MA 01749-3213
USA

Ph: 978-562-7561
Fax: 978-562-9622

Quote

Number: 1114282 Date: 07-May-14

To

MIT-cam
70 Vassar Street
Bldg. 37, Room 276
Cambridge, MA 02139-4309
USA

Quote To

Dale Thomas
Massachusetts Institute of Technology
Laboratory for Manufacturing and Productivity
70 Vassar St Room 35-231
Cambridge, MA 02139
USA

Ph: 617-252-1736

Terms	Ship Via	Salesperson
Per Credit Terms Established		

Quantity	Description	Unit Price	Amount
	Reference: MIT PLEASE REFERENCE OUR QUOTATION NUMBER ON ALL CORRESPONDENCE & ORDERS. Please see the attached Terms & Conditions which are part of this Quotation.		
1	Line: 001 Expiration Date: 06-Jul-14 Part: Rev: TANK 12.5" x 15.5" Deep $839.43 each piece Each	$839.43	
1	Line: 002 Expiration Date: 06-Jul-14 Part: Rev: NRE CHARGE ONLY APPLIES TO FIRST RUN Each	$100.00	
	SUMMARY OF CHARGES: - $100.00 NRE Charge quoted above applies on first run only and is in addition to any minimum charges. BCR PROCESS: - Incoming inspection - Rigging / Special Handling - Surface preparation / masking - Apply coating - Testing - Final Inspection LEAD TIME: - The actual lead-time will be determined at the time of your order. - Standard process lead-time is ten (10) business days. - An additional three (3) business days are required for first time orders due to our engineering review process. BCR NOTES / EXCEPTIONS: - Due to high temperature process, stainless parts may show discoloration. - Quotation based on our standard application process & testing. - The OD should be in tolerance based on process selected, but no verification measurements are quoted.		

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51 Parmenter Road
Hudson, MA 01749-3213
USA

Ph: 978-562-7561
Fax: 978-562-9622

Quote

Number: 1114282 Date: 07-May-14

To	Quote To
MIT-cam 70 Vassar Street Bldg. 37, Room 276 Cambridge, MA 02139-4309 USA	Dale Thomas Massachusetts Institute of Technology Laboratory for Manufacturing and Productivity 70 Vassar St Room 35-231 Cambridge, MA 02139 USA

Ph: 617-252-1736

Terms	Ship Via	Salesperson
Per Credit Terms Established		

Quantity	Description	Unit Price	Amount
	- Parts to be received clean or extra charges may apply. - Parts will be subjected to 750° F. All part content must withstand this temperature (for example, tin, lead, plastic, etc. will be destroyed). BCR is not responsible for damage. - Mask all threaded holes. - Coat interior surfaces. Mask outside surfaces. - There is no charge for our standard Certificate of Compliance. A $25.00 charge shall apply for special certificates. Please specify "Special CofC" as a separate line item on your PO if it applies. - Stripping of coating is an additional charge. DRAWING NOTES / CUSTOMER REQUESTS: - Complete coverage of inside surfaces. - Outside should be masked. TOLERANCES: - Coating thickness: 0.005" - 0.010" - Designated areas for coverage shall be complete and masking as specified. - Measurements are judged on flat surfaces only. SUBSTRATE: - Stainless MATERIALS: - VCT-PE-000-010 black primer - VCT-PA-000-010 clear topcoats OTHER QUOTED CONDITIONS: - Quote based on Finish Class A. - Due to heat exposure, uncoated areas may show discoloration. - Park (tank vessel and cover) to be received without casters attached, along with any other components that cannot withstand 750F temperature exposure (gauges, valves, etcetera). Boyd Coatings Research will not be responsible for any parts that cannot survive the temperature exposure. PACKAGING: - Pricing is based on original packaging being reused and suitable to protect coating parts on their return. This quote includes the labor only for repackaging coated parts into your customer supplied packaging which should be capable of withstanding any type of mishandling in transit.		

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Ph: 617-252-1736

Terms	Ship Via	Salesperson
Per Credit Terms Established		

Quantity	Description	Unit Price	Amount
	- Restoration of poor packaging or lack of packaging is not quoted and will be charged, if needed, at $100.00 per hour plus material on a best effort basis. BCR cannot be responsible for packaging, as we have no insight into the design requirement of the parts. GENERAL TERMS: - This quote is based on Boyd Coatings Research Co. Inc., Terms and Conditions of Sales (attached) - Non standard testing, repairs or packaging requirements may incur charges. - Rigging charges may apply to parts that exceed 150 lbs. - Coating removal $150.00 minimum. - Minimum lot charge will be determined based on specific part and process. - There will be a one time NRE charge on any new part number. Amount will be determined based on specific part and process. - Freight and packaging materials are the responsibility of the customer. - These charge apply to quantities received at Boyd and should not be based on quantities on any given purchase order. - Different parts may be combined to reach a total dollar value on a shipment. However, each coating type will be considered as an order on its own. - Expediting service is available for an additional fee - advance notice is required. In order to expedite parts through production a CSM number must be assigned to you by our Customer Service Department. This number will be used by our Receiving Department to trigger the expedite service. All orders received without the CSM number will risk the chance of not meeting the desired due date. - Credit approval is required for all new customer; all orders will be COD until credit is established. (Please allow a lead time of five (5) business days for processing your Credit Application. Major credit cards are accepted. - All Quotations are valid for 60 days from the date of the quotation. THANK YOU for this opportunity to be of Service.		

647 Side-Loading Hydraulic Wedge Grips

Precision, easy-to-load grips for a wide range of tensile and fatigue applications

Benefits

EASY SPECIMEN INSERTION

» Side-loading lets you quickly and easily insert specimens.

EXCELLENT REPEATABILITY

» These grips clamp onto your specimen in the same position, test after test, to minimize the bending strains that can invalidate your test results.

TENSION & FATIGUE CAPABILITY

» You can use the 647s for both tensile and fatigue tests.

ADJUSTABLE PRESSURE

» Hydraulic pressure can be adjusted, allowing these grips to be used for testing a variety of materials.

MULTIPLE WEDGE SELECTION

» A wide variety of wedges are available to meet your requirements.

Test after test, MTS 647 Side-Loading Hydraulic Wedge Grips clamp your specimen in exactly the same way for consistent, repeatable testing results. Their superior alignment and constant, lateral gripping force minimize the bending strains, vertical loading forces and slippage that can invalidate test results and cost you time.

The hydraulic pressure to these grips is supplied by an external grip supply and is adjustable. This allows the grips to be used for testing a variety of materials, including plastics and ceramics. An adjustable gripping force prevents damage to your specimens from grip or specimen slippage during your tests.

Your specimens are also protected by the 647's preload chamber which locks all moving grip parts in position, eliminating backlash when cycling between tension and compression.

These grips can be mounted on non-hydraulic frames when used with an optional, stand-alone hydraulic pump and valve assembly. They can also be mounted in environmental chambers when equipped with optional, high-temperature hydraulic fluid and seals.

A variety of wedges are available for the 647 grips and are sold separately. These grips are also available in axial-torsional models.

be certain.

Specifications

FORCE RATING

» See tables.

DIMENSIONS & WEIGHT

» See tables.

WEDGE WIDTH

» See tables.

Options

SPIRAL WASHERS

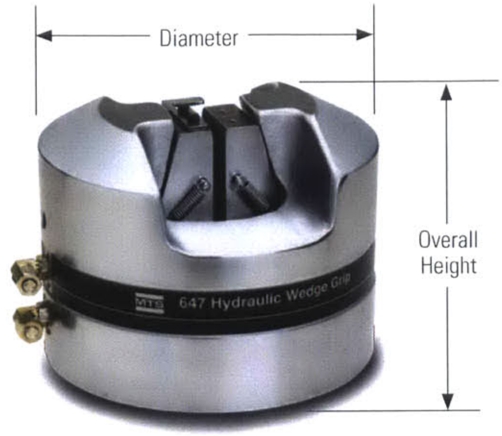
» Use anywhere you need a backlash free connection to your load frame.

WEDGE VARIETY

» Flat, round or vee-shaped wedges with surfaces available for brittle or soft specimens. Water cooled wedges also available in certain sizes.

HIGH TEMPERATURE OPTIONS

» Model 602 extension rods and a hardline fluid supply can be purchased for high temperature testing.



Axial Model 647 Grip Specifications

Model	Dynamic Force	Static Force	Pressure	Temperature* Min/Max	Overall Height	Diameter
647.02B	25 kN (5.5 kip)	31 kN (7,000 lb)	21MPa (3000 psi)	-40°C/177°C (-40°F/350°F)	131 mm (5.2 in)	150 mm (6.0 in)
647.10A	100 kN (22 kip)	120 kN (27,000 lb)	21MPa (3000 psi)	-40°C/177°C (-40°F/350°F)	188 mm (7.4 in)	203 mm (8.0 in)
647.25A	250 kN (55 kip)	333 kN (75,000 lb)	69 MPa (10,000 psi)	-40°C/177°C (-40°F/350°F)	249 mm (9.8 in)	266 mm (10.5 in)
647.50A	500 kN (110 kip)	550 kN (120,000 lb)	69 MPa (10,000 psi)	-18°C to 65°C (0°F to 150°F)	291 mm (11.5 in)	330 mm (13.0 in)
647.100A	1000 kN (220 kip)	1200 kN (264,000 lb)	69 MPa (10,000 psi)	-18°C to 65°C (0°F to 150°F)	414 mm (16.2 in)	444 mm (17.5 in)
647.250	2500 kN (550 kip)	2750 kN (610 kip)	69 MPa (10,000 psi)	-18°C to 65°C (0°F to 150°F)	819 mm (32.3 in)	737 mm (29.0 in)

**Temperatures above 77°C/150°F require a stand-alone grip supply and extension rods.*

Model	Weight	Metric/US Customary Stud Size	Part Number
647.02B	7 kg (15 lb)	M12 x 1.25 (1/2"-20)	056-078-605
647.10A	30 kg (67 lb)	M27 x 2 (1"-14)	047-080-605
647.25A	77 kg (170 lb)	M36 x 2 (1 1/2"-12)	047-080-905
647.50A	148 kg (325 lb)	M52 x 2 (2"-12)	047-595-505
647.100A	386 kg (850 lb)	M76 x 2	053-137-201
647.250	1153 kg (3335 lb)	N/A	Contact MTS

Wedges and attachment kits sold separately.

Axial-Torsional Model 647 Grip Specifications

Model	Axial Force	Torsional Force	Pressure	Temperature* Min/Max	Overall Height	Diameter
647.02B-22	25 kN (5.5 kip)	220 N.m (2000 in.lb)	21 MPa (3000 psi)	-40°C/150°C (-40°F/300°F)	135 mm (5.3 in)	150 mm (6.0 in)
647.10A-05	100 kN (22 kip)	550 N.m (5000 in.lb)	21 MPa (3000 psi)	-40°C/121°C (-40°F/250°F)	188 mm (7.4 in)	203 mm (8.0 in)
647.10A-11	100 kN (22 kip)	1,100 N.m (10,000 in.lb)	21 MPa (3000 psi)	-40°C/121°C (-40°F/250°F)	224 mm (8.8 in)	203 mm (8.0 in)
647.25A-22	250 kN (55 kip)	2,200 N.m (20,000 in.lb)	69 MPa (10,000 psi)	-18°C/65°C (0°F/150°F)	343 mm (13.5 in)	266 mm (10.5 in)

**Temperatures above 77°C/150°F require a stand-alone grip supply and extension rods.*

Model	Weight	Mounting	Part Number
647.02B-22	8 kg (16 lb)	40 mm dia.	100-026-042
647.10A-05	27 kg (60 lb)	M68 x 2 (LH)	049-157-301
647.10A-11	34 kg (75 lb)	M68 x 2 (LH)	049-817-001
647.25A-22	95 kg (210 lb)	M92 x 3 (LH)	056-124-001

Flat Wedge Specimen Specifications

Model Number	Specimen Thickness (T)		Narrow Wedge Set Assembly* Width*		Narrow Wedge Set Assembly* Part Numbers		Wide Wedge Set Assembly* Width*		Wide Wedge Set Assembly* Part Numbers	
	mm	in	mm	in	Diamond Serations	Surfalloy Coating	mm	in	Diamond Serations	Surfalloy Coating
647.02B	0.00 mm to 7.2 mm	0.00 in to 0.28 in	25.4 mm	1.00 in	050-507-906	050-507-917	38.1 mm	1.50 in	054-585-001	054-585-005
647.02B	7.1 mm to 14.4 mm	0.28 in to 0.57 in	25.4 mm	1.00 in	050-507-907	050-507-918	38.1 mm	1.50 in	054-585-002	054-585-006
647.10	0.00 mm to 7.6 mm	0.0 in to 0.30 in	44.5 mm	1.75 in	041-842-101	041-842-108	76.2 mm	3.00 in	046-198-604	046-198-602
647.10	7.1 mm to 14.2 mm	0.28 in to 0.56 in	44.5 mm	1.75 in	041-842-102	041-842-111	76.2 mm	3.00 in	046-198-603	046-198-601
647.10	11.7 mm to 19.1 mm	0.46 in to 0.75 in	44.5 mm	1.75 in	041-842-109	041-842-121	76.2 mm	3.00 in	–	–
647.25	1.0 mm to 11.9 mm	0.04 in to 0.47 in	50.8 mm	2.00 in	041-842-201	041-842-207	101.6 mm	4.00 in	046-198-804	–
647.25	6.10 mm to 17.0 mm	0.24 in to 0.67 in	50.8 mm	2.00 in	041-842-202	041-842-208	101.6 mm	4.00 in	046-198-806	046-198-802
647.25	15.0 mm to 25.9 mm	0.59 in to 1.02 in	50.8 mm	2.00 in	041-842-203	041-842-209	101.6 mm	4.00 in	046-198-805	046-198-803
647.50	0.00 mm to 10.9 mm	0.00 in to 4.3 in	101.6 mm	4.00 in	047-641-606	047-641-611	–	–	–	–
647.50	10.1 mm to 21 mm	0.40 in to 0.83 in	101.6 mm	4.00 in	047-641-607	047-641-612	–	–	–	–
647.50	20.3 mm to 31.2 mm	0.80 in to 1.23 in	101.6 mm	4.00 in	047-641-608	047-641-613	–	–	–	–
647.50	30.4 mm to 41.4 mm	1.20 in to 1.63 in	101.6 mm	4.00 in	047-641-609	047-641-614	–	–	–	–
647.50	40.6 mm to 51.5 mm	1.60 in to 2.03 in	101.6 mm	4.00 in	047-641-610	047-641-615	–	–	–	–
647.100	0.00 mm to 23.0 mm	0.00 in to 0.89 in	–	–	053-137-403	–	–	–	–	–
647.100	23.0 mm to 45.0 mm	0.89 in to 1.77 in	–	–	053-137-402	–	–	–	–	–
647.100	45.0 mm to 67.0 mm	1.77 in to 2.64 in	–	–	053-137-401	–	–	–	–	–

** The wedge set assembly consists of a matched set of four wedges, two specimen guides and socket head cap screws.*

Round Wedge Specimen Specifications

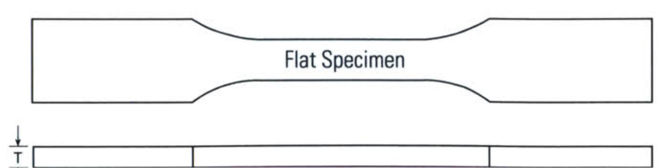
Model Number	Specimen Diameter	Round Wedge Part Number
647.02B	10.0 mm	050-507-912
647.02B	15.0 mm	050-507-913
647.02B	0.5 in	050-507-915
647.02B	1.0 in	050-507-916
647.10	12 mm	041-842-134
647.10	15 mm	041-842-135
647.10	20 mm	041-842-136
647.10	0.5 in	041-842-132
647.10	0.75 in	041-842-133
647.10	1.0 in	041-842-149
647.10	12 mm	046-838-716 (water cooled)
647.10	15 mm	046-838-717 (water cooled)
647.10	0.5 in	046-838-714 (water cooled)
647.10	0.75 in	046-838-715 (water cooled)
647.25	15 mm	041-842-231
647.25	20 mm	041-842-232
647.25	30 mm	041-842-233
647.25	0.5 in	041-842-234
647.25	1.0 in	041-842-235

** The wedge set assembly consists of a matched set of four wedges.*

647.250 Wedge and Liner Sets

Wedge Type	Specimen Size Range		Part Number
Flat*	0 – 29.5 mm 26.8 – 54 mm 51.8 – 79 mm 76.8 – 104 mm	0 – 1.16 in 1.06 – 2.16 in 2.04 – 3.11 in 3.02 – 4.09 in	057-367-101
Vee**	30 – 44.0/57.2 mm 55.8 – 68.9/80.5 mm 78.6 – 93.7/104 mm	1.18-1.73/2.25 in 2.20 – 2.71/3.17 in 3.10 – 3.69/4.09 in	057-367-102
Flat & Vee	Includes the flat and vee wedges described above and single set of liners		057-367-103

** Flat wedge size ranges refer to specimen thickness*
*** Vee wedge diameter ranges refer to top/Side-Loading*



Vee Wedge Specimen Specifications

Model Number	Specimen Diameter (D)		Vee Wedge Set Assembly* Part Number
647.02B	3.0 mm to 8.1 mm Side-Loading 9.4 mm Top-Loading	0.12 in to 0.32 in Side-Loading 0.37 in Top-Loading	050-507-908
647.02B	8.9 mm to 10.9 mm Side-Loading 15.2 mm Top-Loading	0.35 in to 0.43 in Side-Loading 0.60 in Top-Loading	050-507-909
647.10	5.8 mm to 10.2 mm Side-Loading 11.9 mm Top-Loading	0.23 in to 0.40 in Side-Loading 0.47 in Top-Loading	041-842-103
647.10	10.9 mm to 12.8 mm Side-Loading 16.5 mm Top-Loading	0.43 in to 0.50 in Side-Loading 0.65 in Top-Loading	041-842-104
647.10	No Side-Loading 12.7 mm to 19.0 mm Top-Loading	No Side-Loading 0.50 in to 0.75 in Top-Loading	041-842-107
647.10	No Side-Loading 17.0 mm to 22.9 mm Top-Loading	No Side-Loading 0.67 in to 0.90 in Top-Loading	041-842-110
647.25	10.7 mm to 16.8 mm Side-Loading 19.9 mm Top-Loading	0.42 in to 0.66 in Side-Loading 0.78 in Top-Loading	041-842-204
647.25	16.8 mm to 20.0 mm Side-Loading 26.2 mm Top-Loading	0.66 in to 0.79 in Side-Loading 1.03 in Top-Loading	041-842-205
647.25	6.4 mm to 10.2 mm Side-Loading 13.5 mm Top-Loading	0.25 in to 0.40 in Side-Loading 0.53 in Top-Loading	041-842-206
647.50	6.4 mm to 12.7 mm Side-Loading 15.5 mm Top-Loading	0.25 in to 0.50 in Side-Loading 0.61 in Top-Loading	047-641-601
647.50	15.2 mm to 18.3 mm Side-Loading 24.4 mm Top-Loading	0.60 in to 0.72 in Side-Loading 0.96 in Top-Loading	047-641-602
647.50	24.1 mm to 25.1 mm Side-Loading 33.5 mm Top-Loading	0.95 in to 0.99 in Side-Loading 1.32 in Top-Loading	047-641-603
647.50	33.0 mm to 33.0 mm Side-Loading 42.4 mm Top-Loading	1.30 in to 1.30 in Side-Loading 1.67 in Top-Loading	047-641-604
647.50	41.9 mm to 41.9 mm Side-Loading 51.3 mm Top-Loading	1.65 in to 1.65 in Side-Loading 2.02 in Top-Loading	047-641-605
647.100	6.0 mm to 10.0 mm Side-Loading –	0.24 in to 0.39 in Side-Loading –	053-137-407
647.100	10.0 mm to 25.0 mm Side-Loading –	0.39 in to 0.99 in Side-Loading –	053-137-406
647.100	25.0 mm to 44.0 mm Side-Loading –	0.99 in to 1.75 in Side-Loading –	053-137-405
647.100	44.0 mm to 63.0 mm Side-Loading –	1.75 in to 2.5 in Side-Loading –	053-137-404

** The wedge set assembly consists of a matched set of four wedges.*

MTS Systems Corporation
14000 Technology Drive
Eden Prairie, MN 55344-2290 USA

Telephone: 1.952.937.4000
Toll Free: 1.800.328.2255
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E-mail: info@mts.com
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ISO 9001 Certified QMS

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TESTRESOURCES

Mechanical Wedge Action Grips
GT122 Family

GT122 Mechanical wedge action grips feature grip bodies that move vertically to open and close wedge jaws that remain stationary relative to the sample, and open and close laterally. As the handles are tightened manually, the grip bodies move, the jaws are held in position on the sample and open and close laterally. The dual acting wedge jaws also move simultaneously relative to the grip centerline, ensuring correct specimen alignment, removing bending strains that invalidate test results.

Interchangeable JT122 jaws are available matched to the needs to test round and flat samples. These grips save time with a side opening that enables quick and easy sample insertion.

GT122 grips are available with threaded or pin/cup mechanical connections – made to your test machine requirements.

GT122 Family	GT122-10	GT122-50	GT122-100	GT122-200	GT122-300
Maximum Force Capacity	10 kN (2250 lb)	50 kN (11250 lb)	100 kN (22500 lb)	200 kN (45000 lb)	300 kN (67000 lb)
Max Sample Width	40 mm (1.6 in)	40 mm (1.6 in)	46 mm (1.8 in)	45 mm (1.75 in)	49 mm (1.9 in)
Max Sample Thickness	22 mm (0.86 in)	21-26 mm (1.2 in)	19-25 mm (1 in)	19-25 mm (1 in)	29 mm (1.1 in)

Interchangeable Jaws available to size requirements

Jaw	Description
JT122-XXBP	Serrated Jaws for flat samples – several sizes available
JT122-XXBV	V-Jaw for round test samples – several sizes available.

Contact an application engineer to configure a solution to your application requirements.

Instron
825 University Avenue - Norwood, MA 02062-2643
Tel: 781-828-2500 Fax: 781-575-5725 www.instron.com

QUOTATION

Quote To:
Dale Thomas
Massachusetts Institute of Technology
Mechanical Engineering Dept
77 Mass Avenue, Room E25-406
Cambridge, MA 02139
Tel: (207)659-4206
Fax:

cc:

Date: 06/03/2014
Quote# **INSQ98913**

Reply To:
Dave Johnson

Instron
825 University Avenue
Norwood, MA 02062-2643
Tel: 781-575-5320
Fax: 781-575-5725
Email: david_johnson@instron.com

We are pleased to submit the following quotation for your consideration.

Qty.	Part Number	Price

Manual Wedge Action

1 **2716-002**
Wedge Action Grips, Capacity: 100 kN (20,000 lb, 10,000 kg).
Maximum specimen size is face determined.
Temperature Range: -73 °C to 250 °C (-100 °F to 480 °F)
Upper and lower fittings: Type Dm (1.25 in connection with 1/2 in clevis pin).
Requires 25 mm wide (1 in.) faces.
Removable handles.

1 **2703-004**
Faces, Vee Serrated. Specimen diameter range: 7 to 12.7 mm (9/32 - 1/2 in.) 16 teeth per inch. Straight serrations.

SubTotal	**$11,765**
Less University Discount	**-$1,764**
Total	**$10,000**

Pneumatic Wedge Action

1 **2716-111**
Pneumatic Wedge Action Grips. Capacity: 100 kN (20,000 lb, 10,000 kg).
Upper and lower fittings: Type Dm (1.25 in connection with 1/2 in clevis pin).
Maximum specimen thickness: 40 mm (flat).
Maximum specimen width: 75 mm (flat).
Maximum specimen diameter: 50 mm (round).
Clamping length: 70 mm.
Temperature range: ambient only.
Requires faces.
Includes an air distribution kit with both, 1/4 NPTM (7/16-20), and 1/4 inch hose barb end

connections.
An Automatic Air Control Kit or Footswitch is recommended.

Qty.	Part Number	Price
1	**2703-182** Faces, Vee Serrated. Specimen thickness range: 6-17.8 mm. For 2716-110, 111, 120, 121 Pneumatic Wedge Action Grips. Set of four.	
	SubTotal	**$21,631**
	Less University Discount	**-$3,244**
1	Total:	**$18,387**

DELIVERY
4 to 6 weeks from receipt of order, subject to prior orders.

TERMS
Net 30 days from Invoice Date, subject to credit approval.

DELIVERY: Ex-Works
SHIP VIA: Most economical way
FREIGHT: Prepaid and Add

*** PRICES FIRM FOR 60 DAYS ***

WARRANTY: All Instron testing instruments are warranted against defects in material and workmanship for a period of one (1) year from the date of delivery or fifteen (15) months from the date of shipment, whichever comes first. All equipment purchased from Instron but not installed by Instron Service Personnel or Instron authorized representative shall be warranted against defects in material and workmanship for a period of one (1) year from the date of delivery.

All Purchase Orders may be mailed to:
Instron, a division of ITW, Inc.
825 University Avenue
Norwood, MA 02062-2643

Or e-mailed to: info@instron.com

Or faxed to: (781) 575-5725, ATTN: Order Admin.

We accept Visa, MasterCard, and American Express
Prices above are for U.S. destination. Warranty and service commitments only apply to instrumentation installed in the U.S.

PRECISION COATING
A Katahdin Company.

QUOTED TO:
Laboratory for Manufacturing and Productivity at MIT 77 Massachusetts Ave 35-231 Cambridge, MA 02139 Attention: Martin Feldman Email: feldmann@mit.edu Phone:

QUOTE DETAILS	Quote Number: 014202
Part Name: **5 Gallon Pressure Pot**	Part #: **5 Gallon Pressure Pot**
Coating:	PFA Green
Processing Instructions:	Mask exterior. Coat inside bucket and lid, approximate thickness .0010" to .0030" per surface. No after coating dimensions to be met.
Pricing:	1 pieces: $850.000 each Setup Charge: $300.00 per shipment under $3000
Other:	Pricing is valid for all quantities.
Delivery:	2 - 3 weeks
Terms:	Visa/Mastercard/AMEX or COD on 1st order; Net 30 upon credit approval
Expiration:	This quote expires on 8/3/2014

If you need any further information, please contact me directly.

All the best,

Jim Kaemmerlen
Precision Coating Co., Inc.

UPDATED and REVISED: 3/31/2014

STANDARD TERMS AND CONDITIONS OF SALE

1. These are the Standard Terms and Conditions between Precision Coating Co., Inc. (PCCI) and the party contracting the service (Customer).
2. Prices quoted by PCCI are valid until the expiration date stated on the quotation. Thereafter prices are subject to change.
3. For special or experimental coating, finishing or salvage processing, PCCI's charges are not contingent upon the success of the work or the benefit derived therefrom by Customer, and all charges shall be due and payable in any event.
4. PCCI assumes no liability for any loss of or damage to merchandise or material while in transit to or from its plant, whether in trucks or vehicles owned by the Customer or any third party acting on the Customer's behalf, or for any loss of or damage to said merchandise or materials while the same are not in our possession, and for any cause, whatsoever, including, but not limited to theft, fire, casualty, or act of god.
5. Subject to the warranty conditions listed below, PCCI warrants that coating, processing and finishing shall meet Customer's specifications supplied <u>in writing</u> with the order, provided Customer supplies PCCI with the required information and same is attached and made a part of the written purchase documents and is part of the acceptance by PCCI when the Customer's order is received. When Customer specifies methods and procedures to be followed, we shall comply whether or not the desired result is indicated. PCCI does not assume responsibility for the correctness of such methods and procedures or the result when they are followed. It is the responsibility of Customer to provide specific alloy information. PCCI does not warrant that the material furnished by Customer is suitable or fit for coating, processing and finishing. Product to be coated, processed, or finished must be free of residual oils, lubricants and other process-related materials upon receipt at PCCI.
6. No claim for shortage in weight or count or defect in quality, whether latent or patent, will be allowed unless presented in writing within three (3) business days after receipt of material by Customer or Customer's consignee to whom it is delivered, the Customer hereby expressly assuming the risk of discovering such shortage or defect within such time. PCCI will notify the Customer in writing of any shortfall in received parts compared to Customer's paperwork within three (3) business days.
7. Customer agrees to indemnify, defend, and hold harmless PCCI and its employees, from and against any and all demands, claims, suits, actions, judgments, expenses, and attorneys' fees incurred in any legal proceedings and any administrative proceedings brought against PCCI or its employees arising from any injury to persons or damage to property, of any nature, caused by the use of merchandise or material upon which processing or finishing was performed by PCCI. In the event of a proceeding subject to Customer indemnification, PCCI's and its employees' legal counsel shall be selected by PCCI.
8. Customer agrees that PCCI is not a Manufacturer as that term is defined pursuant to 21 C.F.R. s. 820.3 of the US Code of Federal Regulations. Accordingly, Customer acknowledges that PCCI has no responsibility for design input, design output, design review, design verification, design validation, design transfer, or design changes. Customer also acknowledges that PCCI has no responsibility for non-conformity review and disposition pursuant to 21 C.F.R. s. 820.90 of the US Code of Federal Regulations.
9. Deliveries made by us within ten (10) calendar days of the time specified shall be deemed in full compliance with this agreement. It is agreed that PCCI shall have the right to make partial or installment deliveries, for which the Customer shall pay at the contract price. Defective delivery or non-delivery with respect to any installment or partial delivery under this contract shall be a severable breach and shall not give Customer the right to treat the entire contract as breached.
10. All of Customer's merchandise in PCCI's possession shall be subject to a general lien for all monies owing by the Customer to PCCI, whether or not due or payable, and whether or not such monies are owing for work, labor, or services rendered or materials or equipment used in connection with such merchandise.
11. Special tools, racks and fixtures required and their design for the performance of the work described herein designated and built by or on behalf of PCCI shall be and remain PCCI's property whether or not Customer is charged for time and/or material in connection therewith.
12. During storage and transportation of Customer's material, Customer's containers used for delivery to us shall be used and any damage resulting from the use of such containers shall be at Customer's risk. Should Customer desire other packaging or containers, PCCI will charge for material and handling and will provide such service upon receipt of written order.
13. PCCI assumes no responsibility for defective coating, processing or other finish on materials or merchandise previously coated or finished by others. Such defective merchandise will be returned to Customer for refinishing or, at PCCI's option, stripped and refinished in its plant at Customer's expense.
14. In the event Customer requests that an order for products or services which it has placed with PCCI be cancelled prior to shipment, and with which request PCCI agrees, Customer shall be liable to PCCI for all costs incurred by PCCI as a result of such cancellation, including but not limited to, all labor and material costs, cancellation costs to suppliers and unreimbursed advances on goods, if any, together with any specifically identifiable incidental and consequential expenses.
15. This contract contains the complete and exclusive statement of the agreement between the parties in connection with the subject products and/or services and supersedes any previous understandings, communications, commitments, or agreements, oral or written. Any provision of this contract that is invalid or unenforceable under applicable laws with respect to a particular party or circumstance will be severed from this contract with respect to such party or circumstance without invalidating the remainder of this contract or the application of such provisions to other persons or circumstances. The headings used in this contract have no legal effect.
16. PCCI reserves the right to cancel any order and terminate these conditions with immediate effect where Customer (i) breaches these terms and conditions, and fails to remedy such breach within ten (10) calendar days of notification by PCCI, or (ii) makes an

assignment for the benefit of creditors, or proceedings are commenced by or for PCCI under any bankruptcy or insolvency law. Termination shall not relieve Customer from the obligation to pay any amounts that remain due to PCCI, and termination shall not limit either party from pursuing other available remedies.

17. PCCI's failure to exercise, or delay in exercising, any right or remedy provided under this contract or by law shall not constitute a waiver of that or any other right or remedy, nor shall it preclude or restrict any further exercise of that or any other right or remedy. No single or partial exercise of any right or remedy provided under this contract or by law shall preclude or restrict the further exercise of that or any other right or remedy. PCCI's waiver of a right or remedy provided under this contract or by law in relation to another party, or taking of or failure to take any action against that party, does not affect its rights in relation to any other party.
18. In the event it is necessary for PCCI to institute litigation against Customer, or to defend against litigation instituted by Customer, relating to the subject matter of this contract, should PCCI prevail, it shall be reimbursed by Customer for all reasonable attorneys' fees and costs resulting therefrom.
19. PCCI's payment terms are net 30 days and payment term discounts may be offered on a customer specific basis. Accounts exceeding net 30 days are subject to an annualized interest charge of 10% (ten percent) on the outstanding balance of the invoice amount until paid. PCCI reserves the right to seek recovery of any monies remaining unpaid 60 (sixty) days from the date of invoice via collections agencies or through small claims court. In such circumstances, the Customer will be liable for all administrative, collections and court costs.
20. For Customers who desire to pay by credit card, all charges for work quoted will be debited to Customer's credit card ***before*** any work has begun at PCCI. In addition, Customer will be charged a 2.5% service fee for paying by credit card. Any adjustment to the final invoice amount for the order will be credited or debited to Customer's credit card after completion of the order.

The provisions hereof constitute the entire agreement between PCCI and the Customer. Any changes, alterations, waivers or modifications with respect either as to the job performed or the terms of sale or any attempt by Customer to vary in any degree any of the terms of this statement or the offering quote are hereby objected to and rejected, but such proposals shall not operate as a rejection of this offer unless such variances are in the terms of the warranty, description, quantity, price or delivery schedule of the services. Such acceptance shall be deemed to be on the express terms contained herein and without the objected to or rejected changes. In order for any changes, alterations, waivers or modifications of matters objected to or rejected by PCCI to be effective, they must be in writing, signed by a duly authorized representative of the PCCI and the Customer. These terms and conditions shall apply to any order or agreement for the processing of any materials or merchandise. In the event of any dispute concerning this contract or the products sold or services rendered hereunder, suit may be brought only in a court of competent jurisdiction in the Commonwealth of Massachusetts. This contract shall be governed by and construed in accordance with the laws of the Commonwealth of Massachusetts.

PRECISION COATING CO., INC. WARRANTY OF PROCESSING

Any material found, upon inspection by PCCI, to be defective in workmanship or material, where said workmanship or material was furnished by PCCI, will be refinished by PCCI without charge upon delivery FOB to its plant, provided that such materials are returned in the same condition as when originally shipped. All warranties of merchantability and fitness for a particular purpose are limited to the applicable warranty period set forth above. In no event shall PCCI be liable for anticipated or lost profits or for special, punitive, indirect, incidental, or consequential damages. PCCI's liability for any loss or damage of any nature, including without limit, direct, indirect and consequential damage, is limited to Customer's cost (cost being material cost plus direct labor to produce the part) of the material or merchandise **OR** PCCI's coating, processing and finishing price for such material, **whichever amount is the lesser**. This warranty is expressly in lieu of all other warranties, express or implied. Refinishing by PCCI shall be the sole remedy of the Customer.

724 Robbins Road
Grand Haven, Michigan 49417
Web: www.dakecorp.com

Phone 616-842-7110 800-937-3253
Fax 616-842-0859 800-846-3253
E-mail : customerservice@dakecorp.com

TECHNICS 350 CE

July 29, 2014

Quote File #
[Click **here** and type Quote No]

[Click **here** and type Company Name]
[Click **here** and type Address]
[Click **here** and type City, State & Zip]
Attn: [Click **here** and type Name]

Subject: Dake Cold Saw Model Technics 350CE

In response to your recent request, we are pleased to submit the following quotation.

Model No.	Model Name	Voltage (Please Specify)	Price US	Delivery (F.O.B. Factory)
74028-2	Technics 350CE	230-volt 3-phase	$5,995	[Click **here** to enter]
74028-2 + 300674	Technics 350CE	460-volt 3-phase	$5,995 + $525	[Click **here** to enter]

Terms: **TBD**

Installation: Installation is the responsibility of the Purchaser. One instruction manual, including operating instructions, is provided at time of shipment. Additional assistance may be obtained from Dake via telephone. If a Service Technician is requested for on-site installation supervision, additional charges will be incurred. These charges will be quoted separately.

Please review the enclosed Dake Standard Terms & Conditions of Sale.

We would like to take this opportunity to thank you for your interest in Dake and want to assure you we are looking forward to entering your purchase order for the earliest possible delivery.

Sincerely,

[Click **here** and type Name]

SPECIFICATIONS

Machine Type	Pivot head cold saw
Maximum Blade Size	14 inches with 32 mm arbor (2/8/45mm drive pin spacing)
Minimum Blade Size	12 inches with 32 mm arbor (2/8/45mm drive pin spacing)
Spindle Speeds	2 speed
Minimum/Maximum spindle RPM	22 RPM / 44 RPM
Head Feed	Manual
Vise	Manual, cam activated
Maximum Vise Opening	6-5/8 inches
Miter Cutting Capabilities	Up to 45° left / up to 45° right/ 90° right for slot cutting
Controls	CE Certified 24-volt - Handle mounted trigger switch
Horsepower	3.5 HP
Weight	650 pounds
Work Height	40 inches
Overall Height	79 inches
Base Width	27 inches
Depth	39 inches
Lubricant	Flood type unit built into the machine (Mechanical)
Voltage	• Available 230-volt three phase • Available 460-volt three phase (external transformer) **Machine should be wired to main service by a qualified Electrician.**
AMP	• 20-amp service for 230-volts machines • 16-amp service for 460-volt machines
Compressed Air	90 PSI with optional pneumatic vise.
Operating Temperature	No special operating temperature level

CUTTING CAPACITIES

DEGREE	ROUND	SQUARE	FLAT
90°	4-¾ inches	4-1/8 inches	6-¼ inches x 3-½ inches
45° Left	4 inches	3-3/8 inches	3-3/8 inches x 2-¾ inches
45° Right	4 inches	3-3/8 inches	3-3/8 inches x 2-¾ inches

OPTIONS

DESCRIPTION	PART NUMBER	PRICE
Blade starter pack, Three HSS 14" blades (120, 180, and 280 tooth)	79846	$580
78" Loading Table – In-bound with protective cover plates	301644	$1035
78" Unloading Table – Out-bound with scale and adjustable positive stop	301645	$1810
Pneumatic vise – Factory Installed	79827	$2,075

FEATURES

- Heavy-duty low production 2 speed saw, comes with one standard HSS blade.
- Capable of near milled finish cuts with proper blade.
- Heavy-duty gearbox for long dependable life. Taper roller and ball bearing for spindle shaft and motor shaft support. All steel and bronze gears. No plastic gears to break. Internal clutch to prevent over feeding that can cause blade damage. The clutch is adjustable to give your machine many years of precision cutting.
- CE Certified electronics. Low voltage hand control with dead man switch. Thermo over load protection, low voltage protection with emergency stop button. Housed In a watertight electrical enclosure.
- Miters left and right. Set up is precise using the scribed scale on the vise pivot. Vise can be set for making longitudinal cuts.
- Vise faces are hardened and serrated steel, for sure clamping and long life. Vise jaw can be adjusted close to work for maximum holding power.
- Vise is gib adjustable, and with cam lever action for quick secure clamping.
- Optional pneumatic vise can be factory installed, or installed in the field later, in less than 30 minutes. The vise is activated whenever the head is pulled off its rest position.
- Steel base with anti chatter gasket, and material support roller.
- Tool kit for quick blade changes.
- One gallon of coolant
- Blade guard completely covers the blade.
- Stock stop gauge for repetitive cutting.
- Complete CE approved English owners manual, and blade pitch calculator.

DAKE STANDARD TERMS & CONDITIONS OF SALE

All proposals and quotations for the original sale of our products are subject to the following terms and conditions:

ACCEPTANCE OF ORDER: All orders are subject to acceptance by Dake at its main office in Grand Haven, Michigan.

PRICES: Unless otherwise agreed to in writing, all prices are F.O.B. our plant in Grand Haven, Michigan. In any event, the quoted prices become invalid sixty (60) days after date of quotation. Unless otherwise specified in Dake's quotation, installation services and final on-site adjustments are not included in the quotation.

TERMS OF PAYMENT: Terms of payment are as stated in Dake's quotation subject to credit approval by our home office. Dake will invoice Purchaser when the equipment is completed and ready for shipment. Payment terms run from invoice date.

TAXES: Prices do not include taxes. If any sales, use or similar tax is payable to Dake in connection with any transaction or part thereof between the Purchaser and Dake with respect to goods delivered, the Purchaser will, upon demand, pay to Dake the amount of any such tax.

DELIVERY: The proposed shipment date is an estimate and is contingent upon causes beyond Dake's control. Under no circumstances shall Dake have any liability whatsoever for loss of use or for any direct or consequential damages resulting from delay.

PERMITS AND COMPLIANCE: Dake shall not be responsible for obtaining any permits, inspections, certifications, or licenses required for the installation or use of the equipment. Dake makes no promise or representation that the equipment or any services to be furnished by Dake will conform to any federal, state or local laws, ordinances, regulations, codes or standards.

CANCELLATION: We shall have the right to cancel and refuse to complete your order if, in our opinion, you have not established credit to promptly meet the payment terms of your order.

WARRANTY: If, within a period of one (1) year from date of shipment, any part of any equipment sold by Dake is defective in material or workmanship and is so found after inspection by Dake, it will be replaced or repaired at the option of Dake, providing the equipment has been given normal and proper usage and is still the property of the original Purchaser. Purchased components such as Micro Drop mist system or the like, installed as a part of Dake equipment are warranted only to the extent of the original Manufacturer's warranty. Dake is not responsible for any service work performed unless authorized in advance.

THE FOREGOING WARRANTY IS EXCLUSIVE AND IN LIEU OF ALL OTHER WARRANTIES WHETHER WRITTEN, ORAL OR IMPLIED (INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR PARTICULAR PURPOSE). UNDER NO CIRCUMSTANCES SHALL DAKE BE LIABLE FOR ANY INCIDENTAL OR CONSEQUENTIAL DAMAGES.

APPLICABLE LAWS: This quotation or acceptance shall be governed in all respects by the laws of the State of Michigan.

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