<u>Final Report</u>

Senior Design (EML4551) - Spring 2014

Conformability Solutions for Lithium Ion and Lithium Polymer Batteries

Faculty advisors: Dr. Jim Zheng & Dr. Chiang Shih

Team Members:

Jenna Pine – Team Leader (ME)

Niraj Thakker – Communications (ME)

Jianchen Yu – Webmaster (ME)

David Goss – Treasurer (IE)

Roberto Moutran (IE)

Brian Rainbeau (EE)

Contents

Abstract

Batteries are an important part of electronics and machinery. Efficient and compact power solutions are necessary for technological progress. This progress also demands a more flexible size constraint for power solutions. A project was assigned to explore shape conformability in batteries. An important part of this study is the development of a general process for the production of these batteries.

There are many ways to approach the issue of conformability in batteries. Three possible designs were presented, two of which were based on conformability around a surface. After available resources were taken into account, a design was chosen. Before this idea could be completely pursued, a prototype was made. This prototype confirmed theoretical analysis but also highlighted areas for improvement.

Using the data obtained from the tachometer experiment, the battery analyzer and the static thrust theory, it was concluded that the handcrafted batteries will not be able to fly the plane and the origami concept will not sustain flight for a required time, however the large bent prototype will fulfill the objectives of the project.

Acknowledgements

This team would like to express gratitude to Dr. Jim Zheng and Dr. Chiang Shih for sponsoring this project. Thank you to Dr. Wanjun Cao for teaching the team to make batteries, helping to troubleshoot, and providing guidance.

Most importantly, our deepest gratitude is extending to Mark Hagen at the Power Science Lab. This project could not have happened without your advice, support, and knowledge.

Lastly, this team would like to acknowledge the professors, teaching assistants, and staff throughout the FAMU-FSU College of Engineering who helped by giving guidance, advice, and support.

Introduction

Batteries are in widespread use in consumer electronics today. They are also an integral part in several industries such as automobiles, robotics and aeronautics. The main goal in the successful design of a battery is to achieve maximum power output for minimum area occupied. This goal is related to several factors such as material selection, the type of device or vehicle to be powered, available space and type of battery.

Batteries today have their own housing structure which adds additional weight to the overall system and occupies additional space. For example, a car typically has its battery placed under the hood. This increases the overall weight of the car and reduces the amount of free space available for engine components. In the case of an airplane, the battery adds extra weight which increases the amount of fuel required for take-off and to maintain lift. It also changes the center of gravity of the entire system, potentially making the airplane unstable and calls for additional control systems to add stability. In the case of gadgets such as cell phones, their shapes, sizes, and performances are completely dependent on the battery they use.

Instead of simply attaching a battery to the system, another approach would be to make the battery fit within the structure of the system. This would remove the additional weight and space that the battery would otherwise occupy. For example, the heavy battery under the hood of a car could be replaced by designing a battery in the shape of the hood or the door, thus making it a part of the car's structure. For an airplane, the battery could be designed in the shape of the wing and used as a part of the airplane structure. In other words, the battery would be designed to conform to the structure of the device or vehicle it is meant to power.

This report will go through the processes and challenges in manufacturing liquid electrolyte batteries. It gives a brief description of the prototypes used to fulfill the objectives of the project. The report will also discuss various analyses done on the battery before it was attached to the plane.

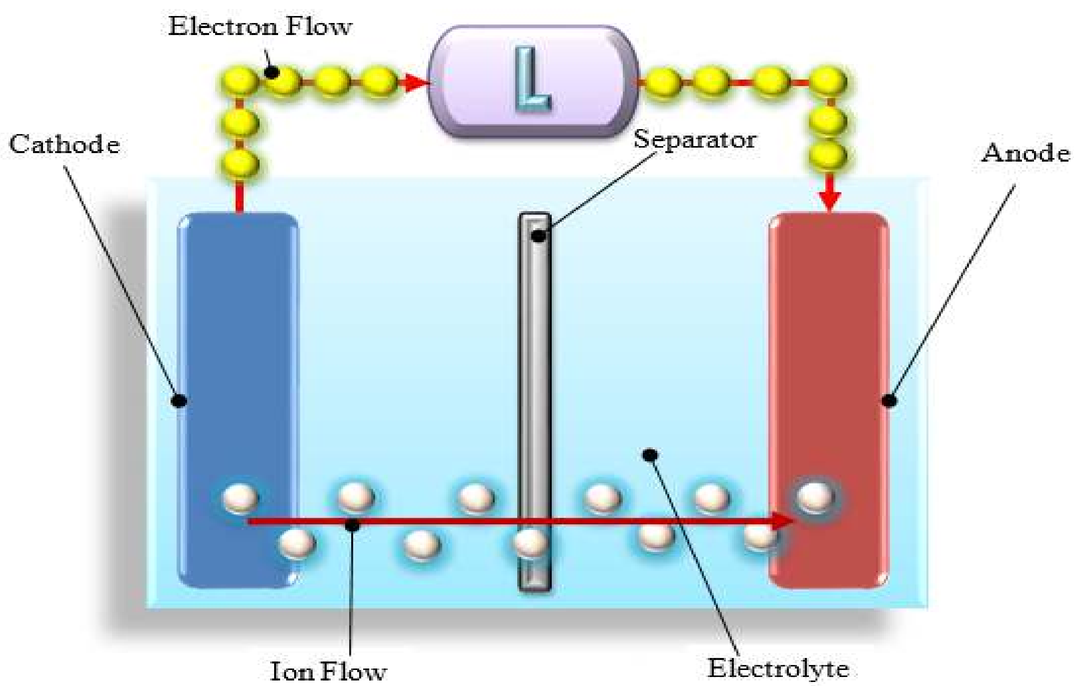
Background Information

Before going into specific project requirements, it is important to become familiar with the general working principles behind batteries. In simple terms, a battery is a device that stores chemical energy in the form of electrons. This chemical energy can be converted into electrical energy (electron flow) in order to supply power to a device and thus perform work. The smallest unit in which this energy conversion takes place is known as a battery cell.

A battery cell consists of two electrically-conductive materials. These materials are known as electrodes, and they have different energy levels. The electrode with the higher energy level is known as the cathode or positive terminal, whereas the electrode with the lower level is known as the anode or negative terminal. Because electrons flow from materials with high energy levels to materials with low energy levels, the cathode and the anode have to be isolated from each other within the cell in order to prevent direct electron transfer. This is typically done through the use of a separator material.

The generic single-cell battery interfaces with the load device through a pair of terminals which are connected to the anode and the cathode. These terminals act as an open circuit that is completed at one end by the load. As electrons flow out of the cathode, the atoms in the material find themselves short an electron and become positively charge ions. These ions are capable of flowing through an electrolyte medium past the separator and into the anode, thus completing the circuit at the other end. This electrolyte medium can be a paste (known as a dry electrolyte) or a liquid (known as a wet electrolyte) and its primary function is to facilitate the transfer of ions between electrodes. The choice of electrode material for each terminal will determine whether a single electrolyte can be used for both, or different electrolytes will be required for each electrode.

Once the circuit is closed, chemical oxidation (loss of electrons) occurs in the cathode material and the released electrons flow through the load into the anode material. Upon arrival at the anode, chemical reduction occurs (gain of electrons). It is this movement of electrons through the load that generates power. Figure 1 illustrates this whole process.



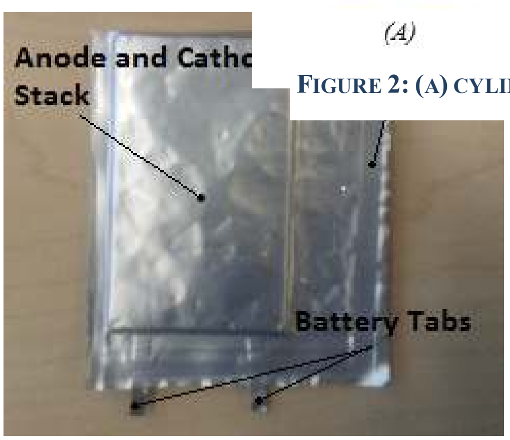
Batteries can be classified by their reusability as follows:

- **Primary.** In this type of battery, the electrochemical reactions that take place within the cell are irreversible. Once all electrons have flowed from the cathode into the anode, the battery is spent and has to be disposed. One of the most common examples of primary types is the cylindrical alkaline battery, which is available in many stores and used to power a wide range of devices.

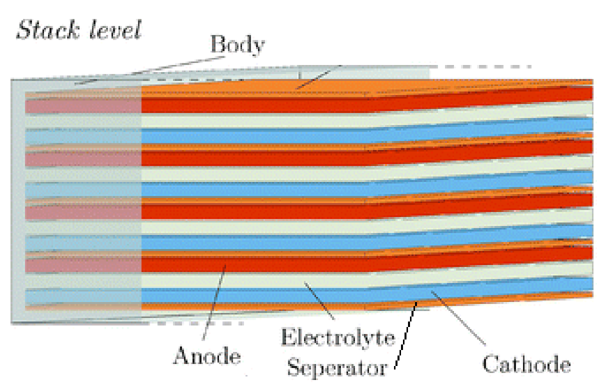
- **Secondary.** In a secondary battery, the electrochemical reactions are reversible through the application of a reverse current (typically done through a charger device). At the end of this process, the battery is ready to be used again. Lithium-ion batteries are a good example of secondary types. They are when rechargability is desirable.

The three main types of battery cells that are in use today are: cylindrical, button and pouch cells. Cylindrical cells are standard store-bought disposable batteries and are shown in Figure 2a. Button cells are flat and round, like their name implies. They are typically used to power very small devices such as wrist watches and laser pointers. Figure 2b provides an example of a button cell battery.

FIGURE 2: (A) CYLINDRICAL CELL (B) BUTTON CELL



A pouch cell is a battery encased in a flexible pouch made out of a foil material. This



third type will be the focus of this project. In a pouch cell, anode and cathode sheets are layered in the desired configuration (this can be series or parallel) and isolated from each other by separator paper. The cell is then wrapped in a flexible, foil-like material that acts as the pouch. Liquid Electrolyte is injected and the pouch is closed with an air-tight seal in order to keep moisture out. Two tabs serve as the interface between the anode and cathode terminals. Figure 3 shows a working lithium ion pouch cell made at the battery lab in the Aero-Propulsion, Mechatronics and Energy (AME) building at the FAMU-FSU College of Engineering. Figure 4 shows a cross section view of a cell pouch.

Pouch cells like the one depicted in Figure 3 are the preferred battery cell type for rechargeable consumer electronics. The foil pouch makes them relatively lightweight and easy to manufacture when compared to the hard casing found in cylindrical and button cell types. Ease of manufacture enables faster production and testing of prototype cells. Lastly, the foil pouch also grants a certain degree of flexibility to the battery. Due to these desirable properties, pouch cell batteries will be the main focus of this project.

FIGURE 4: CROSS SECTION OF POUCH CELL

Project Overview

Scope and Goals

The main objective of this project is to provide the sponsors with a proposal for the design and manufacture of shape conformable batteries. In other words, to come up with a process that can be used to create these batteries. As part of this greater goal, a solution to the problem of conformability in batteries must be proposed. Finally, a proof-of-concept prototype that will be used to showcase this solution must also be produced.

For the prototype portion of the project, the objective is to design a battery that can be integrated into the wing of an unmanned aerial vehicle (UAV) system. The overall design of the battery is open-ended: it can form around the wing, fit inside the wing, or be the wing itself. The focus is on the conformability of the battery. The goal of the prototype is for the UAV system to fly for at least five minutes. A successful flight will be defined by takeoff, uninterrupted flight and landing without accidents or loss of power.

Objectives

- Come up with a solution to the battery conformability problem
- Build a proof-of-concept prototype battery based on this proposed solution
- Integrate this prototype battery into the wing of a UAV system
- Utilize existing technology to stay under budget
- Enable ease of recharging through a detachable design
- The battery must meet the power requirements of the UAV system
- The battery must be safe to use
- Propose an overall process for the creation of shape conformable batteries

Constraints

- Project budget: $2000
- UAV system must be able to fly outside under reasonable weather conditions
- Enough power must be supplied for at least 5 minutes of uninterrupted flight time
- To be completed by Spring 2014

Summary of Quality Function Deployment (QFD)

Sponsor Requirements

Due to the research-based nature of the project, the sponsors have placed very few hard constraints on the team. These requirements are:

- Development of a process to create shape conformable batteries
- A solution to the conformability problem
- Design and production of a proof-of-concept prototype

Process:

The most important of all sponsor requirements was the development of a general process for the creation of shape conformable batteries. The team was required to develop a standard procedure that can be followed in order to produce a variety of shape conformable batteries that can be used to power a wide range of devices. The majority of the team's resources were devoted to this requirement, and the final result is a streamlined process for the hand-manufacture of flat and flexible Lithium Ion cells. This process is detailed in the Design for Manufacturing section.

Conformability:

The sponsors were interested in the team's approach to solve the problem of battery conformability. It was made clear by the sponsors that reformability and battery flexibility were not required, and that the final design was open-ended. The main criteria for success or failure for this requirement will depend on the level of creativity demonstrated by the team in finding and implementing a solution to the problem. The team came up with two different solutions for the problem of conformability, both based on surface conformability of thin batteries. These solutions are detailed in the Design and Analysis section.

Proof-of-concept Prototype:

In order to demonstrate the solution approach chosen by the team, a proof-of-concept prototype was explicitly requested by the sponsors. The prototype consists of a radio controlled (RC) foam airplane modified to work with the shape conformable battery developed by the team. The team conducted successful test flights and was able to demonstrate that the modified RC plane is able to operate successfully with the shape conformable battery.

In addition to the explicit requirements outlined above, the team has come up with a set of unspoken requirements that are critical to the project's success and must be met in order to ensure quality. These unspoken requirements are:

- Meeting the power requirements of the target device
- Reliability of the battery
- Lightweight design
- Rechargeability (includes both the ability to recharge the battery and ease of recharging)
- Safety
- Budget constraints

Design and Analysis

Two battery designs have been created and prototyped as solutions to the conformability problem. The initial approach was to build the batteries by hand using raw supplies both purchased from MTI Corporation and provided from AME. The supplies used are described later in Design for Manufacturing. Only five working hand made batteries were produced and over 20 cells were needed. After the hand crafting approach failed to produce a functional prototype, batteries fulfilling both design options were purchased from PowerStream Inc. The battery analysis focuses on comparing properties of the three different batteries. The mechanical analysis will introduce the RC plane selected and address the concerns about adding mass and altering its center of gravity.

Design Concepts

Flexible Thin Cells

The first solution involves the creation of very thin cell pouches. Because the thickness of the stack inside the pouch is very small, a certain level of bendability is present in the cell pouch. Figure 5 shows possible ways to take advantage of this flexibility by lining the inside or the outside the airfoil with the cell pouches. Surface conformability is achieved because the battery conforms to the surface of the device or structure it is attached to.

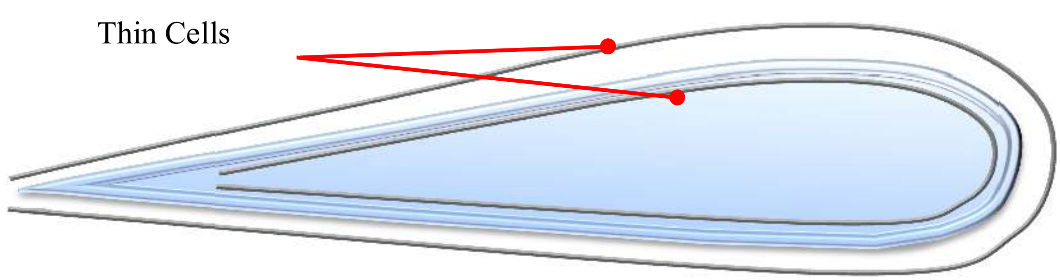


FIGURE 5 THIN CELLS INSIDE AND OUTSIDE AN AIRFOIL

Design benefits:

- Cheap cells. The small amount of material per pouch dramatically speeds up the battery making process per cell.
- These thin cells can be used to layer the outside area of the wing and function as a skin. They can also be used to line up the insides of the wing.

Issues and limitations:

- Material-bound. Significant testing required to determine how the degree of bendability affects cell performance based on electrode material choice.
- Potentially time consuming due to testing requirement to determine bending limitations.
- Inefficient use of space. Low quantity of electrode material in the pouch.

- External pressure required. Low quantity of electrode material inside the pouch will necessitate additional pressure to keep the materials tightly pressured inside in order for the cell to work.
- Low power per cell. Thin design requires a cell with large surface area in order to satisfy power requirements.

Origami Configuration

The second solution involves linking together several small, flat cells within the same battery pack. The cells themselves are rigid and non-flexible, but the linking material that holds the cells together is. This scheme results in a cell array or grid that can be folded in multiple ways and thus has a certain degree of surface conformability. This type of flexible cell grid can then be wrapped around the wing of the RC plane, or around the body of the plane. Figure 6 illustrates this scheme. Figure 7 illustrates the bending between seals.

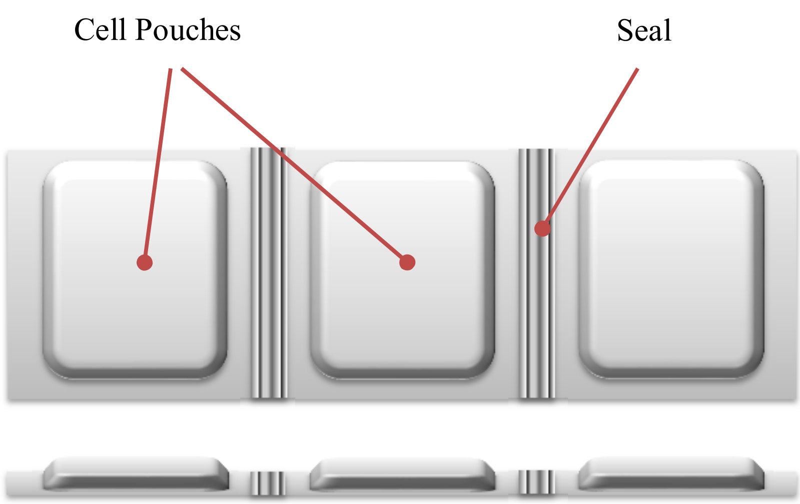


FIGURE 6: CELL GRID DESIGN

FIGURE 7: CELL GRID DESIGN (FOLDING)

Design benefits:

- More configuration options. This type of cell grid opens up a wide range of configuration possibilities, all based on surface conformability. The grid can be designed to be very long and thin, with small cells. It can also be designed to be short but with big cells instead.
- No additional testing required. Since the cells won't be bent or utilized in non-standard ways, no testing is required to determine if there are any loses due to bending.

Issues and limitations:

- Potentially wasteful. If one cell fails or is built incorrectly, the whole grid will have to be thrown away or redone. Modular battery casing will be required to prevent this.

Mechanical Analysis

Although the batteries designed can have many applications, the focus of this project is to operate an RC plane. The Ares Gamma 370 was selected because of its ease of use, durability, and lower price. Figure 8 shows the plane and few important specifications.

Specifications	
Wingspan	38.6 in (980mm)
Length	30.6 in (775mm)
Weight with Battery	455 g
Battery	1000mAh 2S 7.4V LiPo
Charger	DC 2S 7.4V LiPo Balancing and AC adapter
Transmitter	6-channel 2.4GHz
On-Board Electronics installed	Receiver, ESC and 2 servos

FIGURE 8: ARES GAMMA 370 PLANE AND SPECIFICATIONS [7]

An important consideration for a UAV system is weight. For this reason, most are made with Styrofoam and have Lithium Polymer (LiPo) batteries to be very lightweight. With electric planes, calculations for static Thrust (T_s) were used to interpret the effect of mass on the system. Static Thrust is a value which helps analyze whether a plane will take off or sustain flight. It is a function of the propeller's diameter (d), pitch (p), and frequency of rotation (RPM). Static Thrust can be computed using the following equation:

$$T_S = 1.225 * \frac{\pi(0.254 * d)^2}{4}\left[\left(RPM * 0.0254 * p * \frac{1min}{60sec}\right)^2\right] * \left(\frac{d}{3.29546 * p}\right)^{1.5}$$

As a rule, for a plane to sustain flight, the static Thrust must be no less than 1/3 the mass of the plane [13]. Using Excel, this data was recorded as reference to verify any possible battery materials. For ease, Increments of 500 were used for RPM and the two propellers available for the Ares Gamma (8 x 6 and 9 x7) were modeled. An example of the results displayed in table 1. This calculation can also be inverted if mass is known and a minimum flight RPM is desired.

TABLE 1 MAXIMUM MASS CALCULATED FROM STATIC THRUST

RPM	Diameter(d)	Pitch(p)	Static Thrust(T_s)	Maximum Mass
5000	8 in	6 in	168.1 g	504.3 g
	9 in	7 in	274.2 g	822.6 g
5500	8 in	6 in	203.4 g	610.2 g
	9 in	7 in	331.8 g	995.4 g
6000	8 in	6 in	242.1 g	726.3 g
	9 in	7	394.8 g	1184 g

Battery Analysis

The initial approach was to build both designs. The exact process is outlined below in the Design for Manufacture section. Lithium Cobalt Dioxide ($LiCO_2$) cells were made at the AME lab. Over 20 cells were made, but only 3 produced a voltage. Only 1 of those was found to be functioning after charge and discharge testing. Lithium Cobalt Dioxide is considered to have the highest energy density of all commonly used Lithium Ion cathodes, however, in an effort to make an exceedingly thin battery, only one layer of active material was used. Because of this, the functioning battery produced a very low capacity.

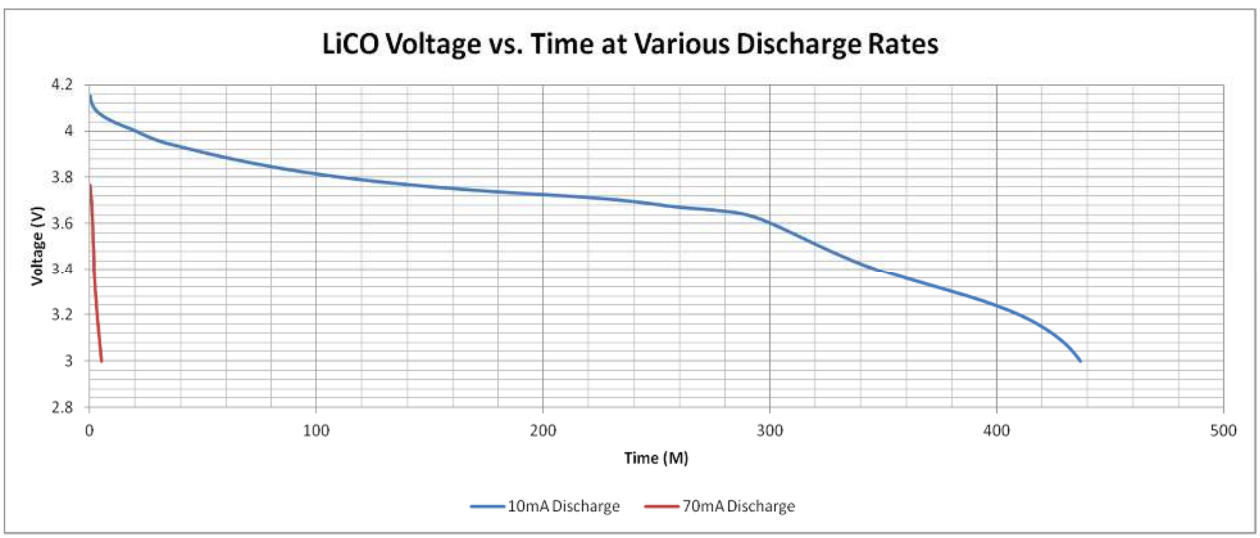


FIGURE 9: $LiCO_2$ CELL DISCHARGED AT TWO RATES

Figure 9 shows how the $LiCO_2$ cell responds to being discharged at 2 different rates. At a 10mA discharge the cell lasted 436.6 minutes and displayed a capacity of 67.7mAh, with voltage ranging from 4.15V to 2.99V. When the same cell was discharged at 70mA it lasted only 5.1 minutes, displayed a capacity of 5.7mAh, with voltage ranging from 3.77V to 2.99V. This is a good illustration of Peukert's law:

$$C_p = I^k t$$

Where C_p is the capacity one-amp discharge rate (in amp-hours), I^k is the actual discharge current (in amps), and t is time [8]. This law states as a higher discharge rate is employed, battery capacity decreases. It is significant to note how the available voltage also decreases as discharge rate increases, which plays a role in the amount of power available.

After failing to make enough cells by hand to run the plane, batteries were bought from PowerStream Corp. To demonstrate both designs, two different size cells were purchased. Table 2 summarizes the batteries purchased.

TABLE 2: PROPERTIES OF PURCHASED LITHIUM POLYMER BATTERIES

Size	Dimensions (T x W x H mm)	Nominal Voltage (V)	Theoretical Capacity (mAh)	Weight (grams)
Large	1.0 x 118 x 270	3.7	2700	85
Small	1.0 x 44 x 61	3.7	180	6

The purchased batteries are made with Lithium Manganese Oxide ($LiMn_2O_4$) cathode and solid polymer electrolyte. Table A in the appendix summarizes the properties of the three different batteries. The different batteries were tested for performance at 1C (1 times the capacity = amps continuous discharge). For example, the 2700mAh battery discharged at 1C, means that it was discharged at 2700mA.

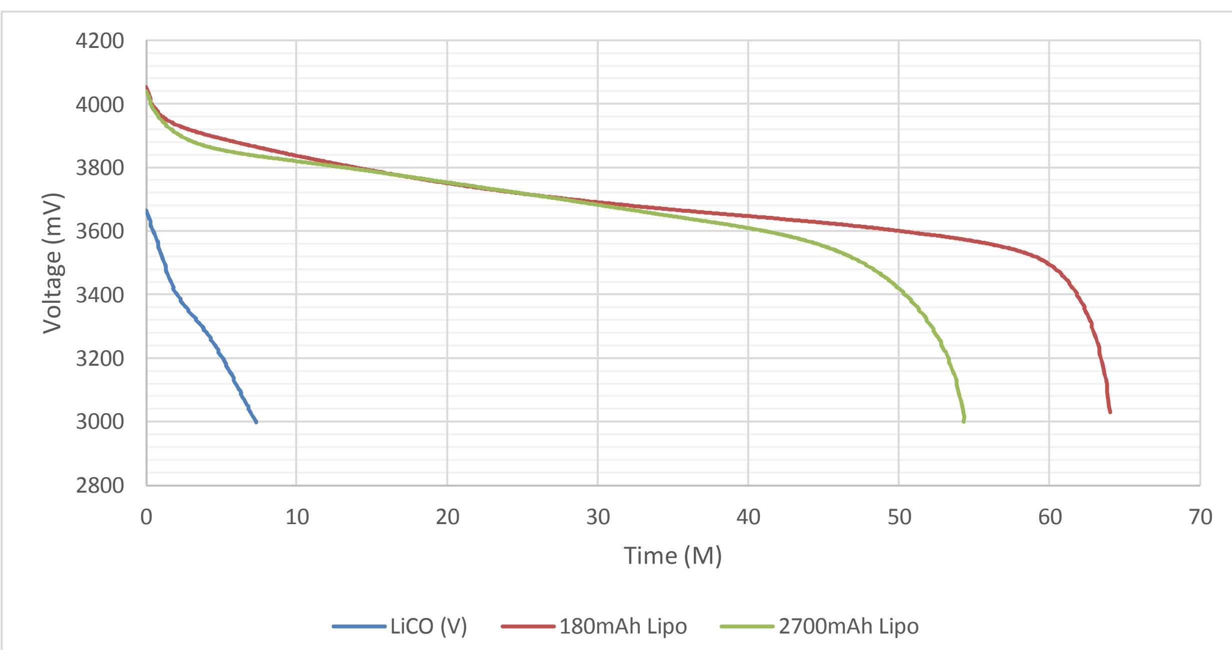


FIGURE 10: VOLTAGE COMPARISON DURING 1C DISCHARGE

Figure 10 shows the Lithium Polymer (LiPo) cells display a steady negative slope voltage drop during discharge with a larger negative slope as the cell nears the end of its discharging ability. The usable maximum voltage for both cells during discharge is over 4 volts. In contrast, the $LiCO_2$ cell has a more constant negative slope over the course of its discharge, while its usable maximum voltage is lower at 3.65 volts. For each cell, the discharge currents are set respective to their capacity due to the difference in size of the tested cells. For example, it would be dangerous to discharge the 180mAh cell at the same rate as the much larger 2700mAh cell. The longer more steady discharge curves are more desirable because it is slowly discharging energy.

With respect to flying an RC plane, the discharge behavior is variable and can sometimes be up to 5-10C. This is problematic for the $LiCO_2$, as over discharging can lead to catastrophic battery failure. For each type of cell, when discharged at a 1C rate, the maximum capacity cannot be realized. Preliminary tests showed a capacity of full charge range between 67.37% and 88.89% for the different batteries. This decrease in capacity is likely due to internal resistance. As more current is drawn from the cell, more energy is lost in the form of heat.

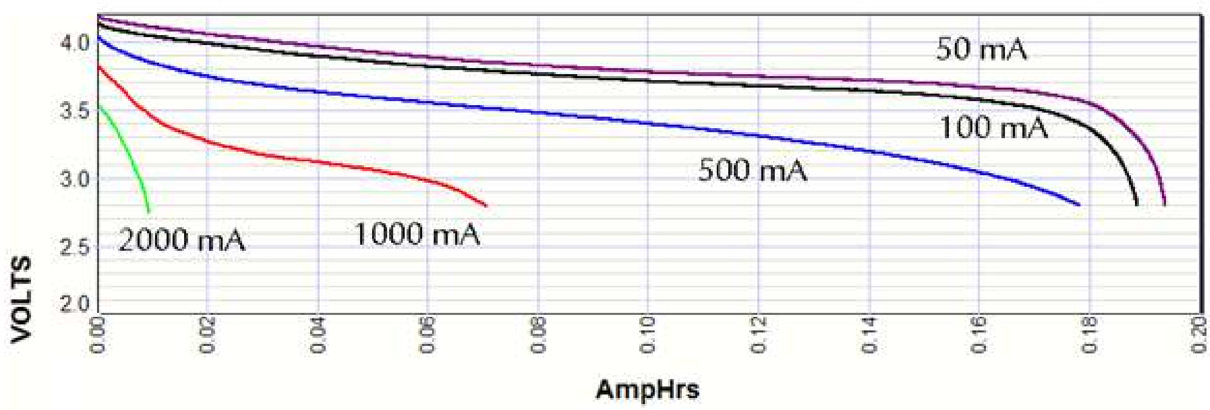


FIGURE 11: VARIOUS DISCHARGE RATES FOR 180 MAH CELL[14]

Figure 11 was supplied by the manufacturer of the Lithium polymer cells used in this project and demonstrates the effect discharge rate has on battery capacity and voltage. The performance of the battery decreases as the load increases. The performance is better from the LiPo batteries and they will be less likely to fail.

Prototype Details

After failing to manufacture the necessary batteries by hand, batteries were purchased. The cells purchased were solid lithium polymer and they were purchased in two different sizes. The larger size had a capacity of 2700 mAh and the smaller one had a capacity 180 mAh. The voltage of both of the battery sizes were the same at 3.7 volts.

Flexible Thin Cells

To utilize the flexible thin cells, the team decided to bend the batteries around the airfoil shape of the wing. The large thin cell batteries already matched the capacity needed for the plane to take off but the voltage was only half or the needed voltage. To compensate for the low voltage, the batteries were connected in series before being connected to the plane interface. With the batteries connected in series, the voltages would add to supply the plane a total voltage of 7.4 volts. Figure 12 illustrates the battery being wrapped around the airfoil.

FIGURE 12: BATTERY BENT AROUND AIRFOIL

To protect the raw cells from being exposed to the elements and any other debris that could be in the air, a plastic sheet was used to cover the battery and wing assembly. As seen in Figure 13, the sheet was secured to the wing with the use of rubber bands to establish an even distribution of pressure on the battery cells.

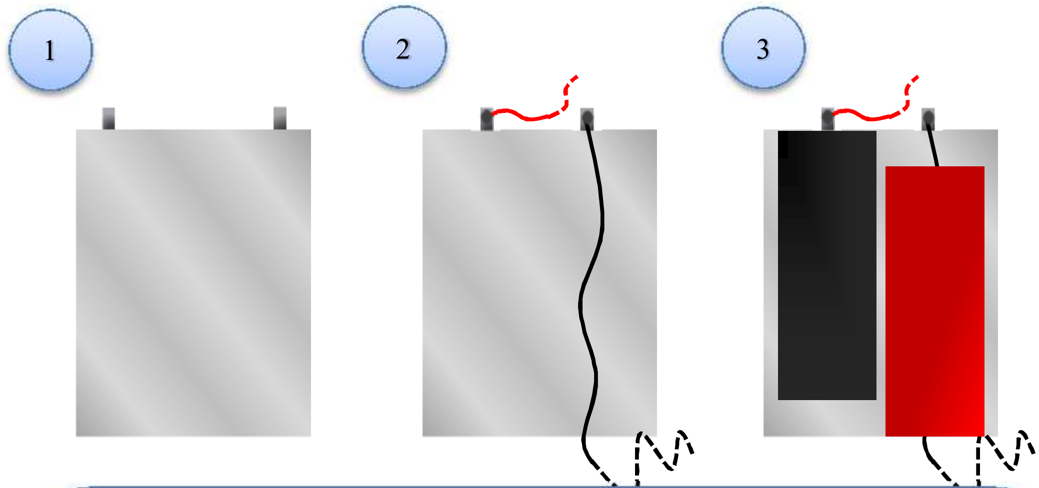
FIGURE 13: PROTECTECTIVE SHEET TO PROTECT RAW BATTERY CELL

Origami Configuration

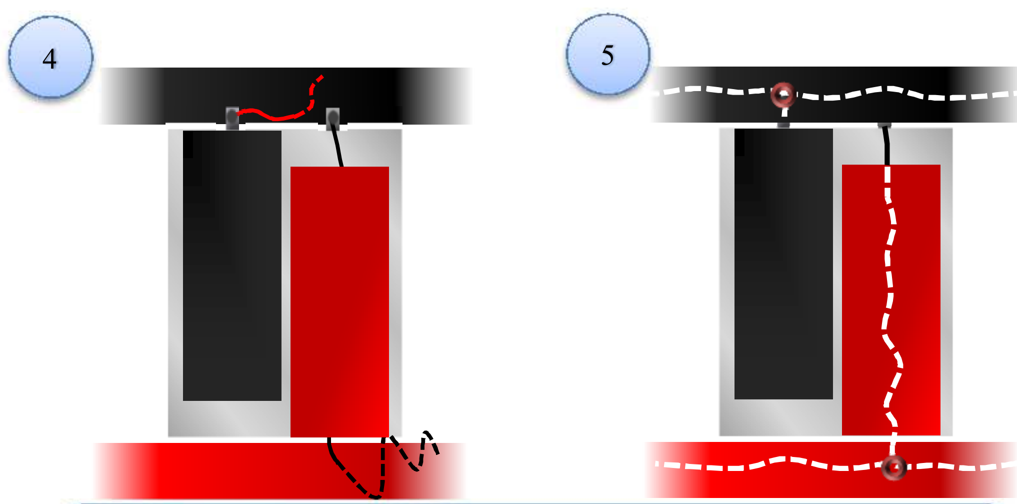
The smaller cells were utilized in a different manner. The small cells only had a capacity of 180 mAh which is far lower than the original battery pack. To make up for this shortage of capacity, the cells were connected in parallel (see Figure 14). The cells were soldered to 9V wire terminals so that they could be connected or disconnected with minimal effort. This also allows for the batteries to be connected in series (if desired) thus making the battery pack more versatile.

In the case of the RC plane, however, it was necessary to connect these batteries in parallel. Figure 15 shows the wires being soldered to the battery terminals. These single small cells were then placed onto contact paper and secured into place through the adhesive sticky side. Figure 16 illustrates the single small cells being secured into place. Similar to the large flexible cells, the individual origami pouches were connected in series before being connected to the plane.

FIGURE 14: RAW CELLS CONNECTED IN PARALLEL

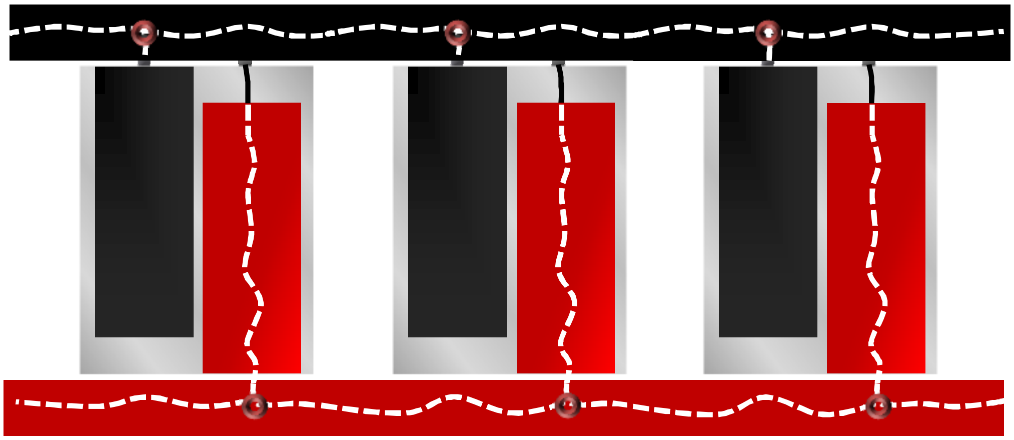


(1) Using the small LiPo cell as starting point.
(2) Wires are soldered to the end terminals. (3)
(3) Non-conductive strapping take is placed on both sides for structural stability, and to keep the wires from moving. Red tape is used to represent the positive terminal, and black to represent the negative terminal.

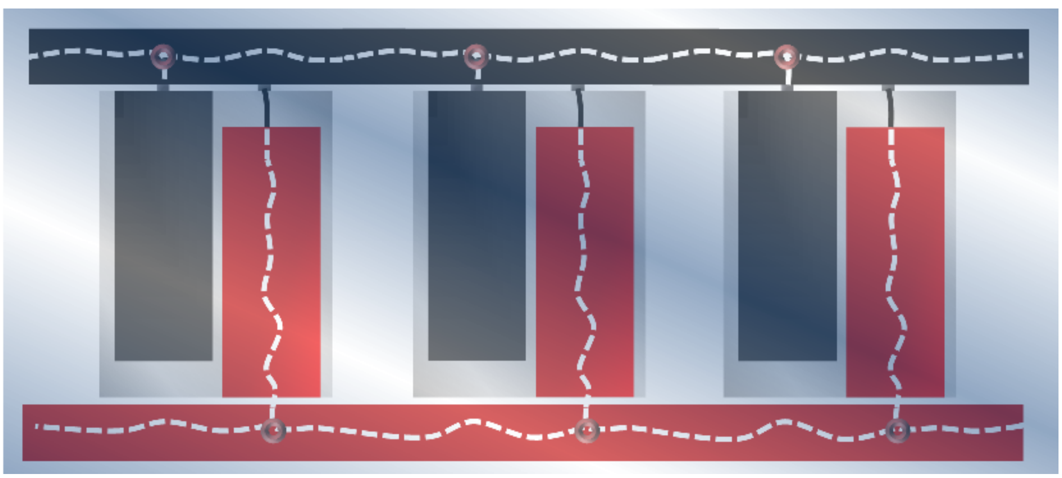


(4) A long layer of color-coded strapping tape is used to create the outside frame of the cell array. The wires that connect all the cells together in parallel will be run through this outside layer of strapping tape
(5) A second layer is applied to encase the wires. Connector terminals are soldered in.

Figure 15: Soldering of Wires to Terminals



Several cells can be linked in a parallel configuration with this scheme. Full flexibility between cells is achieved.



Transparent adhesive paper is used to encase the whole assembly. This is done to isolate the cells from the environment, and to protect any exposed wires.

FIGURE 16: INDIVIDUAL CELLS SECURED WITH CONTACT PAPER

RC Plane Interface and Testing

A direct analysis between the energy supplied by the battery and the work done by the propeller would give a platform to compare different battery prototypes. The team used the tachometer experiment to do this analysis. A tachometer is a device that measures s systems speed.

For the experiment, each of the battery prototypes were attached to the plane and the propeller was rotated at full throttle. The tachometer was used to measure the R.P.M of the

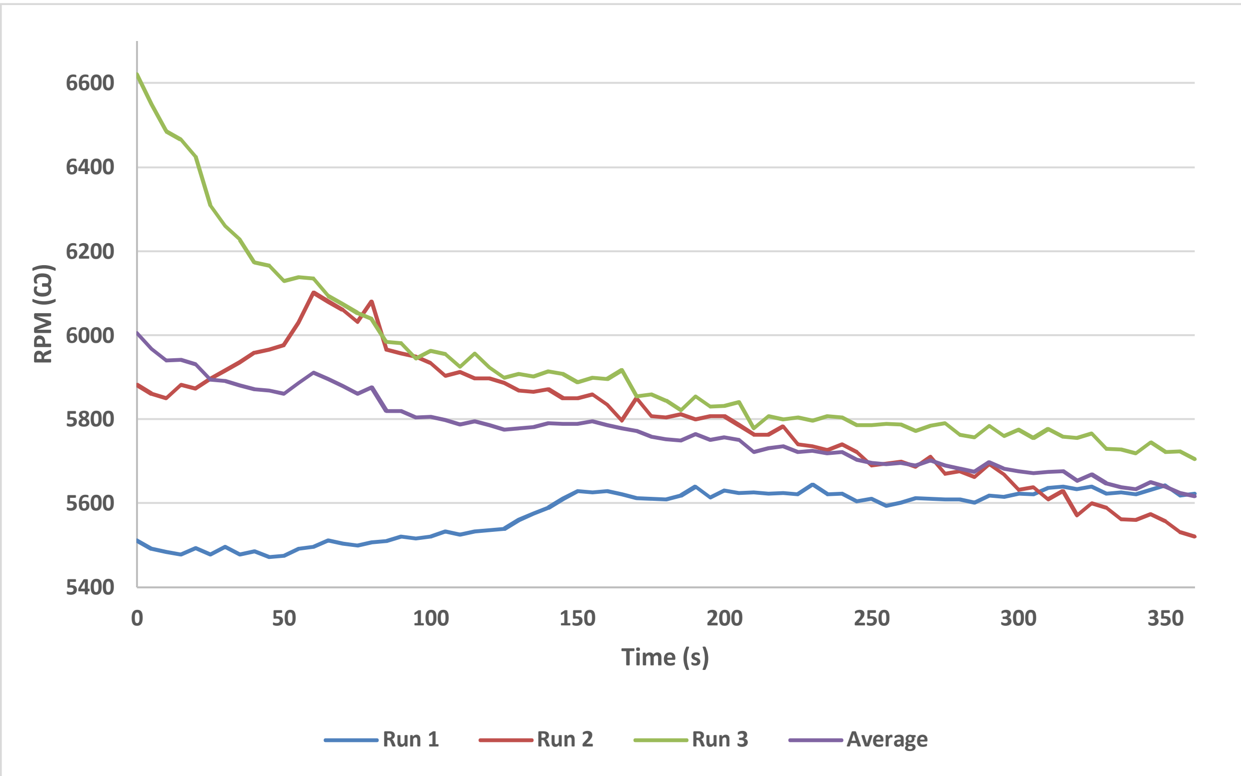


FIGURE 16. R.P.M OF LARGE BENT CELL VS. TIME

propeller when each of the battery prototypes were attached to the plane. A measurement was taken every 5 seconds for 6 minutes. This was done 3 times for each of the battery prototype and a graph similar to Figure 16. was plotted each of the tested battery prototypes. Along with the 3 runs, an average of these 3 runs was also plotted in this graph.

Similar data was obtained for the Origami battery prototype and the stock battery. However, data for the Liquid Electrolyte cells was not obtained. In order for the propeller to run at full throttle, a high instantaneous discharge rate is required. The hand crafted liquid electrolyte cells are unable to discharge at high rate.

The averages for the origami pack, large bent cell and stock battery were plotted below in Figure 17.

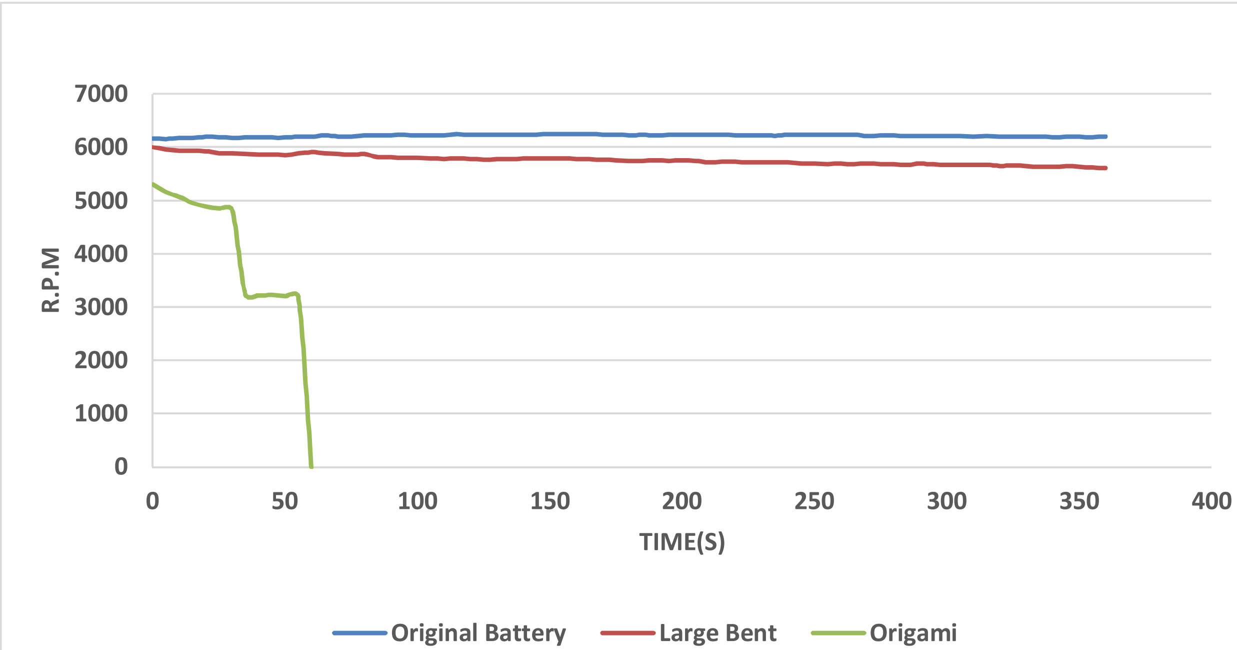


FIGURE 17. AVERAGE R.P.M VS. TIME FOR TWO BATTERY PROTOTYPES

Using the concept of static thrust, minimum R.P.M for each of the battery prototypes were computed. This data is tabulate in Table 3 below.

TABLE 3. MINIMUM R.P.M FOR EACH BATTERY PROTOTYPE

	Diameter(in)	Pitch(in)	Plane Weight(g)	Minimum Thrust(g)	Minimum R.P.M
Original Battery	8	6	485	161.67	3907.6
	9	7			3645.1
Origami Cell	8	6	606	202	4388.3
	9	7			4072.1
Large Bent Cell	8	6	753	376.5	6246.7
	9	7			5754.8

Comparing the data obtained from the tachometer experiment to the data obtained from the theory of static thrust, we can anticipate when the battery will stop supplying enough energy for the RC plane to sustain flight. For propeller diameter of 9 inch, the origami prototype will stop supplying enough energy after approximately 40 seconds. The plane will start losing lift and start its downward decent. However, the large bent cell prototype will supply enough power for 6 minutes. After which the plane will start its downward decent. Hence in order to fulfill the objective of sustaining flight for 5 minutes, the large bent cell prototype will be used.

Design for Manufacturing

Materials

The following materials are required for this process:

- 267mm L x 214mm W x 0.2mm T Li-ion battery cathode sheet (Aluminum foil coated by $LiCoO_2$).
- 241mm L x 200mm W x 0.1 mm T Li-ion battery anode sheet (double sided Copper foil, coated by CMS Graphite).
- Lithium Hexaflourophosphate ($LiPF6$) liquid electrolyte
- Celgard separator film (85mm width, 25um thick)
- Strapping tape
- Aluminum tab as positive terminal (4mm width)
- Nickel tab as negative terminal (4mm width)
- Aluminum laminated film for pouch cell casing

Machinery Required

The following machinery is utilized in this process:

- Semi-Automatic die cutter for pouch cell electrode sheets
- Desktop ultrasonic metal welder (40Khz, 110-240V)
- Compact heating sealer for sealing laminated aluminum casing
- Compact Vacuum Sealer for preparing pouch cells
- 8 Channel battery analyzer for rechargeable cells (6-3000mA, up to 5V)

The following tools are utilized in the process:

- Plastic pipette
- Small clamps (2 per battery)
- 2 metal plates (at least 85mm length, 50mm width)

Wherever appropriate, suitable replacements for the machinery and tools can be utilized so long as their functionality remains consistent, and the process steps are followed properly.

The Process

Electrode Preparation:

The first step towards the manufacturing of these batteries is to prepare the electrodes for folding. These electrodes come in large sheets (refer to the materials section for specific dimensions) as depicted in Figure 18. The press machine is utilized to punch smaller sized electrode layers out of these bigger sheets. The shape of these smaller layers depends on the type of plate being used. Figure 18 depicts a stack of anode and cathode tabs after they have been punched out of the larger sheet.

FIGURE 18. ELECTRODES BEFORE AND AFTER CUTTING

Electrode Folding:

The next step in the process involves the preparation of the basic, single layer (that is, a single anode and cathode stack) cell that will be the core of the battery. The cell is created by folding separator paper between and around the electrodes in order to create a pouch. The exact step-by-step process is depicted in Figure 19.

Once the stack is ready, electrical tape is used to secure the separator paper in place in order to create a pouch that will hold the electrode layers together. The tape is carefully used to secure the cut end of the separator paper in place, as well as to create a pouch at the bottom of the cell. A single piece is applied between the exposed terminals on the top, being carefully not to touch either. The final wrapped cell is shown in Figure 20.

Special care must be taken during the folding of these cells. At no point during this process should the anode and cathode electrodes come into physical contact with each other. Even though there is no liquid electrolyte medium present to facilitate ion exchange at this stage, small-scale chemical reactions can still occur between the different materials. Furthermore, it is imperative to ensure that there is zero contact between electrodes inside the fold, as this would result in a shorted battery that would be unable to charge and discharge.

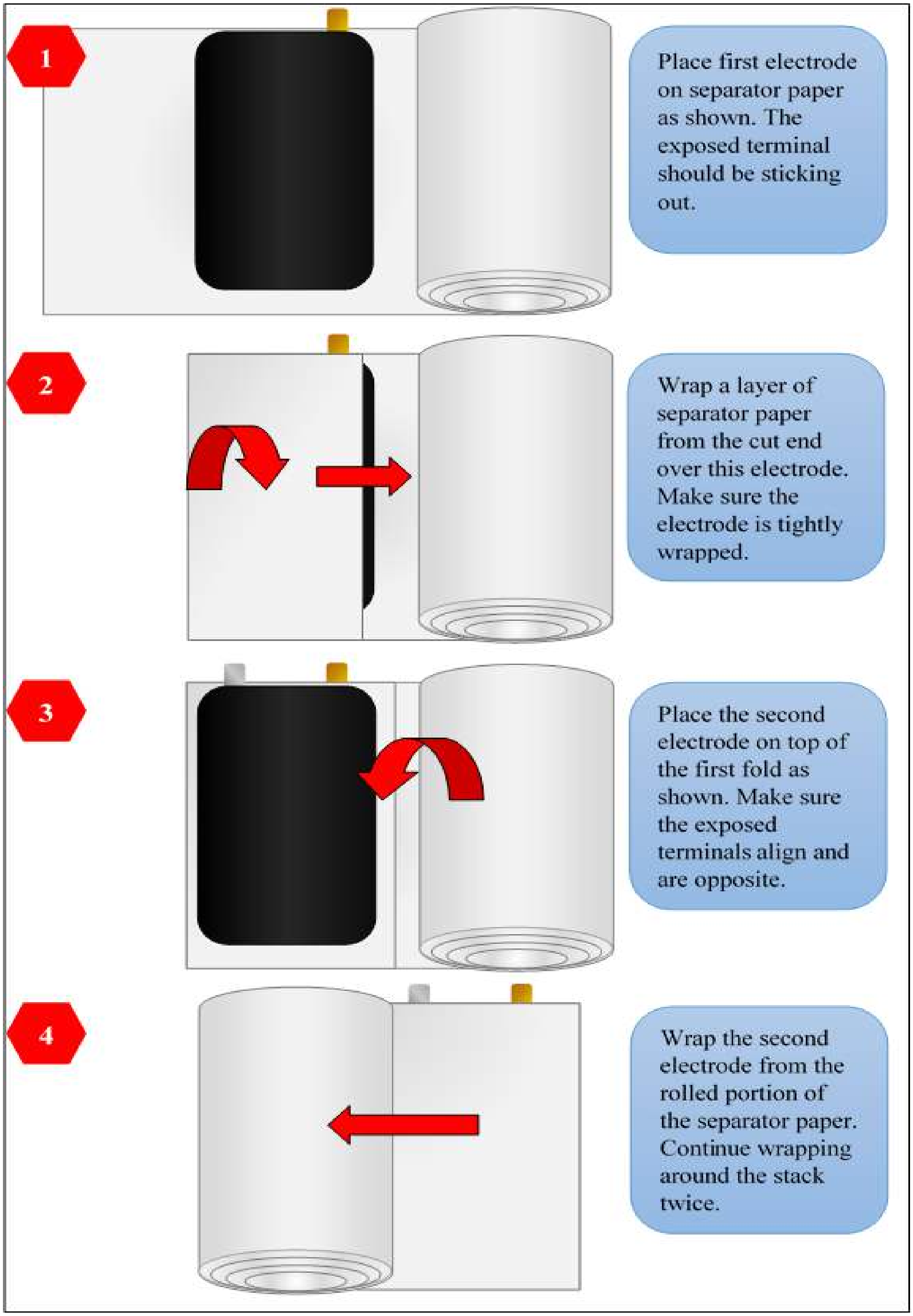


FIGURE 19. ELECTRODE FOLDING PROCESS

FIGURE 20. ELECTRODE STACK AFTER FOLDING

Foil Wrap Preparation and Welding of Terminals:

The cell pouch created in the previous step will be sealed inside a bigger pouch made out of nonconductive foil wrap. The goal is for the foil wrap to be large enough to hold the entire cell, while leaving additional space on one end to allow for excess electrolyte and gases to escape during vacuum sealing and reformation (more on these two processes later). Full instructions for sizing the foil wrap and place the cell correctly inside are shown in Figure 22.

The next step involves welding of the positive and negative terminals to the exposed electrode tabs. These terminals will serve as the interface between the battery and the outside world. The cell with the welded tabs and the welding machine are shown in Figure 21 below.

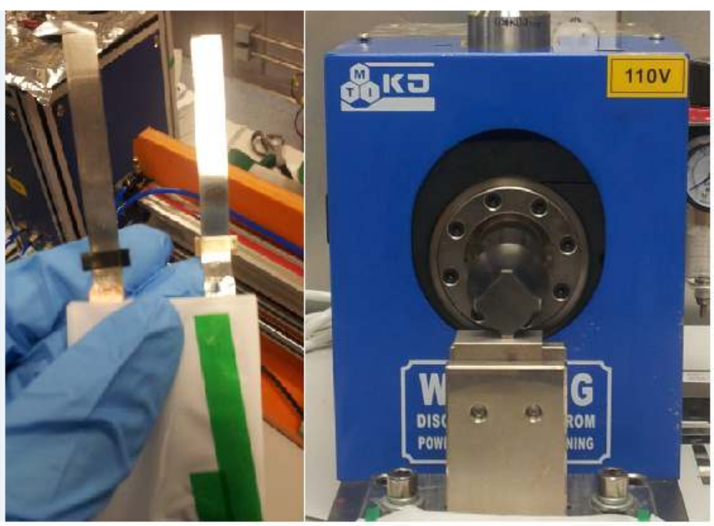


FIGURE 21. WELDING MACHINE

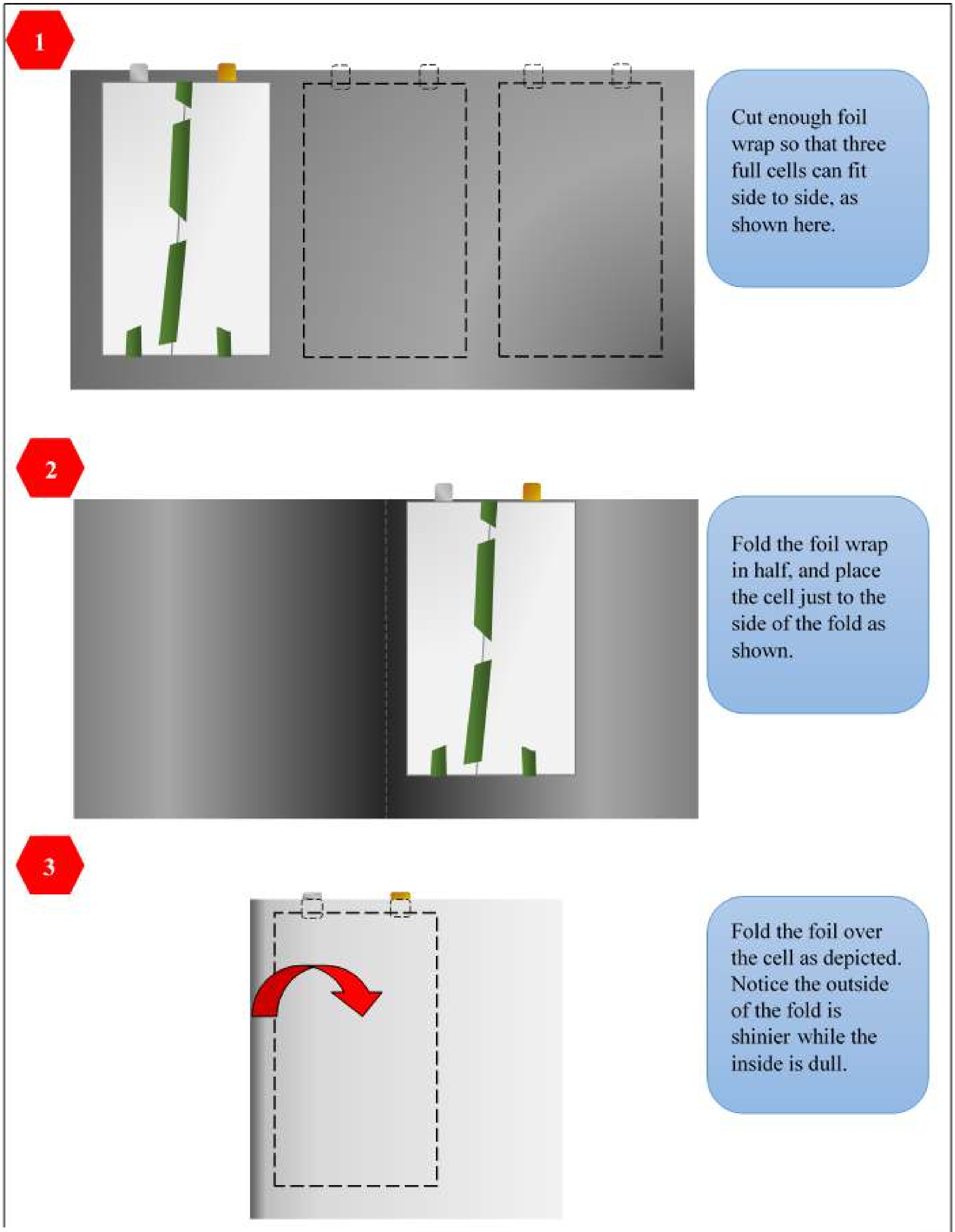


FIGURE 22. SIZING THE ALUMINUM FOIL

First Sealing Pass:

With the cell ready and the foil wrap cut and sized, the next step is the first sealing pass. The sides of the foil will be sealed, leaving the long side open for now. The cell is placed along the middle fold in the wrap, with the welded terminals sticking out of one side. The glue strips on both terminals need to be aligned with each other and with the sealing line. Step by step instructions and visual illustrations for the sealing and aligning of the cell are shown in Figure 24. A batch of pre-electrolyte batteries created using this process so far is shown in Figure 23. The sealing machine utilized is shown in Figure 23.

When large quantities of batteries are desired, it is recommended to make them in large batches up until this point in the process. At this point, the batteries are still not live as there is no liquid electrolyte medium present between them to facilitate ion transfer. Furthermore, additional tools are required for the next steps (clamps and plates) which might not be readily available.

FIGURE 23. PRE-ELECTROLYTE CELLS AND SEALING MACHINE

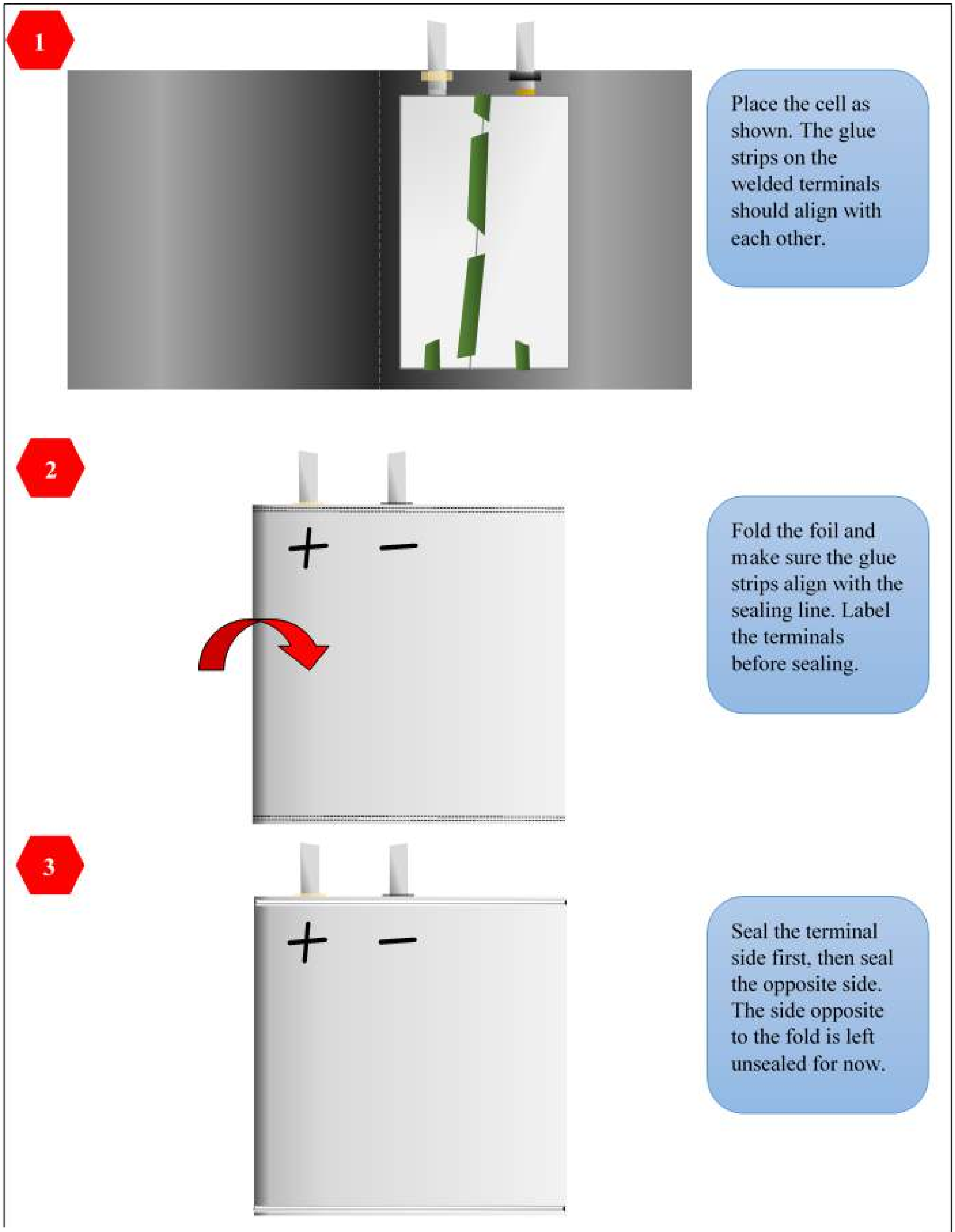


FIGURE 24. SEALING PROCESS

Electrolyte Injection and Rest Period:

At this stage in the process liquid electrolyte is added to the cell through the unsealed long end. The cell is held with the open side facing up, and a pipette is used to insert the electrolyte. For this process, three full pipettes of electrolyte are poured in. This quantity of electrolyte was chosen because it is enough to fully cover the cell for this size of battery. Figure 25 below depicts an operator adding the electrolyte into the cell. From this point onwards the battery is considered to be "live", and the terminals should not come into contact with each other. If they do, the battery will short.

Next, the cell is laid on its side on a flat surface, with the long end bent upwards to avoid the electrolyte from leaking out. The cell will be left to rest for a period of at least 2 hours in order to allow the electrolyte to fully soak the electrodes inside. The rest position of the battery is shown in Figure 26.

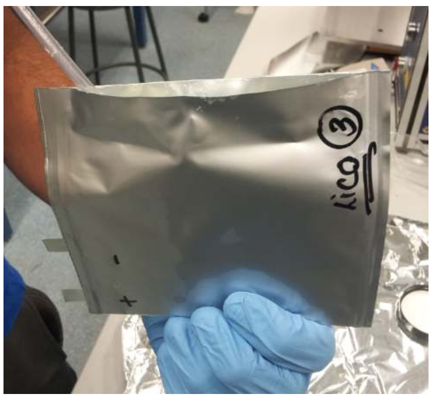


FIGURE 25. ADDING ELECTROLYTE

FIGURE 26. REST POSITION FOR THE ELECTROLYTE

Liquid electrolyte has a very strong smell, and it should be manipulated inside a fume hood. In the absence of one, face masks should be worn by the operators.

Clamping and Vacuum Seal:

After a sufficiently long rest period, about 2 hours, the battery is clamped in preparation for the first vacuum seal. Two aluminum plates are placed on both sides of the wrap and pressed against the cell inside. The two plates are then tightly clamped together. Figure 27 depicts two clamped batteries ready for the vacuum seal. Care must be taken when clamping the cells, as both the aluminum plates and the clamps are made out of metal. They cannot be allowed to come in contact with both terminals at the same time or the battery will short.

FIGURE 27. CLAMPED BATTERY

Before the vacuum seal, any excess electrolyte that has been squeezed out of the cell by the clamping process is carefully poured out. The temperature used for both plates is 180 degrees Celsius. The vacuum sealing machine and the settings are shown in Figures 28 and 29.

FIGURE 28. CONTROLS OF VACUUM SEALER

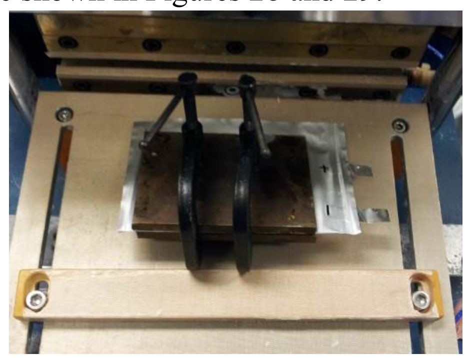


FIGURE 29. VACUUM SEALER TRAY

At this point the battery is ready for initial testing and the formation process.

Formation Process:

The first test once the batteries have been vacuum sealed is to run a voltmeter over the terminals to determine if there is a voltage reading. A reading of zero volts indicates a shorted battery, a sign that something went wrong during the manufacturing process. If the battery registers a voltage, it is connected to the 8 channel battery analyzer in order to be cycled and to begin the formation process. This cycling process will attempt to charge the battery to specified parameters and then discharge it. The time it takes for each cycle to complete depends on these parameters, which are set to 20 mA discharge rate. The battery will be left cycling for at least 24 hours to ensure proper operation. Figure 30 depicts the 8 channel battery analyzer machine with 7 batteries attached for cycling.

FIGURE 30. CYCLING THE BATTERIES

During this continuous charge/discharge cycle, the battery might expand slightly as live operation pushes remaining gas and excess liquid electrolyte out of the cell into the long, empty end of the foil wrap. This is known as formation, and it is a crucial step in making a good, dependable battery. Additionally, the battery analyzer software will generate time graphs for these cycles that show the capacity and voltage of the battery. An example of such a graph is shown in Figure 31.

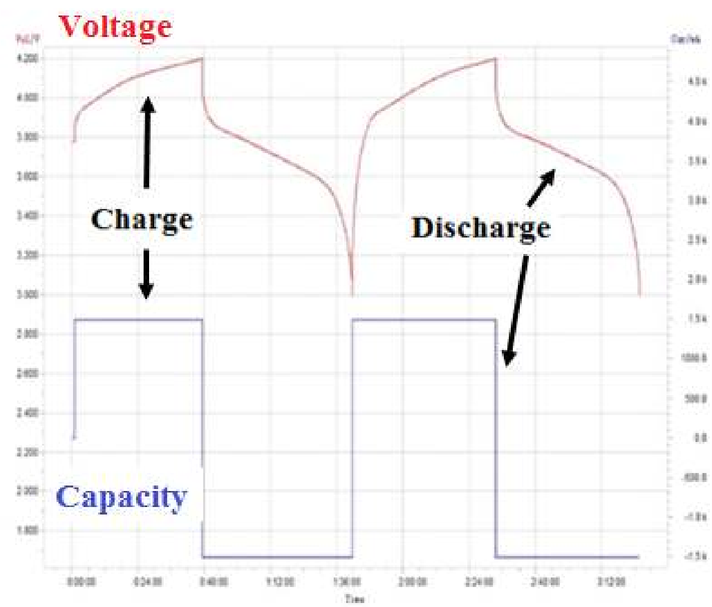


FIGURE 31. VOLTAGE AND CAPACITY

Reopening, Trimming the Long Edge and Final Vacuum:

After the battery has undergone formation for a sufficiently long period of time, it is time to reopen it so that any excess electrolyte and gases can be squeezed out of the long end of the foil wrap. A pair of scissors is used to cut the long end of the wrap, and the excess materials are squeezed out. Figures 32and 33 shows these two steps.

FIGURE 32. CUTTING EXCESS MATERIAL

FIGURE 33. DRAINING EXCESS ELECTROLYTE

At this point, all that remains is to apply the final vacuum seal (Figure 34) and the battery is ready for operation (Figure 35).

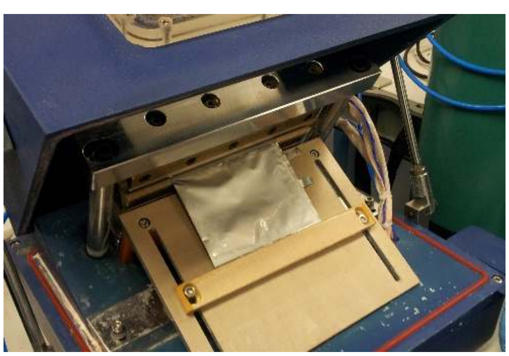


FIGURE 34. FINAL VACUUM SEAL

FIGURE 35. FINAL PRODUCT

Common Problems and Causes

Two general types of issues are commonly encountered when manufacturing this type of battery by hand.

1. Manufacturing Defects

The most common manufacturing defect is a shorted battery. This is likely caused by a problem with the process before the electrolyte phase. Refer to Figure 36 for a full explanation of possible manufacturing defects that could have led to the short. In some cases, the foil wrap can be opened and the cell inspected for visual problems.

The second type of manufacturing defect has to do with electrolyte quantity in the cell. This type of problem will become apparent during the formation process, typically during the first charge/discharge cycle. The battery will start charging properly, but will "die out" at some point during either phase of the cycle. The culprit in this case is lack of liquid electrolyte in the cell. There is simply not enough of it soaking the cell and the electrodes to facilitate proper ion transfer.

Several possibilities that could lead to this lack of electrolyte include:

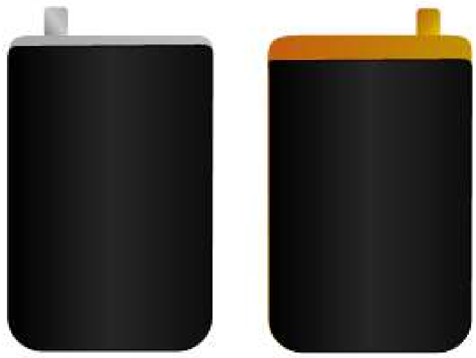
- The battery was clamped too tight, forcing too much liquid electrolyte out of the cell and into the empty and long section of the foil wrap.
- Liquid electrolyte might have leaked out of the wrap during the rest period.
- An insufficiently long rest period will result in an under-soaked cell.
- Not enough liquid electrolyte was injected in the cell.

The solution for these types of problems is simply to be more meticulous during the manufacturing process, and to follow all the steps properly.

2. Material Incompatibility

The second type of issue that results in defective or nonfunctioning batteries has to do with improperly selected cathode and anode materials. Generally, the weight of active material on the cathode should outweigh the active material on the anode by as much as 3 times. In the least the anode and cathode should have equal weighs. If the materials are not evenly matched, key symptoms of this problem will once again manifest themselves during formation cycling. The battery might take an abnormally long amount of time to charge, or might charge properly but fail to discharge. Some of the symptoms of this problem overlap with those for the manufacturing case of low electrolyte amounts. The battery will simply “die out” during formation. Fortunately, proper pairing of electrode materials can (and should be) guaranteed by doing proper research and consulting with vendors.

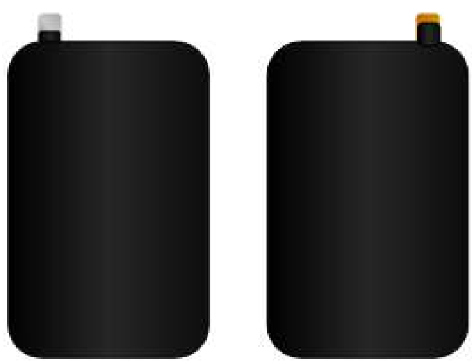
1



When punching the electrode layers, sometimes the sheet can be misaligned in such a way that the exposed, non-carbon coated section of the sheet ends up lower than the tab. This makes shorting between the two tabs easier.

Solution: discard the tab, align sheet more carefully inside plates.

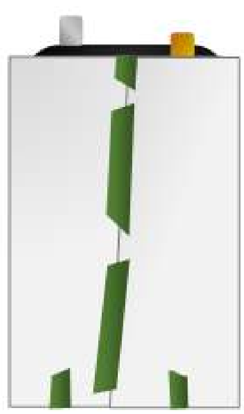
2



The opposite situation can also occur. In this case, the electrode sheet is misaligned and the press cuts too low, leaving a carbon coating on the terminal tab.

Solution: scrape off the carbon coating with a razor edge.

3



When folding the cell by hand, the cells can be misaligned and they might end up sticking out the top or bottom of the separator paper fold. This will result in a short if they stick out of the top, as the exposed tab will be in contact with the misaligned sheet.

Solution: be meticulous during the folding process.

FIGURE 36. POSSIBLE MANUFACTURING DEFECTS

Applications

Most of the electronic devices today are limited by batteries that run them. They are limited by the batteries energy density and its shape. This project was concentrated on the second limitation of the batteries. Shape conformable battery can revolutionize the way electronic devices are shaped and sized. Conformable batteries can give birth to new devices such as curved phone or an electronic watch that can do much more than tell you time and sustain power for long periods of time.

Shape conformable battery packs can eliminate the need for extra space in an electronic device. These batteries would be able to occupy any available space in a device and still be able to supply required power. These batteries can possible eliminate additional weight which is created due to the need for an extra battery space.

Companies like Apple and Samsung are funding projects related to conforming a battery into a curved phone, watches and glasses. The purpose behind these projects is to have a battery that doesn't required an additional storage space and can still supply required energy.

Shape Conformable battery packs can be applied to mechatronics devices like robots. For example, the origami prototype can be used as an integrated part of the robot leg, hand or wheels if configured accordingly. Even in large vehicles like a car or an airplane, these batteries can be integrated as a part of these vehicles rather than occupying excess space.

Risk and Reliability Assessment

All energy storage systems may encounter unexpected conditions whenever used. These conditions can create an accidental or uncontrolled energy release. For batteries, this could mean fire, explosion, or chemical release. Measures should be taken to avoid the consequences of these accidental conditions. Products and production processes can be designed to control the safety with appropriate means.

The Chemical Risk:

The substances contained inside the battery may present a chemical risk, in particular the rupture of casing and leakage. Although it is not common to see the release of substances during normal working conditions, the worst case should always be considered. This is especially important when dealing with lithium. To avoid chemical contact, the lab technicians in the AME building handle all electrolyte in a vacuum glove box. It is opened again only inside the dry room during final assembly of the batteries. Additionally, the user should were gloves, facemask, and lab coat at all times while handling battery materials.

The Electrical Risk:

The state of charge should be controlled in case of overcharge and over discharge, which decelerates the temperature increase of the battery. In addition, the production environment has to be dry enough to prevent short-circuit caused by moisture in the air. This is yet another reason the batteries are made in the dry room of the AME lab. This dry room can provide a humidity of around -40°C dew point.

The Thermal Runaway Risk:

Lithium ion batteries may experience thermal runaway if not handled properly. Explosion in cells can occur if punctured or overheated. The possible consequences of the thermal runaway of a lithium-ion battery are fire/explosion or toxic gas emission. Thermal runaway starts when an exothermic reaction is unregulated, which causes a temperature increase, which causes the reaction speed to increase. The problem experiences a snowball effect and can lead to a drastic end. For lithium batteries. This can occur at temperatures above 80°C [9].

When making Lithium-ion cells with either liquid or solid electrolyte, thermodynamic instability between the carbon anode and the lithium-based electrolyte occurs. As a result of this instability, a porous thin layer of electrolyte solidifies and adds internal resistance. This solid layer is referred to as the Solid Electrolyte Interface (SEI) and servers to moderate thermodynamic instability. Figure 37 depicts this SEI layer inside the battery.

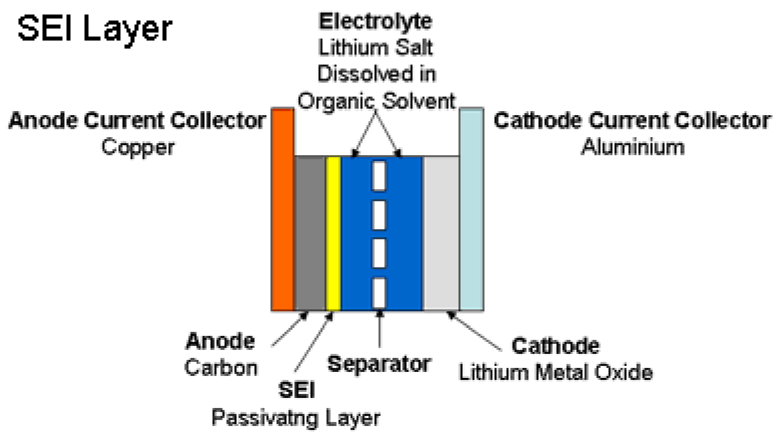
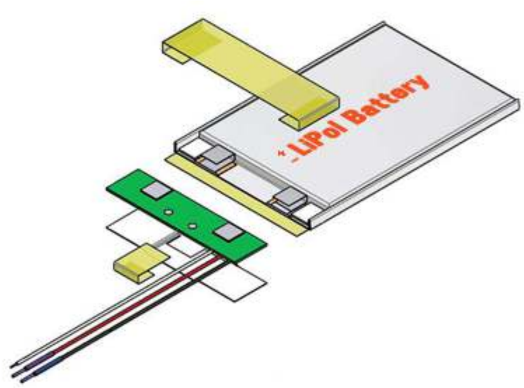


FIGURE 37. SEI LAYER

Thermal runaway can occur if the battery is subject to excessive voltage or current charge/discharge. It begins with the breakdown of the SEI layer, typically at 80^0C. As the SEI layer breaks down it reacts violently with the carbon anode and produces hydrocarbon gas. As gas fills the cell and pressure increases, so does the internal temperature. At 150^0C a $LiCO_2$ cathode will breakdown, releasing oxygen gas into the cell (250^0C for a $LiMn_2O_4$ cathode) and further increasing pressure and temperature. Once hydrocarbon and oxygen gas are present, the increasing temperature eventually causes the cell to ignite. (1)

In recent years a shutdown separator has been introduced to some lithium ion cells. This specialized separator is initially porous, and melts and solidifies during thermal runaway thereby stopping the ion conduction process. (2) Protection circuitry is built into most cells to prevent the most common causes of thermal runaway, but such a circuit is beyond the scope of this project. An example of what such a circuit would look like is presented in Figure 38.



Protection Circuit Design

Protection circuitry is used to control the under/over voltage and current conditions of the cell. In this project, over voltage and current were controlled by the battery charging equipment (the B6AC Pro Battery Charger that was purchased separately). Under voltage conditions are controlled by the UAV system's circuitry, specifically the Electronic Speed Control (ESC). Over current discharge is controlled by the implementation of an in-line fuse. If the cells need to be used in a manner in which they are not easily accessible, a resettable fuse (polymeric positive temperature coefficient device or PPTC) can be used.

The size of the in-line fuses were chosen to keep current within an acceptable discharge rate. Each type of cell has a point where the amount of current leaving the cell in combination with its internal resistance causes friction, and results in a loss of energy in the form of heat. A battery can be modeled as an equivalent circuit with various sources of internal resistance and a capacitor. The figure below shows three different sources of resistance, where Ra, Rm, and RI represent the metallic, electrochemical, and contact resistance of a cell respectively (4).

To find the safe discharge rate of any battery, the cell is charged and discharged at various rates, while an IR temperature sensor is used to determine if there is any increase in temperature.

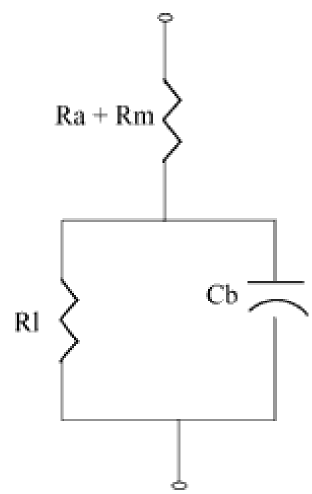


FIGURE 38. EXAMPLE CIRCUIT

Reliability Analysis

There are many instances where there could be a dead or underperforming battery. A fish bone diagram of how this could happen are given below in Figure 39.

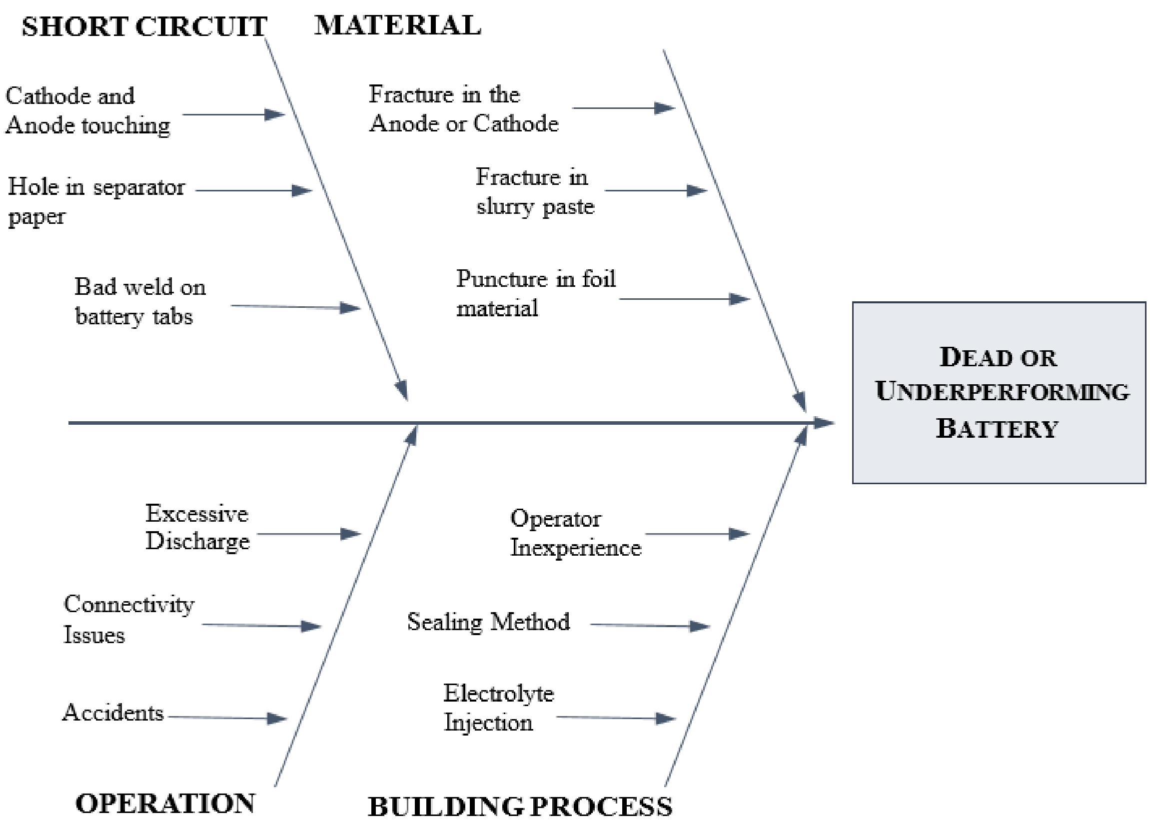


FIGURE 39. POSSIBLE CAUSES OF FAILURE

Procurement

All materials were discussed and approved by sponsors prior to submission. The RC plane, extra wing sets, and foam glue were purchased from HobbyTown USA. The anodes and cathodes were purchased from MTI Corporation. The AME battery lab is supplying the separator paper, Lithium hexaflourophosphate ($LiPF_6$) electrolyte, and the laminated foil pouch material. Table 4 outlines the current standings of all purchases made.

TABLE 3. FINAL PROCUREMENT STATUS

Description	Quantity	Unit Price ($)	Total ($)
Ares Gamma 370 RTF plane	1	129.99	129.99
Wing Set	2	39.98	79.96
Large EPP foam glue	2	9.98	19.96
Li-Ion Battery Cathode - Aluminum foil double coated $LiFePO_4$	2	79.95	159.90
Li-Ion Battery Anode - Copper foil double side coated Graphite	2	59.95	119.90
		Fall Total:	$509.71
Li-Ion Battery Cathode - Aluminum foil double coated $LiFePO_4$	1	79.95	79.95
Li-Ion Battery Anode - Copper foil double side coated Graphite	1	59.95	59.95
Polymer Lithium-ion battery (small) 200 mA	30	10.00	300.00
Polymer Lithium-ion battery (large) 2800 mA	6	28.00	168.00
Battery Charger	1	35.50	35.50
Replacement parts and supplies	1	80.96	80.96
		Spring Total:	**$724.36**
		Grand Total:	**$1234.07**
		Remaining Budget:	**$765.93**

Conclusion

In order to create a shape conformable battery for an RC plane, it was determined that surface conformability across the wings of the plane was a good approach to solve this problem. A lightweight and thin battery can be used to achieve a non-bulky and surface-conformable design that will not upset the aerodynamics of the RC plane. As such, lithium-ion and lithium-polymer cell pouch batteries present themselves as suitable candidates for this type of battery pack. These type of batteries are thin and possess an inherent degree of flexibility.

The conformability solutions proposed and prototyped revolve around two configurations: an Origami-like foldable battery pack, and a large thin cell that is attached to a non-flat surface to achieve true surface conformability. The Origami configuration offers a battery pack that can be folded and used to achieve a certain level of surface conformability. This design is highly modular: additional batteries can be attached (or detached) in series or parallel to increase (or decrease) the capacity or voltage of the battery. The bent cell design offers true surface conformability and is more suitable to be used as a skin or under-skin.

Hand-manufacture of lithium-ion cells was pursued in order to validate and test these conformability solutions. This is a very time consuming process that requires a high degree of skill and understanding of batteries. The team was able to devise and come up with a streamlined process for the creation of very basic lithium-ion cells, at the expense of significant time and resources. Unfortunately, time constraints prevented the creation of more advanced batteries that could have been used to support the design configurations.

Nevertheless, the prototypes were successfully achieved with the outsourcing of lithium-polymer cells to a battery manufacturer. Small-sized lithium-polymer cells were utilized to realize the Origami configuration and demonstrate its modularity and flexibility. Large-sized lithium-polymer cells were utilized to demonstrate the idea of true surface conformability. These batteries were bent to resemble the airfoil shape of a wing, and attached as skin patches with a protective layer of plastic. It was demonstrated that the bent and deformed lithium-polymer cells are able to operate at acceptable rates while conforming to the shape of the wing.

Future Works

General work and tasks required for this project fell into one of two categories: 1) battery technician work, and 2) conformability engineering. The team was successful in the engineering aspect of the project, as an acceptable solution to shape conformability in batteries was provided. The battery technician portion was less successful, as this is a high-skill job that presents abysmal success rates for beginning technicians. Significant amount of trial and error, practice and research was required to figure out a basic (and personalized) process to create a cell. The documentation for this process can be used as a starting point for future teams working on this project.

Four main challenges had to be overcome in order to satisfy the project requirements. First, the team had to learn from scratch how to properly build reliable cells. As the documentation outlined in previous section shows, the creation of a battery by hand is a very time consuming and inexact process. Human error and variability elements are present at every step of the process. Furthermore, handcrafting batteries is as much a science as it is an art. There is an accepted and well known list of raw materials that can be used to create these batteries. However, precise combinations and variations of these materials are closely guarded trade secrets.

Second, prototype constraints steered the team towards a lightweight battery. Sustained flight of an RC plane with a custom battery necessitates a solution that does not negatively impact the aerodynamics of the plane. Had the prototype requirements specified a land vehicle or a robot, the weight of the battery would have been less of a constraint. This would have allowed the team more design freedom to approach the conformability problem.

The third challenge has to do with the power constraints imposed by the choice of prototype. The amount of power required for successful takeoff of an RC plane is far greater than that required for sustained flight. The battery will be subjected to high discharge rates in order to achieve takeoff. This places a heavy burden on the quality and power capacity of the battery. Once again, a simpler prototype would shift emphasis away from the battery technician portion of the work and allow greater focus on engineering a good conformability solution.

Finally, there is the issue of degree of conformability. It was not enough to prove flat surface conformability. The overall shape or arrangement of the battery pack had to be nonstandard. This constraint opens the door to a wide range of interpretations on what exactly constitutes a nonstandard battery. The Origami configuration provides surface conformability and modularity across a non-flat surface due to its multiple folding points. The flat and flexible configuration provides true surface conformability and skin-like behavior, but long-term effects of the bending are unknown at this point.

To summarize:

- Batteries had to be built from scratch

- Batteries had to be lightweight
- Batteries had to be able to sustain the high discharge rate required for takeoff, and still have enough remaining charge for a 5 minute flight
- Batteries had to be shape conformable and in a nonstandard arrangement

The final recommendation from the team is that the project is certainly doable, but too ambitious for the time allotted for a senior design class if starting from zero. Choose two out of four objectives, or provide a clear and well documented starting point.

Bibliography

1. **Server Experts.** LiPo Batteries and Charging for your Model RC Airplane. *L.I. Foam Flyers.* [Online] 2011. [Cited: September 21, 2013.] http://www.longislandelectricrcairplanes.com/learnbatteries.php.

2. **Linden, David.** *Handbook of Batteries.* New York : McGraw-Hill, 2002.

3. *Designing lithium ion batteries for high power applications.* **Ismail, M., Hassan, M.F., Winnie, T., Arof, A.K., Nor, K.M.** 2003. PECon 2003 National Proceedings. pp. 289 – 291.

4. **Zheng, Honghe, et al.** *Fabrication Procedure for Lithium-ion Rechargeable Coin Cells.* Berkeley : Lawrence Berkeley National Laboratory, 2010.

5. *Electrode Materials for Lithium Ion Batteries.* **Kam, Kinson C.** 2012, Material Matters.

6. **Q. Wang, P. Ping, X. Zhao, G. Chu, J Sun, and C. Chen.** Thermal runaway caused fire and explosion of lithium ion battery. *ScienceDirect.* [Online] 06 15, 2012. http://www.sciencedirect.com/science/article/pii/S0378775312003989.

7. Ares Gamma 370 Park Flyer Airplane unstruction manual. *Firelands group.* [Online] 2012. http://ares-rc.com/gamma370/support.asp.

8. Battery types and Battery Efficiency - Peukert's Law. *BD Batteries.* [Online] 2014. http://www.bdbatteries.com/peukert.php.

9. Cell Chemistries. *Woodbank Communications Ltd.* [Online] 2005. http://www.mpoweruk.com/chemistries.htm#sei.

10. Cell Performance. *Woodbank Communications Ltd.* [Online] 2005. http://www.mpoweruk.com/performance.htm.

11. High Rate Discharge Lithium Polymer Battery. *Lipo Battery Co., Ltd.* [Online] 2002. http://www.lipolbattery.com/high%20rate%20discharge%20lithium%20polymer%20battery.html.

12. *The Role of Separators in Lithium-Ion Cell Safety.* **Orendorff, C.J.** 2012, The electrochemical Society Interface, pp. 61-65.

13. **Staples, Gabriel.** Propeller Static and Dynamic Thrust Calculation. *Electric Aircraft Guy.* [Online] July 16, 2013. http://electricrcaircraftguy.blogspot.com/2013/09/propeller-static-dynamic-thrust-equation.html#.U045zKK9bBY.

14. **Lund Instrument Engineering, INC.** Ultrathin Rechargeable Lithium Polymer Batteries from PowerStream. [Online] 2014. http://www.powerstream.com/thin-lithium-ion.htm.

Appendix

TABLE A: PROPERTIES OF BATTERIES USED

Battery Type	2700 mAh Lipo	180 mAh Lipo	Cobalt Li-ion
Usable Max Capacity (mAh)	2700	180	118
1 Cell Weight (g)	85	6	8.25
Capacity (mAh/cm^2)	2	2	2.77
Nominal Voltage (V)	3.7	3.7	3.6
Layers per cell	4	3	1
Cells Used	2	14	16
Total Weight (g)	170	84	132
Power Required for Flight (W)	30.48	25.56	28.31
Amps Required	4.23	3.55	3.93
Discharge Rate Required (C)	1.57	2.82	4.16
Cell Thickness (mm)	1.13	1.00	0.723
Single Cell Area (mm^2)	31860	2684	4250
Cell Volume (L)	0.036	0.0027	0.0031
Energy Density (Wh/L)	292.49	261.55	149.77
Specific Energy (Wh/kg)	123.88	117.00	55.78

TABLE B: COMPARISON OF WEIGHTS WITH THREE BATTERY PACKS

Description	*Stock Plane (g)*	*Modified Plane (g)*	*Weight Increase (g)*
Plane Body	278	308	30
Wings	120	445	325
Plane plus Wings	398	753	355
Stock Battery	57	Not Applicable	Not Applicable
Total Weight	**455**	**753**	**298**

TABLE C: ORIGAMI PACK WEIGHTS

Description	*Weight (g)*
Origami pack #1	62
Origami pack #1 with Connectors	88
Origami pack #2	63
Origami pack #2 with Connectors	90
Total Weight for both packs	**178**

TABLE D: LARGE BENT LIPO BATTERY PACK WEIGHTS

Description	*Weight (g)*
Large LiPo #1 with Wiring	114
Large LiPo #1 bent with Housing	162
Large LiPo #2 with Wiring	116
Large LiPo #2 bent with Housing	163
Total Weight for both LiPo Packs	**325**

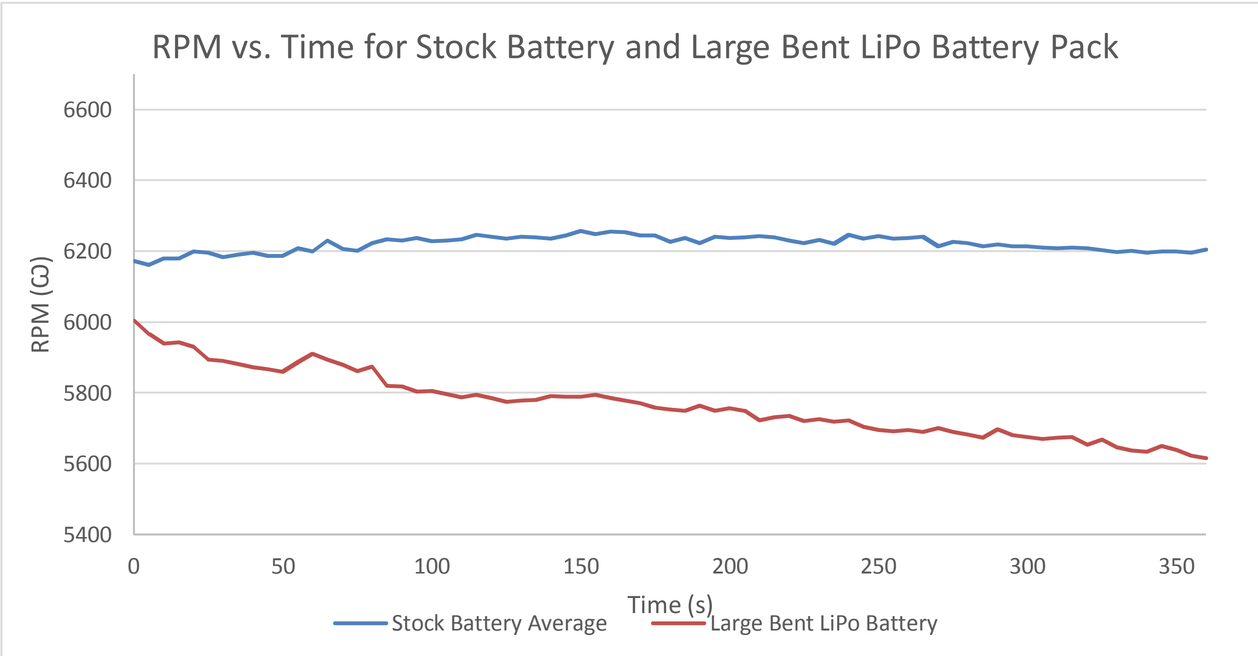


FIGURE A PROPELLER PERFORMANCE AVERAGES FOR STOCK BATTERY AND LARGE BENT LIPO PACK

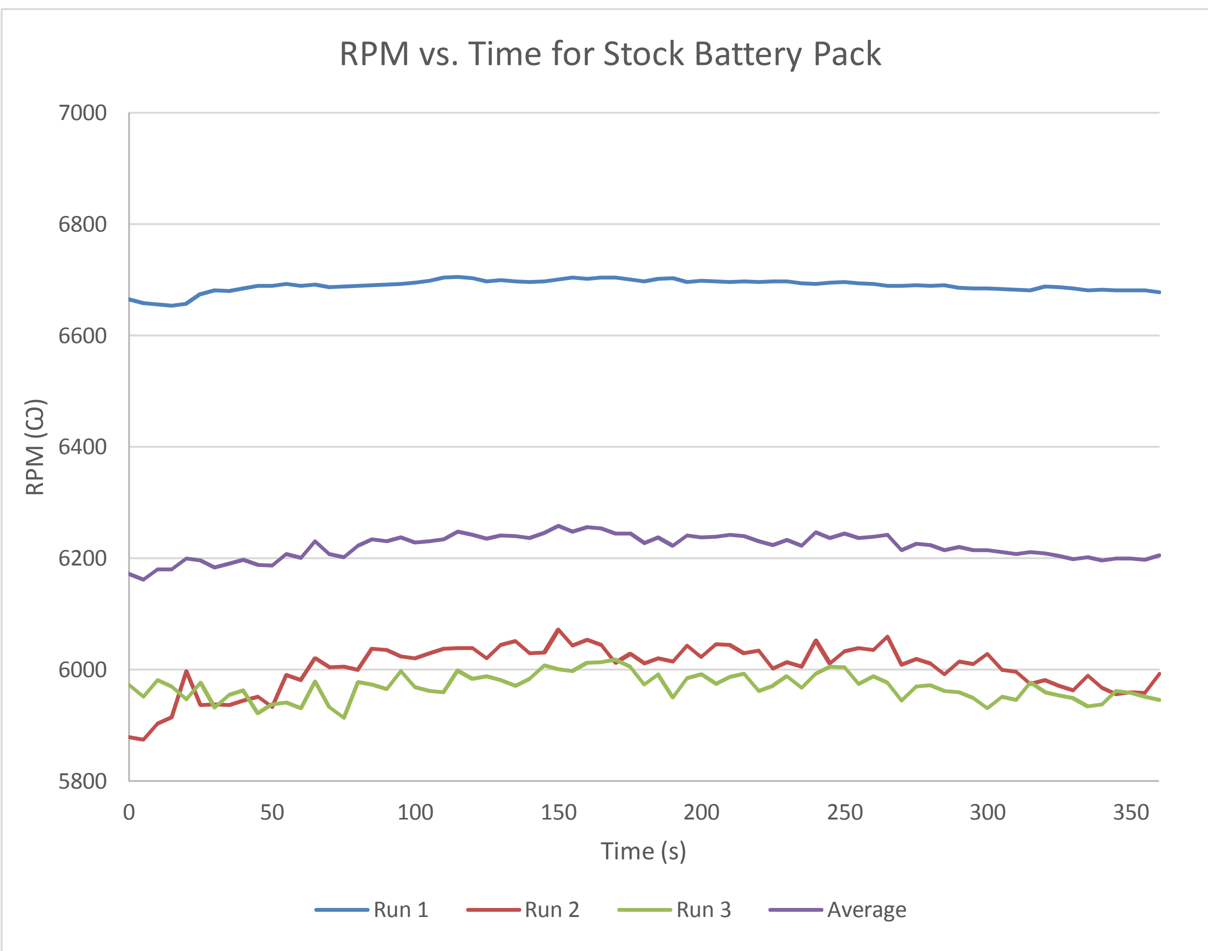


FIGURE B PROPELLER PERFORMANCE WITH STOCK BATTERY

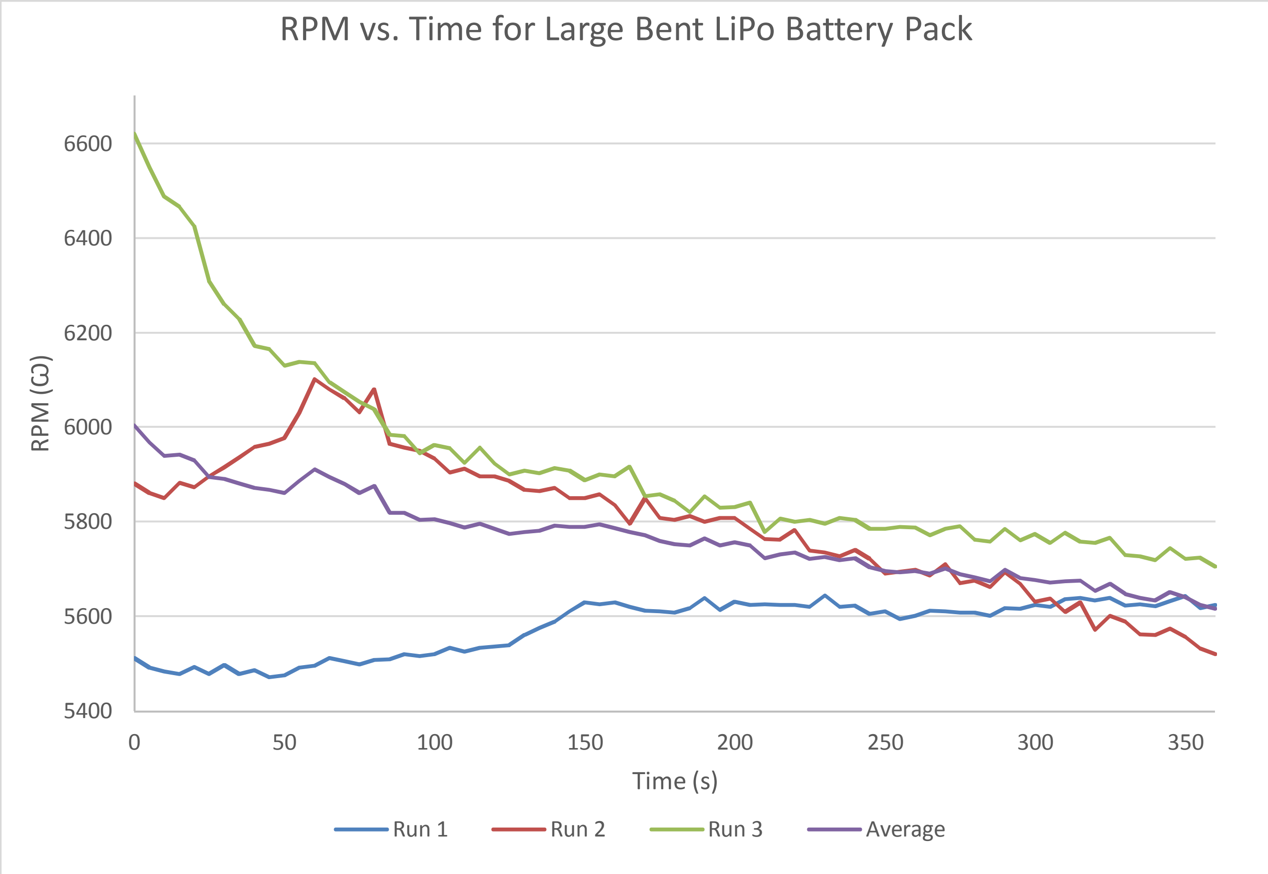


FIGURE C PROPELLER RPM PERFORMANCE FOR LARGE BENT LIPO BATTERY PACK

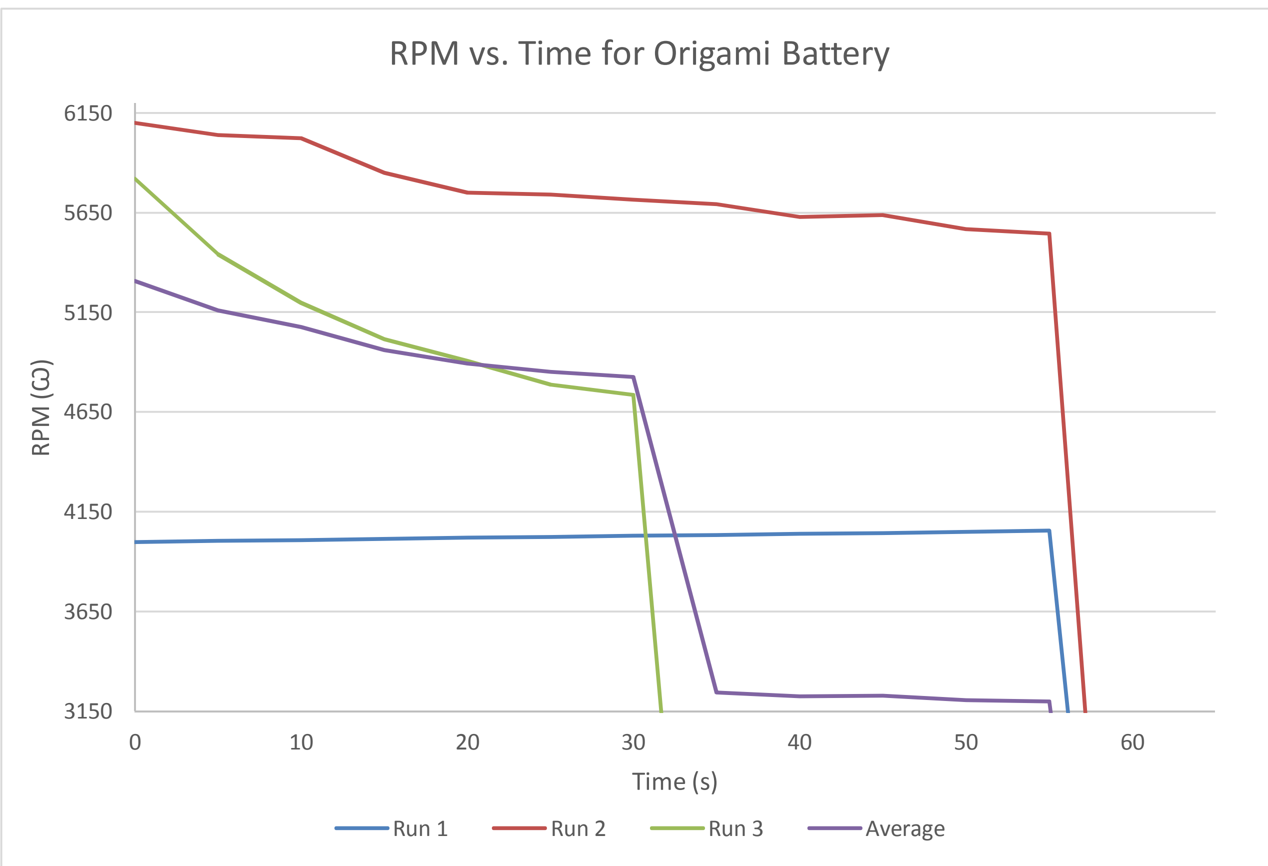


FIGURE D PROPELLER PERFORMANCE ORIGAMI PACK