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Designing a Nano-Drone with Hybrid Structural Energy Storage

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Mechanical Engineering
Senior Design Report

Designing a Nano-Drone with Hybrid Structural Energy Storage

Spring 2016

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Abstract

The Advanced Energy and Sensor Lab at the University of Akron has been working to develop a working flow battery that replaces today's solid batteries. The objective of this senior design project was to replace the conventional lithium-ion battery as the energy storage component in nano-copters with a newly designed hybrid structural battery. In the design, the nano-copter needed to be mechanically supported and store enough energy for flying. In order to accomplish this, the nano-copter weight was reduced so that the flight range could be significantly increased. Therefore, the project was broken into two major parts. The first was the 3D modeling and printing of the hexacopter. The second was working in the research lab to develop a working flow battery. The results were mixed as a hexacopter was successfully printed, but due to delays in battery testing, the team was unable to confirm that the body would successfully house the flow battery. However, near the end of the project, one battery recipe successfully underwent a full 50-hour charge and discharge cycle, reaching 4.2 volts, which is promising. More testing would be needed to confirm its successfulness and compatibility with the hexacopter.

Introduction

As the demand for portable, flexible, and wearable electronics increases, more research is being conducted to design flexible batteries. However, in general “batteries are not keeping pace with developments in electronics technology, where performance doubles every 18 months” [1]. It was not until 2012 that researchers from Seoul National University and the Korea Advanced Institute of Science and Technology published their developments of a flexible lithium ion battery using a mica substrate which had promising results, “capable of a maximum 4.2 V charging voltage and 106 µAh/cm^2 capacity” [2]. Despite these findings, even in 2016, a company called Polyera, that has developed a flexible display wrist band, is still limited in user-friendliness by the battery it employs. The company claims that “over the next few years, Polyera Digital Fabric Technology will enable the products that people have long wished for, and many they have not yet imagined: where devices are no longer hard, heavy, and cold, but soft, ambient, and organic – where the forms they take and the roles they play become more natural and more human” [3].

Fig. 1. A display from Polyera in its pre-alpha stage that wraps around a segmented bracelet

Furthermore, advancements in batteries will be playing an even greater role in the development of electric vehicles and renewable energy technologies since global warming is an increasing international concern. In 2011, researchers proposed and demonstrated a new storage concept, “the semi-solid flow cell (SSFC), which combines the high energy density of rechargeable batteries with the flexible and scalable architecture of fuel cells and flow batteries” [4]. Additionally, the researchers believe that the SSFC design could outpace current lithium ion battery technologies in terms of materials and manufacturing cost.

For these reasons, the Advanced Energy and Sensor Lab at the University of Akron has been working to develop a working flow battery that replaces today’s solid batteries. For the scope of this senior design project, the goal was to replace the conventional lithium-ion battery as the energy storage component in a newly designed nano-copter, which also still ensured structural integrity.

Theory

In the most basic sense, a battery is made of an anode and cathode with a separator in between in addition to an electrolyte. The anode and cathode are electrodes, which are conductors through which electricity can enter or leave. During discharge, the electrons in the anode displace to the cathode. The separator ensures there is not an internal short circuit between the anode and cathode, and the electrolyte provides a medium through which the ions can be transferred. This process is depicted in the figure below.

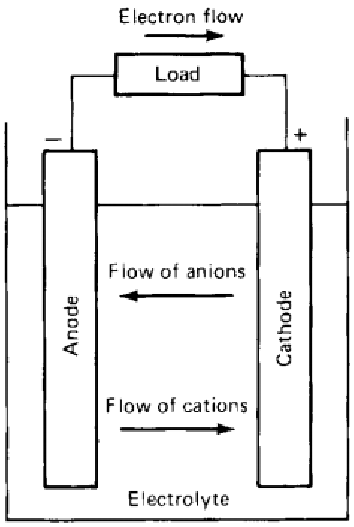


Fig. 2. Electrochemical operation of a cell (discharge) [1]

Batteries can be classified as primary or secondary. Simply stated, secondary batteries can be recharged effectively and primary batteries cannot. Typically, secondary batteries are recharged by passing current through the cell in the opposite direction of discharge; however, some can be mechanically recharged by replacing the electrode material. Secondary batteries have “high power densities, high discharge rates, flat discharge curves, and in most cases good low-temperature performance” compared to primary batteries, but caveats include lower energy densities and poorer charge retention [1].

The amount of active materials in the cell determine the capacity, the “total quantity of electricity involved in the electrochemical reaction” and the types of active materials determine the voltage. Capacity can defined in terms of ampere-hours or on an energy basis as watt-hours. More specifically, the specific energy is given as a ratio on a weight basis and the energy density as a ratio on a volume basis. Therefore, to maximize the energy of the cell, the weight of non-active materials should be minimized since research demonstrates “the weight of the materials of construction reduces the theoretical energy density of the battery by almost 50%" [1]. In the case of this project, a half cell was used and thus the performance is dependent upon the active ingredients for the cathode.

Additionally, along with capacity, voltage is a major factor affecting the energy of a cell, since the specific energy can be calculated by multiplying voltage and ampere-hours/gram. Due to a variety of factors, there is a strong deviation from actual voltage and ideal theoretical voltage. The figure below demonstrates the differences between representations of typical discharge curves and an ideal curve.

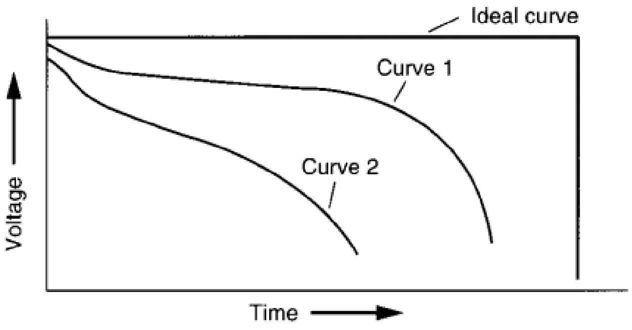


Fig.3. Characteristic discharge curves [1]

Yet another factor which can have a significant effect on battery performance is the mode of discharge. Some of these modes include constant current, constant load, and constant power. An example depicting these differing characteristics for an AA battery discharged under different modes is shown in the figure below.

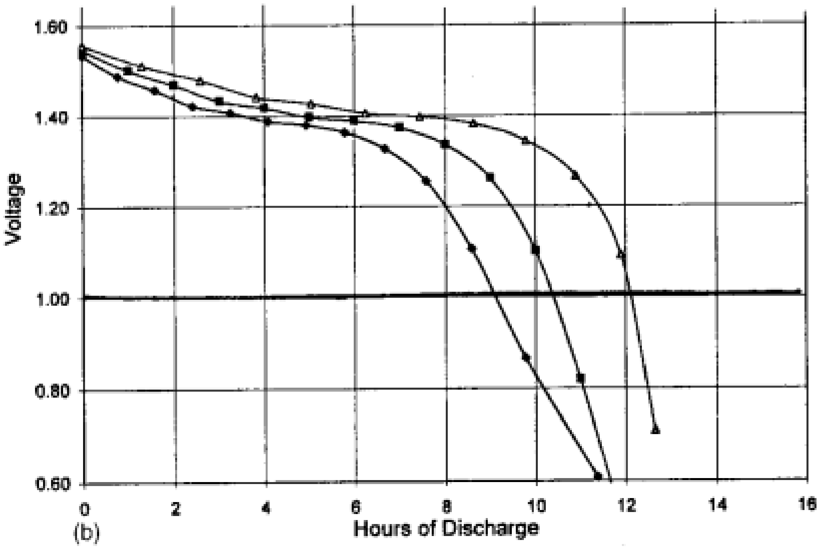
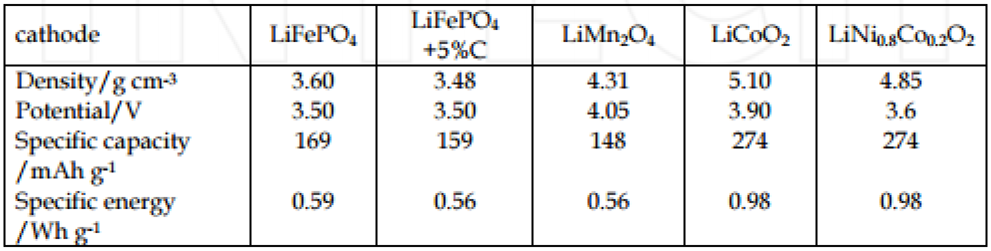


Fig. 4. Characteristics of an AA-size primary battery discharged under constant-resistance, constant-current, and constant power conditions at 5.9 ohms, 200 milliamperes, and 235 milliwatts [1]

In order to better compare the performance of batteries, the C rate (a standard method for indicating discharge and charge) is typically referenced. Other methods include the hourly rate or E rate. A battery discharged more slowly has a higher capacity as it takes time for the ions to get into the cathode. In the case of this project, lithium ions needed time to absorb into the LFP.

For the cathode material, the team first tried $LiFePO_4$ (LFP) and then $LiCoO_2$ (LCO). These materials have been used as cathodes in batteries since the 1900s and 1980s respectively [5, 6]. The figure below shows LCO as favorable amongst several other popular cathode materials.



cathode	$LiFePO_4$	$LiFePO_4$ +5%C	$LiMn_2O_4$	$LiCoO_2$	$LiNi_{0.8}Co_{0.2}O_2$
Density/g cm^{-3}	3.60	3.48	4.31	5.10	4.85
Potential/V	3.50	3.50	4.05	3.90	3.6
Specific capacity /mAh g^{-1}	169	159	148	274	274
Specific energy /Wh g^{-1}	0.59	0.56	0.56	0.98	0.98

Fig. 5. Electrochemical parameters of several cathode materials [7]

For the electrolyte, the team used $LiPF_6$ and aluminum foam as a current collector (Duocel Aluminum Foam 20 ppi, 10-12% density processed from 6101 alloy, and heat treated to T6 conditions). This was an important choice as aluminum "exhibits excellent corrosion resistance in a number of organic solvents containing $LiPF_6$" [8].

Carbon black (Ketjenblack® EC-600 JD) was used as a conductive additive. When carbon black is thoroughly dispersed, it significantly increases the conductivity between the active particles and has the ability to hold the electrolyte [1]. It also has the "same level of performance at approximately 60% of the amount of Ketjenblack EC-300 J" [9]. This was important as it also reduces the weight of the inactive ingredients to improve the battery performance.

Improving the performance of the battery also relies on choosing a good binder to keep the materials together in the cathode. The conventional binder used was PVDF but in 2013, experimental research led to the finding that PVP "retained 94 percent of its original energy-storage capacity after 100 charge/discharge cycles, compared with 72 percent for cells using PVDF" [10]. The team started with PVDF but made the transition to the PVP binder as the project progressed.

Finally, since battery performance and failure is often due to a degradation in the separator, a trilayered separator was used for this project, because “the superior oxidative resistance of polypropylene as compared to polyethylene results in a PP/PE/PP trilayer separator being more stable to an oxidative cell environment” [11].

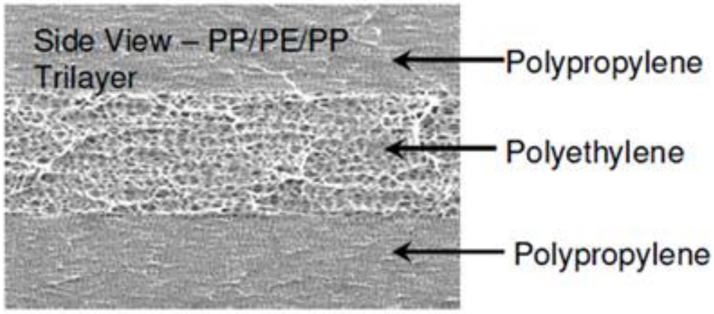


Fig. 6. Side view of trilayer [12]

Design Process

The primary task of this design project was to design a hybrid hexacopter body that was capable of both providing mechanical support to the functional components and housing a newly developed flow battery. The desired result of this process was a reduction in weight and an increase in flight time.

Hexacopter Body Design

The first step in the design process was to research and document the specifications of two mini-copters currently on the market. The mini-copters were dismantled to measure the components. Ideas for potential structural designs for similar mini-copters were discussed and multiple designs were developed. The team broke up into partner groups to come up with models of the mini-copters in SolidWorks. After initial modeling, it was decided to focus the project on the improvement of a 6-rotor design. Two models of the 6-rotor design were generated, each by a different member of the team. Figure 1 shows some early concept sketches for the 6-rotor hexacopter design.

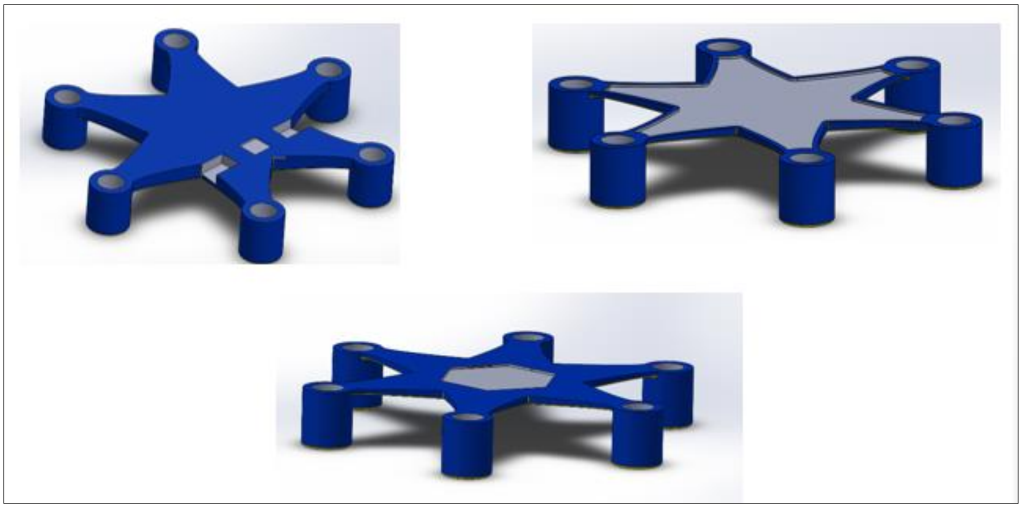


Fig. 7. Concept Sketches

In addition to this early brainstorming, the team began creating working body models in SolidWorks to allow better visualization of proposed solutions. Early iterations of copter design included a separate compartment beneath the body to house the battery, much like the stock body. Another concept generated involved a two-piece body that was permanently affixed, using a nozzle to recharge the fluid of the battery. The final concept generated, which became the focus of the project, was a three-piece body that contained the circuitry in the top portion, a gasket to seal the circuitry from the battery fluid, and the battery/structural support was the bottom portion.

The first iteration of the final concept involved a hexagonal cut for the catholyte that was 2.5 millimeters deep. This iteration also utilized a nozzle design to allow old fluid to be blown out with compressed air and refilled using a syringe. Upon review with Dr. Farhad, a maximum thickness of 0.6 millimeters was selected in order to further reduce weight. The team used a hydraulic jack press to confirm that the aluminum foam current collector would still be porous at such a reduced thickness. In order to maintain a total volume of 70% of the original battery, the radius of the hexagon's circumscribed circle was increased as well.

The final iteration of the hexacopter body came to be after editing the aforementioned changes into the working model. To ensure the structural integrity of the body, the thickness was increased where the motor mounts meet the body arms. Additionally, the nozzle concept was scrapped due to the extreme thinness of the catholyte compartment. The body is now able to be disassembled for battery changing, making use of 2.5mm x 10mm hex bolts that rest on horizontal landings of the body arms. Additional drawings of early iterations, as well as final design are available in Appendix A.

Battery Design

The second part of this design project included working in the Advanced Energy and Sensor Lab at the University of Akron in tandem with Evan Foreman, a graduate student, to develop working prototypes of the flow battery. The team spent about six hours per week, working closely with Evan Foreman, for a total of 25 weeks.

Team members each built coin batteries using a cathode solution of lithium iron phosphate (LFP) on punched aluminum pieces as a preliminary step to get a feel for the process of making a battery. Later on, the team learned the procedure for testing battery recipes. This involved weighing the raw ingredients for the catholyte material (see Appendix B for catholyte recipes). (Before using the active ingredients for the catholyte, foil containers were made so that the materials could be put in the oven to remove any solvent. The powder was also finely grinded with a mortar and pestle). The recipes were all written using a volume percentage of each ingredient. Using the density of each material, the volumes were converted into a weight measurement. Due to the very small weights of the materials, an enclosed scale was used to ensure accuracy. The necessary amount of electrolyte was combined with the cathode powder. In order to make the mixture more uniform, small ceramic balls were put in the vial, and this was placed in homogenizer.

After the catholyte material was made according to the specified recipe, the battery was assembled in an enclosed argon hood in 3D printed housings. However, after testing in the 3D printed housings, the team concluded that the housings were insufficient for our needs. The team decided to use bags made from clear sheet plastic that was heat sealed around an ionic separator. Aluminum and nickel strips, soldered to copper wire, were used to collect the current from the battery and act as terminals. Initially, the bags were heat sealed on the side edges, while the metal strips were glued into the bottom end with special super glue. The glue was also used to seal the top end of the bag once the battery was built. This method did not seal the bags very well and nearly every test battery built failed due to leakage. In an effort to correct this leakage, the team decided to place the entire metal strip inside the bags and have only the copper wire leads coming out of the bottom end. The rubber sheathing on the copper wires allowed the heat sealer to melt the plastic of the bag into the rubber on the wires, resulting in a better seal. Heat sealing was also used once the battery was built in order to seal the top end of the battery. In order to help facilitate ion transfer, the aluminum that was used on the anode side of the battery was replaced with nickel. As a final measure to increase the surface area available to collect current, aluminum foam was inserted on the cathode side between the nickel strip and the ionic separator.

The figure below shows the progression of the multiple iterations of the battery designs.

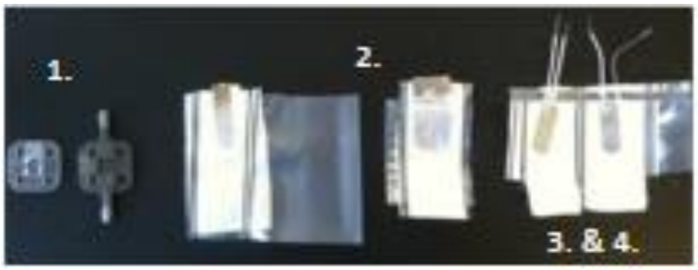


Fig. 8. Battery design progression

1. Fluid full cell contained in a printed plastic housing with nickel leads.
2. Fluid half-cell contained in a plastic bag with single separator with nickel leads. Sealed with glue.
3. Fluid half-cell, plastic bag, double separator, heat crimped, nickel leads soldered to wires.
4. Viscous fluid (peanut butter consistency) half cell, plastic bag, double separator, heat crimped, nickel leads soldered to wires

Testing

Hexacopter Body Testing

The final iteration of the hexacopter body was printed using the Objet Eden laser 3D printer in the basement of Auburn Science and Engineering Center at the University of Akron. The current design has been tested and was found to be capable of housing all functional and circuit components of the original hexacopter. Due to delays in battery testing, the team did not have a chance to confirm that the body will successfully be compatible with the flow battery. Further testing would be necessary.

Battery Testing

The batteries were tested using BT Lab software, which ran each battery through a constant current/constant voltage (CC/CV) charge and discharge cycle at 0.1 mA. The required voltage potential for a full charge was 4.2 V. The energy capacity of the battery, in mAh, was calculated by the software using the charge time and the charging current. A battery was considered successful if it completed a full cycle with no voltage spikes and no voltage drops.

The battery tested on April 22, 2016 underwent a full 50-hour charge and discharge cycle, reaching 4.2 volts. The recipe for the successful battery was as follows: 50 vol% LCO, 35 vol% electrolyte (1M $LiPF_6$ in 7:3 by volume Ethylene Carbonate: Dimethyl Carbonate), 15 vol% C-45 carbon black, and 0.1 wt% PVP (0.1% of the weight of LCO, electrolyte, C-45 was added in PVP). Aluminum foam was added under the nickel strip as a current collector on the cathode side to help increase surface area.

Experimental Data

The data in figure 2 demonstrates that the successful battery described above underwent a full 50-hour charge and discharge cycle. The recipe of 25 vol% LCO, 50 vol% electrolyte, 25% Ketjen carbon black, and 2 wt% PVP never approached the 4.2V maximum charge voltage. Another recipe with a silver-polyester conductive textile between the nickel current collector and the separator (25 vol% LCO, 50 vol% electrolyte, 25% Ketjen carbon black, and 2 wt% PVP) never fully charged. See Appendix B for these additional results.

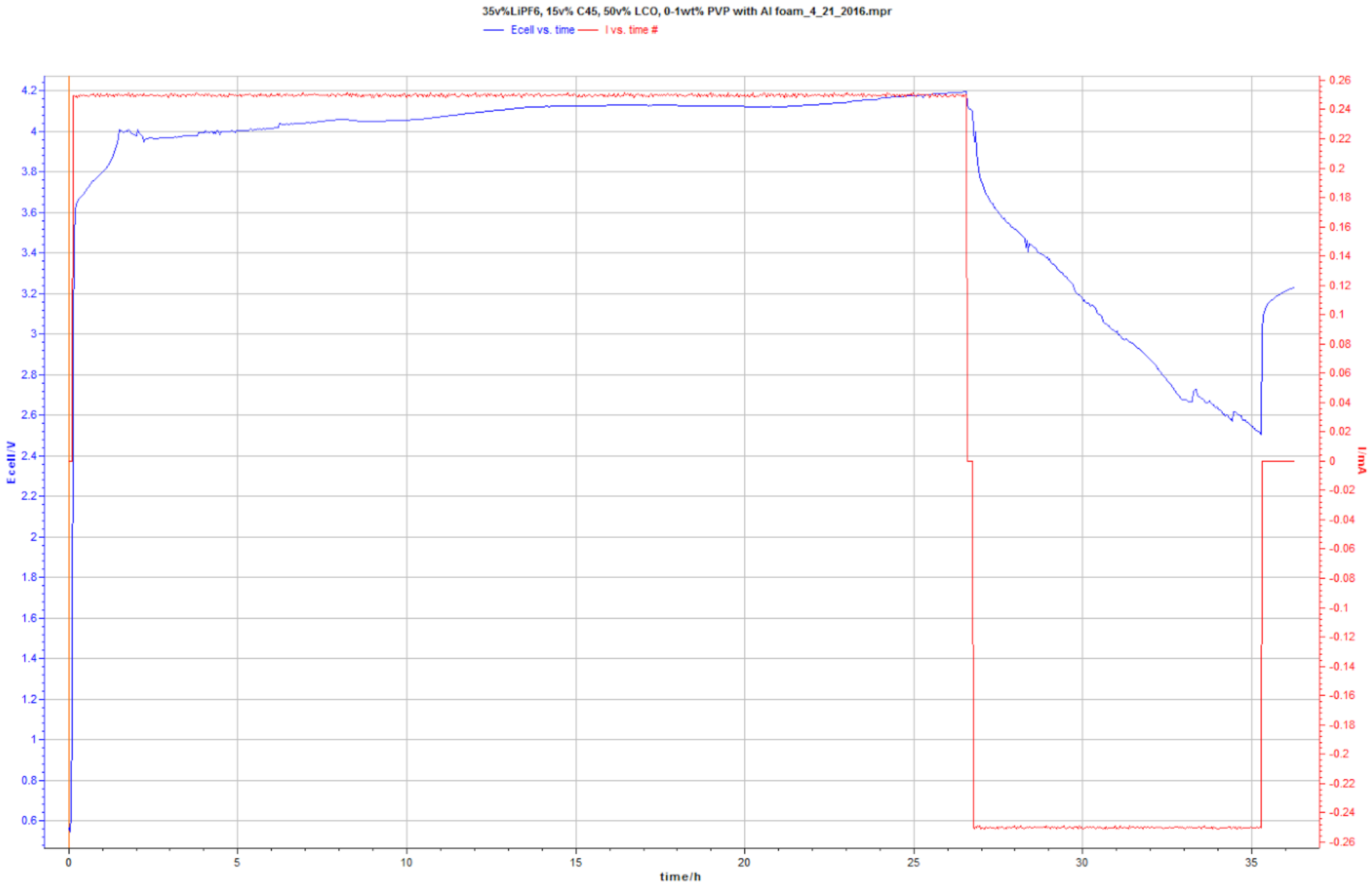


Fig. 9. Successful CC/CV charge and discharge cycle

Conclusion

The team ended the project with a 3D printed hexacopter and working battery design, but due to time constraints was unable to combine the designs together to test for compatibility. Further experimental research is needed to determine optimum recipes of materials used in the design, but since battery performance improvement is now at the forefront of international concern, constant research reviews would be also be necessary to continue this project successfully. It could be the latest combination of binders, separators, current collectors, or electrolytes that could significantly improve the performance of the flow battery.

Recommendations for Future

For future students planning to work to further this design project, we would recommend that the students work in the lab as much as possible to perfect the cathode recipe for the current design. After that is complete, the students should work in the lab to develop and perfect a working anolyte solution in order to replace the lithium chips. In tandem with anolyte development, the students should work to redesign the copter body to accept a full cell flow battery. After development of the full cell battery, the students should then take the perfected recipes and perform a cost analysis to determine the price per mAh. This can be used in order to compare against the traditional Li-ion batteries available today. In addition, the specifications for weight can be compared to Li-ion batteries to ensure the weight reduction is exactly where it needs to be.

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Appendix A

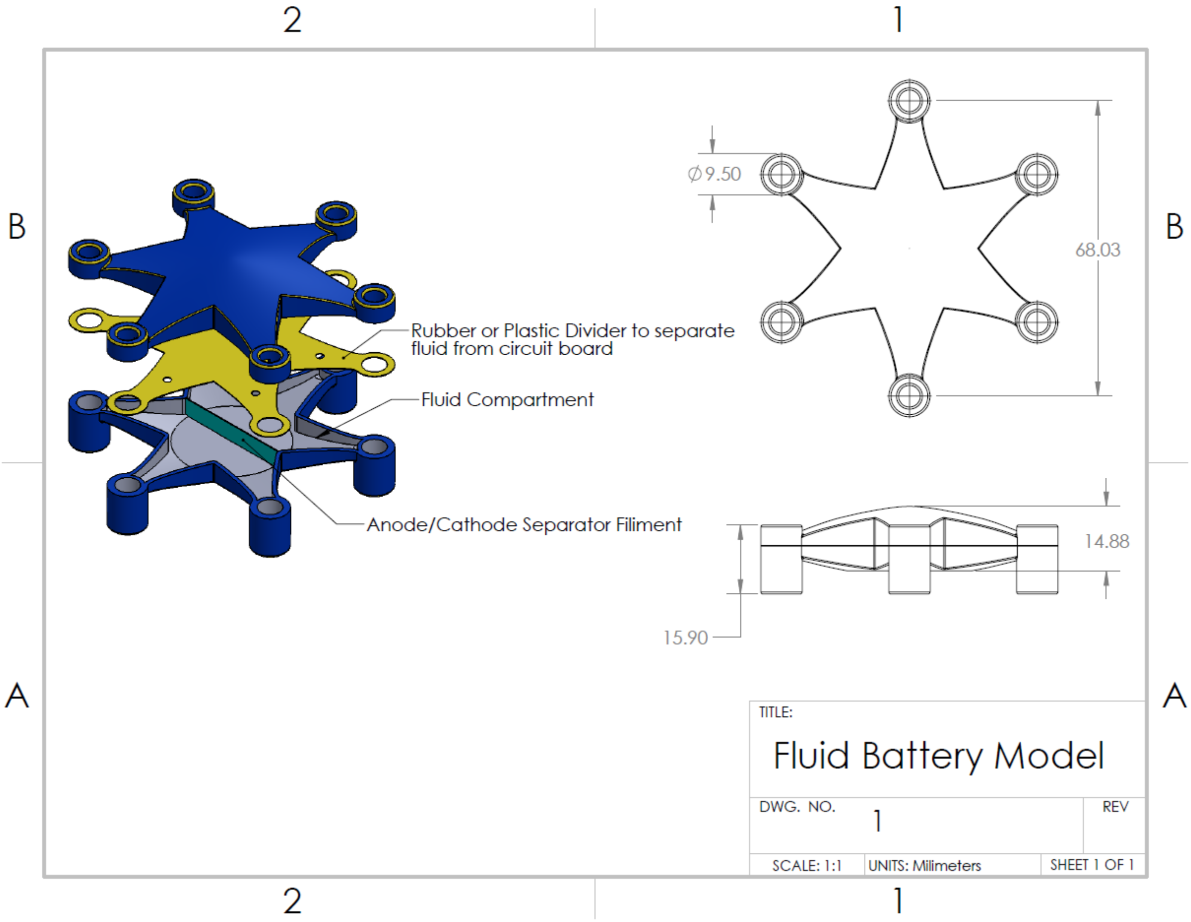

Figure A1 – Preliminary sketch 1 (side-by-side)

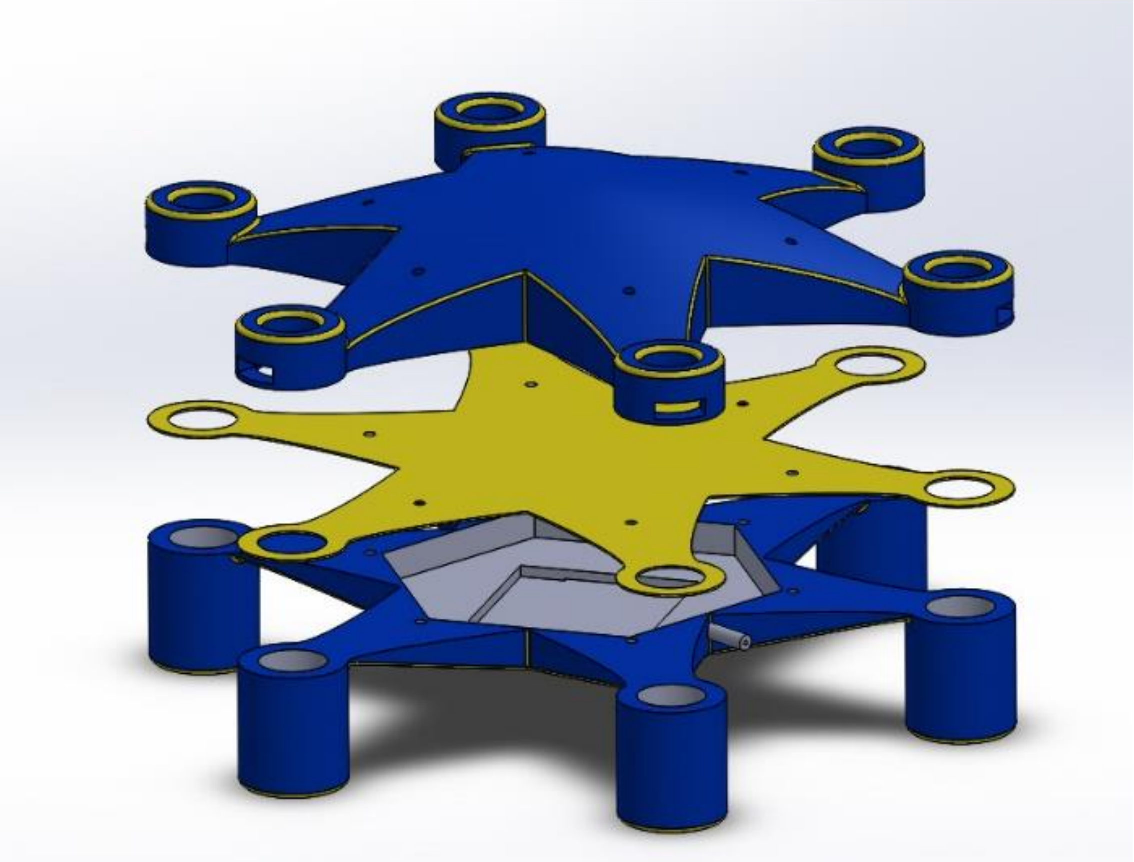

Figure A2 – Preliminary sketch 2 (nozzle)

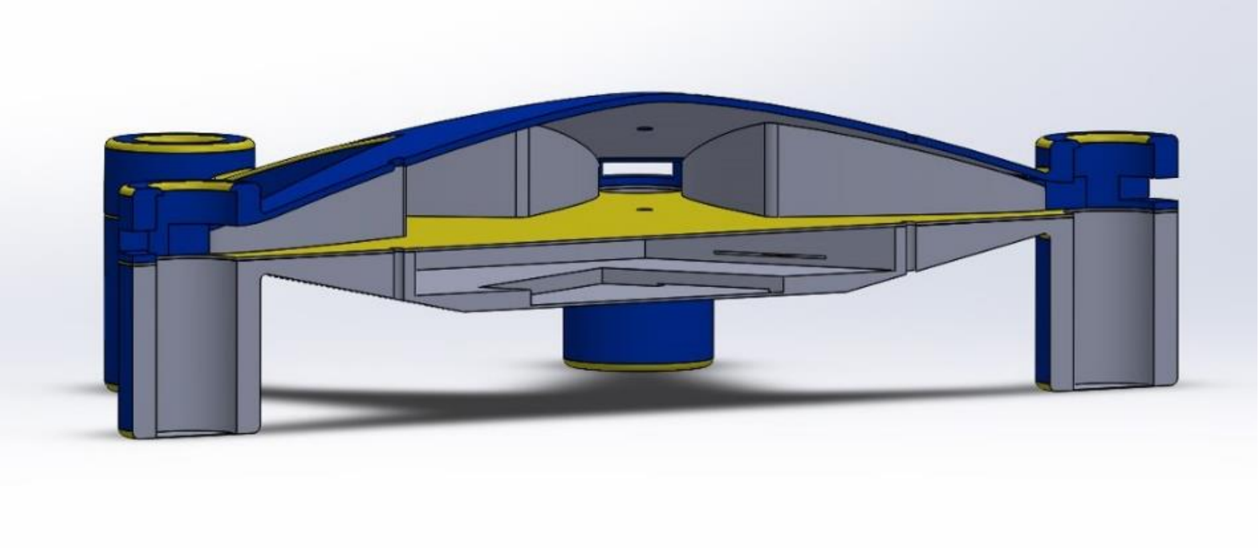

Figure A3 – Section view of preliminary sketch 2 (nozzle)

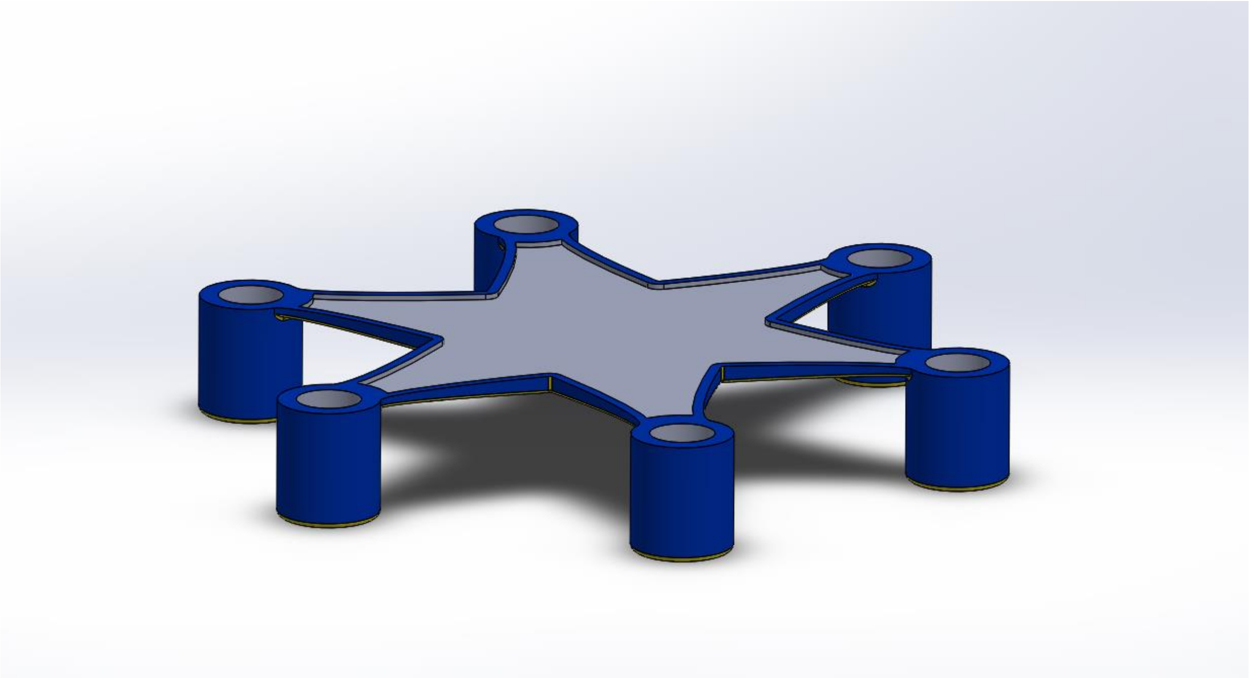

Figure A4 – Preliminary sketch 3 (hollow housing)

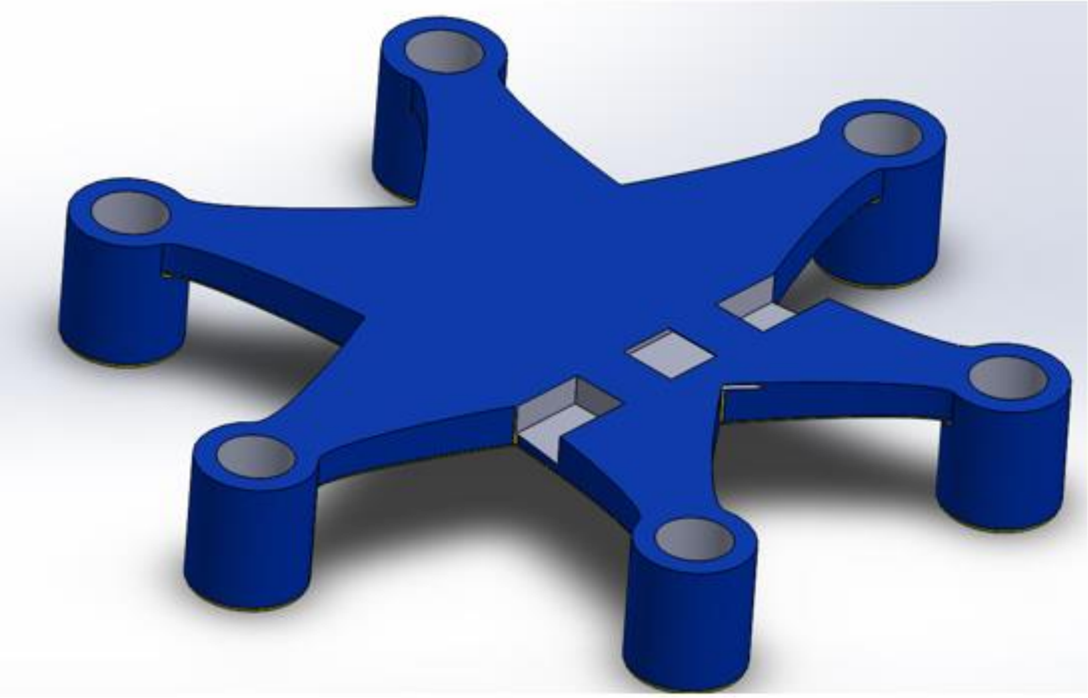

Figure A5 - Preliminary sketch 4 (isolated battery)

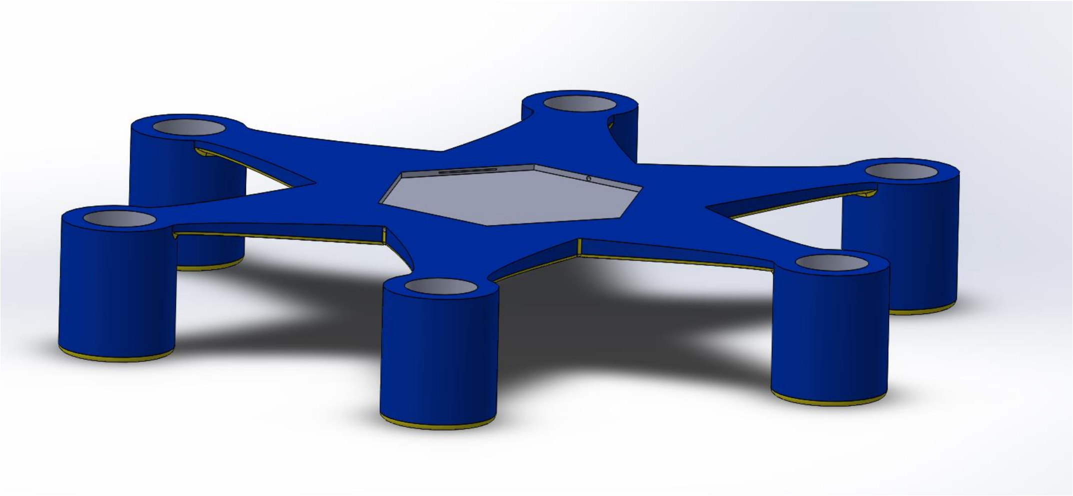

Figure A6 – Preliminary sketch 5 (hexagonal housing)

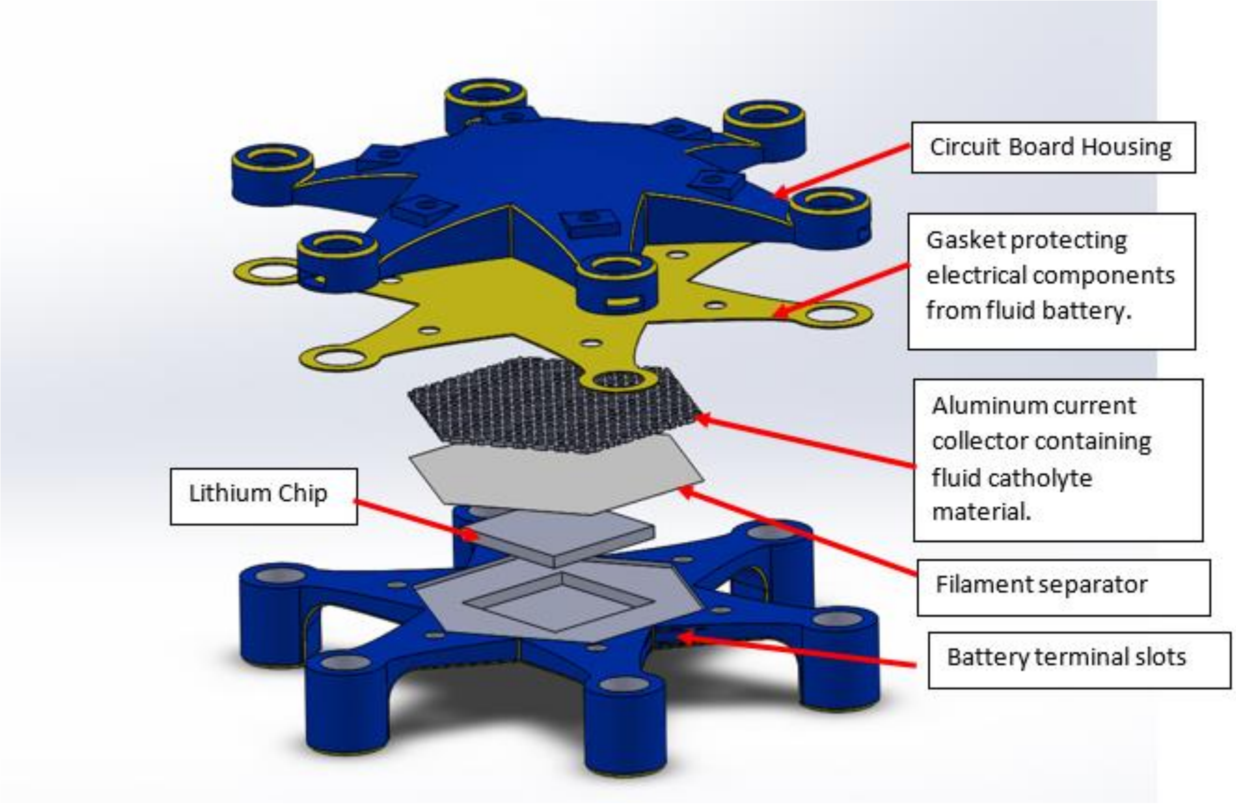

Figure A7 – Final Battery Design

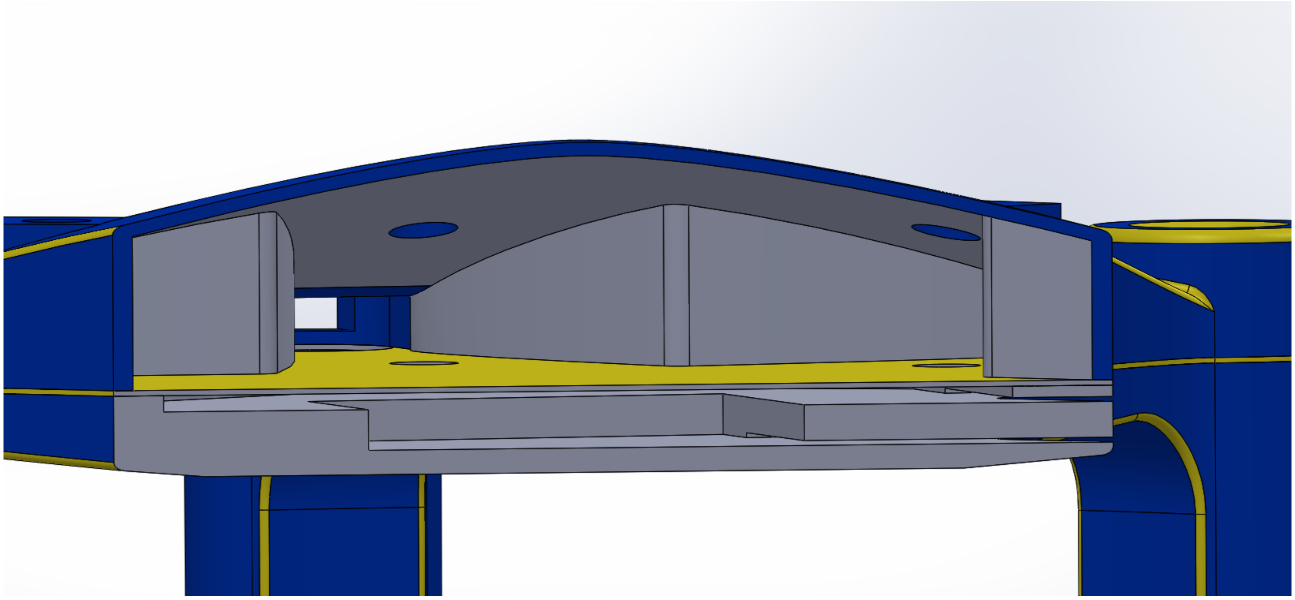

Figure A8 – Section view of Final Battery Design

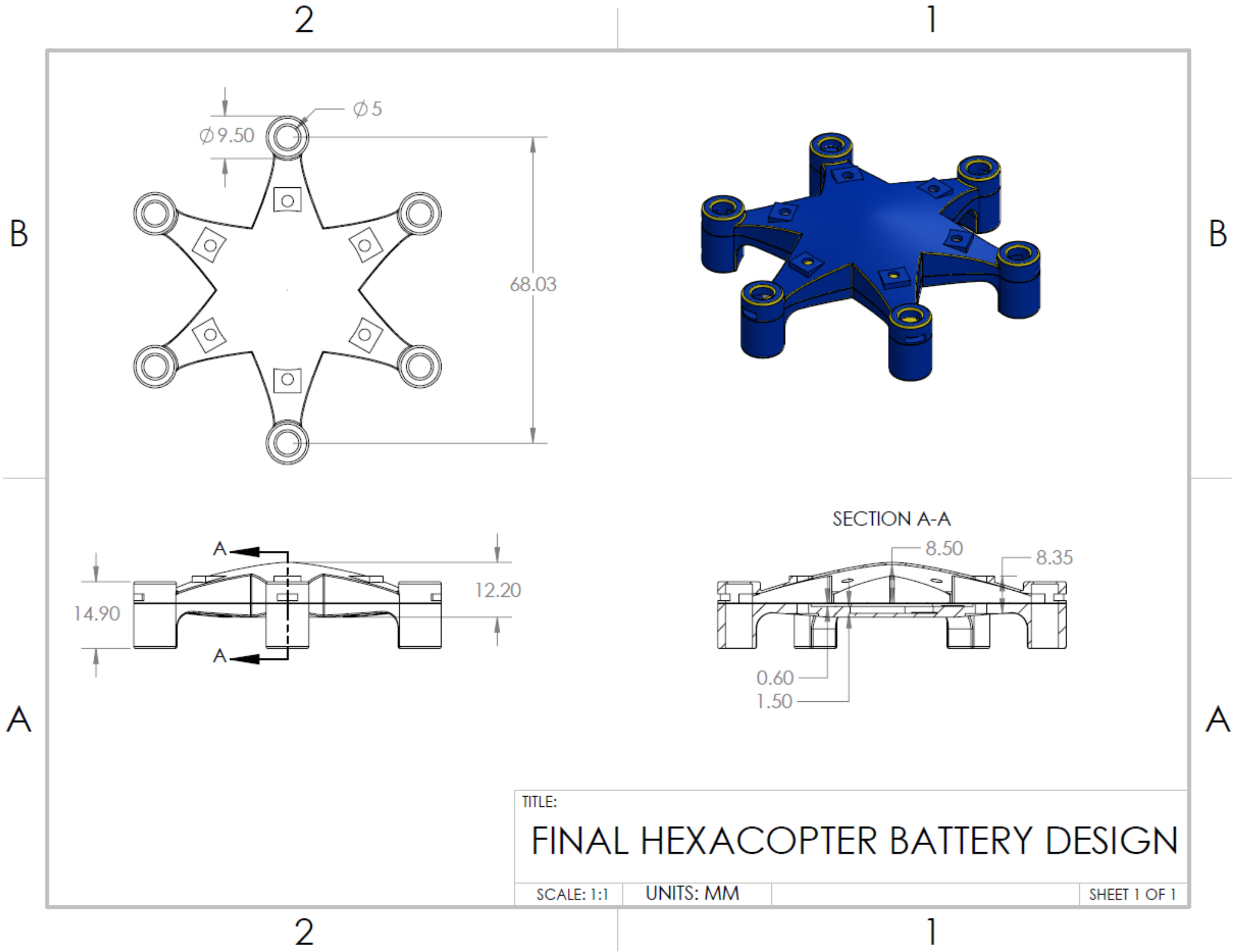

Figure A9 – Final Battery Design Drawing

Appendix B

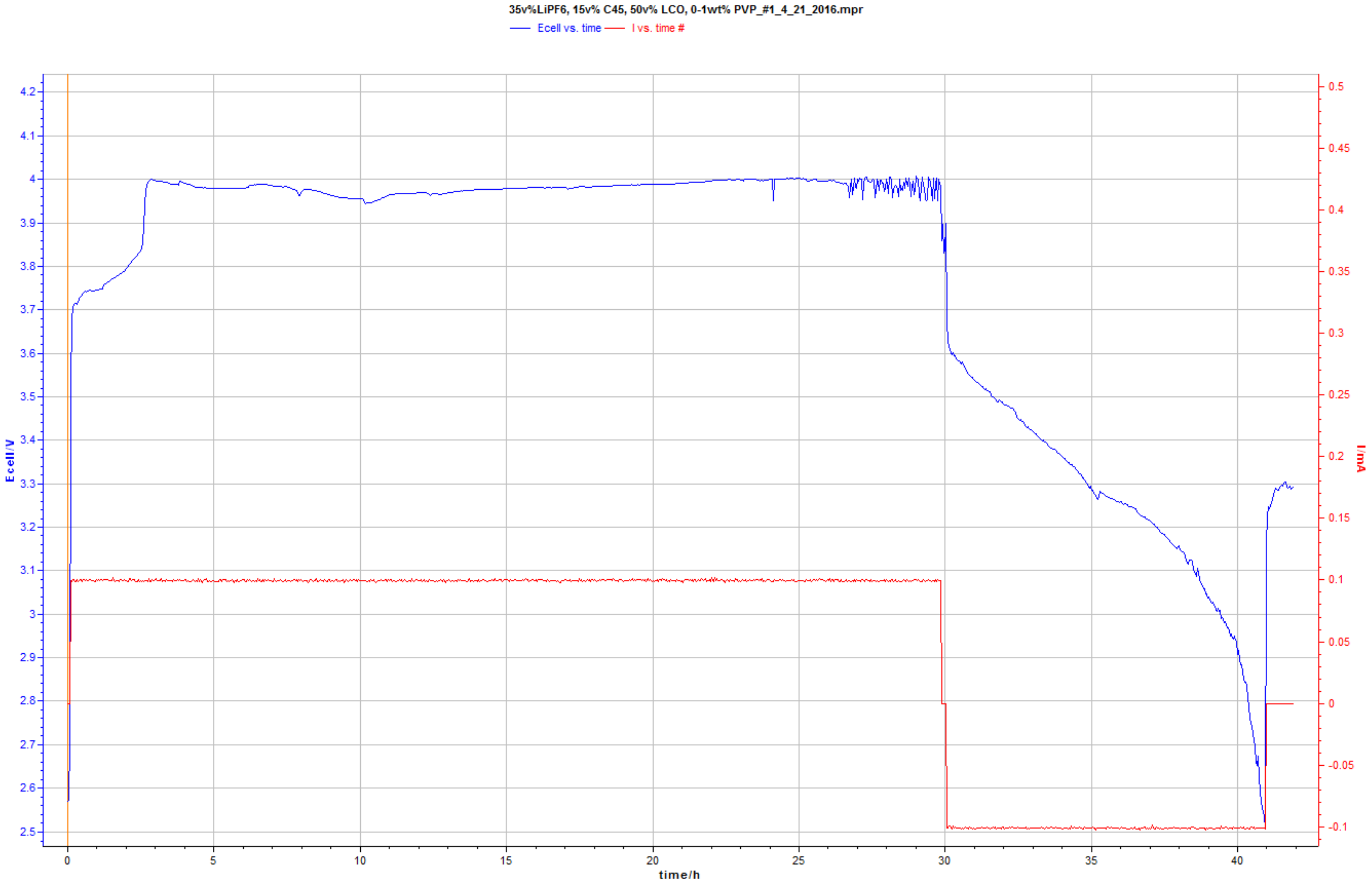

Figure B1 – Working recipe without aluminum foam

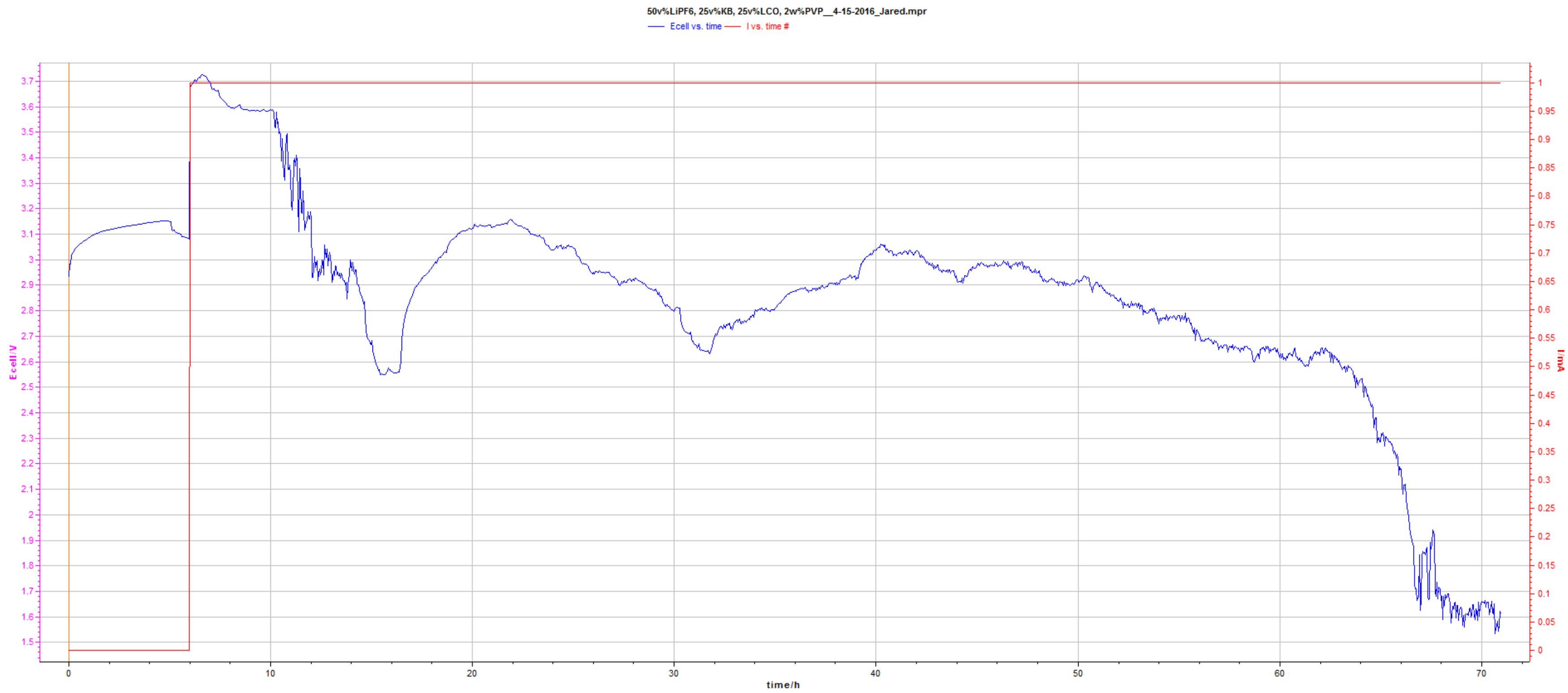

Figure B2 – 25 vol% LCO, 50 vol% electrolyte, 25% Ketjen carbon black, and 2 wt% PVP

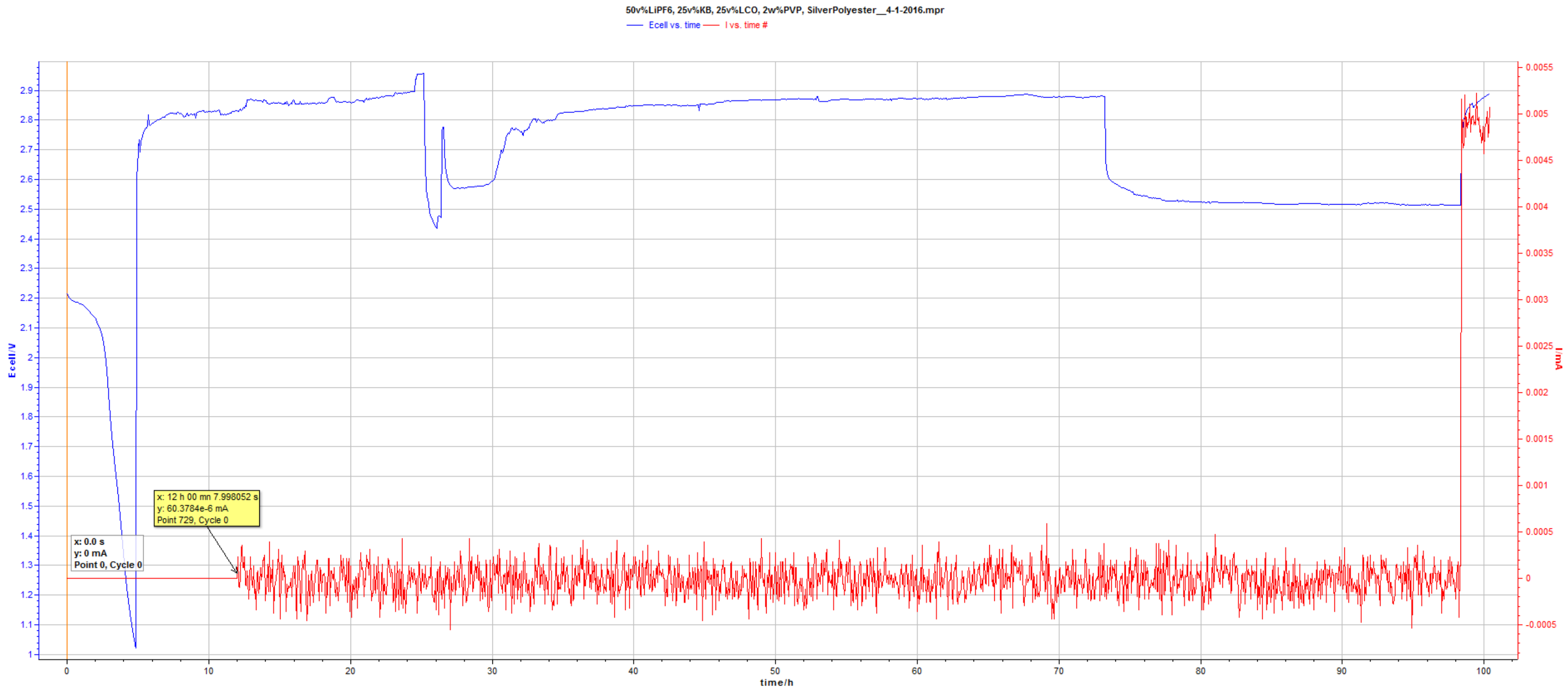

Figure B3 – 25 vol% LCO, 50 vol% electrolyte, 25% Ketjen carbon black, and 2 wt% PVP

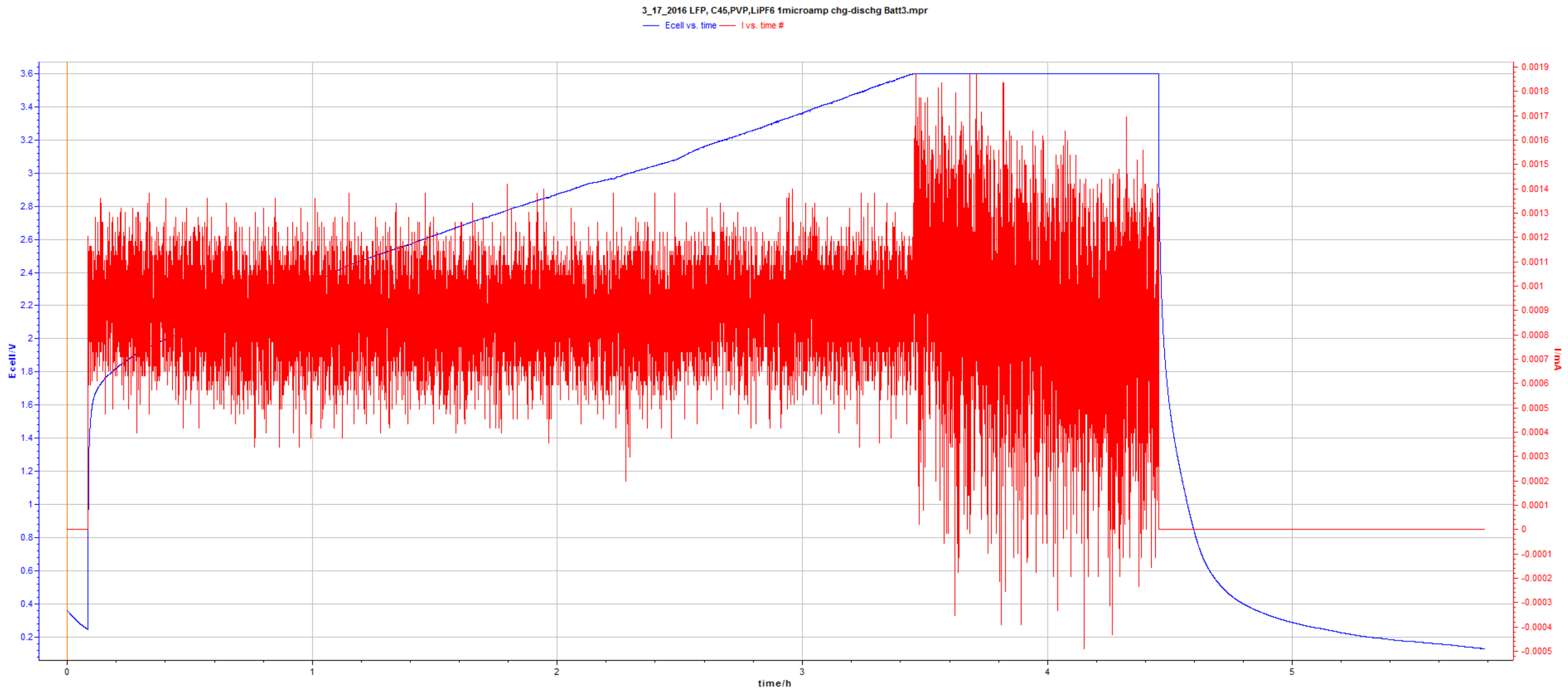

Figure B4 - ~61 vol% LFP, ~34.6 vol% electrolyte. 2.6 vol% C-45, and 1.5 wt%PVP. The casing had an aluminum current collector.