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FINAL PROJECT REPORT**

**Pilot Production Line for Ultra-Safe
High Energy Density Lithium-Metal
Battery Cells**

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Pilot Production Line for Ultra-Safe High Energy Density Lithium-Metal Battery Cells is the final report for EPC-20-027 conducted by Cuberg. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the [CEC's research website](http://www.energy.ca.gov/research/) (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Cuberg sought to develop lithium-metal battery cells with a focus on applications in the aviation and electrical vertical takeoff and landing industries. Cuberg built a groundbreaking lithium-metal battery system with exceptional power output, reduced weight, and long cycle life, which can be used as a battery for electric aircraft applications, improve the range, safety, and price of electric vehicles, and pave the way for other new mobility applications such as drones and ships.

This project funded the setup and commissioning of a large-scale production facility for the design and manufacture of an ultra-safe, nonflammable battery that integrates Cuberg's novel lithium-metal cell technology into a lightweight, high-performance module. Cuberg batteries had already achieved an energy density 50 percent greater than current lithium-ion batteries; this aspect has carried great weight-reduction benefits over into the module platform.

The project targets for production included a low-rate initial production pilot line for the ultra-safe cells, with production volumes up to 55 kilowatt-hours per month and a yield (the percentage of each batch that is of high enough quality to be used) of over 90 percent. Meeting these targets was facilitated by conducting supply-chain feasibility studies, characterizing the ultra-safe cell design, developing a battery management system and a module for incorporating the cell into aircraft, and demonstrating module performance in a customer-relevant setting.

The team assembled full-sized modules with the designed cell as a key deliverable, which showcased the externally validated 270 watt-hours per kilogram module's ability to achieve 692 customer-relevant cycles. This achievement translated into an estimated doubling of an electrical vertical takeoff and landing craft's flight range, from 40 to 86 miles. This project marked a critical step in Cuberg's journey to deliver the world's first lithium-metal battery module.

Keywords: lithium-metal battery cells, electric aviation, electric vertical takeoff and landing

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TABLE OF CONTENTS

Preface	i
Abstract	ii
Executive Summary	1
Background	1
Project Purpose and Approach	1
Key Results and Conclusions	2
Knowledge Transfer and Next Steps	2
Benefits to California Ratepayers	2
CHAPTER 1: Introduction	3
CHAPTER 2: Project Approach	4
Cell Development, Testing, and Production	4
Cell Development: Materials and Design	4
Cell Testing	5
Cell Production	5
Module Design and Production	6
CHAPTER 3: Results	8
Cell Development, Testing, and Production	8
Cell Materials and Design	8
Cell Testing	10
Cell Pilot Production	13
Module Design and Production	16
Module Design	16
Module Production	20
CHAPTER 4: Knowledge Transfer	25
CHAPTER 5: Conclusion	26
Glossary and List of Acronyms	28
Project Deliverables	29

LIST OF FIGURES

Figure 1: Standard Cell with Metal Cathode Current Collector	8
Figure 2: Cuberg's Next-Generation Cell, with Metalized-Film Current Collector	9
Figure 3: Cuberg's Next-Generation Ultra-Safe 17-Ah Pouch Cell with Alternate-Sided Tabs	10

Figure 4: Cuberg Cells.....	13
Figure 5: Thermal Cyclers Used for Overheat Tests.....	13
Figure 6: Final Process Flowchart.....	14
Figure 7: Resistance Values Under Cuberg Testing Protocols.....	18
Figure 8: Surface Temperatures During Discharge.....	18
Figure 9: Lower-Fidelity Electro-Thermal Model.....	19
Figure 10: Cooling on a Module Level.....	20
Figure 11: Module Production Overview.....	22
Figure 12: Excerpt from Presentation Showing Increased Range with Cuberg Module.....	23
Figure 13: Depiction and Details of Flight Profile	24

LIST OF TABLES

Table 1: Flight Profile Test Descriptions and Summaries.....	10
Table 2: Safety and Abuse: Internal R&D Testing	11
Table 3: Excerpt of Cell-Production Data.....	14
Table 4: Phase A of Cell Pilot Production.....	15
Table 5: Phase B of Cell Pilot Production.....	15
Table 6: Trade-off Study for Module Optimization.....	17
Table 7: Cuberg Module Design Specifications.....	22

Executive Summary

Background

In recent years, the performance of lithium-ion batteries has plateaued as materials approached their fundamental limits. Lithium-ion batteries require often costly and heavy safety engineering systems to prevent the flammable electrolyte from catching fire. Lithium-ion batteries do not have sufficient energy density and safety to reach the performance required for mass-market electrification of the automotive and aviation sectors. Many emerging approaches to improve battery performance suffer from major challenges with scalability and manufacturing incompatibility. Increasing flight time, payload capability, and reliability for the electric aviation sector are key pain points for the aerospace industry. Increasing mileage range and improving safety are also keys to accelerating market penetration of electric vehicles and advancing California toward its 2035, 100-percent electric vehicle mandate.

Cuberg developed a next-generation battery technology to address growing demand in the existing electric vehicle and emerging urban air mobility markets. The batteries deliver a step-change improvement in energy density and safety when compared with the best lithium-ion batteries available in the world today. The batteries can deliver the power needed for vertical takeoff and landing and enable unmanned aerial vehicles and electric planes to achieve longer flight times with improved reliability and substantially reduced risks of fire or in-flight break-up than current lithium-ion batteries.

Project Purpose and Approach

The purpose of this project was to design a safety-certified lithium-metal battery suitable for module integration that meets the minimum cell-level electrochemical performance of >300 Wh/L and >275 Wh/kg at a cycle life of 500 or more cycles. This was achieved by creating a low-rate initial production pilot line for ultra-safe cells with production volumes up to 55 kilowatt-hours per month and yields of over 90 percent. Cuberg used these cells to engineer a battery module that meets the minimum module performance of less than a 25-percent loss of energy density when moving from cell to module. This successful module production consisted of producing and shipping module prototypes to customers for validation as well as receiving feedback and commitments for future purchases. Targeted audiences were urban air mobility systems, general electric aviation, and long-range electric vehicles. The high-energy density of Cuberg's state-of-the-art lithium-metal cells produces module-level weight savings that make aircraft and vehicles lighter and more energy-efficient than their traditional lithium-ion counterparts.

Cuberg's main goals in undertaking this project were producing high-quality cells at large scale, building high-performance modules, and producing performance and safety data from these modules. The targeted commercial product was a 20-amp-hour cell with a non-flammable proprietary electrolyte.

Key Results and Conclusions

One of the first results of the project was successfully bringing dry-cell assembly in-house based on lessons learned using a dry cell manufactured by an outside supplier. Cuberg designed and implemented a manufacturing execution system for traceability during the cell manufacturing process, which provided information to help decision makers identify process inefficiencies and pinpoint conditions on the manufacturing floor that required change and optimization. The project results paved the way for the high-rate production of a novel lithium-metal cell for a host of customers and use cases, especially with development of a module to pair with the technology.

Next, the team identified a preferred multi-cell architecture for its first aviation module and developed robust models for thermal simulation modeling. The team chose a 60-cell 4.7-kilowatt-hour module design and a specific energy of 285 watt-hours per kilogram. These results demonstrated the weight and power benefits that lithium-metal cell technology can bring to various mobility sectors, particularly weight-sensitive industries like aviation.

After the initial round of module builds and in-house testing, the module was tested for energy density, power output, resistance, and cycle life under customer-relevant cycling conditions. The module far surpassed initial estimations, reaching 692 cycles using a demanding electric vehicle take-off and landing profile, more than doubling its estimated range from 40 miles to 86 miles when compared with traditional lithium-ion modules of similar size. These results demonstrated the viability of deploying a lithium-metal module solution for the aviation industry, which is key to electrifying that industry.

Knowledge Transfer and Next Steps

These results have been shared broadly in public forums for thought leaders and industry experts as well as the interested general public. The module characterization was first shared at the January 2024 Bloomberg New Energy Finance summit, and the full module validation report was published online for public review and discourse.

Benefits to California Ratepayers

The technology advanced by this project will provide the ratepayer benefits of greater electricity reliability, lower costs, and increased safety by enabling the commercialization and democratization of both electric vehicles and clean aviation services based on renewable energy technologies. The modules developed in this project will provide the critical improvements needed in performance and safety for the broader electric mobility sector (both aviation and automotive). The energy-dense batteries will lead to safe battery packs with lower cost per kilowatt-hour and eventually create cheaper electric vehicles accessible to middle- and lower-income communities.

CHAPTER 1:

Introduction

Cuberg designed and manufactured batteries with next-generation lithium-metal (Li-metal) anodes. Cuberg cells are lightweight, high-performance, and can enable electric mobility applications beyond the capabilities of traditional lithium-ion (Li-ion) technology. Li-metal anode technology pushes the boundaries of electrified performance in intense applications that are particularly difficult to decarbonize. One such application is the aviation industry, which has struggled to adopt electric solutions due to aircraft performance requirements. Cuberg technology is an enabling technology due to its lightweight and high-performance characteristics. This is an important part of expanding California's clean-energy economy by both introducing new technology to the electrification market and by enabling adoption of electric vehicles in a brand-new mobility sector.

The specific scope of this project was the design and manufacture of Li-metal cells, incorporating those cells into a module solution, manufacturing the modules, validating their performance externally, and, finally, delivering a module report. The benefits of capturing this work include exploring the nuances and details of managing a Li-metal battery in a module environment, exploring the limits of cutting-edge battery chemistry performance, and laying the groundwork for electrified propulsion standards that advance market adoption of battery technologies.

The first goal of the project was to demonstrate the viability of producing high-performance, lightweight Li-metal cells. At the time this project was underway, Cuberg was the world leader in manufacturing Li-metal cells of this size (20 amp-hours [Ah]). The next step was to build at high enough volumes to satisfy customer deliveries at a yield that paves the way to lower production costs. The stated goals were 55 kilowatt-hours (kWh) per month, with a yield greater than 90 percent. These volumes satisfied the volumes needed for both external validation and customer testing and also supported development of the module solution.

The next goal was to develop and produce a multi-cell module. Development of the module began with determining the multi-cell architecture and identifying battery management system (BMS) needs, which was completed through both modeling and subcontractor work. The in-house module team then developed the full-sized prototype and delivered it for characterization before external publication.

CHAPTER 2:

Project Approach

The project approach consisted of two major elements: Cell development (testing and production) and module design and production.

Cell Development, Testing, and Production

Cell Development: Materials and Design

The first step of this project was to understand the viability of the cell from both component and design perspectives. Cuberg's Li-metal battery is composed of several complex parts. Like all Li-ion cells, the cell contains an anode, a separator, and a cathode in repeating layers that form a kind of "sandwich," referred to as a jelly roll. Tabs are welded to the anode and cathode layers to allow electrical connections to products. This jelly roll is then fitted into a pouch, usually made of plastic or aluminum. This pouch is then filled with electrolyte to facilitate the transfer of lithium ions that allow the battery to function.

Cuberg performed a viability study on alternative cell components to develop an ultra-safe cell optimized for module integration based on Cuberg's existing commercial product at the time this project began: a 5-Ah pouch cell. For many applications involving module integration, larger formats have been requested (or are required) to increase the specific energy and energy density of the module and pack system. The team explored increases in cell size and capacity, considering alternative materials for each component, as described here.

Anode: Cuberg is currently studying the impact of replacing pure Li-metal anodes with alternative materials. For example, a copper anode current collector offers several benefits: improved manufacturability, flexibility in cell design, increased energy density, and improved safety. From a safety perspective, replacing the extremely reactive lithium metal with a safe and inert copper current collector provides a huge benefit.

Cathode: One development pathway for improving the safety of Cuberg's cells was to use a more stable cathode-active material. Oxygen generated at the cathode reacts exothermically with the anode solid-electrolyte interphase (SEI) and Li-metal increases the cell temperature, causing further oxygen evolution at the cathode.

Electrolyte: The electrolyte is the liquid component of the cell that conducts lithium ions between the anode and cathode, allowing both charging and discharging. Lithium-ion cells require a drastically different electrolyte than lithium-ion battery cells. There are many paths of development for electrolyte that may provide a Li-metal cell with safety characteristics superior to those of Li-ion cells.

Cell Testing

Once designed, the cell must be tested and characterized to fully describe the performance benefits and safety results of the novel cell. Characterizing the electrochemical and safety features of these ultra-safe cell designs required several specialized tests.

Safety and Abuse Tests

These tests were designed to subject Cuberg's cell designs to abusive conditions where failure would be likely. By simulating thermal runaway, internal and external shorts, and overcharges, the properties of the ultra-safe cell components, large format, and alternate tab cell designs were characterized.

All safety and abuse testing was conducted at Cuberg's San Leandro, California, site. This lab was equipped with non-flammable building materials, and ventilation was built in to remove smoke and gas generated during overheat runaway test events. The testing was conducted in a semi-open steel test chamber, with one open side to prevent pressure buildup.

As a part of this project, Cuberg conducted a robust characterization of the new cell design that included drive-cycle testing with realistic flight profiles (higher power draw for takeoff and landing and cruising at a consistent velocity) and a comprehensive safety study, which informed the module design in the next phase of the project.

Flight Profile Tests

Cuberg's cells were tested in realistic protocols that mimic the flight profile of electric vertical takeoff and landing (eVTOL) or electric conventional takeoff and landing (eCTOL) applications. These protocols used high-powered cyclers in Cuberg's test lab to test:

Takeoff Pulse: Either vertical or conventional. This is a high-powered pulse at the battery's top of charge state that simulates an aircraft's takeoff, which consumes a significant amount of power.

Cruise: Cruise is a lower power stage of flight where the protocol simulates the aircraft's nominal travel from its origin to its destination. Cruise stage does not require high power for most applications; however, protocols that mimic aircraft with fixed wings will usually have lower power requirements at this stage than aircraft that do not have fixed wings and rely on motor power for lift (for example, a plane versus a helicopter).

Landing Pulse: The landing pulse is similar to the takeoff pulse, where the protocol simulates an aircraft descending and, in VTOL cases, transitioning back to vertical flight, hovering, and landing. Along with takeoff, this is a very high-powered stage of the flight profile.

Emergency: Flight profiles must include emergency protocols that simulate an event where the aircraft enters an emergency stage. The emergency may be any one of many real-world scenarios.

Cell Production

Following cell characterization, a pilot production roadmap was developed to identify the starting point for building large quantities of Cuberg Li-metal cells. The roadmap contained

requirements to create a pilot line that met the volume and yield targets for the new cell format. In particular, the roadmap outlined the production steps and processes involved, including: takt manufacturing time ("takt" is a common manufacturing term meaning beat or pulse) and key performance indicators; and anticipated production equipment, labor, and raw materials supply chains and traceability requirements. Once the line was up and running, monthly production reports were generated.

Module Design and Production

In parallel with cell production, the multi-cell architecture (how the cells are connected and oriented) for the eventual module product was determined. The goal was to assess Cuberg's cell behavior when integrated into various multi-cell architectures, and to collect data to develop an effective BMS. The Cuberg team compared potential multi-cell architecture designs, collected data under various scenarios, and evaluated the potential performance of those designs. The process comprised four steps: identification of relevant data and information required to develop the BMS and possible multi-cell architectures; data collection; thermal multi-domain simulation; and evaluation.

The Cuberg team worked with customers and the module subcontractor to identify the data and information required to develop an effective BMS and identify available multi-cell architecture solutions. Cuberg then collected the data needed to develop both BMS and electro-thermal battery models. The outputs of those models then informed both the architecture and BMS designs.

The team produced a module development roadmap, which guided the process for developing a battery module that targets high energy and regulatory airworthiness requirements, state-of-health and state-of-charge requirements, and thermal management methods that allow operation in adequate temperature ranges. Cuberg's module roadmap consisted of five major stages:

Concept Development: In this stage, the team developed and evaluated module designs relative to customer requirements for size, weight, and flight profiles. They also evaluated design options and tradeoffs against regulatory requirements and the discharge and charge profiles of both nominal missions and manufacturability analyses.

Preliminary Design: This stage ensured that the basic system architecture was completed with high technical confidence in the model's capability.

Detailed Design: This was the final stage before manufacturing began on the module. Key elements of the module were tested through a series of module-subset parts to evaluate performance in a representative environment.

Initial Build and Evaluation: This stage evaluated the manufacturing process, test and verification plans, and module handling. During this phase the manufacturing process was evaluated for effectiveness, and the determination was made as to whether efficiency gains were possible. Manufacturing equipment was also stress-tested and evaluated during this phase.

Low-Rate Initial Production: This stage produced modules at 50-percent capacity (of the line) to continue validation and testing of the module assembly. Initial production units were key to the verification and validation of module performance.

As the module development was finalized, the prototype module was characterized through the following performance metrics.

Cycling Tests: Cuberg performed standard charge and discharge cycling profiles on the module to reflect the in-the-field performance of state-of-the-art eVTOL vehicles. This involved a pattern of a low-rate charge, followed by a high-rate discharge pulse and a medium-rate constant current discharge, and ended with a final high-rate discharge pulse. The temperature and voltage of the module were monitored throughout the profile to ensure the performance of the cells was within the acceptable parameters. This profile was repeated 100 times before the data were analyzed and reviewed with the team. This testing provided the total voltage (V), capacity (Ah), energy (Wh), specific energy (Wh/kg), and energy density (Wh/L).

Single-Cell Propagation-Resistance (SCPR) Tests: SCPR is one of the most significant aspects of module safety. When one cell experiences a thermal runaway, neighboring cells are shielded from the reaction so remain unaffected.

Power Characterization: The power characterization plans stress-test the performance of the module by assessing the maximum kW power output and assigning the module a maximum pulse power (kW/kg).

Vibration Tests: Mechanical vibration tests in accordance with regulatory compliance testing ensure that the module's mechanical build is sufficient for shipping and operation.

Once the module demonstrated adequate performance, the process was finalized, and each step was documented in the module production report. This was followed by a performance characterization of the module.

CHAPTER 3:

Results

Cell Development, Testing, and Production

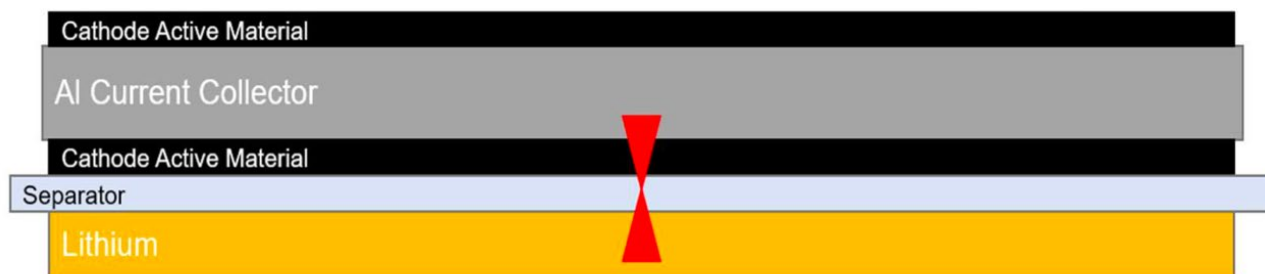
Cell Materials and Design

Key materials selected for the ultra-safe cell design were improvements on the cathode active material, including the cathode current collector and the electrolyte. The team also developed a larger format cell, which resulted in design changes.

Cathode Active Material: One development pathway for improving the safety and performance of Cuberg's cells was to use a more stable cathode active material. Cuberg's current cell design uses high nickel (Ni) content cathode active material. While Ni-rich cathode materials have very high specific capacities, they are generally less thermally stable than their lower nickel-content counterparts. For the best balance between thermal stability and performance, Cuberg will implement more stable Ni-rich cathode materials into its next-generation cells.

Current Collector: Cuberg implemented a metalized film cathode current collector. A metalized film current collector uses a thin polymer base layer coated in thin layers of metal (copper for the anode, aluminum for the cathode) in place of a bulk sheet of the current collector metal. These metalized film current collectors have two main benefits. They have a lower volume and weight, and they also have favorable safety characteristics because the polymer layers will melt and separate the contact layers, stopping a short before it enters thermal runaway. Cuberg implemented these metalized film current collectors into its next-generation cells to reap the joint benefits of higher volumetric and gravimetric capacities and improved safety characteristics.

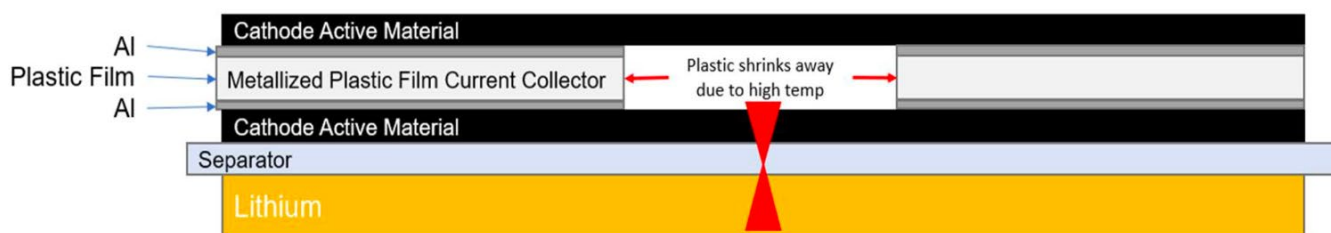
Figure 1: Standard Cell with Metal Cathode Current Collector



Cuberg's initial design, with standard aluminum current collector. When a short develops (red), the aluminum (Al) current collector maintains contact with the short, leading to thermal runaway.

Source: Cuberg

Figure 2: Cuberg's Next-Generation Cell, with Metalized-Film Current Collector



Cuberg's next-generation ultra-safe cell, with metalized film current collector. The current collector consists of plastic with a thin aluminum film on the surface. When a short develops (red), plastic shrinks from the area due to high temperatures caused by the short, thus disconnecting the current collector from the short and preventing thermal runaway.

Source: Cuberg

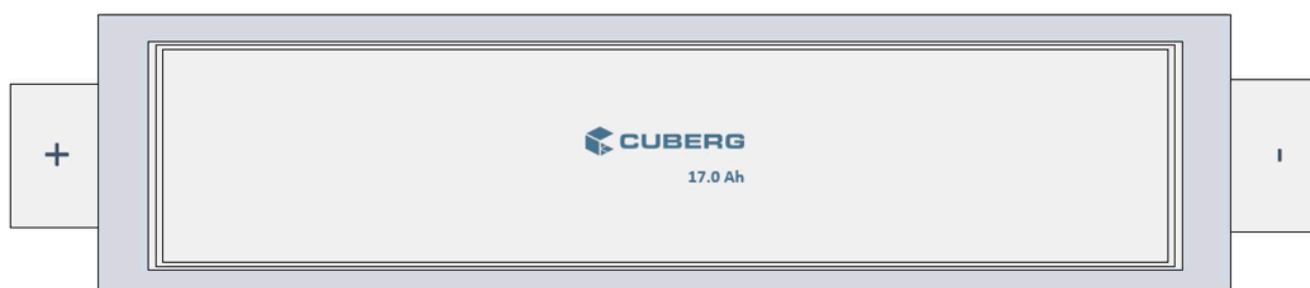
Electrolyte: The electrolyte is the liquid component of the cell that conducts lithium ions between the anode and cathode, allowing charging and discharging. Lithium-metal cells require drastically different electrolyte than lithium-ion battery cells do. There are many paths of development for electrolyte that may provide a lithium metal cell with superior safety characteristics when compared with lithium-ion. First, electrolyte design has a significant impact on the lithium plating quality and surface characteristics on the anode. Lithium plating quality and surface characteristics such as the solid-electrolyte interphase (SEI) play a role in the speed of a thermal runaway event, so designing a class of electrolyte to improve lithium plating and the SEI will in turn create better safety characteristics. Additionally, the electrolyte may be designed with non-flammable components. In lithium-ion cells, the electrolyte is a highly flammable material, which degrades its safety profile. If an electrolyte can be designed without these flammable components, venting and runaway events will likely be far less violent and destructive. Improved electrolyte design has the joint benefits of improving both electrochemical performance and safety.

17-Ah Format: Cuberg's commercial product at the beginning of this project was a 5-Ah pouch cell. For many applications involving module integration, larger formats have been requested (or are required) to increase both the specific energy and energy density of the module and pack systems. Cuberg explored a larger cell format, a 17-Ah pouch cell. Further increases in cell size and capacity will also be explored. Prismatic cell designs up to 100-Ah are also in development. However, the design of a larger format cell requires extensive electrochemical, safety, and abuse tests to ensure that the safety profile is fully understood. Larger formats are desirable for increasing the volumetric and gravimetric energy density of a given application as well as the ease of integration into a module.

On most large format cells, power requirements create the need for larger tabs in the cell design. A larger tab requires development of an "alternate-side" tab orientation, as opposed to Cuberg's initial "same-side" orientation. Including an alternate-side tab orientation has several benefits when compared with Cuberg's earlier design. First, the larger tabs allow higher power usage of the cell. Resistance in the tab of a battery cell is often a limiting factor to cell charge and discharge rates since a higher current passed through a narrow tab leads to a large increase in heat, creating conditions where thermal runaway may occur. A larger tab reduces

the resistance of the tab area and allows higher current usage of the cell. Alternate-side tabs additionally improve thermal characteristics on the cell that improve both performance and safety. Up to a certain point, higher operating temperatures can often lead to improved cell performance. However, temperature uniformity throughout the cell is also critical to cell performance. If most of the heat generated by the cell is generated near the tab area, the cell will develop a temperature gradient from the top to the bottom of the cell, with higher temperatures near the tabs and lower temperatures near the bottom of the cell stack. This may affect electrochemical performance, electrode surface characteristics, lithium plating, and so on, which would both reduce cell performance and increase safety risks. By moving the tabs to opposing sides of the cell, heat is generated equally on both sides, leading to an improved temperature gradient across the cell.

Figure 3: Cuberg's Next-Generation Ultra-Safe 17-Ah Pouch Cell with Alternate-Sided Tabs



Source: Cuberg

Cell Testing

Flight Protocol Testing

Cuberg ran three flight profiles out of four considered on its commercial 5-Ah cell at different operating conditions to characterize cell performance. The test results are summarized in Table 1.

Table 1: Flight Profile Test Descriptions and Summaries

Test	Description	Summary of Results
Flight Profile 1	Simulates vertical takeoff, fixed-wing cruise, and vertical landing, with intermittent emergency protocols.	Cuberg's current 5-Ah cell has been tested extensively at multiple charge rates from 1C to C/6. Probed relationship between charge rate, ambient temperature, and total cycle life
Flight Profile 2	Simulates vertical takeoff, cruise without fixed wing, and vertical landing, with intermittent emergency protocols.	Testing conducted at 113 degrees Fahrenheit (°F) (45 degrees Celsius [°C]) 264 cycles with full 60-minute cruise, C/2 charging

Test	Description	Summary of Results
		330 cycles with 50-minute cruise, C/2 charging Main contributor to higher cycle count (shorter cruises) related to depth of discharge
Flight Profile 3	Simulates vertical takeoff, cruise, and vertical landing, with multiple flights per day. Includes fast charging between flights	Current format successfully tested at two different ambient temperatures: 77°F (25°C): 21 simulated days corresponding to 336 flights 113°F (45°C): 50+ days corresponding to 800 flights
Flight Profile 4	Simulates conventional takeoff, cruise, and conventional landing	Based on customer feedback, Flight Profile 4 was not run.

Source: Cuberg

Safety and Abuse Testing

At the time of writing, Cuberg's internal R&D tests to assess the safety of current battery design were ongoing. Internal research and development (R&D) tests were only conducted on 5-Ah and limited 17-Ah cells. A critical milestone during this project was experimental validation that the thermal cyclers can safely survive induced thermal runaway events. The internal results for safety and abuse testing are summarized in Table 2. They include next steps that Cuberg intended to take prior to acquisition and bankruptcy, which may serve as a guide for similar efforts. Figure 4 shows cells of different sizes developed for testing, and Figure 5 shows the thermal cycler used for overheat testing.

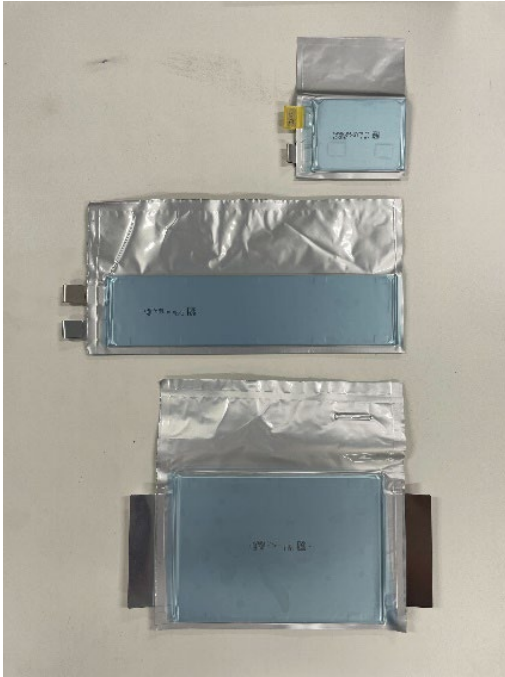
Table 2: Safety and Abuse: Internal R&D Testing

Test	Description	Summary	Next Steps
Overheat Test	An overheat test simulates a thermal runaway event by applying consistent heat to the face of a fully charged battery cell. This heating element forces the degradation and melting of internal cell components.	Two overheat tests run: - Qualitative tests of internal testing infrastructure to ensure cyclers could withstand runaway events - Successfully tested both 5-Ah and 17-Ah cells	Internal R&D testing of 5-Ah, 17-Ah, and new 23-Ah cells - Goals: - Verify Cuberg's internal test infrastructure - Validate the safety of Cuberg's new cell formats

Test	Description	Summary	Next Steps
Nail Penetration Test	A nail penetration test simulates an internal short circuit of the cell by penetrating the surface of the cell with a thin metallic nail. This nail penetrates the layers of anode, cathode, and separator, causing current to spontaneously flow through these broken layers. A short circuit is the most likely cause of failure in most thermal runaway events.	No new tests run	Tests of new cell formats are planned to validate safety. This includes further nail penetration tests for the 5-Ah cell as well as Cuberg's 17-Ah and 23-Ah cells, and ultra-safe Soteria current collector cells.
External Short Circuit	An external short circuit test simulates an external short circuit by contacting the tabs of the cell together through a low-impedance resistor. This simulates an event in which the cell is forced to discharge at a dangerously high rate. This high discharge rate causes heating of the cell and tabs and may lead to a thermal runaway reaction.	No new tests run	Tests of new cell formats are planned to validate safety. This includes further external short circuit tests for the 5-Ah cell, as well as Cuberg's 17-Ah and 23-Ah cells, and ultra-safe Soteria current collector cells.
Overcharge Test	An overcharge test subjects a cell to high continuous charge currents past the maximum voltage of the cell.	No new tests run	Tests of new cell formats are planned to validate safety. These include further overcharge tests for the 5-Ah cell as well as Cuberg's 17-Ah and 23-Ah cells, and ultra-safe Soteria current collector cells.

Source: Cuberg

Figure 4: Cuberg Cells



From top to bottom: Commercial 5-Ah cell, prototype 17-Ah cell with same-sided tab, and prototype 21-Ah cell with alternate-sided tab.

Source: Cuberg

Figure 5: Thermal Cyclor Used for Overheat Tests



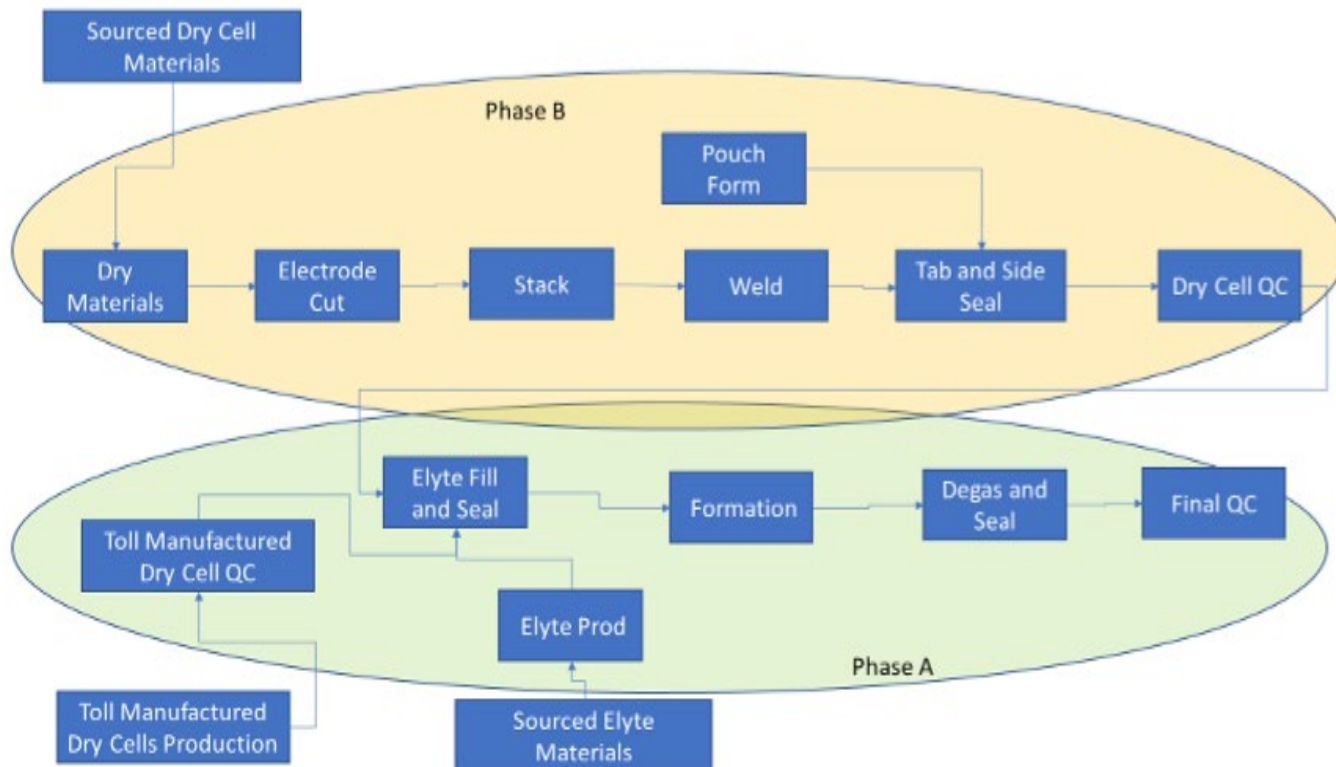
Inside of the intact thermal cyclor after completion of overheat tests. The door (left) and inside of the thermal cyclor (right) remained intact after successfully overheating Cuberg cells to induce thermal runaway. The lack of damage demonstrates the safety of these cells with respect to thermal runaway.

Source: Cuberg

Cell Pilot Production

The pilot production of Cuberg's large-format cell was separated into two phases, shown in Figure 6. Phase A adopted an off-the-shelf manufactured dry cell, and Phase B brought the dry cell assembly in-house. Phase A included an initial production phase using lab-scale equipment due to the time required to bring in semi-automated capital equipment.

Figure 6: Final Process Flowchart



Legend: Elyte = Electrolyte; OC = Quality Control; Prod = Production

Source: Cuberg

Cuberg's existing process for creating and sealing its ultra-safe cells was engineered into the module prototype described in the next section, so was not changed due to the broad process uniformity of manufacturing a pouch cell. The specifics within each process step, however, required substantial fine tuning, learning, and calibration. For example, after stacking and welding, the jelly roll must be lined up accurately so the electrodes align. While this was done previously by a technician's visual inspection, the consistency of the inspection was insufficient. The Cuberg team installed a stacking alignment vision system. This system can automatically notify technicians if the stacking alignment is not to specification, which resulted in improvements to the consistency of the production process. However, the Cuberg team experienced a learning curve while developing the specifications required to implement the system since this was a new piece of equipment.

Results from six months of cell production data are shown in Table 3, with additional information about the manufacturing process and lessons learned.

Table 3: Excerpt of Cell-Production Data

Month	Total cell yield	Cells produced for customers	Cells produced for R&D	Cells shipped externally
Jan 2024	77%	498	777	None
Dec 2023	Skipped due to holiday			

Month	Total cell yield	Cells produced for customers	Cells produced for R&D	Cells shipped externally
Nov 2023	83%	None	429	None
Oct 2023	51%	802	638	120
Sep 2023	67%	1236	812	100
Aug 2023	86%	723	518	4

From August 2023 to January 2024, 6,433 cells (495 kWh) were produced on the pilot production line.

Source: Cuberg

Manufacturing time was split into two categories: handling time and equipment time. Handling time was the operator's manual handling time either between or in addition to equipment time (machine-cycle time). Table 4 and Table 5 show manufacturing times for both phases. Where equipment for small- and large-format cell production differed, the first time shown was the large-format (17+ Ah cell), with time (in parentheses) indicating the value for small-format (5-Ah cell) equipment. All time is in minutes/cell.

Table 4: Phase A of Cell Pilot Production

Step	Electrolyte Prod	Dry Cell QC	Electrolyte Fill & Seal	Degas & Seal	Formation	Final QC
Handling	*TBD	2	0.5 (2)	0.5 (1)	4 (7.5)	2
Equipment	*TBD	0.5	2.5	2 (2.5)	1920*	0.5

* Item was done as a part of a larger batch process with > 1 cell processing at the same time.

Source: Cuberg

Table 5: Phase B of Cell Pilot Production

Step	Dry Materials	Electrode Cut	Stack	Weld	Pouch Form	Tab & side Seal	Elyte Prod	Dry Cell QC	EL Fill & Seal	Degas & Seal	Formation	Final QC
Handling	5*	0	1	2	1	0.5	*TBD	0.5	0.5	0.5	4 (7.5)	2
Equipment	1080*	4.3 (0)	12 (15)	2 (1)	0.3 (1)	2 (1)	*TBD	0.5	2.5	2 (2.5)	1920*	0.5

* Item is done as a part of a larger batch process with > 1 cell processing at the same time.

Source: Cuberg

Cuberg implemented and designed a manufacturing execution system (MES) for traceability during the cell manufacturing process. This system collected and used data to track and document how raw materials were transformed into finished products. This provided information to help decision makers find process inefficiencies and pinpoint which conditions on the manufacturing floor need to be changed or optimized. It also provided full traceability, from raw materials to finished products, which raw-material batches were used for which products, with unique serialization and identification for each item.

To accomplish this, material was scanned at each step in the process for automatic data collection, and an operator digitally logged the results of non-automated checks or work performed. Data such as time, temperature, pressure, and other settings were automatically logged and retained for future reference and quality-control verification. Additional quality improvements included an error-proofing system that had been incorporated to prevent the equipment from using wrong or incompatible settings. All data were warehoused and linked in a manner that enabled analysis within the MES, with outside analysis tools and other programs.

Lessons Learned

Future work for the MES had been planned that would focus on the automation of manual processes like data entry, continued expansion of error-proofing, and standardization of how materials are referenced and labeled in the factory. Additionally, features such as raw-material inventory tracking, overall equipment effectiveness (OEE) and downtime tracking, non-conformance tracking, real-time event notification, and user-defined process design were planned for roll-out. These features would make the MES a more comprehensive and flexible system capable of handling a variety of manufacturing needs.

The Cuberg team dedicated many of its resources to this project, including more than seven technicians and five engineers. Establishing a reliable large-format cell pilot-production line and scaling up reliability and capacity of this line were top priorities in the year leading up to Cuberg's acquisition in late 2023.

Cuberg not only spent significant monetary resources designing, testing, and operating its semi-automatic manufacturing line; it also dedicated significant resources to learning the line so that it could produce high-quality dry cells in-house (Phase B). The process engineering, manufacturing, and test teams worked together to develop and test metrics for cell quality (including minimum/maximum specifications) at each production step, and to create and implement standard operating procedures. Redesigning Cuberg's workflow in its dry room, calibrating processes, and continuing to learn the new semi-automatic equipment, was no easy feat. Because the pilot line was mostly located in Cuberg's relatively small dry room, material flow optimization was extremely important. One of the greatest constraints the team experienced was labor capacity, since operating and learning the semi-automatic production line was both effort- and time-intensive.

Module Design and Production

Module Design

The Cuberg team worked with customers and a module subcontractor to identify the data and information required to develop an effective BMS and identify availability of possible multi-cell architecture solutions. Conversations and evaluation revealed that there were two optimal module configurations: Cuberg's proposed solution and the alternative. A trade-off study of these configurations was performed to optimize module design for the first Cuberg customer. The study was performed based on customer usage profiles and module performance (see Table 6). The Cuberg proposed solution has a higher amperage capacity than the alternative.

The study found that this enabled it to operate at a lower discharge rate while delivering the customer usage profile, meaning that the current at the cell level was lower and voltage drops lower, leading to better thermal performance. The analysis also showed it is possible for the BMS to have a configurable and modular architecture that can be used for various battery multi-cell architectures.

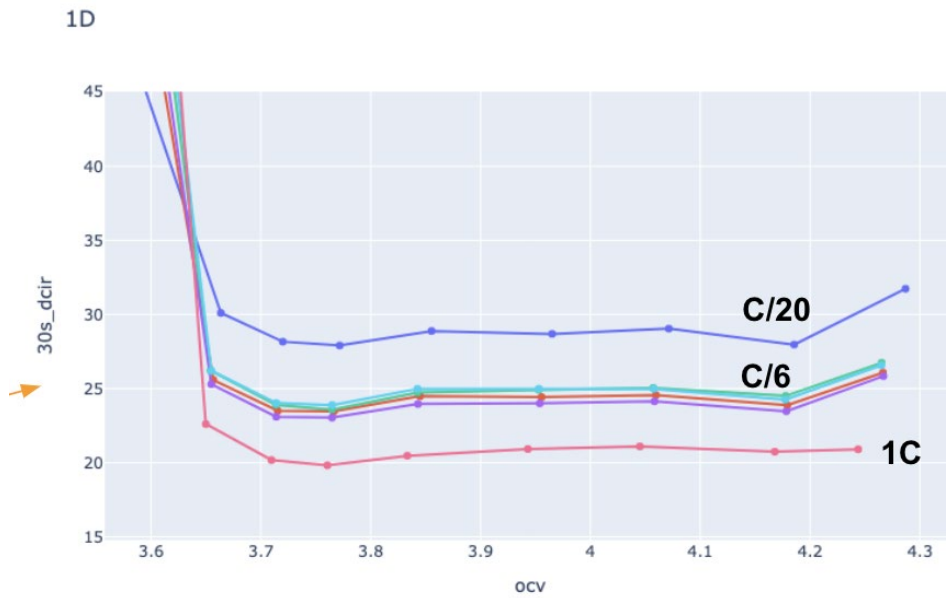
Table 6: Trade-off Study for Module Optimization

Specification	Alternative	Cuberg Proposed Solution
Voltage	36–51.36 V	30–42.8 V
Capacity (Ah)	100 Ah	120 Ah
Module Performance	N/A	Given the customer profile, this configuration has: • Lower C-rate • Lower voltage drop • Better thermal performance
Mechanical and Electrical Design	No significant difference	No significant difference

Source: Cuberg

Following the tradeoff analysis, Cuberg collected the data required to develop an effective BMS. The first type of data collected were resistance values, also described as internal friction, (or opposition) to the electric current. While resistance values are dependent on many factors (such as the previous protocol run, charge rate, and discharge rate) and do not reveal the absolute resistance of cells, they are a helpful metric when analyzing the impedance growth (a type of battery degradation, which can be caused in part by resistance) of the cell over its lifetime. Cuberg developed protocols to collect resistance values under various conditions and discovered that when the charge rate increases, the resistance values decrease, as shown in Figure 7. The same trend was observed with higher-rate pulses. As the team increased the charge rate, the resistance decreased.

Figure 7: Resistance Values Under Cuberg Testing Protocols

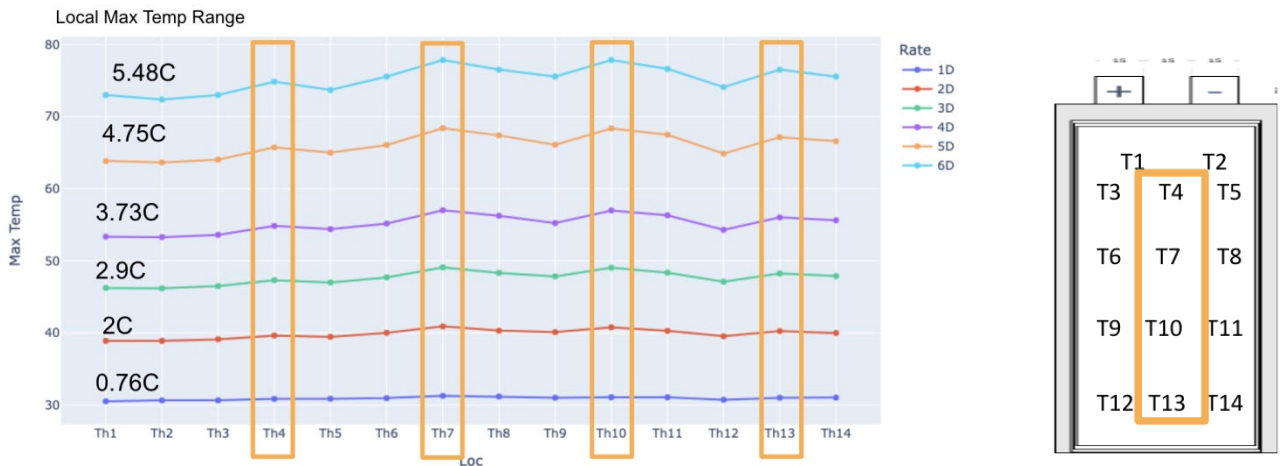


1D 30s Direct Current Internal Resistance at Different Charge Rates Across States of Charge

Source: Cuberg

Thermal characterizations were then performed to measure cell surface temperatures during constant current discharges, at different rates. Figure 8 shows the maximum temperature that was reached during the constant current discharge at each location on the cell. The maximum temperature range across the cell is also shown.

Figure 8: Surface Temperatures During Discharge



Thermal Multi-Domain Simulation Modeling

Source: Cuberg

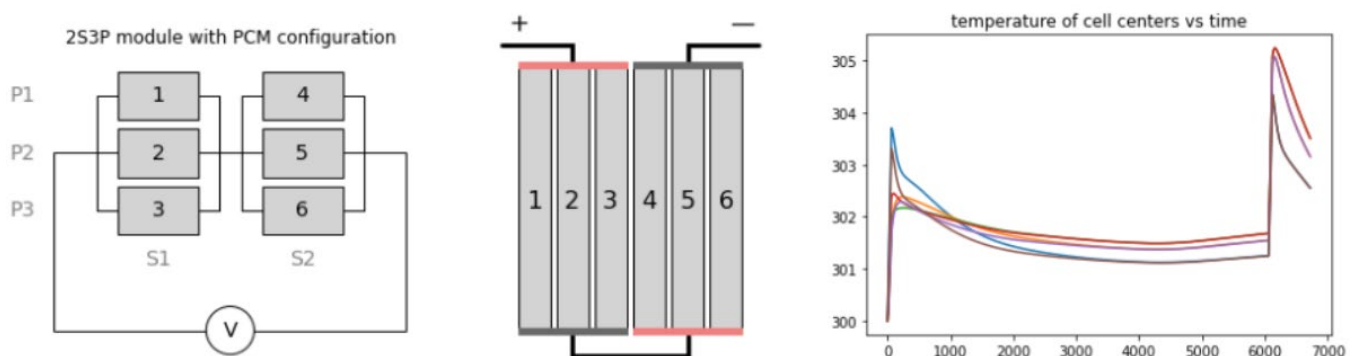
The team developed two sets of electro-thermal battery models at Cuberg, with different degrees of fidelity, which were then used to evaluate BMS characteristics. The purpose of the models was to predict per-cell temperatures over time during drive profiles (or single-cell

thermal runaways) and predict the hottest and coldest cell temperatures throughout the module. This determined the external conditions required to meet the desired drive profile.

In the first lower-fidelity case, the team used an equivalent-circuit model with a lumped thermal model. This model predicted the average temperature of each cell and its intercell material (compression pad) during operation of the system. This model was used to determine both the module configuration and cooling requirements for Cuberg's customers.

Figure 9 shows a representative module configuration. The temperatures of each cell were estimated as a function of time for a representative drive profile, using the heat generation estimated by the equivalent-circuit model. This model demonstrated that the temperature of cell centers can be affected by cell configuration.

Figure 9: Lower-Fidelity Electro-Thermal Model



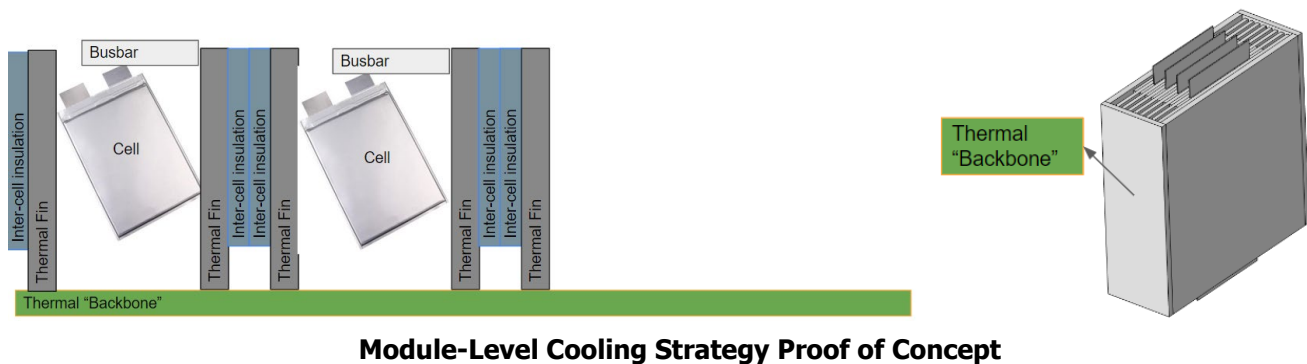
Electro-Thermal Model Based on Equivalent-Circuits and 1D Thermals. The image on the far left shows a module in 2S3P configuration (2 cells in series, 3 in parallel). The middle image shows the configuration as it visually appears. The image on the right shows the temperature of cell centers over time, with temperatures in degrees Celsius on the Y axis and time in seconds on the X axis.

Source: Cuberg

Additionally, the team developed and validated detailed (1D and 3D) thermal models of Cuberg's module. Cuberg's team used the detailed 3D model to design the cooling strategy (active or passive) for the module.

The Cuberg team validated the 3D thermal models using surface temperature measurements. These validated cell models were used to simulate and devise cooling strategies for modules, based on the application. For instance, the validated cell models were used to simulate the effect of a particular module-level cooling strategy as a proof of concept, as shown in Figure 10.

Figure 10: Cooling on a Module Level



Module-Level Cooling Strategy Proof of Concept

Source: Cuberg

The analysis and modeling described allowed Cuberg to gather significant information about the preferred module cell architecture, information, and data critical to BMS development. First, the team found that cell architecture with a higher capacity (namely the chosen solution just described) fits best with customer requirements. Cuberg also found that performing resistance characterization under various temperatures and currents is critical. Cell impedance improves at higher rates and temperatures, and cell surface temperature measurements showed up to a 41°F (5°C) temperature gradient. In addition, the team developed thermal models that successfully predicted cell surface temperatures under various discharge rates, which can be used for cell and module-level thermal management designs. This information was applied to the next steps of characterizing the module and manufacturing a prototype.

Module Production

Cuberg manufactured over 15 modules onsite at its San Leandro facility, and important lessons were learned with each iteration. The module production process reflected a high safety standard, and many of the changes implemented during module production focused on the module's ability to safely handle a potential thermal runaway reaction of cells and limit the spread of that reaction to neighboring cells. This aspect of single-cell propagation resistance (SCPR) drove the majority of the module design changes as it matured.

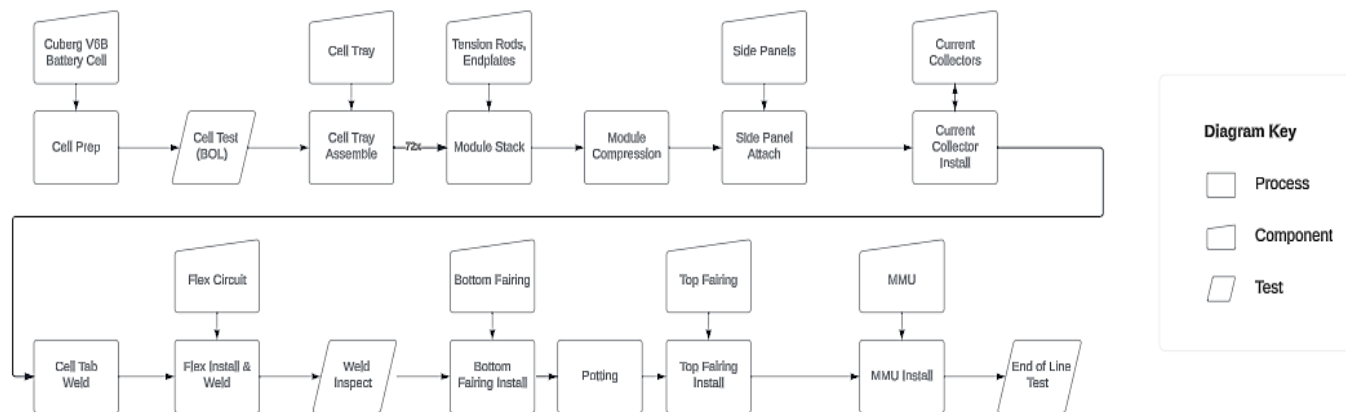
The module was assembled using the following steps, shown visually in Figure 11.

1. Battery cells that finish formation on Cuberg's cell manufacturing line were inspected for total discharge capacity, open circuit voltage, and visual and dimensional compliance using a rigorous set of binning criteria. The different bins delegate cells for internal R&D use, shipping to external testing facilities, or use for module builds.
2. Cells that met binning criteria for module builds were transferred to the module manufacturing area from Cuberg's cell manufacturing line.
3. Upon receiving cells, the module manufacturing team inspected them for defects and prepared them for integration into the module.

4. Cells were tested one more time to ensure that any and all nonconforming battery cells were excluded from the module. Test data were recorded in an MES system and checked against data taken on the final cell quality control (QC).
5. Cells were placed in a small plastic carrier that held a thermally conductive fin on one side and a thermal insulating barrier material on the other side.
 - a. The fin was used to transfer heat from the cell body to the exterior of the module during operation.
 - b. The thermal barrier thermally isolated the cell from its neighbors in case of thermal runaway and improved battery cell performance once integrated into the module.
6. These cell tray sub-assemblies were stacked linearly in a fixture to build up the module with the correct number of cells.
7. The whole module stack was compressed to a known length using a compression machine that monitored the force needed to reach that length.
8. Threaded tie rods were inserted through holes in the cell trays into the module assembly, then torqued to Cuberg's specifications to constrain the module length and ensure a rigid assembly.
9. After the compression process, side panels were installed on the sides of the module, using a thermal epoxy.
10. A fixture was used to hold the panel in place; the module was then placed into a curing oven to cure the epoxy to improve takt time.
11. Once the side panels were adhered, the team installed current collectors on the top and bottom of the module.
12. Once the current collector was installed, the cell tabs were welded onto the current collector.
13. At this point, the module was electrically connected live.
14. Each weld was inspected visually and measured with a battery impedance tester to ensure that the module met the design requirements for electrical resistance.
15. The voltage sensing flexible circuit was installed on the module, which monitored the module's temperature and voltage during operation.
16. The voltage sensing circuit was welded to the current collectors to activate the electrical connection between the circuit and the module.
17. All welds were inspected one final time before moving on.
18. The top and bottom cover were installed on the modules with structural epoxy and placed into the oven to cure.
19. After the covers were fully cured, the module was filled with an expandable foam that insulated all electrical connections from one another in a process known as "potting."

20. Once the potting was complete, the module monitoring board was installed on the end of the module and connected to the sensing circuit.
21. The module ran through an initial end-of-line test, which analyzed the monitoring board functionality, the voltage of the module, and its electrical isolation from the terminals to the exterior frame of the module.
22. After completing those steps, the module underwent its first charge and discharge to measure module capacity and internal resistance.
23. Once those measurements were confirmed and met specifications, the module was finished and ready for either use or further mechanical and electrical testing.

Figure 11: Module Production Overview



Source: Cuberg

Many of the changes and improvements to the module production process were centered on Step 5, ensuring that the material between cells was robust enough to achieve SCPR while being light enough to meet Cuberg’s energy-density requirements. As noted in the Project Approach section, the next steps of this project resulted in external publications and presentations that documented the results of external testing and validation. These results are summarized in Table 7, with references for greater detail provided at the end of the report.

A 60-cell module with specifications shown in Table 7 was externally cycled and validated at TÜV SÜD’s facilities, headquartered in Fremont, California.

Table 7: Cuberg Module Design Specifications

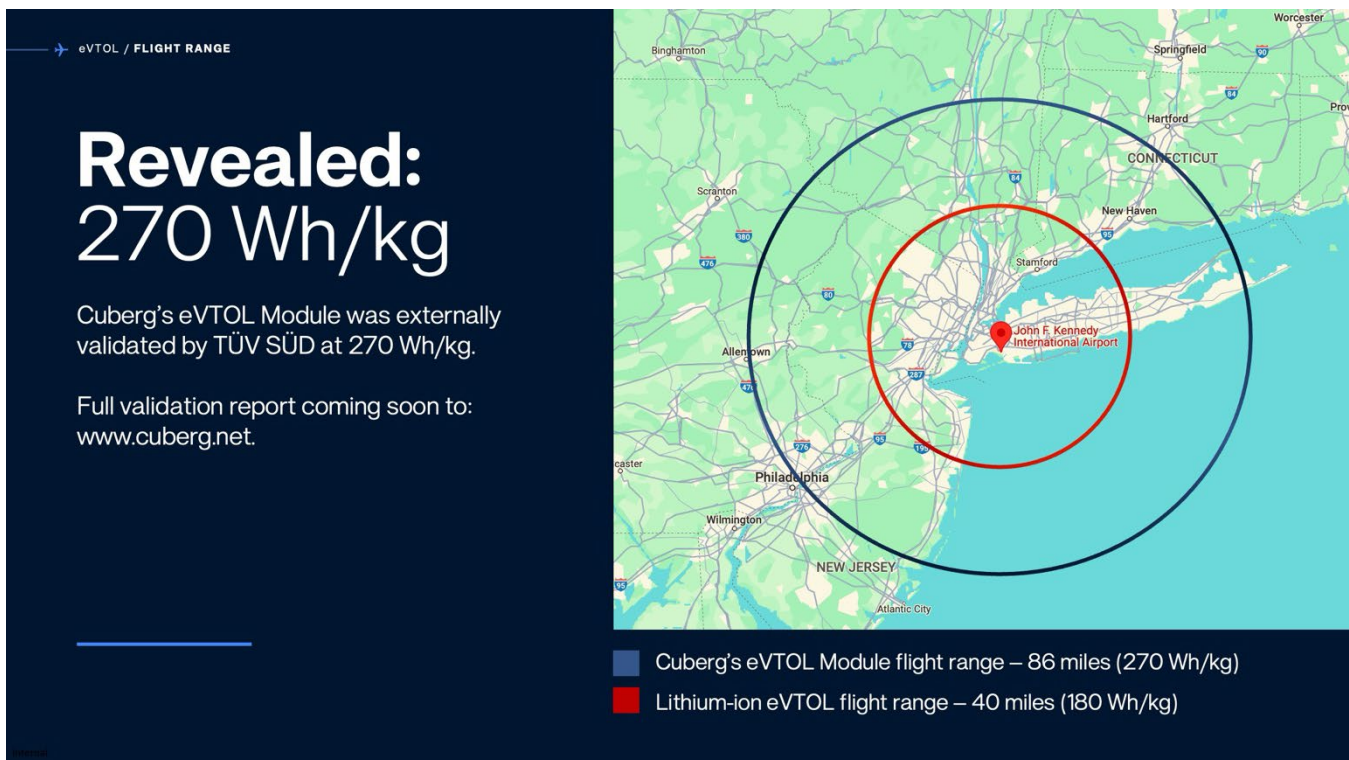
Characteristic	Value	Unit
Cell Count	60	# of cells
S&P configuration	10S6P (10 in series, 6 in parallel)	No unit
Max ToC – Min loaded voltage	42.8-25.0	Volts
Energy (C/20 at 113°F [45°C])	4.7	kWh

Characteristic	Value	Unit
Capacity (C/20 at 113°F [45°C])	122.3	Ah
Specific Energy (C/20 at 113°F [45°C])	284.8	Wh/kg
Module mass	16.4	kg

Source: Adapted from Cuberg's module validation report, published in May 2024.

The module achieved an energy density of over 270 Wh/kg, translating to a normalized 87 percent increase from traditional lithium-ion module flight ranges from 40 miles to 86 miles. This difference is presented in the encircled regions of Figure 12, with Cuberg's flight ranges in blue and traditional lithium-ion flight ranges in red.

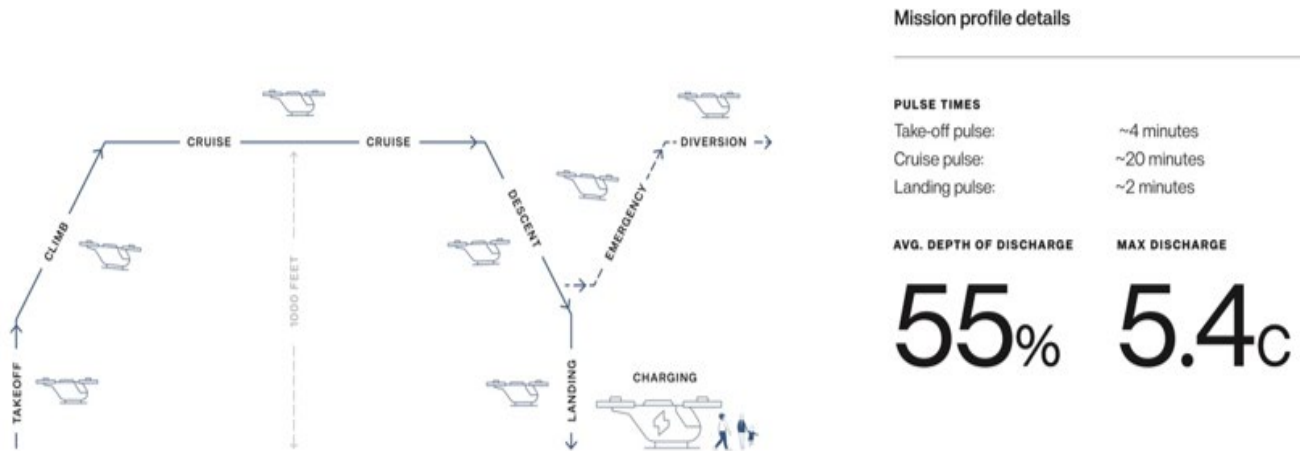
Figure 12: Excerpt from Presentation Showing Increased Range with Cuberg Module



Source: Cuberg, BNEF Summit, January 2024

The module achieved 692 cycles under a demanding eVTOL mission profile, shown in Figure 13. Each cycle, beginning at 100 percent state-of-charge, represented a completed mission profile of a market representative eVTOL flight.

Figure 13: Depiction and Details of Flight Profile



Source: Cuberg

Cuberg's team ended cycling when the module capacity retention reached 90 percent, an end-of-life threshold for some aviation specifications. Throughout testing, the module performed consistently and aligned with the requirements of eVTOL flight. The testing demonstrated linear trend lines for the performance and health metrics of discharge capacity retention, direct current internal resistance, module voltage, minimum module voltage, and maximum cell temperature.

CHAPTER 4:

Knowledge Transfer

These results have been shared broadly in public forums for thought leaders and industry experts as well as the interested general public. The module characterization was first shared at the January 2024 Bloomberg New Energy Finance summit, and the full module validation report was published online for public discourse.

Additionally, the activities and results of this project have been added to the CEC-funded [Energize Innovation](https://www.energizeinnovation.fund/projects/high-performance-battery-systems-power-rise-electric-mobility) (<https://www.energizeinnovation.fund/projects/high-performance-battery-systems-power-rise-electric-mobility>).

CHAPTER 5:

Conclusion

The Cuberg team successfully developed, manufactured, and validated the world's first lithium-metal battery module. This milestone was the culmination of:

- Identifying an ultra-safe cell design.
- Characterizing and validating the safety of that design.
- Ramping up manufacturing efforts with process steps to reach feasible cell yields.
- Designing and building the module prototype.
- Manufacturing and shipping the module for third-party evaluation.

The Cuberg module offered significant opportunities for electrifying high-performance mobility sectors, which traditional lithium-ion battery modules currently do not have the performance to satisfy, including electric aviation. The competitive advantages of the Cuberg module include:

Unique Product Space: Other advanced chemistries that maintain high discharge rates — such as cells with silicon anodes — have not yet demonstrated performance at the module level, nor have they shown the ability to achieve the combined power, energy, and cycle-life performance demonstrated in this research report.

High Specific Energy: Lithium-ion batteries cannot match the specific energy of lithium-metal technology; eVTOL operators who want maximum flexibility in their mission profiles can rely on Cuberg batteries.

Temperature Management: Lithium-ion batteries generate more heat than Cuberg batteries due to higher internal resistance; they also have higher sensitivity to degradation at high temperatures.

High Power Output: Mainstream lithium-ion technologies may struggle with the power requirements of an eVTOL flight profile. Under a comparable mission profile, it is likely that lithium-ion cells would not be able to achieve the same level of performance and cyclability. The high-power requirements of eVTOL missions are likely to rapidly increase resistance and shorten battery life.

The Cuberg module achieved specific energy of 284.8 Wh/kg: an industry-leading accomplishment for electric aviation. This significant improvement in specific energy translates into increased flight ranges which, in turn, enable new use cases for electric aviation. High specific energy enables operators to choose between longer cruise times or heavier payloads, both of which massively expand the universe of profitable-use cases for an eVTOL. Some operators could see their practical range more than double, depending on aircraft and power train design. The 692 cycles achieved by the Cuberg module while using a customer-relevant profile also showcased the longevity of the service life of the module product. Flying an eVTOL

with a Cuberg battery (with full range of 86 miles 692 times), one can fly 66,432 total miles with a fully loaded (4-passenger) aircraft, serve 2,768 passengers on one-way trips, and avoid 29.3 tons of carbon dioxide emissions compared with driving.

Market opportunities for this research are massive in the electric aviation space, where weight and space are the two biggest drivers for economic viability. The results from this module demonstrate that Li-metal solutions can not only achieve the technical results necessary to make it possible to electrify aviation; the pilot production of Cuberg cells demonstrates the manufacturing viability of next-gen Li-metal cells for aviation applications.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Ah	Amp-Hours
Al	Aluminum
BMS	Battery Management System
BNEF	Bloomberg New Energy Finance
C	Celsius
Cycle Rate (C/#)	Expressed as “C” over a number, the cycle rate describes how quickly a battery is charged and discharged.
eCTOL	Electric Conventional Takeoff and Landing
eVTOL	Electric Vertical Takeoff and Landing
Kg	Kilogram
kWh	Kilowatt-Hour
L	Liter
Li-ion	Lithium-ion
Li-metal	Lithium-metal
LRIP	Low-Rate Initial Production
MES	Manufacturing Execution System
Ni	Nickel
OEE	Overall Equipment Effectiveness
QC	Quality Control
R&D	Research and Development
SCPR	Single-Cell Propagation-Resistance
SEI	Solid-Electrolyte Interphase (the thin layer on the surface of an anode that forms during reactions with electrolyte)
UAV	Unmanned Aerial Vehicle
V	Volts or Voltage
Wh	Watt-Hours

Project Deliverables

Project deliverables, including interim project reports, are available upon request by emailing pubs@energy.ca.gov.

Following is a list of project deliverables.

- Viability Test Plan
- Viability Study Report
- Cell Characterization Plan
- Pilot Production Report
- Module Development Roadmap Report
- Module Characterization Plan
- Module Production Report