CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Improved Batteries for California's Zero - Emissions Vehicle Future

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Electric vehicles can move people and products efficiently, at low cost, and with low environmental impact. Personal vehicles and public transportation have significant technical and legislative momentum to electrify their industries, and the aviation industry is poised to follow with the emergence of electric vertical takeoff and landing (eVTOL) and conventional takeoff and landing (eCTOL) aircraft. Cuberg, Inc. is a battery cell manufacturer founded in 2015 and acquired by Northvolt in 2021 that is developing a unique lithium metal battery cell chemistry which can provide immense power output in a compact, lightweight package. High power and low weight are critical attributes for the electric aviation industry to reach commercialization. This project helped develop this battery cell in a small format to provide a proof of concept for high-throughput manufacturing. This project culminated in the development of Cuberg's low-rate initial production (LRIP) line, using existing processes that are repurposed for lithium metal cell manufacturing, which can produce up to 3,000 cells per month. These cells provide exceptional energy density of 370 Wh/kg. The LRIP line is being iteratively improved to provide a high-yield platform to support larger-scale manufacturing projects in support of electrifying the aviation industry and decarbonizing transportation technology.

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.

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

ABSTRACT

Cuberg is a startup company headquartered in San Leandro, California that aims to develop lithium metal battery cells, the first of their kind to be commercialized, with a focus on applications in the aviation and electrical vertical takeoff and landing industry. Cuberg is building a groundbreaking lithium metal battery system with exceptional power output, reduced weight, and cycle-life that can become a battery for electric aircraft applications, eliminate carbon emissions from additional car and truck use, and pave the way for other exciting new mobility applications such as drones or even ships.

This project funded the setup and commissioning of a pilot-scale production facility for manufacturing lithium-metal battery pouch cells. Cuberg batteries have already accomplished an energy density of 50 percent greater than current lithium-ion batteries, and this capacity is expected to only increase. Moreover, the tradeoff between power and energy is much less severe than in lithium-ion cells. Cuberg has already achieved power of up to 2500 watts per kilogram, and it anticipates reaching even higher power targets.

Cuberg's main goal in undertaking this project was to achieve two key outcomes: produce high quality cells and provide these cells for testing and screening. The first commercial format five-amp-hour (5Ah) lithium metal cell with non-flammable proprietary electrolyte was the focus of this grant.

Cuberg used a capital-efficient approach to scale up by contracting with a low-cost manufacturer to produce dry lithium metal pouch cells (cathode, separator, anode, and packaging) to Cuberg's specifications. With this approach, Cuberg avoided more than 95 percent of the capital expense typically required to scale up a new battery technology to pilot production while maintaining tight quality control over intellectual property. By the end of the project, the product prototype was able reach a technology readiness level of TRL 8, allowing the company to sell prototypes to customers for evaluation. In addition, Cuberg has been able to dramatically increase yields from 50 percent up to 80 percent; the increase to the targeted 90 percent is now just an iterative process.

Keywords: Cuberg, Energy density, lithium-metal battery pouch cells, lithium-ion battery, battery cycle-life, high energy density, California Energy Commission

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Background

All-electric vehicles move people and products more efficiently, at lower cost, and with reduced environmental impact. California recently announced that it plans to ban the sale of new gas-powered cars by 2035, moving to electric vehicles (EV), which increases pressure on the battery market to develop technology that can accommodate batteries with more power, longer range, and other specialized capacities. The California Air Resources Board notes that moving to EVs will reduce smog-causing pollution from light duty vehicles by 25 percent by 2037 and result in 9.5 million fewer conventional vehicles sold by 2035. However, current lithium-ion battery technology, crucial for mainstream adoption of EVs, does not have the capability to deliver the power necessary to completely electrify the automotive sector and accomplish this goal.

Cuberg is a startup company headquartered in San Leandro, CA, which aims to develop lithium metal battery cells, the first of their kind to be commercialized, with a focus on applications in the aviation and electrical vertical takeoff and landing (eVTOL) industry. Acquired by Northvolt in March 2021, Cuberg is building a groundbreaking lithium metal battery system with exceptional power output, reduced weight, and cycle-life that can become a battery for electric aircraft applications, eliminate carbon emissions from additional car and truck use cases, and pave the way for other exciting new mobility applications such as drones or even ships.

Rather than reinventing manufacturing processes, Cuberg's lithium cell uses existing processes that are repurposed for lithium metal cell manufacturing. This project, which led to the development of Cuberg's low-rate initial production (LRIP) line, moves California one step closer to commercializing a technology that can be used to supplement existing battery technologies, providing batteries with greater energy density and power and opening the door to fully electrifying California's transportation sector.

Project Purpose and Approach

Cuberg's main goal in undertaking this project was to achieve two key outcomes: produce high quality cells and provide these cells for testing and screening. The first commercial format 5Ah lithium metal cell with non-flammable proprietary electrolyte was the article for this goal.

Cuberg's performance targets were to:

- Achieve a production rate of 3,000 high energy and non-flammable lithium batteries per month in the form of 5Ah pouch cells.
- Obtain high quality control of the lithium batteries produced.
    - Develop a manufacturing and quality control process to enable a yield of >95 percent.
- Make cells readily available, including finding a pathway toward robust safety testing and obtaining the necessary shipping certification for Cuberg cells.

Cuberg used a capital-efficient approach to scale up by contracting with a low-cost manufacturer to produce dry lithium metal pouch cells (cathode, separator, anode, and packaging) to Cuberg's specifications. With this approach, Cuberg avoided more than 95 percent of the capital expense typically required to scale up a new battery technology to pilot production while maintaining tight quality control over intellectual property. By the end of the project, it was anticipated that the product prototype would reach a technology readiness level of TRL 8, allowing the company to sell prototypes to customers for evaluation.

Lessons learned from the project include the following:

- Specially designed equipment is needed to handle the soft lithium metal foil. Due to the softness of the material, lithium foil can be easily damaged with handling, resulting in defects and low-quality batteries. Cuberg custom equipment was designed to account for the material properties and minimize damage in the active regions of the foil once in the sense.
- Supply chain challenges with availability, and with consistency and quality of dry cells have been major components in achieving the desired quality yield metrics. Cuberg has spent significant time in root cause analysis to identify and mitigate the source of performance defects, including tracing these to supplier storage conditions.
- Environmental factors such as temperature and humidity as well as formation times can significantly impact the battery quality and performance.

Cuberg now has a pathway to supplying batteries to its EV customer base and to help drive the certification and adoption of the first battery module for electric aviation.

Key Results

Following are key results from this project.

Manufacturing Line

- Designed, built, and commissioned an LRIP pilot line for Cuberg's commercial cells, with all production equipment (gloveboxes, formation cyclers, test chambers, electrolyte injection machine, vacuum sealer), producing the first batch of cells on the line.
- Accommodated, with this LRIP line, up to 3,000 cells per month. Cuberg is currently producing as many cells as necessary to supply to customers and perform in-house testing (up to 2,600 cells per month).
- Achieved a cell manufacturing yield greater than 80 percent. The team is working to increase the yield to 90 percent and actively performing root-cause analysis leading to lower yield. During the performance of this project, Cuberg has been able to dramatically increase yields from 50 percent up to 80 percent; the increase to the targeted 90 percent is now an iterative process.

Shipping and Distribution

- Set up a shipping/packaging line and obtained safety certification required to ship commercial format cells (UN/DOT 38.3) as well as a prototyping exemption for shipping new R&D prototypes.
- Consistently tracked shipping volumes, which reached more than 2,250 cells shipped in June 2022, in response to customer demand.
- Sold more than 2,500 cells to customers for evaluation, generating $1.7 million dollars in commercial income in 2021. Furthermore, independent validation of the cell performance in 2020 (U.S. Department of Energy's Idaho National Laboratory) and in 2022 (Mobile Power Solutions) confirmed the competitive advantages of Cuberg's technology at a scale sufficient to demonstrate commercial readiness and value.

Product Maturity

- Reached a TRL 8 designation, allowing Cuberg to sell limited quantities of product to customers for test and demonstration of pre-commercial volumes. These sales to a large federal government contractor, multiple electric vehicle takeoff and landing manufacturers, and others are a testament to the quality of the Cuberg cell and the unique advantages it provides.

Partnerships

- Secured a high-profile, strategic partnership with Northvolt, a large-scale preeminent EV battery manufacturer, leading to an acquisition and Cuberg's operation of Northvolt's Advanced Technology Center in the Bay Area. This has resulted in significant growth in operations, which will continue in order to develop next-generation battery cells for the electromobility market.

Knowledge Transfer and Next Steps

Cuberg is developing a next-generation battery technology that addresses growing demand in the emerging electric vertical takeoff and landing (eVTOL)/Urban Air Mobility market, which Cuberg chose as a beachhead market. With this battery technology, electric aviation solutions can deliver greatly improved flight range, payload capability, and operational cost due to increased gravimetric energy density, high safety, and high power. Northvolt's 2021 investment in Cuberg ushered in a new era of press and visibility, which provided Cuberg an elevated platform to use for knowledge transfer to industry players and the general public.

Many customers have been interested in testing the high-performance batteries; however, selection criteria have been focused on companies that have technology, are aligned with Cuberg's focus on customers in the electric aviation sector and have commercialization potential.

Based on the criteria and priorities, Cuberg has developed a strong strategic partnership with an electric aerospace company. The two companies have a joint development agreement to

develop a module and pack with Cuberg cells for the company's eVTOL (electric vertical takeoff and landing) aircraft to increase the range and payload capacity of the aircraft.

Cuberg has also been engaged in industry events, symposiums, and other forms of knowledge transfer and now, as a part of Northvolt, Cuberg's participation in these events and activities has increased.

- *California Battery Forum* – Cuberg hosted the California Battery Forum at its headquarters in 2022 and participated in the Forum in years' past. The Forum, which allows different industry leaders to gather, is sponsored by the California Energy Commission to showcase different parts of the California battery supply chain.
- *Government delegations* – Cuberg has hosted several government delegations during 2022, including those from the European Parliament, the Swedish federal government, the California Energy Commission, and the U.S. Department of Defense.
- *National Energy Storage Summit* – Cuberg's CEO participated in and presented at the Energy Storage Summit in 2022 in a panel discussion entitled "Homegrown Production: Leveraging US Manufacturing Innovations." This discussion, which is now available online, focused on developing a sustainable homegrown supply chain for battery manufacturing. Naturally, this discussion capitalized on Cuberg's LRIP manufacturing line experience.
- *Getting Battery Electric Aircraft off the Ground, McKinsey Panel* – Cuberg participated in a McKinsey panel discussion on how to accelerate the electric aircraft industry.
- *CNBC Feature* – In 2021, CNBC featured Cuberg's LRIP line in a short video, which showed clips of Cuberg's manufacturing process, incorporating the learnings from this project. The feature showcased the technical advantages of Cuberg's lithium metal battery, explained Cuberg's path toward commercialization, and elucidated how the technology fits into Cuberg's target aviation market.
- *Allplane podcast* – Cuberg's CEO Richard Wang was featured on the Allplane podcast to discuss Cuberg's technological advantage, its manufacturing scale-up, and its plans for further expansion. The podcast also discussed Northvolt's acquisition of Cuberg and what that means for Cuberg's technology and scale-up.

CHAPTER 1: Introduction

Lithium-ion (Li-ion) batteries do not have sufficient energy density and safety to reach the performance needed for mass-market electrification of the aviation, drone, high performance automotive, and long-haul trucking sectors. In fact, lithium-ion technology will soon reach theoretical limitations in energy density because the conductivities of most of the electrode materials are not sufficient to attain high-rate performance. Moreover, there is difficulty obtaining strong rate capability while maintaining long cycle-life and safety. In the aviation, drone, high performance automotive, and long-haul trucking sectors, the economics of electrification are closely linked to a battery design that enables longer journeys, reduces transport weight, and improves safety — design characteristics that cannot be met by conventional lithium-ion technology. And many other emerging approaches to improve battery performance suffer from major challenges with scalability and manufacturing incompatibility, which makes development and scale-up too costly and technically risky.

California, therefore, must look to new solutions if it is to reach its goal of transitioning 100 percent of medium- and heavy-duty vehicles in the state to EVs by 2045. California must incubate battery technology outside of the conventional lithium-ion realm to successfully accomplish its objectives.

This project funded the setup and commissioning of a pilot-scale production facility for manufacturing lithium-metal battery pouch cells. In the short term, Cuberg batteries will power unmanned aerial vehicles with better capabilities for search-and-rescue efforts, logistics missions, and monitoring for the agriculture, oil and gas, and utility industries. More broadly, Cuberg batteries will provide the critical improvements needed in performance and safety profiles for the broader electric mobility sector (aviation and automotive). Cuberg batteries have already accomplished an energy density of 50 percent greater than current lithium-ion batteries, and this capacity is expected to only increase. Moreover, the tradeoff between power and energy is much less severe than in lithium-ion cells. Cuberg has already achieved power of up to 2500 W/KG, and it anticipates reaching even higher power targets.

Cuberg's energy-dense batteries will lead to safe battery packs with a lower cost per kWh, creating cheaper electric mobility solutions that will be accessible to middle- and lower-income communities, and improving the reliability of the infrastructure with high performance energy storage systems.

Under the scope of this project, Cuberg planned to design and build out a cost efficient, low-rate initial production (LRIP) manufacturing line with production volumes of up to 3,000 cells per month and a yield greater than 90 percent. It was anticipated that, by the end of the project, this product prototype would reach a technology readiness level of TRL 8, thus allowing the sale of prototypes to customers for evaluation. Additionally, Cuberg planned to create at least 10 manufacturing and engineering jobs for California residents. Cuberg aimed to accomplish the performance metrics shown in Table 1.

Table 1: Cuberg Performance Metric Summary

Performance Metric	Target Performance	Significance of Metric	Outcome
Commissioning equipment for pilot-scale production (Task 3)	Set up all production-scale equipment in new production facility and pro-duce first batch of cells on pilot line	The task of selecting, purchasing, receiving, installing and, finally, commissioning all equipment required for the pilot-scale production line is a significant portion of this project and a necessary step to target cell production.	Cuberg accomplished this metric with some timeline delays due to COVID-19 complications.
Cell production rate (all tasks)	Produce 3,000 cells/month	The number of cells produced on the pilot line is one of the main metrics to gauge success of this project. It is directly correlated to the number of cells that Cuberg can sell to customers and the pace at which the technology can get into the market.	While Cuberg achieved the capacity to produce approximately 3,000 cells per month, it is producing below this number after calibrating with customer demand.
Production line yield (Task 5)	Target yield: >90%	Yield is important to keep costs down and minimize the time required to produce the number of viable cells needed to meet customer demands. Failure to achieve a yield of >90% will result in increased costs, cutting into Cuberg's margins. An iterative approach with gradual process improvements will be necessary to hit this target.	Cuberg readjusted this performance metric over the course of the project due to the ambitious nature of the original yield metric. Cuberg increased the yield from 50% at the beginning of the project to a yield of greater than 80% after solving a number of complications involving moisture content and dry cell issues.
Safety certification (Task 6)	Receive UN 38.3 and DOT 49 C.F.R. certifications	These certifications are required to ship commercial (post-prototype) cells by air, which will improve delivery time to customers in Europe and Asia.	This metric was successfully accomplished, allowing Cuberg to ship cells and prototypes to customers.
Shipping volume (Task 7)	Ship 3000 cells/month	Shipping is necessary for providing cells to customers and end-users.	While Cuberg has the capacity to ship 3,000 cells per month, it is shipping under this amount due to customer demand. Cuberg has shipped upwards of 2,400 cells to customers in a month.

Source: EPC-18-015 Kickoff Presentation and Draft

Cuberg's technology presents key advantages in energy density and safety over current battery technologies, including lithium-ion batteries where the maturity of the technology does not readily allow for additional improvements. Other technologies, such as lithium sulfur, are plagued by fundamental stability, calendar life, and dissolution issues. Solid-state batteries face fundamental scientific obstacles and technical difficulties in fabrication that hinder adoption in the near to medium term.

Cuberg's cell is the battery cell entering the market that meets stringent demand for a high performance (energy and power) and high safety (low fire risk) product and is primed for rapid commercialization. Cuberg's lithium metal technology overcomes the aforementioned barriers with an energy-dense lithium metal anode, which provides exceptional specific energy and power, as well as a proprietary liquid electrolyte, which stabilizes the anode and enables long cycle-life. Cuberg's "secret sauce", a proprietary non-flammable and thermally stable liquid electrolyte, replaces flammable organic solvent-based electrolytes, a key contributor to the poor safety profiles of Li-ion batteries. Moreover, Cuberg's cell technology was developed around large-scale battery manufacturing processes to alleviate scalability and manufacturability issues. Figure 1 shows the Cuberg cell surviving a nail puncture test safely while a comparable Li-ion cell undergoing the same test catches fire.

Figure 1: Cuberg's Cell vs. Commercial Li-ion Cell

Cuberg's technology addresses the growing demand in the emerging electric vertical take-off and landing (eVTOL)/Urban Air Mobility market, Cuberg's beachhead market. When equipped with Cuberg's unique technology, electric aviation solutions will deliver greatly improved flight range, payload capability, and operational cost, providing better capabilities for firefighting, cargo delivery, urban and regional transportation, search-and-rescue efforts, logistics missions, and monitoring for the agriculture, oil and gas, and utility industries. Cuberg has already gained traction with key stakeholders in the EV market, the company's long-term target market segment. Cuberg's energy-dense and safer batteries will lead to the development of safer battery packs with a lower cost per kWh, creating cheaper electric mobility solutions and thus making this more accessible to middle- and lower-income communities. Improved battery packs based on Cuberg's design will also contribute to greater reliability of the EV infrastructure in California, with high performance energy storage systems advancing California's goal to achieve five million EVs by 2030.

CHAPTER 2:
Project Approach

Cuberg's core technology addresses a key performance challenge with lithium-ion batteries: as the technology approaches the fundamental limits of the material, the performance of the batteries begins to plateau. To create new batteries with more energy capacity, durability and power without a safety trade-off, new materials and chemistries are required. Lithium metal anodes can hold significantly more energy than typical lithium-ion and show great promise for new batteries. However, these can be expensive to make, and reducing manufacturing costs by using overseas partners can jeopardize intellectual property in this technology.

Cuberg's unique approach to resolving this performance limit is based on lithium metal batteries with a patented electrolyte formulation that is non-flammable. While Cuberg's initial work relied on using low-cost foreign contract manufacturers, Cuberg's process was designed to be compatible with existing manufacturing methods and readily scale to in-house manufacturing.

The primary goals of this project are to:

- Achieve LRIP for Cuberg's lithium metal high energy and non-flammable batteries.
- Increase market penetration of the EV market by introducing better batteries.
- Accelerate production to increase availability of Cuberg's batteries to drive strategic partnerships and adoption of lithium metal batteries in EVs.

Cuberg has assembled a core team of experts to execute and drive this project forward. Dr. Richard Wang, Cuberg's CEO and Co-Founder, served as Principal Investigator. Dr. Wang graduated from Stanford in 2016 with a PhD in materials science and engineering. His research at Stanford with Professor Yi Cui was supported by a National Defense Science and Engineering Graduate (NDSEG) fellowship and a National Science Foundation (NSF) graduate research fellowship. He studied battery degradation mechanisms at Tesla Motors in 2014 and graduated with a BS in mechanical engineering from the California Institute of Technology in 2011. Dr. Olivia Risset served as Project Manager; she holds a PhD in inorganic chemistry from the University of Florida (class of 2014) and was a scientist at Natron Energy. The project has been supported by a well-rounded, world-class team of employees, including scientists, engineers, and business professionals. Starting with 12 full time employees, the team now comprises 125 full time members. More than 25 Cuberg employees were actively involved in this project.

The first technical task of this project was to build a facility for pilot-scale production of Cuberg's commercial format lithium metal pouch cells. Within a few months, Cuberg turned a 5,000-square-foot office space into a suitable pilot-scale production facility to house the production equipment necessary to produce a few thousand units per month, the project target being 3,000 cells per month. After completion of the facility, Cuberg acquired, set up, and commissioned all necessary pieces of equipment. For each assembly step, Cuberg established

quality control (QC) standards that relied on physical and electrochemical techniques to ensure early detection of defective cells and determine any need for corrective action in the production process. Statistical analysis tools were implemented to aid the QC process. Cells that passed QC checks were then tested internally or shipped to customers for validation.

The main objectives of the project were:

- Building out the facility – In the second quarter of 2018, the team built a new lab space in Emeryville and gained significant experience organizing small construction projects. The project was completed on time and within budget.
- Selecting and commissioning pilot-scale manufacturing equipment – The original team's expertise was heavily focused on R&D. To secure manufacturing expertise, Cuberg hired production engineers, process engineers, and consultants with experience in battery manufacturing.
- Securing the dry cell supply chain – The contract manufacturing model assumes that the supply of dry pouch cells will keep up with customer demand. The global battery industry is heavily commoditized, with hundreds of potential suppliers. The team established strong relationships with a major battery manufacturer in the lithium-ion industry, where dry cell pouches are sourced.
- Establishing reliability and safety systems – The team operates with a strong culture of safety, closely follows peer-reviewed safety literature, and strives to instill system and behavioral-based safety checks in the products. Furthermore, the company continually advances and develops QC mechanisms suitable for scale-up and commercial-level production of the cells.
- Overcoming COVID-19 setbacks – The pandemic heavily disrupted the internal operations, supply chain and customer engagement in 2020. Cuberg had to be creative and make adjustments to internal processes and external-facing activities to provide a safe working environment and abide by the state orders. Like many other businesses, in 2022, the company continues to face negative effects on the supply chain and shipping logistics, resulting in delayed timelines on several projects and with capital equipment.

A technical advisory committee (TAC) was formed to advise Cuberg on the project and its objectives and to provide feedback on performance and associated metrics. Cuberg's TAC for this project included:

- Reza Nikfar, former VP – Asia Operations at Seagate, Founder/Managing Partner at RFA Consulting, and Cuberg COO since May 2020.
- Brian Bartholomeusz, TomKat Center's Executive Director of Innovation Transfer.
- Dr. Michael Bartholomeusz, CEO and Board Director of TruTag Technology and Cuberg's Board Director.
- Dr. Danielle Applestone, Co-founder and CEO of Other Machine Co. and CEO and Co-founder of Daughters of Rosie.
- Dr. Mauro Pasta, tenured Associate Professor of Materials at University of Oxford.

- Dr. Herman Wiegman, CTO of BETA Technologies.
- Peter Blomquist, Director of Business Development at Northvolt.

Key Milestones

The milestones achieved during this project are discussed in the following sections.

Building Out the Pilot-scale Production Facility

As part of the EPC-18-015 project, Cuberg set out to build a facility for pilot-scale production of lithium metal pouch cells. This task was completed in September 2019, ahead of the November 2019 planned delivery date.

Original requirements and approach for the production facility

Lease and modify an existing building or space within an existing building to meet the following requirements for the production line:

- Location in an area with business zoning suitable for a final assembly facility.
- A minimum usable floor space of between 5,000 and 7,000 square feet.
- Fire-rated walls/ceilings to maximize production capability and code compliance.
- A necessary power supply (10kW) to meet formation equipment requirements.
- An HVAC system capable of handling the heat load from equipment.
- Chemical ventilation/exhaust for gloveboxes.

Existing leased facility and modifications made to be used for the pilot production

Cuberg leased a 5,000-square-foot office suite located across the hallway from its existing facility and planned to make the following modifications over the course of the project:

- Wall construction and door installation between the production and office areas.
- Electrical work to provide the necessary power supply (10kW) and installation of 220V outlets.
- Floor tiling – stainless steel plates for the formation/testing station and vinyl tiles for the filling and sealing station.
- HVAC and air balancing work.
- Air ducting system installation for chemical ventilation and glovebox exhaust.
- Unistrut installation for gas cylinder storage.
- Storage area set-up.

Selecting and Commissioning the Pilot-scale Manufacturing Equipment

As part of the EPC-18-015 project, Cuberg set out to build a facility for pilot-scale production of lithium metal pouch cells. In the past few months, Cuberg has been acquiring, setting up,

and commissioning all equipment necessary to produce a few thousand units per month. This task was completed prior to the end of January 2020.

Developing QC Processes

As part of the EPC-18-015 project, Cuberg has developed a QC system for the commercial pouch cells produced in its pilot-scale production facility. The plan to create a robust QC process relied on physical and electrochemical techniques to ensure early detection of defective cells and to determine any need for corrective action in the production process.

Cuberg's QC test plan described below defines the QC checks implemented at each stage of pouch cell assembly, from raw materials to final inspection before shipping to customers, to ensure that the quality and performance of the product are at the highest standards for evaluation and validation.

- The following QC checks were implemented at Cuberg's contract manufacturing partner:
    - Cathode coating
        - Mixing: slurry viscosity
        - Coating: loading level and width
        - Calendaring: loading level and thickness
        - Cathode punching: width and burr size
    - Electrode stacking: alignment (X-rays), weight, thickness, detection of shorts (Hi-Pot)
    - Electrode welding: visual inspection and peel strength
    - Sealing: seal width, thickness, strength, and sealant exposure
    - Final visual inspection
- Once received at Cuberg, the cells are subject to internal QC checks, and more checks are performed throughout the filling and sealing process.
    - Dry cells received at Cuberg are subject to visual inspection and detection of shorts (Hi-Pot) and are weighed. The implementation of these steps allows for early detection of manufacturing defects such as dents, poor seals, and electrode misalignment. An example of a cell that failed visual inspection and one that passed visual inspection is shown in Figure 2.

Figure 2: Cell That Failed Quality Control (left) and Cell That Passed (right)

Source: Photos taken from Cuberg's lab in Emeryville, CA.

- Cuberg's proprietary electrolyte undergoes a series of tests during preparation and filling. Moisture is a critical consideration, as lithium metal is known to react with it to form lithium hydroxide. For a viable electrolyte mixture and batter, the moisture level must be below 100 ppm prior to filling the cell.
- Cuberg cells are vacuum sealed after they are filled to remove any residual gasses from the electrolyte mixture and allow full wetting of the dry cell components. The seal on the pouch can present a weak point for failure and the process ensures that cell width, thickness and strength remain within specific tolerances. Cells that pass through the QC system at each metric are then subject to formation protocols. A final visual inspection of the cell takes place prior to shipping to customers.

Establishing Packaging and Shipping Guidelines

As part of the EPC-18-015 project, Cuberg has identified packaging requirements, trained shipping/receiving staff on hazardous shipping regulations, and established a pouch cell packaging line. Up to 3,000 cells per month can be shipped to customers. The Battery Shipping Report describes the procedures and summarizes the regulations required for shipping Cuberg cells by ground, sea, and air.

Shipping Summary

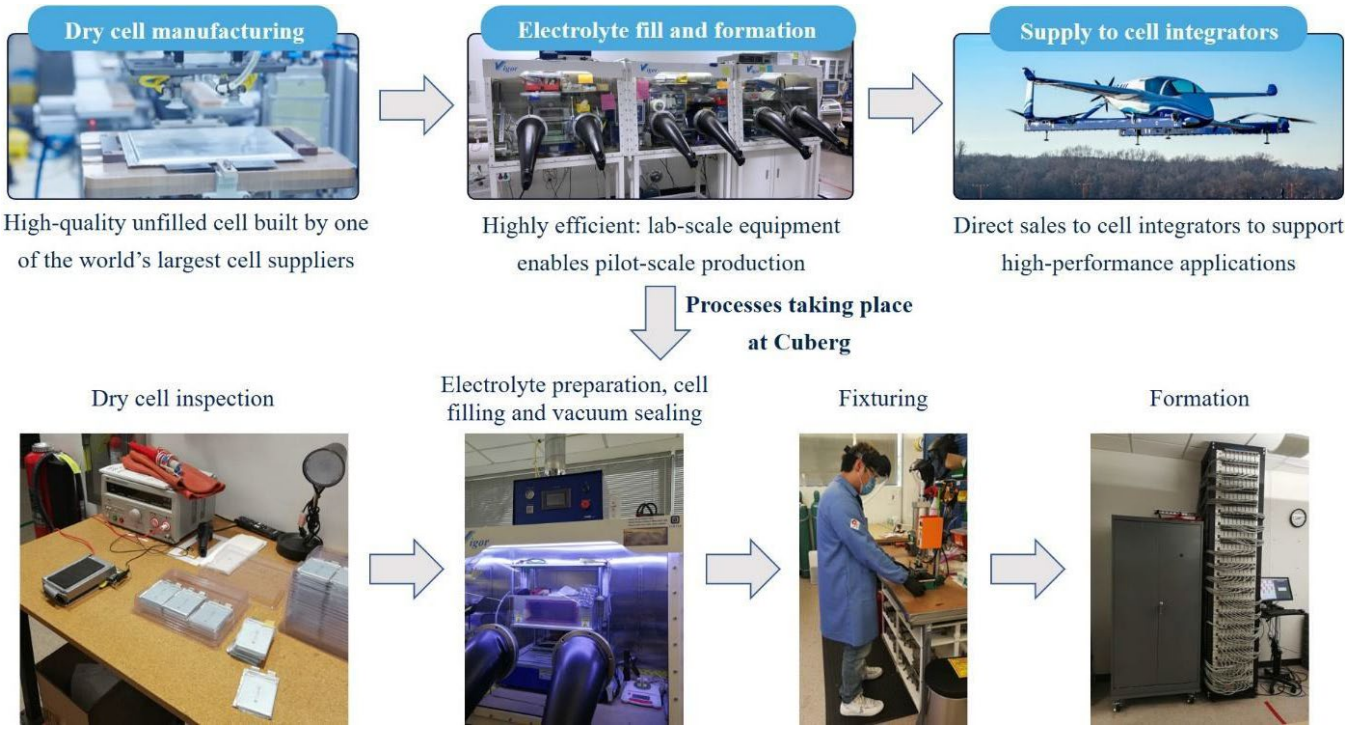
Cuberg has shipped out 1,000+ cells to customers by ground and air for domestic shipments and by air for international shipments. Upon investigation, sea shipping was deemed not suitable for customers due to logistics hurdles and long lead times, which are typically greater than one month.

Cuberg obtained a special permit from the Department of Transportation, DOT-SP-20323, for shipping of lithium metal prototype batteries. As production volumes increased, the cells have been certified under UN/DOT 38.3.

A major goal of this project was to allow Cuberg to scale to a production readiness level that would supply up to 3,000 cells per month to customers as needed. Cuberg was successful in achieving that production readiness level. Figure 3 illustrates Cuberg's overall production

process as a result of the work conducted during this grant. Cuberg's unique product is now being tested with customers in the aviation and high-performance EV markets.

Figure 3: Cuberg's Production Process for Lithium Metal Business



Source: Slide taken from Cuberg EPIC kickoff CEC presentation; photos taken from Cuberg's lab in Emeryville, California.

CHAPTER 3:
Results

This project has been instrumental in helping Cuberg develop its unique battery further and in increasing awareness of the product with key customers. The key results and learnings acquired are summarized in this section.

Product Development and Pilot-Scale Production

During this project, the initial prototype product reached TRL 8 and the technical performance metrics have been mostly achieved, as summarized.

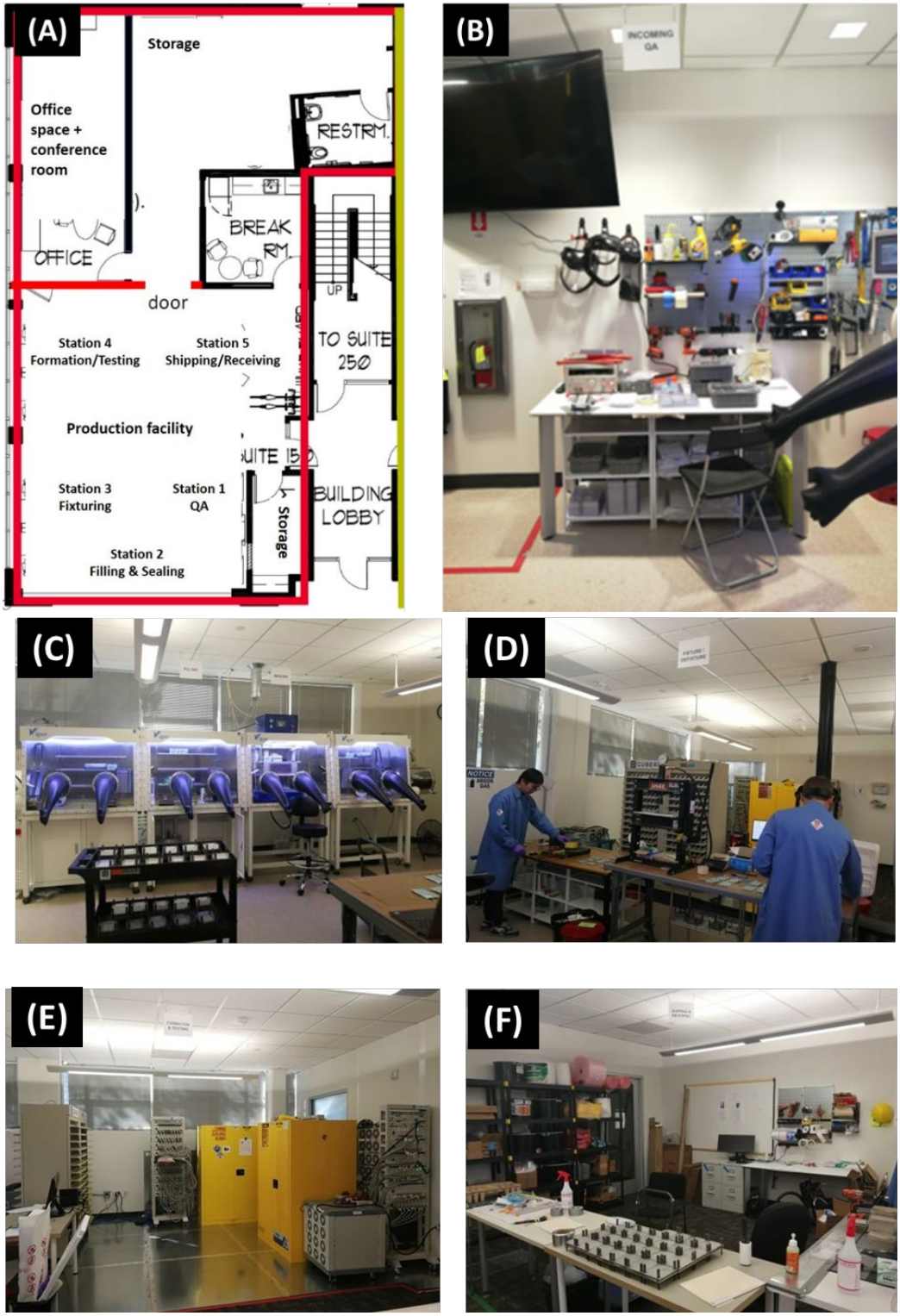
Performance Metric #1: Commissioning equipment for pilot-scale production

Cuberg reached the targeted post-project performance by setting up all production-scale equipment in the new facility and beginning to assemble commercial format cells on the LRIP line in January 2020.

The production facility consists of five key stations for quality analysis (QA): filling, fixturing, forming, and shipping and receiving cells. Figure 4 shows a schematic of the Cuberg facility and pictures of each of the stations used in the process of building a Cuberg cell. Briefly:

- Dry cells are received and unpacked at the receiving station.
- Dry cells are moved to the QA station and inspected.
- Upon passing inspection, cells are carried to the filling and sealing station. Filling with electrolyte is done under inert atmosphere as a safety measure, since lithium metal is highly reactive. Once filled, cells are weighted, degassed under vacuum, allowed to soak, and sealed.
- Sealed cells are taken out of the glove box and mounted into testing fixtures at the fixing station.
- Batches of cells are put through the formation and testing process.
- After testing, viable cells are moved to the shipping station for packaging and shipping to customers.

Figure 4: Schematic of Cuberg Facility and Cell Construction Process



(A) Schematic of the Cuberg Facility. (B) Station 1: QA station for incoming cells. (C) Station 2: Filling and sealing conducted in glove boxes. (D) Station 3: Fixturing of filled and sealed cells. (E) Station 4: Formation and testing of cells. (F) Station 5: Dry cell receiving and finished cell shipping station.

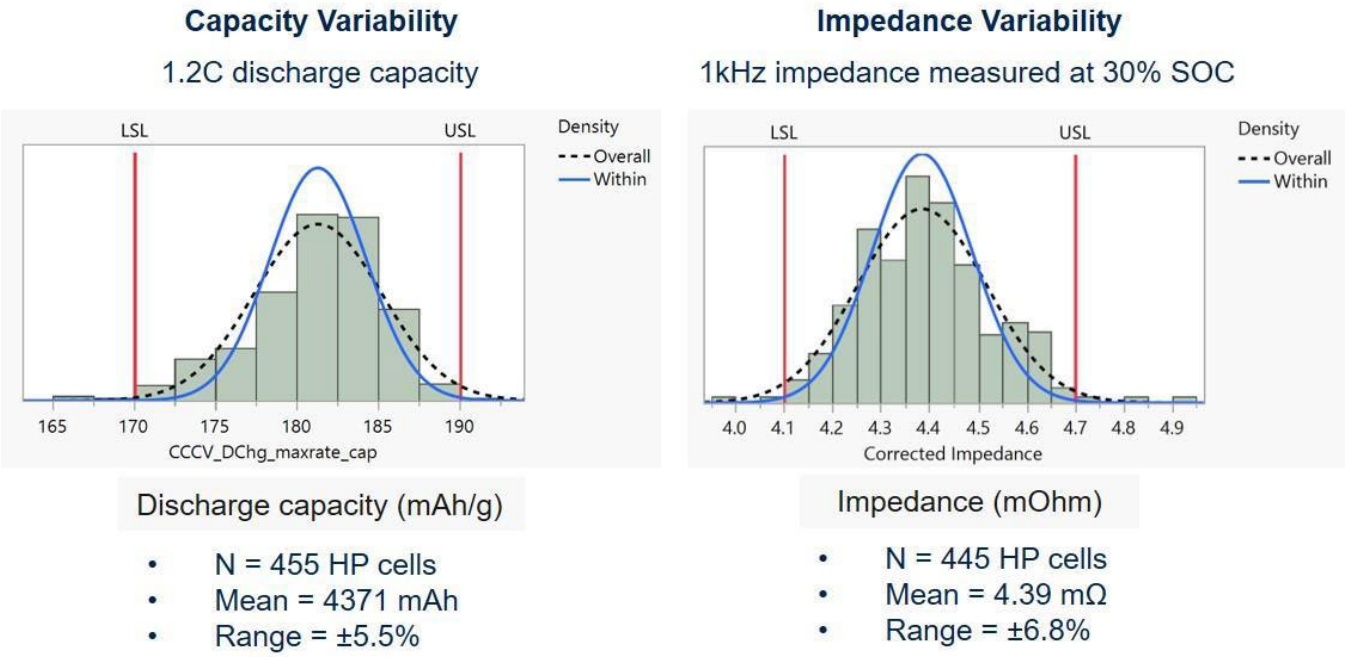
Source: Photos taken from Cuberg's lab in Emeryville, CA.

Performance Metric #2: Cell production rate. Although the targeted performance was 3,000 cells per month, Cuberg currently produces around 1,000 cells per month. The pilot line, processes, and documentation have been designed using 3,000 cells per month as the base-line rate. However, Cuberg is producing as many cells as necessary to supply to customers and perform in-house testing.

Performance Metric #3: Production line yield. The yield target was set at greater than 90 percent, which is ambitious for an emerging technology. Cuberg increased the yield from 50 percent at the beginning of the project to greater than 80 percent. Though significant progress has been made, an ongoing iterative approach with gradual process improvements will be necessary to hit the 90 percent target.

- Implementing the QC plan at Cuberg under the scope of this project significantly increased cell yield from 50 percent in June 2019 to 74 percent overall yield and >90 percent electrochemical yield. Cuberg is currently on track to continue improving yield despite the supply chain challenges of the last two years; root cause analysis behind several key issues, including sealing defects, moisture content and overall dry cell quality, has been performed. Figure 5 shows the electrochemical performance spread of 455 Cuberg cells, with most falling well within the lower and upper limits established for acceptable tolerances.

Figure 5: Cuberg's Production Process for Lithium Metal Batteries



Lessons learned during product development and pilot-scale production. Cuberg readjusted its anticipated production throughput due to COVID's unanticipated effect on customer demand. Cuberg reached its performance metrics (measured by capacity, not by actual throughput) by managing the production line at a lower-than-anticipated throughput and then scaling up quickly once the effects of COVID died down and customer demand

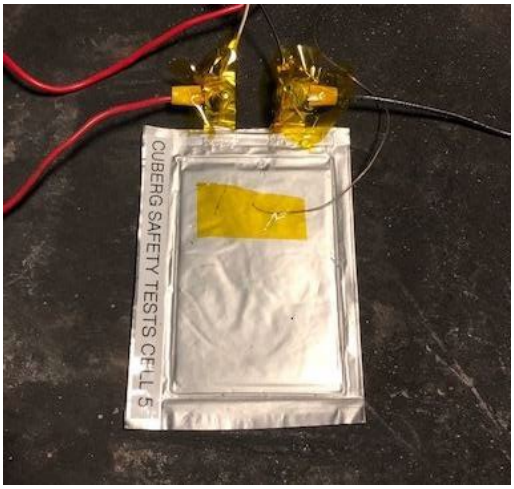
increased. This required rapidly scaling and hiring while managing supply chain delays, capitalizing on Cuberg's ability to be flexible and inventive.

Safety Certification and Shipping Volumes

Performance Metric #4: Safety certification. Cuberg has obtained the safety certification required to ship rechargeable batteries (UN/DOT 38.3) and is currently capable of shipping its commercial cell product by air, which will improve delivery times to customers, especially those located abroad. In addition, Cuberg has obtained a prototyping exemption for shipping new R&D prototypes to key customers, in order for them to validate and provide feedback on the performance. This is a key component as Cuberg continues to develop new and improved iterations of the product to meet customer needs.

- To pursue safety certification, Cuberg cells were put through a rigorous set of safety testing protocols meant to stress the system and demonstrate the safety of Cuberg's unique cell chemistry. The key goal was to develop a better understanding of the Cuberg cell's response to extreme conditions and catastrophic failure. Most often, this failure results in thermal runaway where a feedback loop of exothermic reactions leads to the rapid release of heat energy and hot metal ejecta. The key tests to probe this include known methods of initiating thermal runaway, including overheat, puncture, crush, and external short circuit. The key outcomes of these tests are summarized below.
- External short circuit is the most representative of a potential mode during shipping or handling, as it mimics accidental shorting of the thermals on a metal object. Two key tests were performed, including a fully charged cell connected to a resistor at room temperature. While the local cell temperature reached 67°C (152.6°F), the cell appearance remained unchanged and no evidence of swelling, smoke or fire was observed. Figure 6 shows the cell after testing.

Figure 6: Fully Charged Cell After External Short Circuit Test at Room Temperature



Source: Photo taken from Cuberg's lab in Emeryville, CA.

A 30-percent charged cell stored at 55°C (131°F) was shorted by contact with a metallic conductor for 1 hour. Again, despite reaching a cell temperature of 115°C (239°F) on average, the Cuberg cells passed the test without any notable events.

- Crush testing is similar to the mishandling and destruction of a cell that may occur in a vehicle crash. This is performed at a contract test facility by applying 10kN of stack pressure on a fully charged cell at room temperature. Again, the physical appearance of the test remained unchanged, and no rupture, leakage of electrolyte, or fire was noted.
- Overcharge testing simulates fully charging a cell with a faulty or tampered charger. This failure mode arises if the protection circuitry built into the back fails. Again, this test was done at a contract testing facility where a Cuberg cell was charged for 8 hours at 1.5A. For a baseline, a 100-percent charge at this current takes only about 2 hours.
- Modest outgassing resulting in ballooning of the pouch cell, as shown in Figure 7, was noted after the test, likely due to side reactions. Again, no notable events such as rupture, leakage, or fire were observed.

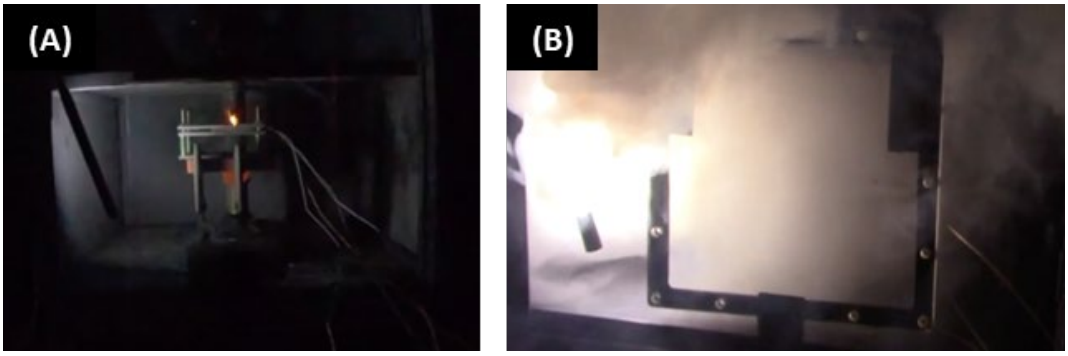
Figure 7: Cuberg Cell Following 8-hour Overcharge at 1.5A

Source: Photo taken from Cuberg's lab in Emeryville, CA

- Puncture testing, also known as a nail penetration test, is a standard in abuse testing of lithium-based batteries. This particular method simulates an internal short across the layers of the cell. The initial test was conducted at a third-party facility, where a nail was used to puncture the layers of a fully charged cell. No adverse effects were observed. Cuberg then developed a more aggressive in-house drill puncture method to ensure that as many layers within the stack are shorted in the process.
- In-house testing at Cuberg also required developing a safe testing environment and chamber in the event of thermal runaway of a cell during testing of cells at the beginning, middle and end of life. Key findings include the following.
    - Cuberg cells do not exhibit any adverse effects if tested at the beginning of life.
    - At the middle and end of life, puncture testing eventually can progress to thermal runaway.

- When compared with a lithium-ion cell tested with Cuberg's in-house method, the Cuberg cell failure is much more contained and does not present with large amounts of smoke, as shown in Figure 8.

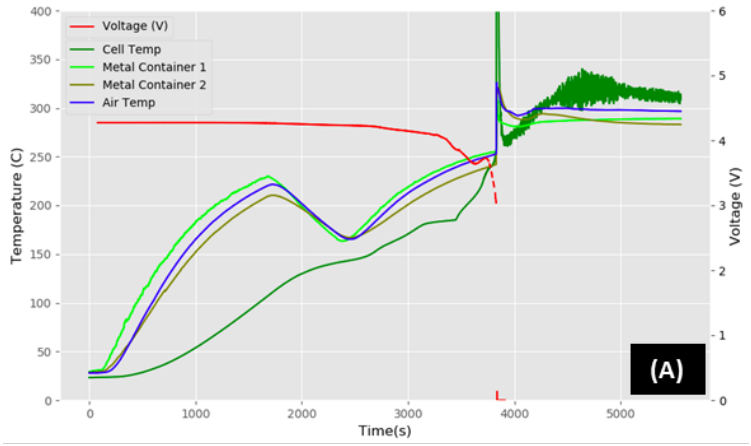
Figure 8: Cuberg Cell Testing

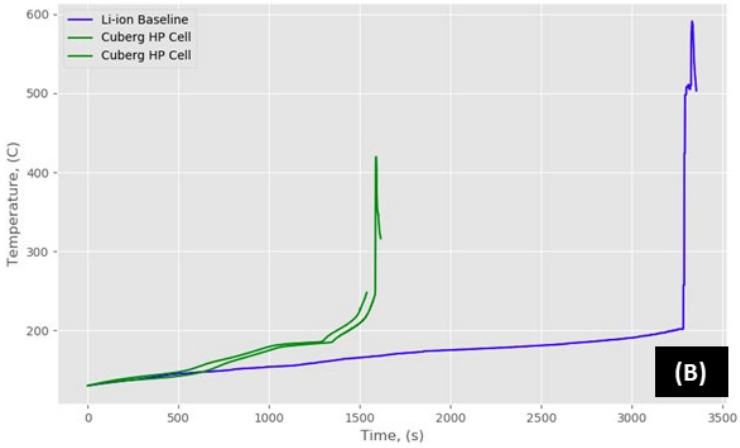


(A) Fully charged 5Ah Cuberg cell at the time of puncture with a spinning 1/32" drill bit.
(B) Fully charged 5Ah Li-ion cell at the time of puncture with a spinning 1/32" drill bit.

- Overheat testing is a common test to determine the thermal runaway onset temperature and the severity of runaway. Cuberg's in-house testing is conducted on fully charged and fixtured cells inside a metal container; they are heated at a rate of 4°C (39.2°F) per minute and then held at 130°C (266°F) for 10 minutes based on the UL1642 safety testing standard. Throughout the test, the external temperature of the cells, the temperature of the metal container, and the voltage of the system are monitored.
    - Cuberg's cells are relatively thermally stable. During the heating profile, there are minimal changes in the voltage until the cell is heated to above 180°C 356°F — at these higher temperatures, the lithium metal in the cell melts, resulting in a short and a corresponding drop in voltage. Thermal runaway in Cuberg's cell typically occurs at a higher temperature than in Li-ion cells. An example of the results from the overheat test and the relative thermal profile compared with a Li-ion cell are illustrated in Figure 9.

Figure 9: Results from the Overheat Test and Thermal Profile





(A) Fully charged 5Ah Cuberg cell undergoing overheat test. (B) Thermal stability of Cuberg's cell compared to a standard Li-ion cell.

Source: Data taken from Cuberg's internal cell data processing software.

Performance Metric #5: Shipping volumes. An efficient packaging/shipping line was established that can fulfill orders and ship out as many cells as necessary to supply customers. Figure 10 is an example of how Cuberg cells are packaged for safe shipping.

- Given the reactivity of lithium metal cells upon exposure to air and moisture, proper packaging of cells is key for safe shipping and handling.
- All Cuberg cells are first wrapped so that the battery terminals are covered to prevent accidental shorting during transportation. Terminals are taped.
- Cells are stacked in custom-made cell trays. Cell stacks are taped together to prevent slipping from the cell shipper container.
- Each stack is then wrapped in anti-static bubble wrap and taped to close. This ensures that the cell stack is electrically isolated and protected from mechanical jostling during shipping.

Figure 10: Packaged Cells

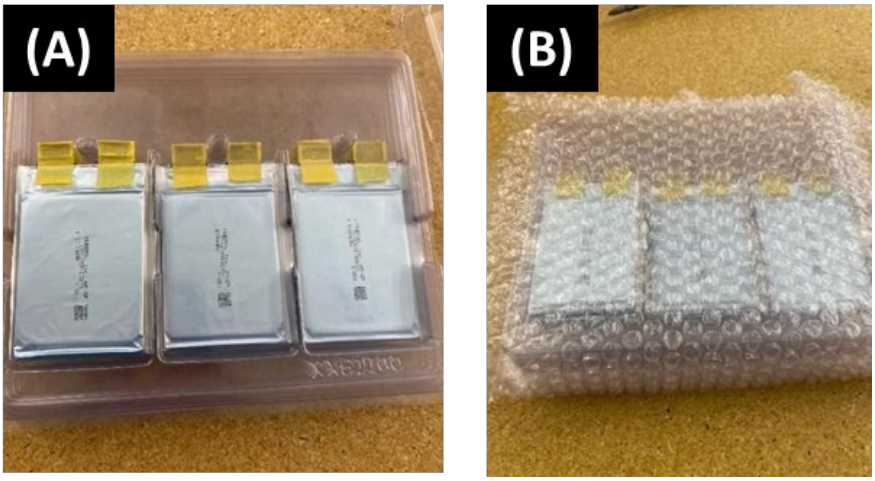


Figure 10: (A) Row of 3 cells in custom container prior to stacking. (B) Stacked cells wrapped with anti-static bubble wrap

Lessons learned during safety certification and shipping. Cuberg learned quite a bit while setting up its packaging and shipping lines, as well as during the process of completing the associated safety certifications. Because Cuberg had not previously been set up to ship dangerous goods and battery cells, the process to initially navigate the associated certifications and regulations was slow at first but, after several shipments, it was easily integrated into Cuberg's processes. The process certifying the safety of the battery cells in accordance with UN 38.3 protocols confirmed that Cuberg's cells are more thermally stable than comparable lithium-ion cells but still do enter thermal runaway. However, the results of the safety tests provided information that could be used for continued development efforts on the electrolyte and cathode components of the cell.

Supply Chain

Lessons learned from supply chain activities. During the project, logistical issues related to the pandemic and increased costs resulting from the trade restrictions with China created hurdles. There were numerous times when battery equipment or inputs to the battery cells were delayed significantly. Because of these delays, the project progress was delayed as a whole. Cuberg did not have a wide and balanced set of trusted suppliers during this project and, instead, was relying on one or two suppliers for each component rather than developing back-ups in case of delay.

As such, Cuberg has incorporated the identification of second- and third-choice suppliers into its business strategy. Moreover, because of these long delays, Cuberg also learned to order back-up parts for long-lead-time items, in case of an issue. Without these critical spares and inventory on hand, combined with the global supply chain shortages and issues over the past several years, the project was forced to move a bit more slowly than anticipated.

Key activities to increase awareness of the Cuberg Product

This section describes Cuberg's key business development activities, the key outcomes of its strategic partnerships, and its key marketing and press activities.

Cuberg has built strong relationships with customers in its beachhead market, resulting from the ability to supply prototypes for them to perform internal testing and validation. In 2021 alone, Cuberg has sold more than 2,500 battery cells and delivered more than 1,100 cells to 20+ customers.

The cumulative successes enabled by this grant led to the acquisition of Cuberg in 2021 by Northvolt, a global supplier of sustainable, high-quality battery cells and systems, headquartered in Stockholm, Sweden. Northvolt is developing the world's greenest battery cell and establishing one of Europe's largest battery factories (https://northvolt.com/). The ability to successfully manufacture high performance and high-quality cells for a fraction of the cost compared to other emerging technologies was instrumental in this merger. As Northvolt's Advanced Technology Center operating in the Bay Area, Cuberg will significantly grow its operations over the next four years — and has already grown the team to more than 100 — to continue developing next-generation battery cells for the electromobility market.

The merger with Northvolt has solidified Cuberg's position and it is now negotiating long-term agreements with a few, handpicked customers, to supply large volumes of cells in the next two to four years.

- **Overcoming Customer Resistance:** Cuberg has a keen awareness of the frequent position of customers to "go with what you know" rather than adopt new technologies. To ensure that its products overcome this barrier, Cuberg regularly engages with clients, remotely and in-person, and sends sample products to key clients during the development process. These samples include pack-level "reference" designs (rather than single battery cells), which can provide a true-to-form example of what clients will use in the field. Through ongoing and close contact with potential customers, Cuberg strove to overcome key hurdles to commercialization, and existing relationships can foster optimized ongoing product development. Cuberg works with its customers as partners in a shared mission of successful energy storage.

As a result of this approach and significant advances in the Cuberg battery chemistry, existing partners are interested in testing new cells and the company is currently on track to deliver almost 1,500 cells to a variety of partners and customers by the end of 2022.

- **Customer engagement pipeline.** This program and the ability to manufacture and supply larger amounts of cells have led to several key milestones in developing the customer pipeline for 2022. Following are a few notable examples:
    - Continued engagement with a prominent electric aerospace startup company to supply modules in addition to cells.
    - A partnership with a French multinational aircraft and defense corporation to pursue a joint proposal to deliver hardware, including Cuberg batteries.
    - An evaluation project with an electric aerospace startup company for a key NASA EPFD program, with a goal of delivering hardware in the first quarter of 2023.
    - On-going conversations for delivery of cells and modules for several eVTOL and eCTOL projects, as well as on-going discussions with other companies exploring electric aircraft programs.
    - Because of their high energy density, Cuberg cells have been generating significant interest in the hypercar sector. Cuberg is in conversation with key companies for several projects in this area.
- **Marketing and press.** Over the past two years, Cuberg has attracted attention in the media and earned high profile visits for its innovative technology. Key engagements include:
    - A June 2021 CNBC video feature on Cuberg's team and technology. As part of the feature, a CNBC team interviewed the Cuberg team and toured the lab facility. The video has garnered more than 500,000 views on YouTube.

- Key features on evtol.com and arstechnica.com, two industry-specific websites, about Cuberg's accomplishments reaching a longer cycle-life than lithium-ion cells. These publications also featured interviews with CEO Richard Wang.
- A 2022 visit from the European Commission Vice-President for Inter-institutional Relations and Foresight, formerly the European Commissioner for Energy. The visit provided Cuberg the opportunity to showcase its progress and promise to international political power players.

CHAPTER 4: Conclusion

During this project, Cuberg was able to fully validate the technology's value proposition, as demonstrated by the strong customer interest and Cuberg's acquisition by Northvolt in March 2021. The ability to assemble prototypes and demonstrate cell performance in 5 Ah commercial cells, which is one key result of this project, was instrumental in the acquisition. From ongoing discussions with the customers, Cuberg learned valuable information regarding features that are preferred, features that are valued less, and features that need improvement to increase market adoption.

- Features the customers valued the most:
    - Energy density – Cuberg's cell, delivering more than 370 Wh/kg, is 80 percent more energy dense compared to the best Li-ion battery technology. High energy density enables electric vehicles with increased driving/flight range.
    - Stability at elevated temperatures – Cuberg's cell operates best around 45°C (113°F), whereas Li-ion cells decay much faster at elevated temperatures. Stability at elevated temperatures removes the need for active cooling in battery packs and modules, reducing the cost and the weight of the pack.
    - Power – Cuberg's cell delivers enough power (> 2,000 W/kg) to enable fast acceleration and vertical takeoff and landing for electric planes.
    - Module safety – Cuberg's cells, with their non-flammable electrolyte, have a 40 percent higher thermal limit than Li-ion cells (thermal runaway onset at 180°C [356°F], compared to 130 °C [266°F] for Li-ion cells), reducing the risk of thermal runaway. However, customers value pack and module safety above cell safety. Once integrated into a product, the pack or module needs the capability of containing an event and preventing any safety-related issue that could affect vehicle passengers.
    - Aircraft production quality standards – Customers in the electric aviation sector have strict production standards that Cuberg will need to adopt once the cells are implemented in aircrafts.
- Features the customers valued the least:
    - Cell safety – Customers are more sensitive to pack and module safety rather than individual cell safety.
    - Today's cost – With no equivalent product on the market, customers are willing to pay a premium for Cuberg's high performance cells, especially in the electric aviation sector.

- Features that need improvement/advancement to increase market adoption:
    - Module implementation – Cuberg currently operates as a battery manufacturer. To reach wide market adoption, the company must meet the demands of customers who are requesting full battery modules that can integrate as a direct replacement for existing battery packs. Under the upcoming BRIDGE grant, Cuberg will design an ultrasafe battery module and integrate it into the world's most efficient and energy-dense pack for use in electric mobility applications, thus paving the way to the longer-term EV implementation goal.
    - Individual cell capacity and format – Based on existing product performance and cell characteristics, Cuberg is proposing to explore alternative designs to enable module integration with: larger cell formats, up to 20 Ah compared to 5 Ah for the existing cells; opposing tab cell arrangements; and other relevant features. These activities will take place as a part of the BRIDGE agreement.
    - Cycle-life – Although the current cycle-life, around 400 cycles, is suitable for electric aviation customers, a longer cycle-life, close to 1,000 cycles, will be required for market-wide adoption in the EV sector. Cuberg is actively exploring new electrolyte formulations and lithium metal protection strategies to enable longer cycle-life.
    - Charge rate – Cuberg cells can recharge in 1 hour to 100 percent SoC (state of charge), which is acceptable for electric aviation customers. However, the EV market has an ultra-fast charge target of 15 minutes. Cuberg's R&D efforts on electrolyte formulations will also address fast charge requirements.
    - Long-term costs – To reach wide adoption in the EV market, Cuberg's technology will need to meet stringent cost requirements, competitive with Li-ion cells (< $150/kWh). Leveraging the Northvolt partnership, Cuberg will be able to take advantage of economies of scale, making costs competitive.

In addition to technical innovations, many valuable lessons around soft innovations and process efficiencies were learned during this project. Expected time and cost savings for future installations is tremendous and there are many benefits in the design of the new 36,000-square-foot facility in San Leandro. A few examples include:

- Equipment selection, pilot line design, and preventative maintenance/safety program – During this project, Cuberg built partnerships with equipment suppliers, learned how to efficiently design and scale up a pilot line, and assembled robust, preventative maintenance and safety programs which will apply to all of the future pieces of equipment.
- Constraints and requirements around the space – The original space in Emeryville was retrofitted to house the existing pilot line. A larger pilot line will be designed and constructed in the new space, considering all of the information collected (electrical, HVAC, plumbing needs and requirements, constraints on construction materials such as flooring).

- A robust quality control plan and associated tools – During this project, Cuberg developed a robust QC plan that will be implemented in all future versions of the product. As a part of this plan, a manufacturing execution system was built to track and document the transformation of raw materials to assembled battery cells.
- Supply chain and logistics – As a part of this project, Cuberg transitioned from R&D activities only to prototyping and manufacturing. The latter require different considerations around logistics and the supply chain, such as determining long-lead-time items, streamlining shipping logistics, building a robust inventory, and diversifying the supply chain in case of a shortage or a sudden increase in quantities needed.

Listed are a few lessons learned that could be valuable to set up a similar project:

- Diversify the supply chain – Logistical issues related to the pandemic and increased costs resulting from the tariff war with China were hurdles on this project. A more balanced set of trusted suppliers would have alleviated some of the negative impact.
- Consider extended lead times associated with larger scales – Perform a thorough analysis of the resources required (bill of materials, personnel, equipment) and allow sufficient time to install and commission.
- Set up a comprehensive safety program that addresses both internal safety protocols and external compliance items.
- Network and learn from experts and consultants so you can innovate without reinventing the wheel.
- Adopt an agile project management style that allows you to timely adapt to customers' evolving needs and keep the product relevant.

This project has been instrumental in helping advance lithium metal battery technology targeting the electric vehicle market and thereby advancing state policy and consumer interests. Designing, constructing, and commissioning a manufacturing line for Cuberg's small format cells provide the foundation on which Cuberg will continue developing and scaling a unique and critical technology that will transform the clean energy market. The project results have the following key implications:

- Helping to advance California's goal of increasing EV adoption to 30 percent in California, allowing the state to meet its target of five million EVs in that year and its updated goal that all new cars and light trucks sold in California be EVs by 2035. Though Cuberg's key customer focus is in the aviation industry, high-power low-weight batteries offer a compelling solution for heavy-duty trucking as well. By supporting the manufacture of small format cells with greater energy density than conventional lithium-ion technology, California is helping to develop cells that will increase EV adoption due to their superior potential for range and power.
- Advancing the safety of clean energy solutions for California ratepayers. Through the learnings of this project, Cuberg will continue advancing a technology that is safer than the conventional technology and without compromising performance criteria. At scale, Californians will have a safer option, without the same flammability concerns.

- Enabling the development of the electric aviation industry and high-performance EV market. Because the electric aviation industry and the high-performance EV market are dependent on higher power battery solutions than currently exist, the development of the Cuberg cell will open the doors to these sectors' development.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
eVTOL	electric vertical takeoff and landing
eCTOL	conventional takeoff and landing
EV	electric vehicle
Li-ion	lithium-ion
LRIP	low-rate initial production
NDSEG	National Defense Science and Engineering Graduate
NSF	National Science Foundation
QA	quality analysis
QC	quality control
TAC	technical advisory committee

Project Deliverables

Performance Metrics Table

Performance Metric	Baseline Performance	Target Performance	Evaluation Method	Significance of Metric	Outcome
Commissioning equipment for pilot-scale production (Task 3)	Low-volume R&D equipment set up and in use for producing prototype cells (1 four-bay glovebox, 512-channel formation cycler, R&D-scale vacuum sealer)	Set up all production-scale equipment in new production facility (gloveboxes and/or dry room, 3 formation cyclers, EIS analyzer, test chambers, electrolyte injection machine, production-scale vacuum sealer) and produce first batch of cells on pilot line	Successful production of cells on new pilot line by September 2020	Selecting, purchasing, receiving, installing, and, finally, commissioning all equipment required for the pilot-scale production line is a significant portion of this project and a necessary step to producing 3000 cells/month. Failure to commission the pilot-line equipment by September 2020 will result in production delays.	Accomplished this metric with some timeline delays due to COVID-19 complications.
Cell production rate (all tasks)	Currently producing 100 cells/month	Production of 3,000 cells/month	Counting the number of cells produced on a monthly basis	The number of cells produced on the pilot line is one of the main metrics to gauge success of this project. It is directly correlated to the number of cells that Cuberg can sell to customers and the pace at which the technology can get into the market. Failure to achieve a production rate of 3,000 cells/month will lead to lower revenues and a slower uptake of Cuberg's advanced battery technology.	While Cuberg accomplished the capacity to produce approximately 3,000 cells per month, it is producing below this number after calibrating with customer demand.
Production line yield (Task 5)	Current yield: 50%	Target yield: > 90%	Performing quality control checks on every cell coming off the production line, including	Yield is important to keep costs down and minimize the time required to produce the number of viable cells needed to meet customer demands.	Cuberg readjusted this performance metric over the course of the project due to the ambitious nature of the original yield

Performance Metric	Baseline Performance	Target Performance	Evaluation Method	Significance of Metric	Outcome
			visual inspection and electrochemical performance (e.g., impedance, nominal capacity, self-discharge) and counting the pass rate	Failure to achieve a yield of >90% will result in increased costs, cutting into Cuberg's margins. An iterative approach with gradual process improvements will be necessary to hit this target.	metric. Cuberg increased the yield from 50% at the beginning of the project to a greater than 80% yield after solving a number of complications involving moisture content and dry cell issues.
Safety certification (Task 6)	Currently certified under prototype special permit	Receive UN 38.3 and DOT 49 C.F.R. certifications	Independent testing of Cuberg pouch cells, as specified in UN 38.3 and DOT 49 C.F.R. certifications (e.g., overcharge, heating, puncture tests)	These certifications are required to ship commercial (post-prototype) cells by air, which will improve delivery times to customers in Europe and Asia. Failing to meet this metric will result in longer shipping times, fulfillment delays, and increased contact with customers regarding delivery updates.	This metric was successfully accomplished, allowing Cuberg to ship cells and prototypes to customers.
Shipping volumes (Task 7)	Currently capable of shipping 100 cells/month	Ship 3000 cells/month	Monthly tracking of cells shipped	Shipping is necessary for providing cells to customers and end-users. Failure to meet the production metric will lead to fulfillment delays and necessitate prompt and compressive review of internal processes and procedures.	While Cuberg has the capacity to ship 3,000 cells per month, it is shipping under this amount due to customer demand. Cuberg has shipped upwards of 2,400 cells to customers in a month.