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FINAL PROJECT REPORT

Hybrid Lithium-Metal Batteries for Low-Cost and Long-Range Electric Vehicles

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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.

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

In this project, Sepion Technologies, Inc. developed a breakthrough lithium-metal battery for battery electric vehicles that supports an improvement in range by more than 40 percent, an improvement in safety, and a reduction in cost. In its reimagined lithium battery, Sepion Technologies combines its platform of membrane-coated battery separators with a novel liquid electrolyte in a battery prototype, which can be manufactured easily using conventional lithium-ion battery manufacturing equipment.

Keywords: next-gen Li-ion battery design, Li-metal battery improvement, battery separator coatings, AI-improved liquid electrolyte, high-energy-density lithium battery design, high-throughput lithium battery screening

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Executive Summary

In this Electric Program Investment Charge (EPIC)-funded project, Sepion Technologies, Inc. (Sepion) successfully scaled the capacity of its lithium-metal (Li-metal) battery prototypes and leveraged cutting-edge developments in computational chemistry and artificial intelligence. This work will accelerate the rate of battery materials development to meet the needs of a rapidly growing and changing electric vehicle market. Sepion's batteries use an innovative, polymer membrane-coated battery separator, discovered initially by researchers at Lawrence Berkeley National Laboratory. This separator was developed over the past decade by Sepion with support from the California Energy Commission's California Sustainable Energy Entrepreneur Development Initiative and Realizing Accelerated Manufacturing and Production for Clean Energy Technologies funding programs. In this Bringing Rapid Innovation Development to Green Energy (BRIDGE) agreement, Sepion built upon this breakthrough battery separator technology by harnessing the power of artificial intelligence and high-throughput battery screening. Using these tools, the Sepion team rapidly discovered new electrolytes to enable high energy density, low cost, and safe Li-metal batteries designed specifically for electric vehicles (EVs). It is with much gratitude for the support of the CEC BRIDGE-funded program that the team at Sepion was able to continue to develop battery materials with a focus on battery electrolyte development and prototype battery performance.

Background

Li-metal batteries have long been known as one of the highest energy-density lithium battery designs, yet there are challenges associated with the chemical instability of lithium in these systems, with chemical degradation, and with scaling for manufacturing in the case of solid-state designs. Despite these challenges, a Li-metal battery can potentially deliver an improvement of more than 20 times in the battery system cycle life, which translates to an improvement in the lifetime of the battery pack and reduces the total cost of ownership. To accomplish this improvement, the Sepion team focused on a design for safety from the materials level, with the application of unique safety features in Sepion's battery prototype, including nonflammable and flame-retardant liquid electrolytes and metallized plastic current collectors to mitigate battery cell failures. Sepion's innovative membrane and electrolyte designs improve lithium transport in a Li-metal battery. The membrane and the electrolyte work together to uniformly move lithium in the battery during charging and discharging and this prevents lithium decomposition and subsequent battery failure. This combination of innovative membrane and electrolyte composition, coupled with high energy-density battery designs, enables the application of next-generation electrode technologies in lithium batteries using today's existing lithium-ion (Li-ion) battery manufacturing infrastructure for battery EVs.

Project Purpose and Approach

The objectives for this program included development of a battery cell suitable for use in EVs. These battery cells must deliver a 40-percent improvement in energy density, translating to a 40-percent improvement in vehicle range, while maximizing safety, battery longevity, and fast charge performance. Sepion's goals included cell-level safety testing, reaching a cycle life of 600 charge and discharge cycles, and fast charge demonstrations of at least 80-percent charge delivery in 30 minutes or less.

Sepion staff engaged in prototyping development activities with multiple cell manufacturing partners across North America (e.g., the Battery Innovation Center), evaluating Li-ion manufacturing strategies at each and testing the performance of Sepion materials in cells made by its partners. Sepion staff conducted site visits to partners and engaged in periodic feedback meetings to ensure that Li-ion fabrication practices could be easily adapted for Sepion's Li-metal battery cell design. Discussions around full cell safety testing and United Nations (UN) 38.3 certification (third-party certification for safe battery shipments) indicated that cell builds at a 2-ampere-hour scale would be required. To align with this priority, the Sepion team pivoted to design and purchase a semi-automated hybrid Li-metal and Li-ion battery pouch cell prototyping line. This line was installed in Sepion's new, 25,000-square-foot research and development facility based in Alameda, California. This line enables flexible production of prototype Li-ion, Li-metal, and anodeless batteries at cell sizes between 500 milliampere-hours to tens of ampere-hours.

In parallel, Sepion's artificial intelligence-improved liquid electrolyte was combined with the results of prototyping development activities to deliver 2-ampere-hour cells with energy densities exceeding program targets of 400 watt-hours per kilogram and 825 watt-hours per liter — a greater than 40-percent improvement over incumbent Li-ion battery energy density, which directly translates to improvements in available vehicle range.

Key Results

This project has enabled full prototype cell development for the innovative Sepion separator coatings with an optimized liquid electrolyte system and electrodes that deliver a full cell solution to automotive customers. This prototype unlocks safe, energy-dense batteries capable of powering EVs for 400 miles at a projected fossil-fuel vehicle price point. These improvements can directly relieve consumer range anxiety and increase equitable access to clean transportation options.

Improving the Sepion team's electrolyte formulation performance in a Li-metal battery was a key result from this project. This improvement was accomplished through an iterative feedback loop in which the Aionics team would use its artificial intelligence-driven machine learning tools to model performance for one million battery electrolytes and then work with the Sepion team to downselect to a small number of electrolytes that could be formulated in the lab. After formulating and testing the electrolytes, the Sepion team shared testing data with Aionics, which then modeled and downselected a new set of electrolyte composition recommendations.

This collaboration accelerated the development of a closed-loop, data-driven battery materials innovation program, which delivered rapid and reliable electrolyte performance improvements. This 15-month program delivered a 3-time increase in prototype Li-metal battery cycle life due to electrolyte improvements. The team developed and optimized a unique liquid electrolyte for stability in energy-dense Li-metal batteries, with nonflammable characteristics, validating the effectiveness of the Sepion collaboration with Aionics.

There were several lessons learned as the Sepion team worked to prototype cell designs focused on safety for Li-metal anodes and liquid electrolytes. One of the project goals included obtaining a European Council for Automotive Research and Development 4 safety rating and UN 38.3 certification to safely ship cells. These activities were delayed when the team learned that this testing was most relevant at a battery cell scale of 2 ampere-hours or larger. The Sepion team designed, purchased, and received a semi-automated prototype battery line (hybrid Li-metal and Li-ion cells) and moved from a research and development site in Emeryville, California to a 25,000-square-foot research and development facility in Alameda, California. While these major endeavors delayed certifications, UN 38.3 certification was received in April 2024 (see Appendix A).

During the facility move, Sepion continued testing of the prototype Li-metal and anodeless cell builds with Sepion's unique liquid electrolyte. This resulted in the development of a multi-ampere-hour Li-metal battery prototype with 400 watt-hours per kilogram energy density (33.3 percent more energy than a state-of-the-art Li-ion battery) at the cell level and in a commercially relevant format, suitable for automotive testing with customers. A significant 7.5-time gain in cycle life was realized from prototype cells demonstrating 60 cycles at the beginning of the program and greater than 450 cycles by the end of the program. EV manufacturers will often rate an EV battery for a minimum of 1,500-2,000 cycles with Li-ion batteries on the market today. Li-metal batteries, like those in development at Sepion, are not in vehicles today and would likely need further development to hit metrics similar to today's Li-ion batteries. Finally, the new electrolyte design, coupled with Sepion's membrane-coated separator, demonstrated fast charge capability, from 10 to 80 percent state-of-charge in 13 minutes, faster than 99 percent of EVs currently on the road. This potential for fast charge is more significant than an improvement in cycle life. This is because it translates to improved lifetime and charging experience of the battery pack, which translates to lower total cost of EV ownership.

Knowledge Transfer and Next Steps

This project focused on improving the performance of Li-metal battery prototypes via a high-throughput experimentation, supported by extensive physics-based simulations for electrolyte formulation. When this approach is combined with machine learning techniques, it enables a rapid development cycle that can be broadly applied to battery materials development projects. Battery requirements will continue to vary, depending on the specific application (for example, EV versus grid storage) and market requirements (for example, future recycling legislation and potential chemical bans). Sepion was able to significantly shorten the development timeline required to make large advances in its hybrid Li-metal battery performance by applying data-driven methods to battery materials optimization and using high-throughput testing in an application-relevant prototype. It is reasonable to assume that this same approach can be adapted to solve battery materials development challenges in a diverse range of battery chemistries for a diverse range of battery applications, such as developing improved batteries for energy storage systems. To transfer knowledge to the community, this approach was shared at the 2023 PlugVolt Conference in Plymouth, Michigan.

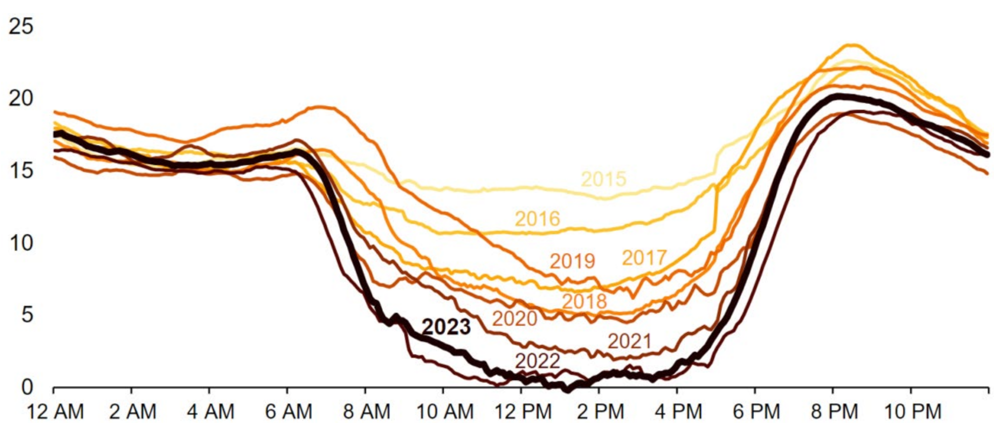
The Sepion team issued a press release in May 2024 upon receiving UN 38.3 certification, and data from this testing was presented at the 2024 PlugVolt Conference in San Jose, California.

CHAPTER 1: Introduction

The price, range, and performance of today's battery electric vehicles (EVs) are strongly influenced by battery cell chemistry. Most EVs on the road today use lithium-ion (Li-ion) battery technology to power the electric motor, a technology that has been in development since the discovery of the rechargeable Li-ion battery in the 1990s. This technology is nearing the theoretical limits in energy density (the amount of energy contained in a specific amount of space or weight), fast charge capability, and lifespan. Further gains in battery EV performance will be incremental until new battery chemistries, which overcome the inherent limitations of today's Li-ion batteries, are developed. However, known emerging battery chemistries, which offer superior range, cost, and performance, currently suffer from chemical stability challenges, which have restricted scale-up manufacturing and commercialization. Until these emerging battery chemistries are stabilized, consumer adoption of EVs capable of reducing greenhouse gas emissions and mitigating the effects of climate change will be limited to early adopters who are able and willing to bear the burden of high vehicle costs.

Electrified public transit and consumer-owned EVs can also be employed as grid-stabilizing agents connected by smart charging systems. This implementation of vehicle-to-grid controlled charging, both single- and bi-directional, can improve electricity grid efficiency by optimizing charging times to level out peak ramping and reduce the need for more conventional baseload generation. Additionally, "spent" EV battery packs are emerging as promising low-cost, second-life grid-storage assets. An estimated $12 billion is needed by 2025 to finance construction of more than 7 gigawatts (GW) of new natural gas plants to mitigate renewable intermittency; this is modeled for past years by the Duck Curve in Figure 1. This need could be mitigated by integrating 1.5 million EVs into California's grid, preventing unnecessary costs to ratepayers. A lowered financial burden from utility bills would ensure that all Californians can enjoy the same access to renewable and efficient energy and the commensurate health and safety benefits.

Figure 1: Duck Curve from California Independent System Operator — Typical Spring Day



Source: California Independent System Operator

Various competing technologies claim to be practical solutions to the energy density and cost limitations of current Li-ion cells, but most have drawbacks that impede their application in EVs. Solid-state lithium-metal (Li-metal) cells are the most widely discussed and suffer from two primary problems. First, demonstrated cycling data on solid-state Li-metal cells shows that they are highly intolerant of charging times that are shorter than 1 hour, putting them in direct opposition to consumer fast charging needs. Second, solid electrolyte manufacturing processes and the use of highly reactive thin Li-foil are incompatible with the existing Li-ion manufacturing infrastructure, radically increasing their cost and time to market. The use of high-silicon content anodes is another proposed solution. While pure silicon anodes are attractive for their high specific capacity and low cost, practically demonstrated anodes are still no more than 20 percent silicon, limiting the energy density benefits. Lithium-sulfur cells have attracted significant attention as well but suffer from high self-discharge rates that are fundamentally disqualifying.

Continued progress toward commercialization of disruptive hybrid Li-metal cells demands development of components, like Sepion's polymer-coated separator, that are compatible with existing Li-ion roll-to-roll manufacturing processes and with further development of electrolytes that are stable to Li metal anodes chemistry and can enable fast charging rates. Sepion's prototype batteries use an innovative polymer-membrane-coated battery separator, discovered initially by researchers at Lawrence Berkeley National Laboratory and developed over the past decade by Sepion with support from the California Energy Commission's (CEC's) California Sustainable Energy Entrepreneur Development Initiative (CalSEED) and Realizing Accelerated Manufacturing and Production for Clean Energy Technologies (RAMP) funding programs. This unique polymer membrane platform forms an additional barrier between the positive and the negative electrodes. Sepion's polymer membrane coating materials have been developed to stabilize the negative electrode and prevent degradation of either electrode from affecting the opposing electrode. Implementation of Sepion's proposed technology solution will result in the ratepayer benefits of relaxed range anxiety and reduced up-front cost of 100-percent battery-powered EVs while paving the way to greater electricity reliability, lower costs, and increased safety by accelerating a 100-percent decarbonized electricity grid.

In pursuit of high energy density, Li-metal cells are generally constructed with thin (30-micron [μm] to 100-μm) lithium foil anodes. This material serves as a reserve of excess lithium that can be tapped by the cell as lithium inventory is lost through unwanted reactivity with electrolyte components or electrical disconnection from the current collector. This increases cycle life at a small cost to specific energy density, which improves the viability for this cell format in EV applications. While attractive in principle, thin lithium-foil anodes are incredibly expensive, variable in quality, pose a safety hazard, and are fundamentally incompatible with existing Li-ion manufacturing infrastructure due to lithium's inherent reactivity with water and oxygen. Furthermore, this excess Li-metal is a large reservoir of chemical potential energy on top of the battery's usable energy that can be dissipated in the event of a cell fire. Given a Li-metal cell with an energy density of 400 watt-hours per kilogram (Wh/kg), containing a 40-μm thick lithium electrode, the energy dissipated in the event of a fire is more than twice that stored in its charge. While Li-metal cells are attractive for improving EV viability, with respect to increasing driving and decreasing cost, the hazards associated with these cell designs must be addressed in thorough designs for safety, beginning with the cell materials.

Together, these cost and safety challenges make the implementation of "anode-free" current collectors, where all lithium comes from the cathode, advantageous to practical high energy-density Li-metal cells. These current collectors serve as a surface onto which lithium is deposited during charging, and their composition directs the physics of this lithium deposition process. As is the case with all Li-ion and Li-metal cells, electrolyte design is essential to maximizing cycle life, fast-charging, and safety. The conceptual chemical design space of possible electrolyte components is vast, and machine learning (ML) approaches are an ideal tool for identifying and refining promising electrolyte candidates from the large datasets created by electrolyte screening. Collaboration with ML experts Aionics was an ideal partnership to efficiently optimize and iterate electrolyte design with data-driven approaches. Using this resource-efficient approach, Sepion anticipates increasing the cycle life of battery EV-relevant hybrid Li-metal cells containing Sepion's polymer-coated separators three-fold and increasing fast-charging capabilities two-fold to meet EV customer targets. The success of this BRIDGE (Bringing Rapid Innovation Development to Green Energy) project's multi-amp hour (Ah) cell cycling and safety tests will attract strategic joint-development agreements with automotive partners and follow-on equity investment needed to bring Sepion's breakthrough Li-metal batteries nearer to commercial reality and nearer to advancing California's energy and climate goals.

CHAPTER 2: Project Approach

The goals for this project included development of a battery cell suitable for use in EVs that delivers a 40-percent improvement in modeled energy density, which translates to a 40 percent improvement in vehicle range while maximizing safety, battery longevity, and fast charge performance. Sepion's objectives included cell-level safety testing (United Nations [UN] 38.3 and European Council for Automotive Research and Development [EUCAR] 4), reaching a cycle life of 600 charge and discharge cycles, and fast charge demonstrations of at least 80 percent charge delivery in 30 minutes or less. In pursuit of these objectives, Sepion leveraged its existing and revolutionary membrane coated separator platform to mitigate electrode cross-talk such as unwanted side-reactions from parasitic side-products, allowing the application of high-nickel NMC (nickel manganese cobalt oxide) cathode materials in battery cells with Li-metal anodes

Research and development within the project comprised three major activities:

1. Sepion scientists and engineers engaged in rapid optimization of liquid electrolytes meeting the demanding requirements of this application using a ML approach supported by computational chemistry simulations and high-throughput experimentation in the laboratory and in prototype battery cells.
2. Sepion scientists proposed a design-of-experiments approach to identify anodes and current collectors to support improvements in cost, energy density, safety, manufacturability, and performance relative to state-of-the-art Li-metal batteries.
3. Sepion scientists and engineers designed a prototype Li-metal battery cell to deliver on safety and performance requirements for EVs. This design uses only conventional Li-ion battery manufacturing processes to ensure that these innovations in Li-metal battery performance could be rapidly adopted without significant modifications to the United States' growing Li-ion battery manufacturing infrastructure.

Sepion staff engaged in prototyping development activities with multiple partners across North America, evaluating Li-ion manufacturing strategies at each and testing the performance of Sepion materials in cells made by these partners. Sepion staff conducted site visits to partners and engaged in periodic feedback meetings to ensure Li-ion fabrication practices could be easily adapted for Sepion's Li-metal battery cell design. The result of these activities was the design and purchase of a semi-automated hybrid Li-metal and Li-ion battery pouch cell prototyping line, installed in Sepion's new 25,000-square-foot Alameda, California-based research and development (R&D) facility. This line flexibly delivers Li-ion, Li-metal, and anodeless lithium batteries at cell sizes between 500 milliampere-hours (mAh) to tens of ampere-hours, which can be tested by Sepion in its more than 2,500-channel testing laboratory. Finally, Sepion's artificial intelligence (AI)-improved liquid electrolyte was combined with the results of the current collector study (Activity 2, above) and battery prototyping development activities to deliver 2-Ah cells with energy densities exceeding program targets of

400 Wh/kg and 825 watt-hours per liter (Wh/L). This represents a better than 40-percent improvement over incumbent Li-ion battery energy density, which directly translates to improvements in available vehicle range.

CHAPTER 3: Results

State-of-the art Li-ion batteries are currently the dominant technology for energy storage in transportation, but they are unable to achieve competitive unit economics (less than $100 per kilowatt-hour) or customer demands of range capability, which is needed to facilitate widespread adoption. The replacement of traditional graphite anodes with Li-metal anodes is one of the most promising technological improvements on traditional Li-ion batteries, due to lithium's 10-fold improvement in theoretical specific capacity and 100-millivolt decrease in reduction potential relative to lithiated graphite. Although there is substantial media attention regarding solid-state Li-metal batteries today, these products face challenges in reaching the market at notable scale for ten or more years due to incompatibilities with incumbent manufacturing infrastructure. Therefore, designing Li-metal batteries to maximize compatibility with existing and planned Li-ion gigafactories, which are focused on producing batteries containing liquid electrolytes, is essential to overcome barriers to market entry on a condensed timeline.

Data-driven Electrolyte Optimization

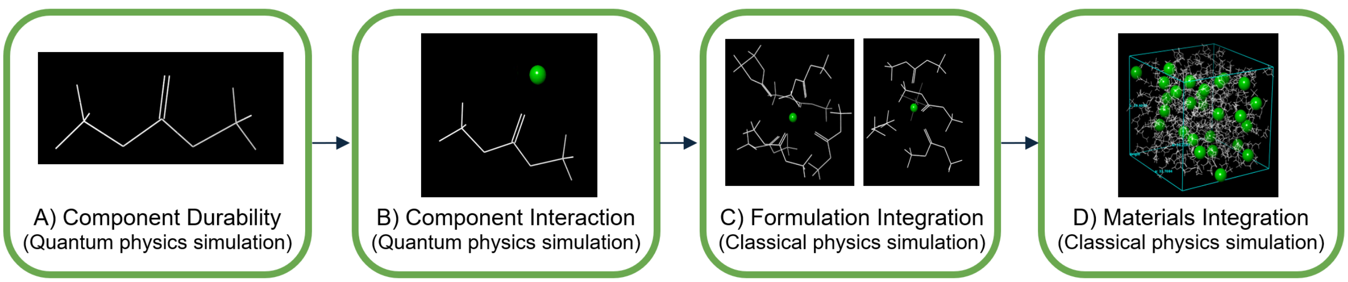
Sepion's strategy for addressing the challenges of Li-metal anode implementation is two-fold. Firstly, Sepion uses data-driven approaches to develop electrolytes, which generate stable and ionically conductive interphases at lithium. Secondly, the team engineers use membrane-coated separator materials, which provide a structurally stable backing for a solid electrolyte interphase, concentrate or exclude helpful or harmful electrolyte components at the lithium surface, and reduce the surface area of lithium electrodeposition by altering lithium coordination and transport at the electrode surface. This project supported the analysis of electrolyte decomposition mechanisms for key, high-performing electrolyte formulations relative to baseline carbonate type electrolytes. During the BRIDGE program, 60,000 battery electrolyte components were screened with the computational chemistry platform.

Electrolyte Design through Computational Chemistry Modeling

Electrolyte design is one of the fundamental challenges of enabling Li-metal batteries for EV applications. In 2021, the project team at Sepion began a closed-loop machine-learning enhanced electrolyte optimization program with the assistance of sub-awardee Aionics Inc. The design space for liquid battery electrolytes, which often contain 5 to 10 components, is nearly infinite, making electrolyte optimization especially resource intensive when approached with conventional high-throughput screening techniques. The professional ML modeling approach that the Aionics team brought to the project was used to predict over 100 million electrolyte formulation properties and downselect to the most optimum formulations for the Sepion team's high-throughput lab screening. Leveraging data-driven approaches to quickly identify electrolyte influence on battery performance substantially reduced the time needed to screen formulations in the lab and resulted in an over 100-percent improvement in cell performance over 10 months. The approach leveraged quantum physics, classical physics, and empirical experimental data in a closed-loop, ML-supported materials discovery program.

During the latter portion of the project, the Sepion team transitioned to using computational chemistry-backed ML modeling, coupled with proprietary algorithms, to continue predicting computational chemistry properties and electrolyte formulation properties. In order to screen the largest number of possible electrolyte candidates and electrolyte formulations, the team at Sepion began developing a high-throughput screening approach similar to computational drug discovery processes. The Sepion screening process followed the steps in Figure 2, where: A) an individual chemical component (white stick structure) is modeled with quantum physics to predict component durability, B) the component interaction between the chemical (white stick structure) from A and a single Li-ion (green sphere) is modeled, C) the formulation integration is studied by classical physics simulation of multiple chemical components (white stick structures) interacting with a single Li-ion, and D) a materials integration simulation is run to study multiple chemical components integrating with multiple Li-ions.

Figure 2: Electrolyte Modeling by Quantum Physics and Classical Physics Simulations



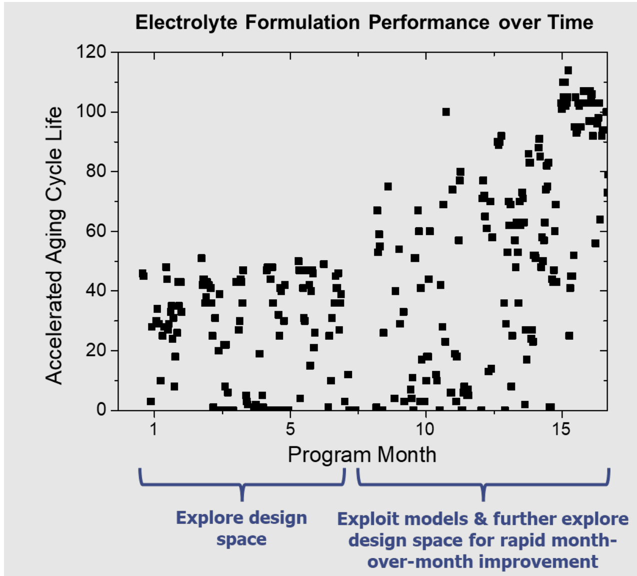
Source: Sepion Technologies, Inc.

These simulations were run on the Schrodinger computational chemistry software platform with the support of ML to analyze and identify promising chemical candidates with target chemical or physical properties. During the project, 60,000 battery electrolyte components were screened with the Schrodinger computational chemistry platform.

High-throughput Electrolyte Formulation with Machine Learning Approaches

During the 15-month electrolyte development period, the project team at Sepion designed and tested over 500 electrolytes in the lab, screening for properties related to energy density, manufacturability, safety, and cell performance. Figure 3 shows progress in cell cycle life improvement (the main evaluation metric) during this period, where the early months of the program focused on exploring the electrolyte composition design space and the later months achieved rapid month-to-month performance improvements in prototype cell cycle life. Prototype batteries built with these novel electrolyte formulations charged to their full capacity in 1 hour and subsequently discharged over 2 hours, in an accelerated manner, to rapidly generate cycle life results for each new formulation to close the loop on the ML models and suggest new compositions for testing.

Figure 3: Electrolyte Performance Improvement Program



Source: Sepion Technologies, Inc.

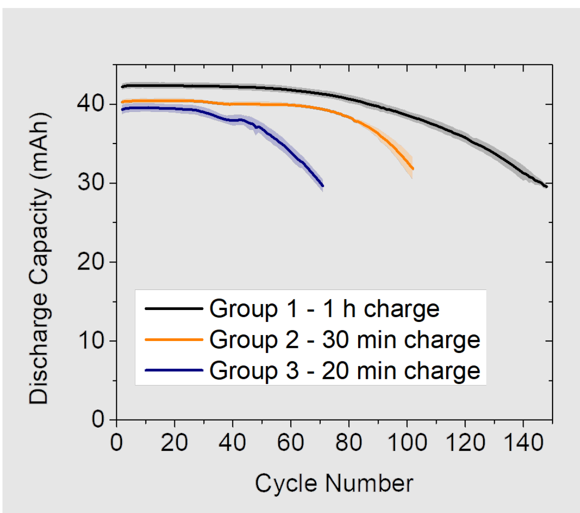
During the first 10 months of the program, the Aionics team had a crucial role in developing ML algorithms that could predict properties of electrolytes relevant to safety, manufacturability, and performance. Electrolyte performance across 10 key properties (density, conductivity, viscosity, separator wettability, freezing point, flash point, lithium reactivity, accelerated aging cell prototype, cycle life, and slower EV-relevant cell prototype cycle life) as a function of initial electrolyte composition was modeled using an ML approach. The models for electrolyte performance, however, are based on initial electrolyte composition, and deviation from prediction is often observed when new components, with novel reactivity mechanisms, are introduced to electrolyte formulations. The collaboration with Aionics modeled over 1,000,000 electrolyte formulations, where 900 formulations were downselected and prepared in the lab by the Sepion team and the key properties listed above were measured. Of these 900 formulations, 200 were found suitable for testing in prototype batteries under accelerated aging charge and discharge conditions. At the beginning of this electrolyte development cycle, electrolytes achieved 1 to 40 charge and discharge cycles in accelerated aging cycling studies. As the ML models improved their recommendations and formulation advancements were made, the development cycle ended with a three-fold performance improvement where the best electrolyte formulated over this time demonstrated approximately 120 charge and discharge cycles on an accelerated aging study. The accelerated aging and performance improvement that was demonstrated during this collaboration was further enabled through utilization of 2,500 battery test channels funded under a CEC RAMP project to feed a high-throughput data-driven electrolyte optimization program.

The project team at Sepion continued electrolyte development after completion of the Aionics collaboration phase of the project. The Sepion team developed proprietary ML modeling approaches based on computational chemistry inputs (outlined in the section titled Electrolyte Design through Computational Chemistry Modeling) to predict optimum electrolyte formulation compositions. Over the last 6 months of the program, an additional 300 electrolyte formulations were prepared, and key properties were measured. Of these new formulations, 100 had suitable properties for accelerated aging studies in prototype batteries and an additional 30 percent improvement in cycle life performance was achieved. Over the course of this development program, 1,200 electrolyte formulations were prepared and 300 of these formulations were built into prototype batteries for accelerated aging studies, where a three-fold improvement in accelerated aging cycle life performance was achieved.

Fast Charge Capabilities of AI-improved Electrolyte with Sepion's Proprietary Separator Technology

Sepion's AI-improved liquid electrolyte was built in prototype battery cells with commercially available cathodes, Li-metal anodes, and Sepion's proprietary membrane-coated separator technology to measure cell charging performance at fast rates. All cells in the study had a nominal capacity of 39 to 43 mAh. Once cells were assembled, they were cycled through a Sepion proprietary formation protocol to prepare the cells for fast charging. Figure 4 shows three groups of cells where: Group 1 cells were cycled on a 1-hour charge and a 1-hour discharge, Group 2 cells were cycled on a 30-minute charge and a 30-minute discharge, and Group 3 cells were cycled on a 20-minute charge and a 20-minute discharge. In comparison, control cells built without Sepion's AI-improved electrolyte could not cycle on the Group 3 protocol (20 minute charging and 20 minute discharging) and showed signs of short circuiting.

Figure 4: Fast Charge Assessment of Sepion's AI-improved Electrolyte



Single-Layer Pouch Cell Prototype Test Format	
Cell Format	Single layer pouch cell
Dimensions	12 cm^2
Capacity	43 mAh nominal
Temperature	30°C
Charge	3.0-4.3V, CC/CV
Discharge	4.3-3.0V, CC
Cathode	NMC-811 (3.6 mAh/cm^2)
Anode	20 um Lithium metal
Separator	Sepion
Electrolyte Loading	2 g/Ah
Stack Pressure	100 PSI
Volumetric Energy Density (Wh/L)	1,120* // 850**
Gravimetric Energy Density (Wh/kg)	390* // 350**

**Modeled for a multi-layer 100 Ah pouch cell*
***Realized in 2 Ah prototype*

Acronym definitions: cm^2=square centimeters, CC=constant current, CV=constant voltage, g=grams, Ah=ampere-hour, PSI=pounds per square inch.

Source: Sepion Technologies, Inc.

With further investigation into the 20-minute charging results, these prototype cells demonstrated the ability to fast charge from 10 percent to 80 percent in 13 minutes. When the performance is compared to available data for commercial systems, this charge rate is faster than that of 99 percent of vehicles currently on the road. This finding demonstrates that

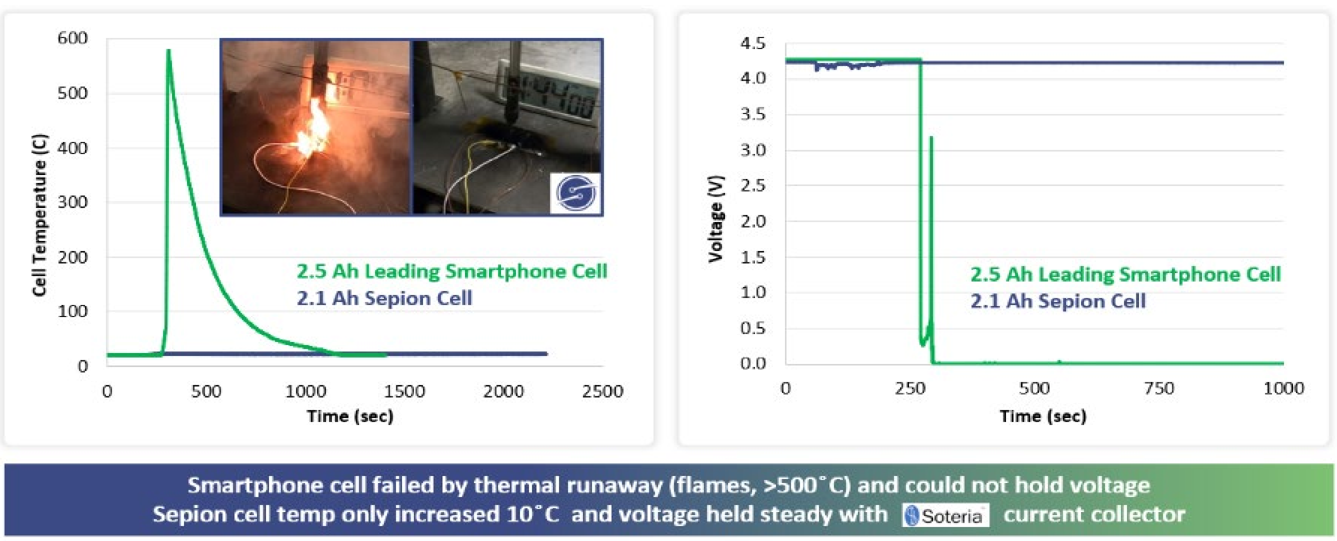
Sepion's approach to data-driven electrolyte optimization produced formulation and battery cell designs with commercial relevance through high-throughput optimization.

Anode-free Current Collector Testing

Design for Safety

Initial testing of the safety of Li-metal battery cells incorporating Sepion's coated battery separator product was evaluated in third-party destructive safety testing of a Sepion 2-Ah battery cell compared to a leading smartphone battery cell. Cells were tested under nail penetration test conditions, and this represents the first study in a planned program to develop a standard battery prototype with safety certification (such as UN 38.3, International Society of Automotive Engineers [SAE] J2464, or Underwriters Laboratories [UL] 2580). In these preliminary safety trials, Sepion's Li-metal battery cell, incorporating Sepion's membrane-coated battery separator, Sepion's liquid electrolyte, and a metallized plastic current collector designed by Soteria, was pierced with a nail while temperature and voltage were monitored. Sepion's Li-metal battery cell performed exceptionally well during this trial, due to the combination of safe and stable materials in the membrane-coated separator and electrolyte as well as the thermal fuse effect provided by the Soteria current collector, which further enables cells to safely mitigate thermal runaway even under the conditions of a forced hard short circuit event. In contrast, the leading smartphone Li-ion battery went into thermal runaway, reaching temperatures of 1,112 degrees Fahrenheit (°F) (600 degrees Celsius [°C]) and releasing all stored energy over approximately 10 minutes, as shown in Figure 5. Remarkably, the Sepion cell continued to hold a charge for the duration of the test period. This differentiated safety performance is made possible through the flame-retardant materials into the Sepion membrane-coated separator and electrolyte materials as well as a refined cell design, including the Soteria current collector. This design puts safety at the forefront and makes consumer peace of mind the central focus in battery product development

Figure 5: Nail Penetration Testing



Source: Sepion Technologies, Inc.

Sepion staff engaged in prototyping development activities with multiple partners across North America, evaluating Li-ion manufacturing strategies of each and testing the performance of Sepion materials in cells made by these partners. Sepion staff conducted site visits to partners and engaged in periodic feedback meetings to ensure that Li-ion fabrication practices could be easily adapted for Sepion's Li-metal battery cell design. Discussions around full cell safety testing and UN 38.3 certification (third-party certification for safe battery shipments) indicated the need for cell builds at a 2-Ah scale. To align with this priority, the Sepion team designed and purchased a semi-automated hybrid Li-metal and Li-ion battery pouch cell prototyping line, which was installed and qualified at Sepion's new, 25,000-square-foot R&D facility in Alameda, California in December 2023. This line enabled flexible production of prototype Li-metal cells at a 2-Ah scale. These cells were shipped to a third-party testing facility and UN 38.3.5 certification was approved in April 2024 (certification is attached in Appendix A). The consumer-focused battery engineering and design-for-manufacturing product development strategies described above are central tenets of Sepion's approach to accelerating battery innovation for EV adoption to ensure a sustainable future for all.

Design for Energy Density

Energy density refers to the amount of electrical energy stored in a battery. It is a very important metric that defines the quantity of energy that a battery can deliver in relation to the battery size or form factor. For example, as energy density of phone batteries has increased, phone batteries can deliver the same battery lifetimes from much smaller batteries with lower mass as technology improves. A typical Li-ion battery for an EV can power the vehicle for hundreds of miles before a recharge is necessary. Continuous improvement to energy density will result in a longer range for passenger vehicles and allow for larger payloads in heavy-trucking applications.

The energy density of a battery can be expressed in relation to the mass of the battery (specific energy density, Wh/kg) or the volume of the battery (volumetric energy density, Wh/L). Optimizing both of these energy density relationships indicates development of battery cells that weigh less and have smaller form factors. The Sepion team outlined a study to investigate optimization and improvement of energy density by reducing the mass and volume of the anode present in a prototype cell. Moving from a graphite anode, commonly used in Li-ion cells, to a Li-metal anode reduces the volume and the mass of the cells, allowing for increased energy density. Further reductions in mass and volume of the anode can be achieved by using a copper mesh or a copper foil that has no lithium present. Table 1 shows modeled energy densities for Sepion prototype cells that contain the anode configurations outlined above.

Table 1: Modeled Energy Density for Energy Dense Anode Configurations

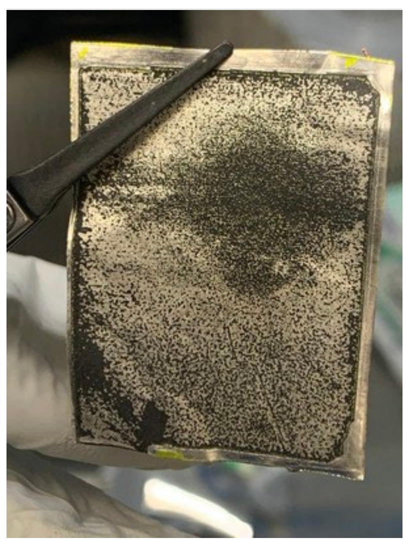
Metric	Graphite Anode (Current Li-ion Technology)	Thin Lithium Foil (40 µm Li on Copper Foil)	Copper Mesh (40 µm Li on Mesh)	Copper Foil (No Lithium)
Specific Energy Density (Wh/kg)	200–300	365	380	425

Metric	Graphite Anode (Current Li-ion Technology)	Thin Lithium Foil (40 µm Li on Copper Foil)	Copper Mesh (40 µm Li on Mesh)	Copper Foil (No Lithium)
Volumetric Energy Density (Wh/L)	600–750	885	1,096	1,299

Source: Sepion Technologies, Inc.

Prototype cells containing commercially available cathodes and separators were assembled with the best performing Li-metal electrolyte, as described in the section titled Fast Charge Capabilities of Artificial Intelligence (AI)-improved Electrolyte with Sepion's Proprietary Separator Technology, and one of the following: (1) a thin, 40-µm lithium anode on a 13-µm copper foil; (2) a 40-µm lithium surface on a 50-µm copper mesh; or (3) a 13-µm copper foil with no lithium (anodeless). All cells were tested for standard quality control and passed all metrics. After passing quality control, these cells were moved to a battery testing chamber where they proceeded through a basic formation protocol that slowly moved lithium from the cathode to the anode and back to establish the protective surfaces in the cell and check that the cell performed as designed. After this formation was complete, the cells were charged to move lithium to the anode to check that lithium was depositing on the copper foil and copper mesh. The lithium morphology on the copper foil was captured in a photo (Figure 6), and all configurations showed predominantly shiny, dense lithium surfaces.

Figure 6: Lithium Layer Observed on Anodes Made of Copper Mesh and Copper Foil



Source: Sepion Technologies, Inc.

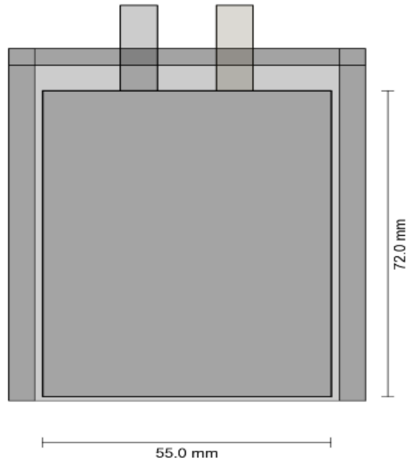
The scope of work for this project outlined a design of experiments (DoE), which is a comprehensive study with a high number of replicates to assess the effect of each experimental parameter (anode geometry, for example), called a factor in DoE nomenclature, on an important performance indicator (battery cycle life, for example), called a response in DoE nomenclature. The DoE approach is particularly powerful, as it can be used to probe the effect of combined factors on the response. Prior to initiating a DoE, it is generally best practice to run small-scope initial studies to verify that the correct ranges for factors have been selected to observe differentiated performance from the response. This initial study was meant to inform the DoE that was planned to investigate anode geometries (Li foil versus copper foil versus mesh), anode compositions (lithium alloys, smooth lithium, rough lithium), and lithium anode thicknesses with 7 to 10 replicates per configuration. This amounts to over 600 cell builds to facilitate comprehensive analysis in a full DoE.

The first scoping factor study was run with three anode geometry configurations, outlined above, and five replicate cells built for each configuration to check consistency of the builds and differentiation in cycling performance. Fifteen cells were built for this scoping study and all cells passed quality checks before being transferred to a battery cycler, where all 15 cells passed formation at slow rates. After formation, these cells proceeded into cycle life testing, where the cells were cycled at faster rates. After a few weeks of cycling, the capacity of these prototype cells began to fade and reach 80 percent. This is a safety cut-off per Sepion team testing procedures, and no further cycling was carried out. The cells with a 40-μm Li anode had a cycle life of 134 plus or minus (±) 10 cycles, the 40-μm Li on the copper mesh had a cycle life of 122 ± 10 cycles, and the bare copper foil had a cycle life of 118 ± 10 cycles. A scoping study for lithium alloys, run in parallel to the anode geometry scoping study, showed similar cycle life performance. Generally, a lack of cycle life differentiation was observed across these two scoping studies. This raises challenges for a DoE approach, as the analysis requires differentiation across the configurations of factors for the analysis to provide insights on which factors are of utmost importance for maximizing cycle life. This cycle life limit of 120 cycles to 150 cycles was observed across other prototype testing that the Sepion team was running at this time, and a quality investigation was initiated to determine the root cause of this observed limitation.

Cell Validation

In battery prototype validation trials, small-format cells were manufactured in 50-mAh, 55 by 72 millimeter active area pouch cell format using NMC-811 cathodes. Battery prototype performance in full cells was tested under a number of test conditions and evaluated using a several key performance indicators, including cycle life, area-specific resistance, and rate capability. Small-format cells were developed during the program period to reduce excess inactive materials and increase energy density, such that the modeled cell-level energy density of the multilayered 2-Ah analogue was greater than 850 Wh/L and greater than 350 Wh/kg (roughly 25 percent and 30 percent greater in volumetric and specific energy density, respectively, than the highest energy-density Li-ion batteries currently on the market). The cell design for battery separator evaluation was standardized as described in Figure 7. This testing vehicle was used for all new component screening, including new electrolyte materials, anode configurations outlined in the section titled Anode-free Current Collector Testing, and cathode materials.

Figure 7: Small-Format Pouch Cell Design



Gravimetric energy density: 365.40 Wh/kg.
Volumetric energy density (USABC v1): 885.34 Wh/L.

Source: Sepion Technologies, Inc.

Prototype battery cell performance with various electrolytes was evaluated using cycle life (number of cycles until 80 percent of initial discharge capacity was reached) as the key performance indicator, with other key performance indicators such as cumulative discharge energy, and tracked for each combination of materials. Prototype cell performance was validated under various cycling rate conditions, including C/3 charge and D/3 discharge, 1C charge and D/2 discharge, and C/5 charge and 1D discharge. The "C-rate" notation denotes the time it takes to charge or discharge a cell, and times are explicitly outlined in Table 2.

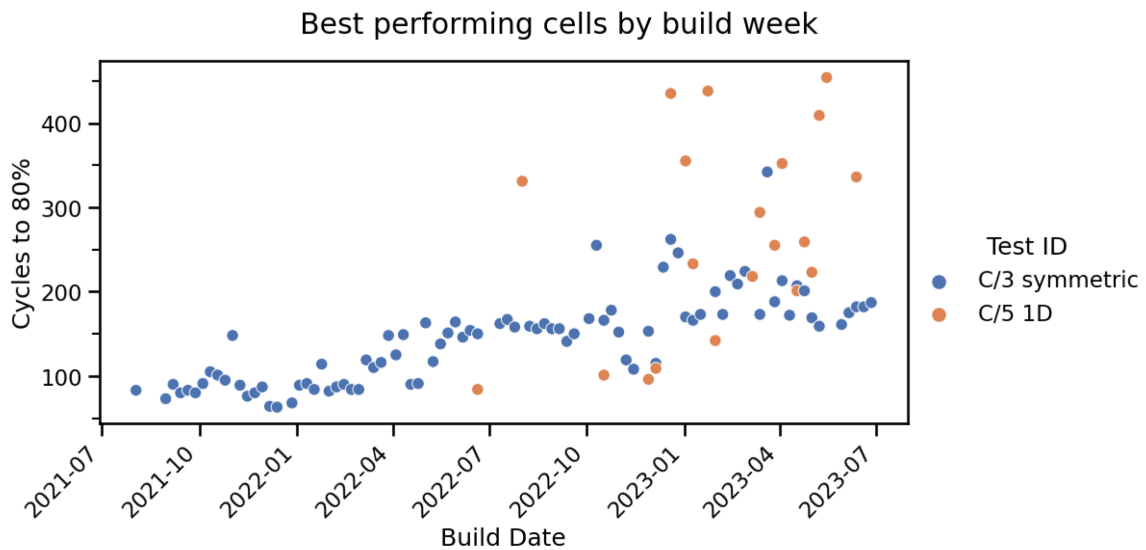
Table 2: Definitions of C-rate Notation for Charge and Discharge Cycles

C-rate Notation	Charge Time ("C" in hours)	Discharge Time ("D" in hours)	Total Time for One Cycle (hours)
C/3 D/3 (or C/3 symmetric)	3	3	6
1C D/2	1	2	3
C/5 1D	5	1	6

Source: Sepion Technologies, Inc.

In described in the section titled Anode-free Current Collector Testing the Sepion team observed a clustering of cycle life performance in the range of 120 cycles to 150 cycles, as part of preliminary studies for the anode DoE, and this was an unexpected result. A quality investigation was opened to determine the root cause of this clustering, as a similar performance was observed in other prototype cell validation studies. Figure 8 shows weekly tracking of cycle life (to 80-percent battery capacity) for the best performing prototype cells that were cycled on a C/3 symmetric cycling protocol or a C/5-1D cycling protocol. From the beginning of this project in July 2021 until October 2022, a ceiling of 150 cycles was hit for most tests, and changes to test parameters and anode materials could not overcome this ceiling.

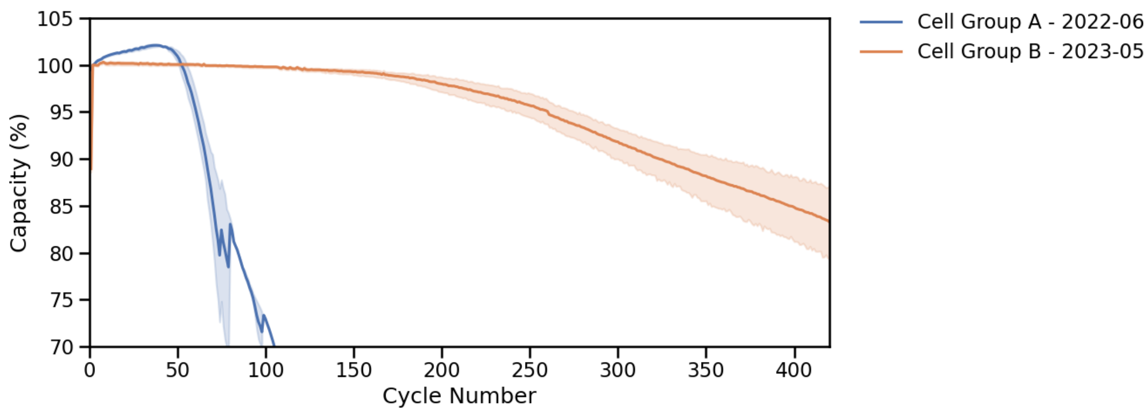
Figure 8: Weekly Tracking of Best Performing Cycle Life for Li-metal Prototype Cells



As the Sepion team continued to investigate the specific causes of these cell failures, a common trend emerged where resistance greatly increased after 100 cycles to 120 cycles. Follow-up experiments were run with multiple electrode cells to probe the source of the resistance and assign it to a cell component. These studies pointed to cathode materials failing and causing the resistance increases that were observed. To further confirm these cathode-centric failures, these cells were taken apart and scanning electron microscopy was used to image the individual cathode particles; it was observed that the cathode particles were cracking, leading to the resistance rise and early cell failures. New, higher quality cathodes were ordered and they arrived in October 2022, which allowed the Sepion team to overcome the previous 150-cycle ceiling.

The cathode quality investigation generated several lessons learned and recommendations, including sourcing alternative cathodes from multiple vendors to find higher quality cathode materials. Variations were observed across suppliers, which led the Sepion team to establish more rigorous incoming qualification procedures to ensure continued receipt of high-quality materials. By combining the ML-mediated electrolyte development, outlined in the section titled Data-driven Electrolyte Optimization, with cell designs and lessons learned, as described in the sections titled Anode-free Current Collector Testing and Cell Validation, respectively Sepion was able to take prototype batteries from fewer than 100 cycles (to 80-percent battery capacity) in June 2022 to more than 400 cycles in May 2023, as displayed in Figure 9.

Figure 9: Cycle Life Improvement (C/5-1D Cycling) from June 2022 to May 2023, with High-Quality Cathodes



The Sepion team developed a multi-Ah Li-metal battery prototype format with 400 Wh/kg energy density (33.3 percent more energy than a state-of-the-art Li-ion battery) in a commercially relevant format suitable for automotive application testing with customers. The team gratefully acknowledges the support of the CEC, through the BRIDGE program, in achieving a significant 7.5-fold gain in cycle life from prototype cells, from 60 cycles at the beginning of the program to greater than 450 cycles by the end of the program. Finally, the new electrolyte design, coupled with Sepion's membrane-coated separator, demonstrated fast charge capability from a 10-percent to an 80-percent state-of-charge in 13 minutes, faster than in 99 percent of vehicles currently on the road.

CHAPTER 4: Conclusion

New battery materials are critical to delivering mass-market EVs that surpass customers' expectations for the range, "refueling time," and price established by internal combustion engine vehicles. Once this trifecta is met, achieving California's climate goals in the transportation sector will switch from being a government push to a consumer pull. Already, Californians with the financial means to afford EVs are adopting them at a faster rate than the rest of the country. Investments in home-grown materials and manufacturing innovations will help the state move from early adopters to an early majority. The Sepion battery separator products advanced in this program have demonstrated performance advantages that hold the promise of meeting the trifecta of range, fast charging, and price. Through this project, Sepion demonstrated order-of-magnitude gains in prototype battery cycle life due to rapid, AI-facilitated electrolyte screening and cathode quality assessments from fewer than 50 to more than 400 cycles, and demonstration of 20-minute fast charge (0 percent to 75 percent state-of-charge) capabilities. Additionally, various anode configurations were validated, and "anode-free" current collectors were prototyped in high-capacity multi-layer pouch cells. In the process of making these gains, multiple challenges were overcome, and the lessons learned offer opportunities for the state to accelerate domestic battery innovation and production.

Building competitive battery components and cells at an automotive-relevant capacity requires a substantial investment in infrastructure. The support of the CEC has enabled Sepion to continue growing battery prototyping capabilities and has allowed Sepion to strategically choose when third-party contractors were needed. Bringing these capabilities in-house and eliminating the reliance on third-party contractors for prototyping activities have allowed scaling prototype battery builds to original equipment manufacturer-relevant sizes for sample evaluation. Many other California-based innovators face similar challenges in demonstrating the value propositions and scalability of their products. Continued support for similar programs and investment in a California public-private battery prototyping facility will help de-risk the path to market for new innovations.

Workforce development is a critical area where the state and the federal government can continue to accelerate development of battery manufacturing and supply chains. Individuals with experience, deep technical knowledge, and any passable level of leadership skills are employed predominantly by large companies that can afford steep salaries that continue to rise. One notable positive impact of the current enthusiasm for e-mobility and batteries is that there is a wealth of smart, mission-aligned but inexperienced professionals excited to break into the field. The state should encourage and financially incentivize the University of California system as well as vocational and community colleges to rapidly invest in and establish battery-centric training facilities. These programs should center on students developing greater expertise in fields like electrochemistry, analytical chemistry, materials science, quality control, design for manufacturing, roll-to-roll coating, battery data analytics, and soft skills to facilitate rapid professional growth and effective collaboration.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
±	plus or minus
Ah	ampere-hour
AI	artificial intelligence
BRIDGE	Bringing Rapid Innovation Development to Green Energy
°C	degrees Celsius
C	battery charge time
C-rate	the time it takes to charge or discharge a cell,
CalSEED	California Sustainable Energy Entrepreneur Development Initiative
CC	constant current
CEC	California Energy Commission
cm^2	square centimeters
CV	constant voltage
D	battery discharge time
DoE	design of experiments
EPIC	Electric Program Investment Charge
EUCAR	European Council for Automotive Research and Development
EV	electric vehicle
°F	degrees Fahrenheit
g	gram
GW	gigawatt
Li	lithium
Li-ion	lithium-ion
Li-metal	lithium-metal
mAh	milliampere-hour
ML	machine learning
NMC	lithium nickel manganese cobalt oxide
NMC 811	lithium nickel manganese cobalt oxide, with eight parts nickel to one part manganese to one part cobalt
PSI	pounds per square inch
R&D	research and development

Term	Definition
RAMP	Realizing Accelerated Manufacturing and Production for Clean Energy Technologies
SAE	International Society of Automotive Engineers
Sepion	Sepion Technologies, Inc.
UL	Underwriters Laboratories
µm	micron
UN	United Nations
UN 38.3	United Nations manual of tests and criteria, subsection 38.3 for International Air Transport Association (IATA) and United States Department of Transportation (DOT) requirements for shipping/ transporting lithium batteries
Wh/kg	watt-hours per kilogram
Wh/L	watt-hours per liter

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Project Deliverables

EPC-20-015 BRIDGE Scope of Work Tasks

Task 1: Program Reporting

- Draft Final Report
- Final Report

Task 2: Data-Driven Electrolyte Optimization

- Design for Energy Density Electrolyte Test Plan
- Infrastructure and Inventory Update
- Electrolyte Supply Chain and Cost Model Report

Task 3: "Anode-Free" Current Collector Testing and Validation

- Current Collector Testing Plan
- Critical Project Review Report #1
- Current Collector Supply Chain and Cost Model Report

Task 4: Cell Validation, Safety Testing, and Market Facilitation Activities

- Full Cell Design Report
- Safety Certification and De-Risking Plan
- Intellectual Property Management Plan
- Customer Testing Report
- Pilot Manufacturing Plan

Task 5: Evaluation of Project Benefits

- Kick-off Meeting Benefits Questionnaire
- Mid-term Benefits Questionnaire
- Final Benefits Questionnaire

Task 6: Technology/Knowledge Transfer Activities

- Technology Transfer Plan
- Summary of Technical Advisory Committee Comments
- Technology Transfer Summary Report
- Energize Innovation Update.

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

APPENDIX A: Sepion Technologies UN 38.3.5 Certification for 2Ah Li-metal Pouch Cells

January 2025 | CEC-500-2025-004

APPENDIX A:
Sepion Technologies UN 38.3.5 Certification for 2Ah Li-metal Pouch Cells

Project No. EA7248.01
Revision 1

Document Number: EA-0072

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CERT #6836.01 & 6836.02

Test Summary per UN 38.3.5

Mfg Company Name	Sepion Technologies
Mfg Company Address	950 Marina Village Pkwy Suite 102
Mfg Company City, State, Country, Postal Code	Alameda, CA, USA, 94501
Mfg Contact Name	Johnny Stefanski
Mfg Contact Email	Johnny@sepiontechnologies.com
Mfg Contact Phone Number	1-650-799-1167
Product Name(s)	2Ah Sepion Li-metal Pouch Cells
Product Part Number(s)	2.2 Ah Cell
Nominal Voltage (V)	3.77
Rated Capacity (mAh)	2200
Mass (g)	26
Rated Energy (Wh)	8.294
Product Type	Cell, Secondary (Lithium Ion), Small
Test Standard	UN38.3, UN Manual of Tests and Criteria, 7th Revised Edition, Effective January 1, 2020; Amendment 1, 2021
Overall Test Result	**PASS**

Product Photo

<u>Component Test Results</u>

Altitude (T.1)	PASS
Thermal (T.2)	PASS
Vibration (T.3)	PASS
Shock (T.4)	PASS
External Short Circuit (T.5)	PASS
Crush/Impact (T.6)	PASS
Forced Discharge (T.8)	PASS

**Note: Test T.7 (Overcharge) is applicable to secondary pack-level testing only.*

Release Approved By

Name: Glenn Wang, Program Manager
Date: 2024-04-05