CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Scaling Up Pilot Production of Nano porous Membranes for Battery Storage Technologies

June 2024 | CEC-500-2024-062

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ACKNOWLEDGEMENTS

We are thankful for the guidance and support from the following organizations and agencies: The Molecular Foundry, Lawrence Berkeley National Laboratory, US Department of Energy, The Cell Assembly Modeling and Prototyping (CAMP) facility at Argonne National Lab, and Washington Clean Energy Testbeds (WCET).

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

This project supported low-rate initial production and supply chain de-risking of advanced lithium battery separator products that enable longer range and lower cost lithium batteries. To achieve this, Sepion Technologies expanded their capabilities for polymer synthesis 10-fold, their roll-to-roll coating capabilities 200-fold, implemented new process quality control methods improving yield from <50 percent to 95 percent, and validated separator product performance in lithium batteries. The company is now sampling with key automotive original equipment manufacturers, battery manufacturers, and separator manufacturers to bring the product closer to market entry.

Keywords: polymer membrane coated battery separator, polymer membrane platform, battery stabilizing technology, high energy density lithium batteries, battery industry workforce

Please use the following citation for this report:

Golden, Jessica and Peter Frischmann. 2024. *Scaling Up Pilot Production of Nano porous Membranes for Battery Storage Technologies.* California Energy Commission. Publication Number: CEC-500-2024-062.

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Executive Summary

In this California Energy Commission Electric Program Investment Charge (EPIC)-funded project, Sepion Technologies successfully scaled its polymer membrane coated battery separator to low-rate initial production in Emeryville, CA, advancing the vision of growing California into America's domestic lithium battery manufacturing hub. Battery separators are a critical part of a battery – they are the primary mechanism for extending the life of a battery so that it can charge and discharge repeatedly. The separator ensures that only certain parts of the battery are allowed to move back and forth between the positive and negative ends while charging and discharging. Sepion's polymer membrane platform, proposed originally by scientists at Lawrence Berkeley National Laboratory and developed for commercial application by scientists and engineers at Sepion Technologies, enables the application of next-generation electrode technologies in lithium batteries utilizing today's Li-ion battery manufacturing infrastructure. This technology serves as a direct replacement for state-of-the art battery separators, allowing battery developers and automotive manufacturers to safely increase electric vehicle (EV) range by 40 percent and reduce the up-front cost of EV batteries by up to 15 percent ($/kWh), reducing two major hurdles to mass EV adoption – EV driving range and EV cost.

Background

The price, range, and performance of today's battery electric vehicles are dominated by the battery cell chemistry. Most electric vehicles on the road today use lithium-ion battery technology to power the electric motor, a technology which has been in development since the discovery of the rechargeable lithium-ion battery in the 1990's and which is nearing the theoretical limit of energy density – the amount of energy contained in a specific amount of space or weight – and performance factors like fast charge capability and lifespan for the technology. Further gains in battery electric vehicle performance will be incremental until new battery chemistries are developed which overcome the inherent limitations of today's lithium-ion batteries. However, these emerging battery chemistries which offer superior range, cost, and performance, currently suffer from stability challenges which have limited their use. Until such time that these emerging battery electrode chemistries are stabilized, adoption of electric vehicles capable of reducing greenhouse gas emissions and mitigating the effects of climate change will be limited to early adopters who bear the burden of high vehicle costs. Sepion Technologies' battery separator and chemistry can accelerate the mass adoption of electric vehicles and address the root cause of equitable access to electric vehicles by stabilizing these next generation battery chemistries and ensuring their performance, safety, and reliability meet the needs of all new car buyers.

To deliver these new battery technologies from the research stage to commercial readiness, Sepion Technologies leverages a unique polymer membrane platform, added to the battery cell in the form of a coating which is applied to the battery separator. This membrane is used to form an additional barrier between the positive and negative electrodes, specifically controlling reactions at the negative electrode which, when no barrier is present, typically result in early cell failure in high energy density (long range optimized) battery cell chemistries. These polymer membrane coating materials were developed to stabilize the negative electrode, prevent degradation from either electrode from affecting the opposing electrode, and thus to enable the application of emerging sustainable, low cost, and energy dense electrodes in electric vehicle applications.

During the execution period of the work funded by the California Energy Commission, Sepion Technologies demonstrated the ramp-up of these polymer membrane coated battery separators from the research laboratory stage to low-volume initial production using industry standard and low-cost roll-to-roll manufacturing practices at its facility in Emeryville, California. Further, Sepion built upon the knowledge developed in this program to open a new headquarter facility located in Alameda, California, powered by 100 percent renewable energy, and dedicated to pilot production of the enabling battery separator products to meet the diverse needs of the electric vehicle industry and new car buyers.

Project Purpose and Approach

The project aimed to demonstrate the ability to produce a unique, differentiated battery separator product which is capable of stabilizing next-generation battery chemistries. Before project initiation, Sepion Technologies demonstrated lab-scale successes in small format hand-built battery cells using research laboratory bench-coated samples produced one-at-a-time at the size of an 8.5 x 11 inch sheet of paper. With funding from the California Energy Commission's "Realizing Accelerated Manufacturing and Production for Clean Energy Technologies" solicitation, Sepion Technologies installed and optimized a roll-to-roll battery separator coating line to produce its coated battery separator product in a continuous roll, analogous to the larger rolls which are used in commercial scale battery manufacturing facilities, with the goal of demonstrating a production rate and process for its polymer membrane coated battery separator product which can be scaled to commercial production volumes at competitive cost (<$1.50 per square meter). Funding from this project also supported validation of Sepion's polymer membrane coated battery separator product and its ability to stabilize high energy density batteries compared to conventional battery separators which do not employ Sepion's polymer coating. This validation was performed both in small, manually manufactured battery cells as well as in medium format two amp-hour battery cells produced semi-automatically, similar in size and format to a mobile phone battery. Finally, this project supported testing to demonstrate the capability of the coating to improve battery performance and safety. The tests validated that the scaled-up polymer coated separator product improves the stability, longevity, and safety of high energy density lithium batteries using next-generation lithium metal anodes.

Key Results

Several key technical milestones were met during this project, setting the stage for long-term public benefits, including the validation of the ability of the Sepion coating to improve fast-charge rates, improve safety by eliminating the formation of dendrites, improve battery longevity, and improve battery energy density. During the course of this program, Sepion scaled up production of the polymer coating material by 100 times, to one kilogram batches, producing enough polymer material in each batch to supply one long-range battery-electric vehicle. Further, Sepion scaled its laboratory-scale battery separator from small-batch to continuous production.

The technical validation of the Sepion coating along with its demonstration of ramped-up production capabilities enabled $16 million in new private investment (November 2021) and facilitated sampling with a wide range of automotive customers and battery suppliers. New knowledge gained from this program justified investment in additional scale up infrastructure beyond the capacities supported by Realizing Accelerated Manufacturing and Production for Clean Energy Technologies (RAMP).

This project further supported workforce development activities including recruiting with a focus on diversity, equity, and inclusion; as well as professional development and training for 26 employees new to the battery industry.

Technical milestones toward low-rate initial production

With RAMP funds, the Sepion team demonstrated a 10-fold increase in polymer production scale, a 200-fold increase in roll-to-roll coating capacity, coating yield improved from <50 percent to 95 percent, the coating process was optimized to meet Bay Area Air Quality Management District requirements, and samples were delivered to eight potential customers for validation.

Benefits to ratepayers, public, and environment

Because 85 percent of lithium batteries are manufactured in Asia, there is a large talent gap that must be filled for the US to compete on a global stage in the new energy economy. In the course of this project, Sepion Technologies trained 26 employees in California, the majority of whom were hired from adjacent industries with no experience in batteries or battery materials and were provided significant training to strengthen the burgeoning battery industry workforce in California.

Knowledge Transfer and Next Steps

Results from the RAMP project were made available to the public through program reports. In addition, Peter Frischmann, CEO of Sepion Technologies, advised the California Energy Commission on battery safety initiatives and battery technology development. Pete spoke on panels assembled to discuss stationary energy storage system safety, addressing senior leadership from California Energy Commission, California Independent System Operator, and the California Public Utilities Commission. Jessica Golden, Director of R&D, Materials at Sepion spoke on public panels such as the EPIC Forum "Creating California's Advanced Lithium Battery Ecosystem." Sepion provided feedback regarding California's Lithium Valley and attended an in-person event on April 25, 2023, in Calipatria to boost awareness with the federal government on the national impact of the project.

A California supported cell prototyping facility with reduced rates for grantees and state entities would accelerate the path to market for battery materials startups in the state by helping demonstrate performance improvements at greater scale without forcing each company to become cell production experts. The scope of work supported by this RAMP project was expanded upon and will continue to move advanced separator products to market.

CHAPTER 1: Introduction

In the state of California, 50 percent of total greenhouse gas (GHG) emissions and 80 percent of air pollutants result from transportation. In 2020, in response to the global climate crisis and in pursuit of environmental justice, Governor Gavin Newsom announced executive order N 79 20, requiring that all new cars and passenger trucks (light duty passenger vehicles) sold in California be zero-emission vehicles (ZEV). This order was codified by the California Air Resources board, which set out a year-by-year plan to increase ZEV adoption rates in the state to 100 percent by 2035. This regulation requires automakers to deliver an increasing number of ZEV to Californian customers each year, starting in 2026. Meanwhile, additional credits and incentives provided by the California legislature make nascent ZEV technologies more accessible to new car buyers. Together, these policies will fuel a needed acceleration in ZEV adoption rates. However, the magnitude of the challenge to transition to 100 percent ZEV remains immense. For scale, as of 2021, only 2.7 percent of vehicles registered in California were ZEV (in total, 1.7 percent were battery electric vehicles (BEVs)).

In addition to state- and federally- driven policy and incentives designed to accelerate adoption rates, ZEV technology must improve. It is not enough for ZEVs to be mandated and subsidized; they must also be a preferred choice to ensure a high rate of consumer adoption. Technologists in battery materials development, manufacturing, and the automotive industry must design ZEVs with superior performance at cost parity relative to incumbent internal combustion engine vehicles.

There are three metrics for which BEVs must be carefully designed to incentivize mass adoption: range, lifetime, and up-front cost. At the battery cell level, these translate to energy density, cycle life, and unit cost (dollars per kilowatt-hour ($/kWh)). These metrics, however, are often at odds; while some battery technologies offer improved cycle life and cost, they may do so at significantly decreased energy density (low range). Meanwhile, high energy density (long range) battery technologies often suffer from decreased cycle life (lifetime). Most BEVs on the market utilize lithium-ion batteries for the main vehicle pack; and most of the observed trade-offs in BEV $/KWh occur as the cathode, the positive electrode within the battery cell, is modified for various market needs (high power, fast charge, long range, long lifetime).

The cathode is the single largest cost-driver in an EV battery, and its composition is the primary performance driver for both energy density and cycle life in a lithium-ion battery. Although cathode chemistries vary between automakers and even models/model year for a given automaker, there is a gradual and increasing market force within the BEV industry to transition to newer cathode materials with lower cobalt content and higher nickel content, to bring the cost of the battery down and meet up-front cost parity with comparable internal combustion engine vehicles. With the increasing cost of nickel, it is anticipated that new, cobalt-free and low or no-nickel content cathodes will also emerge, and as competition to deliver the trifecta of battery performance criteria increases, more new cathode chemistries will emerge and the challenge of increasing their stability will need to be addressed.

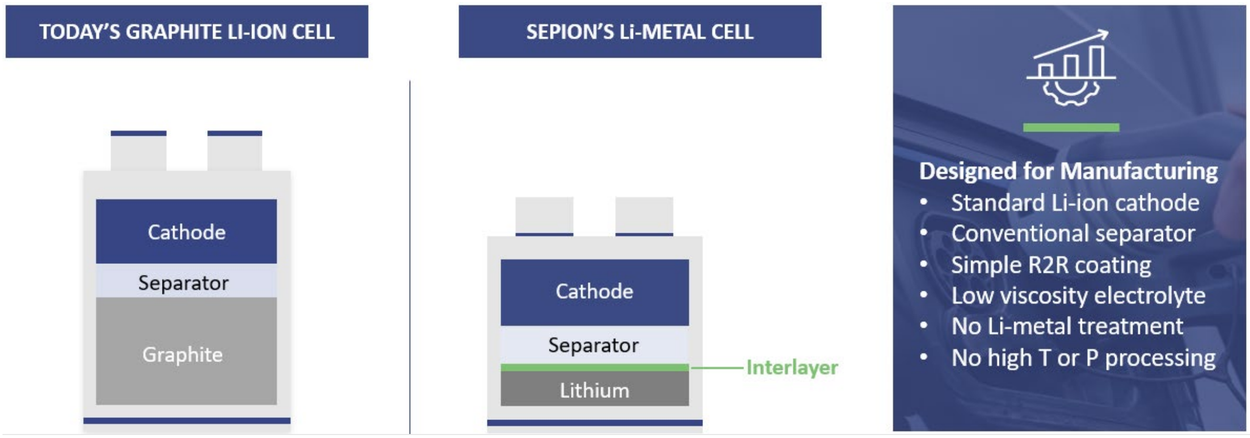
Whereas cathodes are a primary cost driver, anodes offer the lowest hanging fruit to increase vehicle range. Incumbent anode materials, graphite and hard carbon, are traditional anode chemistries with theoretical specific capacities around 350 amp-hours per kilogram (Ah/kg). Alternatively, promising anode alternatives such as silicon and lithium offer 10-fold improvements in specific capacity that practically translate into more than 40 percent rise in specific energy, a metric closely correlated to electric vehicle range.

In 2015, Sepion Technologies, Inc. was spun out of Lawrence Berkeley National Laboratory by researchers who had developed platform of materials to solve such problems in emerging battery chemistries. Specifically, the Sepion team identified a platform of polymer materials which form highly selective membranes that can be manufactured using low-cost R2R manufacturing processes. These selective membrane materials are characterized by nano-scale pores that are intrinsic to the polymer chemistry, and these pores provide a selective barrier to allow certain ions, like lithium, to cross the membrane while preventing larger ions and small particles from crossing from one side of the battery to the other. This platform of materials offers an incredible tool which can be used to mitigate the effect of the degradation of newer, less stable but high energy density and low-cost cathode materials from propagating further battery degradation by interacting directly with the anode. The application of Sepion's nanoporous polymer materials in lithium-ion batteries enables the utilization of high energy density and low-cost cathodes without the typical negative impact on cycle life.

During the project period, there was an unprecedented shift in the automotive industry, spurred in part by state and federal policy changes focused on reducing GHG emissions as well as the reality of a tenuous petroleum fuel supply, wherein automakers increased investment and focus on medium- and long-term battery innovation for BEVs. A key technology area emerged as the likely source of the next great step-change in battery performance and cost – lithium metal batteries. In lithium metal batteries, the anode, the negative electrode, which is comprised of graphite in a lithium-ion battery, is replaced with lithium metal. This potentially reduces the bill of materials and manufacturing cost of the battery cell, greatly increases the cell energy density, and simultaneously offers a pathway to improve a fourth key consumer-focused performance metric: fast charge.

In addition to emerging cathode chemistries, Sepion's polymer membrane interlayer offers several important value propositions to support the medium-term and long-term transition from lithium-ion to lithium metal batteries, most notably making lithium metal anodes more stable, longer lived, and safer than lithium metal batteries which employ conventional separators and liquid electrolytes. Early innovators in the lithium metal space posited that solid state electrolyte was the clearest path to commercialization of energy-dense lithium metal batteries, neglecting the multi-billion dollar implication of a complete overhaul of manufacturing practices and infrastructure which will be required for the industry to fully adopt solid state battery technology as an alternative to lithium-ion. Sepion's polymer membrane coated battery separator product design, however, makes lithium metal batteries feasible using conventional lithium-ion manufacturing practices. By virtue of its selectivity and its effects on lithium plating and stripping, Sepion's polymer membrane coated battery separator works in synergy with advanced liquid electrolytes to yield stable, long-lasting, and safe lithium metal batteries using conventional Li-ion manufacturing practices and equipment (Figure 1).

Figure 1: Sepion's Polymer Membrane Coated Battery



Sepion's polymer membrane coated battery separator works by creating a nanostructured "interlayer" at the anode surface, which works in synergy with advanced liquid electrolytes to yield stable, long-lasting, and safe high-energy density lithium metal batteries using conventional Li-ion manufacturing practices and equipment.

Source: Sepion Technologies

With the transition into lithium metal battery component development, the need to scale Sepion's production capabilities became even more important, as market pull for enabling technologies increased. Through this program, Sepion demonstrated scaled-up production of a low-cost polymeric membrane separator, a key component of Li-ion and emerging Li-metal batteries. Integration of Sepion's battery separator product in lithium metal batteries imparts enhanced lifetime, enhanced safety, and improved energy density, while simultaneously helping lower cell production costs and mitigating supply-chain risk by enabling low-cost, highly abundant cathode materials. Together, these improvements to lithium battery technology allow for broader deployment of low-cost renewable energy generation with the reliability and dispatchability of fossil fuels.

CHAPTER 2: Project Approach

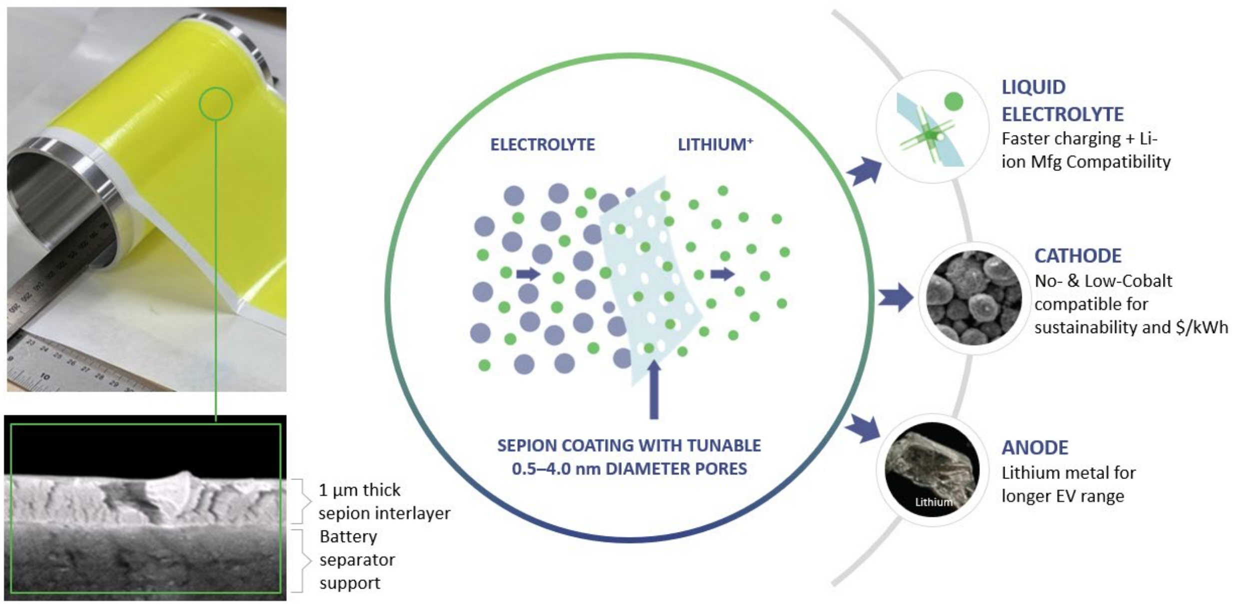
Lithium-ion batteries are, in their most basic form, based on a simple device architecture. Each part of the device is another layer in the device "stack". The stack of a lithium-ion battery is composed of an anode, the negative electrode, followed by a separator, and topped with a cathode, the positive electrode. The separator exists in the device to ensure that the anode and cathode cannot make electrical contact - that is that they cannot get close enough for electrons to flow directly from one electrode to the other. When the electrodes do touch, as can arise when the battery stack is misaligned or when the cell is damaged, a catastrophic failure mechanism, called a "hard short" may occur, which causes intensive resistive heating at the site of the hard short, potentially inducing a thermal runaway event which can result in fire and explosive reactions resulting from rapid electrode decomposition. The primary function of a battery separator is to prevent a hard short. However, the stack as described cannot yet function as a battery. Although electrons must not be able to flow between the electrodes, for the battery to function as an energy storage device, the working ion (Li+ in this case) must be able to flow, with minimal resistance, between the cathode and anode during charge and discharge, respectively. Thus, although separators must ensure physical and electrical isolation between the cathode and anode, they must allow for ionic communication between the electrodes. This is achieved by making the separators porous, with pore sizes large enough for liquid electrolyte to easily flow between the anode and cathode.

The current battery separator industry is dominated by polyolefin-based separator materials; these materials are simple carbohydrate polymers which have good electrochemical stability (they do not react with the electrodes) and fair thermomechanical properties under typical battery operating conditions. Polyolefins are thermoplastic materials, meaning they can be melted and extruded to form films. They are not intrinsically porous, so pores must be generated in the manufacturing process to facilitate ion transport through the separator; there are two dominant manufacturing processes in the polyolefin battery separator industry, termed "wet process" and "dry process". The resulting porous polyolefin film separator from each process will have pores on the order of tens of nanometers to just under one micrometer in diameter. These large pores allow for liquid electrolyte to flow through the battery separator, enabling low-resistance ionic communication between the electrolytes and therefore allowing for battery operation.

Sepion's battery separator product enhances the performance of conventional battery separator materials via the addition of an additional layer to the device stack, in the form of a thin, uniform coating of a nanoporous polymer membrane on the anode-interfacing separator surface (Figure 2). This polymer membrane, referred to as an "interlayer", imparts several additional characteristics that enable the next generation of high energy density, long lifetime, and inexpensive lithium-ion and lithium metal batteries:

- Ion-selectivity based on ion size, wherein small ions like the Li+ ion are easily transported between electrodes whereas large ions such as cathode degradation products Mn^{2+} and Ni^{2+} are blocked
- Enhanced wettability of battery separator with liquid electrolyte, improving ionic conductivity of the separator and accelerating the manufacturing process of battery devices
- Concentration of Li+ ions in the interlayer at the anode interface, improving Li+ plating (charging) and stripping (discharging) performance in lithium metal batteries

Figure 2: Uniform Coating of the Polymer Membrane



A sample of Sepion battery separator product produced via R2R coating of Sepion interlayer material onto polyolefin separator is shown. The interlayer material is coated to form a conformal surface coating (as shown in the cross-sectional SEM image on bottom left) on the anode-interfacing surface of the separator. Sepion's battery separator product is designed with nanostructured pores that provide selective transport of Li+ ions, enabling the application of emerging electrodes such as lithium metal and high nickel content and cobalt-free cathodes using liquid electrolytes using conventional Li-ion battery cell manufacturing procedures and equipment.

Source: Sepion Technologies

Applying Sepion's interlayer in the battery is achieved by a scalable solution processing technique. Specifically, the polymer is dissolved in a suitable solvent until a homogeneous coating solution, referred to as an "ink" is achieved. The ink is then coated onto the surface of the battery separator, using one of several possible techniques such as doctor blade coating, Mayer rod coating, gravure or micro gravure coating, or slot die coating.

Early demonstrations of Sepion's technology were performed using laboratory scale processes analogous to manufacturing scale processes, which allowed for early reduction in the risk of manufacturing scale-up using capital-light infrastructure. Polymers were synthesized in small glass vessels at scales of 1-100 grams, and coatings of these polymers onto battery separators were achieved using laboratory bench-scale techniques. However, battery device manufacturing and testing requires a high number of replicates to screen for and eliminate rare and potentially hazardous failure modes (manufacturing defects, shorting, or unfavorable electrochemical reactions between cell components such as the anode, cathode, separator, and electrolyte). To achieve the required number of replicates for feasibility studies using bench-scale techniques, several subsequent batches of coated material must be produced. Full technology validation is complicated by the random error inherent to small batch formulation and coating. Further, bench coated samples are too small to manufacture a medium format pouch cell prototype battery cell (2 Ah of battery capacity, about the size of an iPhone 8 battery). These battery cells require up to a meter of continuous separator to wrap the multiple layers of anode and cathode in the battery pouch without allowing electrical contact. Thus, for the purposes of technology validation, fabrication of medium- and large-format prototype battery cells, and demonstration of low-rate initial production, dedicated R2R equipment for battery separator coating was identified, commissioned, and re-tooled to improve product performance.

The goal of this program is to demonstrate low-rate initial production of battery membrane components at manufacturing readiness level (MRL) 8 that unlock new low-cost, long-lived energy storage solutions as an essential foundation for California to reach 1.5 million ZEVs by 2025 and 100 percent carbon-free electricity by 2045. This goal, which grew out of an imperative to produce enough battery separator material to keep up with automotive and battery manufacturer demand for samples, as well as to facilitate Sepion’s agile research and development (R&D) and manufacturing processes in a rapidly growing and changing battery market, is comprised of three task stages:

1. scale up production of battery separator demonstrating a clear path to meeting the cost, conductivity, and lifetime targets required for application in electric vehicles and long-duration energy storage devices from one-off prototype production to the Low-Rate Initial Production stage;
2. validate the performance and safety of battery separator in batteries meeting system-level targets (marginal energy cost ≤100 $/kWh); and
3. conduct market facilitation activities addressing supply chain, workforce needs, and other deployment challenges to confirm high volume production readiness.

The scaled-up production of Sepion’s battery separator product was de-risked in this program by breaking it into three steps: polymer scale-up, ink formulation and optimization, and pilot coating trials. In the polymer scale-up stage, a scale-up polymer manufacturing partner was contracted to execute polymer scale-up and deliver 100 g – 1 kg batches of polymer material for ink production and coating process development. Small batch polymerization optimization and materials development work was conducted internally at Sepion, whereas large batch polymerization reactions were conducted at Sepion’s selected contract polymer manufacturer. Ink formulation trials were conducted internally at Sepion using small batches of polymer ink in various solvents suitable for R2R coating. Ink validation is performed using a combination of ex situ quality analysis and trial coatings; specific ink metrics such as surface energy, viscosity, homogeneity and total solids content are used to screen inks before coating trials. Initial coating trials of inks were performed using bench coating processes (doctor blade and Mayer rod coating techniques). Preferred inks were scaled up and brought to a contracted battery prototyping center where initial trials of R2R production of Sepion's coated battery separator product was performed. Insights from these trials were used in the design, sourcing, commissioning, and upgrade of a R2R coating tool installed at Sepion's HQ facility in Emeryville, CA. Subsequently, all ink qualification and coating process development was performed on the R2R coater. This coater performs both R&D coating operations (1-6 meters) as well as process development and low-rate initial production (20-50+ meters) of optimized coatings which are now used in all Sepion R&D and low-rate initial production operations.

Membrane performance validation trials were likewise conducted in three steps: (1) development and testing of *ex situ* membrane Key Performance Indicators (KPIs), (2) fabrication and testing of small-format battery cells, and (3) external fabrication of medium-format (2 Ah) prototype cells and safety testing thereof. In the first step, a set of membrane KPIs was established, testing protocols for each were implemented, and a database to track coating quality analysis was established. Successful coating attempts were transitioned into the second phase, wherein a set of battery cells (4 minimum) were fabricated, and battery cell performance was evaluated and compared to performance of cells without Sepion's coating (control cells). Finally, successful demonstrations of small-scale battery performance were scaled up using R2R coating techniques to deliver rolls of battery separator for scaled-up internal small-format pouch cell fabrication and testing as well as external medium-format prototype pouch cell manufacturing and testing. Third party medium format prototyping and testing was selected as a capital-light approach to battery prototyping using established prototyping lines at third party manufacturers. This approach allowed Sepion to screen four different battery manufacturing processes and develop insights around preferred prototyping infrastructure for Sepion's own facility. Additionally, medium format cells are at additional risk of thermal runaway due to the total amount of energy stored in the cell, so testing early prototypes poses a heavy infrastructure risk if the appropriate safety precautions are not planned and designed for in the battery cell testing laboratory. Pushing initial testing of medium format cells to experienced third party battery prototyping and testing facilities ensured that innovative approaches to cell design to meet program targets could be tested with validated engineering controls in place. Likewise, battery abuse and safety testing must be validated by an independent party before being accepted by most battery original equipment manufacturers (OEM) and automotive customers, and furthermore requires the purchase and commissioning costly equipment to appropriately quantify results; conducting safety testing with a third party was a capital-light method to perform safety testing and ensure the results are valid for sharing with customers.

Finally, Sepion conducted market facilitation activities aimed at addressing battery separator membrane market barriers, supply chain risks, workforce readiness, and regulatory approvals. These activities to facilitate market entry and scale-up included attending trade shows and conferences, and hosting discussions with key stakeholders up and down the value chain, predominantly focused on battery separator manufacturers, battery OEMs, and automotive manufacturers. Sepion's California Energy Commission RAMP program technical advisory committee was instrumental in this effort. This committee included industry experts in lithium ion and emerging lithium metal batteries, R2R coating, membrane production, chemical production, manufacturing scale-up, electric vehicle battery technologies, project management, and business development.

Sepion's innovative membrane is a key component to unlocking safe, energy-dense batteries capable of powering electric vehicles for 400+ miles, a metric that relieves consumer range anxiety and redefines electric mobility. Sepion's platform membrane technology is adaptable — providing near-term benefits for today's Li-ion batteries and pushing the boundaries of what is possible with next-generation Li-metal anodes. This program was designed to overcome barriers to the achievement of the State of California's statutory energy goals by scaling up production of advanced battery membranes for market facilitation of zero emission vehicle battery packs and ultra-low-cost system-level storage that enables renewable resources to displace gasoline and natural gas assets.

CHAPTER 3: Results

Scale up of Sepion Battery Separator Product From Laboratory Scale to Pilot Production

The first technical task of this program was the scale-up of the Sepion battery separator product from laboratory scale to pilot production. This effort was itself divided into three key stages (1) polymer material production scale-up, (2) polymer coating ink formulation and optimization, and (3) pilot-scale manufacturing process development of polymer interlayer coated battery separator product. The program resulted in the translation of Sepion's battery separator product initially demonstrated at bench-scale using 10-30 cm long sheets to Li-ion gigafactory-compatible R2R battery separator production demonstrated at 60+ meters in length, a 200-fold improvement in scale with simultaneous improvement in product performance and uniformity.

Polymer material production scale-up

Initial polymer production capacity at the bench scale was limited to 1-100 grams in 1 and 2-liter chemical reaction vessels. Sepion worked with a California-based contract manufacturer to run initial polymer production process development demonstrations, resulting in a scale improvement of 10x to a total of 1 kilogram of polymer material per batch using 50-gallon reactors, equivalent to that needed for 1000 m^2 of coated separator production, or just over 8,000 meters in length of battery separator produced on Sepion's R2R battery separator production line. This quantity of material, produced in a single batch polymerization reaction, yields enough coated battery separator product to fabricate 8,000 medium-format 2 Ah prototype cells or 280,000 small-format single-layer pouch cells.

During the project period, small batch molecular design R&D trials were conducted to evaluate the effect structural modification of the polymer material. A total of 73 chemically unique polymer interlayer materials were screened in lithium metal batteries with high nickel content, low cost, and high energy density NMC-811 cathode active materials. This program yielded an improved polymer interlayer product which maintained the same benefits of the original prototype polymer interlayer, while adding additional valuable performance properties relevant for emerging lithium metal batteries such as reduced lithium plating overpotential, improved transference number, and reduced charge transfer resistance which cumulatively improve lithium plating and stripping uniformity, extending the cycle life of lithium metal batteries. The production of this second-generation polymer interlayer was demonstrated using identical manufacturing processes and equipment relative to the first-generation polymer material.

Polymer quality analysis during polymer process development optimization was evaluated using molecular weight and molecular weight distribution analysis and polymer purity was determined using nuclear magnetic resonance spectroscopy at either of two California-based analytical chemistry contract facilities. Modified synthetic procedures (stoichiometry, heat, solvent, solvent purity, stir rate, and reaction scale) and modified polymer isolation and purification procedures were screened to optimize polymer purity, yield, and performance. No statistical relationship between polymer scale and polymer quality was found; in other words, increasing scale had no effect on polymer quality. Reaction yields after purification for the preferred polymer interlayer using optimized production and purification conditions averaged 87 percent over 13 batches.

Polymer coating ink formulation and optimization

Polymer coating ink trials were run to improve polymer interlayer coating quality, reduce manufacturing costs, and maintain permissible solvent emissions levels under the California Division of Occupational Safety and Health (commonly known as CAL/OSHA) and Bay Area Air Quality Management District regulations assuming an annual low-rate initial production volume of 10,000 m2 of battery separator product. An environmental regulation consulting firm was contracted to support manufacturing operations emissions analysis. Coating ink solvent selection and polymer solids mass loading were the two key parameters affecting coating quality, manufacturing cost, and emissions levels.

A set of 48 solvents including water were screened in ink formulation trials and a total of more than 500 inks comprising varied solvents and solids content were evaluated for quality and screened for R2R coating trials. Ink quality was determined for each batch using standardized operating procedures to determine ink homogeneity, viscosity, and post-processing solids content as determined by gravimetric analysis of oven-dried ink aliquots. Of the more than 500 inks formulated and tested for quality, 368 inks were validated as suitable for coating trials.

Varied ink viscosity, solids content, and surface tension data were used to model coating quality during process development. These models are now employed to support ink formulation and coating production for all new and scaled-up interlayer materials.

Pilot-scale manufacturing process development of polymer interlayer coated battery separator product

At the start of the program period, Sepion employed equipment suitable only for bench-scale coating trials. Initial R2R coating production process development trials on battery separator were conducted at Washington Clean Energy Testbeds (WCET). The initial target product specification window for the coated battery separator product was large, so that individual coating quality analysis metrics could be related to battery performance. In these trials, the target thickness of the coating layer was between 0.5-5 micrometers (um) in thickness, and coating uniformity was evaluated using gravimetric analysis, Gurley densometer analysis, and atomic force microscopy. These studies resulted in a narrowed product specification window, targeting thin coatings with complete, uniform, defect-free coverage of separator pores as evaluated by Gurley densometer and gravimetric analysis techniques. These trials supported the identification of R2R coating equipment for coating at Sepion’s HQ facility.

Evaluation of possible R2R coater tools for installation and operation at Sepion’s HQ facility in Emeryville, California was performed using several factors: price, footprint, lead time, manu-facturer warranty, roller type, web width, tension control, production rate, and production versatility (coating technique, coating thicknesses, drying technique, dryer length, and dryer temperature range). The preferred tool was selected among a group of three available R2R coaters within program budget constraints. The R2R coating tool was sourced, installed, and commissioned at Sepion's HQ facility in April 2019. The coater was progressively optimized and retooled by Sepion's coating engineering staff to improve coating quality, production rate, and versatility. To the original 150 mm wide R2R coater equipped with a gravure coating module was added a corona treatment module, a custom-manufactured precision slot-die coating module, and a precision pull-drive motor with digital controller, each of Sepion's design. Additional retooling of rollers, including modification of roller position, the addition of shims for web curling control, and the addition of precision backing rollers were achieved. These improvements allowed Sepion to overcome several production challenges faced during pilot coating trials: among these, the most challenging were tension control, substrate curling, repeating pattern defects, coating surface coverage, and down- and cross- web coating uniformity.

As described in the preceding section, during the program period, a total of 378 polymer ink formulations suitable of R2R manufacturing were qualified for pilot-scale manufacturing process development. A total of 620 coating trials were conducted during the program period, 458 of these were conducted using Sepion's R2R tool. The addition of the precision slot die coating module was instrumental in achieving high quality coatings withing product specification at high manufacturing yields. Compared to gravure coating, which uses a coating pan containing the polymer ink and is therefore subject to solvent vaporization (and therefore change in viscosity and solids content) during long production runs using volatile solvents, the slot die method utilizes a syringe pump, so polymer ink remains consistent throughout long runs. The slot die coating module yields high quality coatings of 60+ meters with excellent cross- and down-web uniformity (less than 0.1 um thickness variation for a 1 um coating).

Manufacturing yield of Sepion's preferred polymer interlayer on standard control base battery separator substrate increased from <50 percent using bench coating methods to >95 percent using R2R methods (Q4 2022), and coating quality improved across all metrics.

Validation of Sepion Battery Separator Product Performance

The second technical objective was to demonstrate the performance of in-house pilot-produced battery separator products to improve the safety and reliability of assembled batteries. The validated coatings produced using R2R coating techniques were evaluated for application in battery cells in combination with advanced battery electrolytes developed by Sepion using a combination of *ex situ* and *in situ* performance testing. Among the testing procedures used to screen polymer interlayer coated battery separator products for battery testing included: polymer solubility, polymer swelling, wettability of coated separator, and Li+ ion and Mn^{2+} diffusivity through the polymer membrane. The design of appropriate battery electrolytes for combination with advanced anode and cathode materials was out of scope of this project and funded through a separate program; however, the program results were used to screen in new, sequentially optimized electrolytes into testing with Sepion's polymer interlayer product in full cells.

Validated polymer interlayer coated battery separator found to be compatible with advanced lithium metal battery electrolytes were evaluated in lithium metal battery cells. As there is currently no accepted standard for lithium metal battery design, significant cell engineering design effort was dedicated to improving the performance and demonstrating the value propositions of Sepion's polymer interlayer coated battery separator product for enabling the next generation of low-cost, high energy density lithium metal batteries. Small- and medium-format battery pouch cells were configured to conform to commercially aligned cell energy density targets (>800 Wh/L and >350 Wh/kg) using thin lithium anode foils, high energy density, low cobalt content NMC-811 cathodes, and lean electrolyte loading. All cell design factors were modeled to maximize energy density and fast charge capability while keeping the total modeled cost at <$100/kWh.

The substrate battery separator material additionally plays a key role in battery performance, as described in the introduction. Thus, a selection of 45 commercial battery separator products with widely varying properties were evaluated in battery cells with and without (control) the polymer interlayer coating. Battery performance was evaluated as a function of base separator material (polyethylene, polypropylene, cellulose, and composites thereof), thickness (9-25 um), porosity (38-55 percent), surface energy, tensile strength, tensile elongation, puncture strength, and thermomechanical stability. Coating trials were conducted on battery separators using both bench and R2R processing techniques; 30 battery separator products were evaluated as suitable substrates for production of Sepion's polymer interlayer coated battery separator product. Successful coating production demonstration using Sepion's R2R coater was achieved under target product specification limits using all 30 of the target substrates.

Sepion's R2R produced polymer interlayer coated battery separator products were validated in two cell formats. In the first battery cell validation stage, all coated battery separators were screened in small format battery cells using uncoated base separator as controls. Differentiated interlayer products demonstrating high cycle life and good reproducibility (in the form of minimal cell-to-cell variation in cycle life and cumulative discharge energy) were then screened in medium format >2 Ah prototype cells.

During the program period, to accelerate battery testing R&D, cell testing infrastructure was significantly expanded from 96 channels to over 1,200 channels, and Sepion's capacity to build battery cells grew from intermittent based on researcher availability, to consistent production of over 200 cells per week with a dedicated staff of battery fabrication technicians, test technicians, and battery test and production engineers. Each individual channel is dedicated to testing one single-layer lithium metal battery cell, and cells are cycled on and off channels as they are built and tested to 70 percent of initial discharge capacity. The incorporation of R2R coated battery separator fabrication methods into Sepion's R&D program enabled large experimental designs focused on testing and improving battery separator performance simultaneously. In-house testing capabilities for up to 80 multi-Ah battery cells were also installed and commissioned. This vastly increased battery cell production capacity and test infrastructure enabled the implementation of highly controlled and productive product validation and materials optimization programs running in parallel. These programs allow Sepion to validate its coated battery separator products in the varied and continually evolving cell architectures and under varied battery cycling conditions inherent to the emerging lithium metal battery EV market while continuing to make improvements to its battery separator and co-optimized electrolyte products.

In battery separator development and validation trials, small format cells were manufactured in 50 mAh 3 x 4 cm active area pouch cell format using NMC-811 cathodes. Over 6,000 small format lithium metal pouch cells were fabricated and tested at Sepion in 2022; of these, over 3,000 small format lithium metal battery cells were tested using in-house R2R produced polymer interlayer coated separators. These tests included a total of 624 unique cell designs (electrolyte and separator combinations) and battery testing conditions (fast-charge accelerated rate testing, EV-standard C/3 charge and discharge rate testing, electric vertical take-off and landing aircrafts slow-charge, fast discharge, variable rate testing, and variable temperature testing) to thoroughly evaluate and optimize battery separator product performance. Battery separator performance in full cells was evaluated using a number of key performance indicators under the varied testing conditions described above including cycle life, area-specific resistance, transference number, pulse power performance, 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 multilayered 2 Ah analogue was >850 Wh/L and >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 Table 1. This testing vehicle was used for all new component screening, including base separator, polymer coating, and electrolyte materials. Battery separator performance with various electrolytes was evaluated using cycle life (number of cycles until 80 percent of initial discharge capacity) as the key performance indicator, with other key performance indicators such as cumulative discharge energy and ASR tracked for each combination of materials. Coated battery separator performance was validated under various rate conditions, including C/3 charge and C/3 discharge, 1C charge and C/2 discharge, and C/5 charge and 1C discharge.

Table 1: Single-Layer Pouch Cell Prototype Test Format

Cell Format	Single layer pouch cell
Dimensions	12 cm^2
Capacity	50 mAh nominal
Temperature	30°C
Charge	3-4.3V, CC/CV
Discharge	4.3-3V, CC
Cathode	NMC-811 (3.5-4.0 mAh/cm^2)
Anode	20 um Lithium metal
Separator	Varied
Electrolyte Loading	2 g/Ah
Stack Pressure	100 PSI

Volumetric Energy Density* (Wh/L)	800
Gravimetric Energy Density* (Wh/kg)	350

*modeled for a multi-layer 2Ah pouch cell

Source: Sepion Technologies

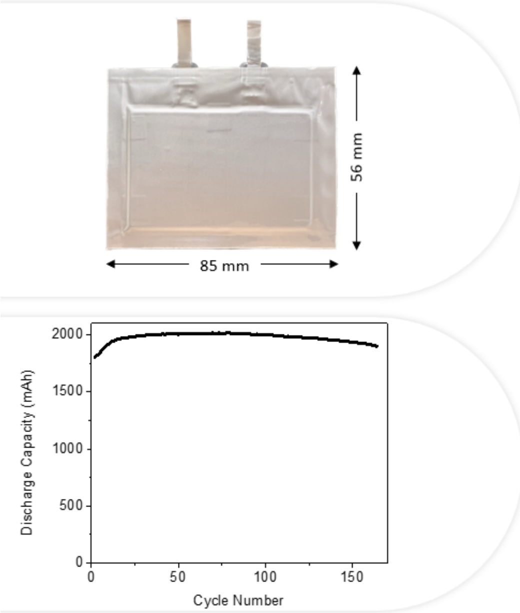
Additional investigation into battery separator performance was conducted in analogous Li|Li symmetric cell format. This advanced testing vehicle was used to determine wetting period, bulk resistance, charge-transfer resistance, SEI resistance, Li^+ transference number, exchange current density, nucleation overpotential, and Sand's time for various combinations of coated battery separator and liquid electrolyte. High performing coated battery separators were compared to uncoated battery separators to determine the effect of the coating on these key performance indicators for lithium metal battery performance.

Although it is feasible to manually stack multi-layered cells to achieve an in-house 2 Ah prototype cell with no external support, it was important in this program to ensure high manufacturing readiness level. Therefore, prototyping partners using various Li-ion manufacturing processes were selected to evaluate the manufacturing readiness level of Sepion's battery separator product using conventional Li-ion manufacturing procedures.

Medium format >2 Ah prototypes were produced using multi-layered pouch cell designs at four different prototyping facilities. All prototyping partners were selected in North America. These facilities varied in the production techniques used to fabricate the 2 Ah prototype cells, from fully manual stacking techniques to semi-automated pouch cell stacking. A combination of factors including the COVID-19 pandemic and resulting supply chain crisis, the manual and semi-automated fabrication techniques utilized in medium format prototyping at the selected facilities, and high labor costs resulting in a high manufacturing cost per prototype cell significantly limited the total number of cells Sepion was able to source for medium format testing during the program period; in total, 68 >2 Ah lithium metal battery cells were received and tested-in house from four prototyping partners to validate Sepion battery separator product performance.

Validation in cells, both small- and medium-format, yielded continual improvement in cell performance during the program period, as well as validation of the ability to integrate Sepion's R2R produced coated battery separator product into multilayer 2 Ah prototype cells using conventional Li-ion manufacturing process as a "drop-in" replacement for conventional battery separator materials. Figure 3 depicts the performance of three energy dense 2 Ah lithium metal cells comprising Sepion's coated battery separator product which was built using conventional Li-ion manufacturing procedures using a Li-ion prototyping line at one of Sepion's selected prototyping partners. Sepion's coating provides high cell-to-cell uniformity, stable cycling performance, and high energy density – all features which are critical to demonstrating the feasibility of lithium metal battery cell production and application in electric vehicles.

Figure 3: Performance Validation in Medium Format of Coated Battery Separator



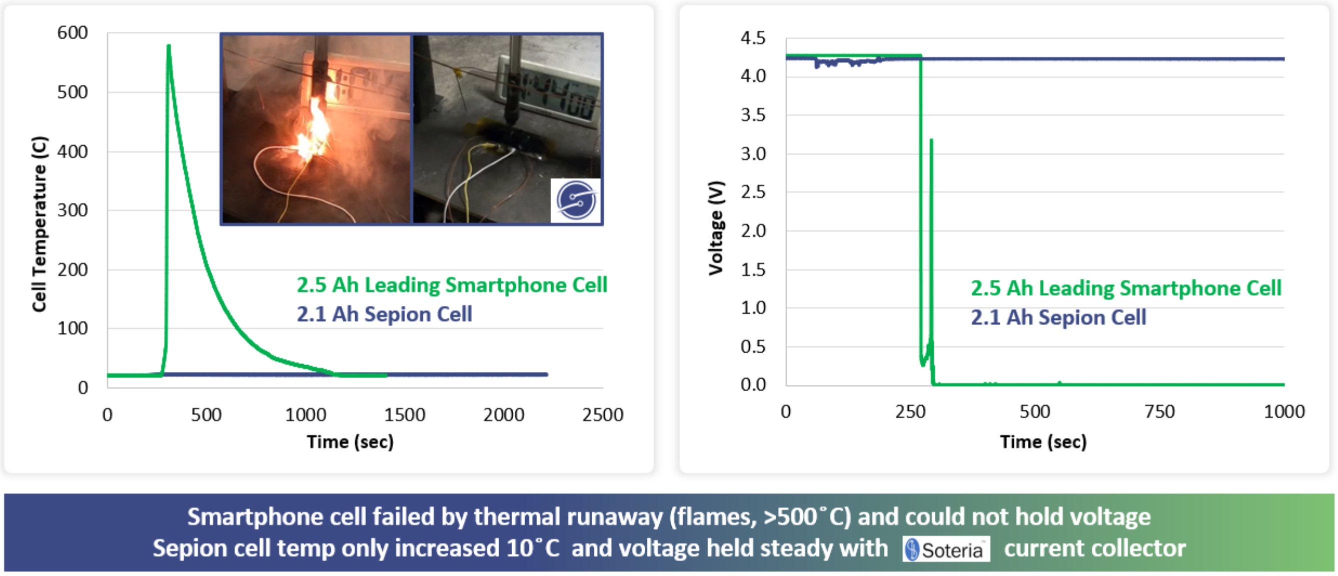
Sepion Medium Format Prototype	
Cell Format	Pouch
Electrode Stack Dimensions	56 x 85 x 2 mm (L x W x H)
Capacity	2080 mAh nominal
Temperature	30°C
Charge	3-4.2 V, CC/CV (C/3)
Discharge	4.2-3 V, CC (C/3)
Cathode	NMC-811 (3.8 mAh/cm^2)
Anode	20 um Lithium metal
Separator	PE + Sepion Interlayer
Electrolyte Loading	2.0 g/Ah
Stack Pressure	100 PSI
Volumetric Energy Density* (Wh/L)	805
Gravimetric Energy Density* (Wh/kg)	350

**C/3 at beginning of life; estimated volume via USABC standards*

Source: Sepion Technologies

Initial testing of the safety of lithium 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, which represents the first study in a planned program to develop a standard battery prototype with safety certification (such as UN38.3, SAW J2464, or UL2580). In these preliminary safety trials, Sepion's lithium metal battery cell, built incorporating Sepion's interlayer coated battery separator, Sepion's liquid electrolyte, as well as a metallized plastic current collector designed by Soteria was pieced with a nail while monitoring temperature and voltage. Sepion's lithium metal battery cell performed exceptionally during this trial due to the combination of safe and stable materials in the interlayer 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 600 C and releasing all stored energy over ~10 minutes. 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 simultaneous incorporation of stable, non-flammable and flame-retardant materials into Sepion interlayer and electrolyte materials design as well as a carefully refined cell design, including the incorporation of components such as the Soteria current collector, designed with battery safety and consumer peace-of-mind as the central focus in battery product development.

Figure 4: First Demonstration of Sepion Membrane Format



First demonstration of Sepion medium format 2.1 Ah prototype lithium metal cell using Soteria current collector and Sepion coated battery separator vs. leading smartphone Li-ion cell in a nail penetration test. Sepion cell remained stable and held a charge during nail penetration test, demonstrating that careful engineering of battery cell architecture and design of inactive materials (electrolyte and separator) can yield a stable and safe lithium metal battery, outperforming commercial Li-ion battery products.

Source: Sepion Technologies

The consumer-focused battery engineering and design-for-manufacturing product development strategies described above are central tenants of Sepion's approach to accelerating battery innovation for EV adoption to ensure a sustainable future for all.

Battery Separator Market Facilitation

Throughout the course of this project, diverse activities were pursued and deliverables executed to increase the likelihood of successful scale up and commercialization of advanced battery separators. Key activities and deliverables are summarized.

- Membrane market facilitation
  - Addressed membrane market barriers, supply chain risks, workforce readiness, and regulatory approvals to facilitate market entry and ramp-up.
  - Actively engaged with potential partners and customers to discuss prospective strategies to gain assurance in product.
  - Conducted platform-specific market studies, including detailed producibility trade studies, risk assessments, and prioritized unit cost reduction efforts.
  - Optimized and validated detailed design-driven engineering cost model with production data.
  - Produced cost model informed by yield rate analyses with pilot line results.

  - Developed de-risking plan to validate and formalize suppliers in preparation for commercialization, including establishing long-lead procurement plans.
  - Analyzed and validated supply chain and supplier quality assurance by ensuring all materials, human power, tooling, test equipment and facilities are proven on pilot line and are available to meet the planned low-rate production schedule.
  - Completed an industrial capabilities assessment addressing stable and proactive production rate and quantity changes in response to contingency and support objectives.
  - Addressed workforce needs through tailored education and outreach, and by hiring and training technicians and engineers with practical manufacturing experience/knowledge.
  - Prepared and executed a Training Schedule (per classification) that included off-site training by third party entities and on-site in-house company training.
  - Hired and trained key personnel to support the project: a Vice President of Operations; Engineering Manager – Production; a team of five battery cell fabrication technicians; a battery test technician; a Staff Scientist – Process Chemistry; a Staff Engineer – Battery Testing; a Staff Engineer – Coating; and a team of two Research Associates – Coating.
  - Demonstrate capability, empathy, and a clear understanding of the materials impact on safety certification to provide awareness of any hurdles in regulatory approval for customers.
- Production readiness plan:
  - Prepared a plan evaluating:
    - Critical production processes, equipment, facilities, personnel resources, and support systems needed to produce a commercially viable product.
    - Internal manufacturing facilities, supplier technologies, capacity constraints imposed by the design under consideration, design-critical elements, and the use of hazardous or non-recyclable materials.
    - Production costs.
    - CapEx requirements for full-scale production.
    - Implementation plan for full production.
    - Completed planning, identification, lease, and architectural design completion for next-stage pilot scale manufacturing.
- A new contract manufacturer was contracted to produce 2 kg of polymer using 50 gallon reactor systems in pursuit of a goal to produce 10,000 m2 of coated battery separator product annually.
- Additional market facilitation activities:
  - Evaluated licensing model and determined business model for revenue generation using coated membrane product.

- Filed necessary patent applications to defend product both domestically and internationally.
- Developed and actively maintain trade secret knowledge to maintain competitive edge.

CHAPTER 4: Conclusion

New battery materials are critical to delivering mass-market electric vehicles that surpass customers' expectations for range, "refueling time", and price established by internal combustion engine vehicles. Once this trifecta is met, achieving California's climate goals will switch from being a government push to a consumer pull. Already Californians with the financial means to afford electric vehicles 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 to move from early adopters to an early majority. Sepion's battery separator products advanced in this program have demonstrated performance advantages holding promise of meeting the trifecta of range, fast charging and price. With these RAMP funds, the company demonstrated order-of-magnitude gains in demonstrated raw materials production and quality. In the process of making these gains, multiple challenges were overcome, and the lessons learned offer up 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. Prior to the support of the California Energy Commission, these capabilities were beyond Sepion's reach, forcing the company to rely on partners and 3rd party prototyping facilities to demonstrate the feasibility of scaling Sepion's key components and integrating them into devices. These devices would then be shipped back to Sepion, tested, then shipped to customers for evaluation. Even with our highly committed and talented partners, it could take 4–6 months from the time samples are requested to the time Sepion can deliver those samples to customers, making this arrangement untenable moving forward in this rapidly growing market. Many other California-based innovators face similar challenges demonstrating the value propositions and scalability of their products. Continued support for the RAMP program and investment in a California public-private battery prototyping facility will help reduce risks on the path to market for new innovations.

Workforce development is a critical area where the state and federal government can contribute to accelerate onshoring battery manufacturing and supply chains. Even with the necessary infrastructure, the electrify-everything revolution has exacerbated a severe shortage of experienced, domestic battery professionals. Workforce development is operating in and will continue to operate in for a decade or more, a job seekers market. 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.

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Project Deliverables

Task 1 – Final project report

- Draft final report outline
- Final report outline
- Draft final report
- Final report

Task 2 – Scale Up Battery Membrane to Pilot Production

- Membrane production quality assurance/quality control protocols report
- CPR Report #1

Task 3 – Validate Membrane Performance

- Membrane performance metrics report
- Battery performance assessment report
- CPR report #2

Task 4 – Membrane market facilitation activities

- Draft battery membrane production risk assessment
- Final battery membrane production risk assessment
- Draft supply chain and industrial capabilities assessment report
- Final supply chain and industrial capability assessment report
- Training schedule
- Job duty description
- Safety certification analysis

Task 5 – Evaluation of project benefits

- Kick-off meeting benefits questionnaire
- Mid-term benefits questionnaire
- Final meeting benefits questionnaire

Task 6 – Technology/knowledge transfer activities

- Initial fact sheet
- Final project fact sheet
- Presentation materials
- High quality digital photographs
- Technology/knowledge transfer plan
- Technology/knowledge transfer plan report

Task 7 – Production readiness plan

- Production readiness plan