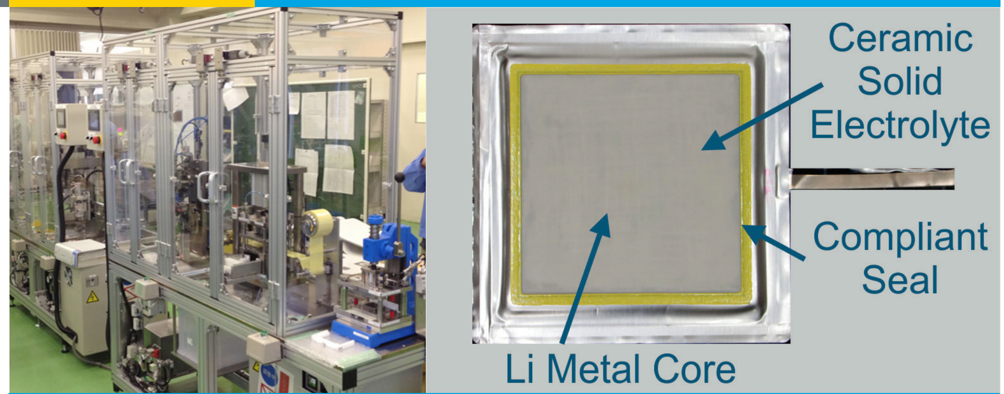


The pilot scale manufacturing line for protected lithium electrodes was designed, built, installed, and optimized during this project (left) in order to manufacture water-stable protected lithium electrodes (right). *Courtesy of PolyPlus.*

# Manufacturing of Protected Lithium Electrodes for Advanced Lithium-Air, Lithium-Water, and Lithium-Sulfur Batteries

Developing a Lower Cost and Higher Energy Density Alternative to Lithium-Ion Batteries

## Introduction

As the world moves toward increased electric transportation and the use of renewable sources of energy for grid power, advanced electrochemical energy storage technologies will become more and more important. The introduction of electric vehicles in the United States and abroad has fueled a global race to develop and manufacture new types of batteries that are lighter and lower in cost than incumbent technologies.

To achieve step-change improvements in performance, battery chemistries that combine unusual materials are needed. Lithium-air, lithium-water, and lithium-sulfur batteries demonstrate exceptionally high energy densities (two to 10 times higher than lithium-ion), using raw materials that are low cost or even free. However, the use of lithium metal as an electrode in a secondary battery presents unique challenges. Solving these problems would boost domestic battery manufacturing in this globally competitive, emerging technology area.

PolyPlus Battery Company has developed the protected lithium electrode (PLE), an invention that enables the use of lithium metal as an electrode in a secondary battery. Currently, the only commercial source of the lithium-ion-conductive ceramic membranes used to construct PLEs is foreign-based. Providing a domestic source of these membranes would reduce costs and give the United States a competitive advantage. In order to realize the reduced cost, it is also imperative to demonstrate that PLE-based batteries can be manufactured and scaled to high-volume production.

This project focused on developing the novel manufacturing processes necessary to fabricate PLEs at scale. It also involved producing solid electrolyte membranes for PLEs that have sufficient mechanical strength, ionic conductivity, and chemical stability to be competitive in the global battery market.

## Benefits for Our Industry and Our Nation

Developing the manufacturing capability to produce PLEs will enable the introduction of advanced lithium batteries with higher energy densities and should lead to a reduction in cost of more than 50% (relative to competing technologies). If successful, this technology will advance new and emerging product markets and provide U.S. manufacturers a significant competitive advantage in emerging battery markets. Using lithium batteries with PLEs in electric vehicles would significantly reduce greenhouse gas emissions and energy consumption.

## Applications in Our Nation's Industry

There is significant market potential for applications using PLEs, including electric vehicles, grid storage, military applications, and others. Low-cost, high performance, ultra-lightweight, and compact batteries based on PLE technology may enable a new generation of portable devices. Other applications may include oceanographic exploration, oil and gas exploration, autonomous underwater vehicles and buoys, and unmanned aerial vehicles for both commercial and U.S. military markets.

## Project Description

This project developed the manufacturing technology that can produce PLEs for lithium-air, lithium-water, and lithium-sulfur batteries. Project objectives included the development of solid electrolyte membranes that provide sufficient lithium-ion conductivity, mechanical strength, and chemical stability, scalability to high-volume manufacturing, and ultimately reduction of the cost of these batteries relative to competing products.

The technology will help facilitate the emergence of a domestic supplier of solid electrolyte membranes and accelerate the commercialization of PLE-enabled battery technologies.

### Barriers

- Cost-competitiveness of novel battery technologies depends on demonstrating manufacturability through high-process efficiency, scale-up, and safety.
- Developing thinner membranes that provide higher rate performance is challenging for secondary lithium-air applications because the mechanical strength of the membranes decreases as membranes thickness is reduced.
- Solid electrolyte stability can be compromised in certain saltwater environments due to sodium ion exchange.

### Pathways

During this project, the chemistry and processing of solid electrolytes was optimized and modified for use in lithium-air, lithium-water, and lithium- sulfur batteries. The full manufacturing process for solid electrolytes was addressed, including raw material selection, powder preparation, tape- casting and sintering, and final part finishing and handling. A pilot production line was designed, built, and used to produce PLEs. These PLEs were tested in lithium-air, lithium-water, and lithium- sulfur batteries. Testing results will be used to adjust membrane chemistry and processing as needed, ultimately resulting in a pre-commercial technology. The technology was transferred from bench-scale to pilot scale, demonstrating the potential for high-volume production.

### Milestones

This project began in 2012 and successfully completed in 2015.

- Pilot line is fully operational and guidelines established for lithium-water PLE (Completed).
- Develop specifications for primary lithium-air PLE and process for lithium-water membranes (Completed).
- Develop specifications for rechargeable lithium-air PLE and process for lithium-air membranes (Completed).
- Develop specifications for lithium- sulfur PLEs and process for lithium- sulfur membranes (Completed).
- Complete scale up of PLE pilot manufacturing and scale up of membranes for pilot manufacturing (Completed).

## Commercialization

The PLE manufacturing technology developed during this project is necessary for the commercial success of lithium-water, lithium-air, and lithium-sulfur battery technologies. After manufacturability of the PLE technology was demonstrated on the pilot scale, focus was on market development and commercial introduction of the new technologies. Given that the lithium-water and lithium-air batteries are more mature than the lithium-sulfur, it is likely that the first market for these batteries will be for military applications. However, the potential for a rechargeable lithium-sulfur battery for automotive and electronic applications has attracted the interest of major manufacturers in these markets, which may accelerate the commercial introduction of the lithium-sulfur system.

## Project Partners

PolyPlus Battery Company Berkeley, CA
Principal Investigator: Dr. Steven Visco
E-mail: svisco@polyplus.com

Corning Incorporated
Corning, NY

Johnson Controls Incorporated
Milwaukee, WI

## For additional information, please contact

Bob Gemmer Technology Manager
U.S. Department of Energy
Advanced Manufacturing Office
Phone: (202) 586-5885
Email: Bob.Gemmer@ee.doe.gov ■