ALL SOLID STATE BATTERIES ENABLED BY MULTIFUNCTIONAL ELECTROLYTE MATERIALS

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SOLID POWER INC.
JUNE 24, 2021

PROJECT ID: BAT486

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## Overview

### Timeline
- Project start date: October 2019
- Project end date: September 2022
- Percentage complete: 60%

### Budget
- Total project funding $1,250,000
  - DOE share: $1,000,000
  - Contractor share: $250,000
- FY 2020 funding: $430,000
- FY 2021 funding: $420,000

### Barriers
- Need a solid state electrolyte (SSE) enabling solid-state battery for EV
- Need scalable processes for solid state cell fabrication
- Need an EV battery capable of > 1000 cycles and > 350 Wh/kg

### Partners
- University of California San Diego
- Project lead: Solid Power Inc.
Impact
• Development of a solid state electrolyte enabling high energy solid state batteries
• Fabrication of solid state battery cells in roll-to-roll processes
• Demonstration of large format solid state Li cells for the EV market

Objective
Develop solid state Li metal cells enabled by multifunctional solid state electrolytes for use in EVs
    — Cell capacity \( \geq 2 \text{ Ah} \)
    — Useable specific energy \( \geq 350 \text{ Wh/kg} \)
    — Cycle Life \( \geq 1,000 \text{ cycles} \)
    — Cost \( \leq $100/\text{kWh} \)
<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Description of Milestone or Go/No-Go Decision</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 2019</td>
<td>Precursor and equipment secured</td>
<td>Complete</td>
</tr>
<tr>
<td>March 2020</td>
<td>Cathode down-selected</td>
<td>Complete</td>
</tr>
<tr>
<td>June 2020</td>
<td>Cathode loading ≥ 3.5 mAh/cm² demonstrated</td>
<td>Complete</td>
</tr>
<tr>
<td>September 2020</td>
<td>Go/No-Go: SSE ionic conductivity ≥ 3 mS/cm and full cell cycle life ≥ 200</td>
<td>Complete</td>
</tr>
<tr>
<td>December 2020</td>
<td>Solid state cell charge rate ≥ 0.5 C demonstrated</td>
<td>Complete</td>
</tr>
<tr>
<td>March 2021</td>
<td>Pouch cell ≥ 200 mAh fabricated</td>
<td>Complete</td>
</tr>
<tr>
<td>June 2021</td>
<td>SSE critical current density (CCD) ≥ 18 mA/cm² demonstrated</td>
<td>On Target</td>
</tr>
<tr>
<td>September 2021</td>
<td>Go/No-Go: SSE ionic conductivity ≥ 5 mS/cm and full cell cycle life ≥ 500</td>
<td>On Target</td>
</tr>
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**APPROACH**

- Develop a **Multifunctional SSE**
  - high Li conductivity (up to 10 mS/cm)
  - high electrochemical stability (0 – 4.5V)
  - fast charge capability (2C)
  - large scale manufacturing process compatibility

- Apply Li metal anode and Ni-rich NMC cathode in the solid state cell for high energy density

- Adopt roll-to-roll process for solid state cell fabrication for low cost cell production

- Deliver solid state Li cell of ≥ 2 Ah for performance demonstration
**TECHNICAL ACCOMPLISHMENTS**

**SSE DEVELOPMENT**

- Sulfide based SSE has been developed with high conductivity and stability
  - It met the Year 1 targets and is on track of meeting Year 2 targets
  - Li ion conductivity of \(4.5 \times 10^{-3} \text{ S/cm}\) at 25 °C, 10 times higher than baseline LPS
  - Critical current density (CCD) > \(6.0 \text{ mA/cm}^2\), 5 times higher than baseline LPS

### Current status of conductivity and CCD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Year 1 Target</th>
<th>Current Status</th>
<th>Year 2 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (mS/cm)</td>
<td>≥ 3</td>
<td>4.5</td>
<td>≥ 5</td>
</tr>
<tr>
<td>CCD (mA/cm²)</td>
<td>≥ 6</td>
<td>12</td>
<td>≥ 18</td>
</tr>
</tbody>
</table>
• SSE separator film has been fabricated in a R2R mode
  • The film was coated with a slurry-cast method
  • NMC cathode was also coated R2R
  • SSE was laminated to cathode to form a bi-layer film

SSE separator coated by a slot-die coater

NMC cathode coated by a slot-die coater

Bi-layer film formed by a lamination process
- NMC/Li solid state pouch cell containing the multifunctional SSE has been demonstrated
  - Baseline pouch cell ≥ 5 mAh was demonstrated in Year 1
  - Large format pouch cell ≥ 200 mAh has been successfully assembled and is under evaluation in Year 2
  - Final prototype pouch cell ≥ 2 Ah demonstration is on schedule in Year 3
Pouch cell cycle life ≥ 200 has been demonstrated

- **Cell test**
  - Lab pouch cell at 6 mAh
    - NMC622 cathode (at 3 mAh/cm²)
    - 70 µm SSE separator
    - 35 µm Li anode
  - 2.8 – 4.2V, C/5 – C/5, and 25°C

- **Cell performance**
  - 93% capacity retention after 220 cycles
    - Met Q4 milestone of 200 cycles

*Capacity fluctuation is due to the ambient temperature change*
Pouch cell rate capability has been demonstrated

- **Cell test**
  - Lab pouch cell at 6 mAh
    - NMC622 cathode (at 3 mAh/cm²)
    - 70 µm SSE separator
    - 35 µm Li anode
  - 2.8 – 4.2V, +0.1C/-0.1C to +1C/-1C, 70°C
- **Cell performance**
  - 95% capacity retention at C/2, when compared to C/10
    - Met Q5 milestone of C/2 charge
  - Testing at lower temperatures in progress
Solid Power has established the pilot-scale capability at both material and cell levels.

**SSE Precursor**

The SSE precursor developed in-house and via partners for low cost and optimized for mass production of electrolyte and cells.

**Electrolyte**

Best all-around solid electrolyte materials produced using low-cost scalable processes.

**Production**

Pilot scale production using the same equipment as conventional Li-ion to quickly enable low-cost GWh-scale production.

**Prototype Cell**

Multi-Ah pouch cells deliver >50% energy advantage over Li-ion while also being inherently safer.
This is the first year that the project has been reviewed
COLLABORATION AND COORDINATION

• Solid Power Inc. (Prime; PI: Dr. Pu Zhang)
  – Material synthesis, process development, cell assembly, and cell test

• University of California San Diego (Subcontractor; PI: Dr. Shirley Meng)
  – Material characterization and cell failure analysis
REMAINING CHALLENGES AND BARRIERS

• Achieving high rate capability and low temperature performance
  • Further improvement of the electrolyte conductivity and stability
  • Optimization of electrode and separator formulations for lower resistance
  • Further development of cell stack fabrication processes for optimized interfaces

• Understanding solid state cell performing mechanisms
  • Both chemical and mechanical changes during the cell operation
  • Cell failure modes
  • Engagement of industrial and academic partners
PROPOSED FUTURE RESEARCH

• Demonstrate a solid state cell with 500 cycles in a 300 Wh/kg design by Q8
  • Electrolyte with improved stability → longer cycle life
  • Thinner separator ≤ 60 µm → higher specific energy and energy density
  • Lower resistance cell → cell operation at room and lower temperatures

• Deliver a prototype pouch cell ≥ 2 Ah with 1000 cycles, 350 Wh/kg by Q12
  • Optimized electrolyte → cycle life ≥ 1000
  • Separator ≤ 40 µm → specific energy ≥ 350 Wh/kg
  • NMC with >80% Ni content (validation pending) → potentially ≥ 400 Wh/kg
SUMMARY

• The team met all the Year 1 targets and is on track of meeting Year 2 targets
• A multifunctional electrolyte was developed with a Li ion conductivity of 4.5 mS/cm at 25°C
• The SSE separator and electrodes were fabricated in a R2R mode
• A solid state Li metal pouch cell has been demonstrated and the cell retains 93% of initial capacity after 200 cycles
• Pilot scale production capabilities have been established for both the electrolyte synthesis and large format cell assembly within Solid Power
THANK YOU!