

Sensor-based Prognostics for Safe Batteries for Electric Aircraft

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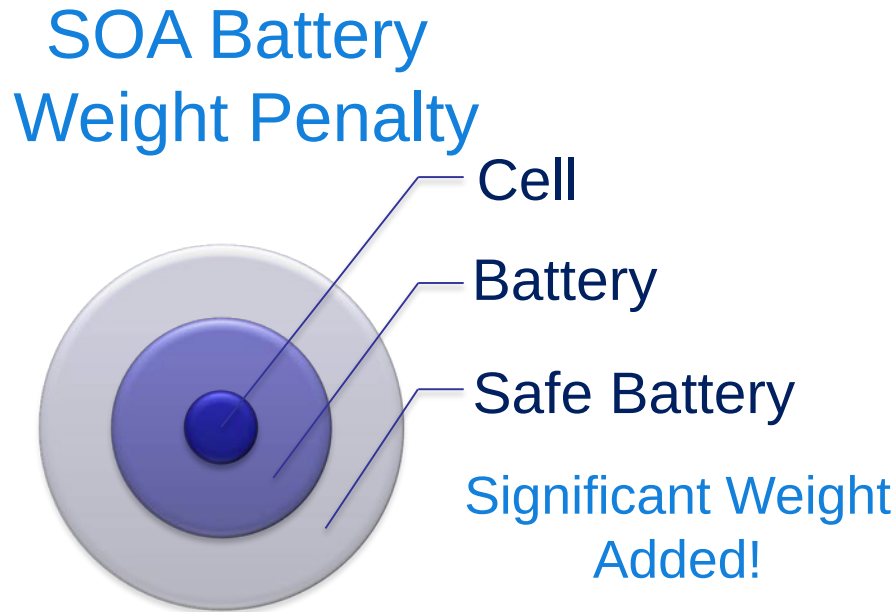
Agenda

- Motivation & Project Overview
- Battery Failure Analysis
- Sensor Development
- Nondestructive Evaluation
- Battery Modeling & Failure Prognostics
- Summary

MOTIVATION & PROJECT OVERVIEW

The Challenge

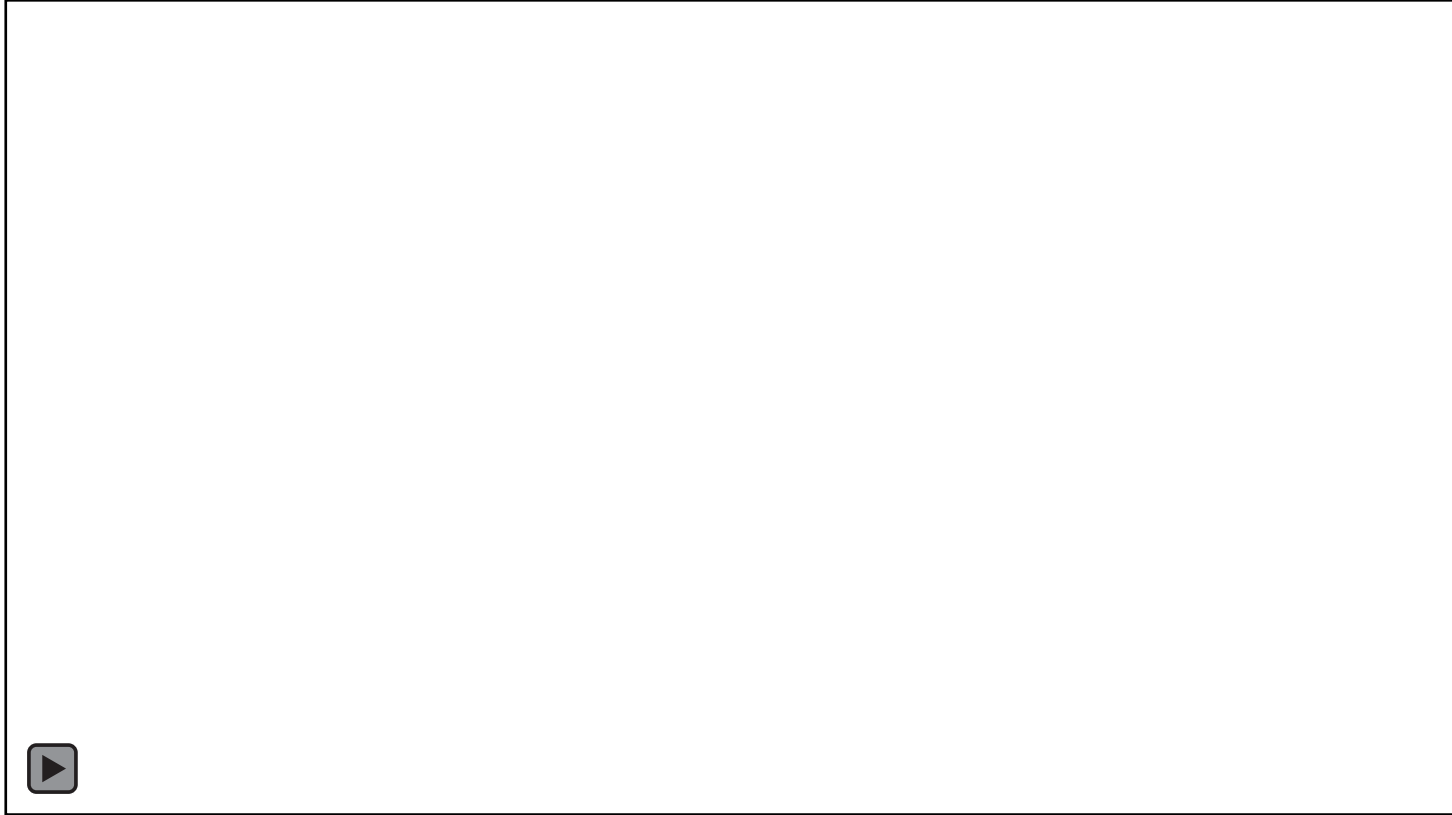
Emerging electric aircraft concepts need better performing, safer energy storage



Next-gen Battery
Chemistry



Battery Thermal Runaway



The Goal

- Eliminate catastrophic failures with early fault detection
- Improve safety of existing batteries + accelerate adoption of next-generation batteries
- Demonstrate battery pack capable of hazard detection
 - Warning to shut down before abuse conditions lead to fire
 - Weight savings of >10% for X-57 battery

A safe, high energy battery to
disrupt the electric aircraft industry

Technology Development

Battery Failure Analysis

- Reproducible techniques to induce failure
- Failure precursor identification

Sensor Development

- Micro-sensors for real-time monitoring within cells
- Multi-functional parameter measurement

Nondestructive Evaluation (NDE)

- In-situ and off-line techniques
- Battery health data without damage
- Advanced NDE data analysis

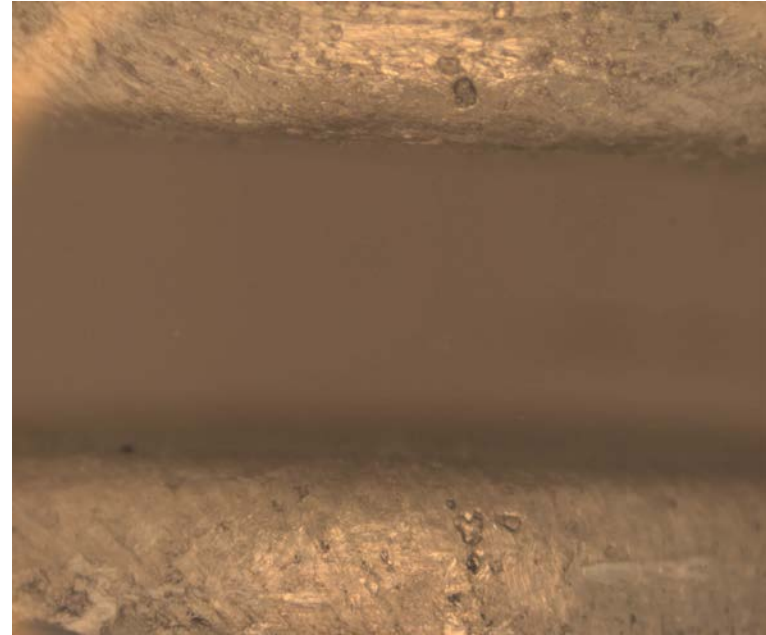
Modeling & Failure Prognostics

- Multiphysics modeling
- Fault algorithm + failure prognostics
- “Smart” battery management

BATTERY FAILURE ANALYSIS

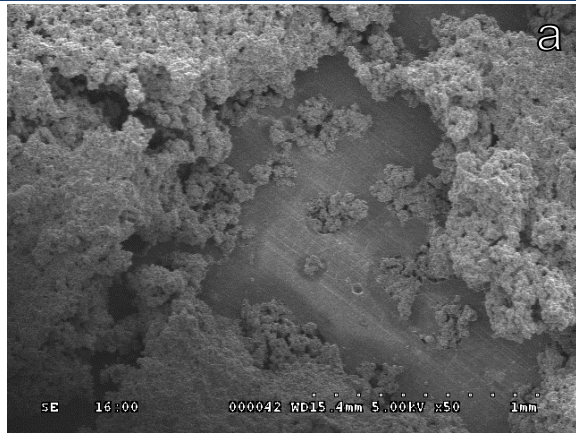
Failure Precursor Experiments

- Lithium dendrite growth
 - Li-ion vs Li metal chemistries
- Identify reproducible & relevant dendrite growth conditions
- Failure precursor identification
- Feed into sensor development, NDE activities & fault detection algorithms

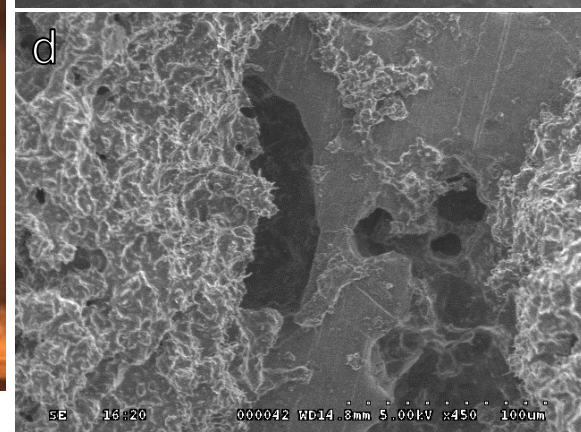
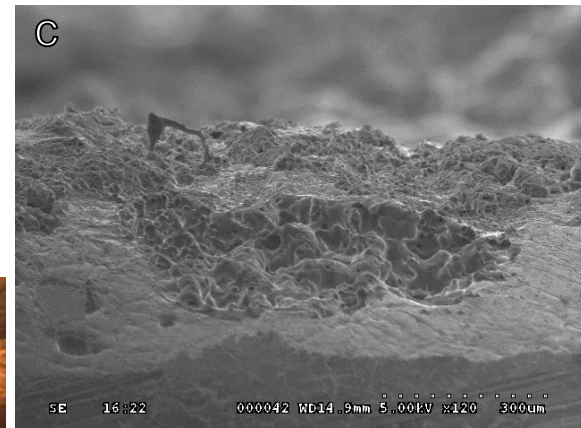
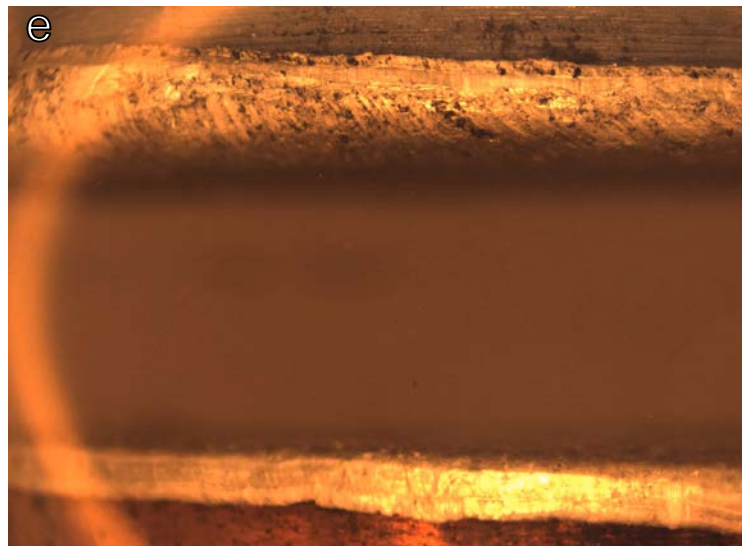


Lithium dendrite growth

Lithium Dendrite Imaging



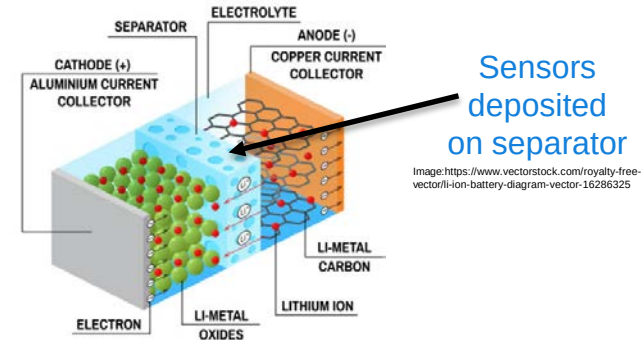
(a-d) SEM images of Li metal
cycled in symmetric cell
(e) Optical cell time-lapse of
dendrite growth during abuse



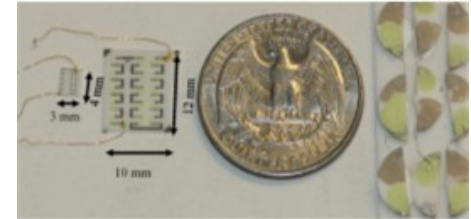
SENSOR DEVELOPMENT

Sensing Objectives/Challenges

- Sensors embedded within the battery monitor a range of parameters and changing conditions
- Functionality in battery environment
 - Deposition onto porous separator may create fabrication & adherence challenges
 - Electrolyte/chemicals may interfere with functionality & survivability of sensors
- Minimal impact on battery functionality while communicating key battery health data



Miniaturization Example

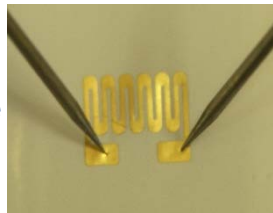


Hand fabricated (baseline), shadow mask, and photoresist processing

Sensor Development Status

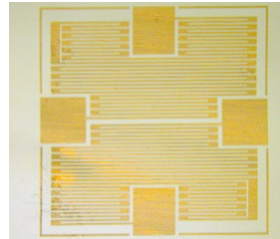
- Four sensor materials successfully deposited on separator
 - Au, Pt, Ti, and NAFION
- Sensors can be deposited on both sides and in multiple locations on the separator, and are operational in electrolyte
- Good adherence; continuity verified by resistance measurements
 - Shadow mask and photoresist processing can be used for sensor processing

Au serpentine pattern
produced by shadow mask



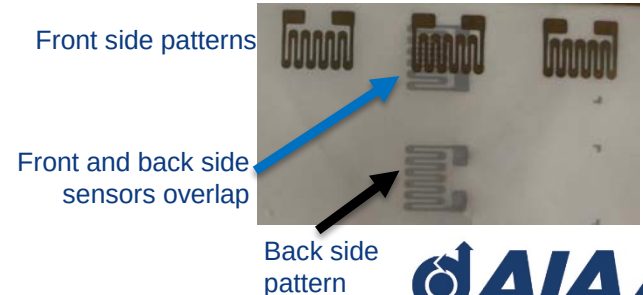
4.3 x 2.3 mm;
370 μ m line
width

Au strain mask pattern produced
by photolithography process



6.4 x 6.4 mm;
~50 μ m line
width

Sensor patterns on separator



Front side patterns

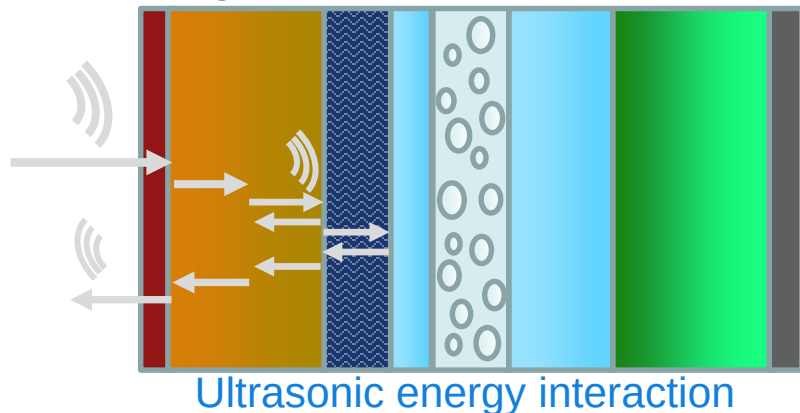
Front and back side
sensors overlap

Back side
pattern

NONDESTRUCTIVE EVALUATION

In-service and Off-line Monitoring

- X-Ray CT for “as-built”, baseline, and off-line inspections
- Ultrasonic signals continuously scan for damage precursors in service
- NDE modeling to optimize, predict, and quantify energy-damage interaction

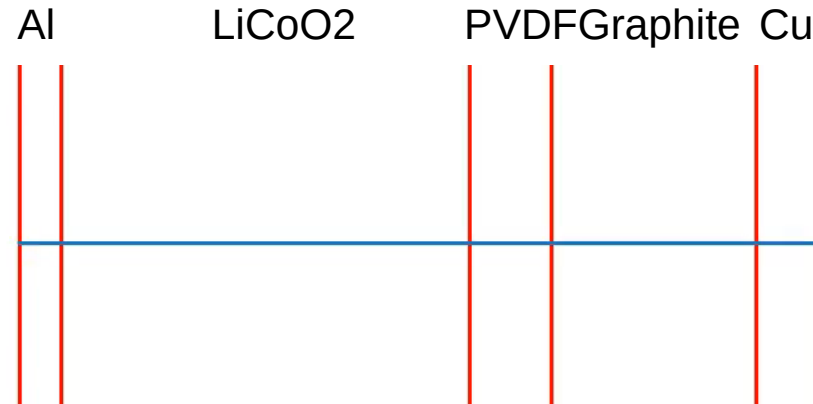


Example: UT sensor
7mm Diameter
0.2mm thick

Physics-based NDE Modeling

- Modeling the energy-material interaction
 - 1D Elastodynamic Finite Integration Technique to simulate bulk wave inspection of multi layer material
 - Predict changes in material state using inverse problem solving
 - 3D solvers to simulate guided wave inspection in full batteries cells
 - Inform in-situ inspection results
 - Simulation of X-Ray inspection
 - Define limits of damage detectability
 - Optimize system parameters

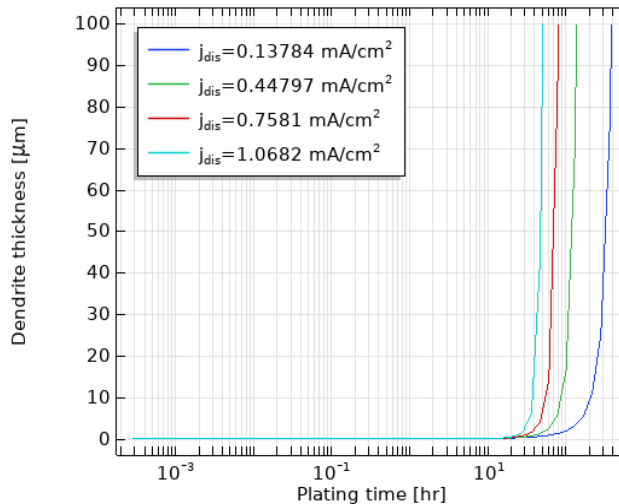
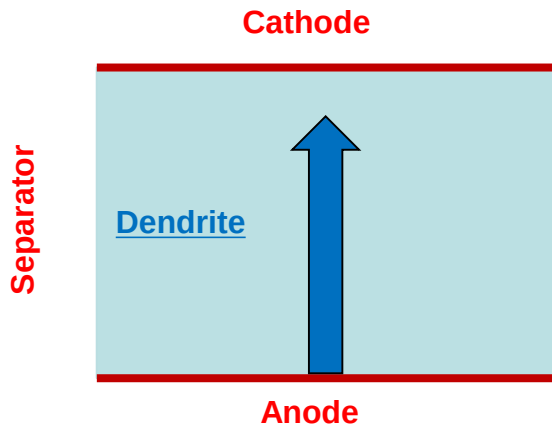
1D Ultrasonic
simulation example



BATTERY MODELING & FAILURE PROGNOSTICS

Multiphysics Modeling and Prognostics Approach

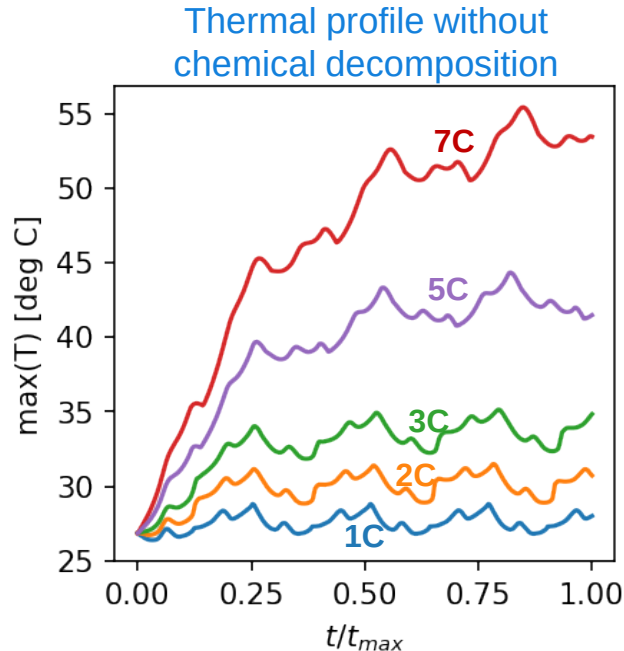
- Identify and model physics-based battery failure modes
- Identify and model cell-based response functions for failure detection
- Develop prognostic algorithms for failure predictions
- Utilize machine learning to help differentiate nominal vs off-nominal



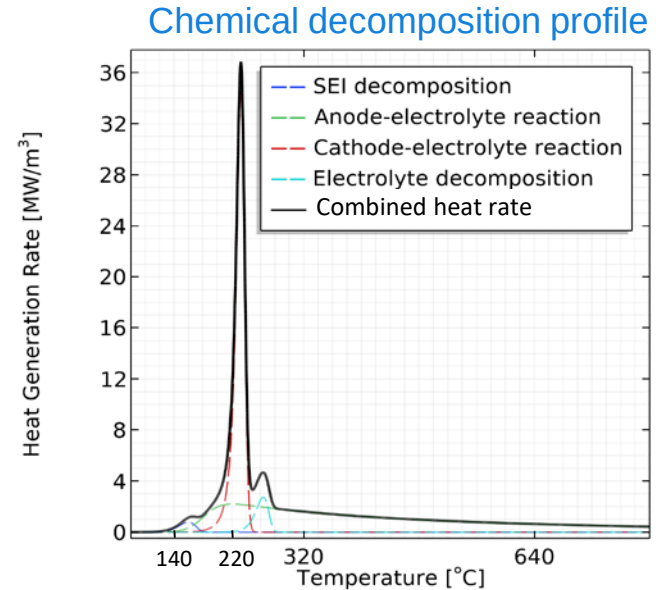
- Model predicts dendrite growth vs time
- Cell short-circuits when dendrite spans 100 μm separator

Thermal Response + Decomposition Kinetics

- Thermal response due to thermodynamics, ohmic, and electrochemical heat components



- Exothermic decomposition reactions
- Temperature rise during short circuit is often followed by thermal runaway



SUMMARY

System-level Impact

Existing solutions reduce severity but NOT likelihood of battery failure

- **Detect** failure mechanisms and **avoid** fires
 - Early warning from **within** cell
- Improved aircraft performance
 - Better state-of-health resolution
 - Enhanced reliability
- Accelerated introduction of next-generation chemistries
- Weight reduction

Safe Batteries



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