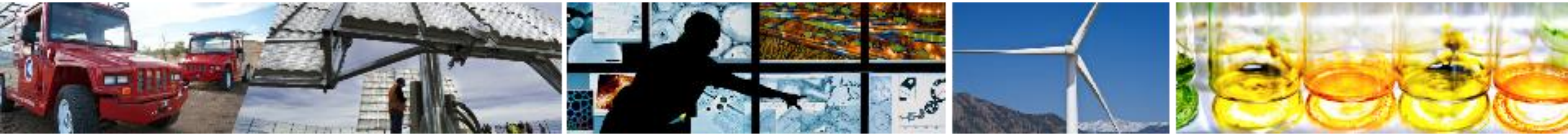
Project ID #bat298

June 12, 2019

Efficient Simulation and Abuse Modeling of Mechanical-Electrochemical-Thermal Phenomena in Li-Ion Batteries

PI: Kandler Smith, Presenter: Shriram Santhanagopalan

National Renewable Energy Laboratory



Team: Nathaniel Sunderlin, Kae Fink, Chuanbo Yang,
Qibo Li, Andrew Colclasure, **National Renewable Energy Laboratory**
Joshua Lamb, Loraine Torres-Castro, **Sandia National Laboratories**
Daniel Abraham, Andrew Jansen, Dennis Dees, **Argonne National Laboratory**
Kelly Carney, **Forming Simulation Technologies LLC**
Amos Gilat, Jeremy Seidt**, Ohio State University**

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

This project was originally awarded in response to VTO FY15 Lab Call. Since then it has attracted partnerships from the Industry and other government agencies.

Timeline

- Project start date: Oct. 2015
- Project end date: Sept. 2019
- Percent complete: 90%

Budget

- Total project funding: $ 3.35M
  - DOE share: 100%
- Funding received in FY 2016: $1.05M

  Funding received in FY 2017: $1.05M

  Funding received in FY 2018: $ 600k

  Funding received in FY 2019: $ 650k

Barriers

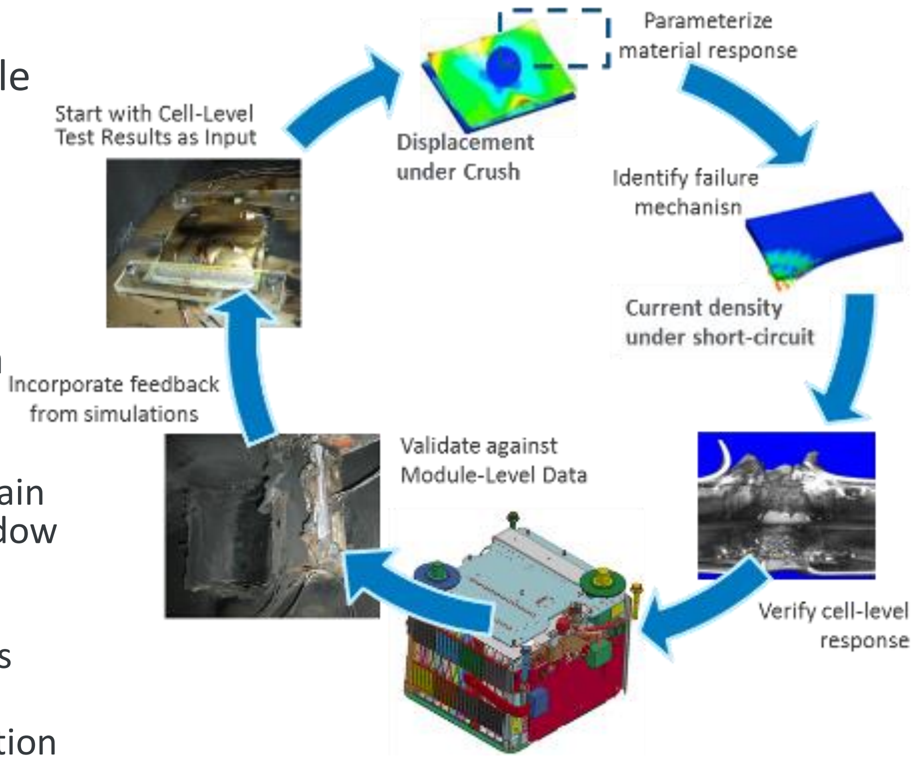
- Gap between modeling tools and cell design process in the industry
- Lack of simulation tools integrating mechanical failure and abuse response of batteries for practical assessment of battery safety
- Limited understanding of complex failure mechanisms resulting in expensive over-design of batteries

Partners

- Argonne National Laboratory (ANL)
  - Pouch cells and data for parameter estimation
- Sandia National Laboratories (SNL)
  - Cell-level mechanical abuse testing for validation of mechanical models
- Oak Ridge National Laboratory (ORNL)
  - Component level mechanical test data
- Forming Simulation Technologies (FST), Ohio State University (OSU), George Mason University (GMU)
  - Integration with LS-DYNA
- Crash Safety Work Group at USCAR
  - Feedback on models and test methods
- Lead: National Renewable Energy Laboratory (NREL)

Relevance

- VTO launched the Computer-Aided Engineering of Batteries (CAEBAT) project to develop validated modeling tools to accelerate development of batteries, in support of vehicle electrification R&D to reduce dependence on imported oil.
- Over 45 different end users from the community have adapted NREL's modeling approach developed under CAEBAT.
- In FY18, we implemented feedback from beta testing results to:
  - Expand identification of the model parameters (especially for mechanical properties) to high strain rates (up to 1000/s) and wider temperature window (as high as 180^{o}C)
  - Increase computational efficiency by integrating both the mechanical and electrochemical models into a single platform (LS-DYNA)
  - Simulate complex failure modes including validation of the propagation models using multi-cell test cases
  - Close gaps between materials R&D and CAEBAT modeling tools
- These additions have expanded our user base to include several new partners from the Industry as well as other government agencies.



CAEBAT models simulate a variety of practical operating conditions and abuse response characteristics of batteries, tightly integrating material development and pack level performance. Virtual design using advanced computational tools significantly reduces development time and cost of batteries.

Project Structure

Project Title: Computer-Aided Battery Engineering Consortium

Project Leader
NREL, Kandler Smith

Task 1 Computational Efficiency
PI: Shriram Santhanagopalan

- **Cell/Electrode Making**
  ANL, Daniel Abraham, Pierre Yao, Dennis Dees

Task 2 Mechanical ECT Models
PI: Shriram Santhanagopalan

- **Material Characterization**
  OSU, Amos Gilat
- **Abuse Testing**
  SNL, Joshua Lamb
- **Cell/Module Fabrication**
  ANL, Daniel Abraham
- **Integration with LS-DYNA**
  FST, Kelly Carnie; **GMU,** Paul Dubois

Task 3 Microstructure Modeling
PI: Kandler Smith

- **Microstructure Modeling**
  TAMU, Partha Mukherjee
- **Fabrication/Testing**
  ANL, Daniel Abraham, Pierre Yao

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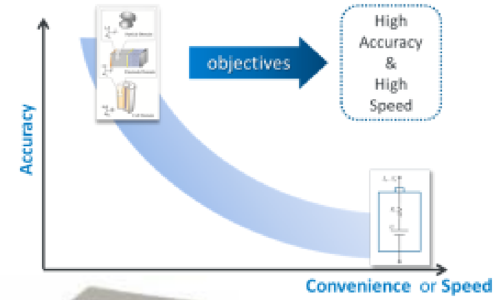
Relevance

Objectives for March 2017 – March 2018

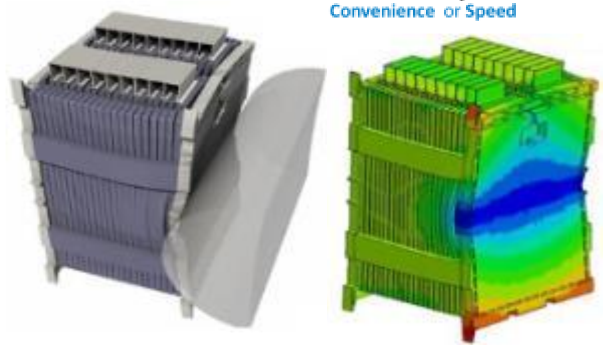


Computational Efficiency

- Integrate electrochemical simulations using user-defined elements in LS-DYNA to simultaneously solve electrochemical/thermal and mechanical models.

Mechanical-Electrochemical-Thermal (MECT) Models

- Include complex loading conditions such as high strain-rates and shear-induced failure
- Develop materials database for mechanical properties abuse scenario
- Present comparison of multi-cell propagation models



Initial demonstration of efficient thermal, electrochemical, and mechanical models

<u>Impact</u>: By making disruptive CAE design tools available on desktop computers for use by the battery community, this effort supports the following goals identified by the VTO:

1. Reduce the number and duration of battery test cycles in the industry to enable a path to \$80/kWh electric vehicle (EV) battery costs by drastically
2. Reduce module/pack costs by maximizing insight gathered on failure modes in batteries from a limited subset of tests currently performed

In FY18 alone, models developed by NREL under CAEBAT have been licensed out to 7 different entities.

Milestones

	Milestone Name/Description	Deadline	Milestone Type	Status
Computational Efficiency	M 1.2 Submit journal article investigating spatial heterogeneity due to electrode processing variations. Report on 3D microstructure electrochemical model algorithm enhancements for improved computational speed, accuracy, and scalability	12/31/2018	Qtr. Progress Measure	Complete
	M 1.2 Demonstrate electrochemical models enhanced with mechanical and/or multi-reaction mechanisms with application to VTO materials research	09/30/2019	Qtr. Progress Measure	On Track
Mechanical Abuse	M 2.1 Document implementation of mechanical abuse simultaneous coupling in the form of case studies (.k files) that can be distributed to end users	03/31/2019	Annual SMART Milestone	Complete+
	M 2.2 Present final report on the MECT models at the Vehicle Technologies Office Annual Merit Review	06/30/2019	Qtr. Progress Measure	On Track

+ We have made these .k files available for licensing on the DOE's Tech Transfer Portal.

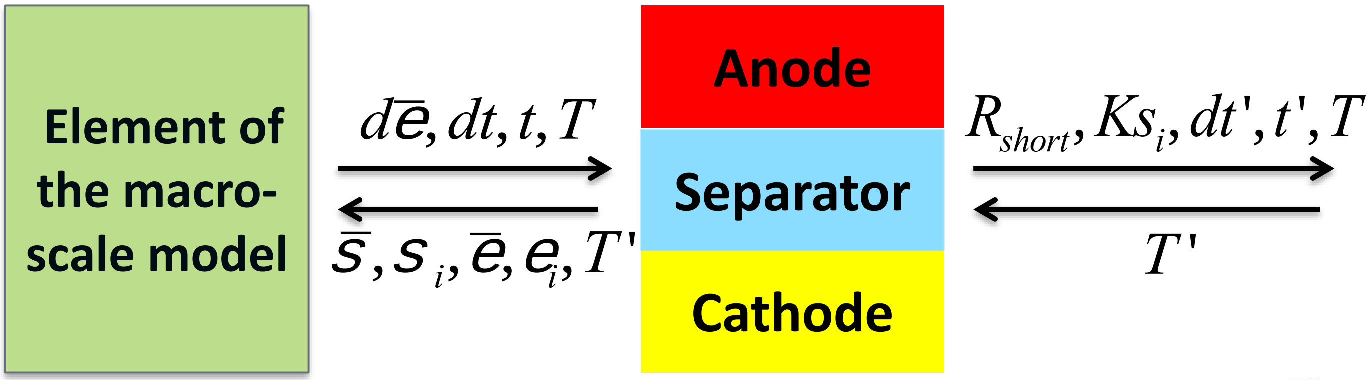
Based on comments from previous year's AMR Reviewers and feedback from beta testing of these models, we performed additional experimental measurements to characterize mechanical properties of electrodes at higher strain rates and under failure due to shear on top of the scheduled test plan for this milestone.

In FY18 we have included material degradation with cell-aging *across a period of six years*, as well as *mechanical response at temperatures as high as 180°C*, making this the most comprehensive materials database for battery cell components.

Task 1 – Computational Efficiency

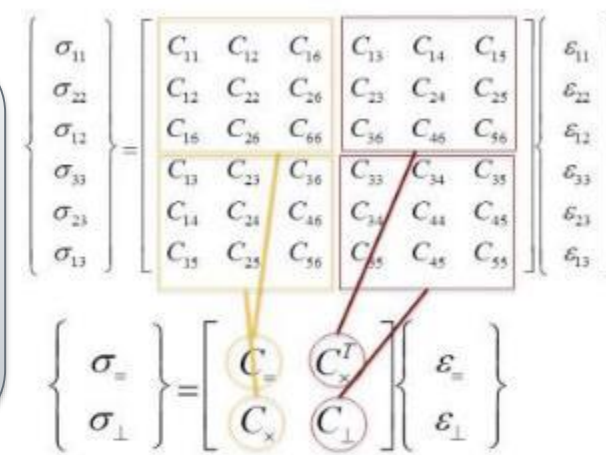
Approach: Multiscale Simultaneous Coupling

Macro-scale 3D homogenized mechanical-thermal model | **Meso-scale quasi-3D mechanical-thermal model** | **Pseudo 2D electrochemical-thermal model**



C. Zhang, J. Xu, L. Cao, Z. Wu, S. Santhanagopalan, 2017. *Journal of Power Sources*, 357, pp. 126-137.

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}$$



Approach for Coupling Methodology

- Retain fidelity of damage models at the component level (e.g., separate failure criteria for separator, current collector, etc.)
- Solve for potential and temperature as additional degrees of freedom at the component scale
- Simulate multi-cell effects using a micro-mechanical homogenization scheme

In FY18, we implemented the above computational scheme using:
i) user-defined material models (loosely couple the electrochemical-thermal models with the mechanical response models)
ii) using custom user-defined elements that enable users to solve for concentration, potential and mechanical deformation in a tightly coupled simulation using LS-DYNA.

Approach: Constitutive Model Development

Step 1. Develop physics-based component models

$$\sigma_{ij,j} + \rho f_i = \rho u_{i,tt}$$

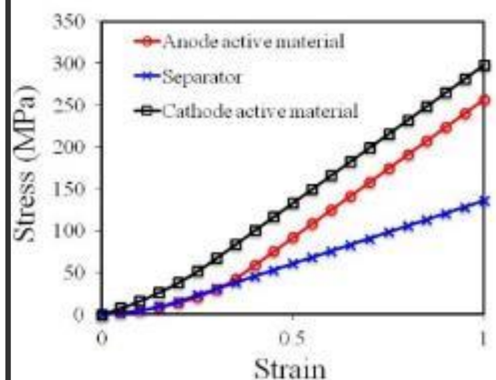
$$\sigma_{ij} = C_{ijkl}\gamma_{kl}$$

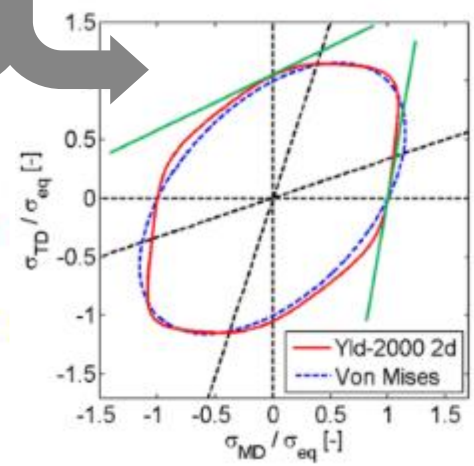
$$E = \begin{cases} E_{max} e^{\beta(\varepsilon - \varepsilon_p)} & \varepsilon < \varepsilon_p \\ E_{max} & \varepsilon \geq \varepsilon_p \end{cases}$$

Step 2. Obtain model parameters

Approach a:
Calibrate parameters out of component-level stress-strain data

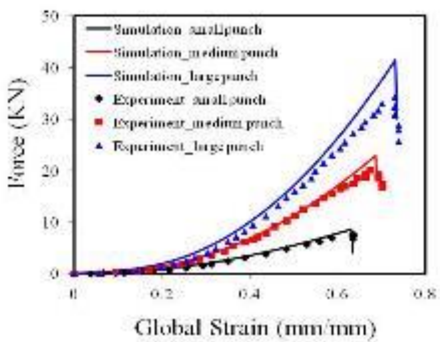
Approach b:
Phenomenological models for material properties





$$\bar{\sigma}(\sigma) = \bar{\sigma}(\sigma_{xx}, \sigma_{yy}, \sigma_{xy}) = \frac{1}{2^{1/a}}\left(|S_I' - S_{II}'|^a + |2 \cdot S_I'' + S_{II}''|^a + |S_I'' + 2 \cdot S_{II}''|^a\right)^{1/a}$$

Step 3. Validate against independent data set



Cell-level data vs. model

Allowing the direct use of experimental datasets measured from components (electrode, current collector, separator, etc.) as input to cell-level simulations, or cell-level data as input to module level simulations, the approach provides alternatives to developing time-consuming material models, if the users choose to do so.

FY18 Accomplishments: Implementation of User Defined Elements

- USRSLD is the main subroutine for solid elements
- It calls several other subroutines
- In FY18, we built demo cases to illustrate implementation for other types of elements

subroutine usrsld – Called from outside of dyn21b.f

subroutine usrsld_b – Compute b and g matrix

subroutine usld_b101 Element routine Compute b and g matrix (Needed to be reordered when xdof are used)

subroutine usrsld_b2b – Compute volume of integration point and "real" b matrix

subroutine usrsld_str – Compute strain and rotational increments

subroutine usrsld_grd – Compute deformation gradient

subroutine usrsld_frc – Internal force assembly

subroutine usrsld_kmt and usrsld_kgm – Assemble material and geometric stiffness

subroutine usld_m101 Element routine is called whether using usld_e101 (discrete) and usld_b101 (integrated) – Called from outside of dyn21b.f

Subroutines highlighted green were modified.

Subroutines highlighted red were not modified.

Several subroutines in LS-DYNA were modified to implement concentration and potential as additional degrees of freedom. Six case studies were built for distribution to end-users, to illustrate capabilities of our implementation.

FY18 Accomplishments: LS-DYNA Card for Electrochemical Parameters

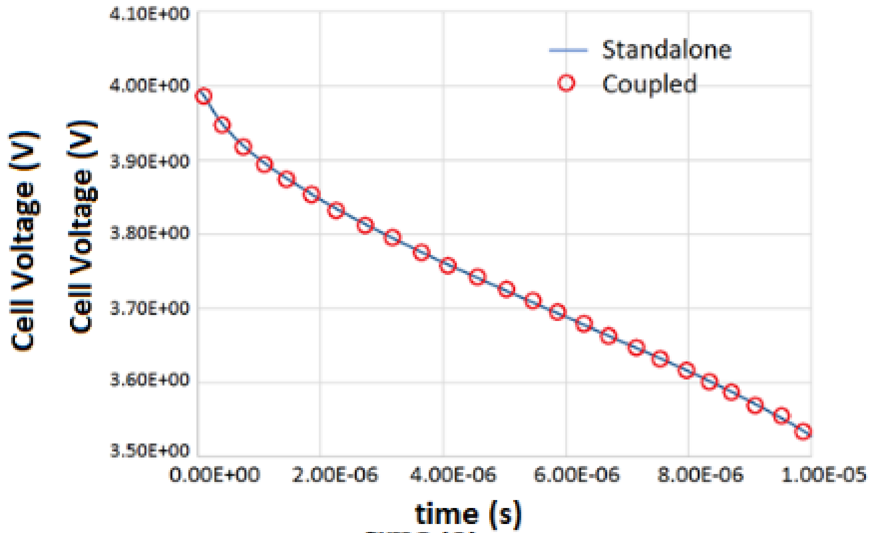
- Electrochemical parameters can now be input using the *MAT_USER_DEFINED data card in the keyword file, alongside mechanical properties:

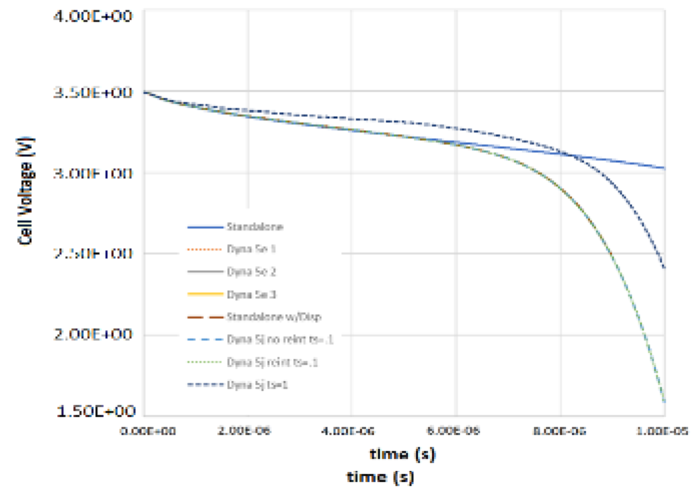
```
*MAT_USER_DEFINED_MATERIAL_MODELS
$#     mid        ro        mt       lmc       nhv    iortho     ibulk        ig
         4 1.0000E-6        41        37         4         0         3         4
$#   ivect     ifail    itherm    ihyper      ieos
         0         0         0         0         0
$#       E        PR         K         G    IREINT     ALPHA
  100.0000   0.20000  106.6667     160.0         0    1.E-9
$#     EMA       PRA   POROA0    ATHICK       EMS       PRS  NOT_USED    STHICK
  0.320e+3  0.000000      0.36     0.130  0.320e+3  0.000000      0.36     0.020
$#     EMC       PRC   POROC0    CTHICK     RSPOS     RSNEG      DSOL   POROPOS
  0.320e+3  0.000000      0.36     0.110   8.0E-06   8.0E-06  7.5E-10 0.385E+00
$# POROSEP   PORONEG  SIGMAPOS  SIGMANEG     DSPOS     DSNEG      KPOS      KNEG
 0.724E+00 0.485E+00 100.0E+00 100.0E+00   1.0E-14   3.9E-14 2.334E-115.0307E-11
$THETA0POS THETA0NEG      RSEI     TPLUS      VCUT
 .4555E+00 .9551E+00  1.23E-04 0.363E+00   2.0E+00

E and PR are currently not being used
K and G are being referenced on ibulk and ig on
the first card, and they determine the timestep

$ IREINT - REINITIALIZATION AT EVERY TIMESTEP
FLAG
$ 0 - NO REINITIALIZATION
$ 1 - REINITIALIZATION AT EVERY TIME STEP
$ ALPHA - CELL THERMAL DIFFUSIVITY
```

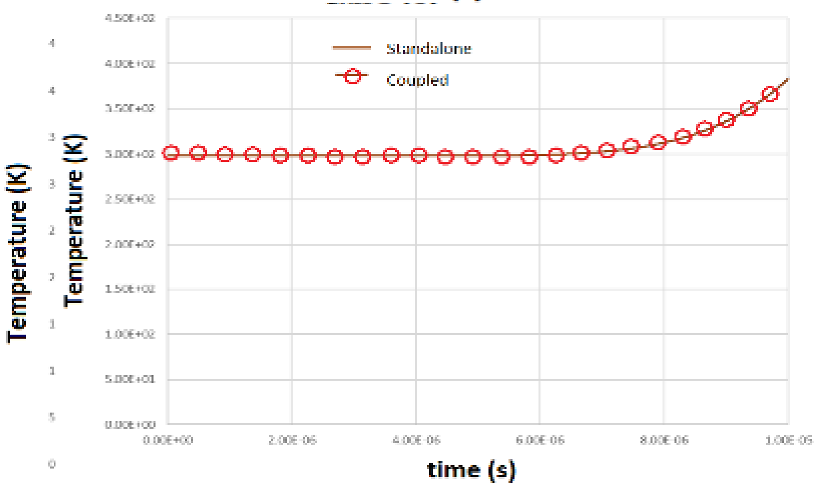
UMAT Mechanical Properties (In red)

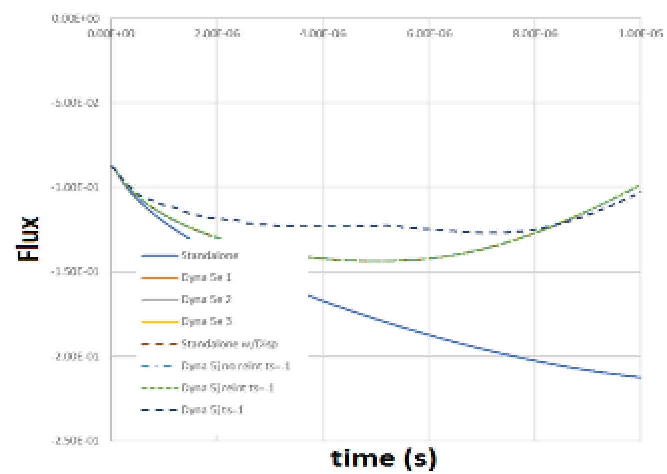
UMAT Electrochemical Properties (In green)

FY18 Accomplishments: Simulation results from User-Defined Elements









On 120 cores of NREL's HPC machine (Peregrine), simulation of single cell response on the 3D prismatic geometry takes ~23 minutes

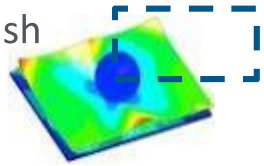
Memory allocation, array numbering scheme and a few other issues still being finalized.

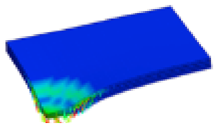
Task 2 – Mechanical-Electrochemical-Thermal Modeling of Abuse Phenomena

Approach: Mechanical Modeling

<u>Objective:</u> Predict battery behavior during a crash event to optimize safety and weight reduction

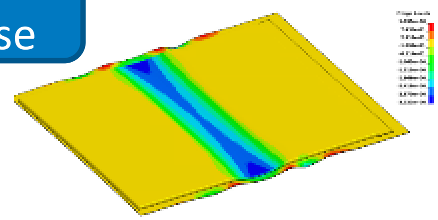
Displacement under Crush



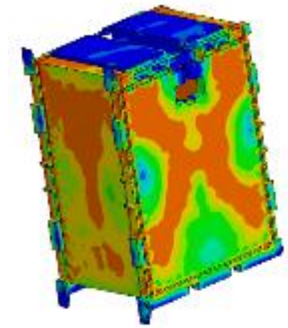


<u>Step 2:</u> Explicit simulations parameterize material response

Predicts cell temperatures to $\pm 10^{o}$C



<u>Step 4:</u> Scale to module level



Current density under short circuit

Photo Credits: Jim Marcecki, Ford

<u>Step 3:</u> Simulate cell-level response for multiple cases

<u>Step 5:</u> Validate against experimental data

<u>Step 1:</u> Start with component and cell-level test results as input

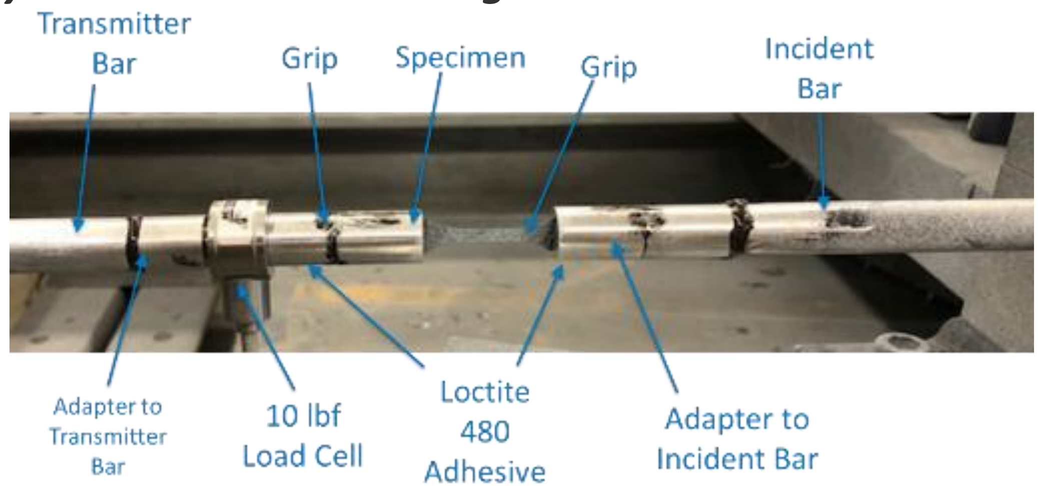
Goal: Identify localized failure modes and onset loads to within 30 MPa

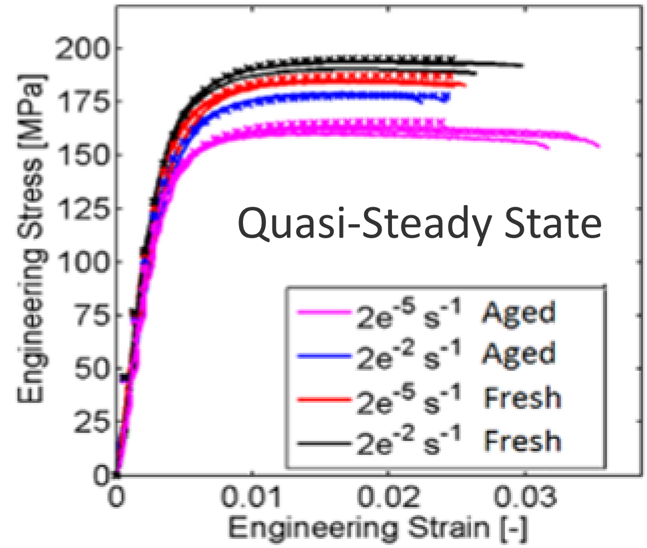
<u>Sample Input:</u>
- Stress-strain curves for cell components (separator, current collector, etc.)
- Failure strengths for particles
- Mechanical data for cell packaging
- Temperature vs. C-rate for cell
- Abuse reaction data from calorimetry for specific chemistries

<u>Sample Output:</u>
- Current distribution among the different cells within the module
- Localized heat generation rates far away from damage zone
- Stress distribution across multiple parts of the battery module

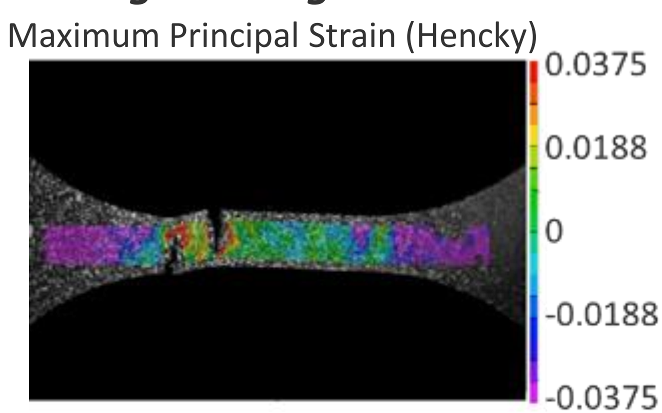
FY18 Accomplishments: Abuse Response at High Strain Rates

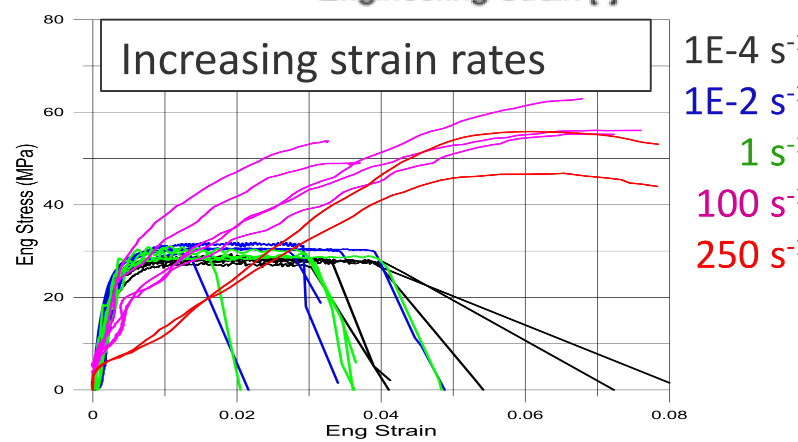
Dynamic Test Fixture Design





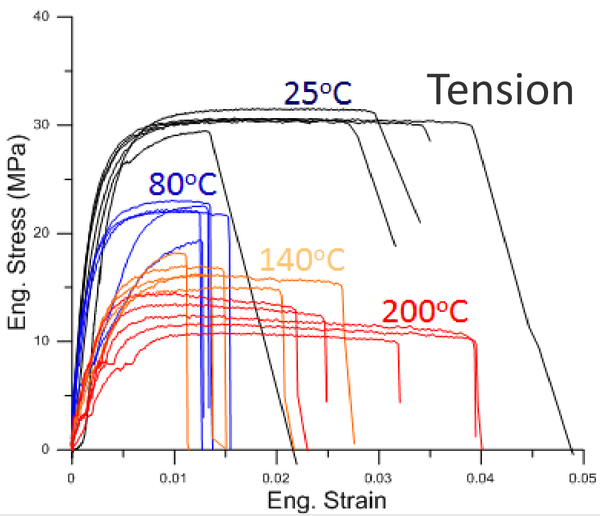
High-Speed Digital Image Correlation Data

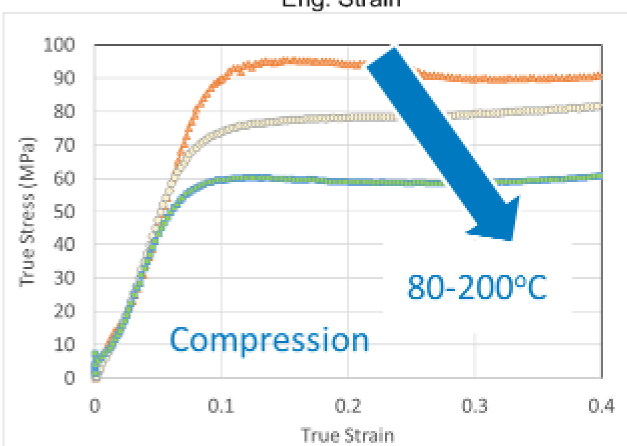




- In 2018, the team designed a test fixture to measure dynamic response of cell components at high strain rates (100-250 /s) in response to reviewers’ comments from the previous AMR.
- These results are currently being into cell-level models.
- Strain rates over 100/s show a different failure mode.

FY18 Accomplishments: Mechanical Response at Abuse-Temperatures





10 lbf load cell

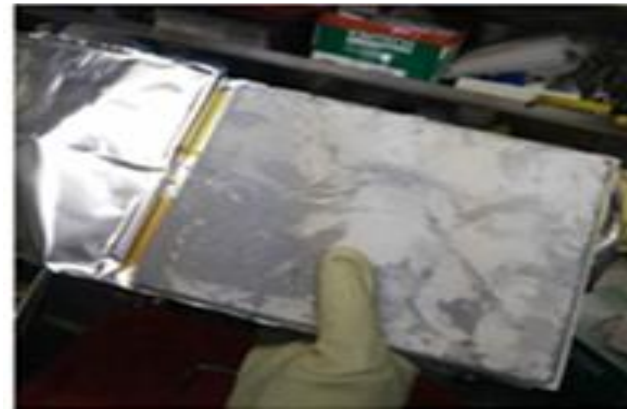
Ceramic Heating Element

Grips (same as long bar tests)

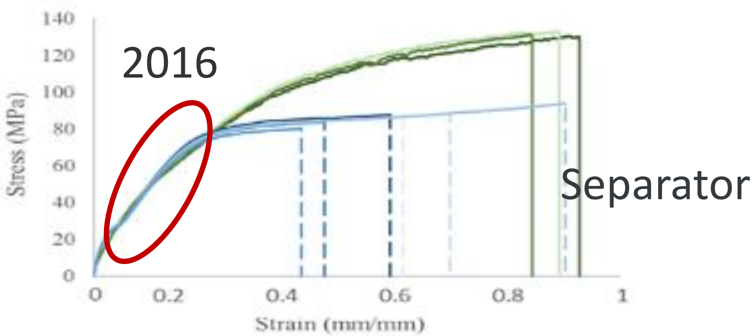
- All component-level test data available thus far only included limited temperature effects.
- For the first time, in FY18, we collected stress-strain data at <u>temperatures as high as 200°C</u>, making the constitutive models relevant to simulate deformation at abuse temperatures.

FY18 Accomplishments: Mechanical Response of Aged Cells

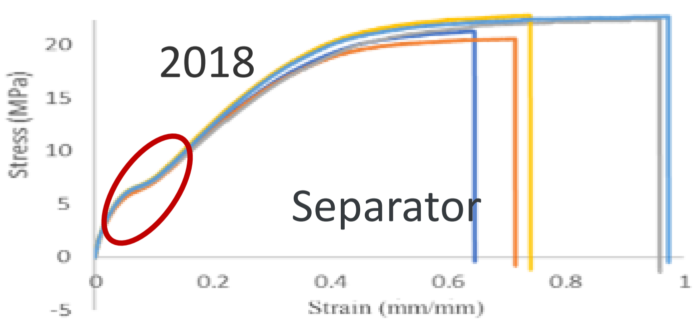
Cell #	C-rate	Voltage Window	Temperature	End of test Capacity (Ah)
0	Fresh	--	RT	42.4
1	1C/1C	4.1-3.0 V	45°C	37.31
2	2C/1C	4.1-3.0 V	25°C	32.87
3	1C/1C	4.2-3.0 V	25°C	33.3
4	1C/1C	4.2-3.0 V	23°C	32.11

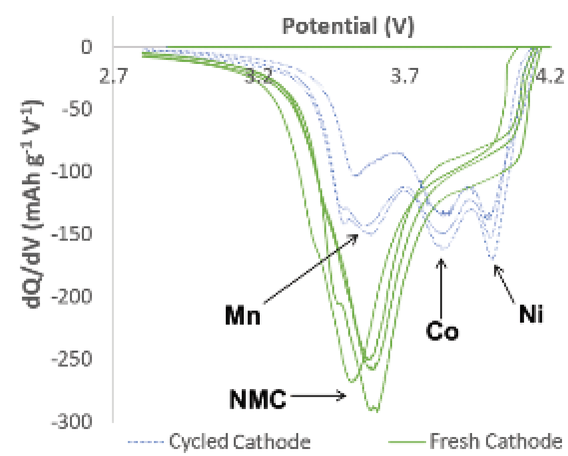


Cells were aged over an extensive period of <u>5 years</u> and periodically disassembled to measure changes in failure parameters with aging.



Delamination of plies

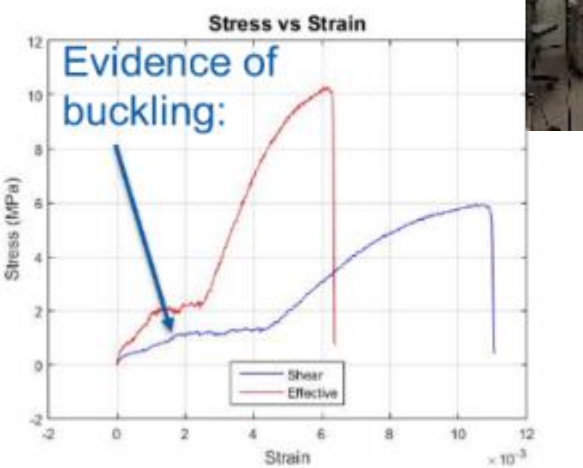


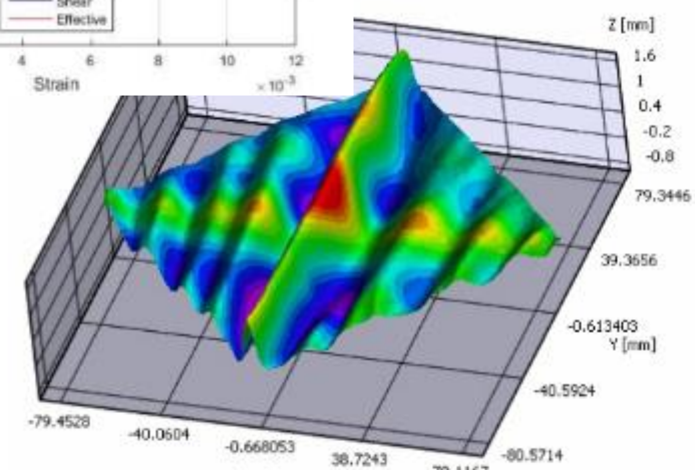


S. Santhanagopalan, L. Cao, J. Hartig, and Z. Wu, “Characterizing Battery Safety on Aged Cells." Invited presentation at the 231st Meeting of the Electrochemical Society, ECS Trans. 2018 77(11): 199-208; doi:10.1149/07711.0199ecst

In Plane Mechanical Properties

Picture frame test set-up following ASTM D8067 results in buckling of the samples in the out-of-plane direction.





Visual evidence of buckling from imaging data

- As part of understanding complex failure modes, we designed methodology to measure in-plane mechanical properties.
- These measurements will enable parameterizing criteria for shear-induced failure, for example. There is no test procedure, nor data for such failure modes in non-bonded composite thin film layers.
- However, this task still remains challenging – two different test fixtures are currently being evaluated. Samples buckle when using the picture-frame test and we are addressing edge effects when using the alternate fixture.

S. Santhanagopalan, Y. Chen, Q. Li, C. Yang, V. Babu, Y. Ding, “Dynamic Response of Lithium-ion Batteries Subjected to Mechanical Failure under High-velocity Impact” Presented at the Army Science and Technology Symposium (2018)

FY17 Summary of Cell-Level Validation Case Studies

Component Level				
Loading Conditions	Temperatures	Cathode Chemistries	Cell Formats	Orientations
8	1	2	2	3
5 of 8 (3 additional loading conditions were added after feedback from AMR last year)	Material models for cell components at RT are now available	2 (LCO, LMO/NMC)	1 (3 Ah Cells)	3 sets complete (Machine Direction Transverse Direction Diagonal Direction)

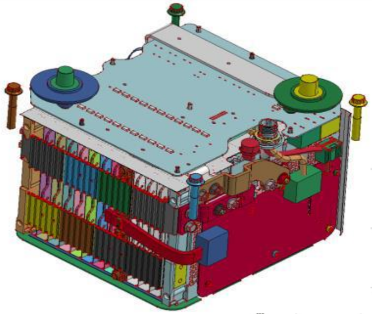
Cell Level				
Loading Conditions	Temperatures	Cell Chemistries	Cell Formats	Orientations
4	4	2	2	3
2 of 4 (Bending tests and drop tests still pending)	1 of 4	1 (LCO)	1 (3 Ah Cells)	Response for 2 through-plane orientations were validated (Diagonal Tests were new)

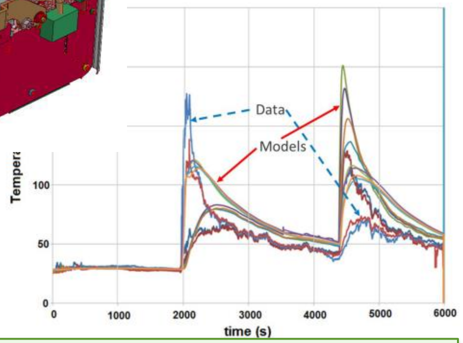
FY18: Multi-Cell Validation Case Studies

Protected information is covered in the Quarterly Reports to the DOE and not shown here.

- <u>*Case 1:*</u>
  - 5 Ah <u>LCO</u>/Graphite chemistry cells
  - <u>Pouch</u> format cells
  - 5 cells stacked back-to-back with <u>no electrical contact</u>
  - Aluminum and Copper cooling plates of different thicknesses (1/8", 1/4", ½")
  - Compression from the top; cylinder indentation (bar crush) from the sides
- <u>*Case 2:*</u>
  - 6 Ah <u>NMC</u>/Graphite chemistry cells
  - <u>Prismatic cells</u> with aluminum cans
  - <u>5S1P</u> (all cells <u>electrically connected</u> in series)
  - Blunt rod from the top and sides; different SOCs
  - Cells implanted with NREL's ISC device at different locations
- <u>*Case 3:*</u>
  - 32 Ah (<u>LMO+Li-Nickel-Oxide</u>)/Graphite chemistry cells
  - <u>Laminate</u> pouch cells
  - <u>2S2P</u> electrical configuration
  - Bar crush following USABC protocol for modules
- <u>*Case 4:*</u>
  - 16 Ah (<u>LMO+NMC</u>/Graphite) chemistry cells
  - <u>Pouch</u> format cells
  - <u>Modules</u> of <u>4Sx5P</u> w/ side and end brackets
  - Bar crush across two orientations

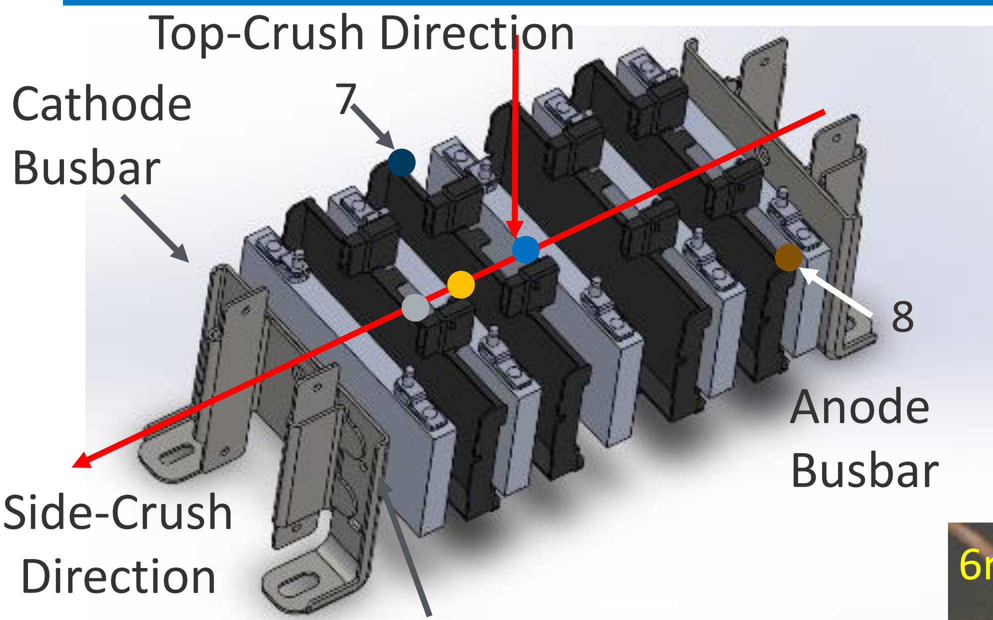
Q. Li, C. Yang, S. Santhanagopalan, K. Smith, J. Lamb, L.A. Steele, L. Torres-Castro, "Numerical Investigation of Thermal Runaway Mitigation in a Passive Thermal Management System," Submitted.

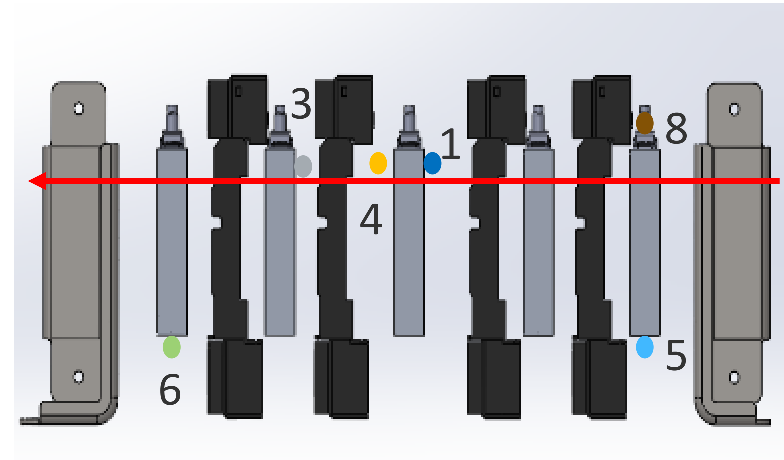


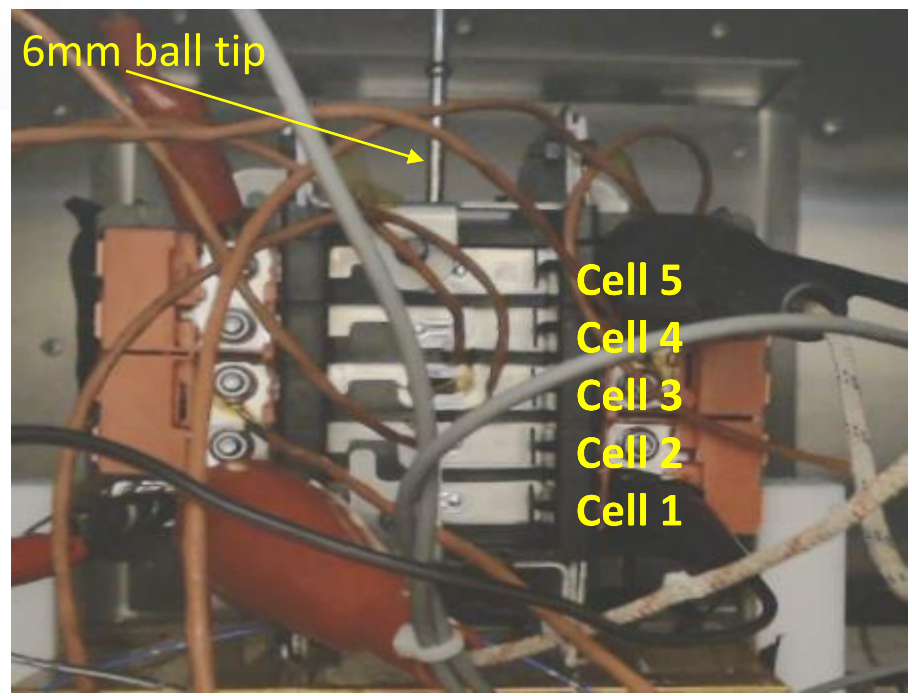


Y. Chen, S. Santhanagopalan, V. Babu, Y. Ding, "Dynamic Mechanical Behavior of Lithium-ion Pouch Cells Subjected to High-Velocity Impact", Composite Structures 2019, 218, 50-59.

FY18: Blunt-rod Test Simulations



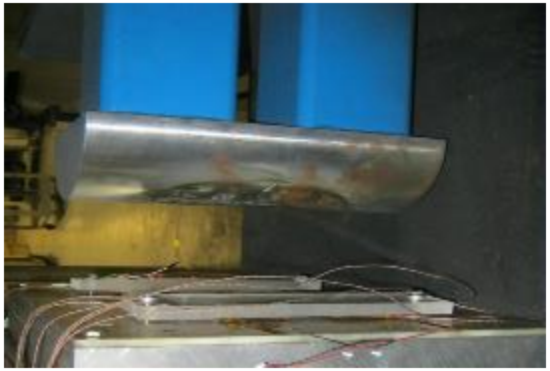


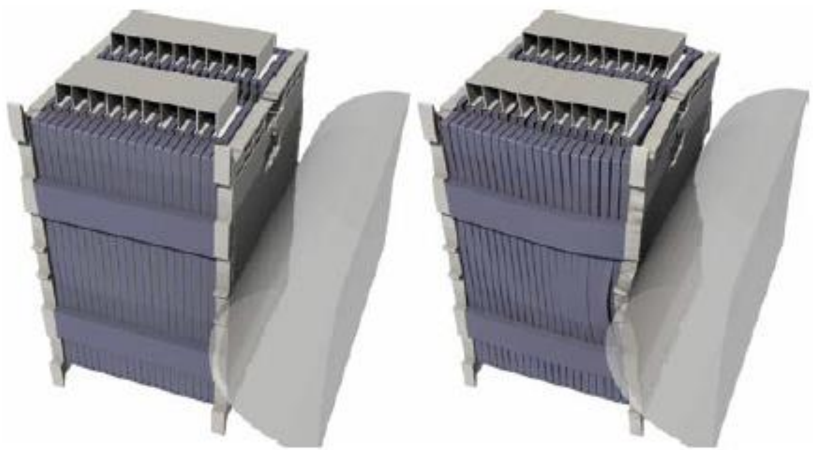


Test Set-up Description:

- 5S1P String of high-power 6 Ah Cells (NMC/Graphite)
- Module Voltage 17.75 V (60% SOC)
- Aluminum cooling plates
- Thermocouple locations (1-8) shown on schematic: TC2 recorded ambient temperature in the chamber
- Load cell capable of 50kN max. load
- EUCAR 2 response recorded for both top and side-crush

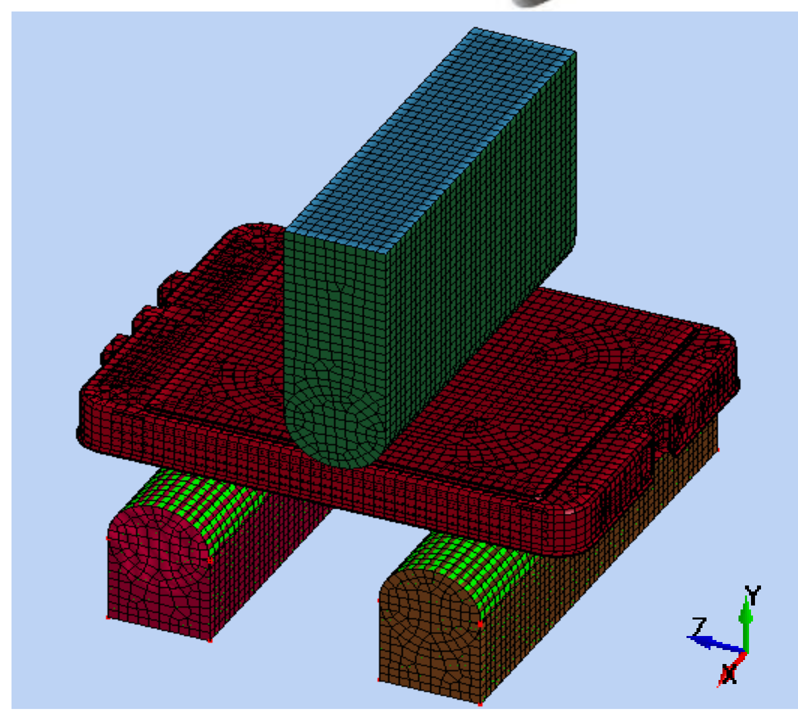
FY18: Other Validation Studies Underway





- 4S5P modules tested in earlier phase
- Data already available…
- Module level mechanical-only simulations completed under CAEBAT-II
- Coupling w/ ECT simulations being implemented

- Multi-axial Crush data from Nissan-Leaf Modules



Future Work....

- In FY19, we will emphasize expanding user-base for the models. The six case studies demonstrating the model capabilities will be listed with Lab Partnering Service and the DOE's Tech Transfer portal.
- The team will complete validation studies for multi-cell test articles.
- We plan on making a databank of mechanical response for cell components at various strain rates and temperatures available to the community.
  To the best of our knowledge, the high strain-rate data and high-temperature data presented in here is the most comprehensive characterization of mechanical properties of battery electrodes.
- We are planning a few more publications to include results from complex loading, high strain-rate results.
- Beyond 2020, with decommissioning of CAEBAT underway, we are working to integrate the modeling tools into various focused materials programs initiated by the DOE.

***Any proposed future work is subject to change based on funding levels.**

Response to Previous Year Reviewers' Comments

- Comment: The reviewer suggested that in the design of experiments, the Taguchi fractional factorial design, the project team needs to decide which factors (porosity, thickness, diffusivity) and levels of experiments need to be repeated to reduce time.
  Response: Following recommendations of this reviewer, the project team initiated a sensitivity analysis to determine which properties of the electrode control performance of the cell. These studies are included as part of Poster# bat299 presented by Kandler Smith.
  Based on the parameter sets identified by the modeling activity, the CAMP facility at ANL fabricated two rounds of electrodes under the extreme fast charge program as well.
- Comment: Part of the focus of the future work should be on the applicability of the work on the design of battery packs.
  The focus for FY18 has largely been on practical implications of the models.
  In addition to the dataset from SNL, we have recently teamed up with the Crash Safety Workgroup at USCAR as well as another OEM to demonstrate scalability of the models.
  In FY19, we will have access to experimental pack-level failure-propagation data which we hope to be able to leverage towards additional validation studies.

Response to Previous Year Reviewers' Comments (Contd.)

- Comments: The project plan to use dynamic loading tests to characterize failure at higher strain rates is more reasonable than static testing.
  The PI should also seek a discussion with some experts at SNL about strain-rate effects. There are researchers at SNL and Lawrence Livermore National Laboratory who do these strain rate effects (Split-Hopkins) measurements everyday.
  Response: In FY18, the team partnered with Ohio State University and George Mason University to generate realistic experimental data under dynamic loading conditions using the Split-Hopkins bar measurements.
  We have also reached out to our partners at SNL and ORNL, to create a common databank that can be used by researchers across the board.
- The heat-transfer model needs a little more work. The PI should set up some quick experiments to determine the thermal conductivity of each of the materials by themselves and then the bilayer conduction. The reviewer also proposed that the PI consider interface conductance.
  Response: In FY18, the team partnered with Ohio State University and George Mason University to generate realistic experimental data under dynamic loading conditions using the Split-Hopkins bar measurements.
  We have also reached out to our partners at SNL and ORNL, to create a common databank that can be used by researchers across the board.

Collaborators and Partners

Industry Advisory
USCAR/CSWG
Bill Stanko, Yibing Shi,
Saeed Barbat,
Guy Nusholz

Project Leader
NREL, Kandler Smith

Task 1 PI
Shriram Santhanagopalan

Task 2 PI
Shriram Santhanagopalan

Task 3 PI
Kandler Smith

Cell/Electrode Making
ANL, Daniel Abraham, Andrew Jansen, Dennis Dees

Material Characterization
OSU, Amos Gilat

Abuse Testing
SNL, Joshua Lamb

Integration with ANSYS and LS-DYNA,
FST, Kelly Carnie; **GMU,** Paul Dubois

Microstructure Modeling
TAMU, Partha Mukherjee

Fabrication/Testing
ANL, Daniel Abraham, Andrew Jansen

Key Contributors:
- Leigh Anna Steele, SNL
- Chris Grosso, SNL
- Jerry Quintana, SNL
- Loraine Torres-Castro, SNL
- June Stanley, SNL
- Genong Li, ANSYS
- Chuanbo Yang, NREL
- Qibo Li, NREL
- Nate Sunderlin, NREL
- Kae Fink, NREL
- Yanyu Chen, NREL

Summary

- **Task 1**. Computational Efficiency

  - Efficiency and stability of mechanical models was significantly enhanced by implementing electrochemical models into LS-DYNA using User-Defined Elements.

  - Six case studies were built and licensed out to participants from Industry for initial testing and their feedback is being incorporated into these tools.

- **Task 2**. Simultaneously coupled mechanical-electrochemical-thermal model for mechanical abuse simulation
  - Dynamic response of the cells was incorporated by measuring mechanical response of components at strain rates as high as 250 /s.
  - Temperature range for property measurements was expanded (as high as 200^{o}C) to account for property changes at high temperatures experienced by cell components under battery abuse.
  - Multi-cell validation has been expanded to include four different sets of experimental data, with support from various partners.
  - Complex failure modes and fracture response are currently being investigated. These are still very challenging, given the limited amount of prior work available in the literature.

Acknowledgements

- We appreciate support and funding provided by Vehicle Technologies Office at the U.S. Department of Energy
  - Brian Cunningham
  - Samuel Gillard
  - David Howell

Thank You 5,12,17,24,28,41-43

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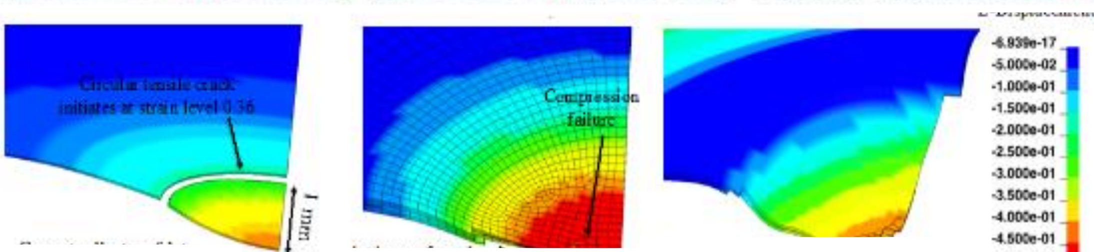
PR-5400-71207

Technical Back-Up Slides

Mechanism of Failure Initiation Following a Crush

Side facing the indenter



Copper foil Layer 1
Failure of Copper Foil

Anode Layer 4

Cathode Layer 6
Cathode-Anode Short

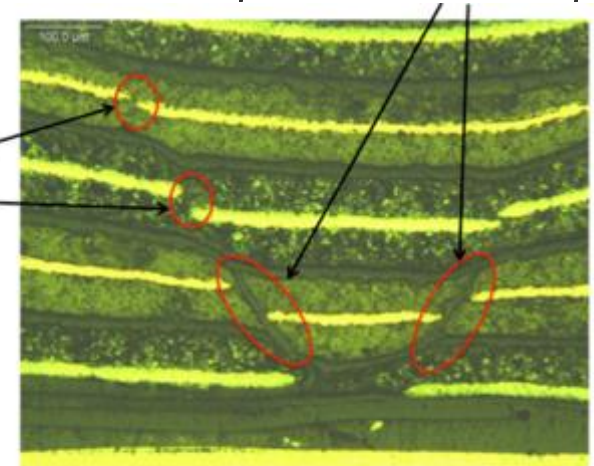
C. Zhang et al., *J. Power Sources*, Accepted (Mar. 2017)

Sahraei et al. *Journal of Power Sources*, 2014

Cell-level crush tests used to have a "pass" or "fail"

Shear failure of active material layers within a battery

Copper foil fails before separator ruptures

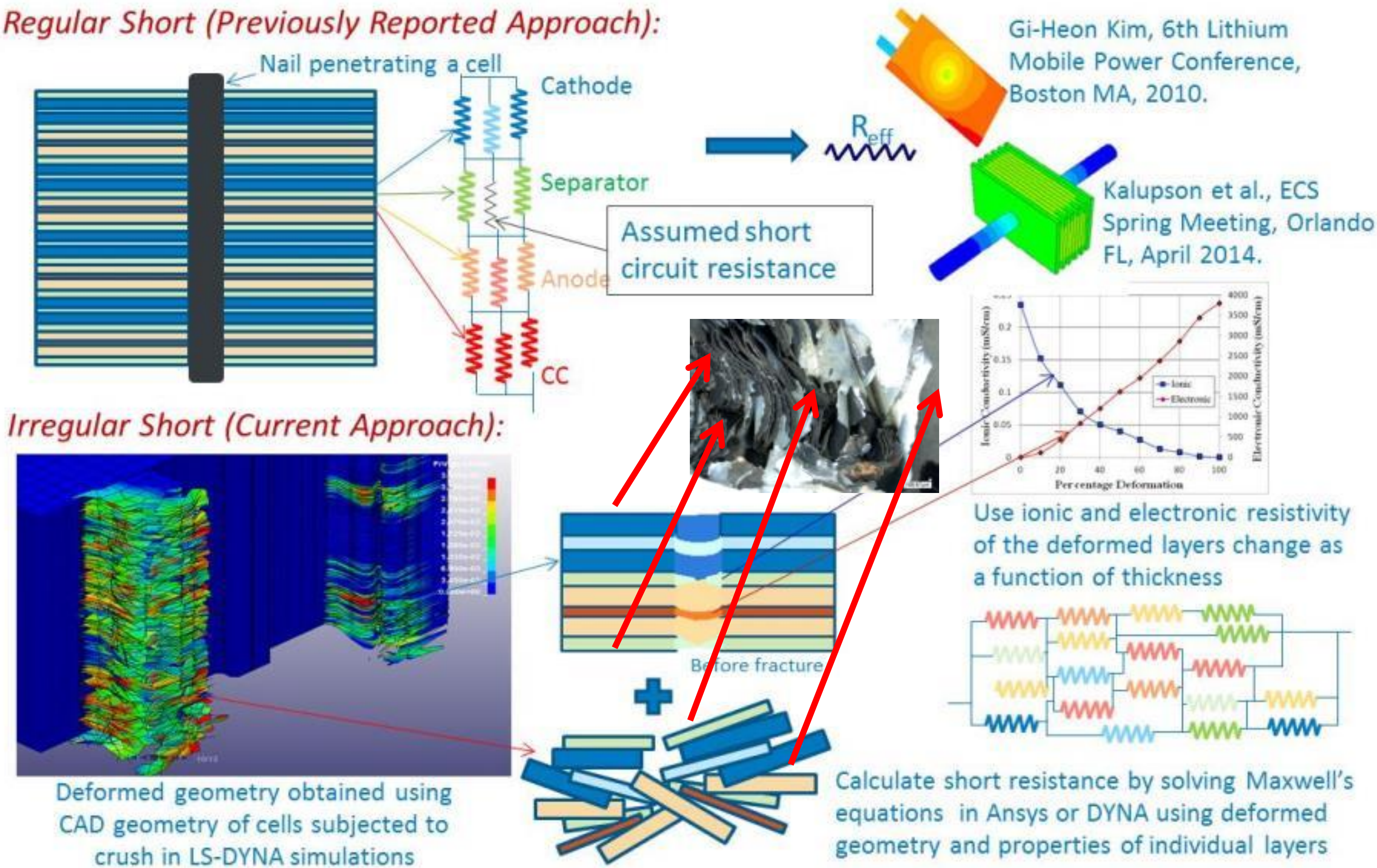


Wang, Shin et al., *Journal of Power Sources* 306 (2016): 424-430.

<u>Outcome</u>

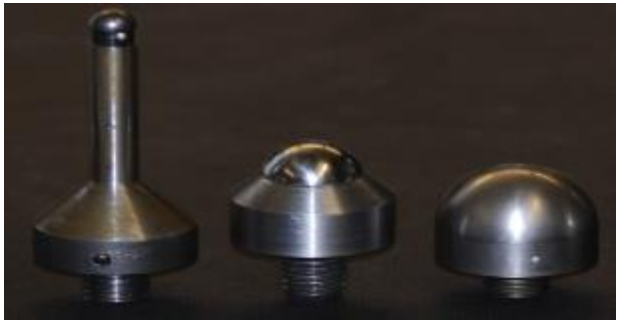
- Comprehensive understanding of failure thresholds and propagation mechanism for each component within the cell
- Better explanation of test data results and recommendations for test methods
- Light-weighting/right-sizing of cells without compromising safety

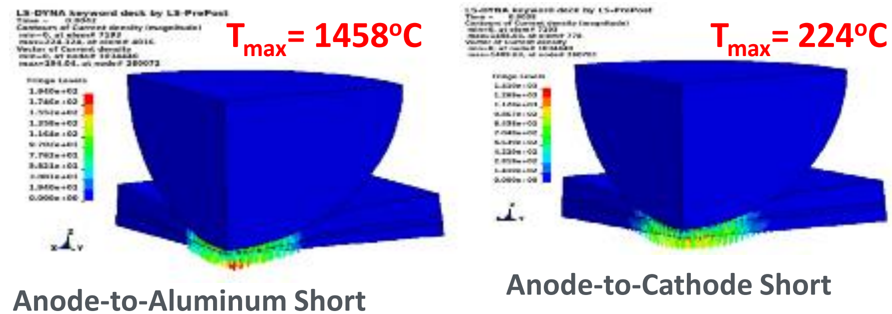
Estimating Short-Circuit Resistance



Cell-Level Results

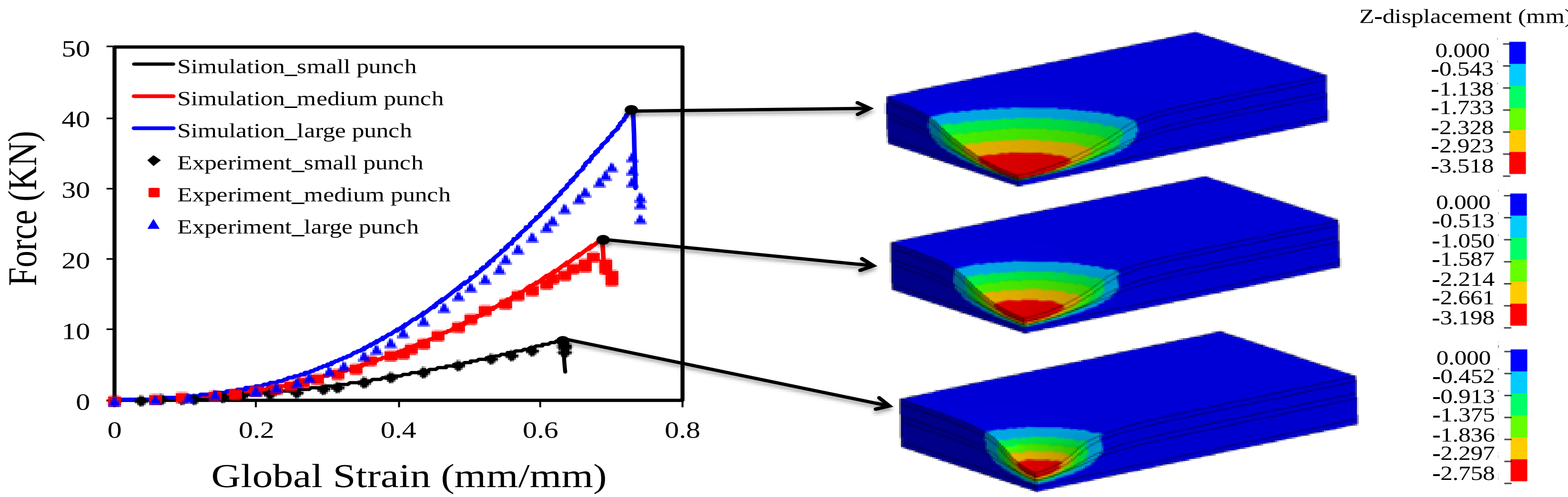
Sahraei et al., *Journal of Power Sources,* 2014





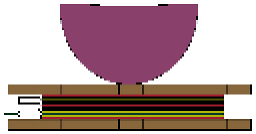
Cell Thermal Response under various types of short-circuit

S. Santhanagopalan, Presented at the International Battery Seminar & Exhibit, 2017.



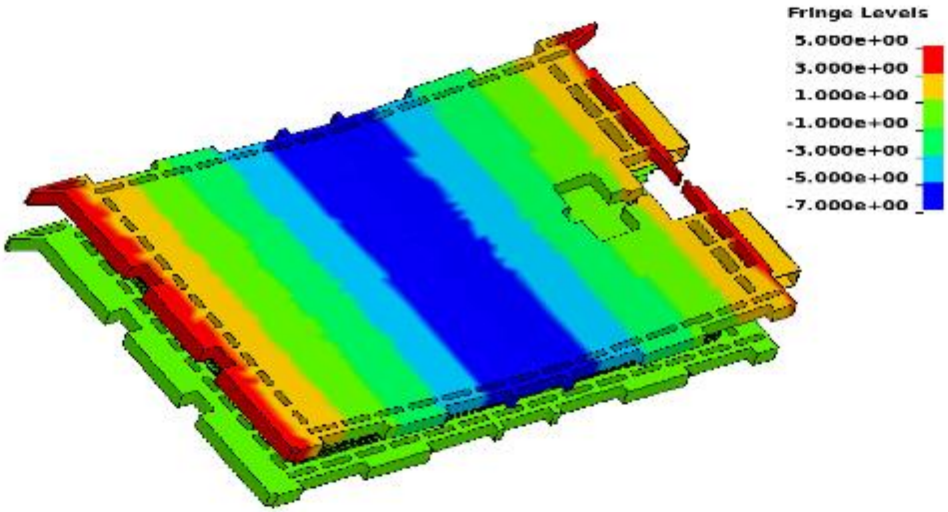
Models adequately capture mechanical and thermal response under different test conditions.

Multi-Cell Simulations: Sample Results

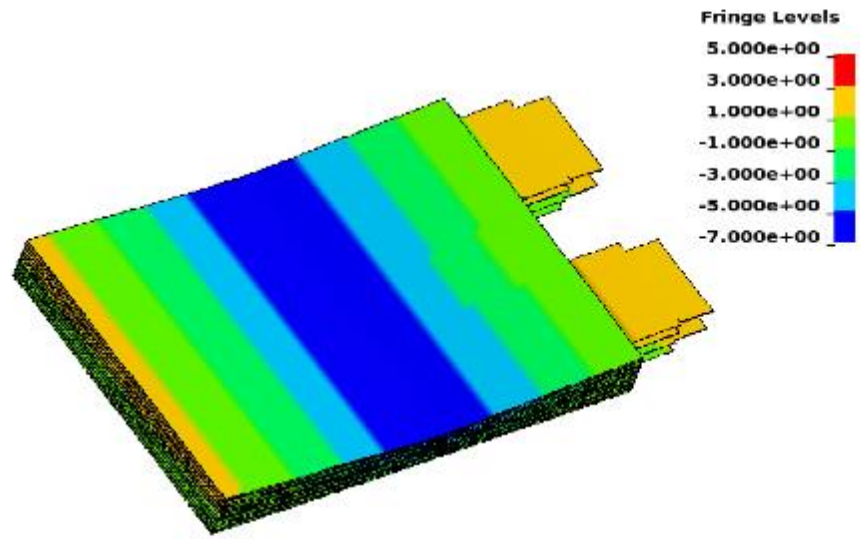


S. Santhanagopalan, Presented at the International Battery Seminar & Exhibit, 2017.

Deformation of packaging material



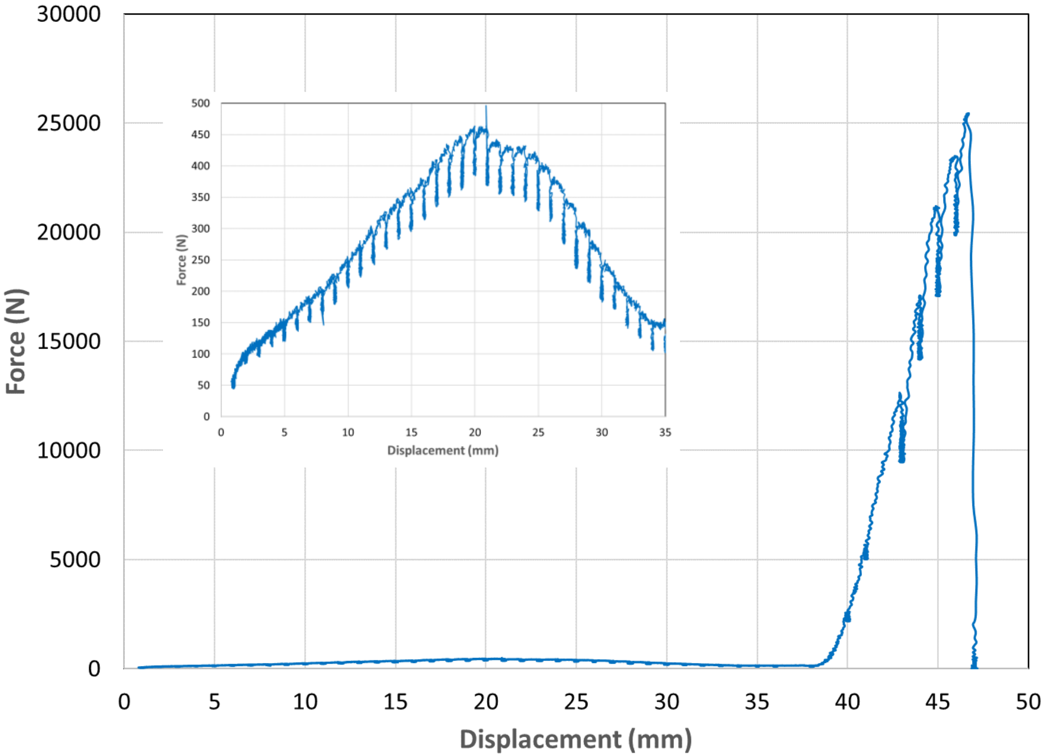
Deformation of the cells



Models show that:

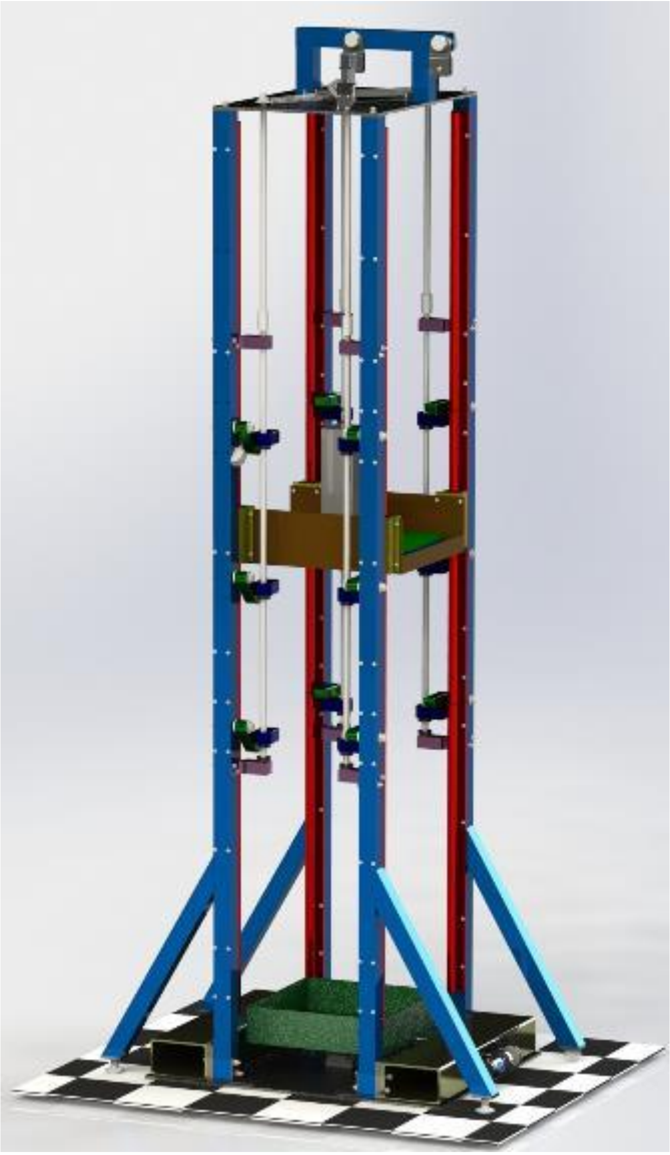
- The packaging can prevent deformation of the cells by as much as 50% under these crush test conditions.
- There is a significant scope to lightweight the pack even after the safety threshold is met.

Three-Point Bend Test – Fully Charged Cell



- Bend portion of test shows a yield of ~450 N.
- Cell failure required a compressive force of ~25 kN.
- “Pre-load” portion of bend observed where initial compression is applied to cell before bending occurs.
- After yield of cells to bend, the cell is put into compression.

Drop Tower – Impact Tester



Specifications:

- Overall height: 14 feet (4.3 m)
- Drop height: up to 10 feet (3.1 m)
- Drop weight: 50 to 500+ pounds (22.7 – 226.8 kg)
- Max impact velocity ~ 25.4 ft/s (7.74 m/s)
- Impact force (assuming a 6” stopping distance): 10,000 lbs-f (44,482 N)
- Remote operation
- Data collection:
  - Displacement
  - Impactor velocity
  - Force at impact
  - Temperature
  - Voltage

Figure Credit: Joshua Lamb, SNL

Drop Tower – Impact Tester

Current Status:

- ✓ CAD model – complete
- ✓ Drawing package – complete
- ✓ Hardware bill of materials (BOM) – complete
- ✓ Controls box design – complete
- ✓ Controls BOM – complete
- ✓ BATLab personnel to order all controls hardware – near complete
- ○ Build request, including drawing package – submitted to contractor
- • BATLab personnel to order all hardware for build – waiting on contractor readiness
- • BATLab personnel to complete final assembly of drop tower – waiting on completion of contractor build

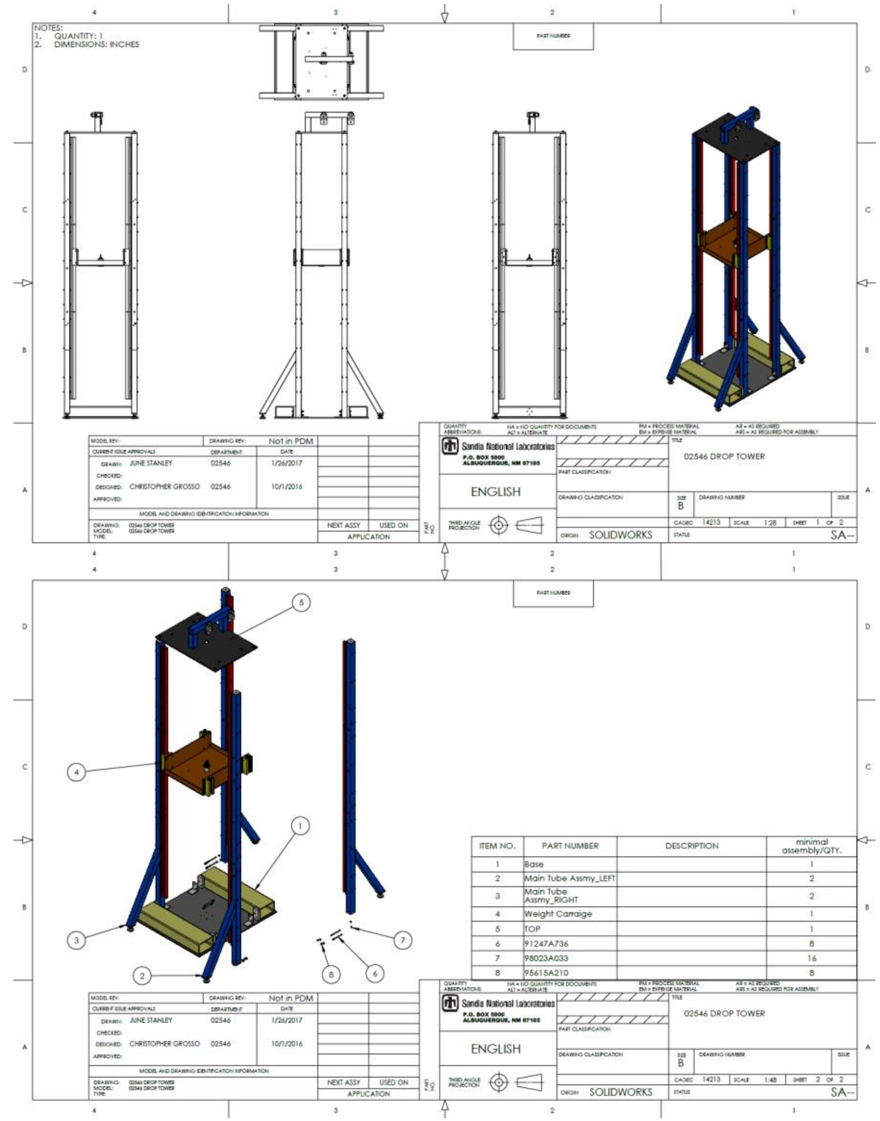


Figure Credit: Joshua Lamb, SNL