SAND2015-10740PE

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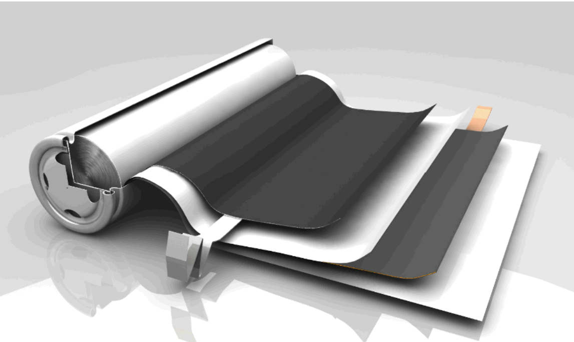
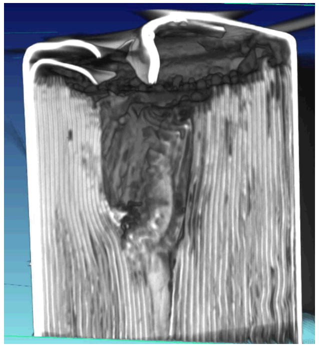

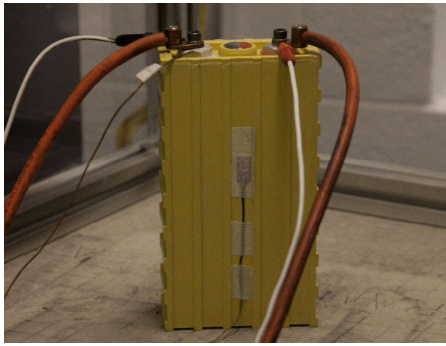

Battery Safety R&D at Sandia National Laboratories

Joshua Lamb and Christopher J. Orendorff

Sandia National Laboratories

NITE Visit

December 8, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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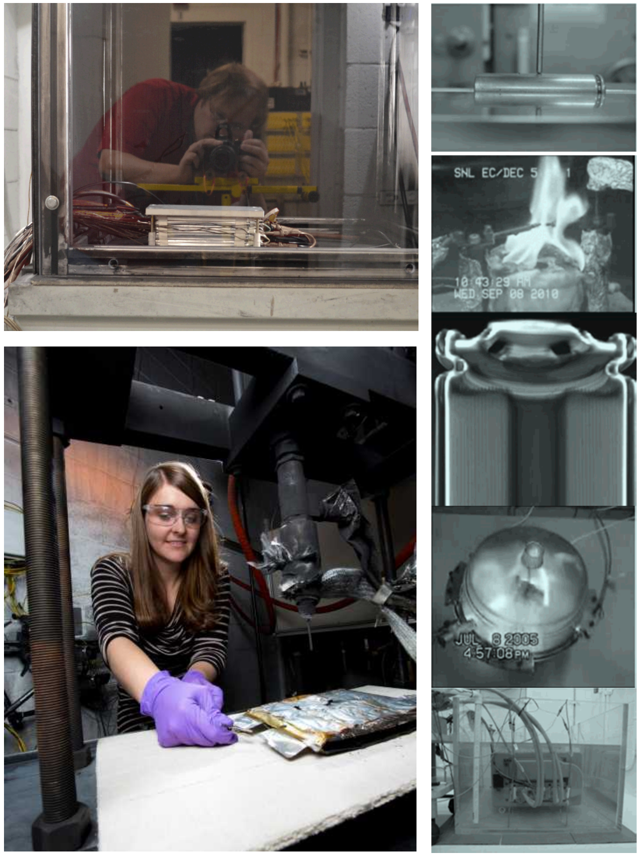
Capabilities and Infrastructure

- ***Battery Abuse Testing Laboratory (BATLab)***
- ***Cell Prototype Facility***
- ***Battery Calorimetry***
- ***Modeling and Simulations***
- ***Materials Development R&D***
- ***Thermal Test Complex (TTC)***
- ***Burn Site, Laurence Canyon***

Thermal Test Complex (TTC)

Battery Abuse Testing Laboratory (BATLab)

- **Comprehensive abuse testing platforms for safety and reliability of cells, batteries and systems from mWh to kWh**
- **Cell, module, and battery system hardware deliverables for testing**
- **Mechanical abuse**
  - **Penetration**
  - **Crush**
  - **Impact**
  - **Immersion**
- **Thermal abuse**
  - **Over temperature**
  - **Flammability measurements**
  - **Thermal propagation**
  - **Calorimetry**
- **Electrical abuse**
  - **Overvoltage/overcharge**
  - **Short circuit**
  - **Overdischarge/voltage reversal**



Burn Site Test Site

Full Scale Battery Testing Facilities

- ***Owned by SNL Fire Sciences Dept.***
- ***Design for large scale fire testing and high explosives (up to 100 kg)***
- ***Construction/design suitable for large scale battery abuse testing (10s of kWh Li-ion)***
- ***Fully instrumented data acquisition capabilities***

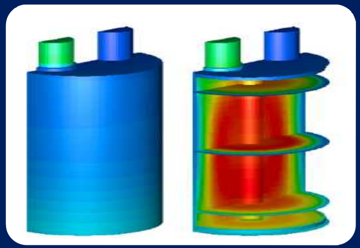
Understanding Battery Safety

Materials R&D

- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

Testing

- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Large scale thermal and fire testing (TTC)
- Development for DOE Vehicle Technologies and USABC



Simulations and Modeling

- Multi-scale models for understanding thermal runaway
- Validating vehicle crash and failure propagation models
- Fire Simulations to predict the size, scope, and consequences of battery fires

Procedures, Policy, and Regulation

- USABC Abuse Testing Manual (SAND 2005-3123)
- SAE/UL procedures and standards
- R&D programs with NHTSA/DOT to inform best practices, policies, and requirements

Program Support & Collaborations

Sandia National Laboratories

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

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NATIONAL LABORATORY

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Challenges with Lithium-Ion Materials

Sandia National Laboratories

Lithium-ion Materials Issues:

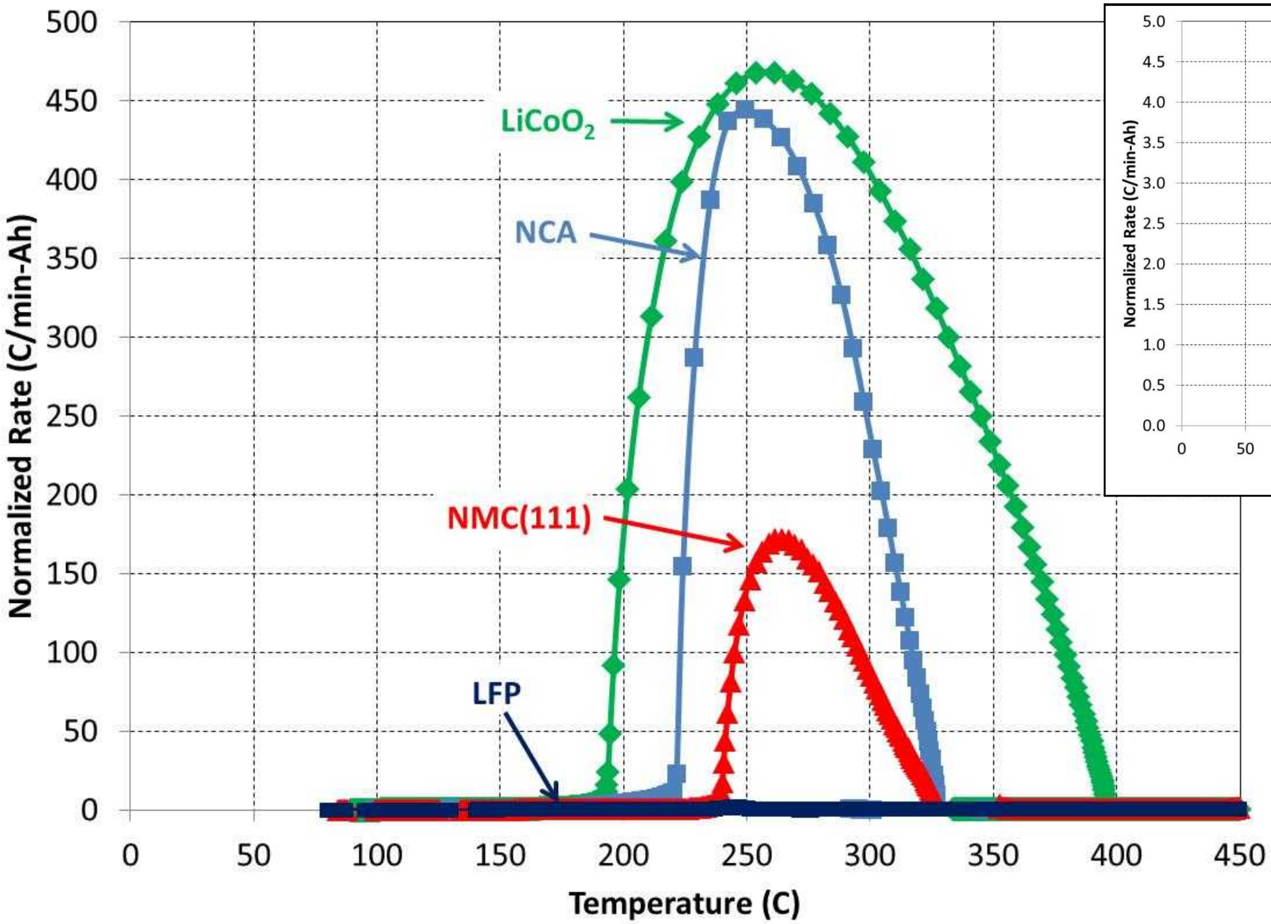
- Energetic **thermal runaway**
- Electrolyte **flammability**
- **Thermal stability** of electrolytes and separators
- Inherent **intolerance** of abuse conditions

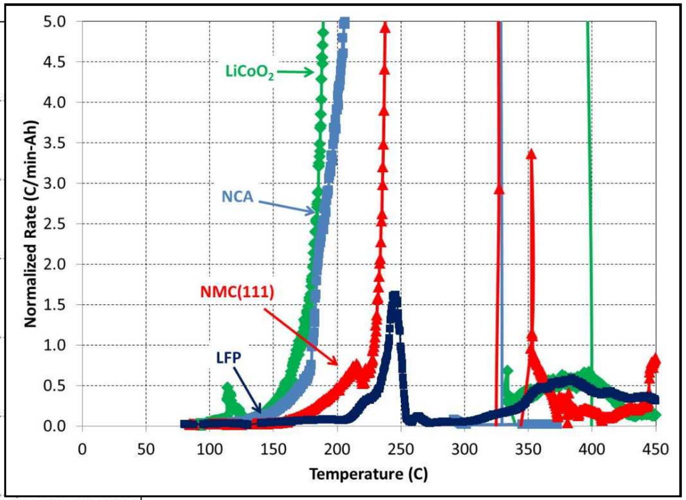
Materials choices and interfacial chemistry can impact these safety challenges

Calorimetry of Lithium-ion Cells

Sandia National Laboratories

Understanding the Thermal Runaway Response of Materials in Cells



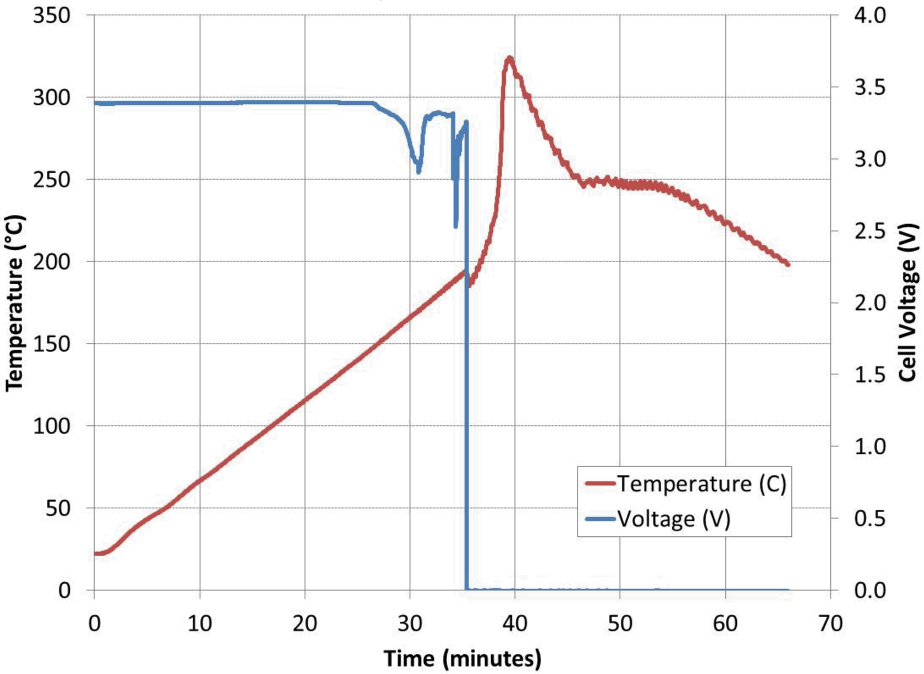


High Rate Runaway	
Cathode	$\Delta H_{runaway}$ (kJ/Ah)
$LiCoO_2$	15.9
NCA	9.8
NMC111	8.3
LFP	2.4

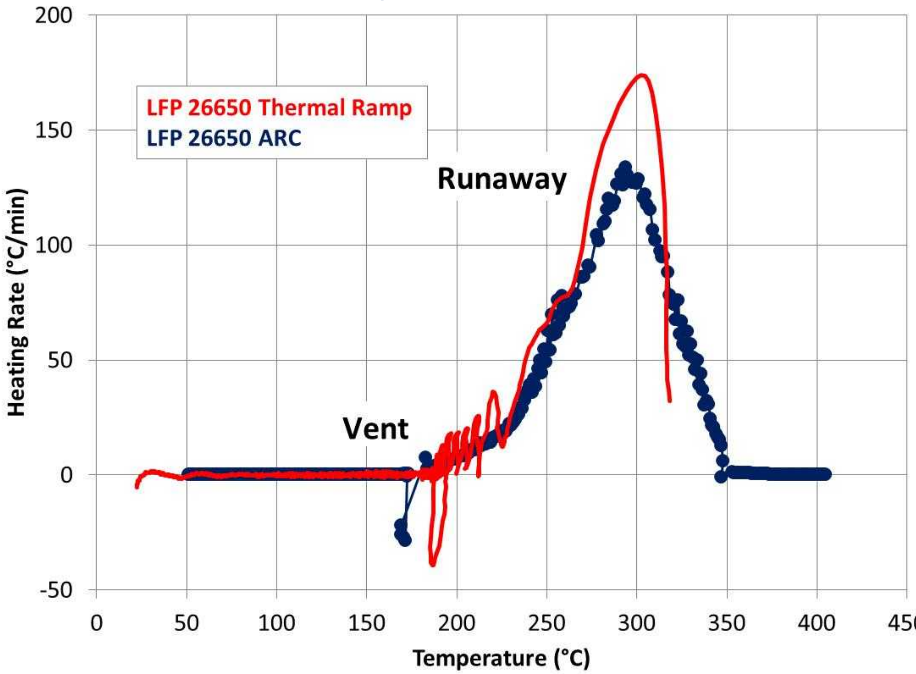
Can high energy cathodes behave like LFP during thermal runaway?
Where do high capacity Si/C anodes fit on this plot?

Characterizing Thermal Runaway

Thermal Ramp

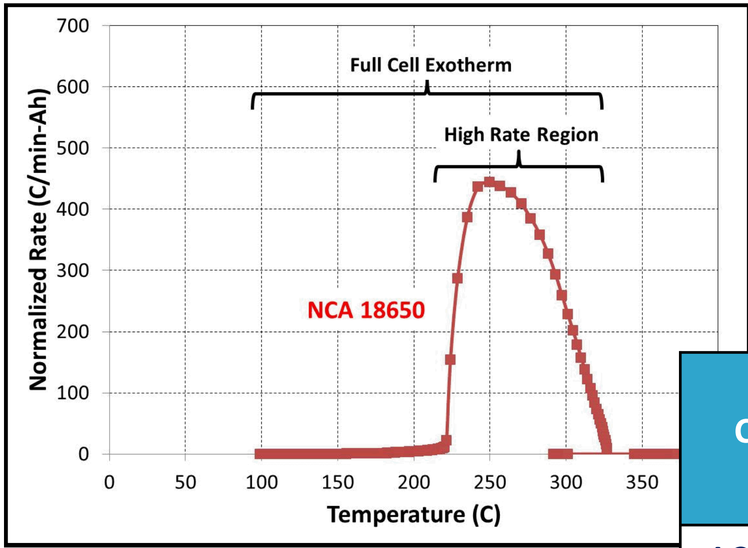


Thermal Ramp + ARC



- Consistent cell behavior between thermal abuse and calorimetry experiments
- Greater total temperature rise observed for the ARC experiment because it is in an adiabatic environment
- May be able to use these data to compare results obtained between the two types of experiments

Characterizing Thermal Runaway



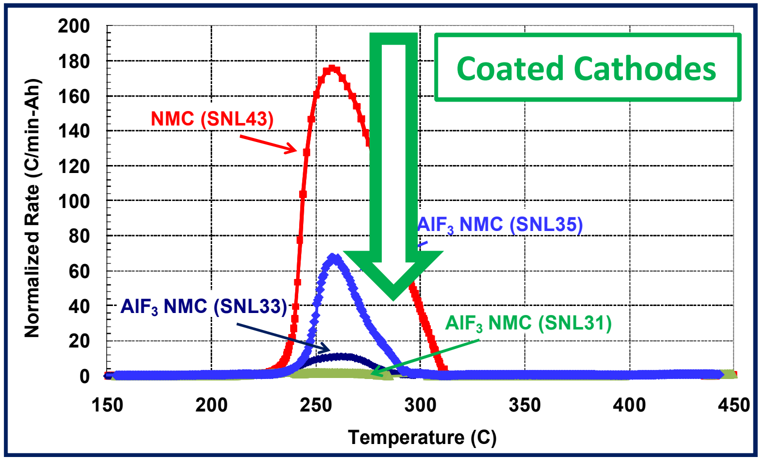
- *Full cell runaway enthalpy shows a significant amount of heat generation from even an LFP 18650 cell*
- *But that heat is generated at much different rates for the different cell types*

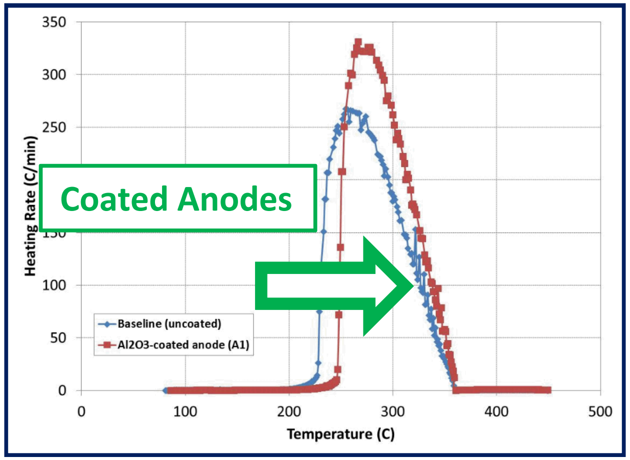
Cell Type	Capacity (Ah)	Runaway Enthalpy (kJ/Ah)		Peak Heating Rate (W/Ah)
		Full Cell	High Rate Region	
LCO 18650*	1.2	28.4	15.9	281
NCA 18650*	1.0	21.6	9.8	266
NMC 18650*	0.95	22.0	8.3	105
LFP 18650*	0.9	18.0	2.4	1
LFP 26650*	2.6	8.2	4.6	65
LFP 26650‡	2.6	8.0	4.5	65
*ΔH based on dT (exotherm) ‡ΔH based on dT/dt (exotherm)				

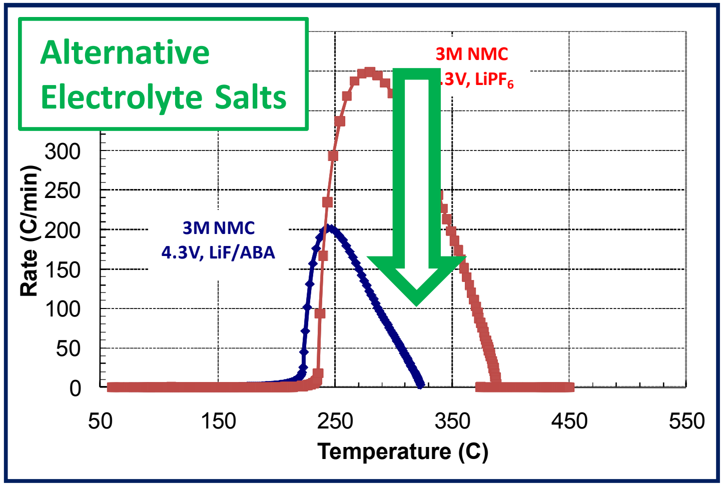
Data provide a quantitative measurement of the runaway enthalpy

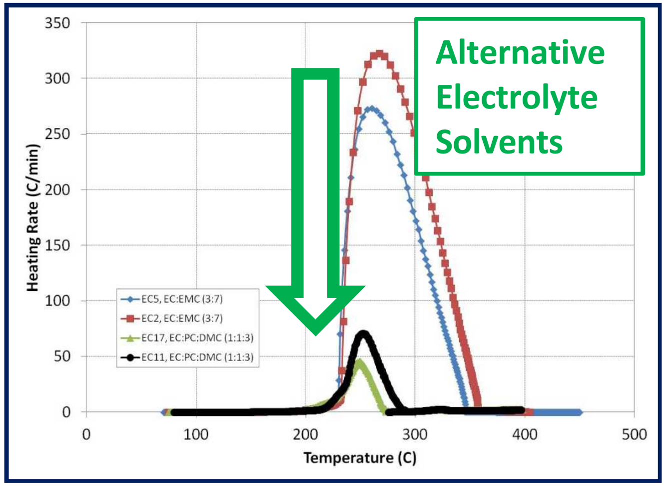
Improving Runaway Response

NMC/Graphite cells







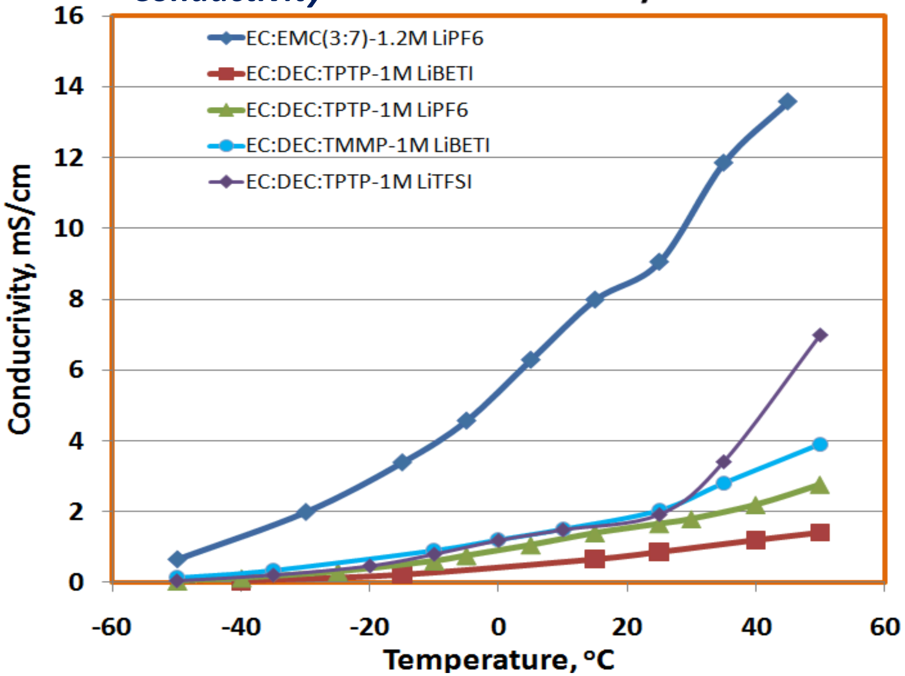


Materials choices can be made to improve the runaway response in cells
Reducing runaway enthalpy and kinetics has direct implications in battery system safety

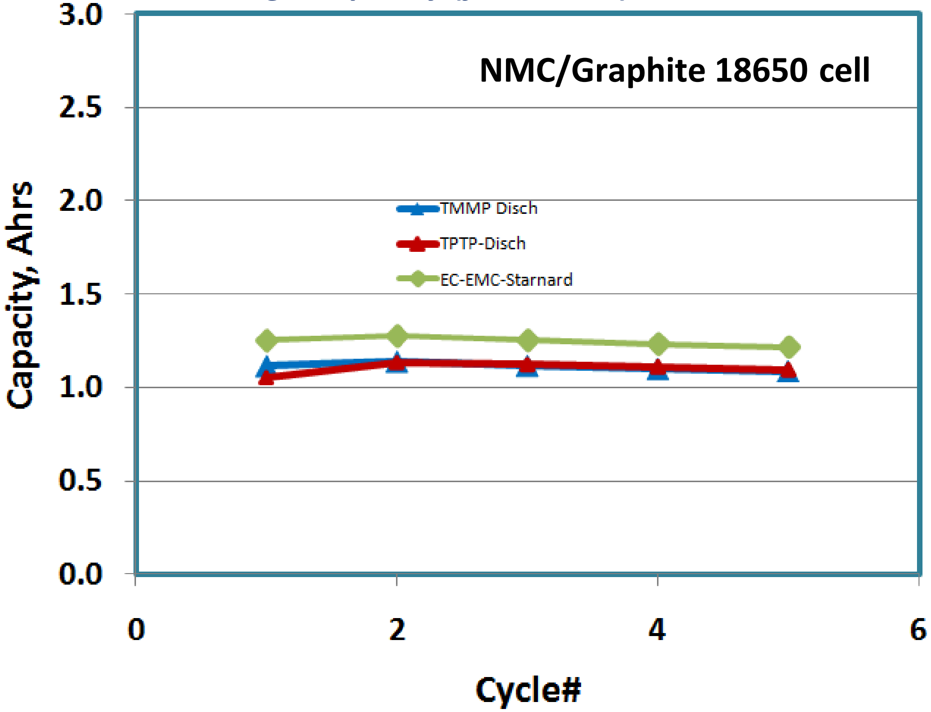
Electrolyte Flammability

Sulfonimide/Hydrofluoro ether (HFE) Electrolytes to improve thermal stability and flammability

Conductivity



Discharge Capacity (formation)

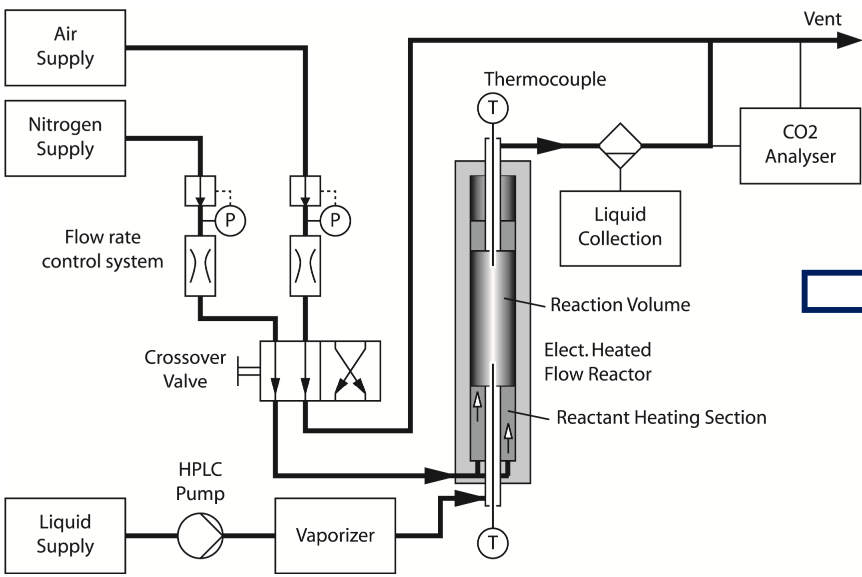


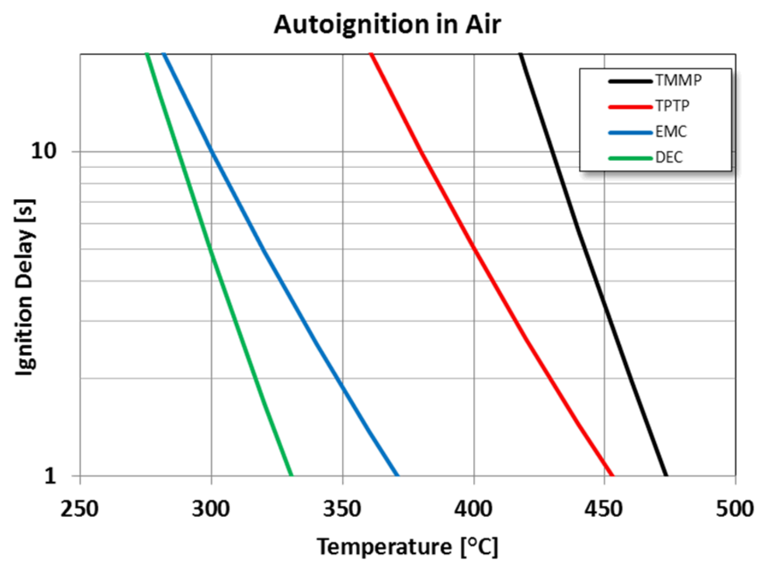
HFE electrolytes have conductivities on the order of 2 mS/cm
HFEs show comparable discharge capacity in NMC/Graphite cells compared to $LiPF_6$/carbonate electrolytes

G. Nagasubramanian et al. J. Power Sources 196 (2011) 8604-8609

Electrolyte Flammability

Sulfonimide/Hydrofluoro ether (HFE) Electrolytes to improve thermal stability and flammability





Autoignition measurements at ambient pressure are a more relevant measure of battery electrolyte flammability than measurements at elevated pressure
HFEs have significantly higher autoignition temperatures in air relative to carbonate solvents

C. J. Orendorff et al. SAND2012-9186, "Advanced Inactive Materials for Improved Lithium-Ion Battery Safety"

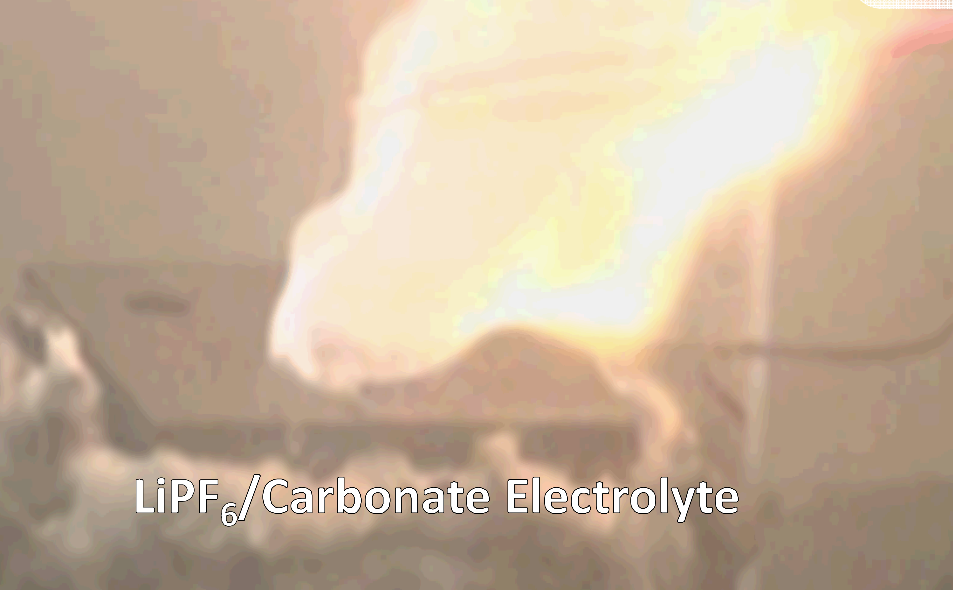
Electrolyte Flammability

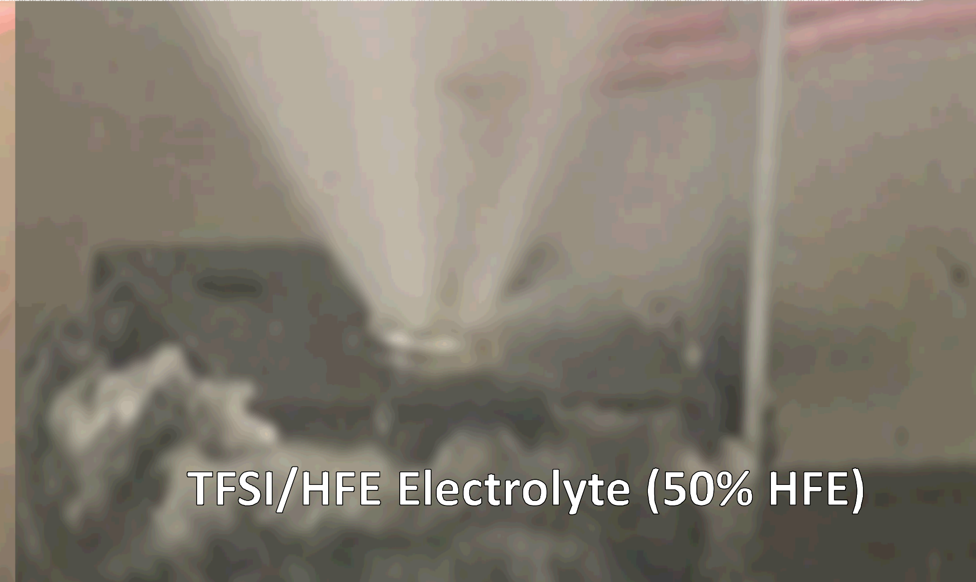
Flammability measurements

- *Conventional bulk liquid fuel flammability measurements (e.g. ASTM D56) do not accurately reflect flammability representative of a cell failure in a battery*

Cell Vent Flammability Test (CVFT)

Electrolyte	Ignition (Y/N)	ΔTime (vent-ignition) (s)	Burn time (s)
EC:DEC (5:95 v%)	Y	1	63
EC:EMC (3:7 wt%)	Y	3	12
50% HFE-1	N	NA	NA
50% HFE-2	N	NA	NA





Tools can be applied to electrolyte development efforts to evaluate electrolyte flammability performance

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Flammability tools developed under Sandia LDRD Program

G. Nagasubramanian et al. J. Power Sources 196 (2011) 8604-8609

Battery System Field Failures

Field failures could include:

- Latent manufacturing defects
- Internal short circuits
- Unique use or **abuse conditions**
- Control failure (low voltage, control systems, connectors, boards, not battery initiated)

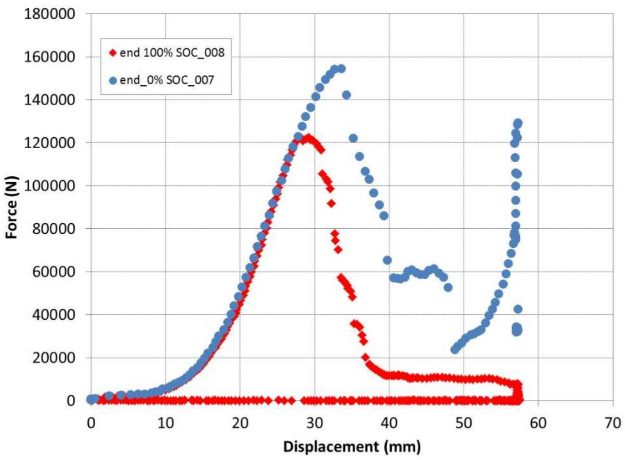
Any **single point failure** that **propagates** through a entire battery system is an **unacceptable** scenario to ensure battery safety

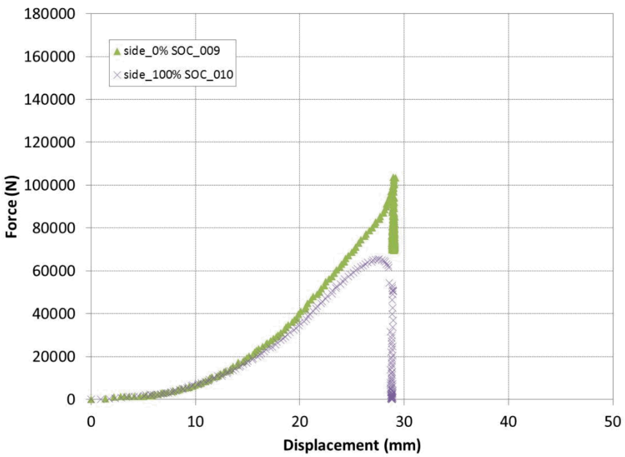
Tesla Model S fire in October 2013, where the fire was isolated to the front portion of the vehicle and did not propagate through the entire battery

USCAR Crash Safety

Sandia National Laboratories

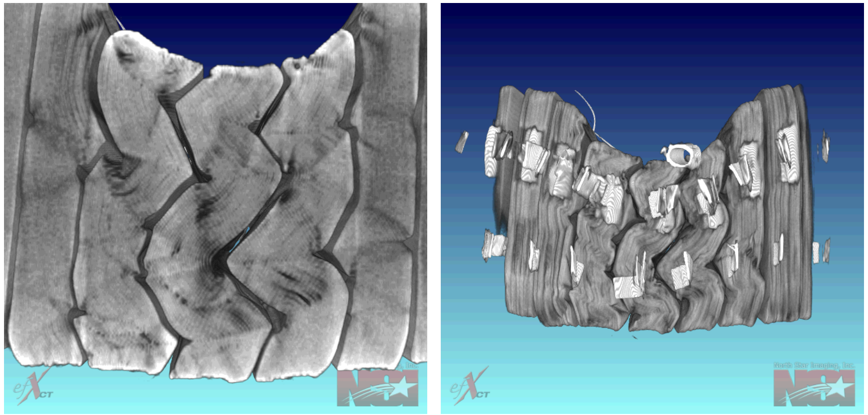
Mechanical behavior under compression





Analog "pole test" of a battery

CT analysis to study structural failure modes

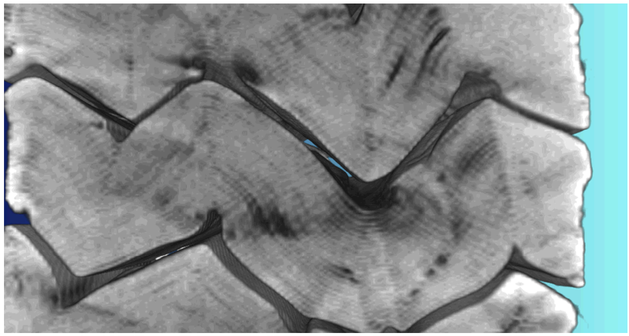


Determining baseline mechanical behavior of batteries during crush/impact testing
Testing support to validate mechanical models for batteries during a crash scenario

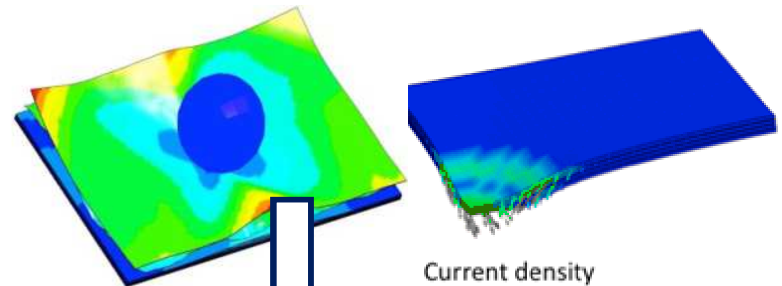
Crash Safety Modeling

Computer Aided Engineering for Batteries (CAEBAT) DOE VTO and NREL

Battery Crush Experiment (SNL, USCAR)



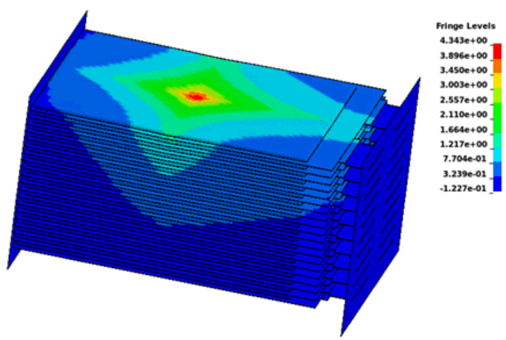
Cell-level Mechanical Model (MIT)



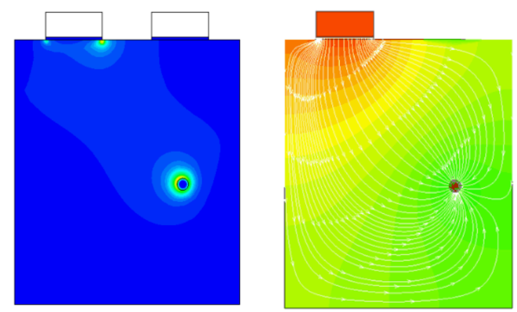
Current density
contour and vector

Integrated Thermoelectrochemical & Mechanical Model (NREL)

Thermal Cell-to-Cell Propagation Model



Thermoelectrochemical Model

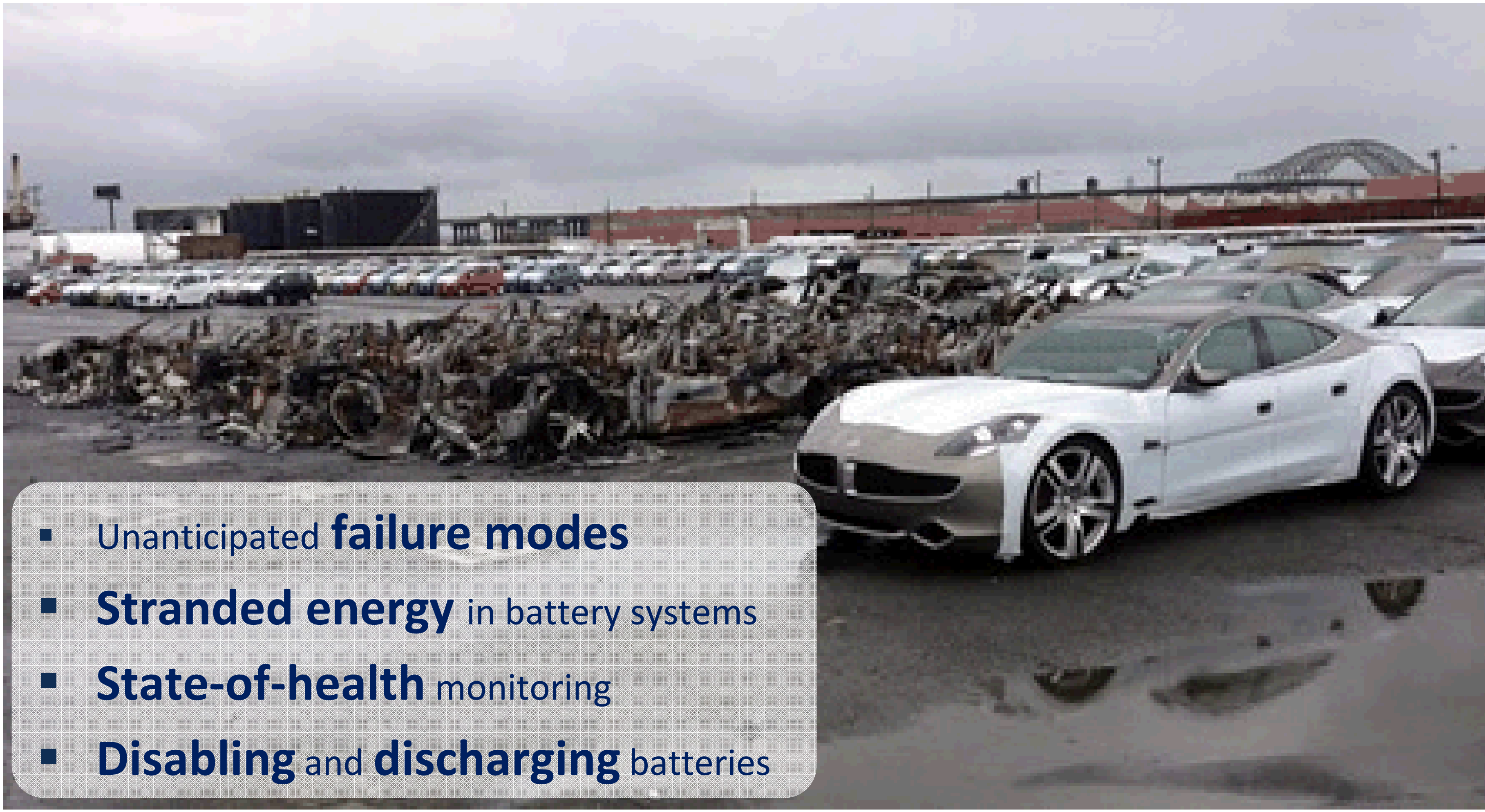


Use battery crush data to validate the integrated model
Develop a predictive capability for battery thermal runaway response to mechanical insult

Standards, Regulation, and Policy

- **USABC** Abuse Manual (SAND2005-3123) and current revision
- **Testing** development, evaluation, and validation (Propagation testing procedure SAND2014-17053)
- Work on **SAE J2464, UL 1642**
- Testing support for **DOT/NHTSA** to inform **best practices, regulation, and policy**

Standards, Regulation, and Policy



- Unanticipated **failure modes**
- **Stranded energy** in battery systems
- **State-of-health** monitoring
- **Disabling** and **discharging** batteries

Fisker incident in the wake of Super Storm Sandy , New Jersey

Lithium-Ion Battery Challenges

- **Energetic thermal runaway**
  - Anode and cathode decomposition reactions
- **Electrolyte flammability**
  - Low flashpoint electrolyte solvents
  - Vent gas management
  - Fuel-air deflagrations
- **Thermal stability of materials**
  - Separators, electrolyte salts, active materials
- **Failure propagation from cell-to-cell**
  - Single point failures that spread throughout an entire battery system
- **Managing residual stored energy**
- **Diagnostics/prognostics to understand stability in the field**

Acknowledgements

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- Josh Lamb
- Scott Spangler
- Jill Langendorf
- Lorie Davis

Battery Safety R&D Program at Sandia: http://energy.sandia.gov/?page_id=634
ECS Interface Issue on Battery Safety: http://www.electrochem.org/dl/interface/sum/sum12/if_sum12.htm