Exceptional service in the national interest

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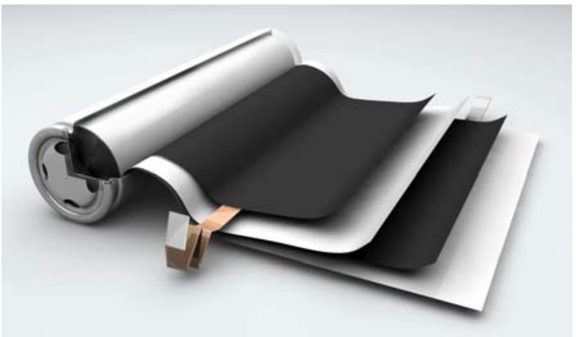

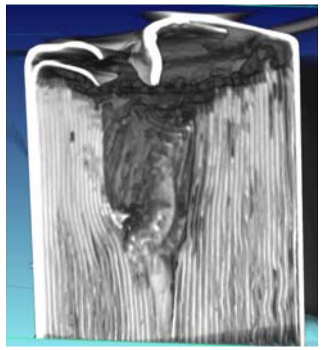

Battery Safety R&D at Sandia National Laboratories

Christopher J. Orendorff

Sandia National Laboratories

FAA Fire Systems Working Group Meeting

October 30, 2014

SAND2014-19659 PE

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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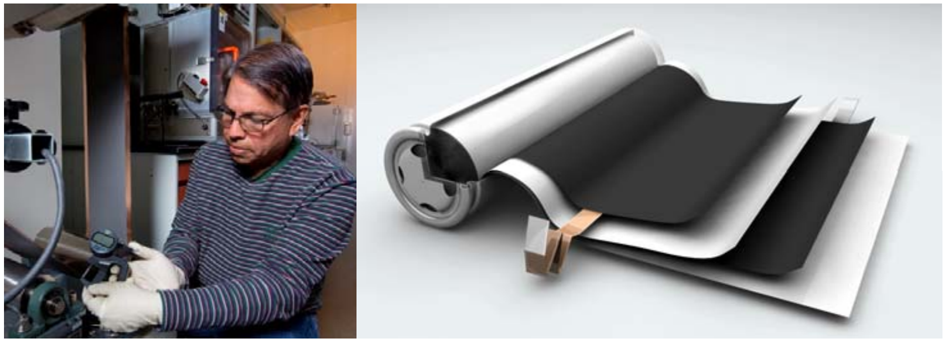
Outline

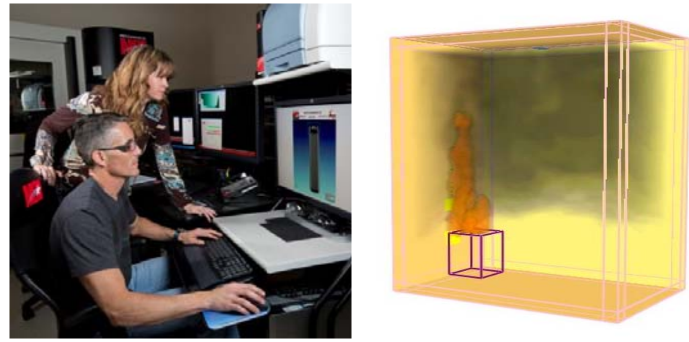
- **Overview of the Battery Safety R&D Program**
  - **Capabilities**
  - **Battery Abuse Testing Laboratory (BATLab)**
  - **R&D Interests and support**
- **Materials-level battery safety**
  - **Battery calorimetry**
  - **Nonflammable electrolytes**
- **System-Level battery safety**
  - **Improving control system architecture**
  - **Vehicle crash modeling**
  - **Failure propagation**
  - **Battery fires**

Capabilities

Sandia National Laboratories

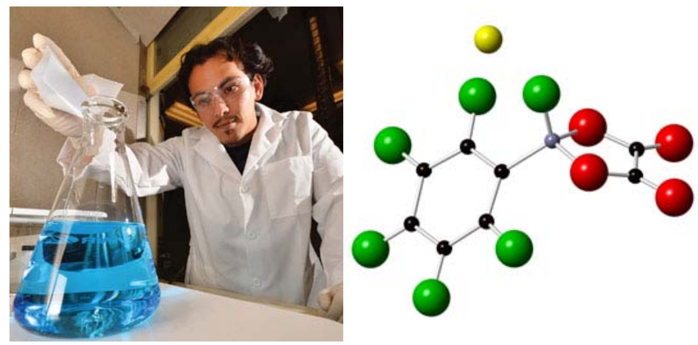


Cell Prototyping Facility

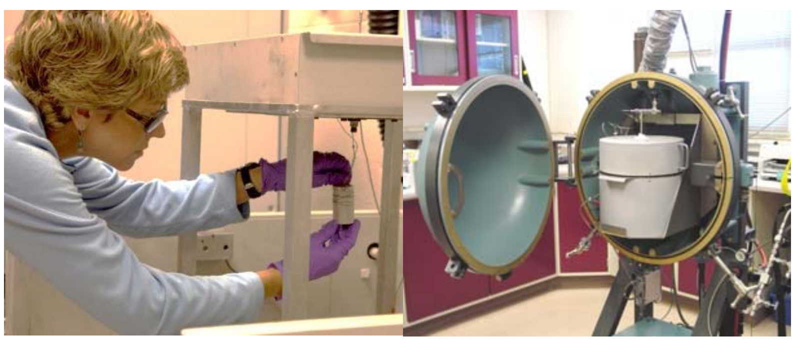


Modeling and Simulations

Battery Abuse Testing Laboratory (BATLab)



Materials R&D

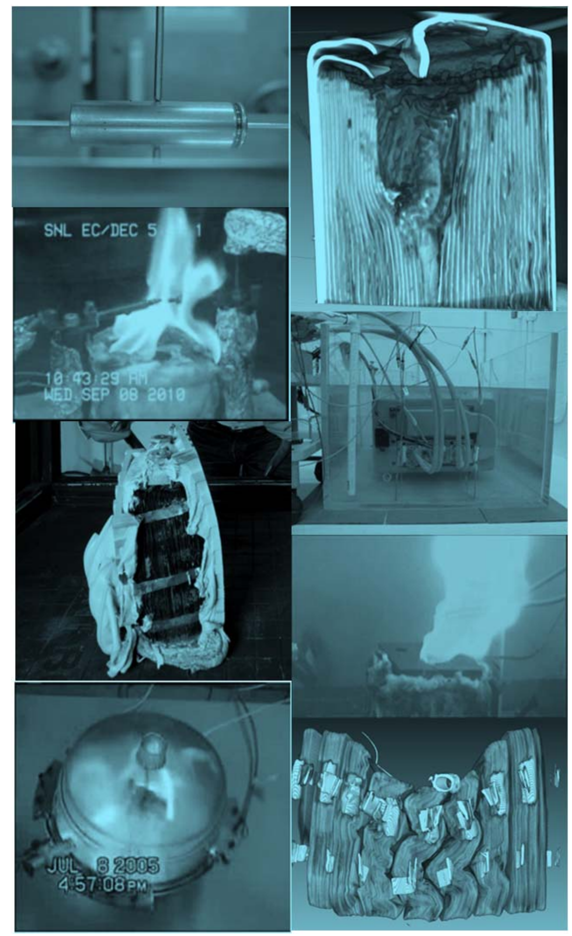


Batttery Calorimetry

Large Scale Testing Facilities

Battery Abuse Testing Laboratory (BATLab)

- **Comprehensive abuse testing platforms for cells, batteries and systems from mWh to kWh**
- **Program support primarily from the ground vehicle sector**
- **Mechanical abuse**
  - **Penetration**
  - **Crush**
  - **Impact**
  - **Immersion**
- **Thermal abuse**
  - **Over temperature**
  - **Flammability measurements**
  - **Thermal propagation**
  - **Calorimetry**
- **Electrical abuse**
  - **Overvoltage/overcharge**
  - **Short circuit**
  - **Overdischarge/voltage reversal**



Program Support & Collaborations

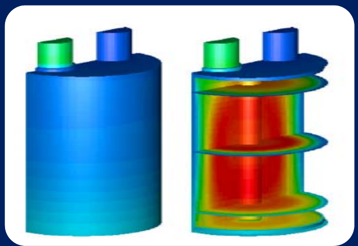
Understanding Battery Safety

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 Dynamics (FDS) and Fuego simulations to predict the size, scope, and consequences of battery fires

Procedures, Policy, and Regulation

- USABC FreedomCAR Abuse Testing Manual
- SAE J2464, UL1642
- Testing programs with NHTSA/DOT to influence policies and requirements

Materials-Level Battery Safety

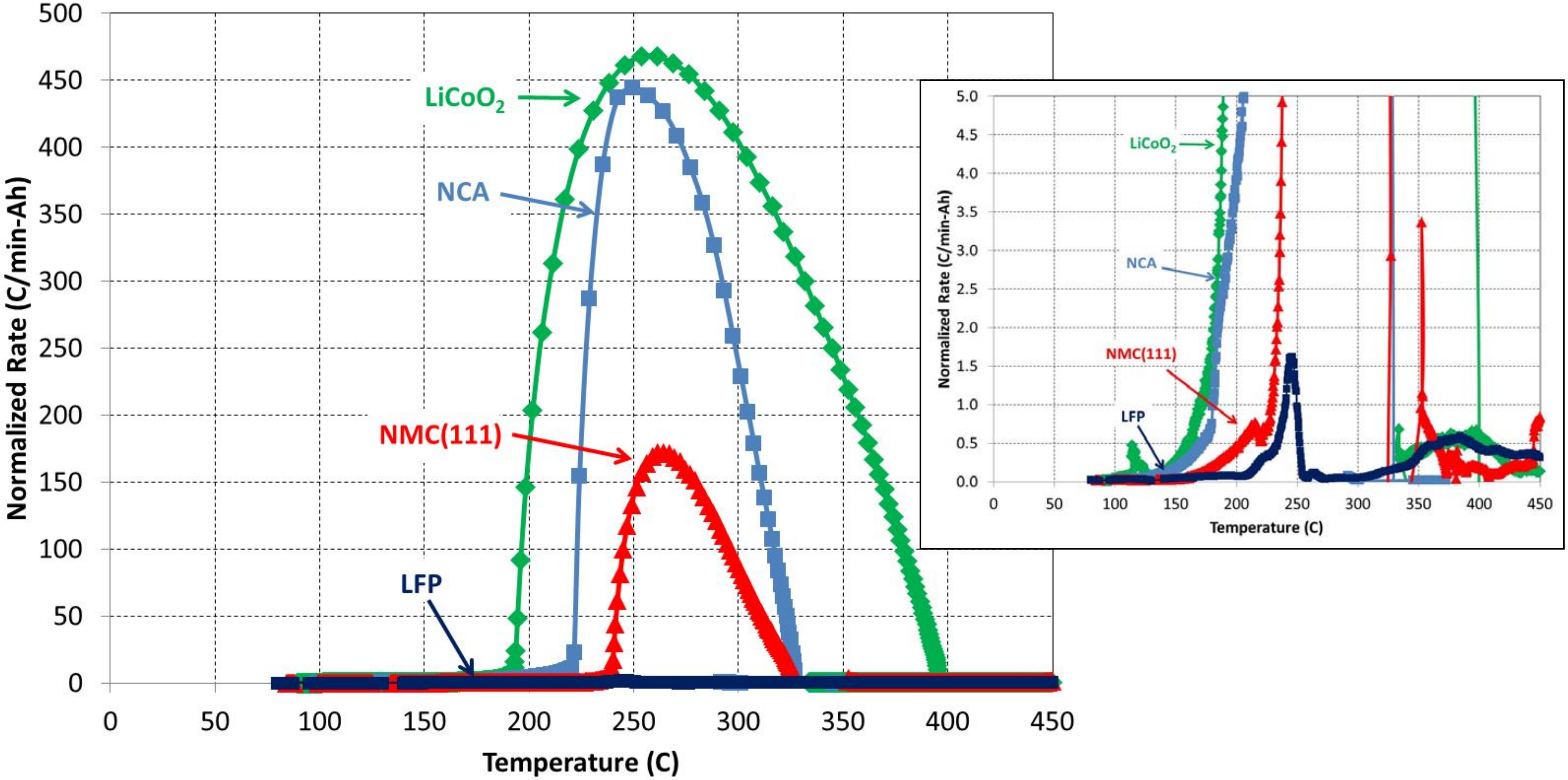
Lithium-ion Materials Issues:

- 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

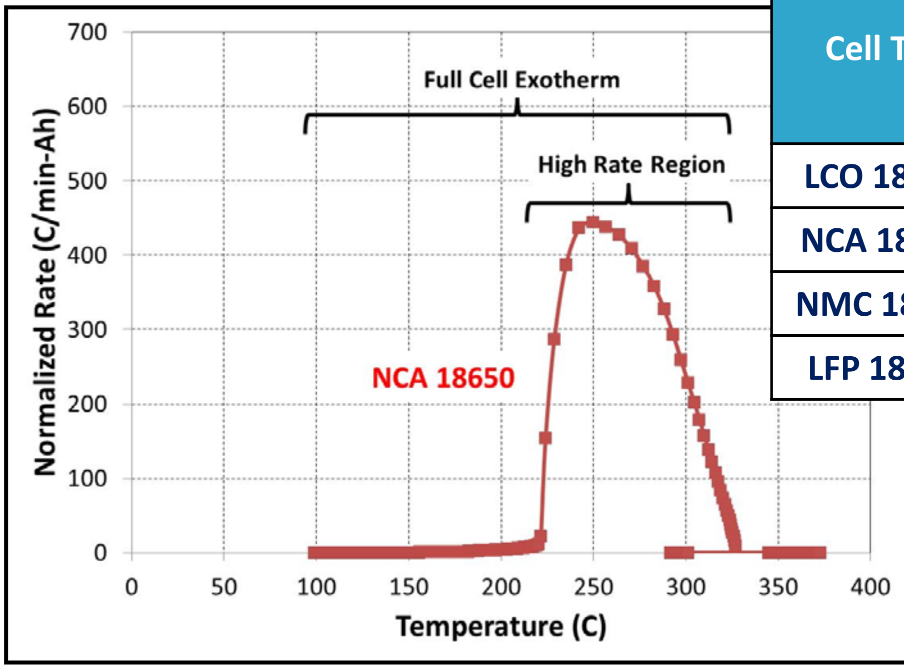
Calorimetry of Lithium-ion Cells

Understanding the Thermal Runaway Response of Materials in Cells



Can high energy cathodes behave like LFP during thermal runaway?
Where do "beyond lithium-ion" technologies fit on this chart?

Characterizing Thermal Runaway



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

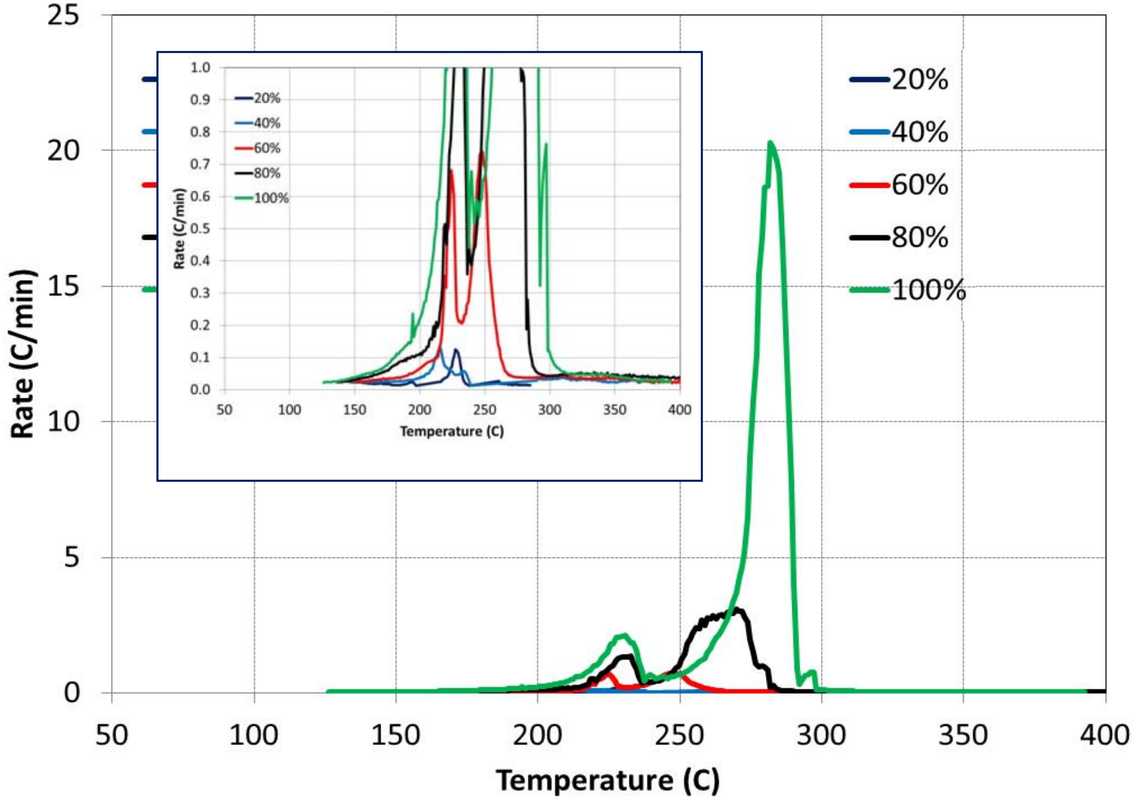
- ***Full cell runaway enthalpy shows a significant amount of heat generation from even an LFP 18650 cell***
- ***But that heat is generated at much different rates for the different cell types***

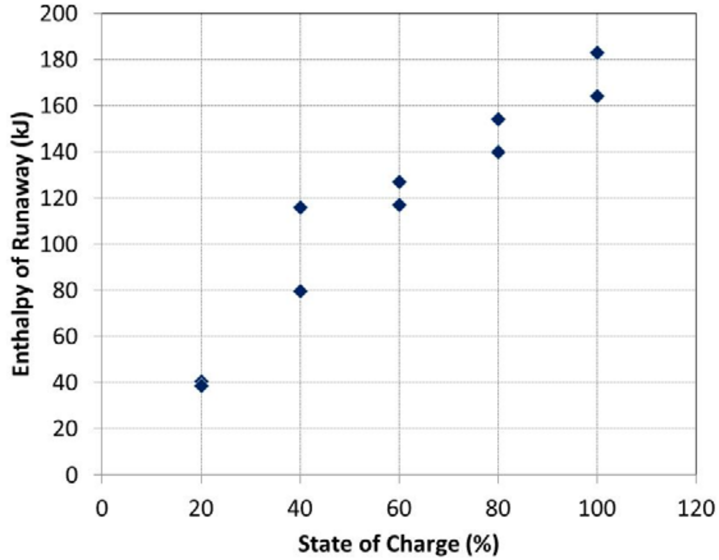
Data provide a quantitative measurement of the runaway free energy

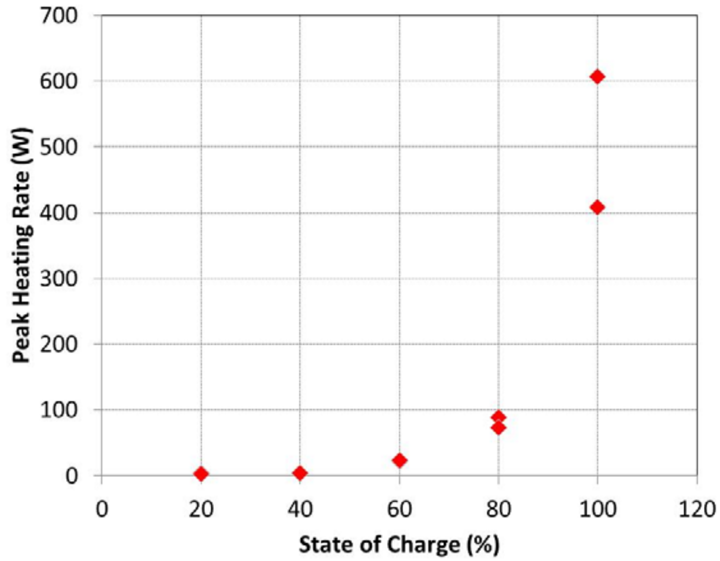
Effect of Cell State of Charge (SOC)

Sandia National Laboratories

15 Ah $LiMn_2O_4$ EV Cell





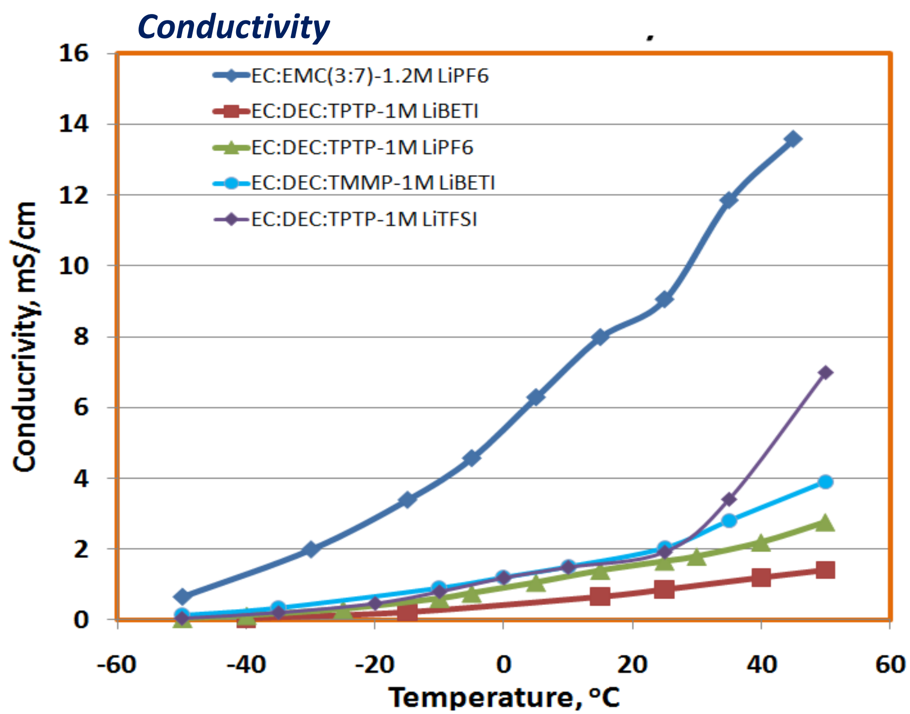


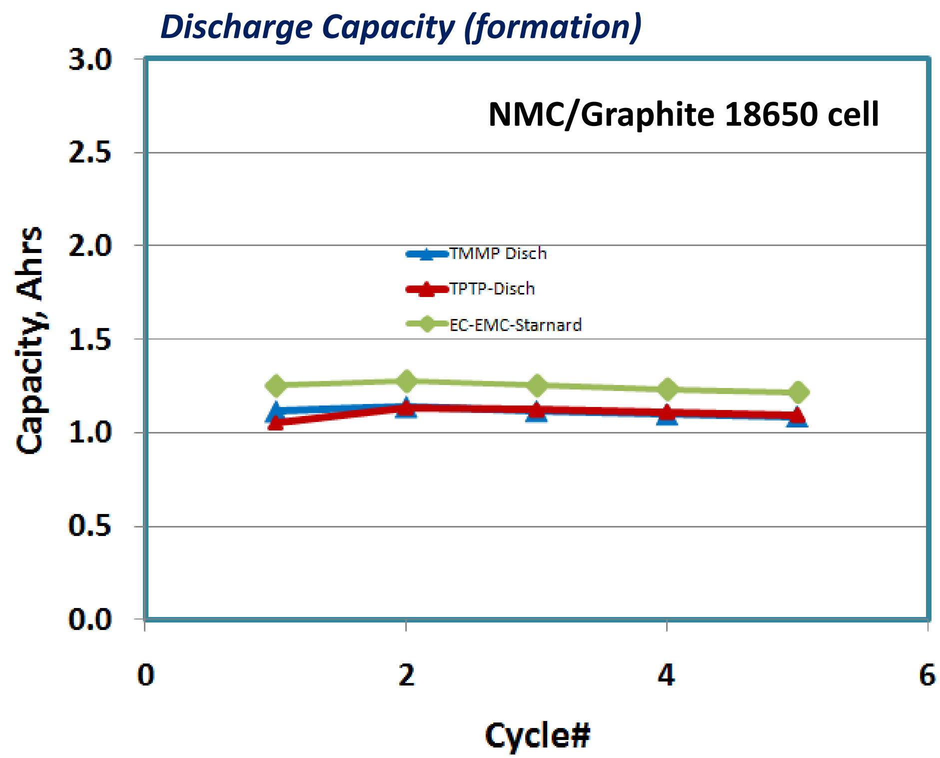
ARC measurements can be used to quantify runaway free energy as a function of SOC

NHTSA www.nhtsa.gov

Electrolyte Flammability

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



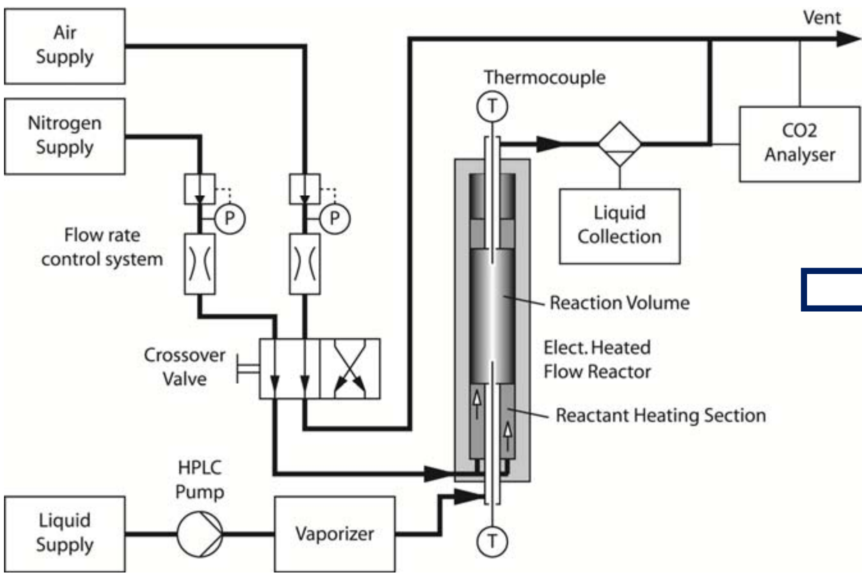


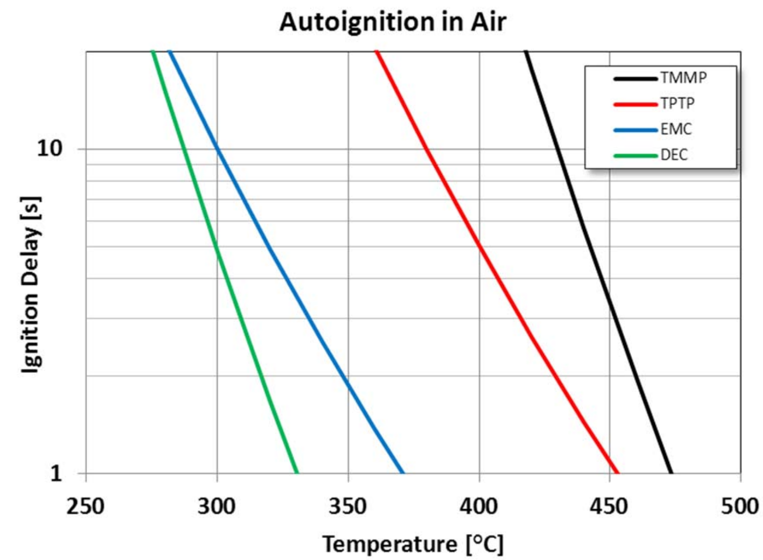
HFE electrolytes have conductivities on the order of 2 mS/cm
HFEs show comparable discharge capacity in NMC/Graphite cells compared to $LiPF_6$/carbonate electrolytes

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***

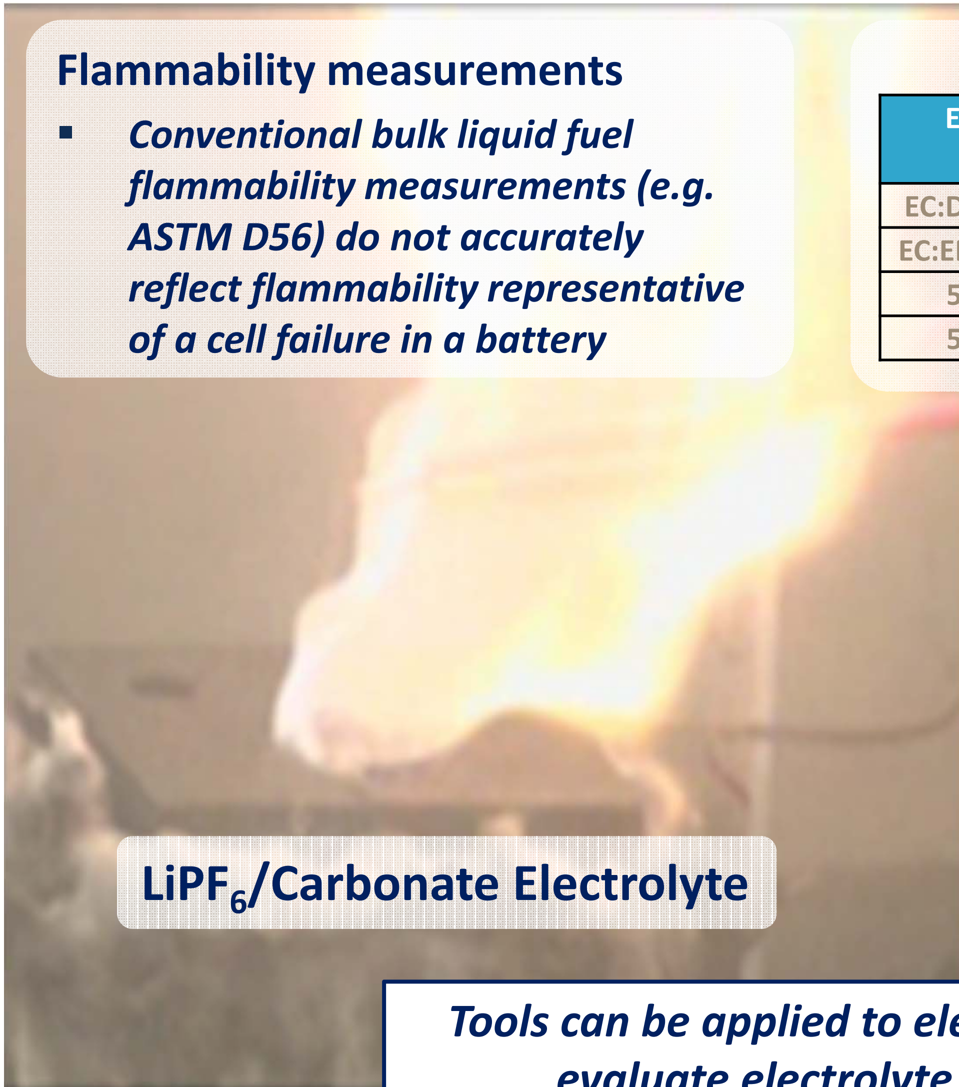
Electrolyte Flammability

Flammability measurements

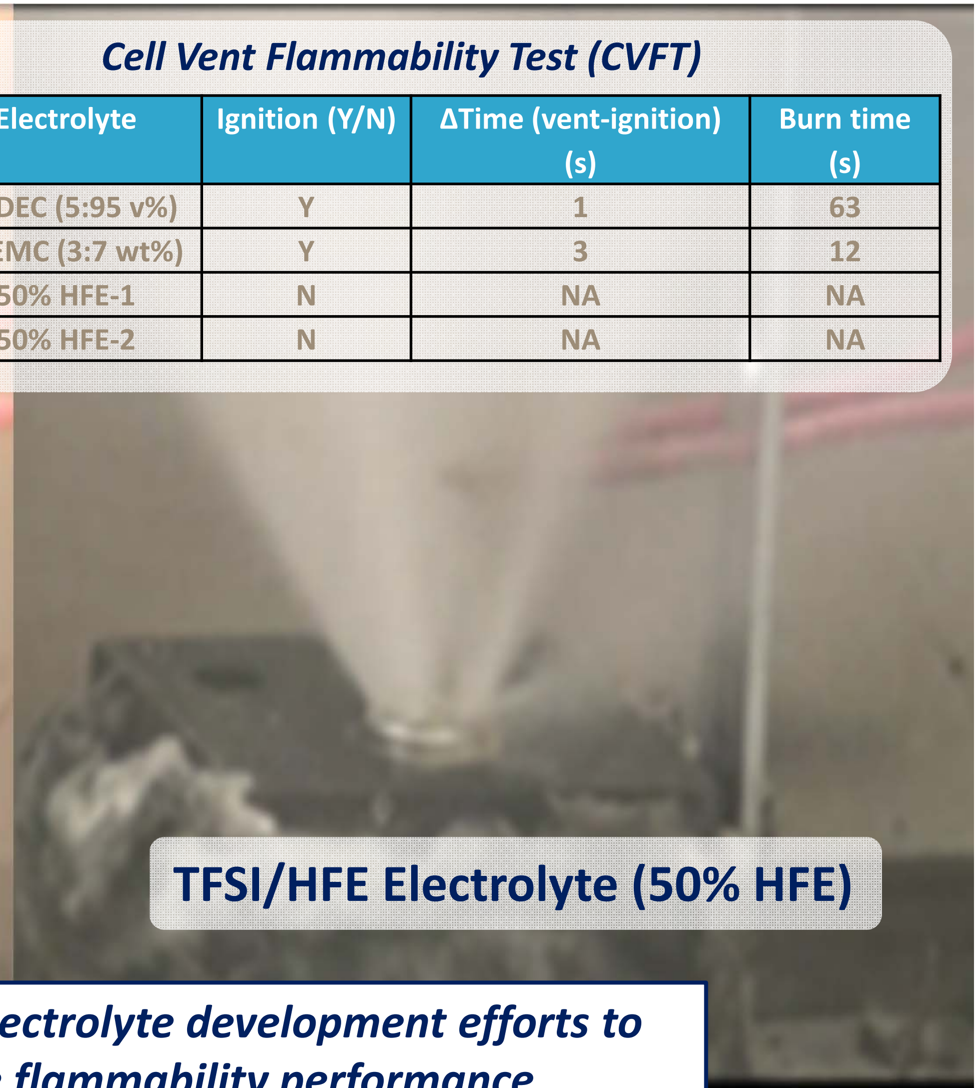
- *Conventional bulk liquid fuel flammability measurements (e.g. ASTM D56) do not accurately reflect flammability representative of a cell failure in a battery*

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



$LiPF_6$/Carbonate Electrolyte



TFSI/HFE Electrolyte (50% HFE)

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

Flammability tools developed under Sandia LDRD Program

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

System-Level Battery Safety

Field failures could include:

- Latent manufacturing defects
- Internal short circuits
- Misuse or **abuse conditions**
- Ancillary component issues

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

Fisker incident in the wake of Super Storm Sandy , New Jersey, 2012

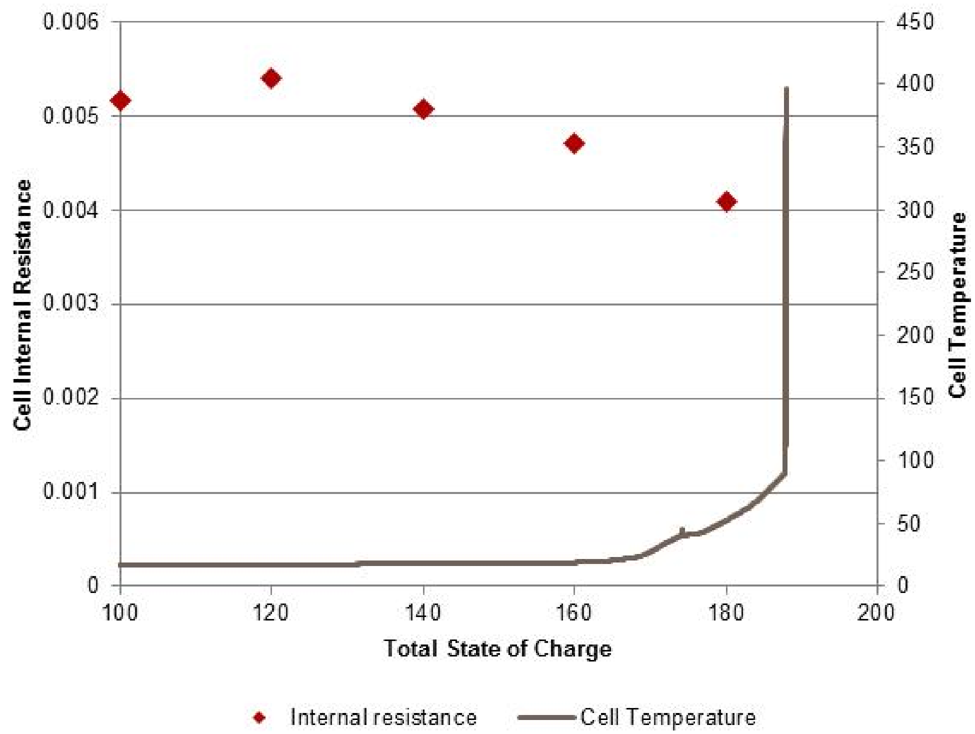
Informing Battery Management Systems

Development of a battery state-of-stability (SOS) diagnostic tool set

Battery management systems (BMS)

- Measure **symptoms** of battery health (temperature, voltage, cell imbalance, etc.
- Need to be able to **diagnose the root cause** of a stability or safety issue
- Could benefit from the ability to perform active **diagnostics** or **prognostics**

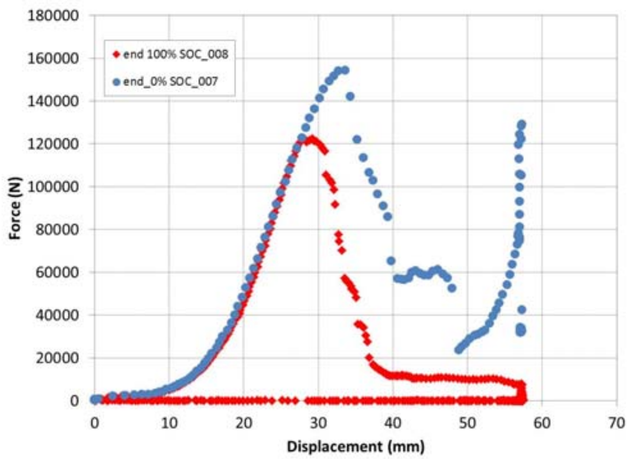
Rapid Impedance Measurement Tool

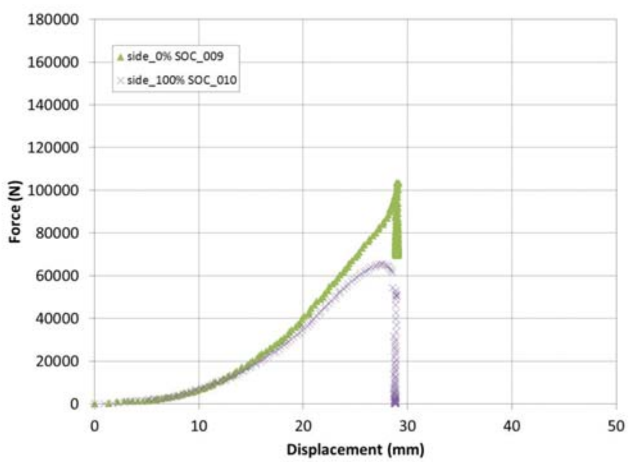


Diagnostic tools developed to for the next generation control architecture for battery management

USCAR Crash Safety

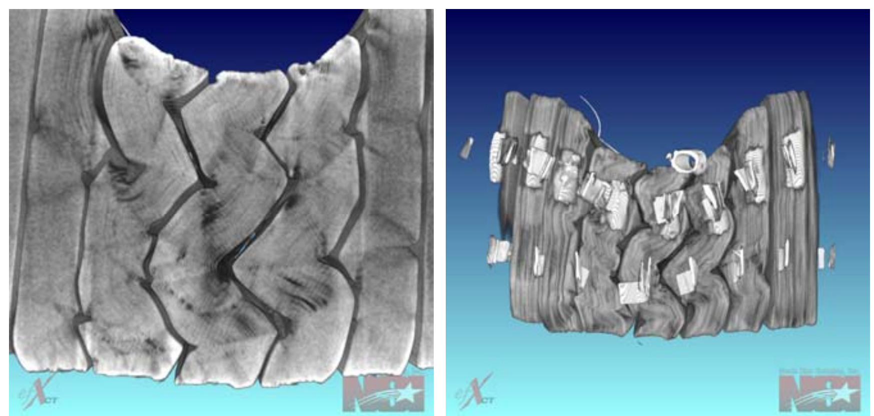
Mechanical behavior under compression





Analog "pole test" of a battery

CT analysis to study structural failure modes

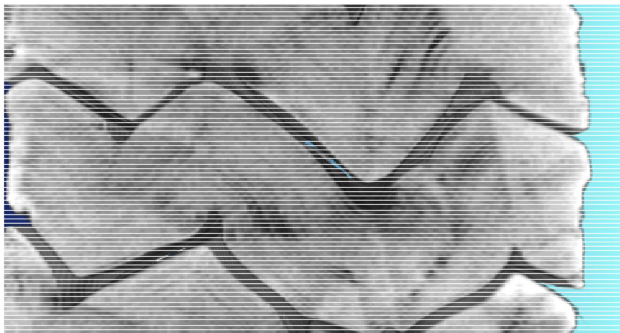


Determining baseline mechanical behavior of batteries during crush/impact testing
Testing support to validate mechanical models for batteries during a crash scenario

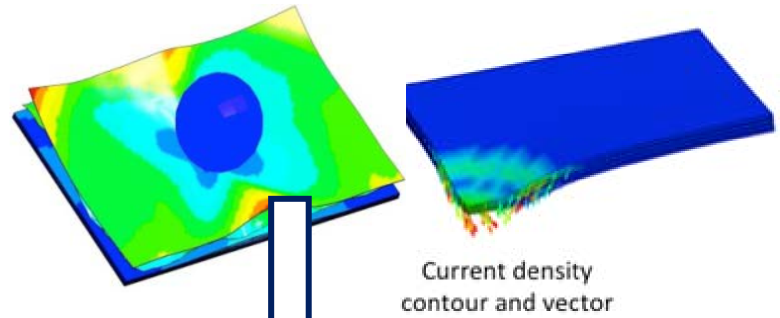
Crash Safety Modeling

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

Battery Crush Experiment (SNL, USCAR)

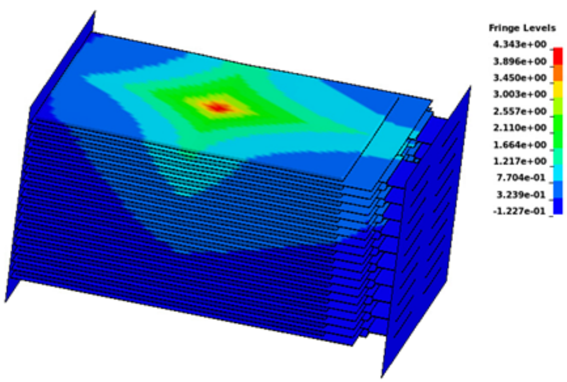


Cell-level Mechanical Model (MIT)

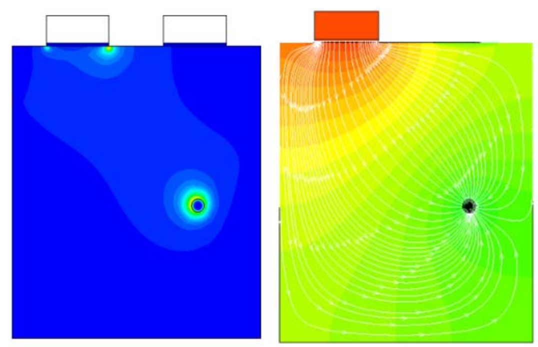


Integrated Thermoelectrochemical & Mechanical Model (NREL)

Thermal Cell-to-Cell Propagation Model



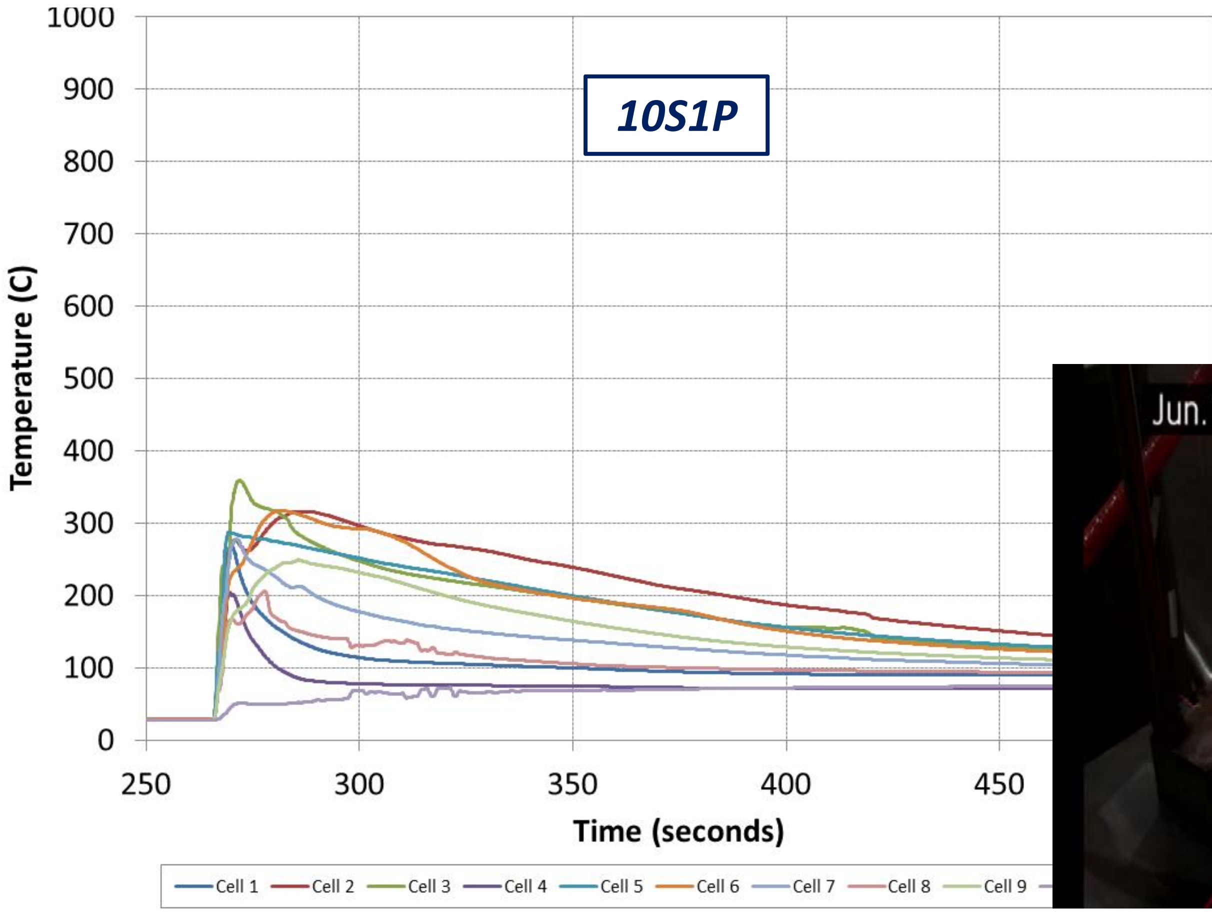
Thermoelectrochemical Model

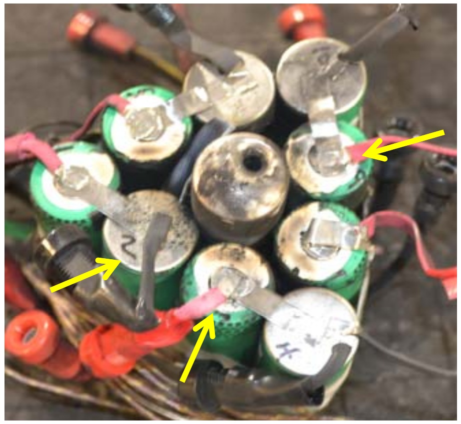


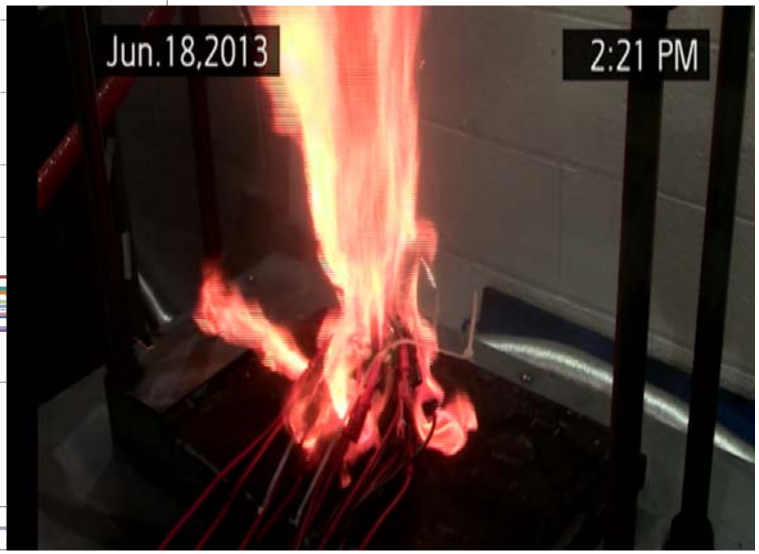
- ***Use battery crush data to validate the integrated model***
- ***Develop a predictive capability for battery thermal runaway response to mechanical insult***

Failure Propagation Testing

10S1P and 1S10P configurations
2.2 Ah 18650 cell packs (92 Wh at 100% SOC)
Failures initiated by mechanical insult to the center cell (#6)







10_pack_series_18650_experimental_wide_view_061813.mp4

Limited propagation of the single point failure in the 10S1P pack

Orendorff, C. J. et al. SAND2014-17053, October 2014, "Propagation Testing Multi-Cell Batteries"

Failure Propagation Testing

10S1P and 1S10P configurations
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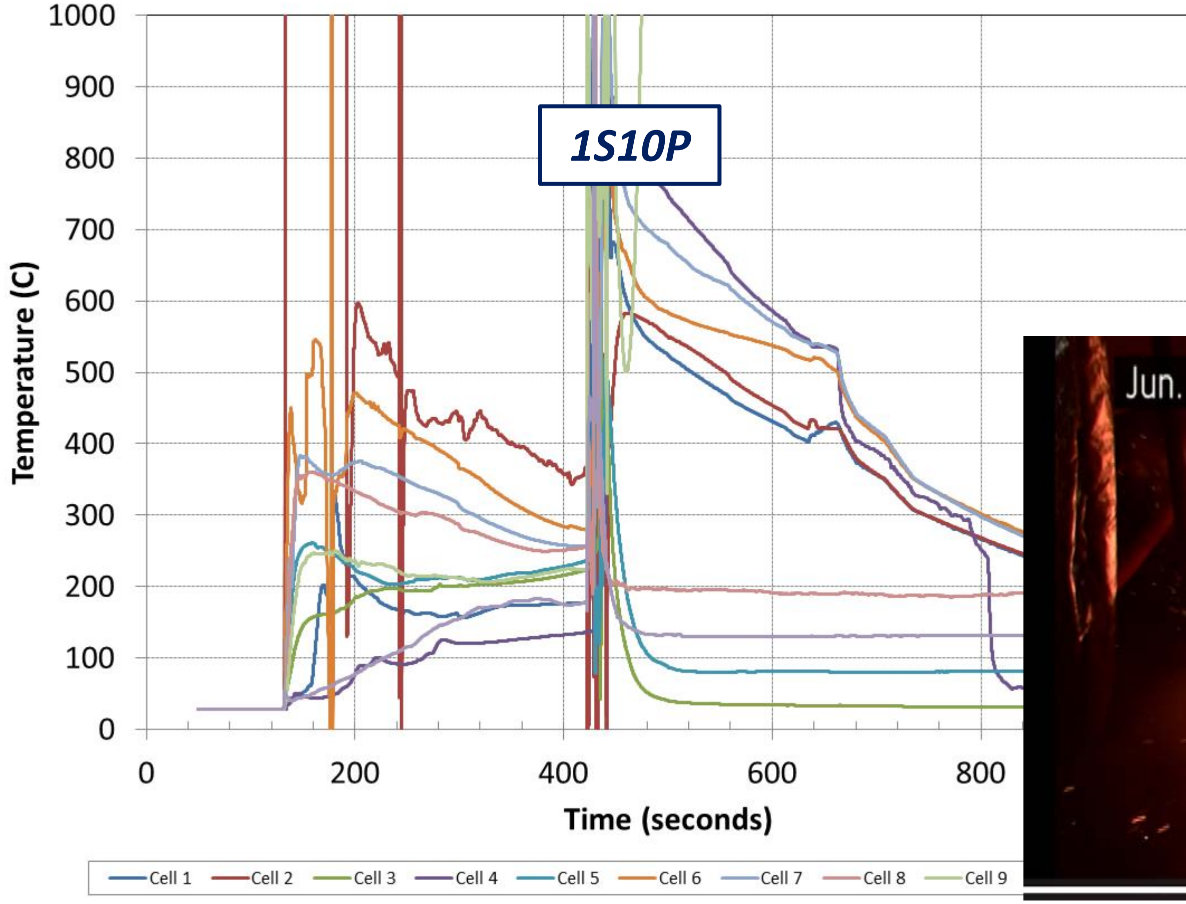
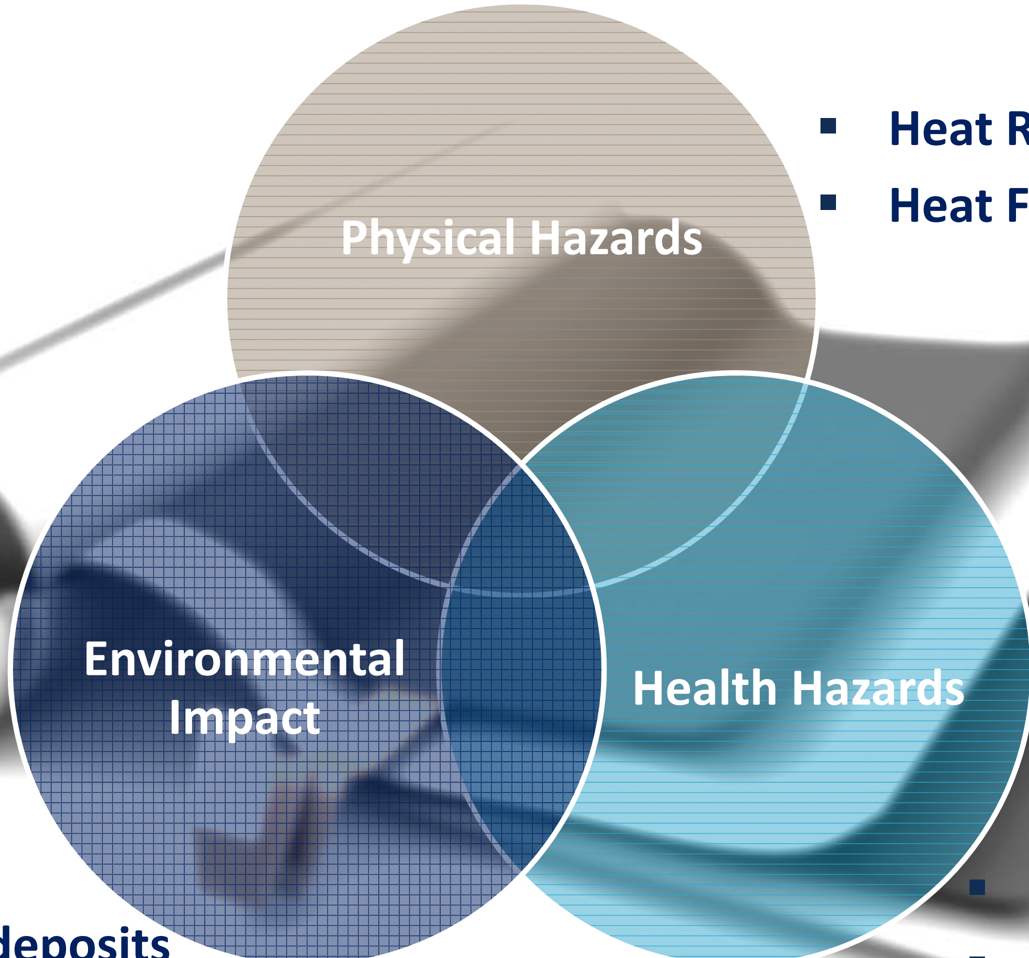


final_event_10_pack_parallel_18650_experimental_061713.mp4

Complete propagation of a single point failure in the 1S10P pack

Understanding Battery Fires



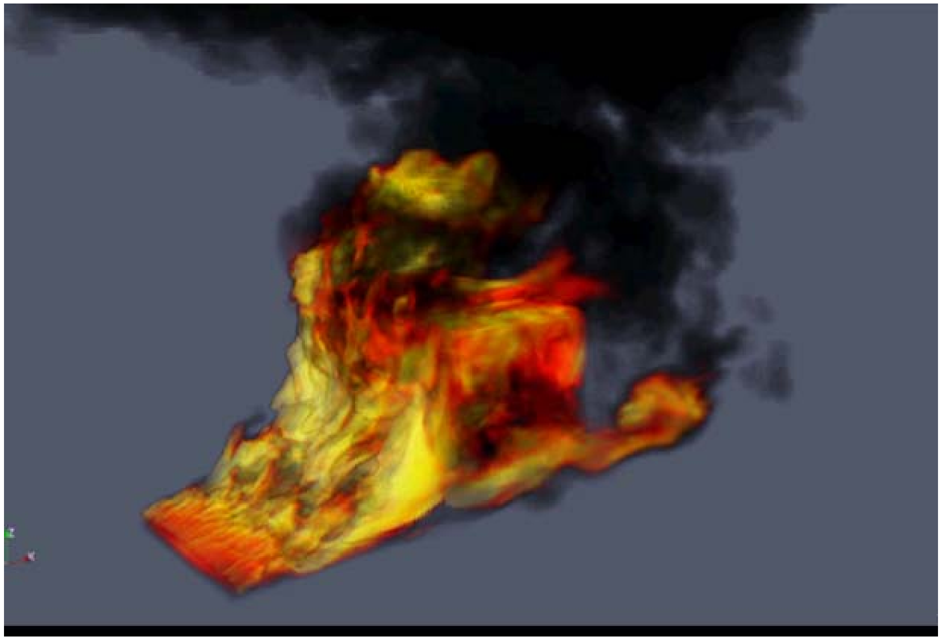
- Heat Release Rate (HHR)
- Heat Flux

- Particulate deposits
  - ground/water
- Air emissions/air quality

- Toxic gas species
- Particulates released
  - Carcinogens
  - Respirable fraction

Experiments and Simulations

10MeterOutdoor.mpg



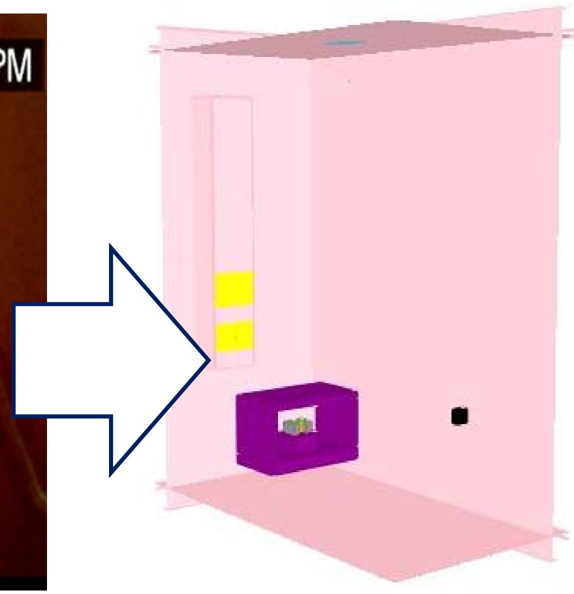
fire_06_06_23_LQ.avi

- While large scale testing capabilities exist, it is **impractical to test every failure mode** scenario at every size scale
- **Leverage** the significant investments that the Department of Energy has made at SNL in **Advanced Scientific Computing (ASC)** for Science-based Stockpile Stewardship, and adapt the code to **energy storage safety analysis**
- Started this work focusing on modeling battery fires and their consequences **(physical hazards, health hazards, environmental impact)**

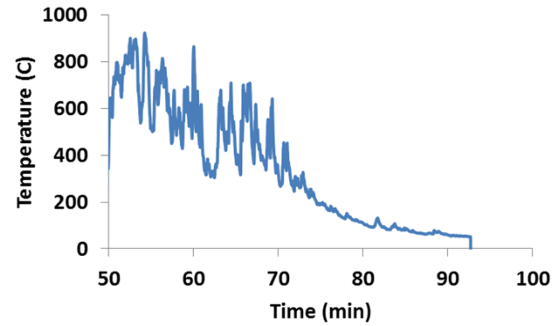
Impact on Infrastructure

Experiment

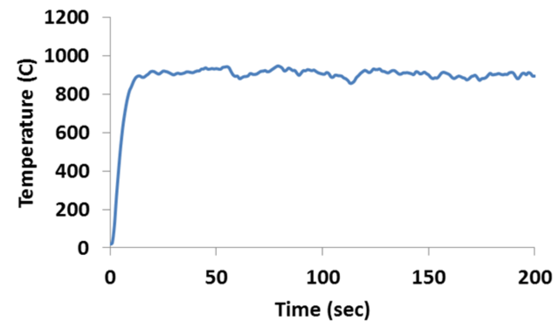
Simulation



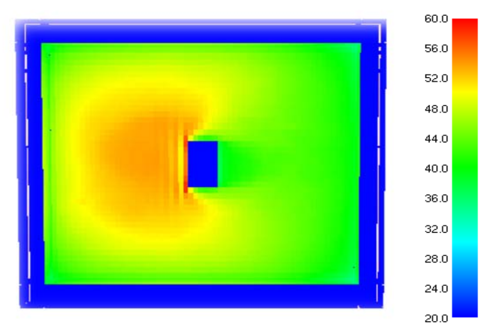
Measured battery temperature



Simulated battery temperature



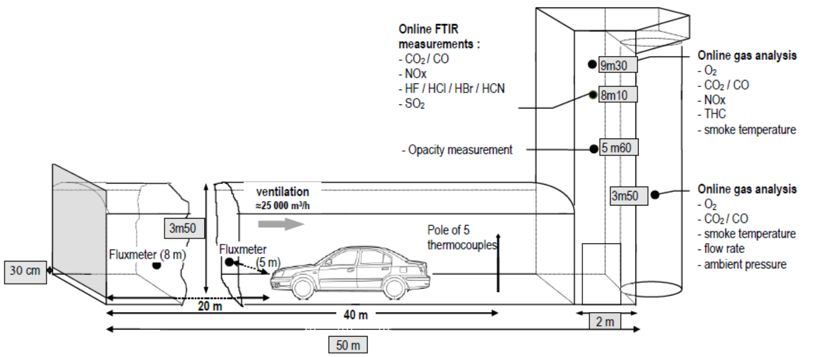
Simulated bay ceiling temperature



- Scale up experiments to **validate models** (Wh → kWh → MWh)
- Feedback to **design** storage systems
- Inform **fire suppression** system design
- Provide to regulatory agencies (NFPA, NHTSA), utility companies, etc.

Health and Environmental Impact

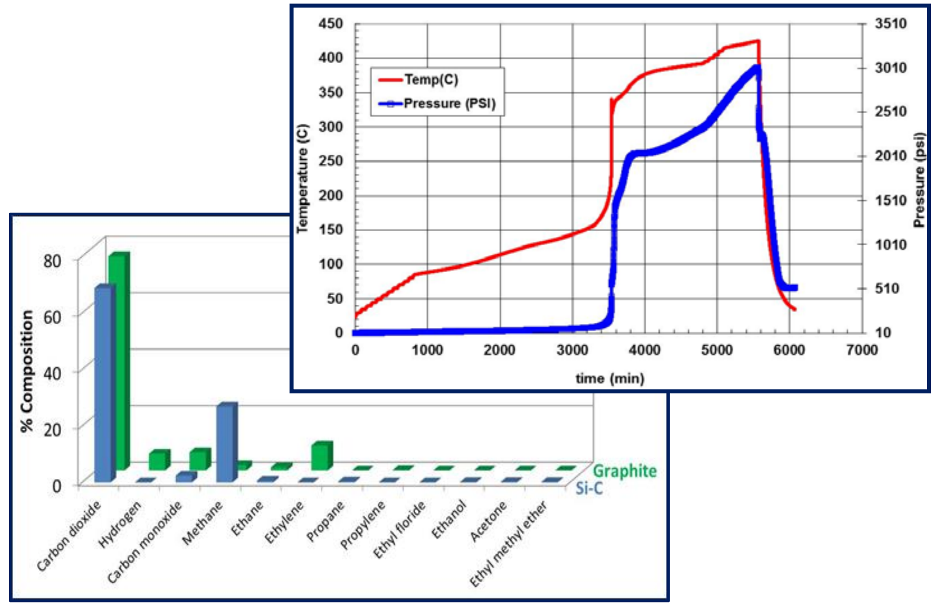
EV and ICE vehicle fire emissions analysis:



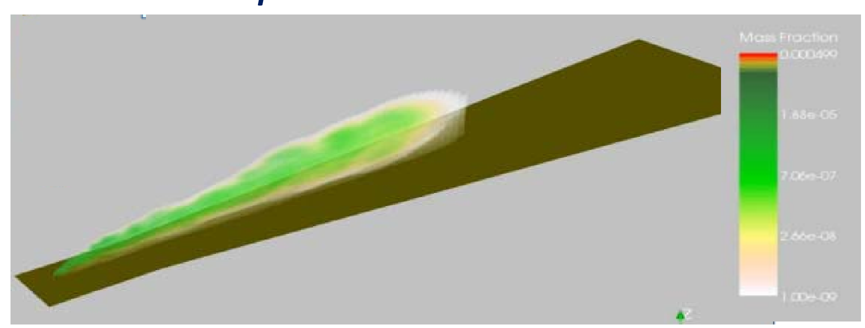
Tested element	*EV manufacturer 1*	*ICE vehicle manufacturer 1*	*EV manufacturer 2*	*ICE vehicle manufacturer 2*
Test	*Fire*	*Fire*	*Fire*	*Fire*
Nominal Voltage (V)	330 V [a]	-	355 V [a]	-
Capacity (Ah)	50 Ah [a]	-	66,6 Ah [a]	-
Energy (kWh)	16,5 kWh [a]	-	23,5 kWh [a]	-
Mass (kg)	1 122 kg	1 128 kg	1 501 kg	1 404 kg
Lost mass (kg)	212 kg	192 kg	278,5 kg	275 kg
Lost mass (%)	19%	17%	18,6%	19,6%
Online gas analysis – total quantity of emitted gases (FTIR and online analyzers)				
CO_2 (g)	**460 400**	**508 000**	**618 490**	**722 640**
CO_2 (mg/lost g)	*2 172*	*2 646*	*2 220,8*	*2 627,8*
CO (g)	**10 400**	**12 040**	**11 700**	**15 730**
CO (mg/lost g)	*49*	*63*	*42*	*57,2*
HF (g)	1 540	621	1 470	813
HF (mg/lost g)	*7,3*	*3,2*	*5,3*	*3*
Thermal effects				
Maximal HRR (MW)	4,2 MW	4,8 MW	4,7 MW	6,1 MW
Heat of combustion (MJ)	6 314 MJ	6 890 MJ	8 540 MJ	10 000 MJ
Heat of combustion/unit mass loss (MJ/ kg)	29,8 MJ/kg	35,9 MJ/kg	30,7 MJ/kg	36,4 MJ/kg

[a] *Characteristics of the battery pack of the EV*

Gas pressure/volume & chemical analysis:



Fire emissions plume simulation:



StackEffluent_second.mpg

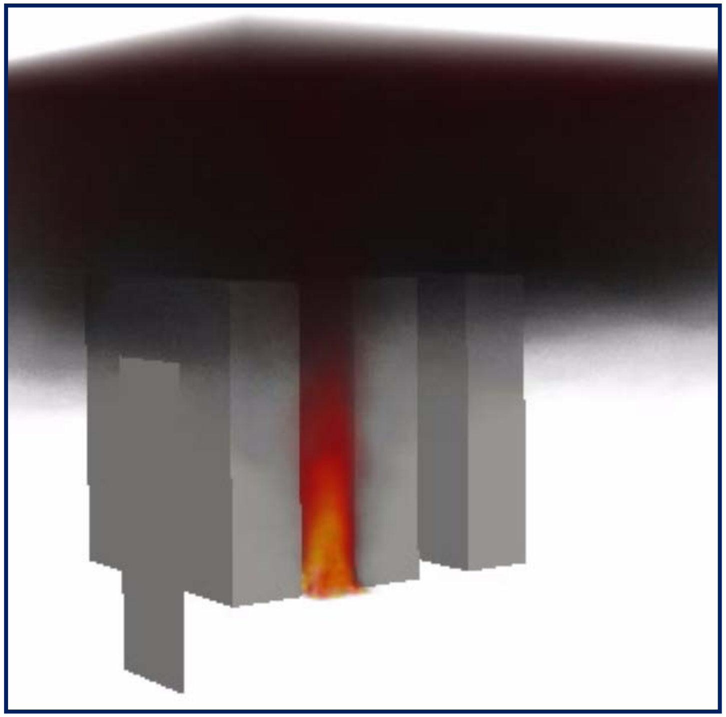
Multiple approaches used to analyze and model gas emissions from battery system fires

Lecocq, A. et al. International Conference on Fires in Vehicles, FIVE 2012

Environmental Parameters

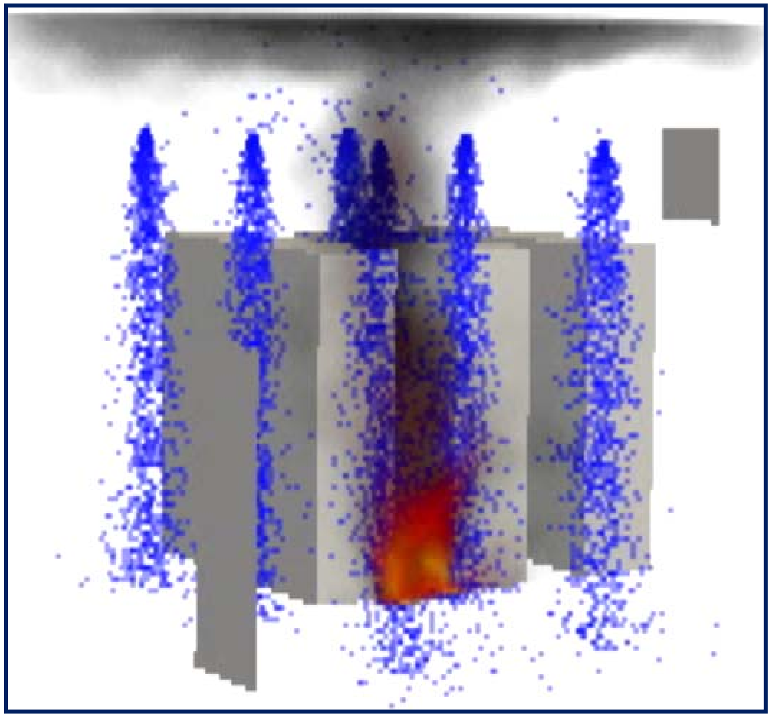
Hydrocarbon fuel fire adjacent to battery rack (grid storage example)

No ventilation



noVentilationFinal_VR.avi

Sprinkler suppression



suppressionMovie_start.avi

- ***Model predicts adjacent object surface temperature, interior temperature, internal pressure in response to the fire***
- ***Example uses water as a suppressant, but others (CO_2, Halon, etc.) can be incorporated***

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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- Harry Moffat
- Tom Wunsch
- Leigh Anna Steele
- Josh Lamb
- Pete Roth
- Mani Nagasubramanian
- Kyle Fenton
- David Ingersoll
- 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*