Opportunities and Needs in Battery Middle-Life

The price of degradation
The value of prognostics

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Thanks to
DOE (ARPA-E), U.S. ARMY (TARDEC), NSF, NIST
A123, Amphenol, Daimler, Ford, GE, and Samsung

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Li-ion Cells : Human Like

Poke them and they can *bleed* and burst into *flames*
Hate to be over-worked
Fussy about external pressure
Dislike extremes in temperature
Diverse
All cells must die, sometime

Many shapes and sizes

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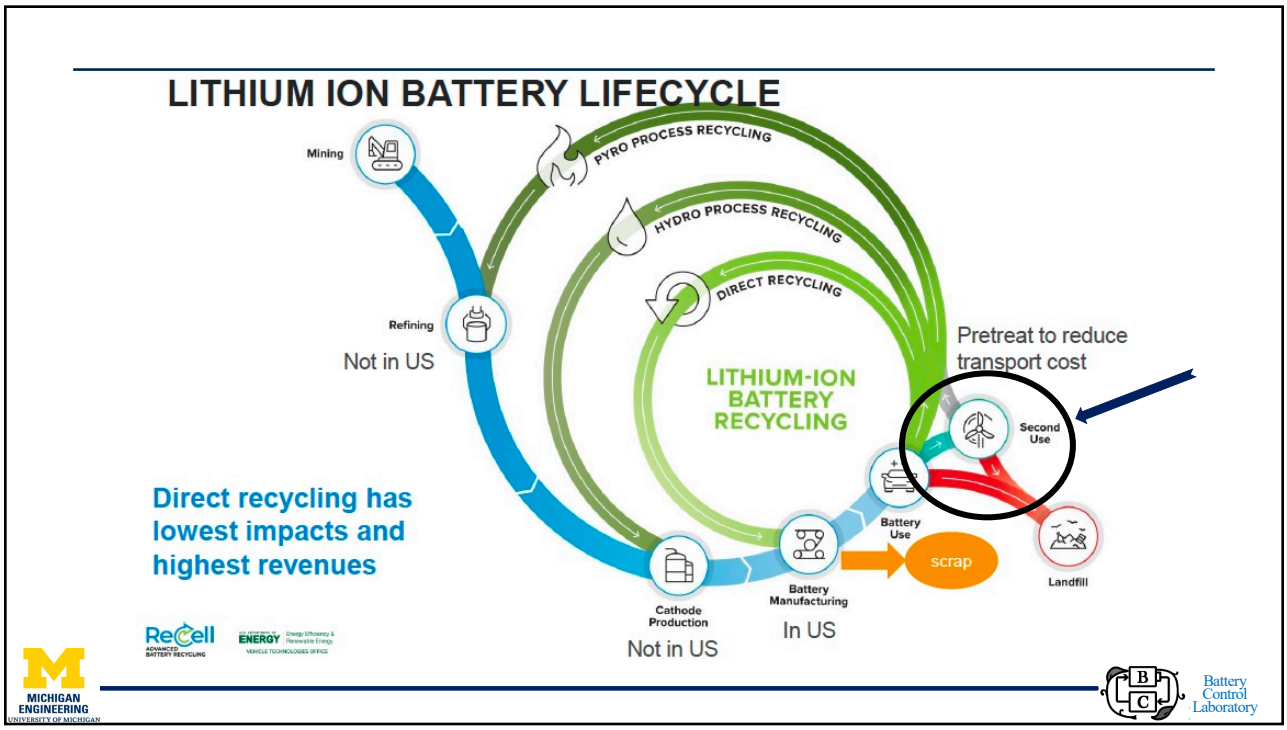
LITHIUM ION BATTERY LIFECYCLE
Mining
PYRO PROCESS RECYCLING
HYDRO PROCESS RECYCLING
DIRECT RECYCLING
Refining
Not in US
LITHIUM-ION BATTERY RECYCLING
Pretreat to reduce transport cost
Second Use
Battery Use
scrap
Landfill
Direct recycling has lowest impacts and highest revenues
Cathode Production
Not in US
Battery Manufacturing
In US
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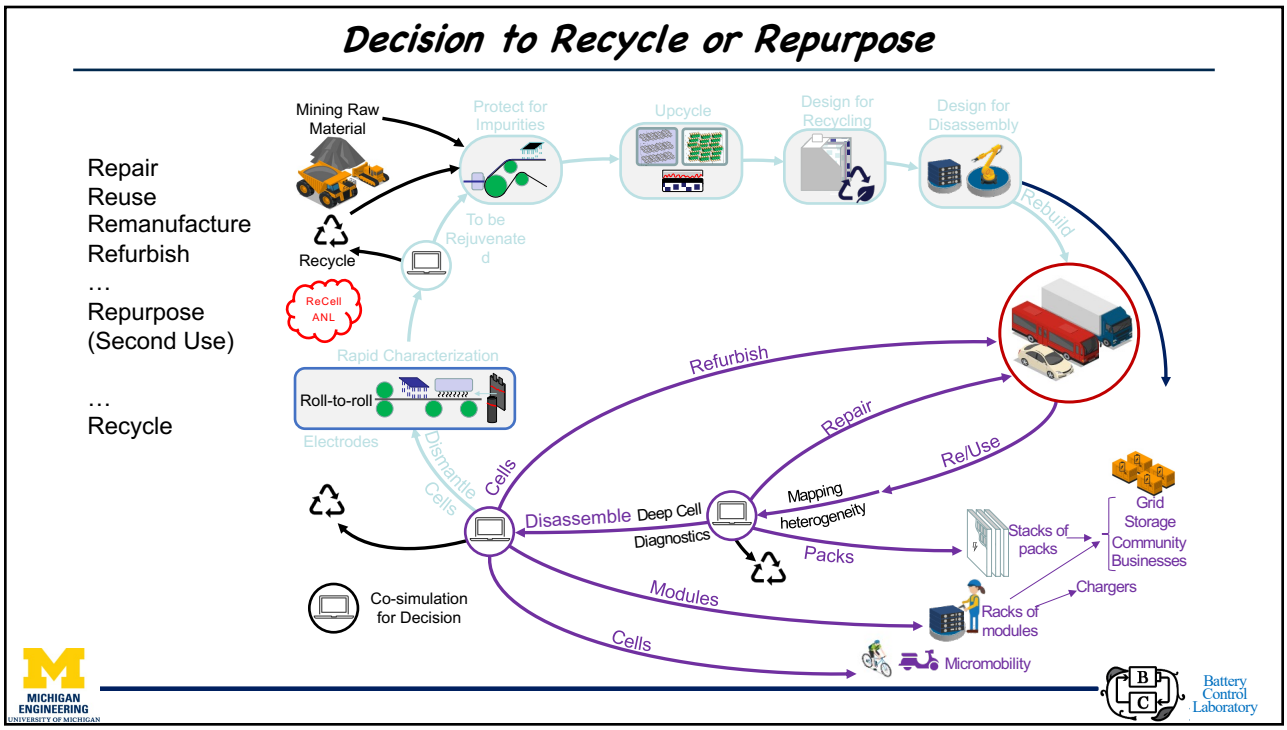
Decision to Recycle or Repurpose
Repair
Reuse
Remanufacture
Refurbish
…
Repurpose
(Second Use)
…
Recycle
Mining Raw Material
Protect for Impurities
Upcycle
Design for Recycling
Design for Disassembly
Rebuild
To be Rejuvenated
Recycle
ReCell ANL
Rapid Characterization
Roll-to-roll
Electrodes
Dismantle Cells
Refurbish
Repair
Re/Use
Disassemble Cells
Deep Cell Diagnostics
Mapping heterogeneity
Packs
Modules
Cells
Co-simulation for Decision
Stacks of packs
Racks of modules
Grid Storage
Community
Businesses
Chargers
Micromobility
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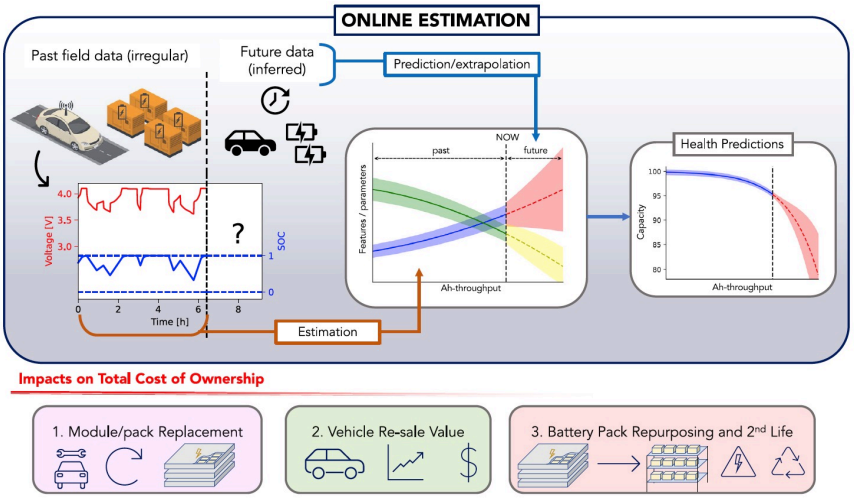
Learning from Field Data



Diagnostics (key features)
Estimation of internal states
Learn pattern
Predict
...

Act:
Manage Assets
Adjust Use & Maintenance
Redesign-Improve

The challenge and opportunity of battery lifetime prediction from field data, https://doi.org/10.1016/j.joule.2021.06.005

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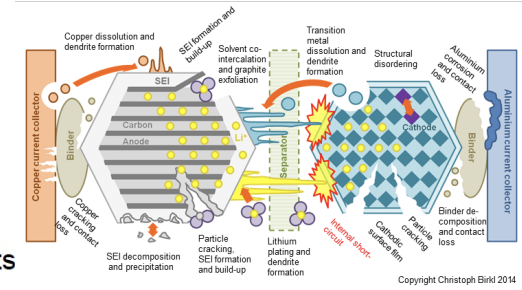
Battery Life & Safety

Battery State Estimation instead of driving blind

Inside every cell

What we are protecting against

- Electrolyte oxidation / reduction
- Lithium Plating (Dendrites)
- Electrode stress/cracking
- Internal cell defects
- Thermal runaway



What we currently monitor

- Temperature
- Voltage
- Current

What we Control

- Current
- Coolant Flow and Temp

Groups of cells

from Dr. Ilan Gur, ARPA-E Program Director

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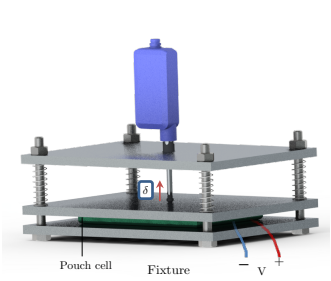
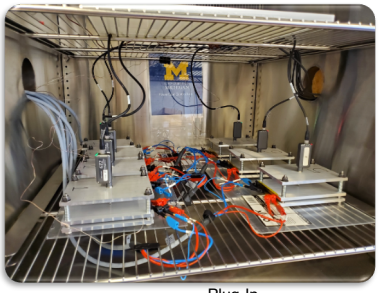
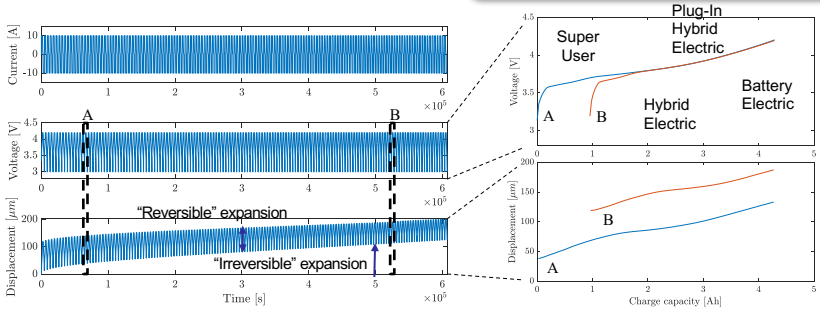
Accessing and Testing Many cells







Cai, T. et al. Modeling Li-Ion Battery Temperature and Expansion Force during the Early Stages of Thermal Runaway Triggered by Internal Shorts. *JECS*, *166*(12), A2431.

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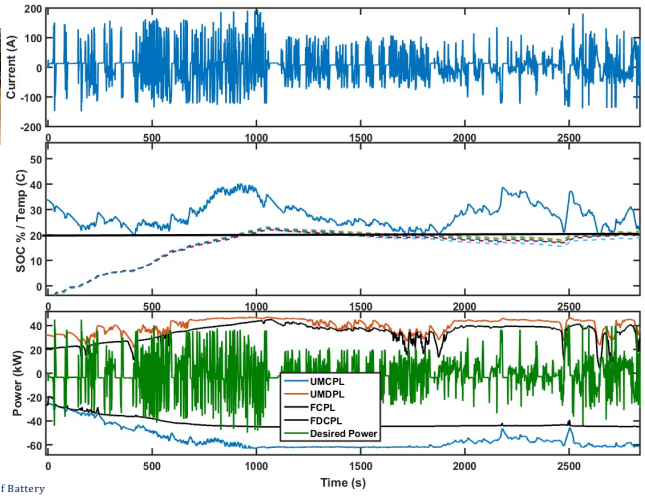
Winter Cycle, from -5°C and 30% SOC

Pack Data



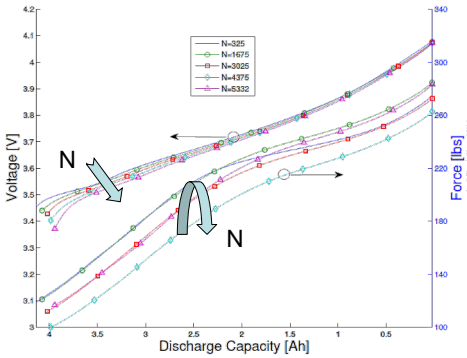
N. Samad, Y. Kim, J. Siegel and A. Stefanopoulou, "Influence of Battery Downsizing and SOC Operating Window on Battery Pack Performance in a Hybrid Electric Vehicle",VPPC 2015, Oct 2015

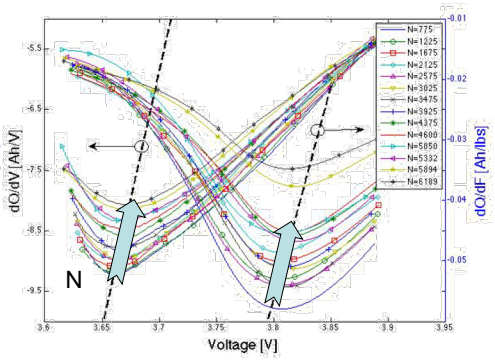
8

Provable Capacity estimation

Voltage (V) decreases consistently but by small amount with cycles.

The peaks of dF/dQ and dV/dQ curves are consistently shifting with cycles.





Force or pressure changes and can reveal a lot of information!!

The force/ressure peak happens at higher voltages so packs do not need to deep-discharge!

N. Samad, Y. Kim, J. B. Siegel, A. Stefanopoulou, "Battery Capacity Fading Estimation Using a Force-Based Incremental Capacity Analysis," Journal of The Electrochemical Society Vol. 163 Issue 8, pp. A1584-A1594, Jan 2016

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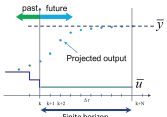
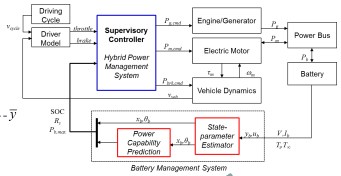
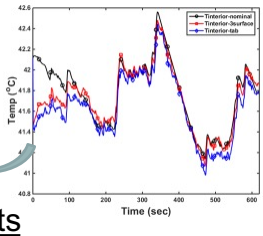
Adapt and Learn Power Limits

Prediction

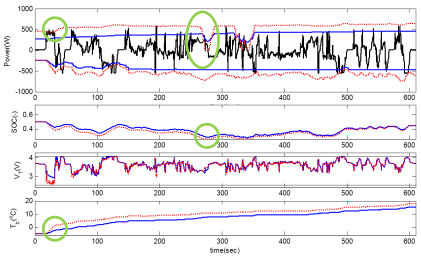




Estimation



Control



Benefits

- Reduce Degradation
- Age Conscious
- Dynamic limits can be more conservative when necessary for health and safety.
- Battery utilization (Whr throughput) can be increased or the packs can be rightsized as compared to static predetermined limits.

Y. Kim, et al "Optimal Power Management for a Series Hybrid Electric Vehicle Cognizant of Battery Mechanical Effects", ACC, 2014

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Battery Utilization

State of Charge (SOC) and Health (SOH) Need to highlight its importance

Aim to achieve 5% SOC&SOH accuracy

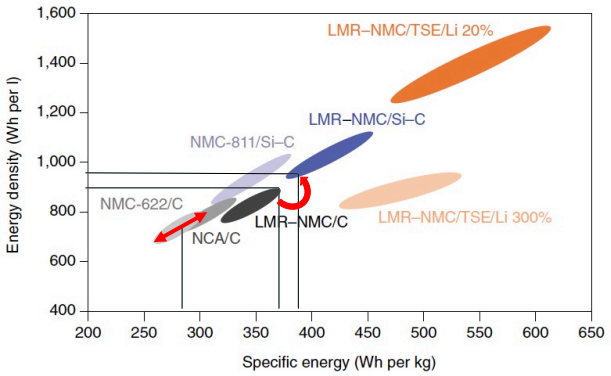
To realize SOC/SOH importance:
→ A fully degraded pack has lost 20% of its ability to hold charge
→ Compare with chemistry advancements 5% SOC accuracy is equivalent to jumping from C to the Si-C anodes

Unfortunately even 10% SOC accuracy is hard to achieve at aged conditions.

nature energy REVIEW ARTICLE

Performance and cost of materials for lithium-based rechargeable automotive batteries

Richard Schmuch, Ralf Wagner, Gerhard Hörpel, Tobias Placke and Martin Winter



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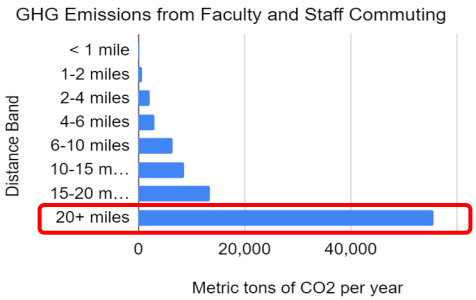
EV Adoption by U-M Community = Workplace Charging

120,000

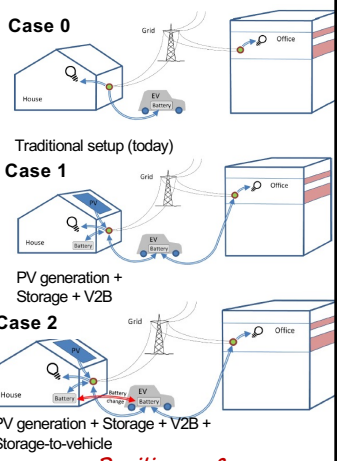
mtCO$_2$eq/yr

Commuter (employee & students') emissions equal **44%** of UMs Scope 1 emissions



About 40k faculty and staff vehicles in use, of which 10k are long-distance commuters (20+ miles)

Long-distance commuters account for 60% of faculty and staff commuting emissions, which total to roughly 90,10 metric tons of CO_2e per year
= ~30% of scope 1 emissions



Resilience & Renewable Energy Storage

High utilization: Assess Continuously Degradation

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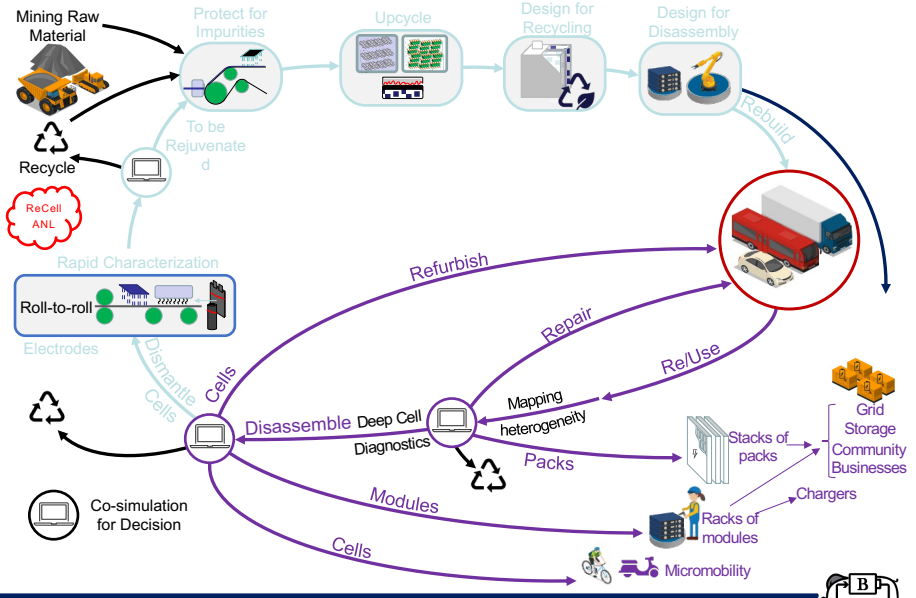
Accurate estimation of Degradation is a key goal!

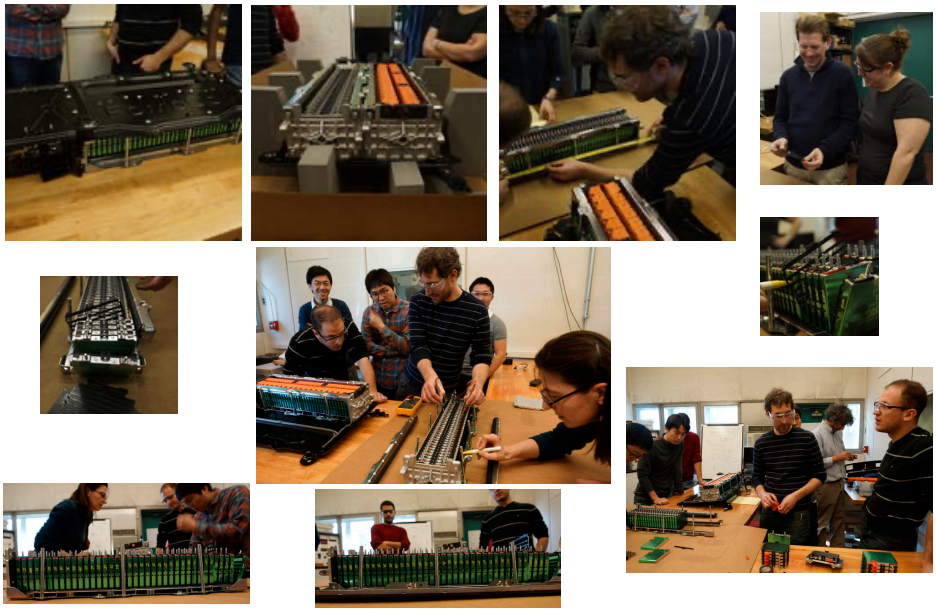
Decision to Recycle or Repurpose

Repair
Reuse
Remanufacture
Refurbish
…
Repurpose
(Second Use)

…
Recycle



Pack Disassembly at University of Michigan, Auto Lab



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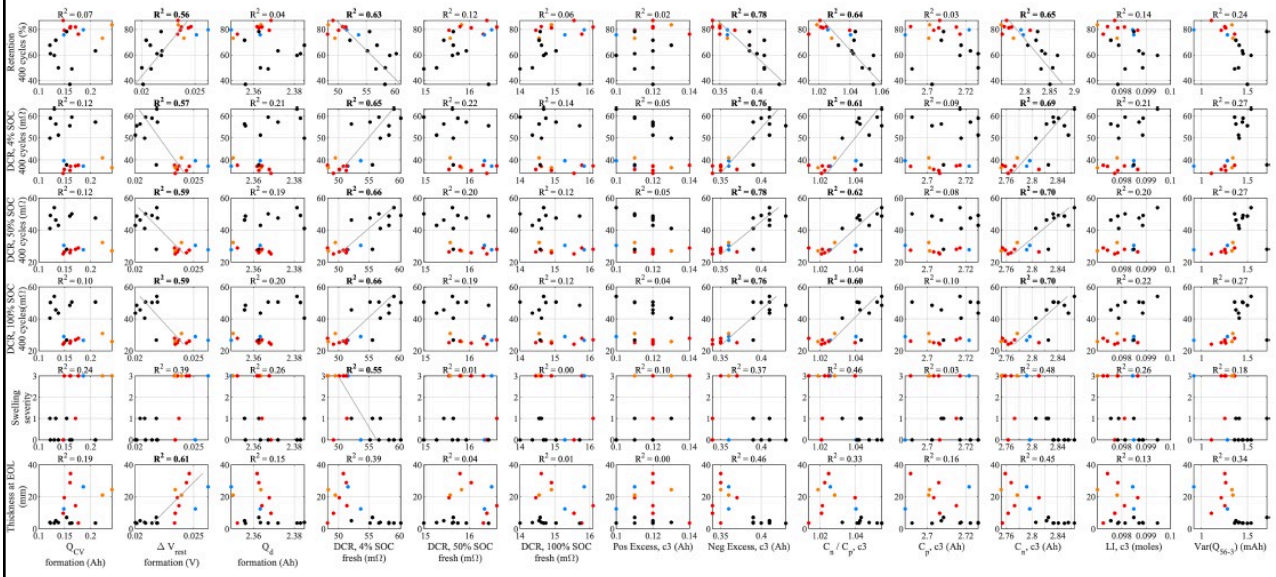
High-Throughput Testing …



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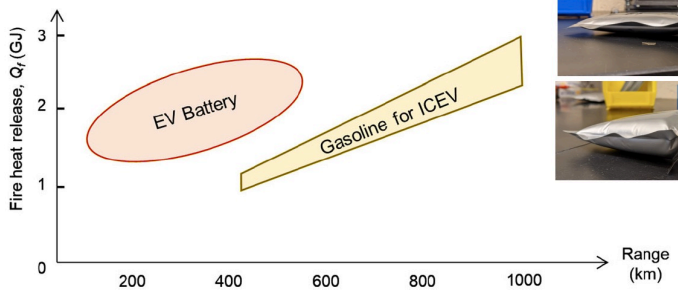
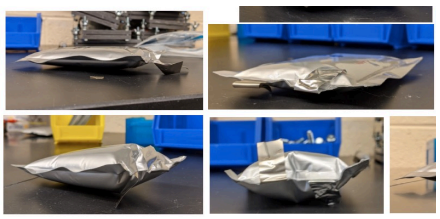
Fire Heat Release of Burning Vehicle Fuel





- The heat of combustion from Li-ion cells in aa pack will be twice as big as the heat of combustion from a gasoline vehicle (same range)
- EVs need 500-8,000 gallons of water and foam to suppress fires
- No guarantee there will not be a re-ignition later and harm nearby assets and emergency responders

Sun, Peiyi, et al. "A review of battery fires in electric vehicles." Fire technology (2020):

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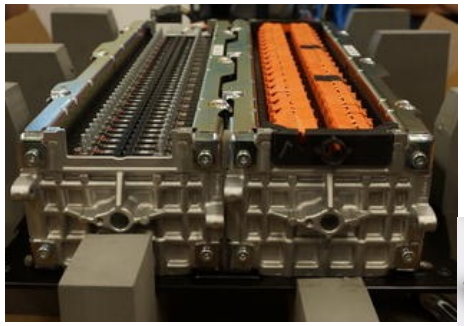
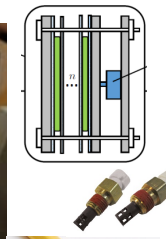
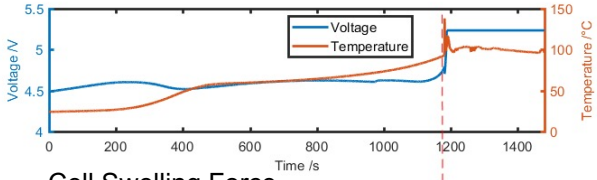
Consider a Multi-Sensor Approach (Current ,Voltage ,Temp, Pressure ,Gas)

- Large packs and energy storage systems need to be engineered beyond containing thermal runaways

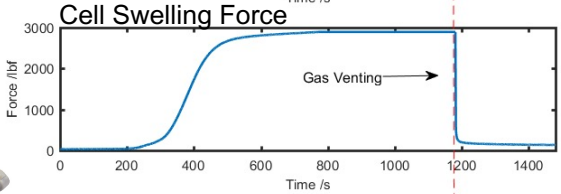




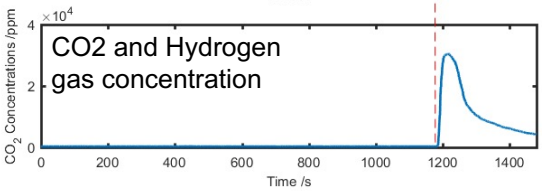
Voltage, Temperature



Cell Swelling Force



CO2 and Hydrogen gas concentration



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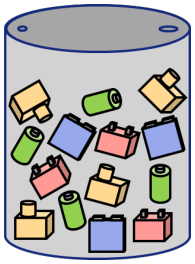
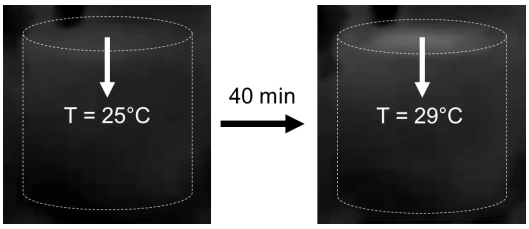
Battery State of Safety (SOS) Estimation

Detecting and Managing Thermal Runaway in Storage Facilities

- Used batteries are stored in a large drum or cabinets (0.2 m^3)
- Infrared Camera is too slow (40 min) to identify a thermal event, before it spreads to nearby cells



- Gas sensor (CO2, H2, …)
- Pressure sensor detects vent within a fraction of a second only if sealed



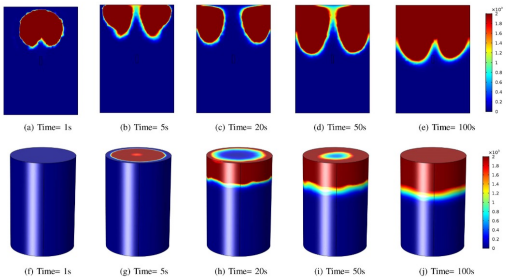


Fig. 3: CO_2 Concentrations in PPM. (a-e) Cross-sectional View at x=0; (f-j) Surface Concentrations

Cai, Ting, Anna G. Stefanopoulou, and Jason B. Siegel. "Early Detection for Li-Ion Batteries Thermal Runaway Based on Gas Sensing." ECS Transactions 89.1 (2019): 85

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The price of degradation
The value of prognostics

Thanks to

Jason Siegel,
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Tino Sulzer, Andrew Weng
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A123, Navitas, Ford, Samsung, and GE

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