Battery Lifetime Prediction and Management along with Safety and the Transition

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

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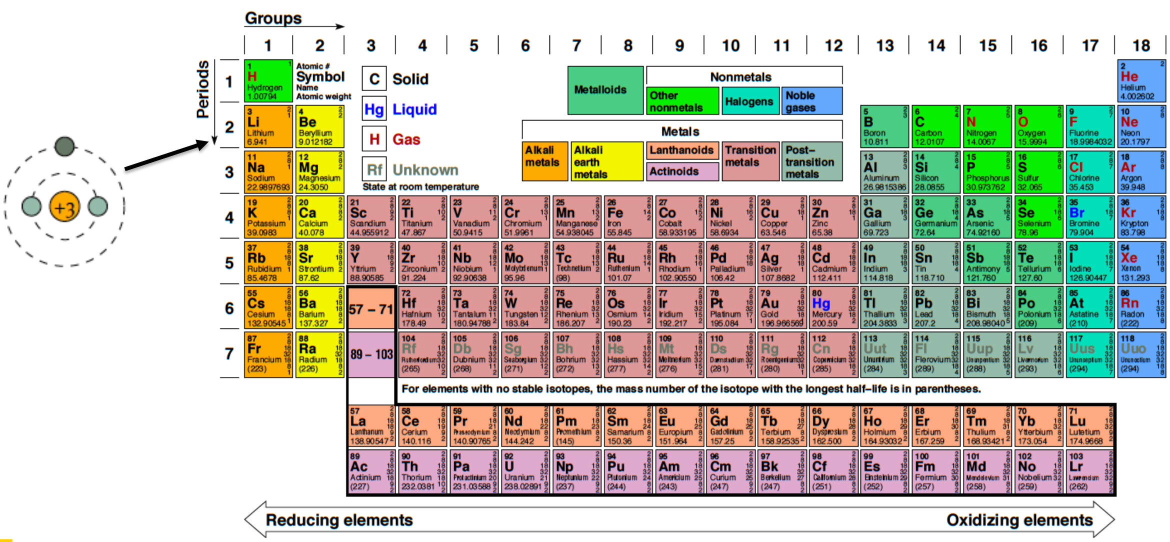
Lithium-Ion Battery 101



G. Plett, Battery Management Systems, Vol I, Battery Modeling, Artech House Publishers

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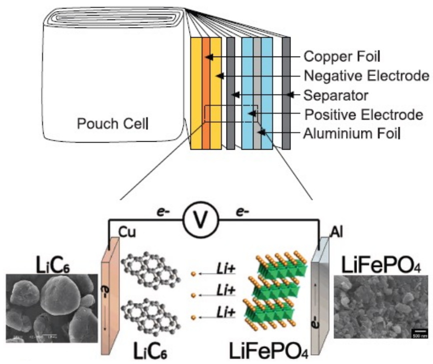
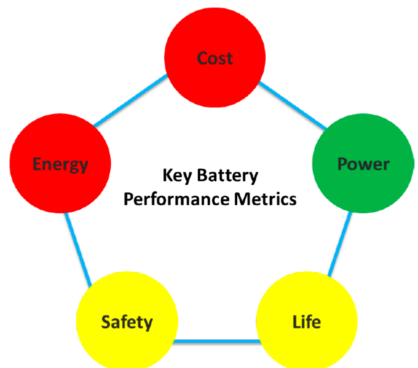
Li-ion Battery Operation

Five Layers



Five Metrics



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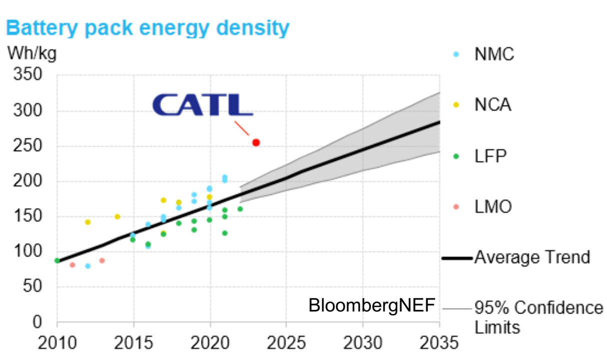
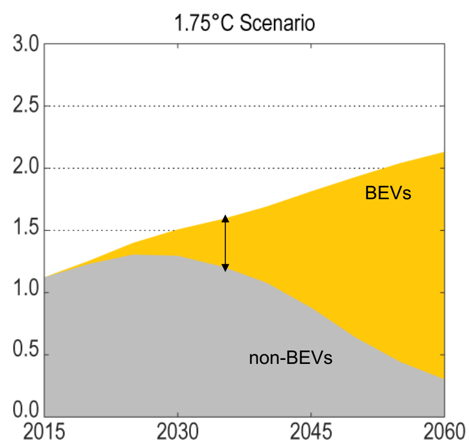
Batteries Bonanza

US Goal: 50% of LDV sales by 2035 (10,000,000 EV/year)
→ produce 2000 prismatic cells per min



IEA has projected that
500M BEVs are needed globally by 2035
to maintain global warming at 1.75 degrees



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Batteries Galore

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Batteries are like Humans

- Hate to be overworked
- Fussy about external pressure
- Dislike extremes in temperature
- Diverse in chemistry, size, and shape
- Statistically faulty
- All cells must die, sometime

GM Brownstown Battery Assembly Plant Worker Tina Oaks attaches a wiring harness on a Spark EV battery pack Tu May 13, 2014;
J.F. Martin for GM, appeared in Detroit Free Press Dec 18, 2018

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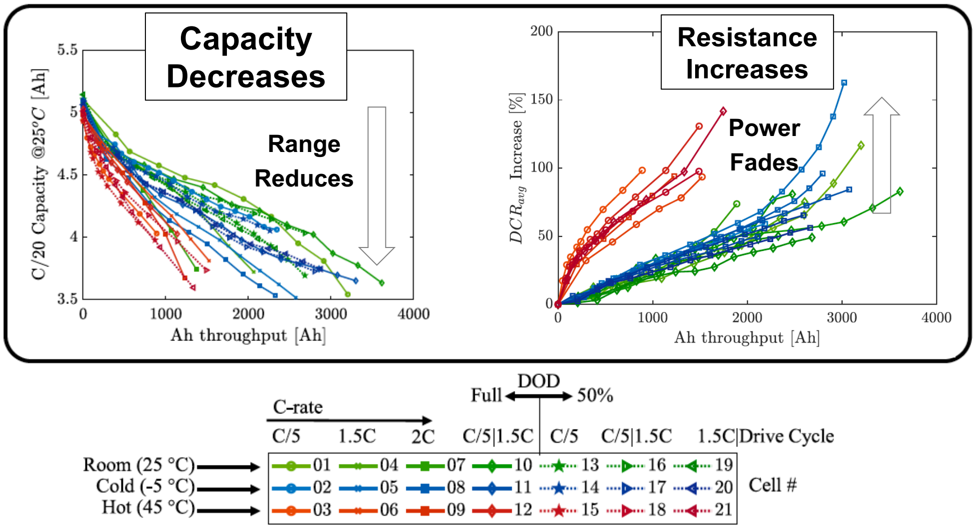
Cell-level Degradation



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Mohtat et al, JECS 2021
Mohtat et al, JPS 2021

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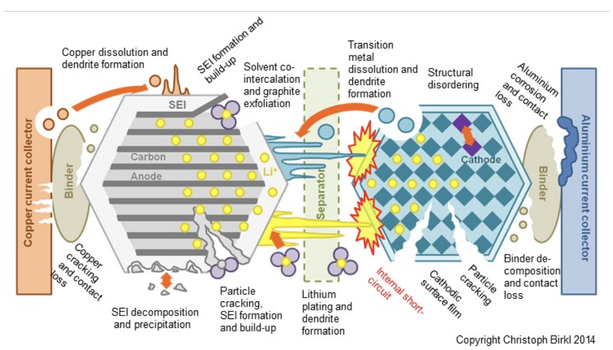
Causes → → Degradation Mechanisms →→ Effects

Cause
Time
High Temperature
High V/SOC
Current Load
Low Temperature
Stoichiometry
Mechanical Stress
Low V/SOC



Effect
Capacity loss
Power fade

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Modified from Birkl et al. 2017

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Limited Internal Measurements

Cause
Time
High Temperature
High V/SOC
Current Load
Low Temperature
Stoichiometry
Mechanical Stress
Low V/SOC

Driving Blind?

Effect
Capacity loss
Power fade

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Modified from Ilan Gur

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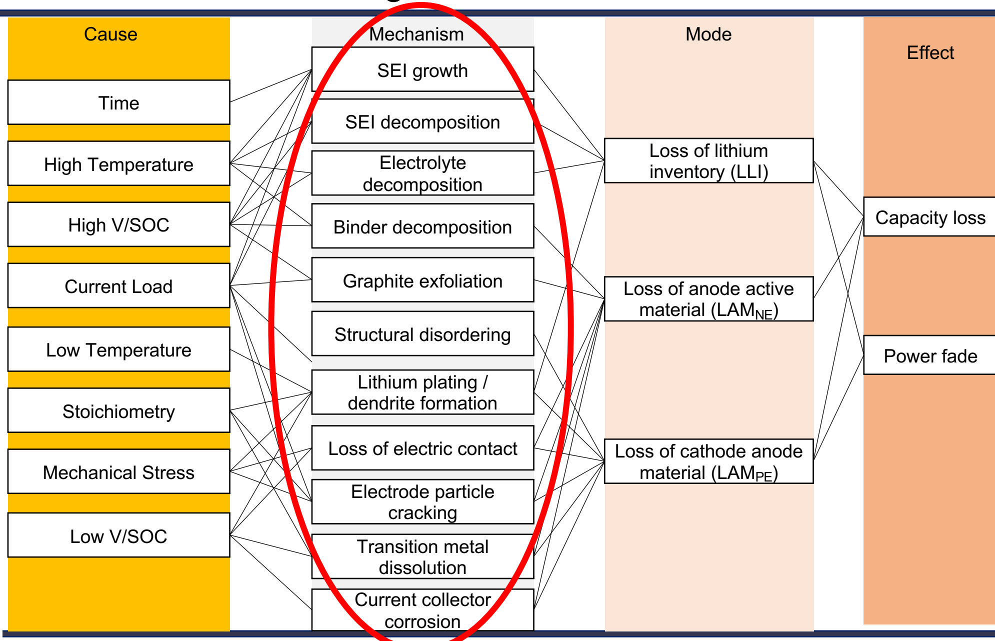
Degradation Mechanisms



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Modified from Birkl et al. 2017

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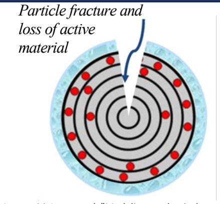
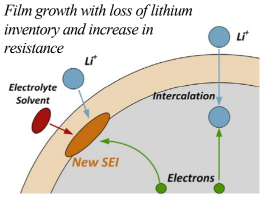
Battery Digital Twin



Laresgoiti, Izaro, et al. "Modeling mechanical degradation in lithium ion batteries during cycling: Solid electrolyte interphase fracture." *Journal of Power Sources* 300 (2015): 112-122.



Yang, Xiao-Guang, et al. "Modeling of lithium plating induced aging of lithium-ion batteries: Transition from linear to nonlinear aging." *Journal of Power Sources* (2017)

Mechanical Degradation

$$\sigma_h(r,t) = \frac{2E\Omega}{3(1-\nu)}\left(\frac{1}{R_p^3}\int_0^{R_p}\rho^2 c_s(\rho,t)d\rho - \frac{c_s(r,t)}{3}\right)$$

$$\frac{d\varepsilon_s}{dt} = \beta_{LAM}\left(\frac{\sigma_{h,surf}}{\sigma_{critical}}\right)^{m_{LAM}}$$

SEI

$$j_{SEI} = -k_{SEI}c_{EC}^s exp\left(\frac{-\alpha_{SEI}F}{RT}\eta_{SEI}\right)$$

$$-D_{SEI}\frac{c_{EC}^s - c_{EC}^0}{\delta_{film}} = -a_s j_{SEI}$$

$$\eta_{sei} = \phi_s - V_R - U_{SEI}$$

$$\frac{\partial c_{SEI}}{\partial t} = \frac{-a_s j_{SEI}}{2}$$

$$\delta_{film} = \frac{1}{a_s}\left(\frac{c_{SEI}M_{SEI}}{\rho_{SEI}}\right)$$

$$R_{film} = \omega_{SEI}\frac{\delta_{film}}{\kappa_{SEI}}$$

$$n_{Li,loss} = \int_0^{t_{end}}\left(\int_0^{l^-} Aa_s\left(\frac{j_{SEI}}{2}\right)dx\right)dt$$

Single Particle Model

$$\frac{\partial c_s}{\partial x}(r,t) = \frac{1}{r^2}\frac{1}{\partial r}\left[D_s r^2\frac{\partial c_s}{\partial r}(r,t)\right]$$

$$\frac{\partial c_s}{\partial x}(0,t) = 0$$

$$D_s\frac{\partial c_s}{\partial r}(R_p,t) = -j_{tot}$$

$$c_s(r,0) = c_{init}$$

$$a_s = \frac{3\varepsilon_s}{R_p}$$

$$j_{tot} = \frac{I}{a_s lA}$$

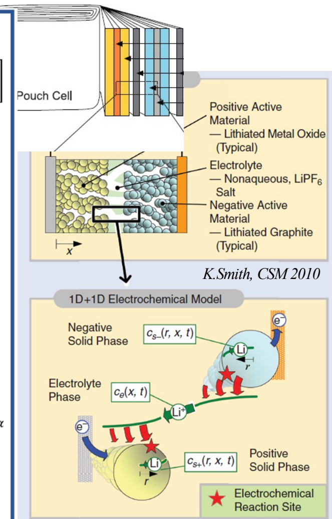
$$j = \frac{i_0}{F}\left(e^{\frac{(1-\alpha)F}{RT}\eta} - e^{\frac{-\alpha F}{RT}\eta}\right)$$

$$i_0 = k_0(\bar{c}_e)^\alpha(c_{s,max} - c_{ss})^\alpha(c_{ss})^\alpha$$

$$\phi_s = \eta + V_R + U(c_{ss})$$

$$V_R = R_{film}Fj$$

$$V(t) = \phi_s^+ - \phi_s^-$$



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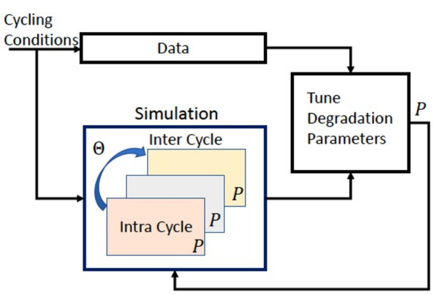
Calibrated Digital Twin Predicts Degradation over Life



Automatically tune degradation model parameters until a good fit with experimental data is found.

Intra-cycle states

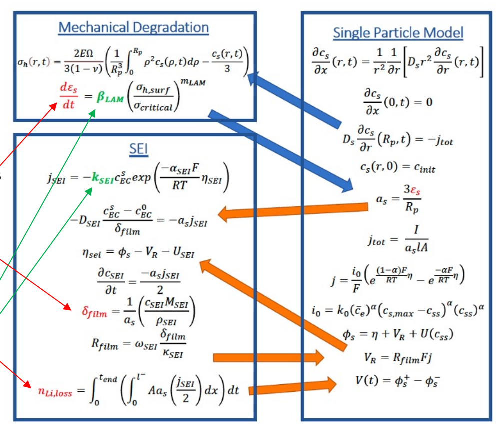
$$\boldsymbol{x} = \begin{bmatrix} c_s^+ \\ c_s^- \end{bmatrix}$$

Inter-cycle states

$$\boldsymbol{\Theta} = \begin{bmatrix} \delta_{\mathrm{SEI}} \\ \varepsilon_s^- \\ \varepsilon_s^+ \\ n_{\mathrm{Li,s}} \end{bmatrix}$$

Parameters

$$\boldsymbol{P} = \begin{bmatrix} k_{\mathrm{SEI}} \\ \beta_{\mathrm{LAM}}^- \\ \beta_{\mathrm{LAM}}^- \end{bmatrix}$$



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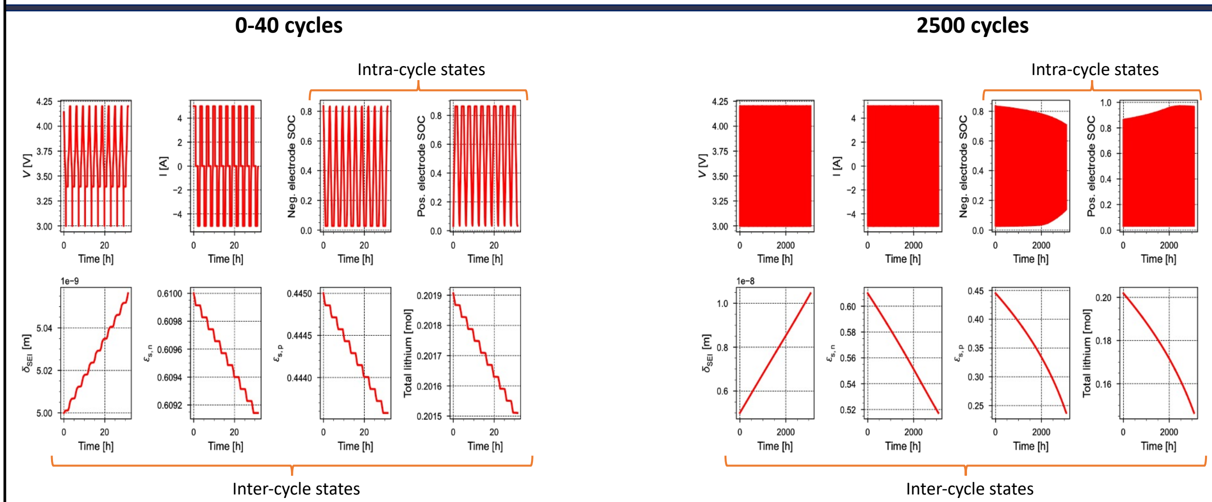
Intra-Cycle and Inter-Cycle Simulation of Battery Life



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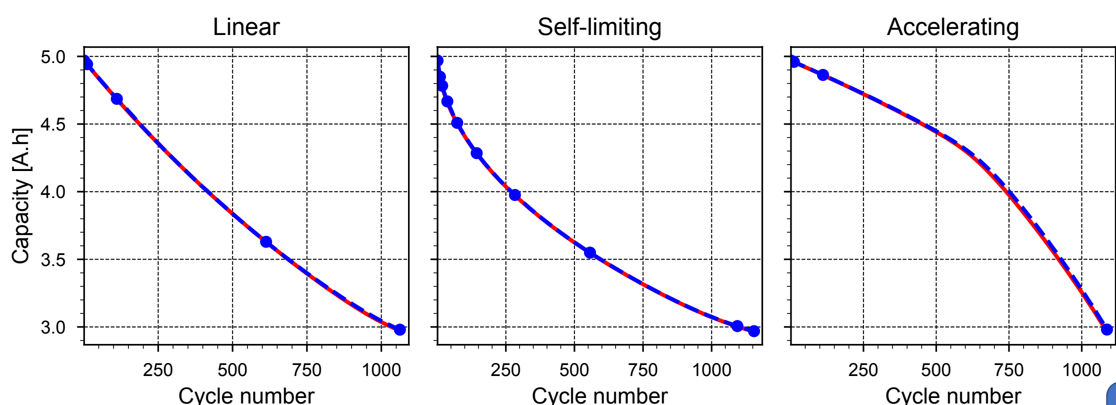
Degradation Patterns



Knee

Linear degradation

Self limiting degradation

Accelerating Degradation

Accelerated battery lifetime simulations using adaptive inter-cycle extrapolation algorithm,
V Sulzer, et al J. of The Electrochem. Society 2021

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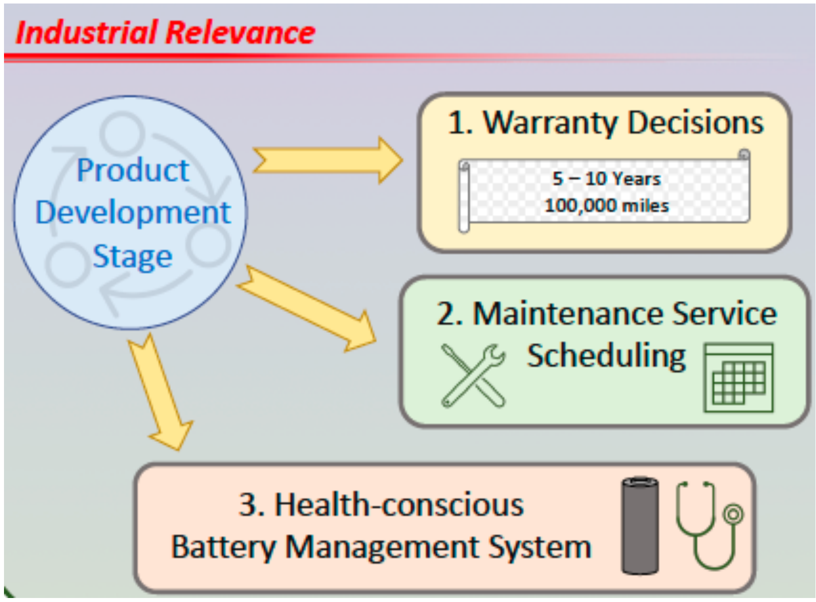
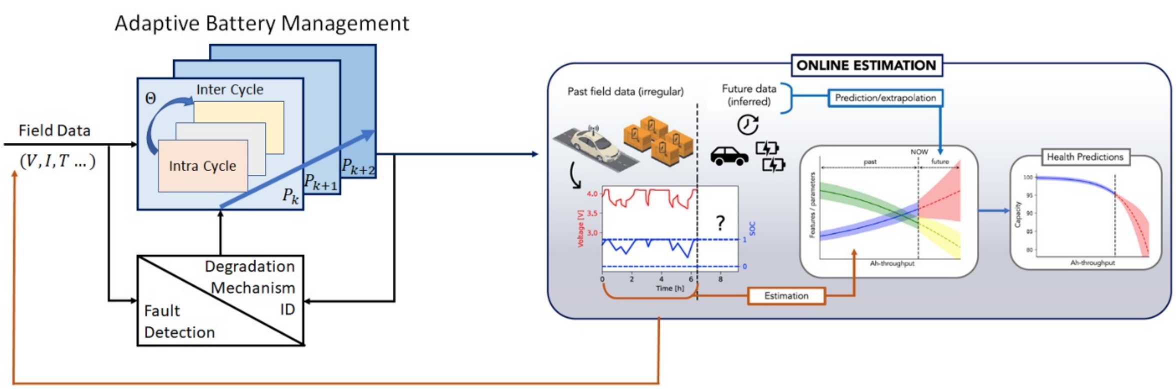
Value of Life Prediction to EV Manufacturers



Monitoring Use & Predicting the Remaining Useful Life



Sulzer, V., et al. "Accelerated battery lifetime simulations using adaptive inter-cycle extrapolation algorithm". *JECS21*
Pannala S. et al, "Methodology for Accelerated Inter-Cycle Simulations of Li-ion Battery Degradation with Intra-Cycle Resolved Degradation Mechanisms"' ACC 2022

Beyond Electrical Features
The Mechanical Frontiers

Degradation and Cell Expansion
Cause or Effect?

Based on
P. Mohtat, S. Lee, A. Stefanopoulou, J. Siegel, "Towards better estimability of electrode-specific state of health: Decoding the cell expansion," *Journal of Power Sources* 427, 101-11 2019.

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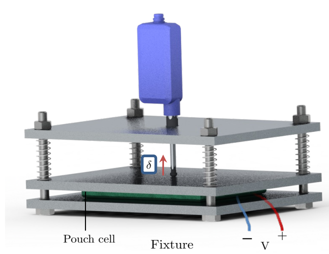
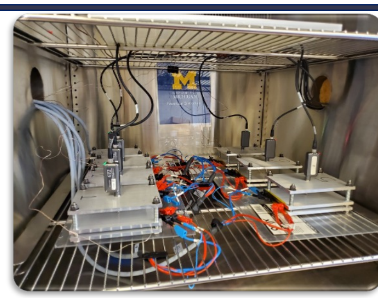
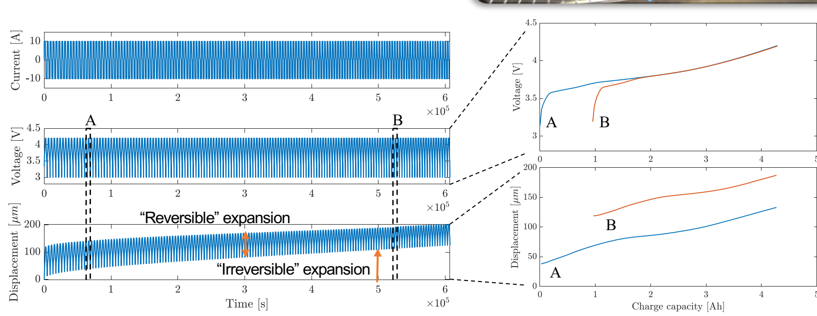
Experiments: Cell Capacity, Resistance, & Thickness







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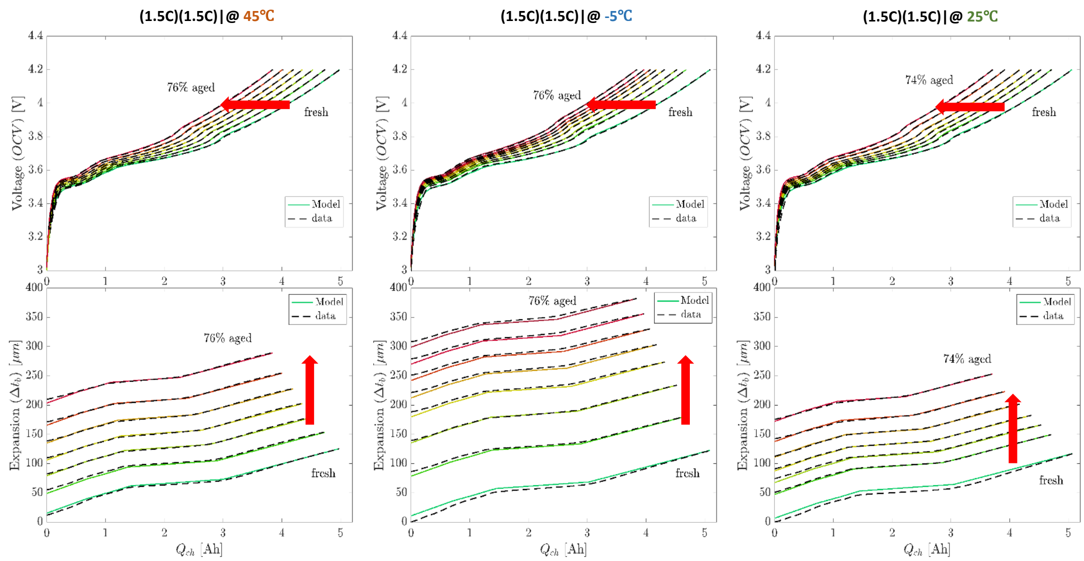
Aged Cells: Expanding in Thickness

Irreversible expansion from

- SEI growth
- particle fracture, and
- plating



P. Mohtat, et al(2021). "Reversible and Irreversible Expansion of Lithium-Ion Batteries Under a Wide Range of Stress Factors". *J. of Electroc Soc.* 2021

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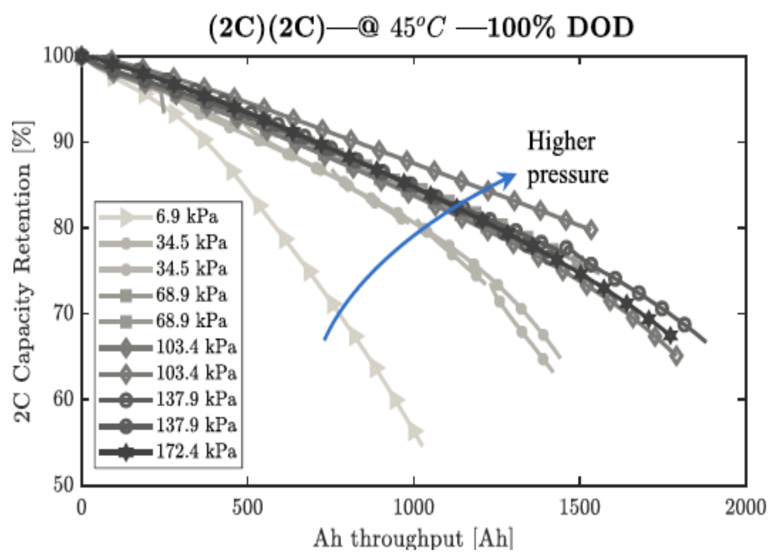
Pressure Matters

<u>Packaging:</u>

- High Energy Density
- Protection
- Thermal Propagation
- Longevity
- Repair, ReMan, Refub,
- Recycle

The <u>Goldilocks Principle</u>: Pressure should neither be too low nor too high

P. Mohtat, et al(2021). "Reversible and Irreversible Expansion of Lithium-Ion Batteries Under a Wide Range of Stress Factors". *J. of Electroc Soc.* 2021



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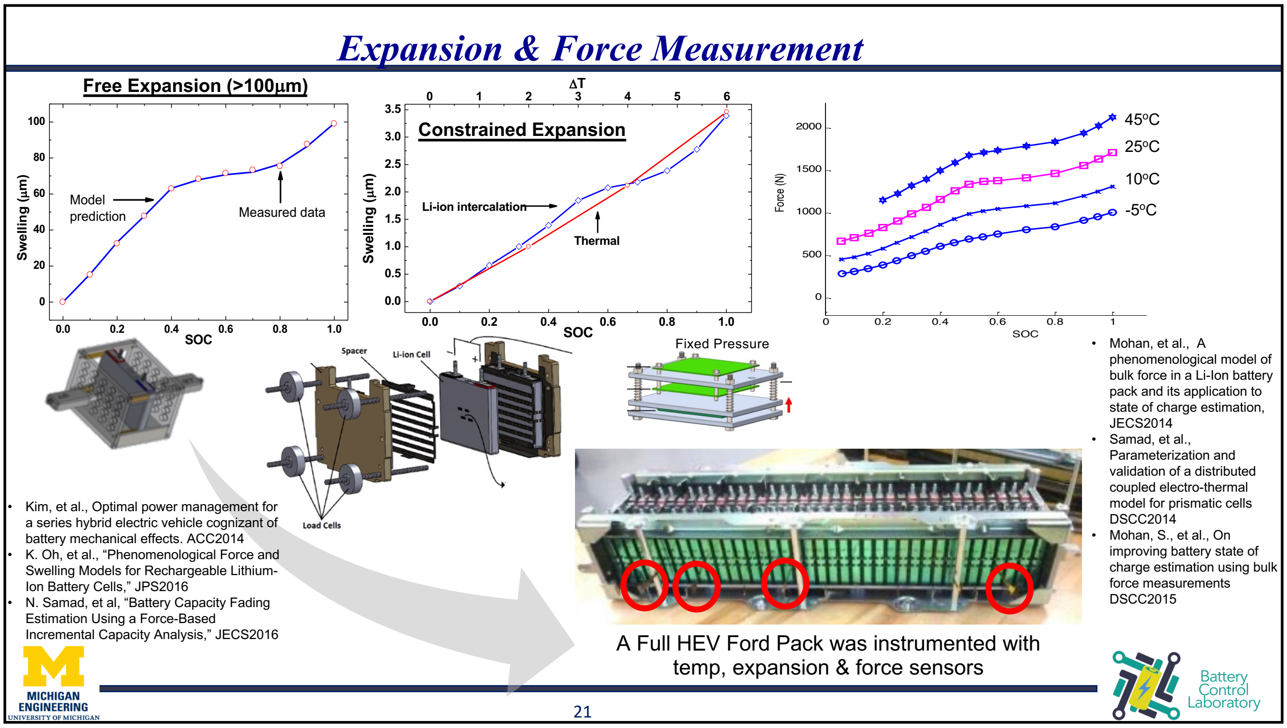
Expansion & Force Measurement
Free Expansion (>100μm)
Swelling (μm)
Model prediction
Measured data
SOC
ΔT
Constrained Expansion
Li-ion intercalation
Thermal
Force (N)
45°C
25°C
10°C
-5°C
Spacer
Li-ion Cell
Load Cells
Fixed Pressure
Kim, et al., Optimal power management for a series hybrid electric vehicle cognizant of battery mechanical effects. ACC2014
K. Oh, et al., "Phenomenological Force and Swelling Models for Rechargeable Lithium-Ion Battery Cells," JPS2016
N. Samad, et al, "Battery Capacity Fading Estimation Using a Force-Based Incremental Capacity Analysis," JECS2016
Mohan, et al., A phenomenological model of bulk force in a Li-Ion battery pack and its application to state of charge estimation, JECS2014
Samad, et al., Parameterization and validation of a distributed coupled electro-thermal model for prismatic cells DSCC2014
Mohan, S., et al., On improving battery state of charge estimation using bulk force measurements DSCC2015
A Full HEV Ford Pack was instrumented with temp, expansion & force sensors
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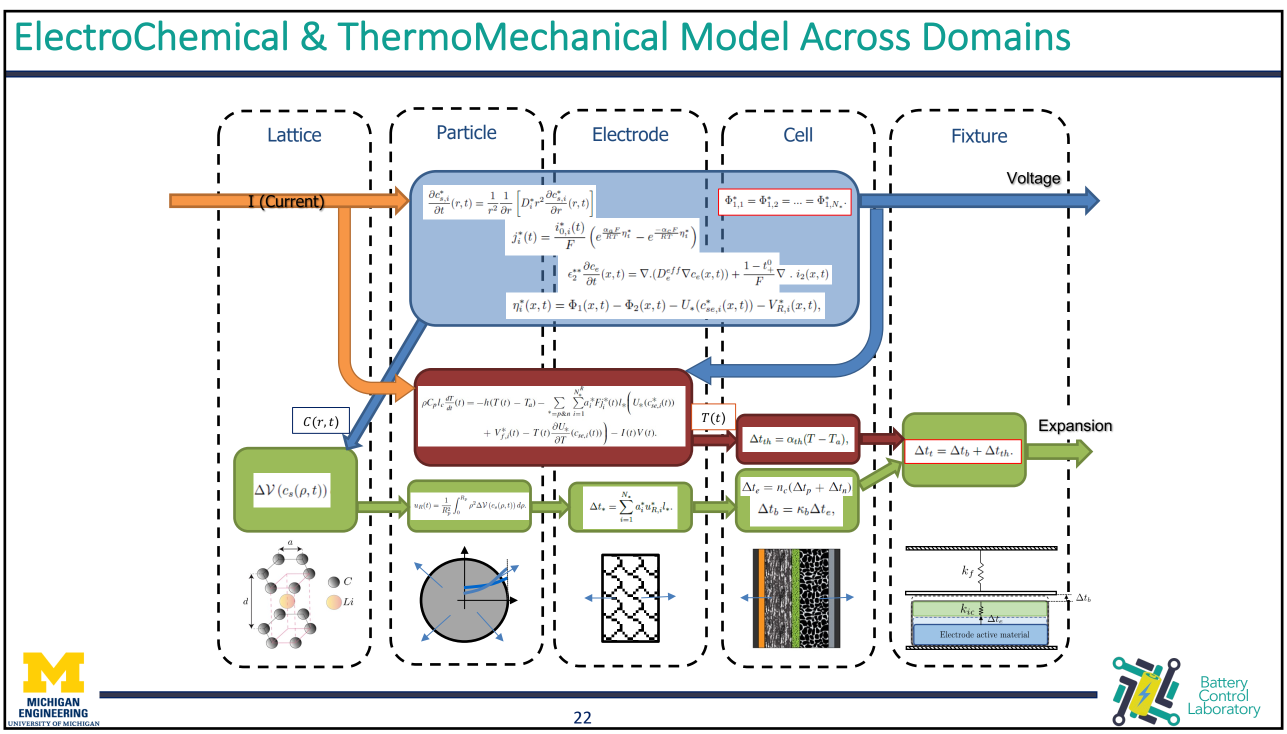
ElectroChemical & ThermoMechanical Model Across Domains
Lattice
Particle
Electrode
Cell
Fixture
I (Current)
Voltage
Expansion
C(r,t)
T(t)
Electrode active material
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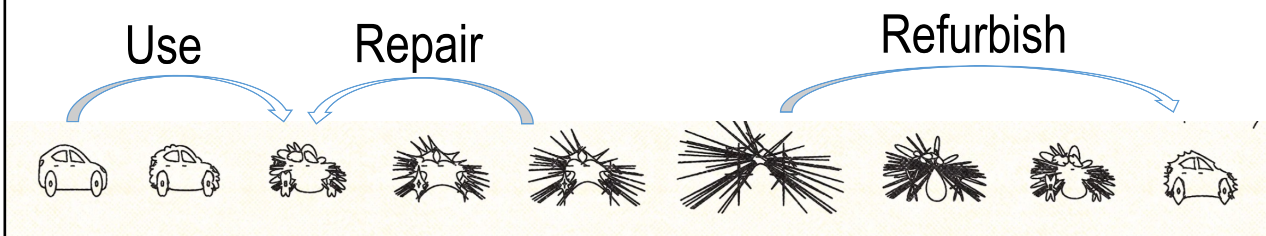
Second hand EVs: Repair & Refurbish



For Equitable Battery Ecosystem

Battery is 30-40% of EV cost

$2.5B US industry in engine remanufacturing

6,000 machine shops in North America

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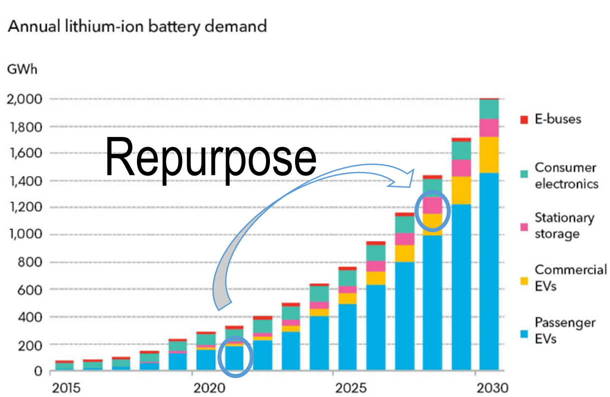
2nd Life: Value of Repurposing



Source: Bloomberg NEF 2019 Electric Vehicle Outlook

Leveling battery competition between grid storage and EVs

Decarbonizing the grid with frequency regulation & energy arbitrage

Improving fast charging economics

Supporting building decarbonization

Fitzgerald et al., 2015

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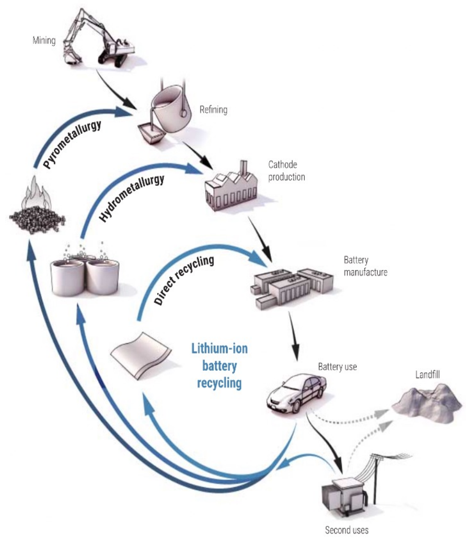
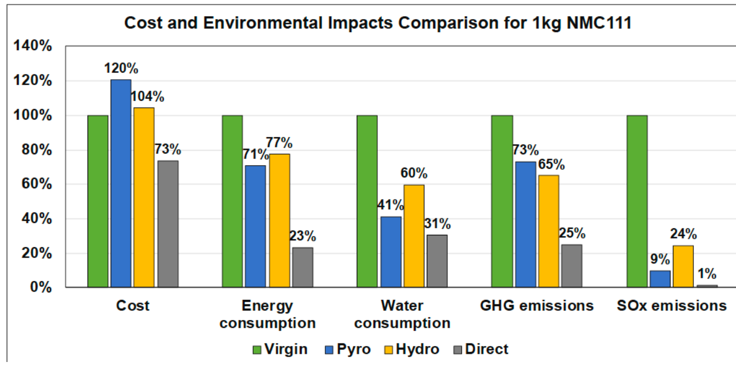
Recycle





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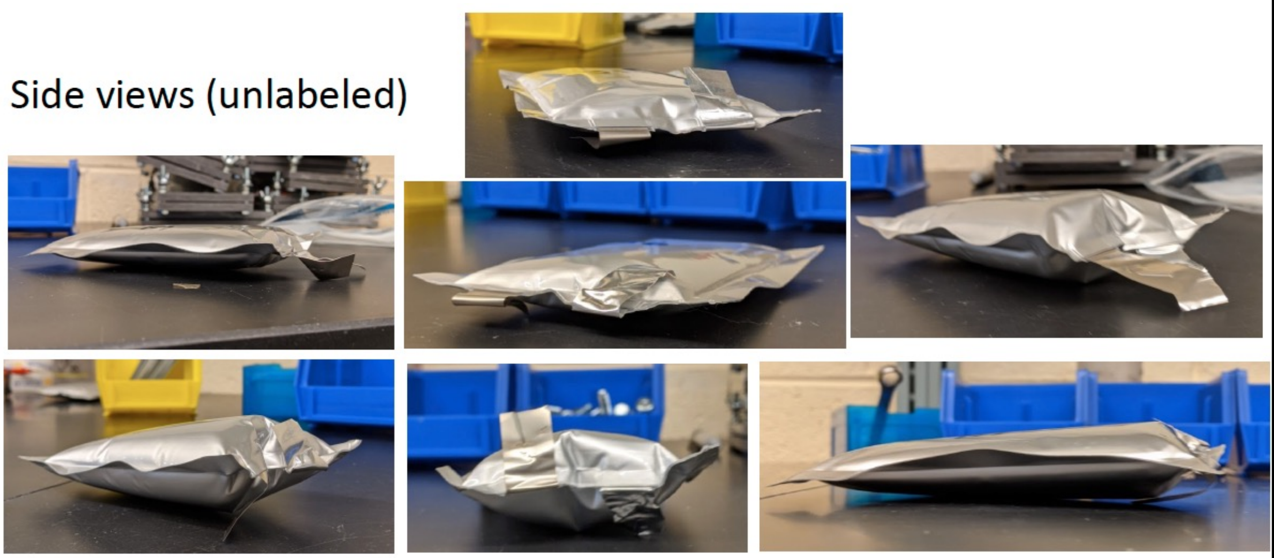
Safe Handling and Transportation?

Side views (unlabeled)



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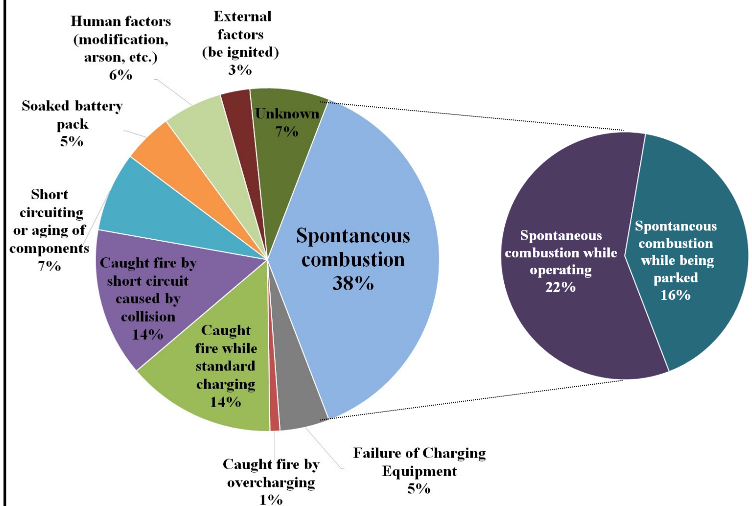
EV Accidents



- Limited data does not show higher probability of EV fires after collision.
- Many EV accidents occurred without collision or other abuse conditions, so good detection methods are required.
- Recent recalls highlight the need for better battery fault diagnostics from manufacturers worldwide

World-wide Battery Fire Accidents Summary 2013-2019

Source: Xiong, Rui. International Battery Safety Workshop, 2019

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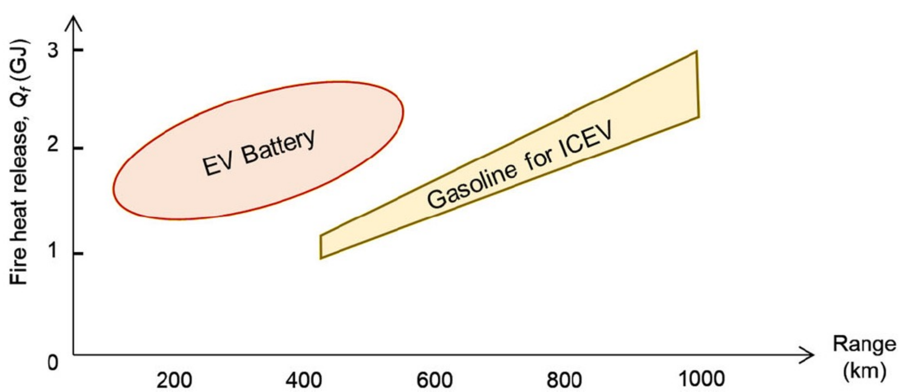
Heat Released from Vehicle Fire



- Li-ion batteries are powerful! A small 2-3 Ah cell has
-- 11Wh (30kJ) of electric energy
-- 90Wh (270 kJ) of chemical energy

- The heat of combustion from Li-ion cells in a pack will be twice as big as the heat of combustion from a gasoline vehicle of the same range

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

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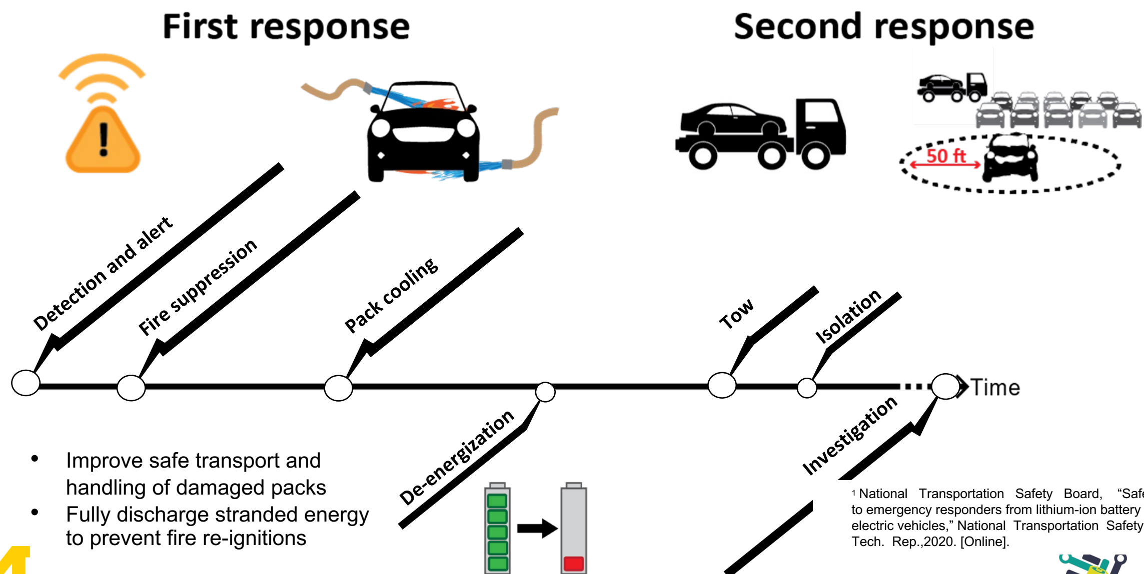
EMERGENCY RESPONSE



- Improve safe transport and handling of damaged packs
- Fully discharge stranded energy to prevent fire re-ignitions

[1] National Transportation Safety Board, "Safety risks to emergency responders from lithium-ion battery fires in electric vehicles," National Transportation Safety Board, Tech. Rep.,2020. [Online].

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Existing methods are slow and resource intensive

Discharge solutions at the pack-level:

OEM discharge tools[2]

Figure: Midtronics GRX-5100 EV/HEV Battery Service Tool (connected to a vehicle and discharging on right)
Source: NHTSA Stranded Energy Assessment Techniques and Tools 2020

Source: Team RRCO Battery Recycling Prize

[2] E. Rask, C. Pavlich, K. Stutenberg, M. Duoba, G. Kelleret al.,"Stranded energy assessment techniques and tools," National Highway Traffic Safety, Tech. Rep., 2020.

Submersion in (salt) water

In the Netherlands, crews load a BMW EV into a water bath after the battery began smoking inside a car dealership last spring. (Courtesy of Central and West Brabant Fire Brigade) Source: NFPA Journal

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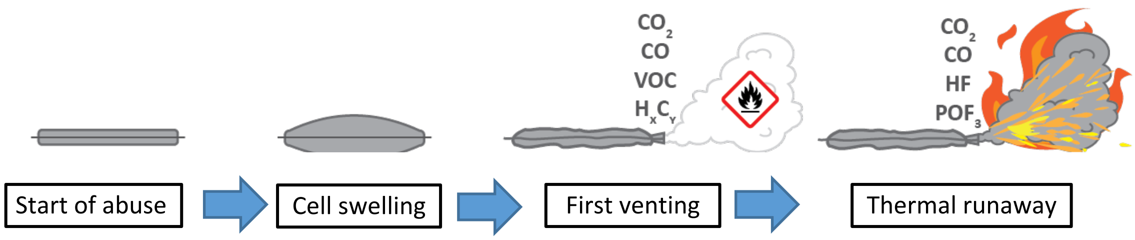
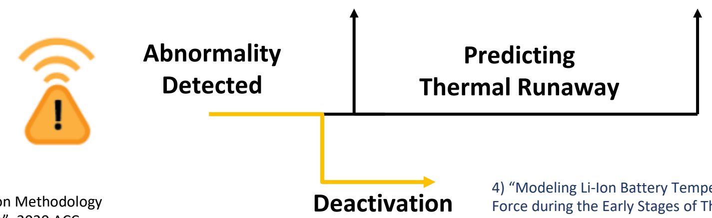
Integrated Sensing: Pressure and Gas Sensing



1) "**Internal short circuit trigger method for lithium-ion battery based on shape memory alloy**." JECS (2017)
2) "Early Detection for Li-ion Batteries Thermal Runaway Based on Gas Sensing", 2019 ECS Transactions.



3) "Battery Internal Short Detection Methodology Using Cell Swelling Measurements", 2020 ACC
4) "Li-ion battery fault detection in large packs using force and gas sensors", 2020, IFAC

4) "Modeling Li-Ion Battery Temperature and Expansion Force during the Early Stages of Thermal Runaway Triggered by Internal Shorts," *JECS*, 2019
5) "Equivalent circuit model for high C-rate discharge with an external short circuit." ACC 2022

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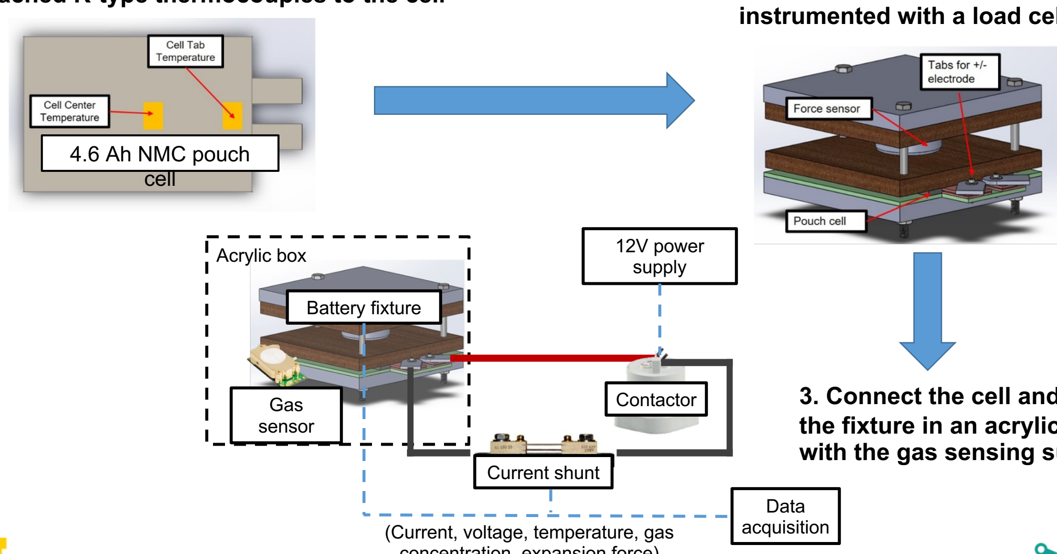
De-Energization with External Short circuit (ESC)

1. Attached K-type thermocouples to the cell

2. Secure the cell in the fixture instrumented with a load cell



3. Connect the cell and place the fixture in an acrylic box with the gas sensing suite

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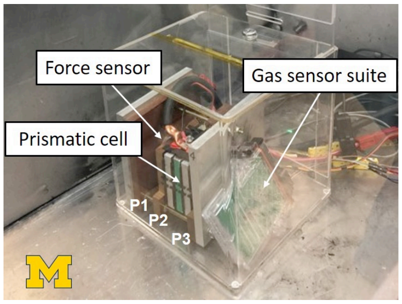
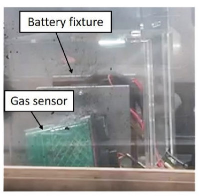
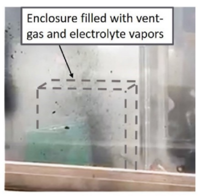
Cell External Short Circuit Experiment

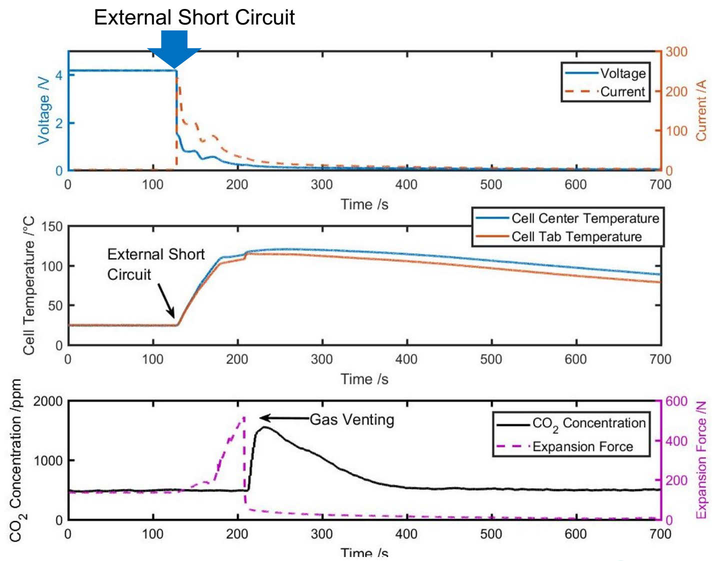




Before Gas Venting



After Gas Venting



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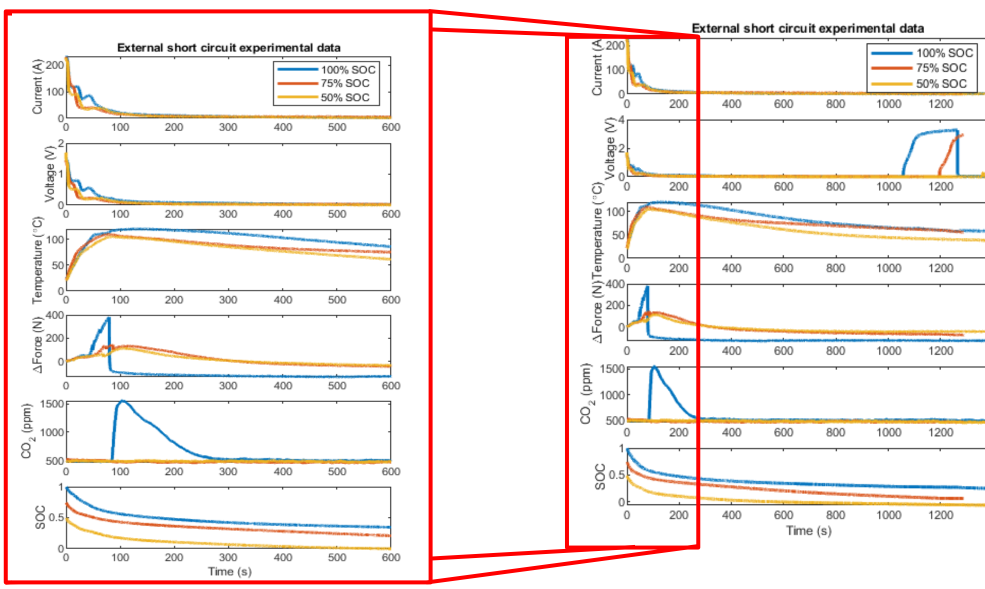
Cell electrical, thermal, and mechanical response to ESC



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External short circuit electrical model

Nominal single RC equivalent circuit battery model:

$$S\dot{O}C = -\frac{1}{Q}I(t)$$

$$\dot{V} = -\frac{1}{R_1C_1}V_1 + \frac{1}{C_1}I(t)$$

$$V_t(t) = V_{ocv} - V_1 - (R_s + R_{tab})I(t)$$

External short circuit elements:

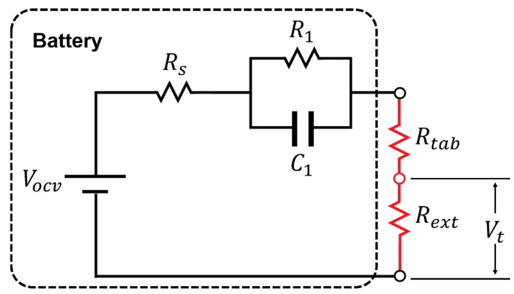
$$R_{tab} = \frac{1}{I_0}\left(V_{ocv}(SOC_0) - V_{t,0}\right) - R_s(SOC_0)$$

$$R_{ext} = \frac{V_{t,0}}{I_0}$$

RC modification for diffusion-limited current:

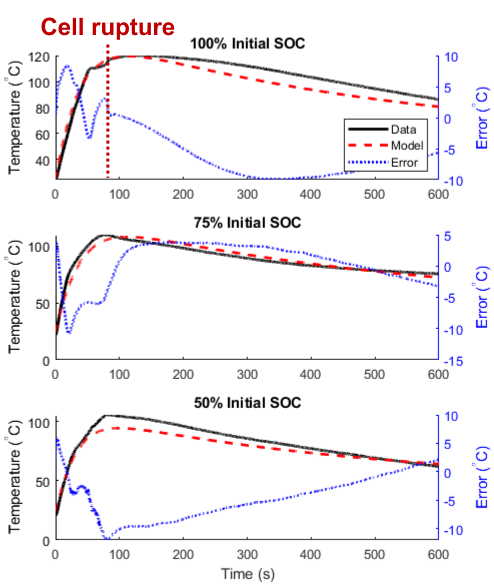
$$R_1 = a\tilde{R}_1(SOC)$$

$$C_1 = b\tilde{C}_1(SOC)$$

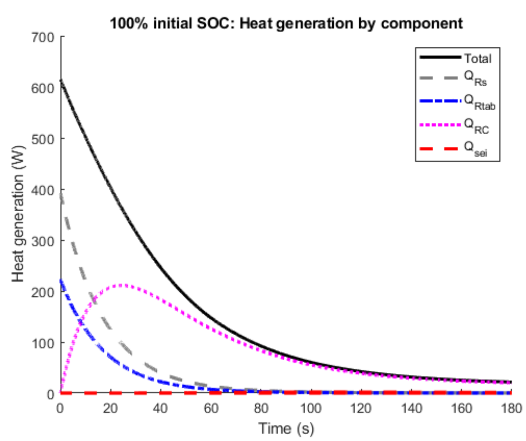


- Nominal consists of only 2 ODEs and 5 parameters
- R_s, R_1, and C_1 are functions of SOC
- With a current pulse, we can estimate all nominal parameters at the current SOC except capacity

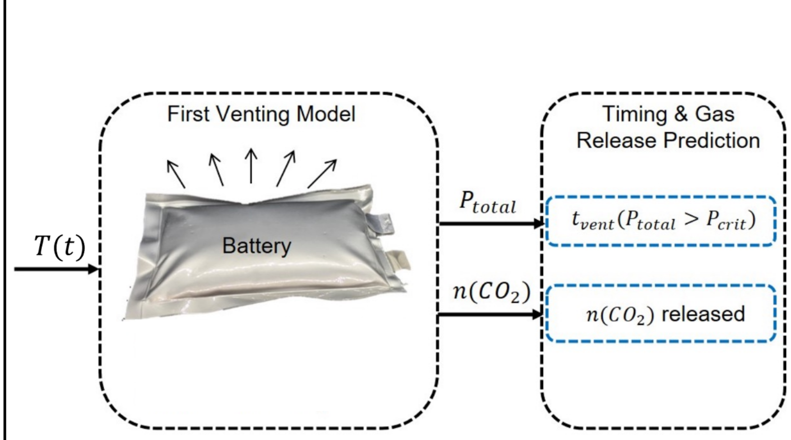
Thermal model validation

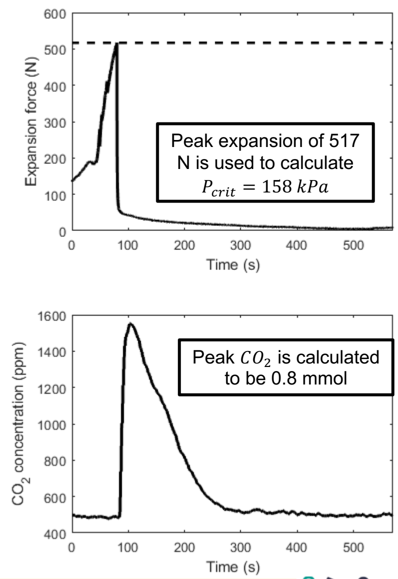


- Almost all heating is from Ohmic heat
- Error in current will strongly propagate to the thermal model



Overview of the internal pressure model





Cai, Ting, et al. "Modeling Li-ion Battery First Venting Events Before Thermal Runaway." Modeling, Estimation and Control Conference 2021.

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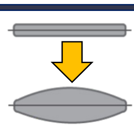
Modeling cell internal pressure



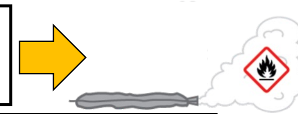
Internal cell pressure:

$$P_{total} = P_{sat} + P_{CO_2}$$

? >

Critical venting pressure:

$$P_{crit} = \frac{F_{max}}{A_{surf}} + P_{atm}$$



Electrolyte vapor saturation pressure:

$$P_{sat} = y_{EC} \cdot P_{sat,EC} + y_{DMC} \cdot P_{sat,DMC}$$

Gas pressure from generated CO_2:

$$P_{CO_2} = \frac{n(CO_2)RT}{V_h}$$

Electrolyte component saturation pressure:

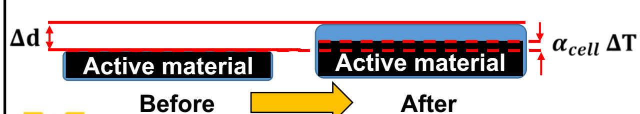
$$log(P_{sat}/kPa) = A - \frac{B}{T/K + C}$$

Component	A	B	C
DMC	6.4338	1413.0	-44.25
EC	6.4897	1836.57	-102.23

Amount of CO_2 from gas evolution model:

$$n(CO_2) = \frac{m_{an}(x_{SEI,0} - x_{SEI})}{2M_{C_6}}$$

$$\frac{dx_{SEI}}{dt} = -A_{SEI} \cdot x_{SEI} \cdot \exp\left(-\frac{E_{SEI}}{k_b T}\right)$$



Cell head volume from expansion:

$$V_h = V_{h,0} + A_{surf} \times (\Delta d - \alpha_{cell} \cdot \Delta T)$$

$$\Delta d = L\ \frac{\Delta\sigma}{E}$$

$$\Delta\sigma = \max\left(P_{total} - \sigma_0 - P_{atm}, \frac{E \cdot \alpha_{cell} \cdot \Delta T}{L}\right)$$

Cai, Ting, et al. "Modeling Li-ion Battery First Venting Events Before Thermal Runaway." Modeling, Estimation and Control Conference 2021.

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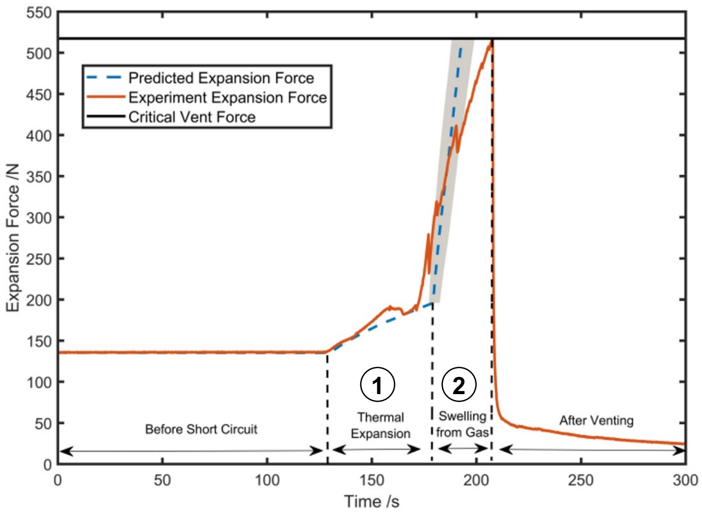
Model results: Expansion and total CO_2 gas release



- Two expansion force measurement slopes due to
  1. Thermal expansion of the active material
  2. Cell swelling due to gas generation
- Measured peak CO_2 concentration is within the predicted range accounting for K-type thermocouple accuracy (± 2.2°C)

Table 3. CO_2 Gas Generation from Model Prediction and Experiments (mmol)

Model			Experiment
CO_2 amount before venting	CO_2 amount after venting	Total CO_2 amount	Total CO_2 amount
0.25 - 0.42	0.35 - 0.55	0.6 - 0.97	0.8

Cai, Ting, et al. "Modeling Li-ion Battery First Venting Events Before Thermal Runaway." Modeling, Estimation and Control Conference 2021.

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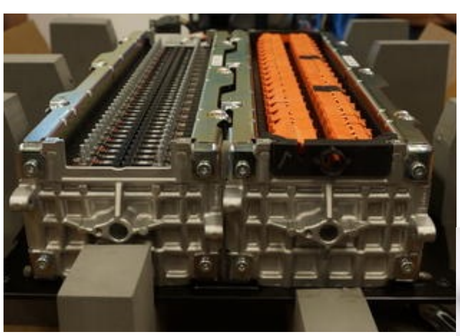
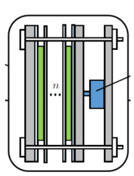
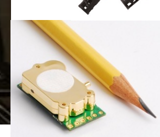
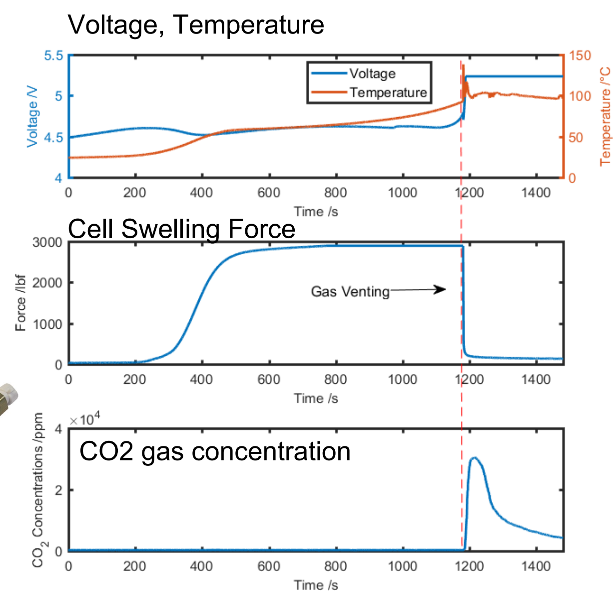
A Multi-Sensory Approach (I,V,T,F/P,G) for Pack Safety

- Cell overcharged to 4.8 volts before gas venting occurs
- Force shows good response during overcharging, and drops rapidly after gas venting
- Gas detection shows rapid response after the force drops









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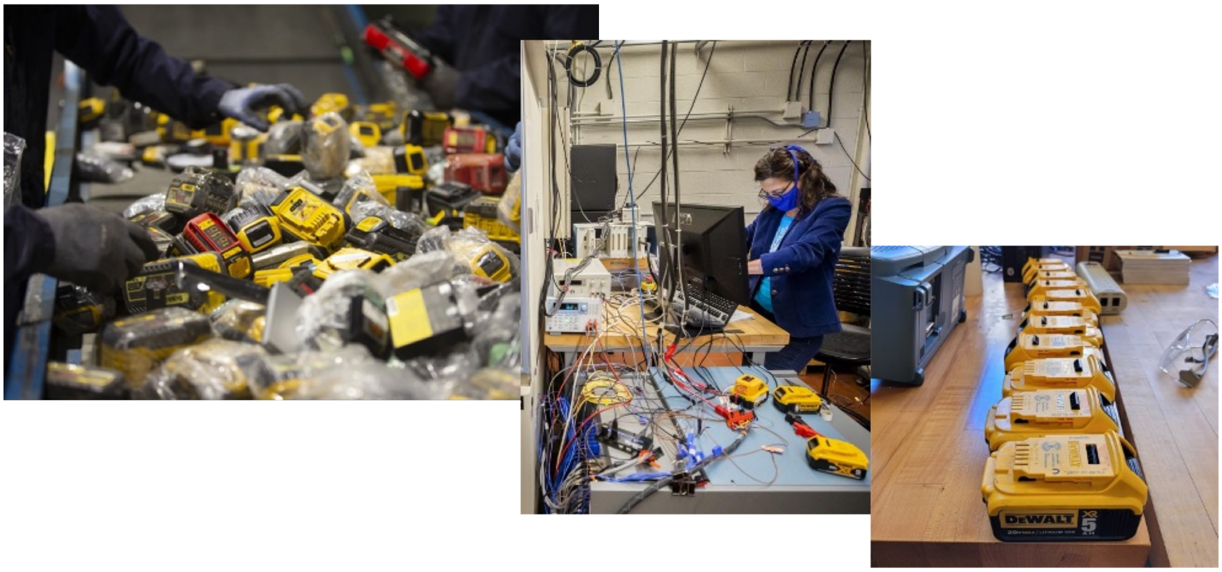
Managing Discarded Batteries



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Policy & Labeling for Waste Management

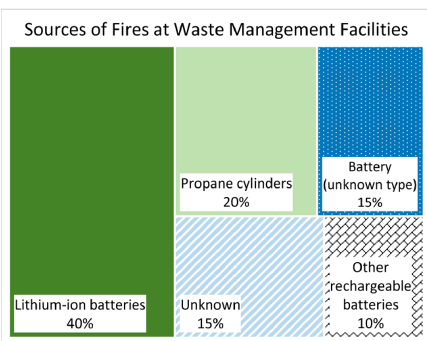

Figure 4: Sources of Fires at California waste management facilities, according to a 2018 survey by the California Product Stewardship Council

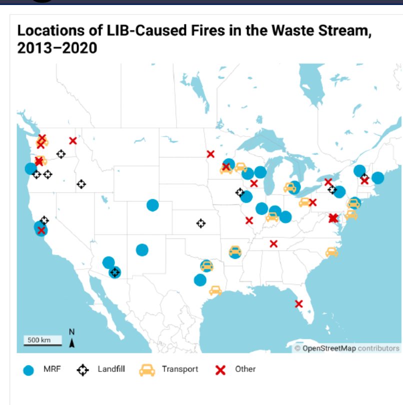

Figure 7: Locations of LIB-caused fires across the United States, 2013–2020

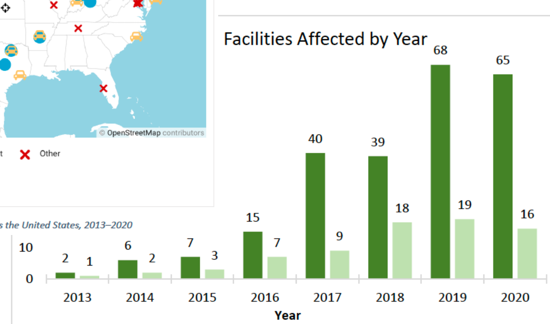

Figure 5: Facilities affected and number of fires by year

An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling, EPA Office of Resource Conservation and Recovery, EPA 530-R-21-002, July 2021

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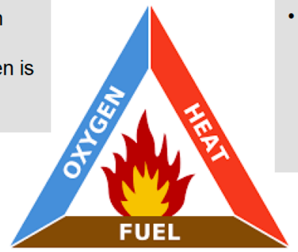
Safety … for Next Gen Batteries

Oxygen
- Cathodes such as NMC, NCA, LCO used in LIBs contain and can release oxygen
- If the cell packaging is compromised, oxygen is present in ambient air



Heat
- External sources such as a garage fire
- Internal sources
  - Exothermic chemical reactions such as SEI formation/degradation
  - Electrical short in battery resulting in large currents
    - Heat=i^2RT (Joule's Law)

Solid State Electrolyte

~~**Fuel**~~
- ~~Many components in the cell can burn, but the most flammable is the liquid organic electrolyte~~
- ~~If the cell is heated, the electrolyte is also volatile resulting in high pressure that can rupture the cell forming a flammable aerosol~~

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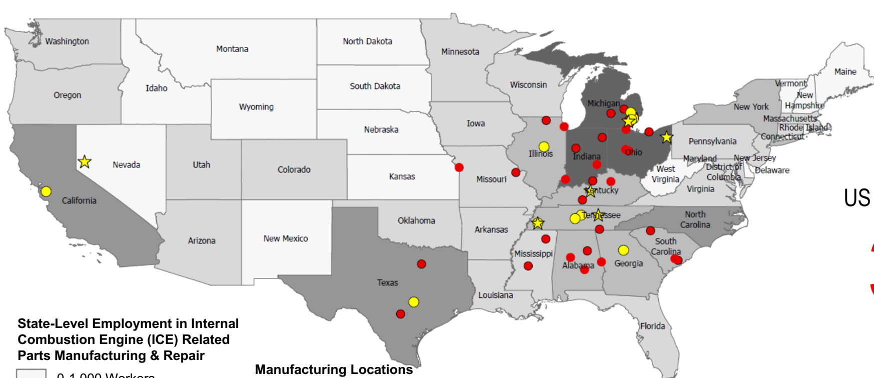
Auto Manufacturing & Repair Employment



State-Level Employment in Internal Combustion Engine (ICE) Related Parts Manufacturing & Repair
- 0-1,000 Workers
- 1,001 – 5,000 Workers
- 5,001 – 10,000 Workers
- 10,001 – 20,000 Workers
- 20,001 – 40,000 Workers

Manufacturing Locations
- EV Battery Plants, Current &
- Announced
- EV Production, Current & Announced
- Hybrid / Hybrid & ICE Production
- ICE (Gas, Diesel) Production Only

1.8 million

US Jobs in Auto Manufacturing & Repair

303,000

of these Auto Jobs are in ICE-Related Transition.

How many

Jobs will be created in a Battery Economy?

"US Automotive Sector Employment and Early Evidence of the Employment Impact of the Transition to Battery Electric Vehicles" by Rebecca Pickens and Anna Stefanopoulou (https://drive.google.com/file/d/1s4mQZwn_tsltEI8HnIUIL-O0CoQmiC-k/view)

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Battery industry survey confirms lack of workforce with necessary skills

- ~75% of respondents are planning to hire <1 year & 71% have hired in the past year
- 90% identified limited # of applicants with required skills
- 44% did not find local applicants with required skills

	2-year Community College (n=35)	4 Year College/ University (n=43)
Battery materials (chem engineering, mat science)	12	32
Mining	5	7
Electrical	13	15
Power Electronics	11	17
Software/Battery Management	12	22
System Design	8	21
Prototyping	11	18
Battery Testing	21	23
Safety (electrical, hazmat, fire, etc.)	15	14
Application of batteries (installation, operation, etc.)	12	13
Design for Waste management	9	16
Battery Recycling	13	18
Environmental engineering	4	14
Project management	12	16
Technical lead/ management	7	19
Supply chain management	11	16
Manufacturing including plant design	10	22
Installation of battery systems	14	8
Operation and Maintenance of systems	11	10
Electrical skills for battery technicians (high voltage)	20	13
First response to battery fires	13	8

NAATBatt INTERNATIONAL Member Survey (n=67, r=40%)

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By Alyssa McQuilling - Southernresearch.org

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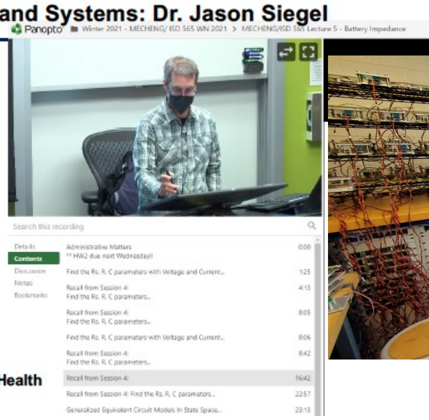
Team Effort

Teaching Battery Control and Systems: Dr. Jason Siegel

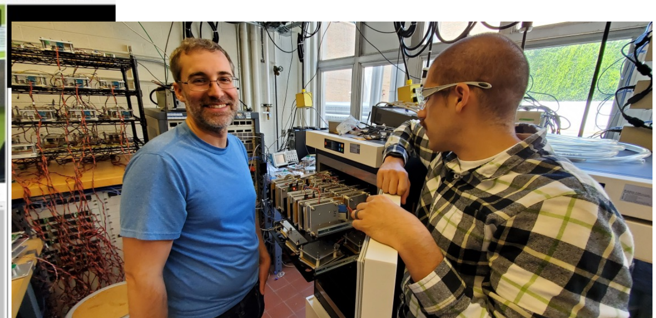
For Senior, Ms, PhD students In campus and On line since 2011.



Lecture 5: Autoregressive battery model for tracking resistance increase

Electric resistance (R) varying
Resistance depends on temperature

- **Gradual → Degradation: State of Health**
- **Abrupt → Coolant fault**



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Thank you!

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THE UNIVERSITY OF MICHIGAN BATTERY LAB

University of Michigan Battery Lab
Greg Less, Technical Director

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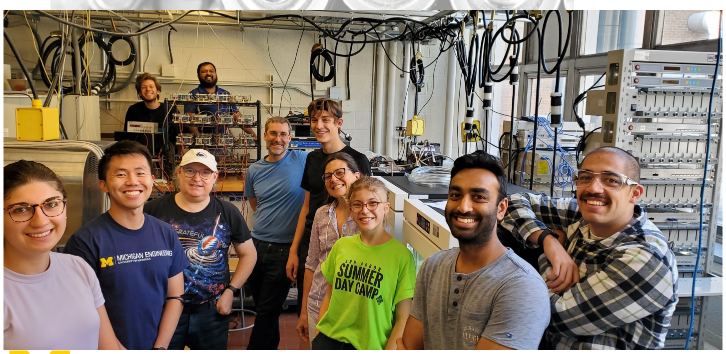

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Amphenol, Daimler, Ford, GM, GE, Voltaic
A123, Navitas, Samsung, and LG

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