LITHIUM-ION BATTERY FIRES

Tall Buildings fire safety network

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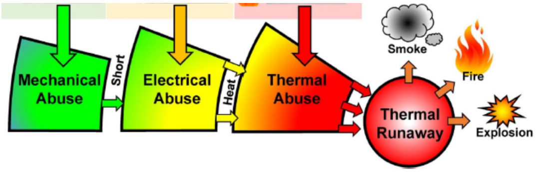
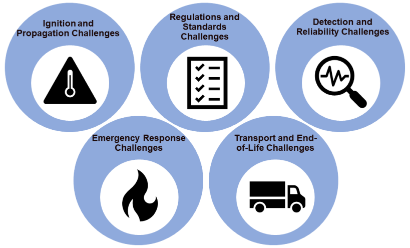
KING'S College LONDON

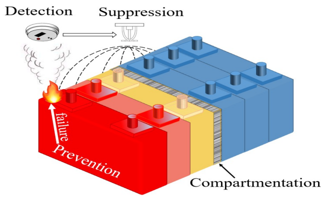
OVERVIEW

Fire safety incidents and failure mechanisms

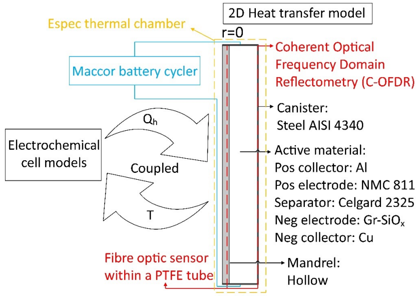


Safety challenges faced by industry and academic contributions



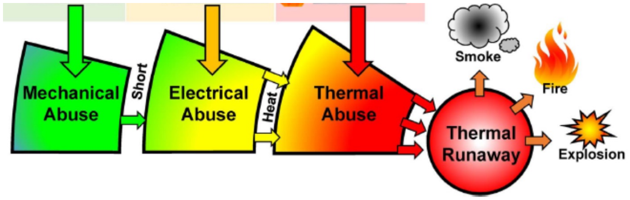


Fire spread and thermal modelling



PART I

Fire safety incidents and failure mechanisms



FAILURE?

8 cells, nail penetration

You’ve seen in the presentation before mine from Prof Christensen the effects!

FIRE HAZARDS AND SAFETY INCIDENTS

Application	Company	Year	Incident description
Cell phone	Nokia	2003-07	Sudden failure in batteries of mobile phones.
	Kyocera Wireless	2004	
	Samsung	2016	
Notebook	Sony	2006	Sudden failure of batteries powering notebooks.
Electric Vehicle	Chevrolet	2011	Chevy Volt on fire weeks after crash test.
	Tesla	2013	Model S on fire after hitting debris.
		2013	Model S on fire after crash.
		2016-19	Model S suddenly on fire while parked.
	Jaguar	2018	i-Pace suddenly on fire while parked.
Aerospace	Boeing	2013	Sudden failure in auxiliary units of Dreamliner 787.
Hoverboard	Various	2015-17	Sudden failure in many hoverboard's batteries.
Marine	Corvus Energy	2019	Hybrid-battery ferry on fire due to coolant leaking.
Stationary energy storage systems	Various	2017-19	Battery fires in large grid-connected systems

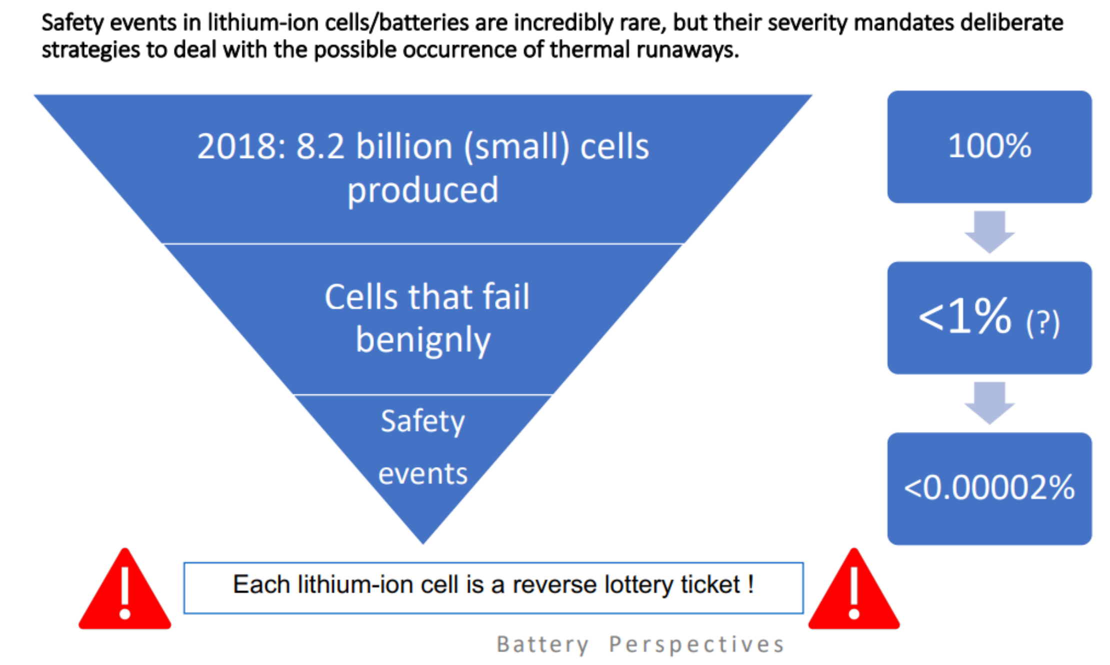
Tesla Model S released smokes while being driven

Pure battery electric bus caught fire in a charging station

Battery overheated and started a fire in a Dreamliner 787

Meta-review of fire safety of Lithium-ion batteries: gaps between industry challenges and research contributions. L. Bravo Diaz, X. He et al. Journal of Electrochemistry Society 167 (2020) 090559

FIRE HAZARDS AND SAFETY INCIDENTS



0.00002% (tier 1 manufacturers are on 6 or 7 decimals): impressive, but impressive enough?

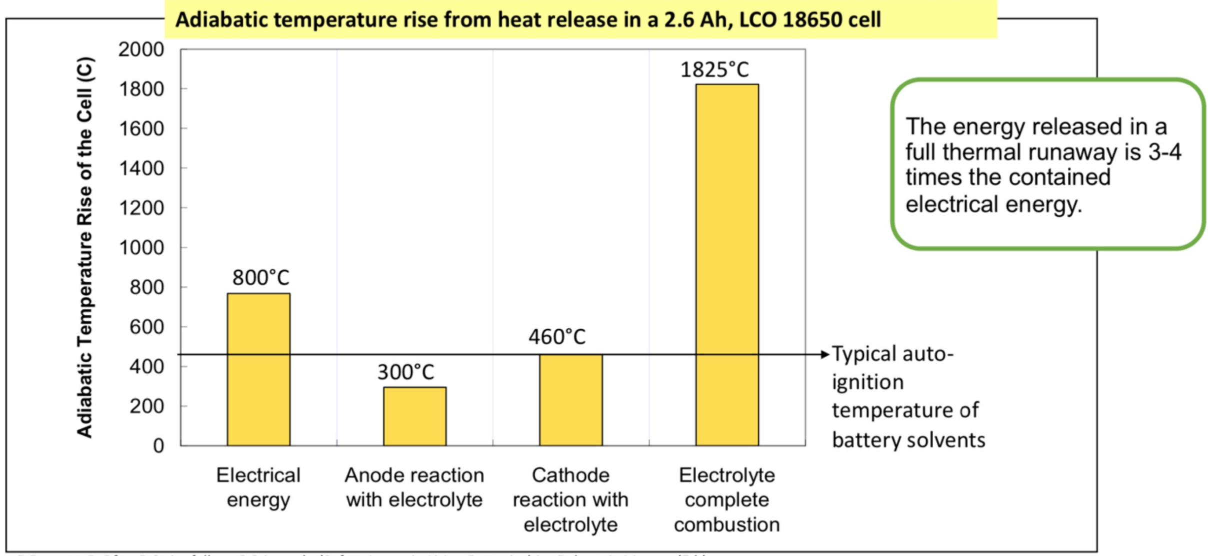
Only a small fraction but the increasing cell production means we'll see more safety incidents

Only few make their way to the media (China reported 140 incidents in 2019)

Process	Temperature Range (°C)	Energy release[1]	Energy release in an 18650 cell
Decomposition at anode	80 -120 150 - 300	300 – 450 J/ g-anode 1200 – 1400 J/g-anode	~ 9.6 – 13.3 kJ
Decomposition at cathode	150 - 300	1500 – 1800 J / g-cathode	~ 16.8 – 30 kJ
Self-reaction of salt with solvent	250 - 400	900 J/g electrolyte	~2.5 – 5.4 kJ
Complete combustion of solvent[2]	Auto-ignition temperature ~ 450	18 kJ / g solvent	**90 – 126 kJ**

[1] Approximate values estimated from DSC and ARC testing of cell components: charged anodes and cathodes, and typical electrolyte compositions;
[2] Please note that there is insufficient oxygen available inside an 18650 cell to effect complete combustion of the solvent. However, if vented at high temperatures or vented in the presence of an ignition source the solvent can burn outside the cell.

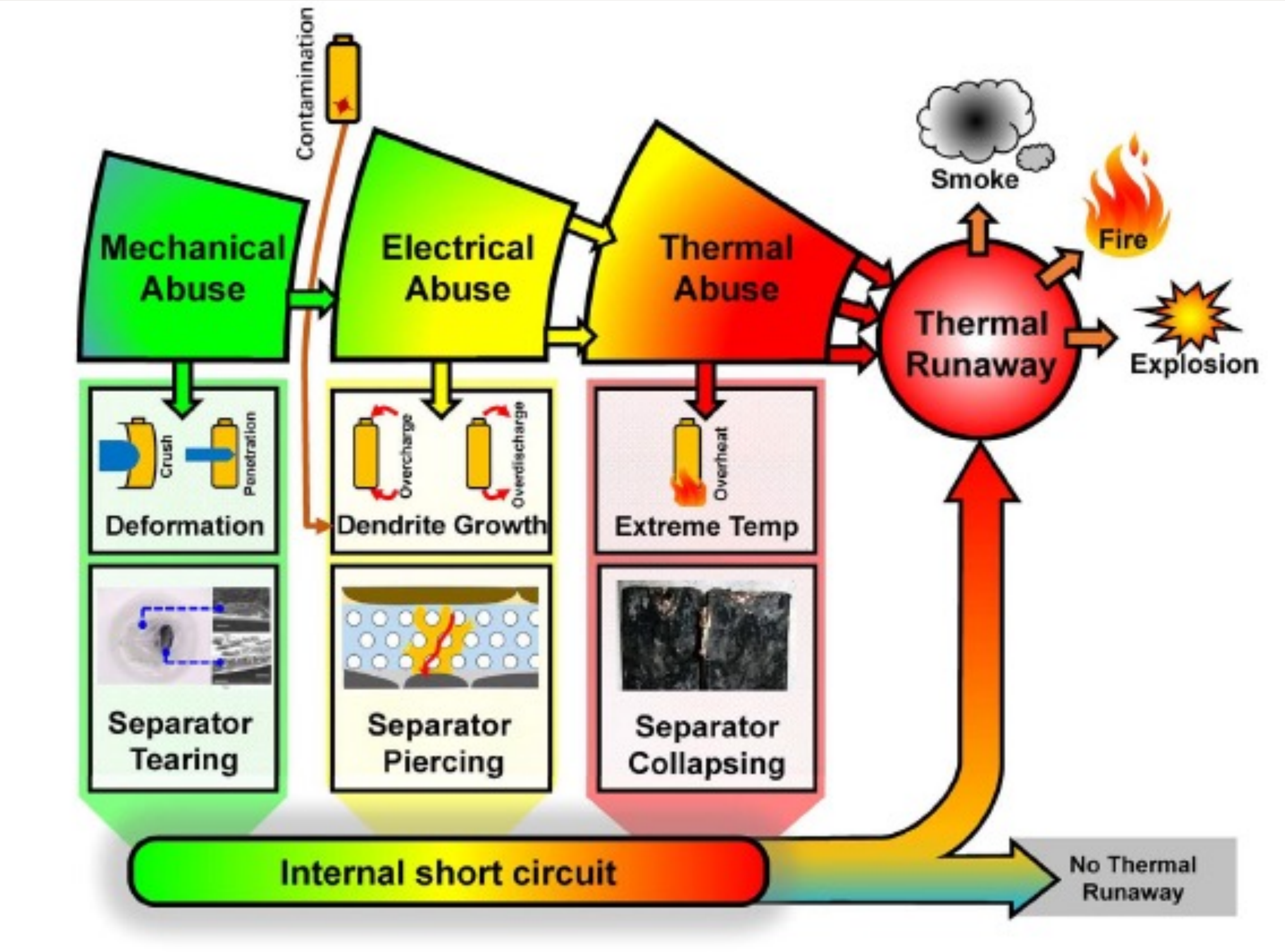
The electrical energy in the cell alone is sufficient to raise the cell temperature over 700°C under adiabatic conditions, which is why heat transfer is always important.



B.Barnett, D.Ofer, R.Stringfellow, S.Sriramulu (Safety Issues in Li-Ion Batteries) in: Robert A. Meyers (Ed.), Encyclopedia of Sustainability Science and Technology, Springer Science, 2012

EDV and battery business possibly in China after 2020. AABC Asia. 2019. Hsueh-lung Lu

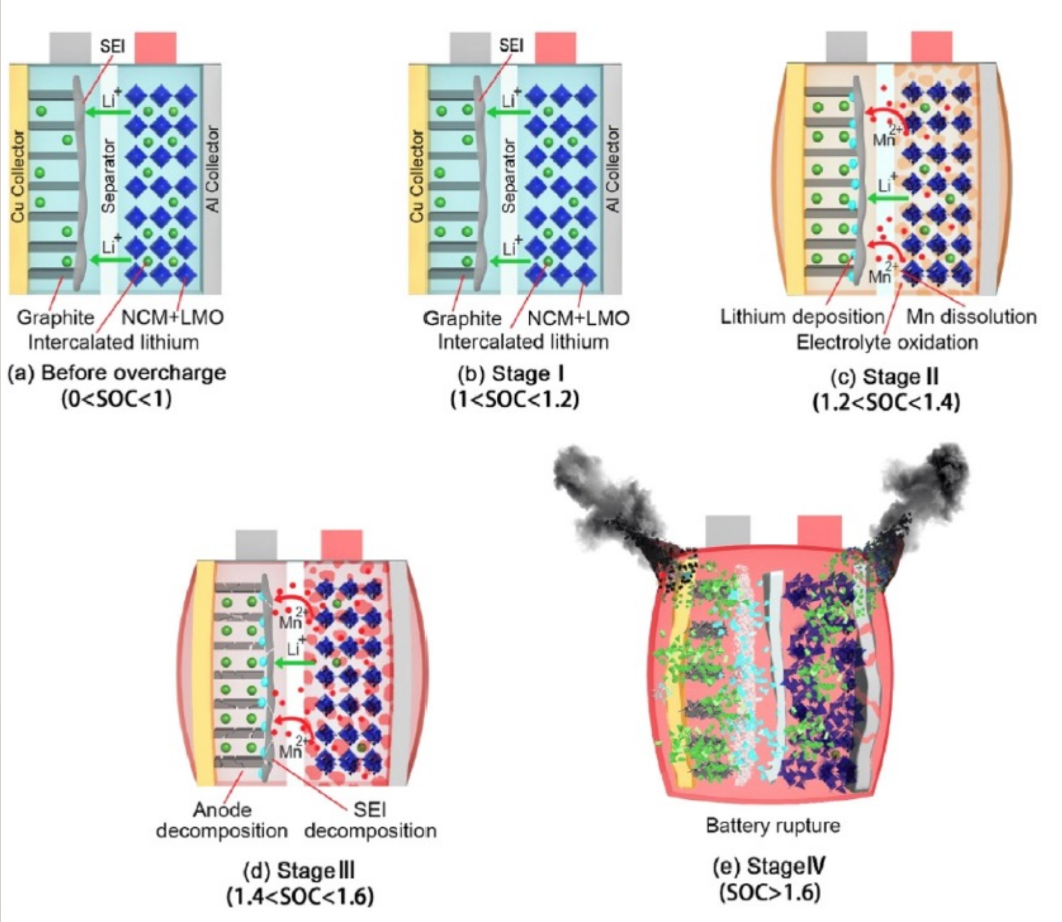
FAILURE MECHANISMS



Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. X. Feng et al. Energy Storage Materials 10 (2018) 246–267

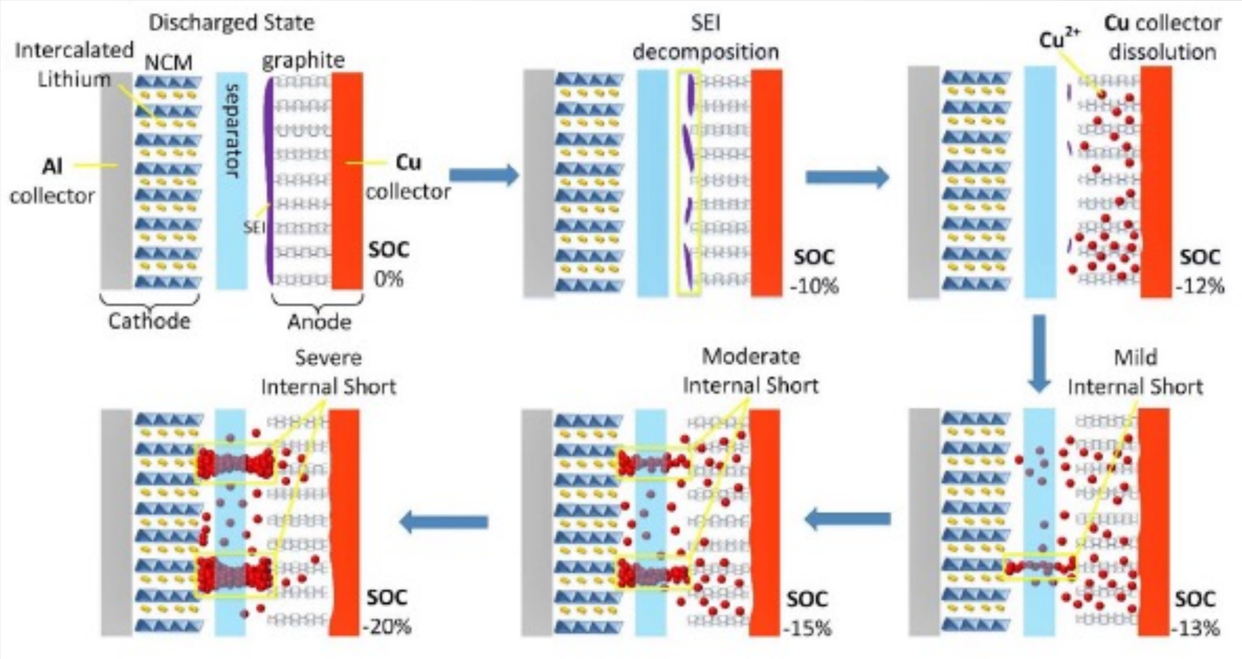
FAILURE MECHANISMS

Cell overcharge



An electrochemical-thermally coupled overcharge-to-thermal-runaway model for lithium ion battery. Ren et al. J Power Sources 2017; 364 :328–40 .

Cell overdischarge



Mechanism of the entire overdischarge process and overdischarge-induced internal short circuit in lithium-ion batteries. Guo et al. Sci. Rep. 6 (2016) 30248.

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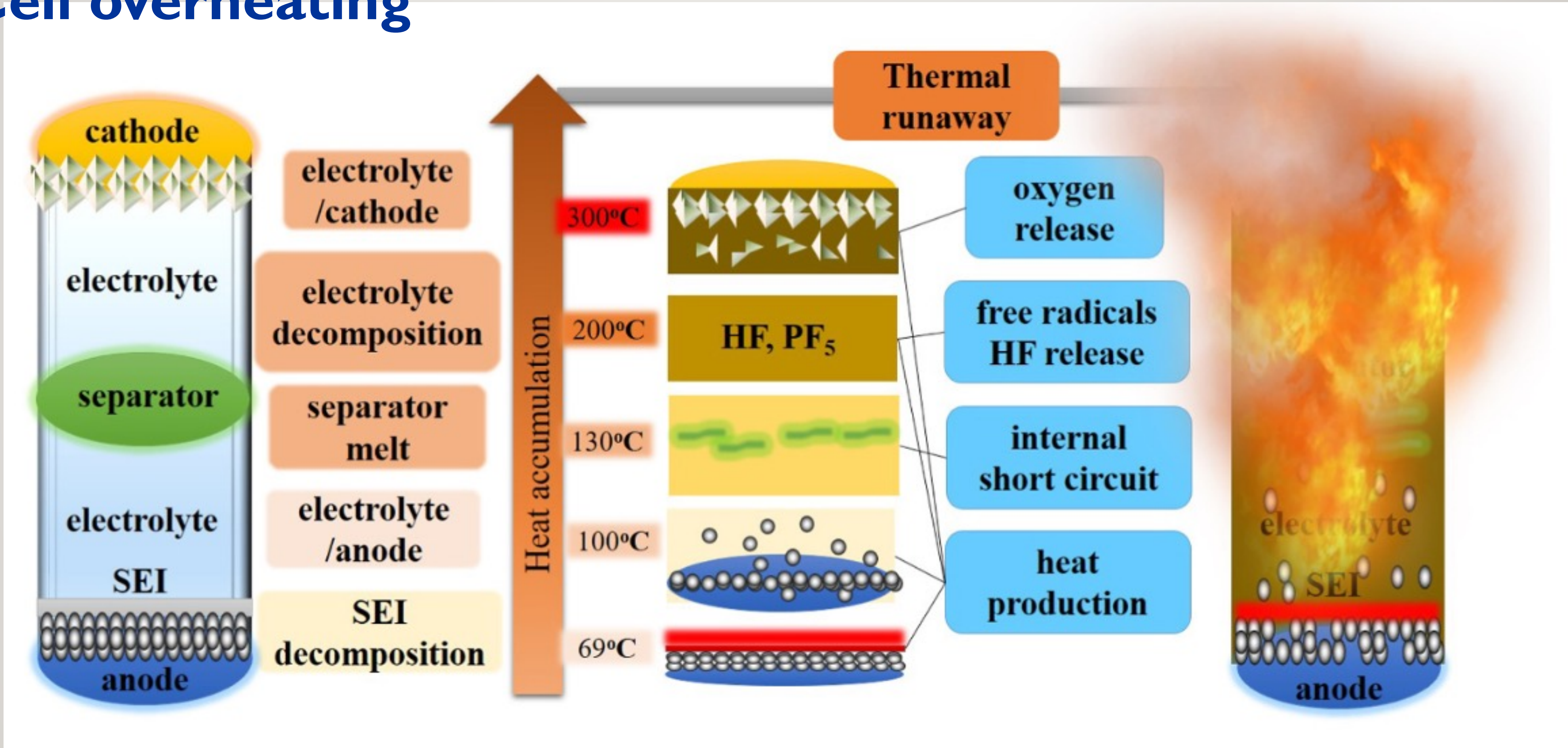
FAILURE MECHANISMS

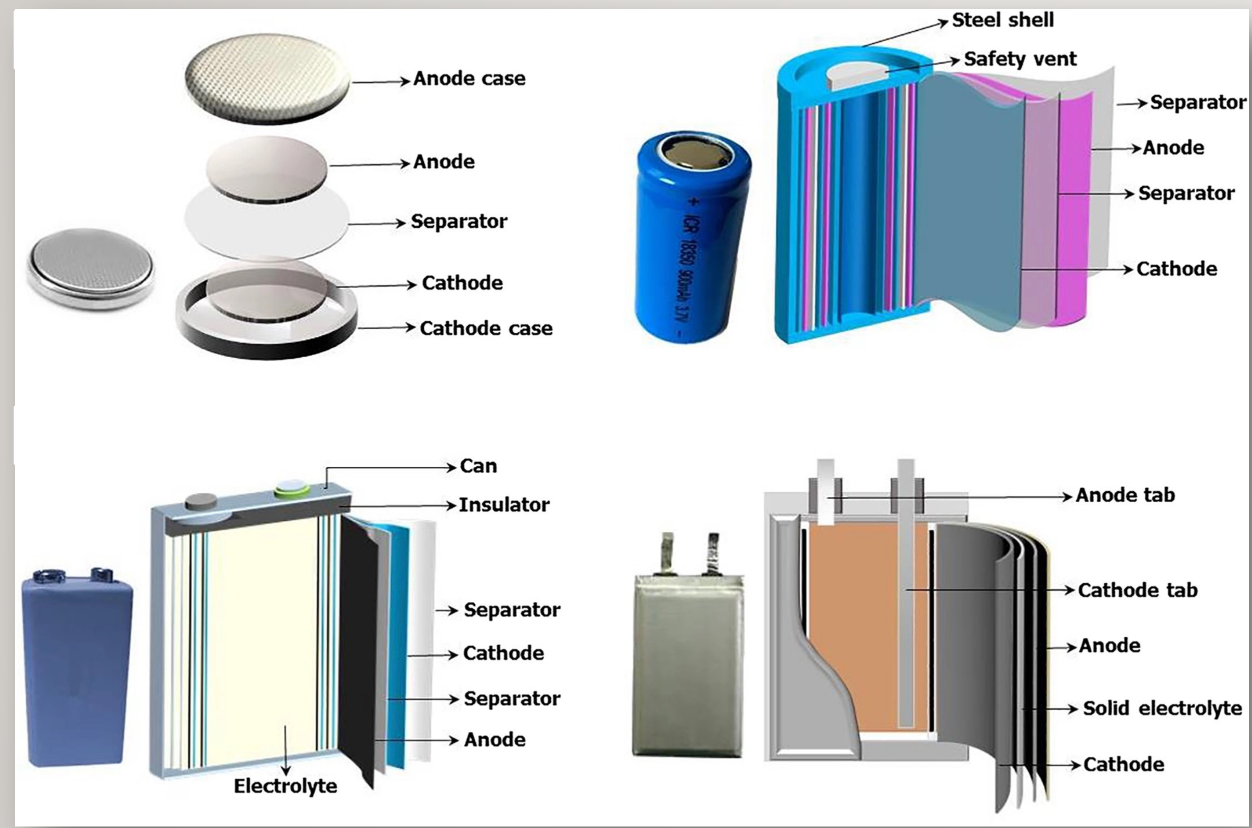
Cell overheating



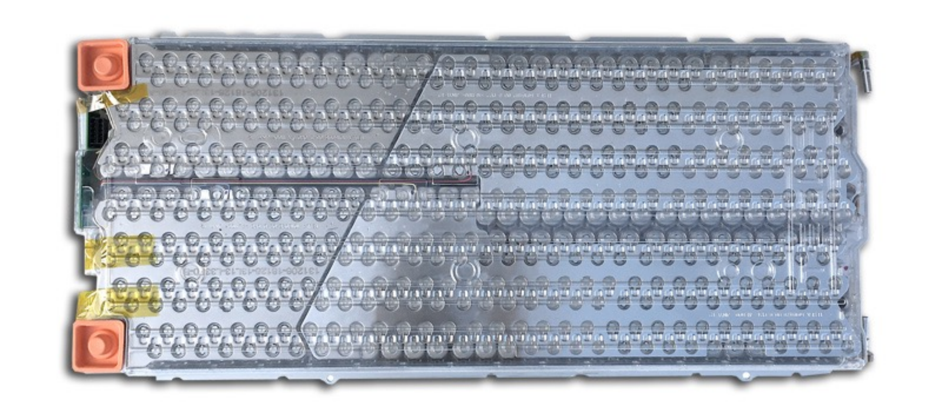
Progress of enhancing the safety of lithium ion battery from the electrolyte aspect. Wang et al. Nano Energy 2018; 55 :93–114 .

DIFFERENT TYPES OF GEOMETRIES

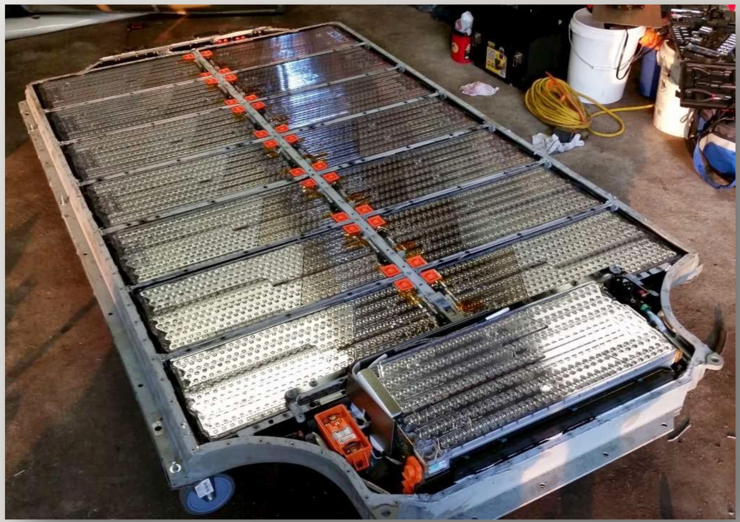
Cell



Module



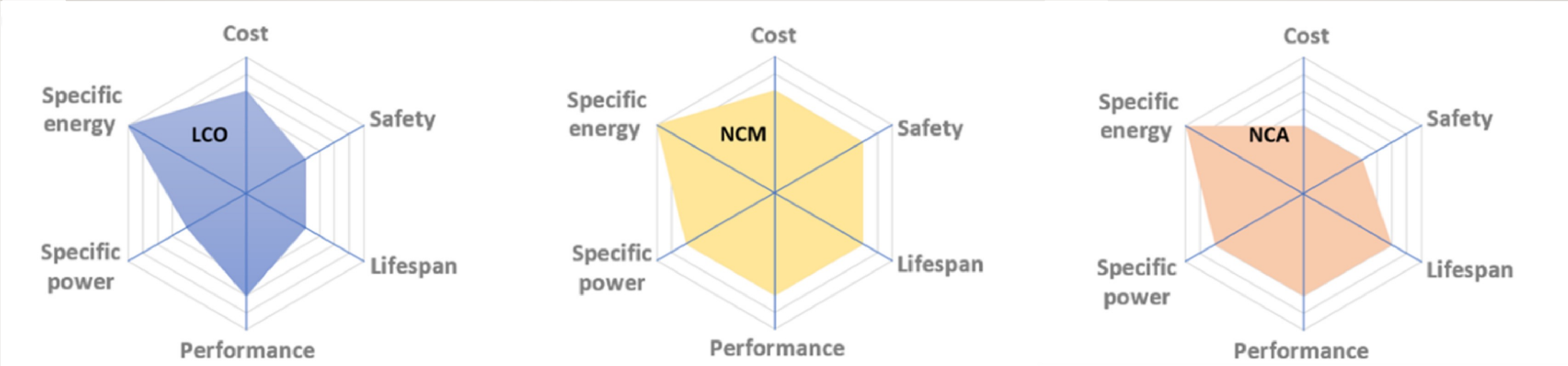
Pack

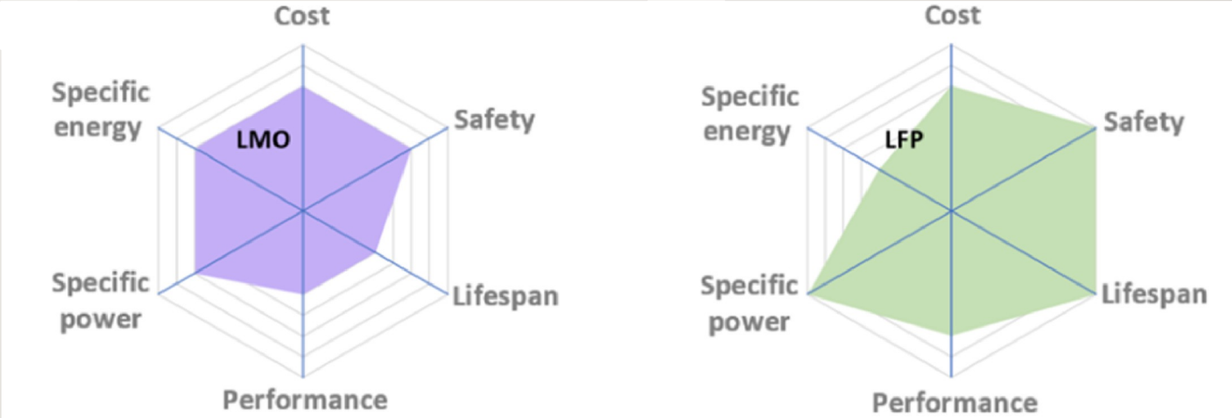


Y. Liang *et al.* *InfoMat* **2019**, 1, 1.

DIFFERENT TYPES OF LIB BATTERY CHEMISTRIES

- Depending on the battery chemistry, the properties can vary significantly



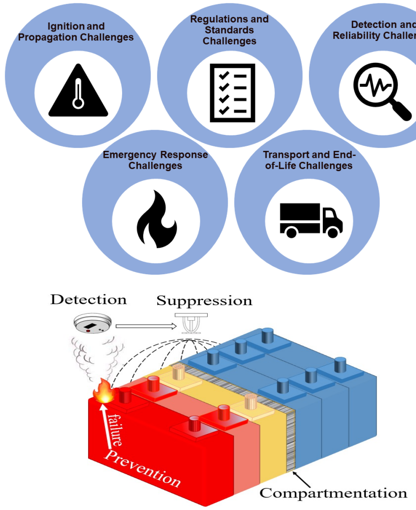


$LiMn_2O_4$ (LMO)
$LiFePO_4$ (LFP)
$LiCoO_2$ (LCO)
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)
$LiNi_{1-x-y}Mn_xCo_yO_2$ (NMC)

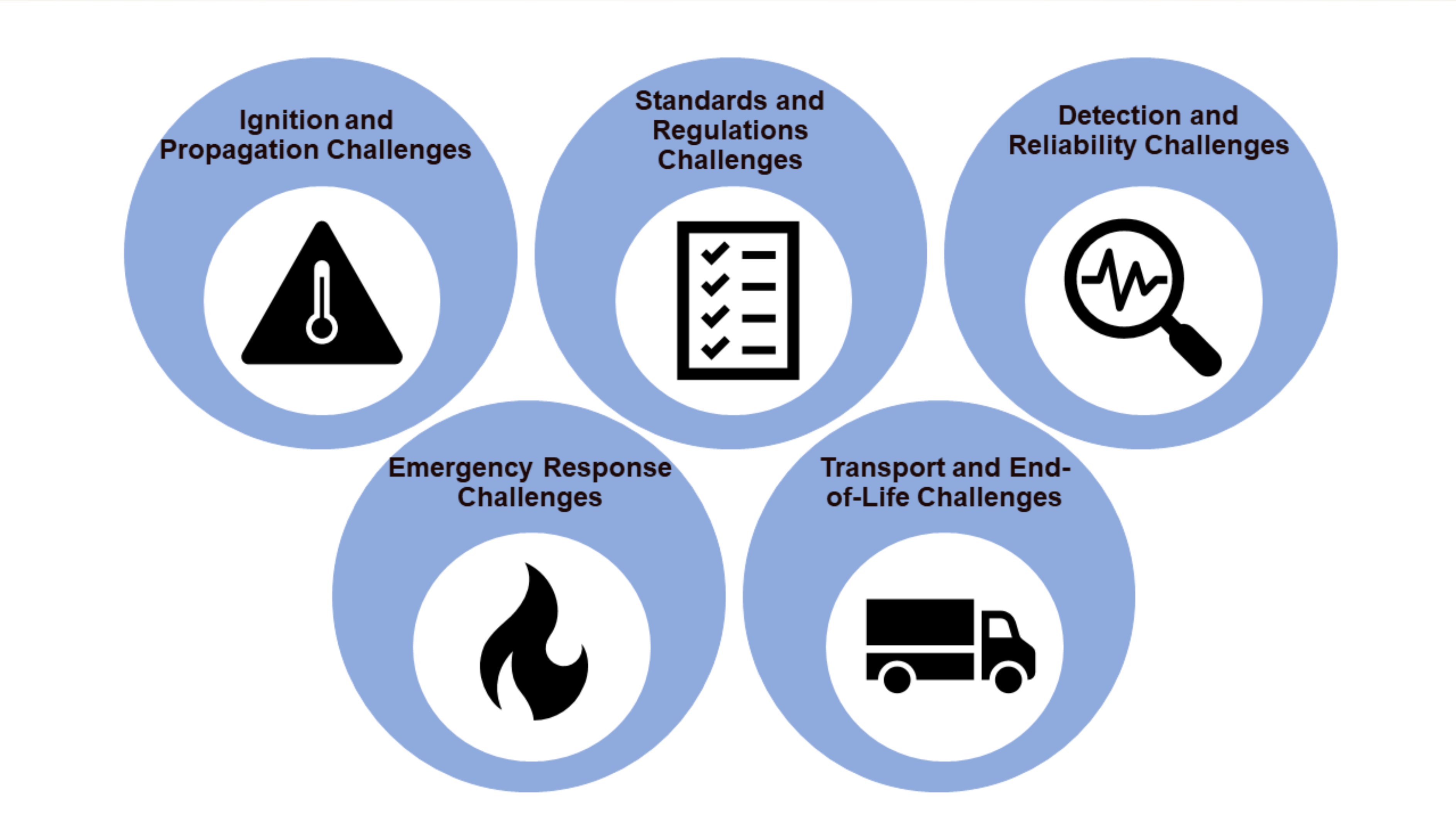
P. Guan *et al. J. Energy Chem.* **2020**, 43, 220.

PART II

Safety challenges faced by industry and academic contributions



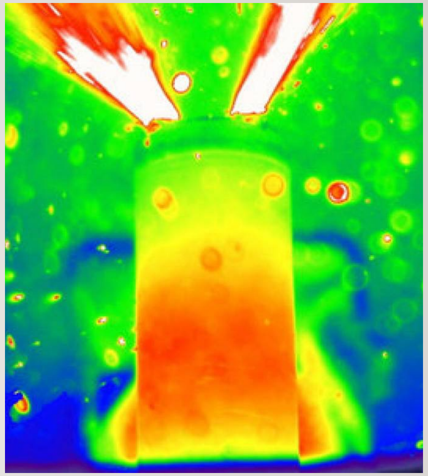
SAFETY CHALLENGES FACED BY INDUSTRY



Meta-review of fire safety of Lithium-ion batteries: gaps between industry challenges and research contributions. L. Bravo Diaz, X. He et al. Journal of Electrochemistry Society 167 (2020) 090559

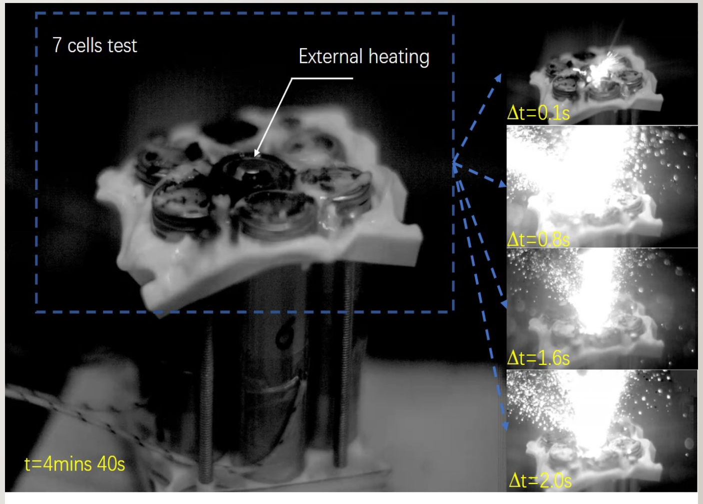
SAFETY CHALLENGES FACED BY INDUSTRY

Ignition challenges



- **Manufacturing defects** (internal)
- No repeatable **method** of driving cells into TR representative of in-use failure modes
- Link between the **type of abuse and the time to ignition** and relationship with SOC, chemistry and SOH.
- Understanding **crash-related ignition**

Propagation challenges



- Link between the **type of abuse** and **propagation**
- No reliable **method** to propagation representative of use cases
- Influence of **chemistry, SOC, SOH, current, location**, ignition source and oxygen availability on **propagation**
- Direct any **vent gases** safely away from passengers
- Testing at **module and pack level** to understand fire propagation

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SAFETY CHALLENGES FACED BY INDUSTRY

Standards and regulations challenges

- Standards available may not be representative of **real-world scenarios**
- Lack of **harmonisation** on testing conditions, testing parameters and pass/fail criteria
- Very different **TR methods** and test setups, conditions (SOC, temperature, charging rates)
- Controversy on **internal short circuit** TR testing
- Range of conditions that **change the severity** of the response to abuse
- Testing at **component level** might not be comparable to testing at **system level**
- **Aging (SOH)** influence on safety characteristics

JRC exploratory research : Safer Li-ion batteries by preventing thermal propagation - Workshop report: summary & outcomes (JRC Petten, Netherlands, 8-9, March 2018). Ruiz, V. & Pfrang, A. (2018).

SAFETY CHALLENGES FACED BY INDUSTRY

Detection and reliability challenges

- **Emergency landing/stop**
- **Reliability** of the **BMS** (surface sensors)
- **Additional protection strategies** beyond the BMS
- Development of **fault-tolerant battery systems**
- Lack of **transferability** across scales
- Battery models are **cell-dependent**, and can only be inferred from **voltage**, **current**, and **limited surface temperature** data

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SAFETY CHALLENGES FACED BY INDUSTRY

Emergency response challenges

- **Key factors** on **heat** release rate from a battery fire and the rate and toxicity of **gases**
- **System-level** fire safety lack of publications
- **Limited database** of fire incidents in the field
- Fire **extinguishing agents** on battery fires to avoid **re-ignition**
- Extinguishing **time**, water **volume**, harmful gasses **emission**s, and risk of **re-ignition** due to water induced shorts
- Large emissions of **toxic gases**

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SAFETY CHALLENGES FACED BY INDUSTRY

Transport and end-of-life challenges

- Differences in battery **transport regulations** across countries, regions & modes of transport
- Transport of damaged or **defected cells**
- Electrical, thermal, chemical, and fire **risks** when re-using, recycling or disposing batteries
- Significant **manual labour** for partial or complete disassembly

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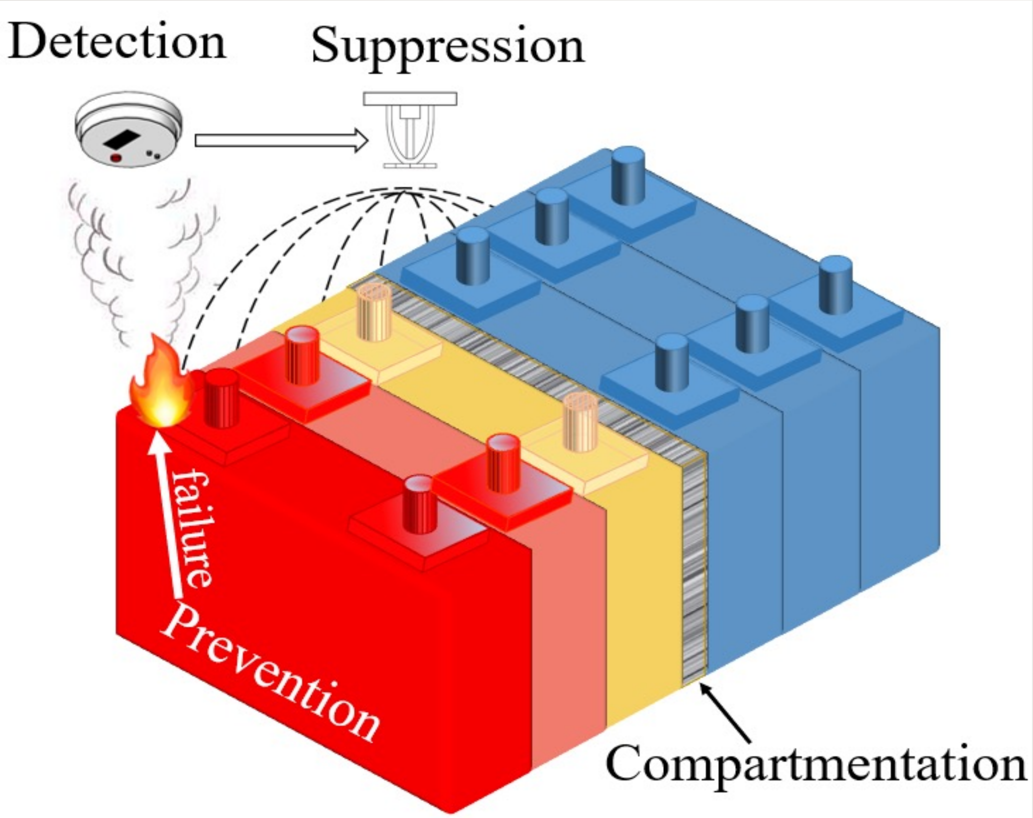
CONTRIBUTIONS FROM ACADEMIC RESEARCH



Protection layers	Scale	Key technologies
Prevention	Component, cell, module, pack	Cathode and anode modification, electrolyte additive, shut down or ceramic-coated separator, positive temperature coefficient device, vents, battery management system.
Compartmentation	Module, pack	Barriers, battery management system, sealed metal container.
Detection	Cell, module, pack	Battery management system (voltage, temperature, deformation), different detector (heat, smoke, off gassing).
Suppression	Cell, module, pack	Smothering, cooling, chemical suppression, isolating.

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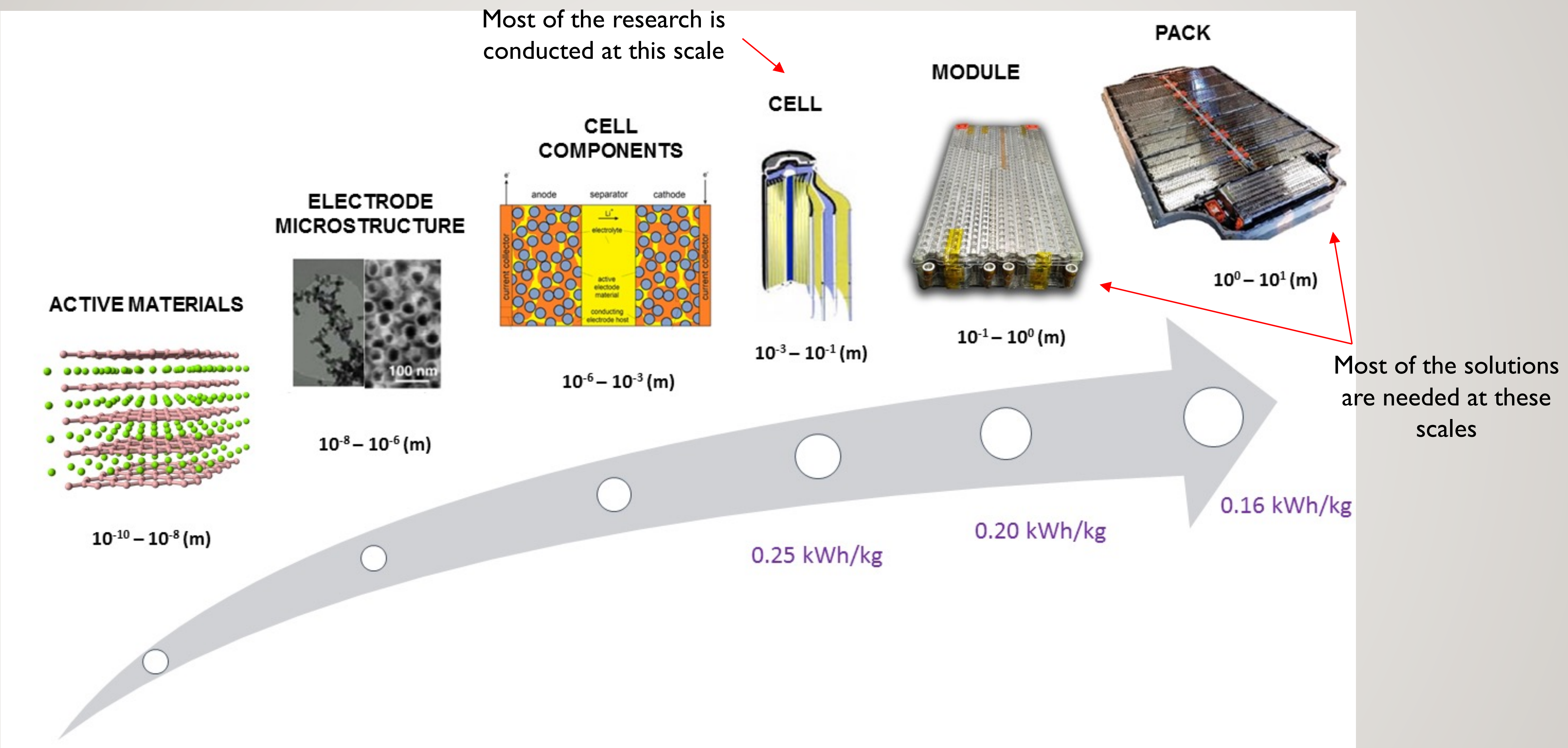

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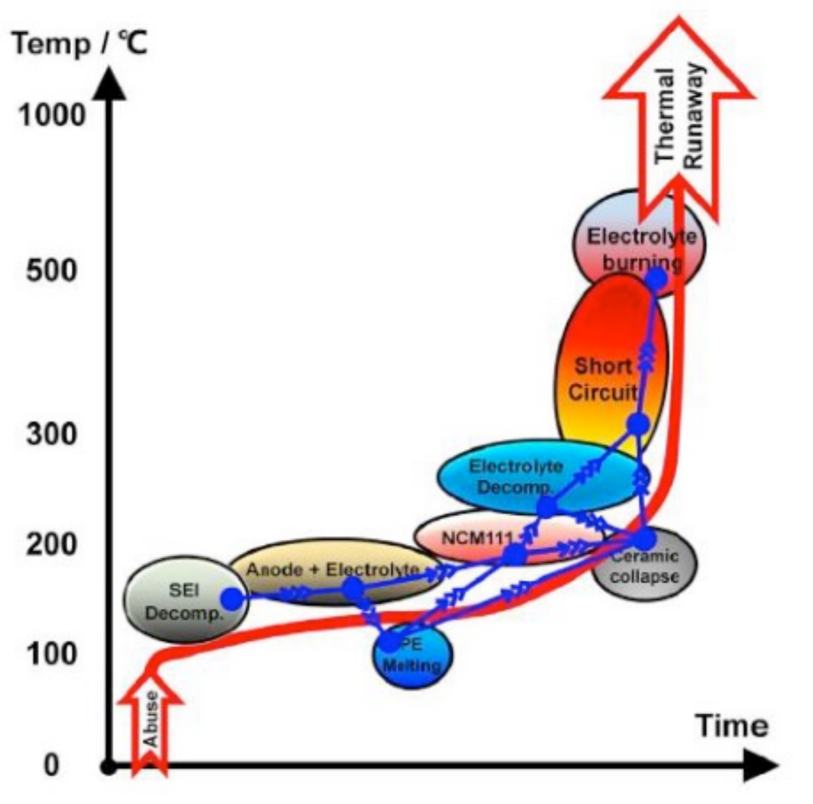
KEY RESEARCH GAPS

- Fundamental **mechanisms of TR (**sub-categories)
- **Link** type of **abuse** and **time to initiate TR** (crash-related abuse) & type of **abuse** and severity of fire **propagation**.
- **Pre-normative research** to improve standards and regulations.
- Adaptive control measures to **detect TR** from a **limited number of sensors**.
- Focus towards **module and pack scales** to understand fire dynamics & propagation instead of cell and component level.
- **Transferability** of modelling and diagnostics techniques (**scales**).
- **System level fire testing** (repeatability, sensitivity to test conditions and scalability for fire extinguishing approaches).
- Academic research focuses at prevention. Further efforts on **detection, compartmentation and suppression** are needed.



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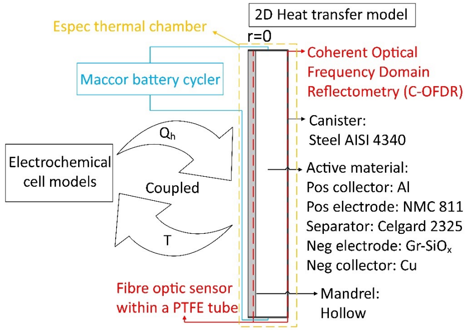
PART III

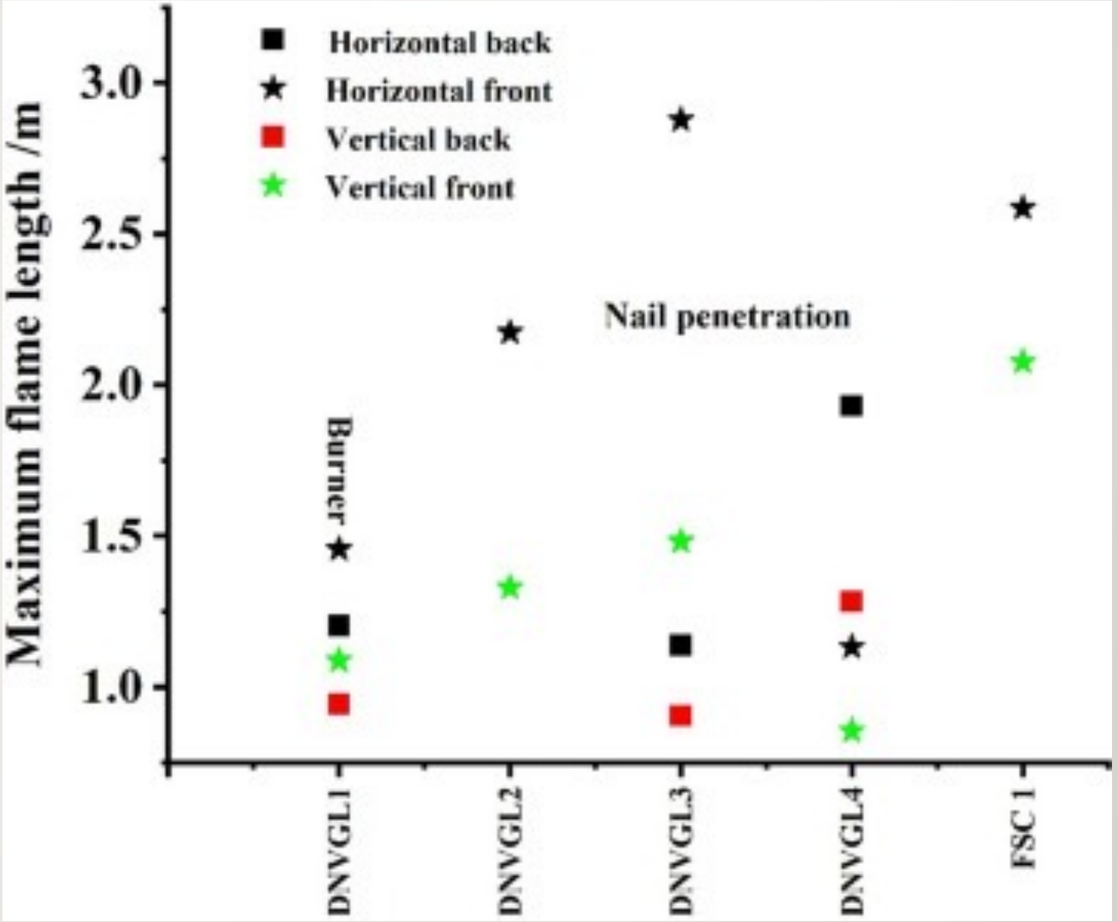
Fire spread and thermal modelling



THERMAL AND MECHANICAL ABUSE OF ELECTRIC VEHICLE POUCH CELL MODULES

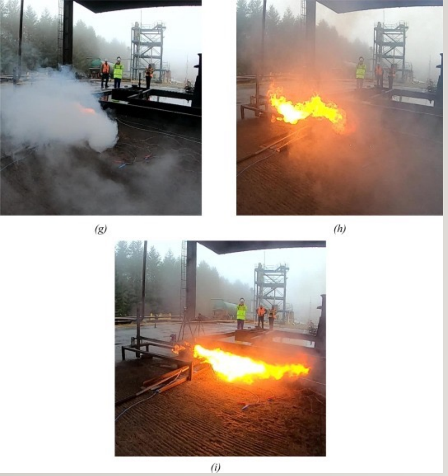
P Christensen et al, Thermal and Mechanical Abuse of Electric Vehicle Pouch Cell Modules *Applied Thermal Engineering 2021*

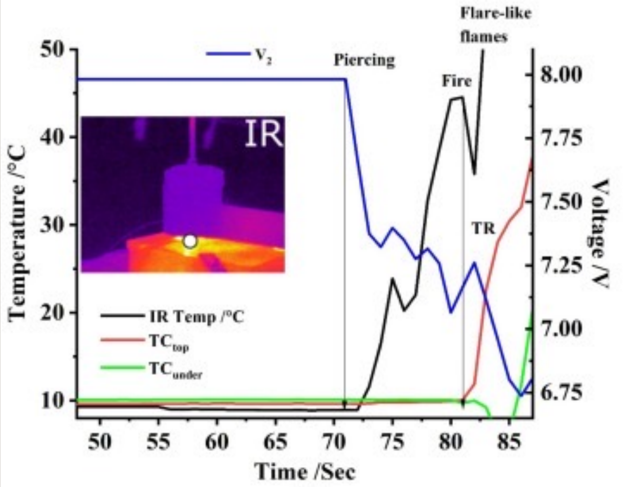
FLARE LENGTH

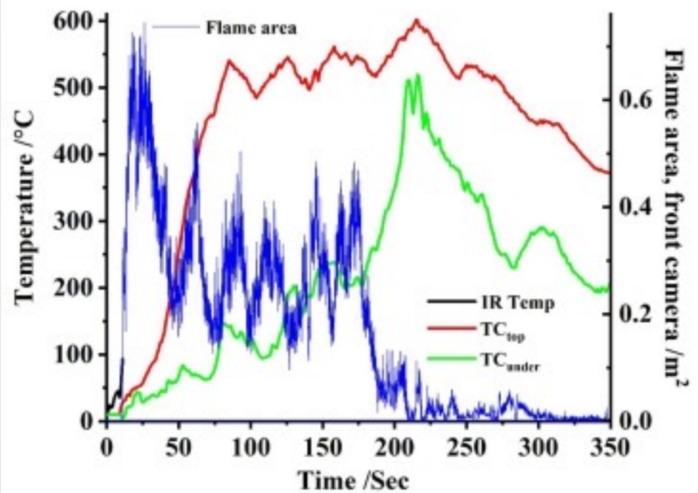


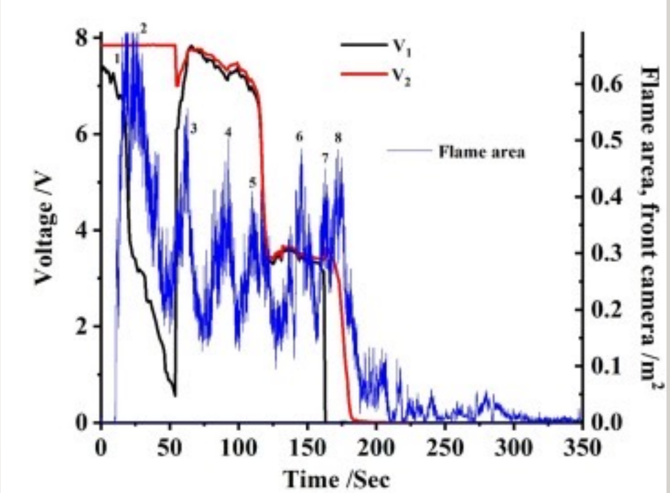
Thermal and Mechanical Abuse of Electric Vehicle Pouch Cell Modules, P Christensen et al, *Applied Thermal Engineering 2021*

DETECTION







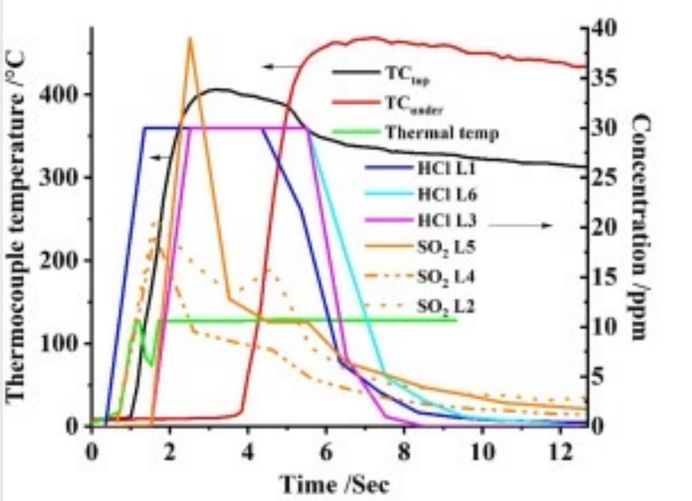


Voltage doesn't drop? Detection? BMS?

Thermal and Mechanical Abuse of Electric Vehicle Pouch Cell Modules, P Christensen et al, *Applied Thermal Engineering 2021*

NO IGNITION?

nail penetration at 50% SOC.
a) was taken 26.47 s after the nail penetrated the module completely;
b) was 35.47 s after penetration
c) 52.13 s after penetration.

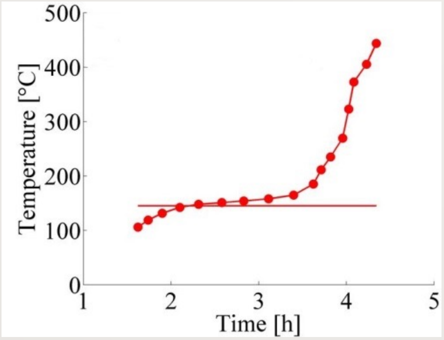


Flammable smoke! Overpressure? Explosion?

AND WHAT ABOUT QUANTITY EFFECT? SELF-HEATING IGNITION

Self-heating ignition is caused by internal heat generation due to low temperature chemical reactions and insufficient cooling, causing what is known as thermal runaway leading to ignition and fire.

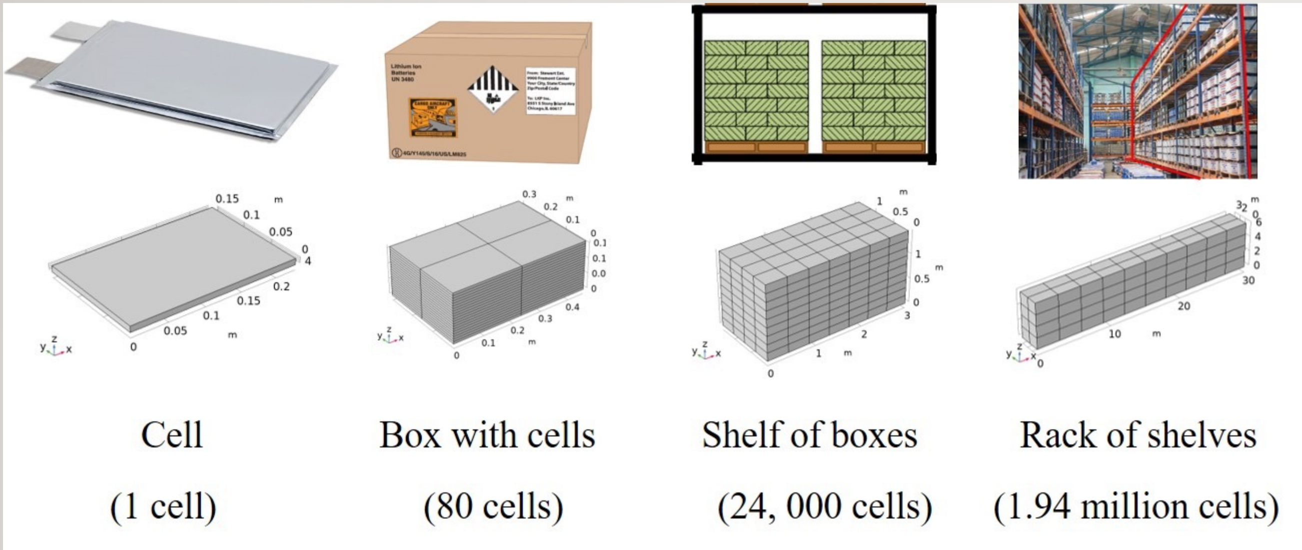
E-vehicle battery pack



Self-heating thermal runaway

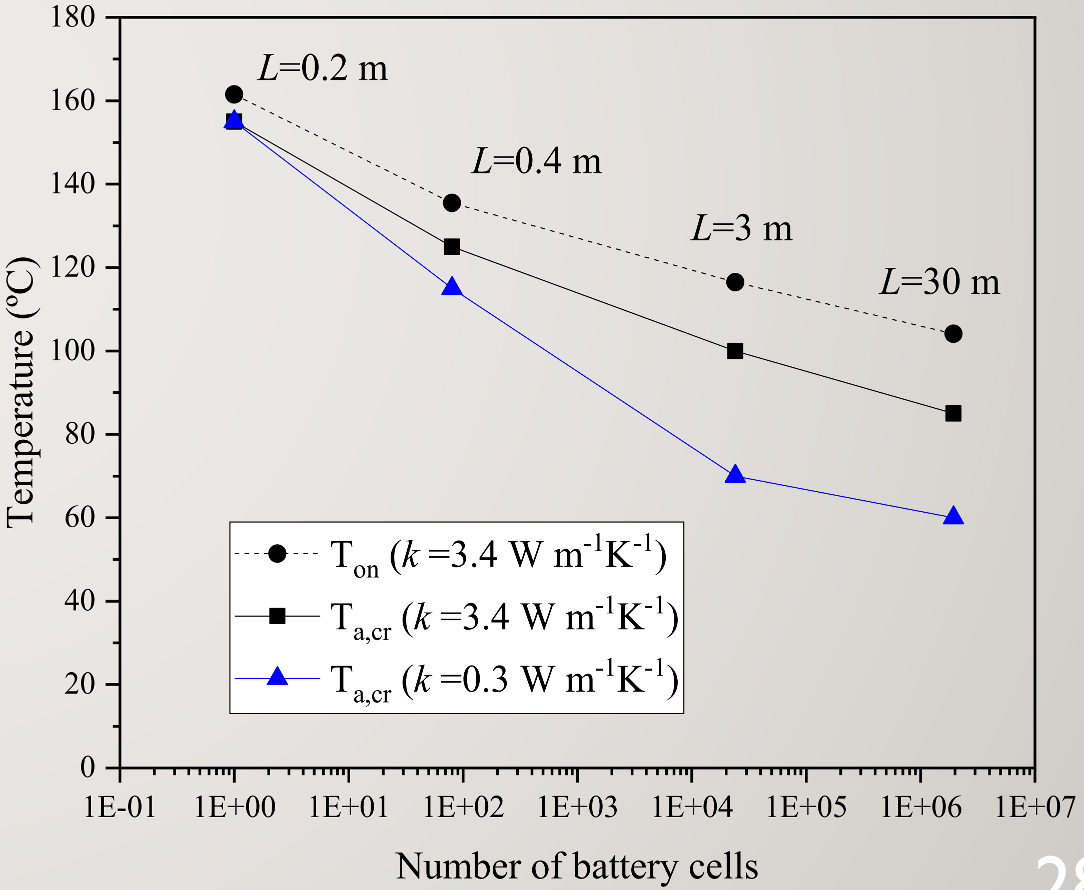
Battery caused fire

Self-heating ignition of Lithium-ion batteries (LIBs) during storage



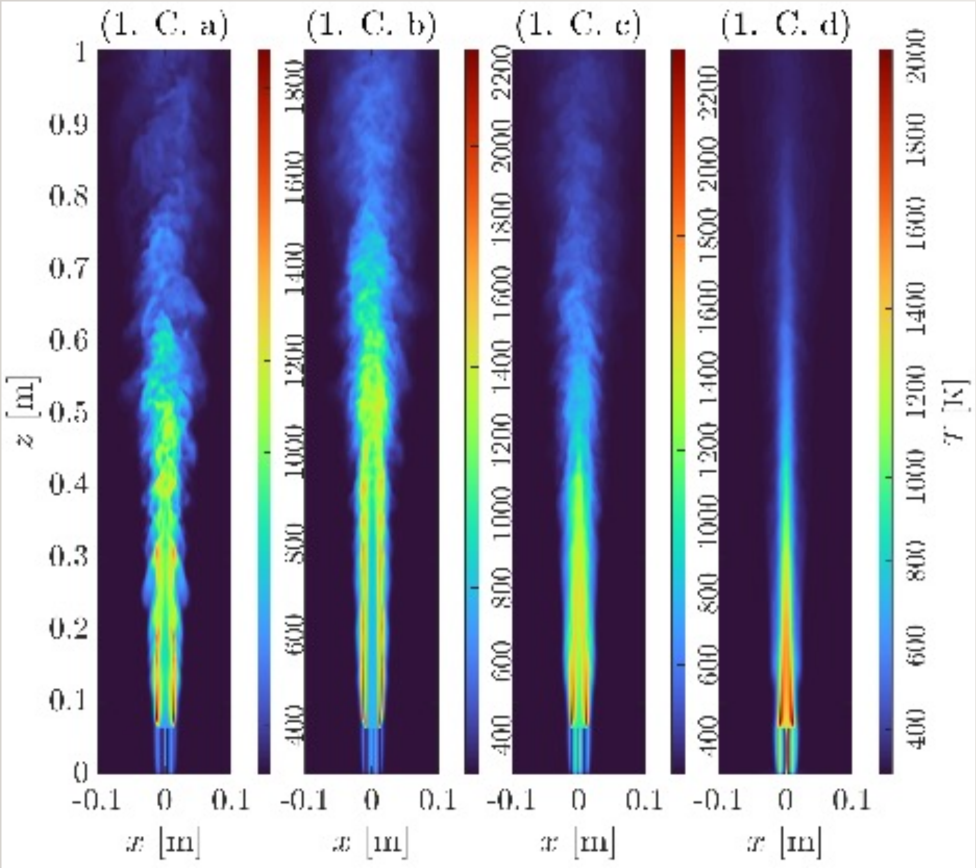
Simulate four typical LIB storage scenarios

Critical ambient temperature ($T_{a,cr}$) to trigger self-heating ignition of LIB ensembles decrease significantly with the increase of the size of ensembles.



Numerical study of scale effects on self-heating ignition of lithium-ion batteries stored in boxes, shelves and racks
Hu et al, *Applied Thermal Engineering (2021)*

SO HOW DO WE MODEL BATTERY FAILURES?



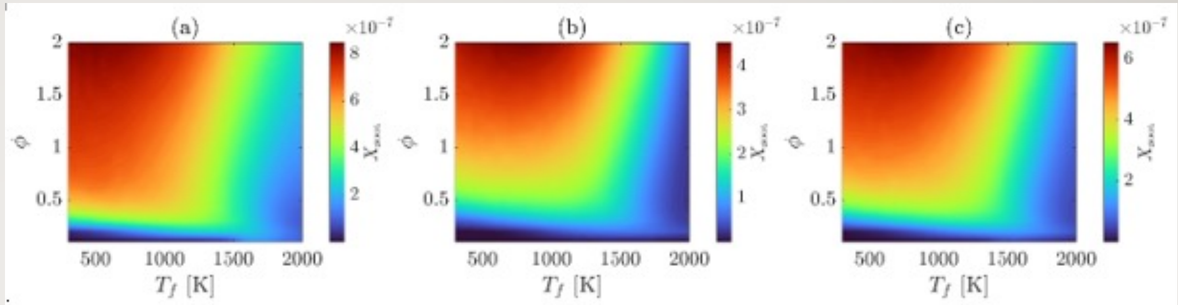


Fig. 2. Soot volume fraction produced in 1-D combustion of the battery vented gases with (a) LCO, (b) LFP and (c) NMC cathodes.

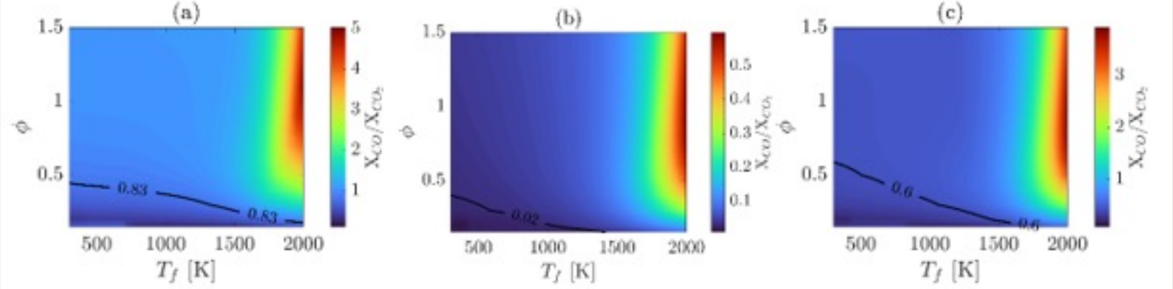
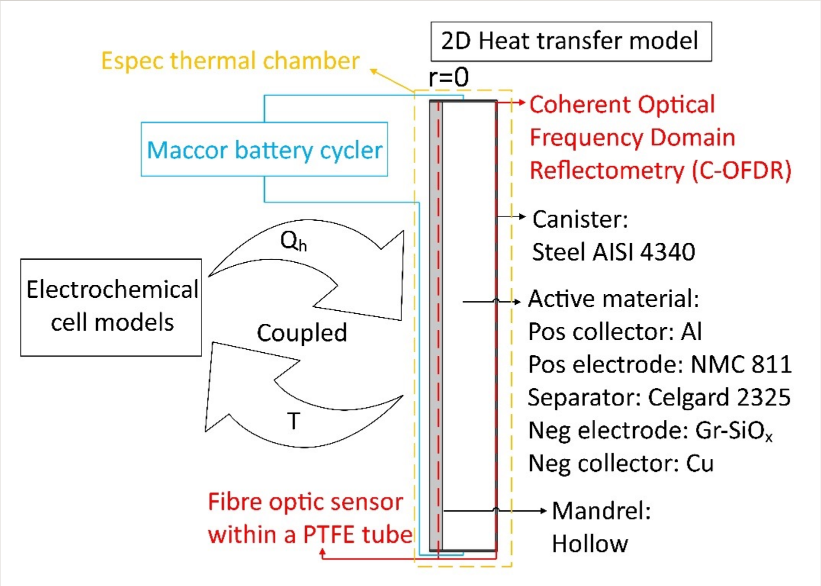
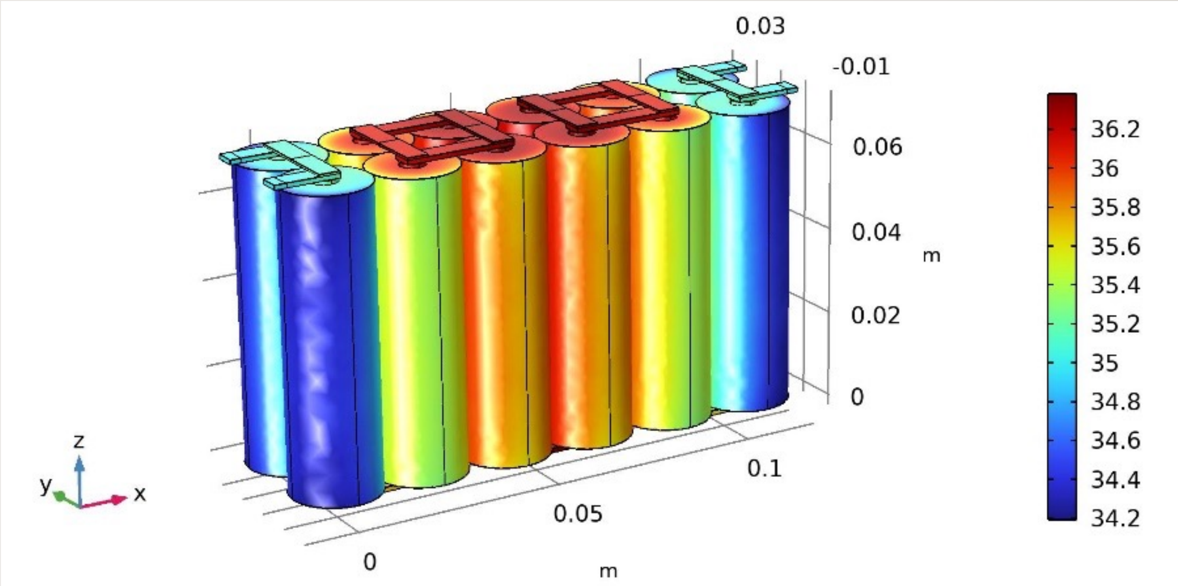


Fig. 3. CO/CO_2 in 1-D combustion of the vented gases with (a) LCO, (b) LFP and (c) NMC cathodes.

Sadeghi, H; Restuccia, F: Jet flame propagation emanating from a 18650-type Lithium-ion battery with LCO, LFP and NMC cathodes (***in review***)

AND WHAT ABOUT THE COMPLEX THERMAL EFFECTS?





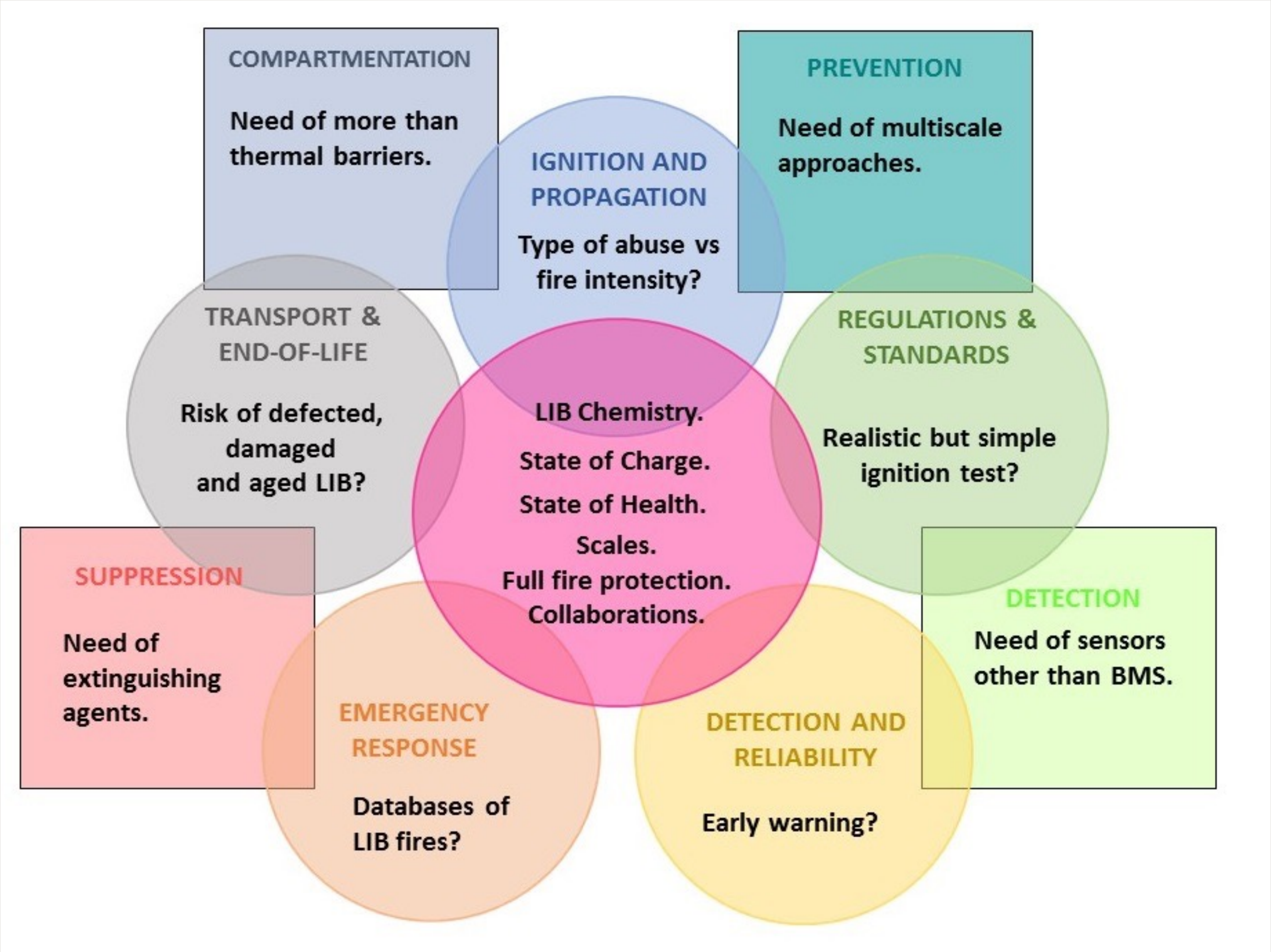
The electrochemical- thermal model (schematic view), in which the electrochemical models provide the cell thermal source to the thermal model (2D). The thermal model returns the obtained temperature to the electrochemical model. Validated with experiments

An experimentally-verified thermal-electrochemical simulation model of a 21700 cell using a lumped semi-empirical battery model
Sarmadian et al, *HEFAT-ATE2022 and Applied Thermal Engineering (Best Paper Award)*

EPSRC Engineering and Physical Sciences Research Council

EPSRC Prosperity Partnership with Jaguar Land Rover, project EP/R004927/1

WHERE DO WE GO FROM HERE?



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REFERENCES AND ACKNOWLEDGEMENTS

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https://doi.org/10.1007/s10694-020-01011-y

https://kclpure.kcl.ac.uk/portal/files/178190312/C2._Sarmadian_HEFAT2022_thermal_electrical_model.pdf

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