QUEEN'S UNIVERSITY BELFAST

QUEEN'S UNIVERSITY IONIC LIQUID LABORATORIES
QUILL

Hybrid Thermal Runaway Propagation Prevention for Lithium-ion Batteries in EVs

David McAreavey

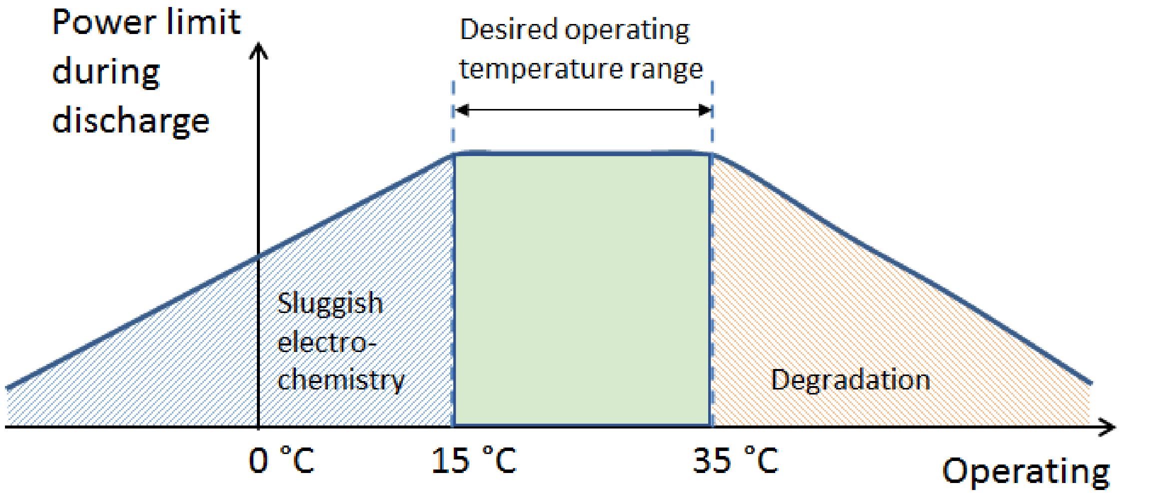
QUILL MEETING, 25/03/2024

Battery electric vehicles (BEV)

	IC Ford F150	Electric Ford F150
Energy density	46.6 MJ/kg	0.46-0.72 MJ/kg
Energy source weight	62.6 kg (23 gallon)	816.5kg (standard range)
Vehicle weight	1845.7 kg	2948.35 kg
Battery/fuel vehicle weight percentage	3.4%	27.7%

Challenges with the Ultimate Energy Density with Li-ion Batteries
https://www.ford.com/trucks/f150/models/f150-limited/

Project overview



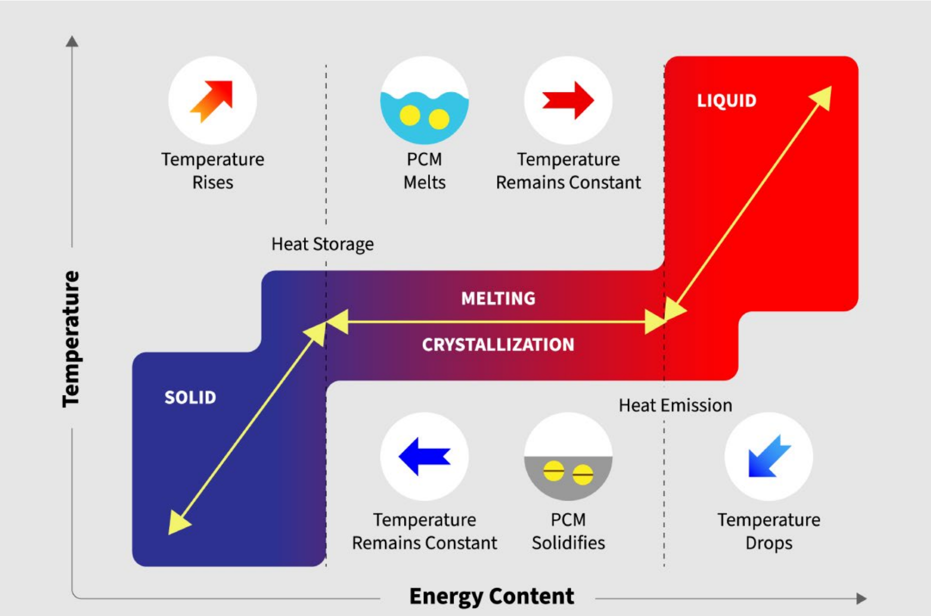
Reproduced from reference

- Inadequate cooling system
- Cells at low states of health
- Cells discharged at too high a rate

Reproduced from reference

Löbberding H, Wessel S, et al. From cell to battery system in BEVs: Analysis of system packing efficiency and cell types. World Electr Veh J. 2020;11(4):1–15.
Sun P, Bisschop R, Niu H, Huang X. A Review of Battery Fires in Electric Vehicles. Fire Technology. 2020

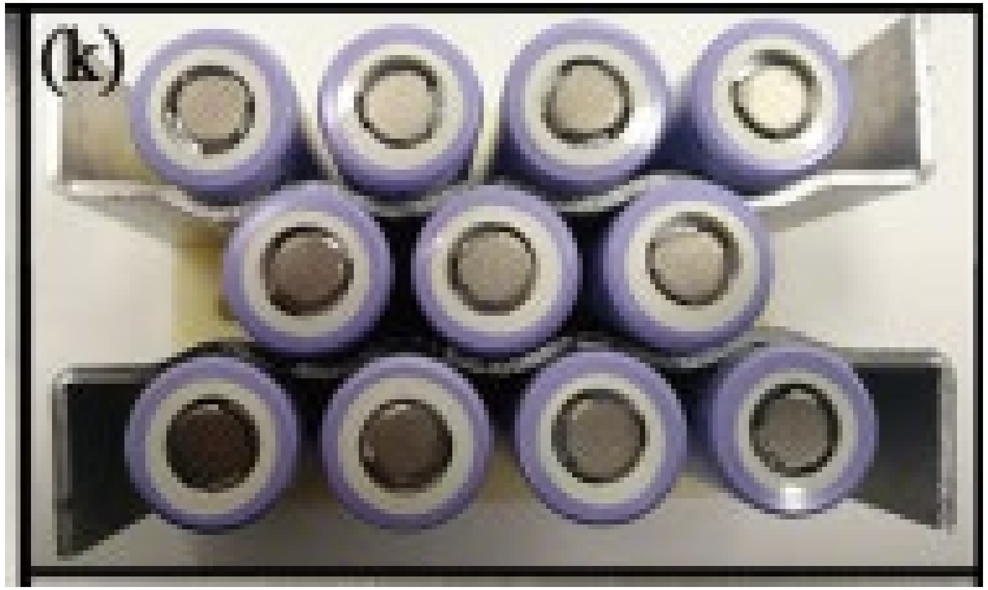
Interstitial materials



Reproduced from reference

PCMs

Aerogels



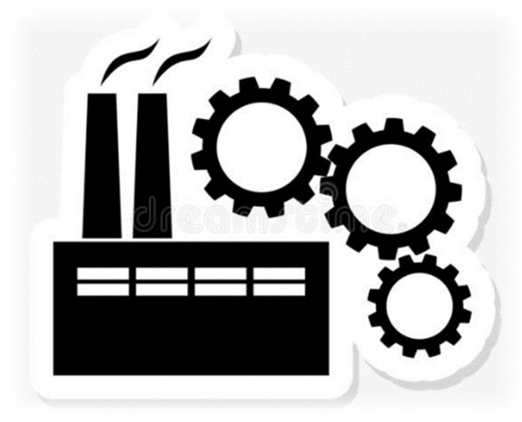
High conductivity

Metal plates
Graphite sheets

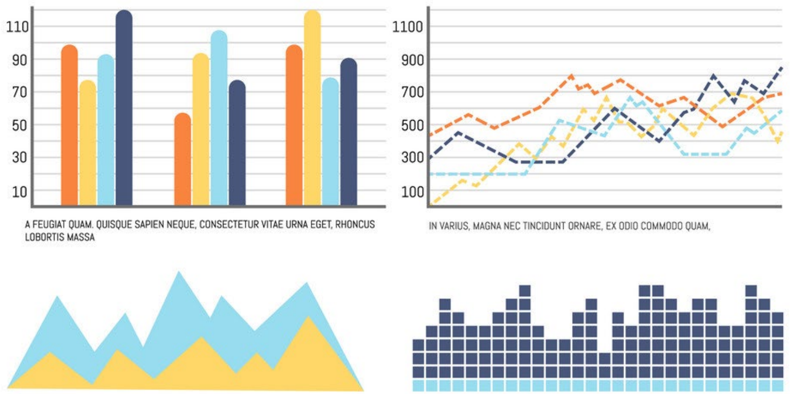
Phase change material https://thermtest.com/phase-change-material-pcm

Introduction

Industry Trends



Past Data



Consumers

Research

Introduction

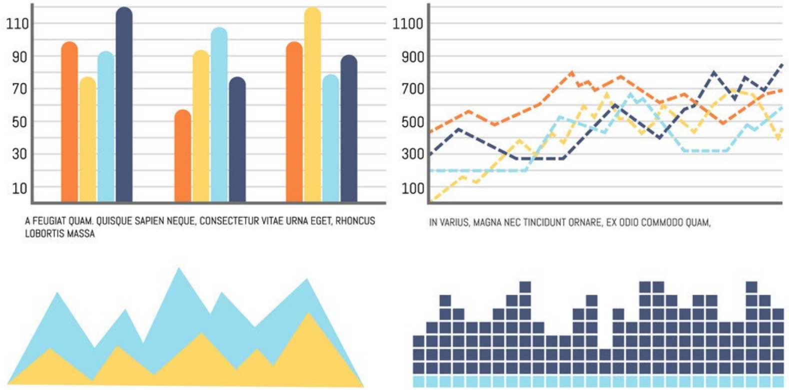
Industry Trends

Energy density

Cell cost

Price parity

Past Data



Consumers

Research

Introduction

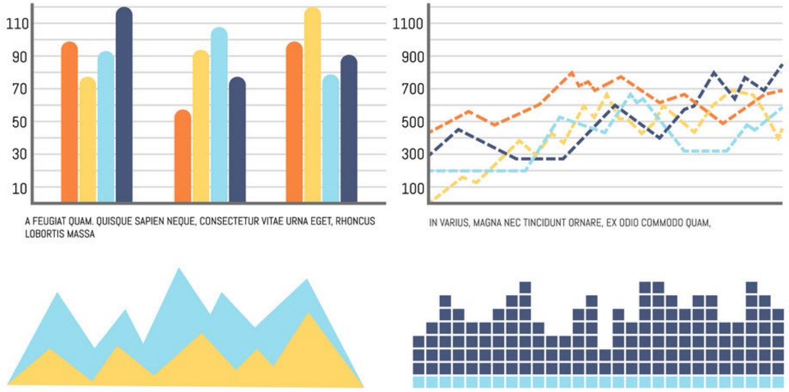
Industry Trends

Energy density ↑

Cell cost ↓

Price parity

Past Data



Consumers

Range demand ↓

Safety concerns ↑

Consumer priorities for EV adoption, 2018 and 2020

Greater concerns are shown in orange.

2020 Global Auto Consumer Study	FRANCE		GERMANY		ITALY		UK		CHINA		US	
In your opinion, what is the greatest concern regarding all battery-powered electric vehicles?	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020
Driving range	31%	28%	35%	33%	4%	27%	26%	22%	25%	22%	24%	25%
Cost/price premium	32%	22%	22%	15%	19%	13%	24%	16%	9%	12%	26%	18%
Time required to charge	11%	15%	11%	14%	18%	16%	13%	16%	12%	15%	10%	14%
Lack of electric vehicle charging infrastructure	16%	22%	20%	25%	44%	32%	22%	33%	18%	20%	22%	29%
Safety concerns with battery technology	4%	11%	5%	10%	7%	10%	6%	12%	22%	31%	8%	13%
Others	6%	2%	7%	3%	8%	2%	9%	1%	14%	0%	10%	1%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Sample size	1,083	1,266	1,287	3,002	1,048	1,274	965	1,264	1,606	3,019	1,513	3,006

Source: Deloitte Global Auto Consumer Study[18]

Deloitte Insights | deloitte.com/insigl

Research

Introduction

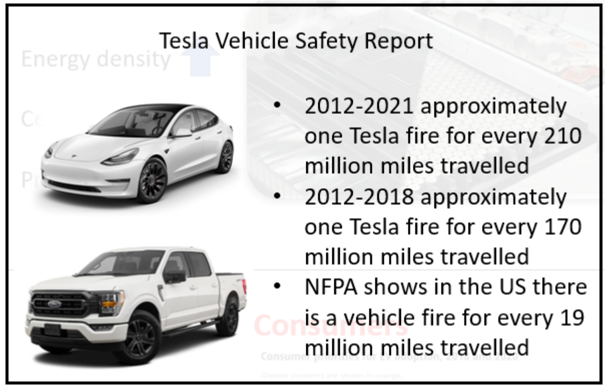
Industry Trends

Energy density ↑

Cell cost ↓

Price parity

Past Data

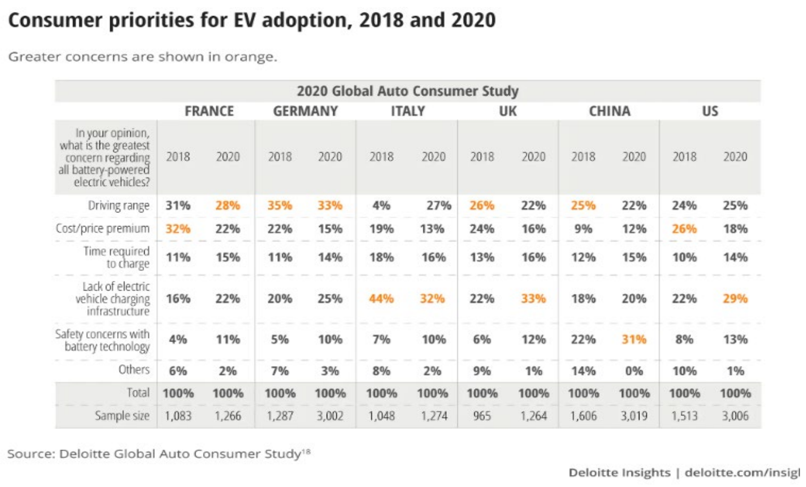


- Inconsistent picture of the frequency of EV fires/runaway events
- Small data sets

Consumers

Range demand ↓

Safety concerns ↑



Consumer priorities for EV adoption, 2018 and 2020

Greater concerns are shown in orange.

2020 Global Auto Consumer Study

	FRANCE		GERMANY		ITALY		UK		CHINA		US	
In your opinion, what is the greatest concern regarding all battery-powered electric vehicles?	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020
Driving range	31%	28%	35%	33%	4%	27%	26%	22%	25%	22%	24%	25%
Cost/price premium	32%	22%	22%	15%	19%	13%	24%	16%	9%	12%	26%	18%
Time required to charge	11%	15%	11%	14%	18%	16%	13%	16%	12%	15%	10%	14%
Lack of electric vehicle charging infrastructure	16%	22%	20%	25%	44%	32%	22%	33%	18%	20%	22%	29%
Safety concerns with battery technology	4%	11%	5%	10%	7%	10%	6%	12%	22%	31%	8%	13%
Others	6%	2%	7%	3%	8%	2%	9%	1%	14%	0%	10%	1%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Sample size	1,083	1,266	1,287	3,002	1,048	1,274	965	1,264	1,606	3,019	1,513	3,006

Source: Deloitte Global Auto Consumer Study[18]

Deloitte Insights | deloitte.com/insigl

Research

Introduction

Industry Trends

Energy density
Cell cost
Price parity

Past Data

Tesla Vehicle Safety Report

- 2012-2021 approximately one Tesla fire for every 210 million miles travelled
- 2012-2018 approximately one Tesla fire for every 170 million miles travelled
- NFPA shows in the US there is a vehicle fire for every 19 million miles travelled

- Inconsistent picture of the frequency of EV fires/runaway events
- Small data sets

Consumers

Range demand
Safety concerns

Consumer priorities for EV adoption, 2018 and 2020

Greater concerns are shown in orange.

2020 Global Auto Consumer Study

In your opinion, what is the greatest concern regarding all battery-powered electric vehicles?	FRANCE 2018	FRANCE 2020	GERMANY 2018	GERMANY 2020	ITALY 2018	ITALY 2020	UK 2018	UK 2020	CHINA 2018	CHINA 2020	US 2018	US 2020
Driving range	31%	28%	35%	33%	4%	27%	26%	22%	25%	22%	24%	25%
Cost/price premium	32%	22%	22%	15%	19%	13%	24%	16%	9%	12%	26%	18%
Time required to charge	11%	15%	11%	14%	18%	16%	13%	16%	12%	15%	10%	14%
Lack of electric vehicle charging infrastructure	16%	22%	20%	25%	44%	32%	22%	33%	18%	20%	22%	29%
Safety concerns with battery technology	4%	11%	5%	10%	7%	10%	6%	12%	22%	31%	8%	13%
Others	6%	2%	7%	3%	8%	2%	9%	1%	14%	0%	10%	1%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Sample size	1,083	1,266	1,287	3,002	1,048	1,274	965	1,264	1,606	3,019	1,513	3,006

Source: Deloitte Global Auto Consumer Study[18]

Deloitte Insights | deloitte.com/insigl

Commercial
Nissan leaf
BMS -Air cooled battery pack

Commercial
Tesla model 3
BMS -Indirect liquid cooling with intumescent foam

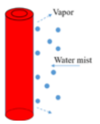
Commercial
BMW
BMS -AC cooling system (refrigerant)

Research
Phase change materials

- Paraffin wax
- Rubitherm (RT15)

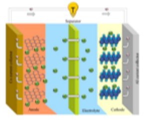
Research
Dedicated suppressants

- Water mist
- Dry powders
- CO_2



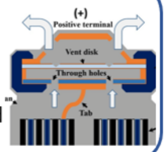
Research
Cell material modification

- Electrolyte
- Separator
- electrodes



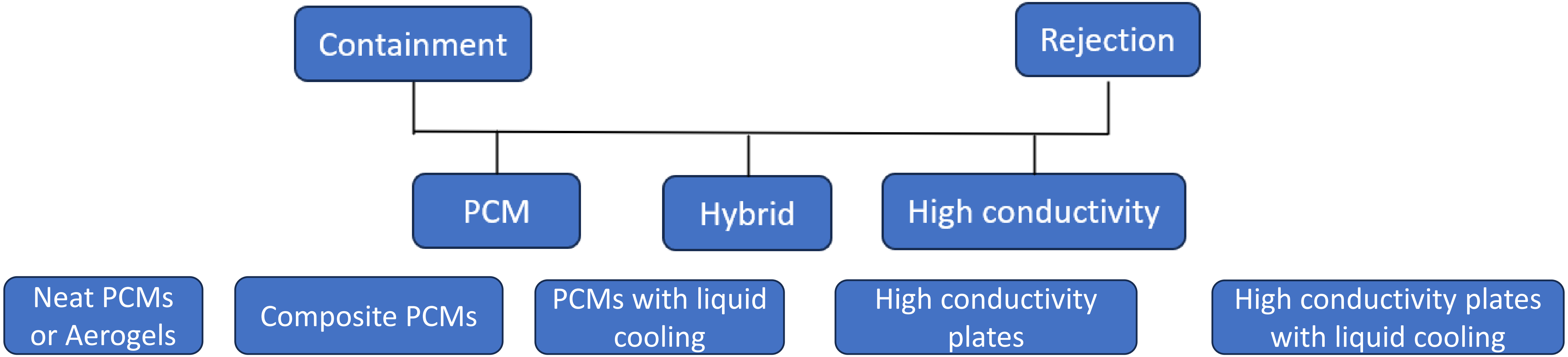
Research
Early detection

- Vent gases
- Cell swelling
- Temperature based detection



- https://www.patentsencyclopedia.com/app/20100086844
- LaMonica M. MIT Technology Review . 2012. Available from: https://www.technologyreview.com
- Koch S, Birke KP, Kuhn R. Fast thermal runaway detection for lithium-ion cells in large scale traction batteries. Batteries. 2018;4(2):1–11.
- Kshetrimayum KS, Yoon YG, Gye HR, Lee CJ. Preventing heat propagation and thermal runaway in electric vehicle battery modules using integrated PCM and micro-channel plate cooling system. Appl Therm Eng . 2019;159(May):113797. Available from: https://doi.org/10.1016/j.applthermaleng.2019.113797
- Liu Y, Duan Q, Xu J, Li H, Sun J, Wang Q. Experimental study on a novel safety strategy of lithium-ion battery integrating fire suppression and rapid cooling. J Energy Storage . 2020;28(December 2019):101185. Available from: https://doi.org/10.1016/j.est.2019.101185

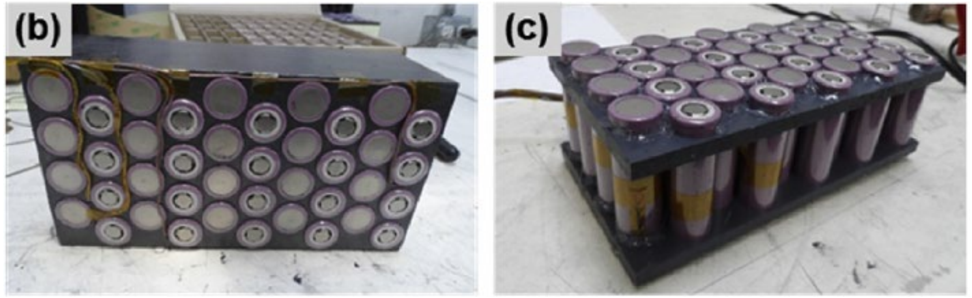
Interstitial materials



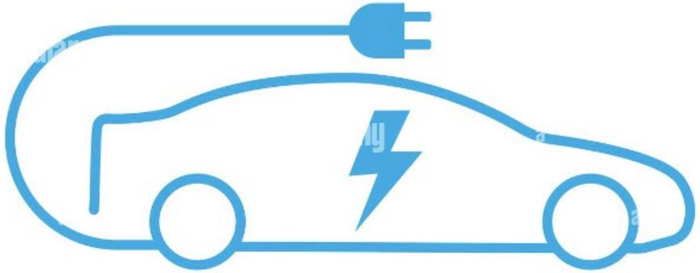
- Spectrum of interstitial materials and options.
- Optimisation of these systems for the pack design is important – considering thermal conductivity and conduction paths.
- The combination of systems often shows greater success than any single approach.
- Flammability of PCMs remains a sticking point.

Novelty

- This work wants to look at the viability of applying interstitial materials to an EV when considering:
  - Weight
  - Volume
  - Energy
- Consider the integration of a thermal runaway propagation system alongside thermal management.

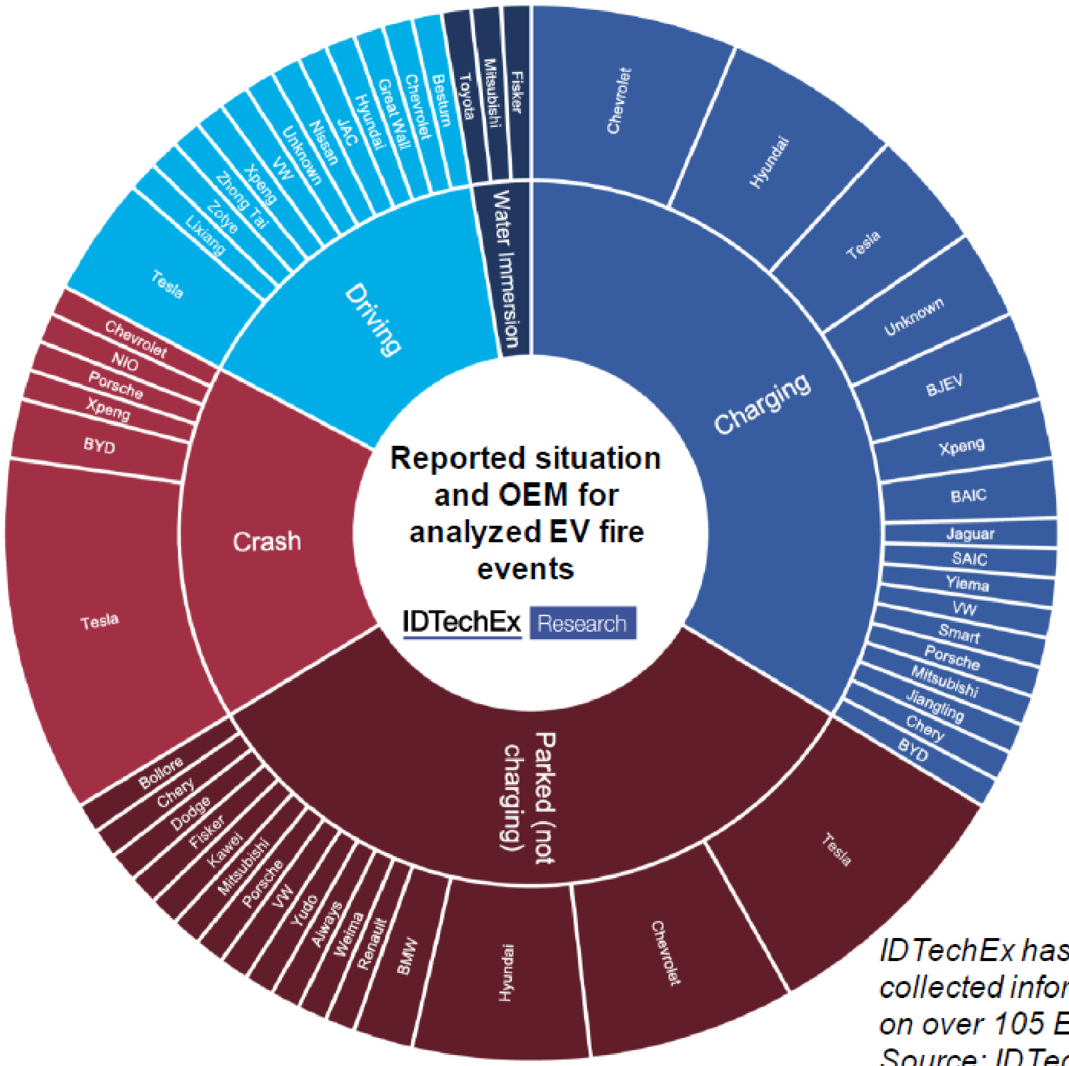


Preventing thermal runaway propagation



Lab testing and theory → Application specific parameters

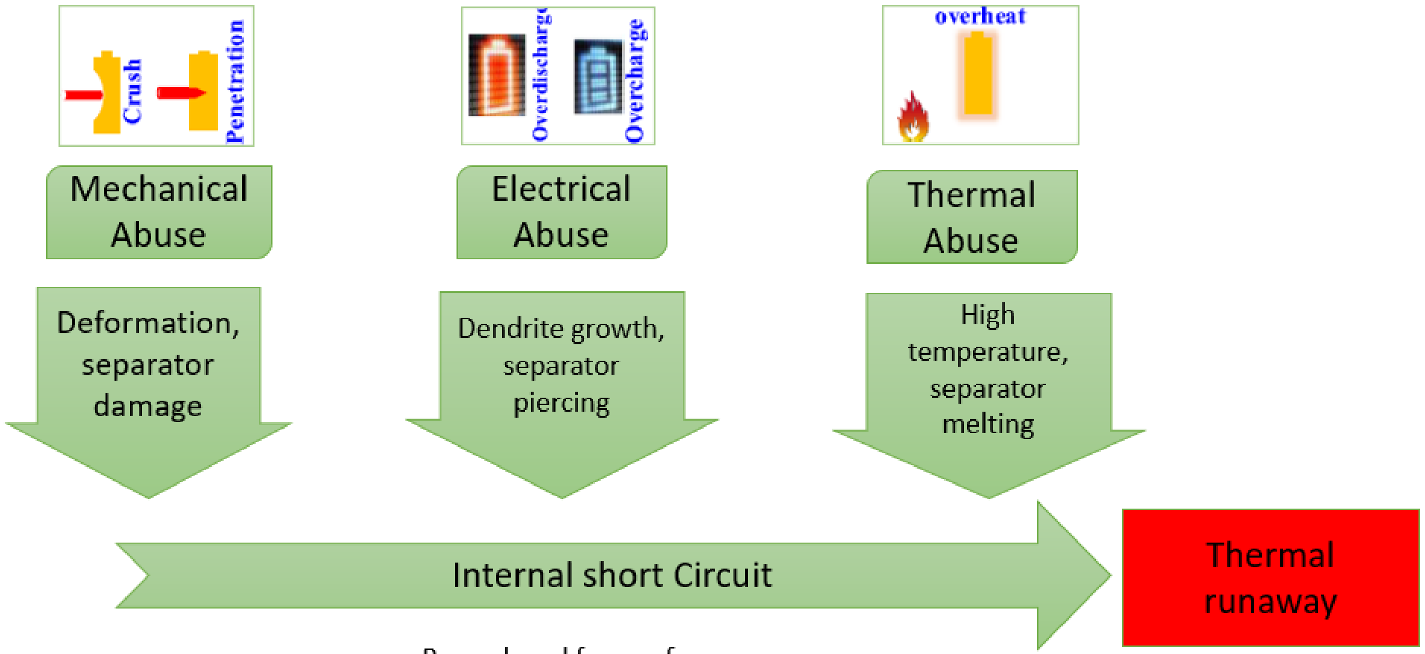
Initiation Scenarios



Reproduced from reference

IDTechEx has collected information on over 105 EV fires. Source: IDTechEx.

- Electrical abuse - Dendrite growth
- Thermal abuse – Separator damage
- Physical abuse – Crash scenario

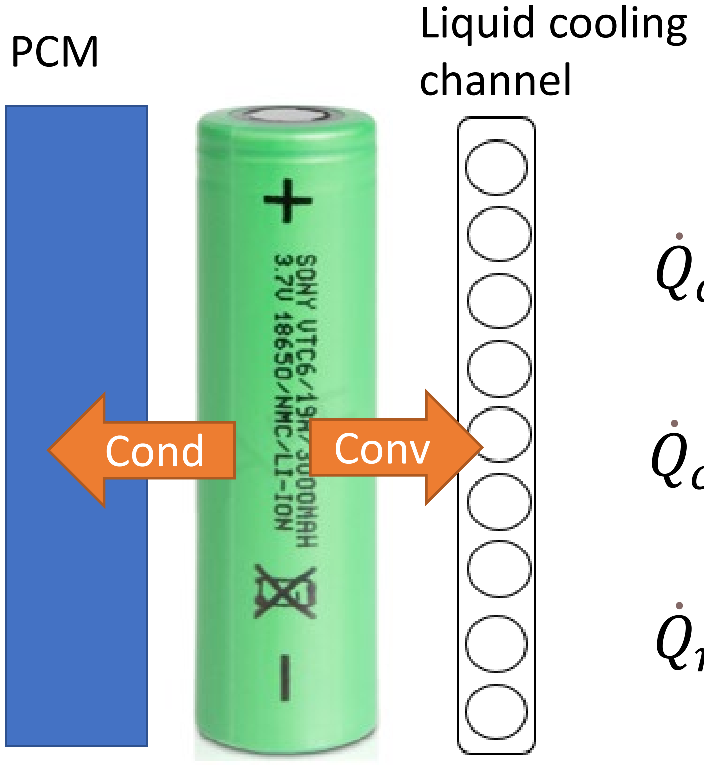


Reproduced from reference

Lai X, et al. Mechanism, modelling, detection, and prevention of the internal short circuit in lithium-ion batteries: Recent advances and perspectives. Energy Storage Mater 2021;35(October 2020):470–99. Available from: https://doi.org/10.1016/j.ensm.2020.11.026

Edmondson, J., & Collins, R. (n.d.). *Slide 1 Fire Protection Materials for Electric Vehicle Batteries 2023-2033 Fire protection and thermal runaway propagation limiting materials for electric*. www.IDTechEx.com/FPM/research@IDTechEx.com

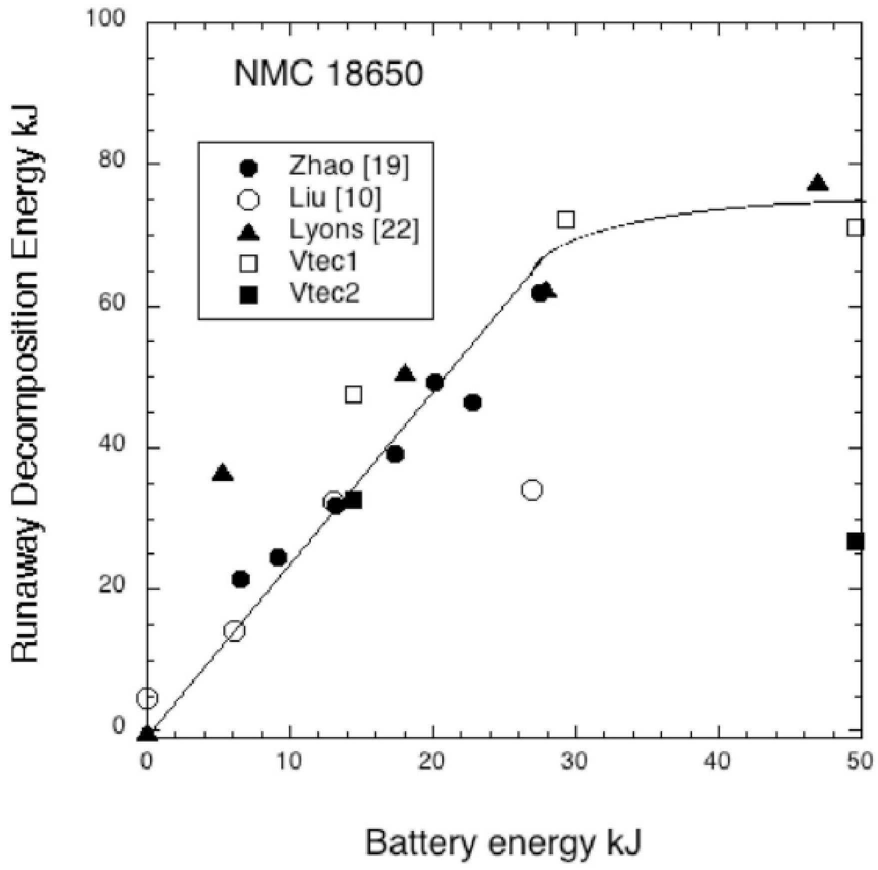
Governing Equations of Calculations



$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \quad \text{(W)}$$

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \quad \text{(W)}$$

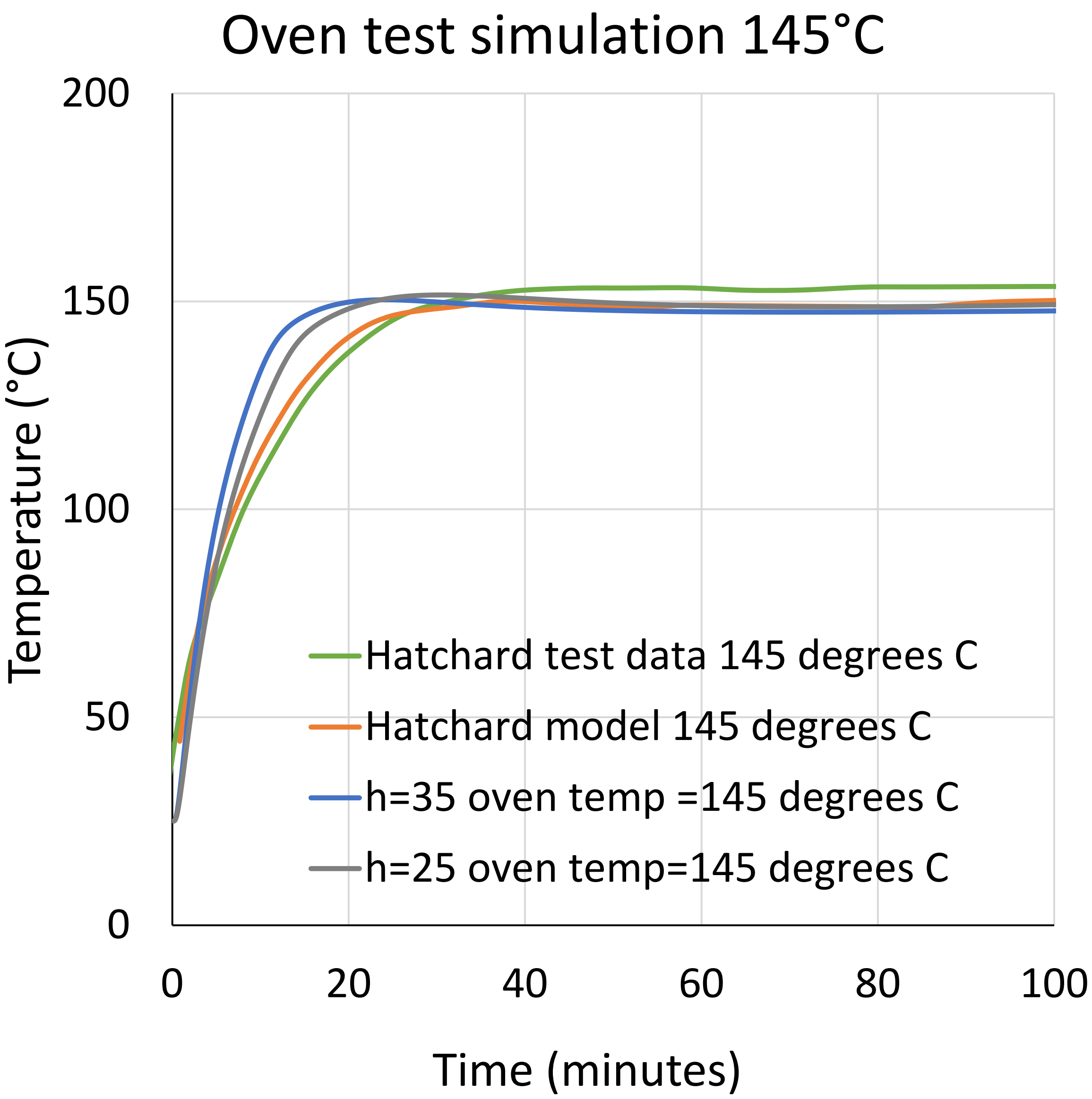
$$\dot{Q}_{rad} = \sigma\varepsilon A\left(T_s^4 - T_{amb}^4\right) \quad \text{(W)}$$

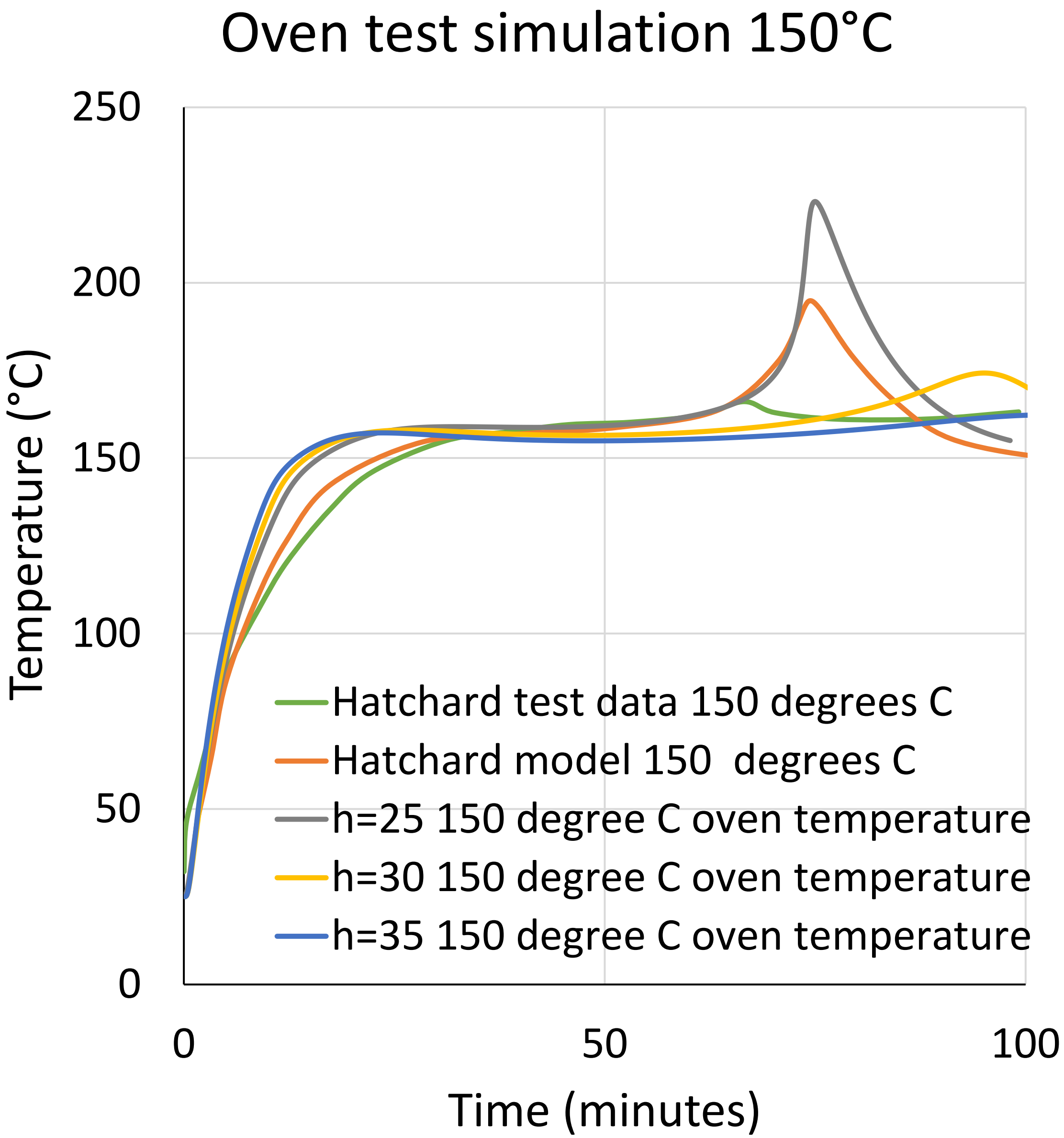


Reproduced from reference

Cengel Y, J. Ghajar A. Heat and Mass Transfer, Fundamentals & Application, Fifth Edition in SI Units. McGraw-Hill, 5th Edition. 2015.
Quintiere JG. More on methods to measure the energetics of lithium ion batteries in thermal runaway. Fire Saf J. 2021;124(April):103382. Available from: https://doi.org/10.1016/j.firesaf.2021.103382

Oven tests 2D MATLAB





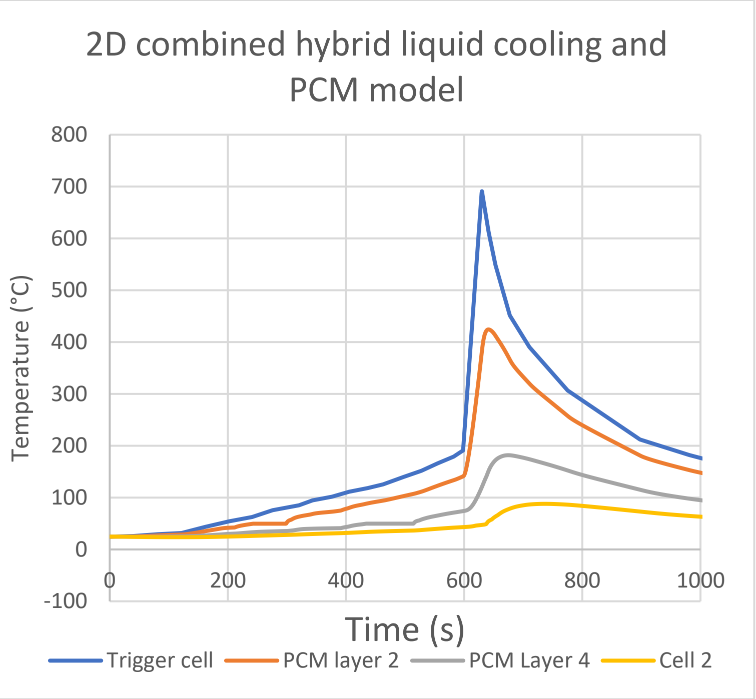
Model development

Excel → MATLAB → COMSOL

Excel

Simplified 2D model

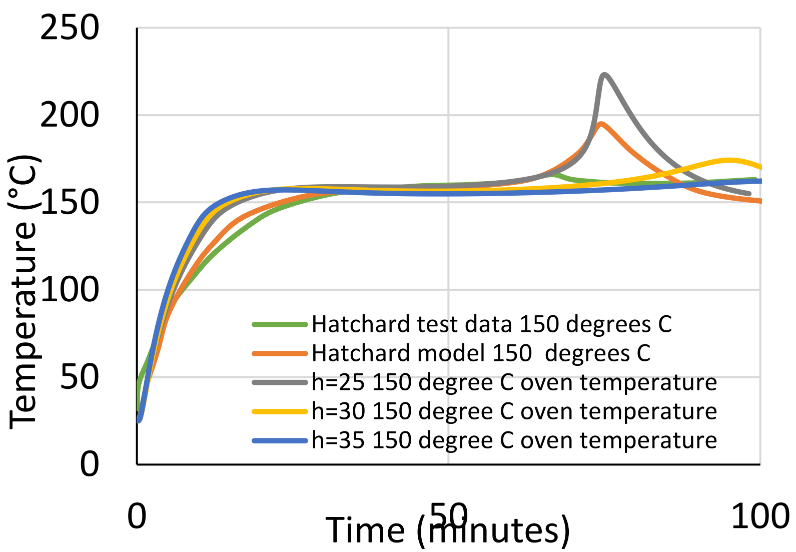
Difficulty in calculating with small enough time steps and dealing with thermal gradients.



MATLAB

More developed 2D kinetics model

- Improvements calculating with a small time interval and dealing with thermal gradients.
- Still some problems with instability, some safeguards installed in early versions.

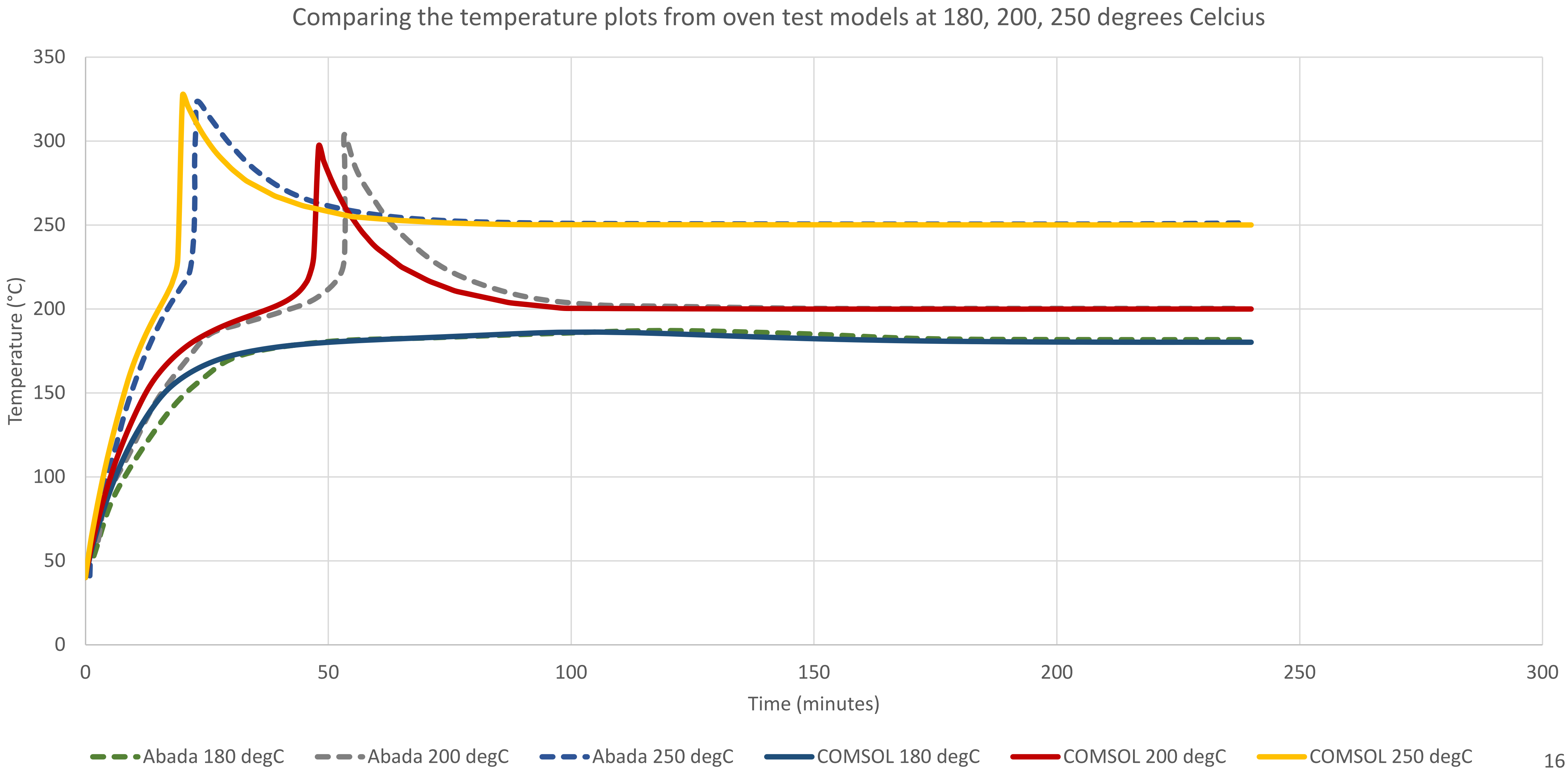


COMSOL

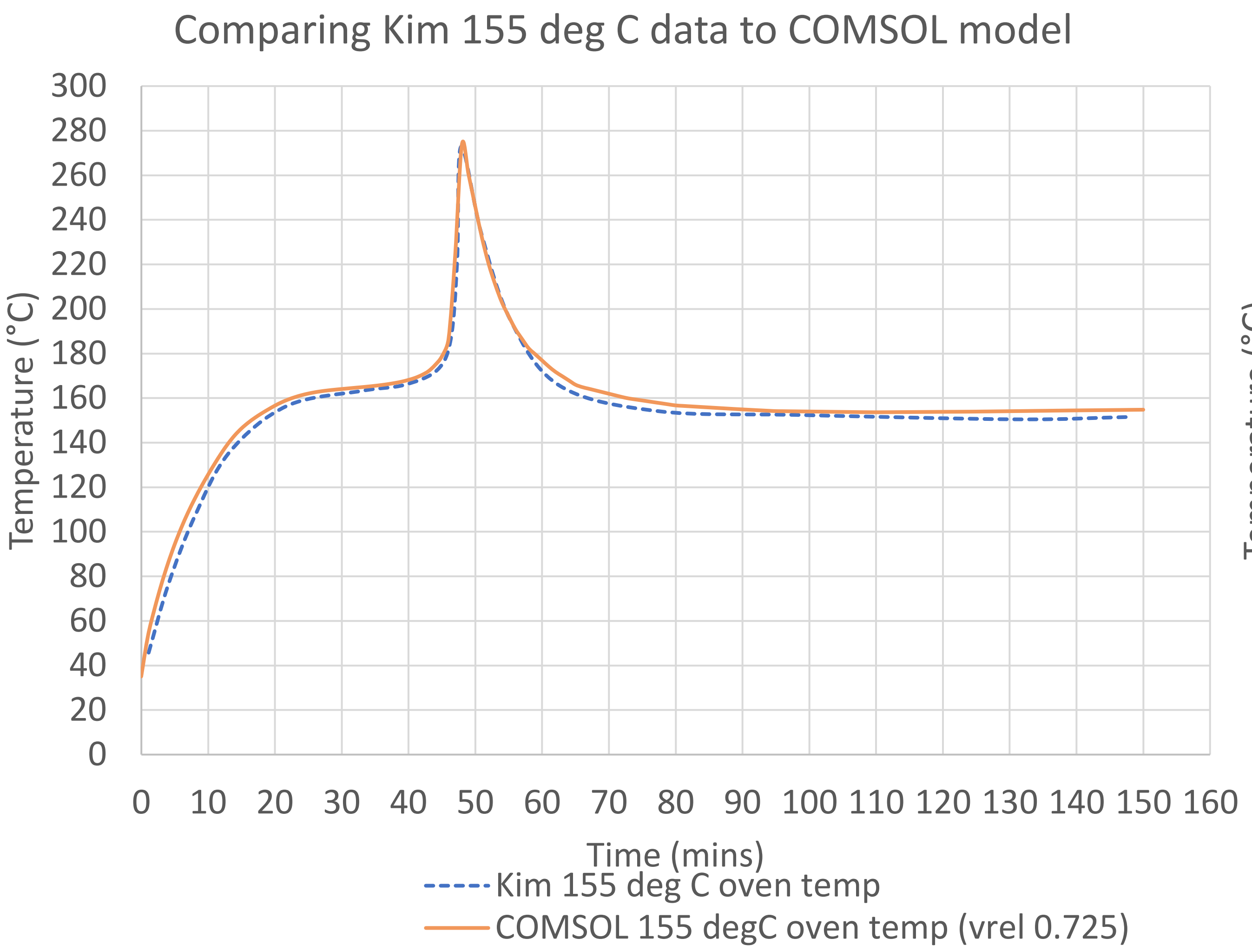
3D model, resolving shell, lumped jelly roll and active material and mandrel.

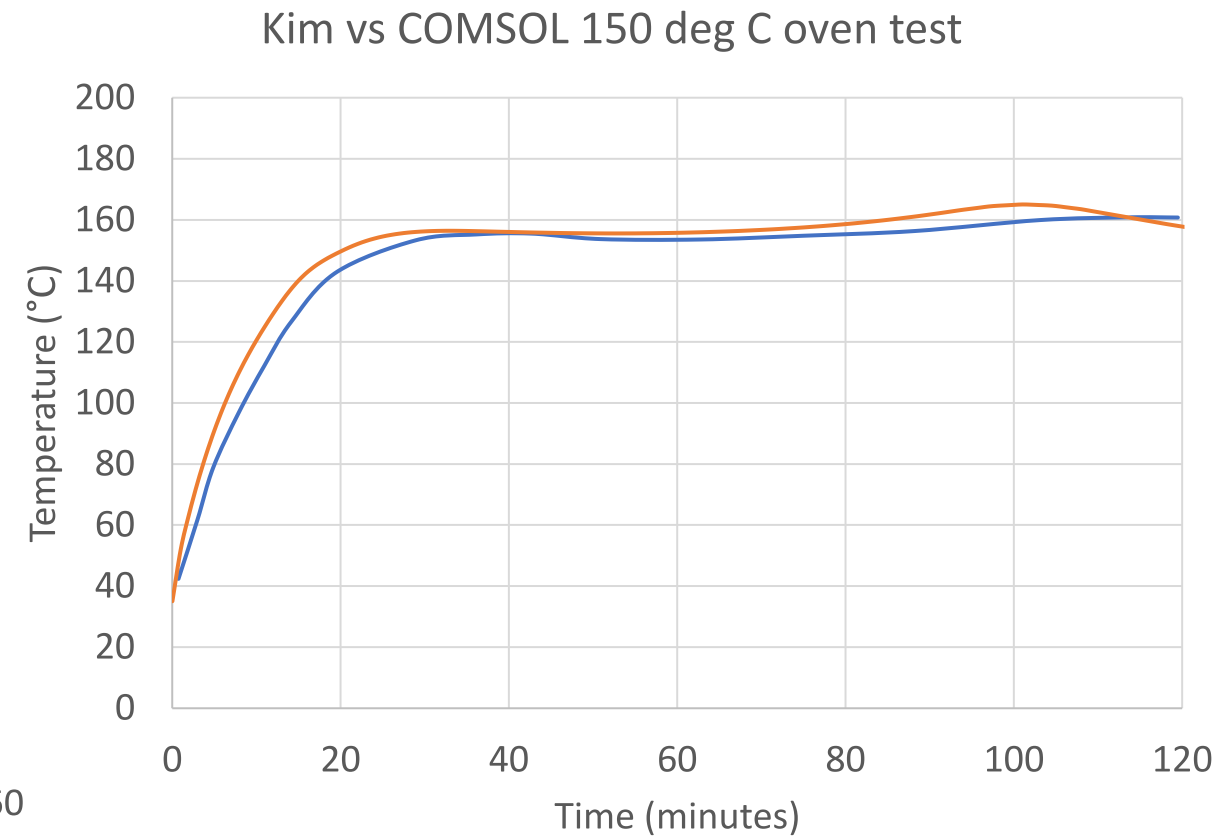
Further improvements with steep gradients and accuracy of the simulations.

Validation of LFP against oven model

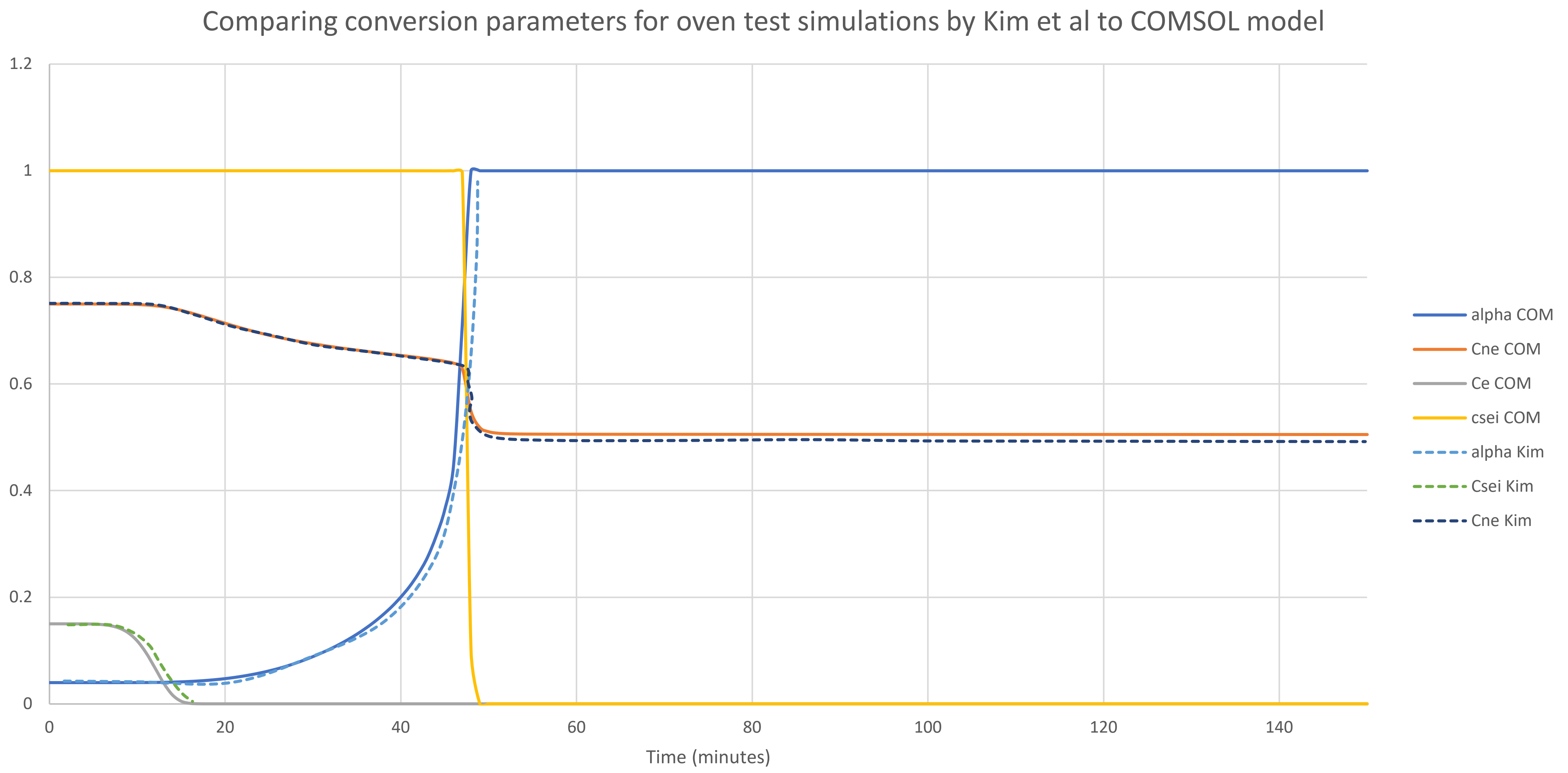


LCO oven test model



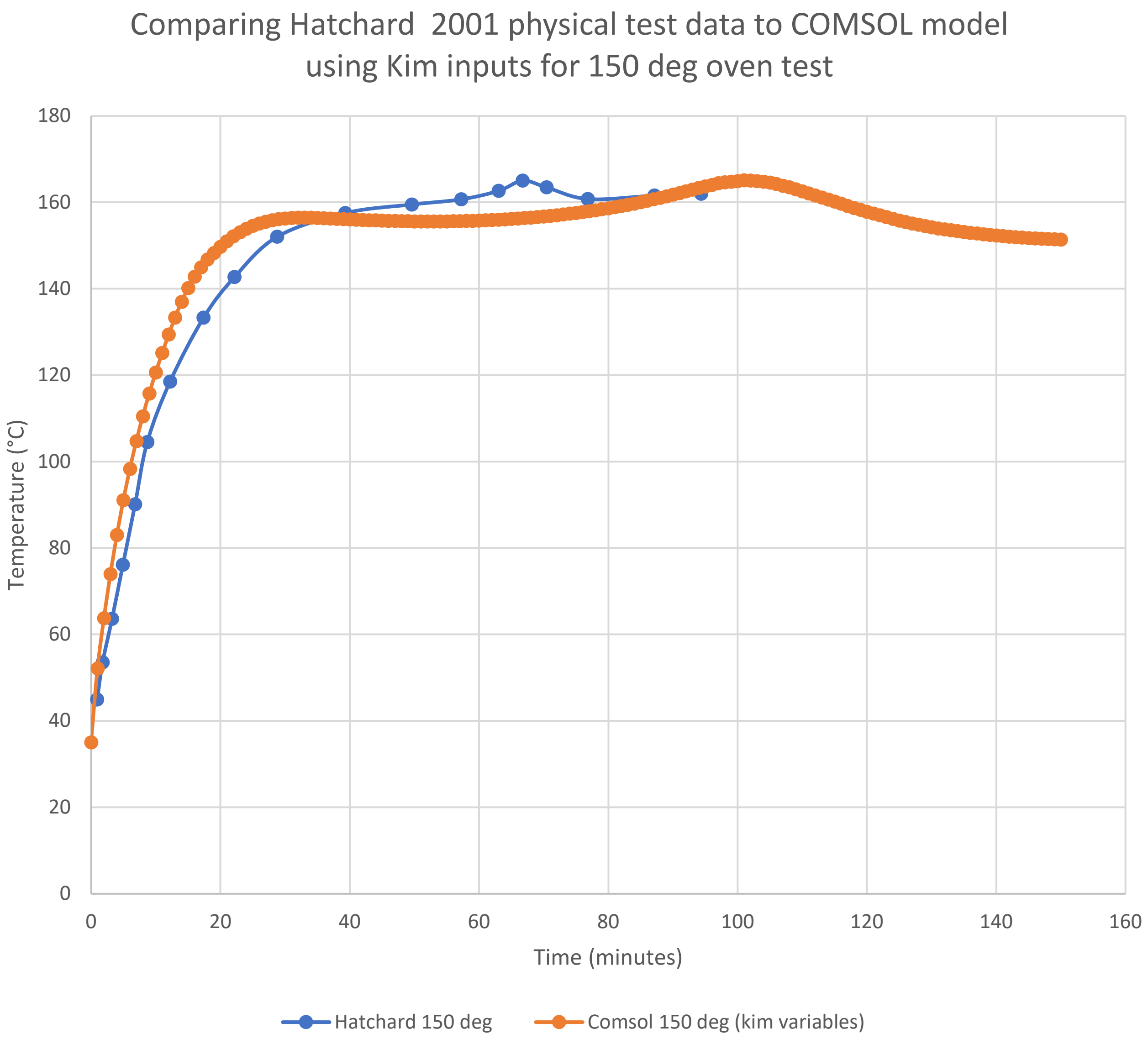


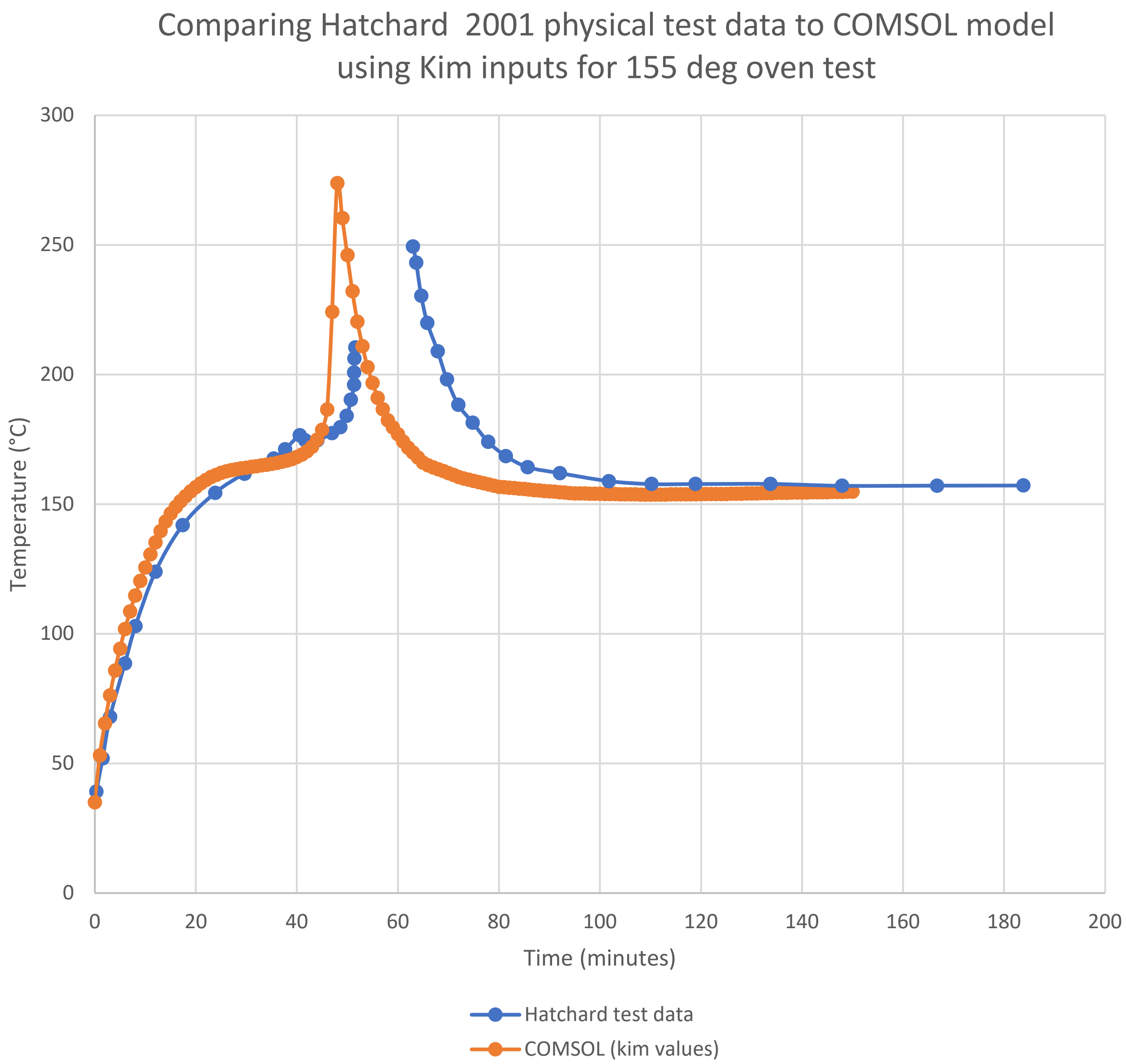
Comparison of conversion metrics



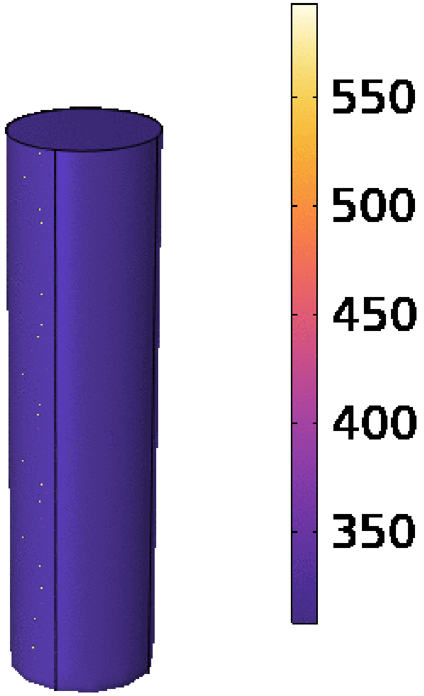
Alpha – conversion degree of positive electrode
Cne – reaction of intercalated lithium at anode
Ce – proportion of electrolyte remaining
Csei – sei decomposition

Comparison with test data

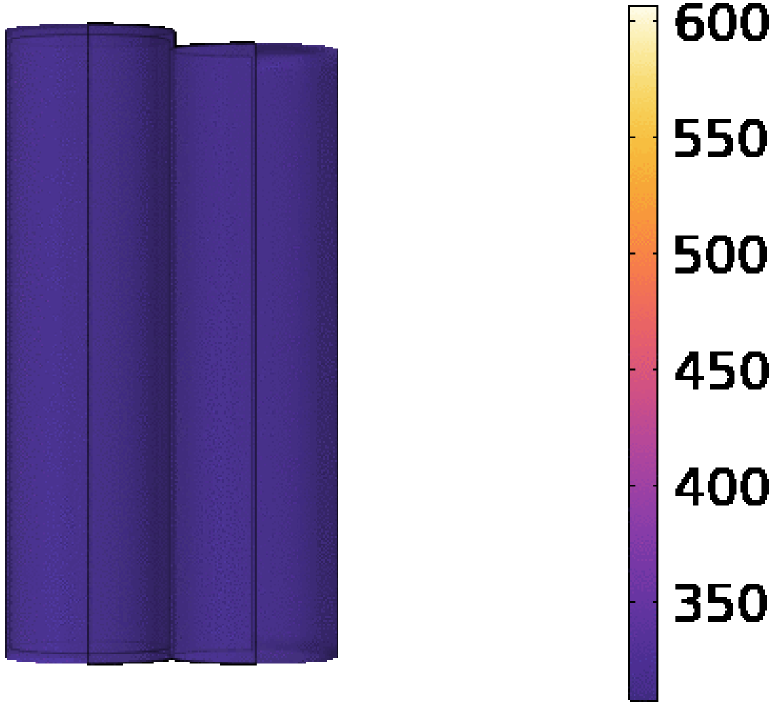




Animations

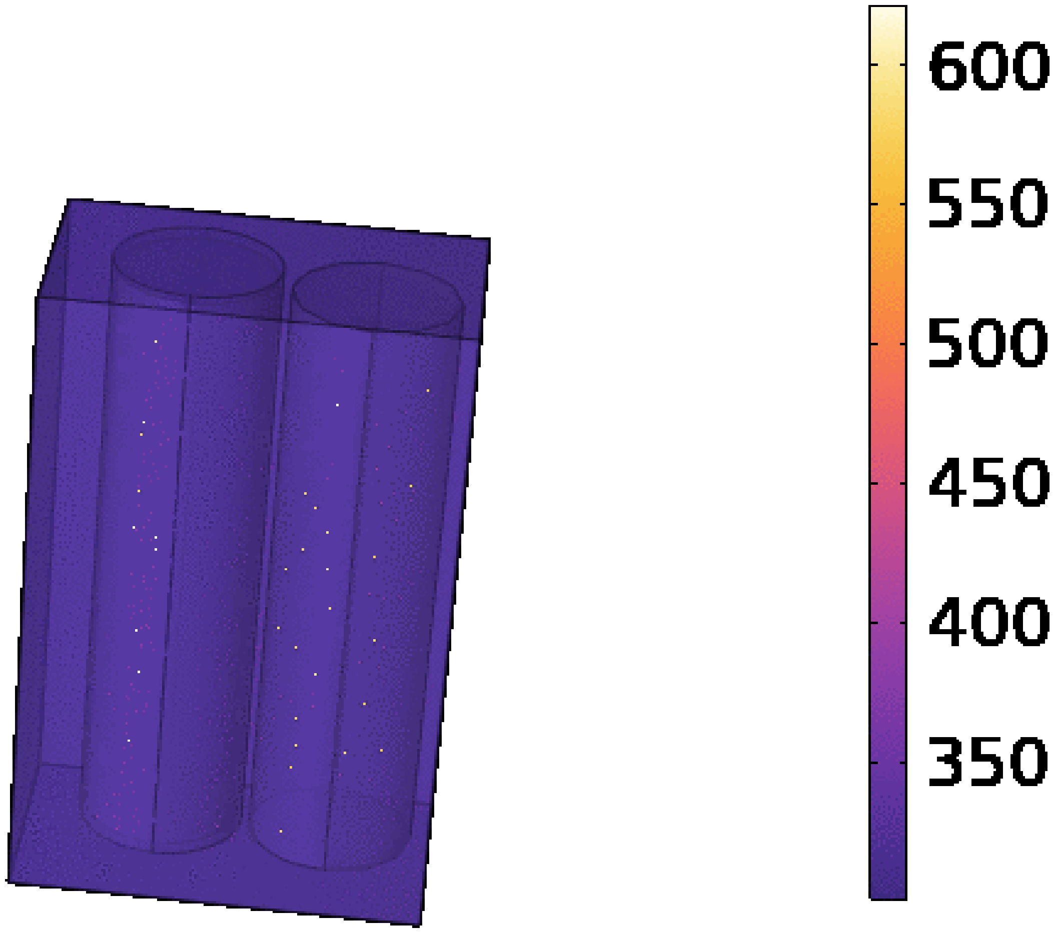


Single body, no can
(confirms spatial dependence)

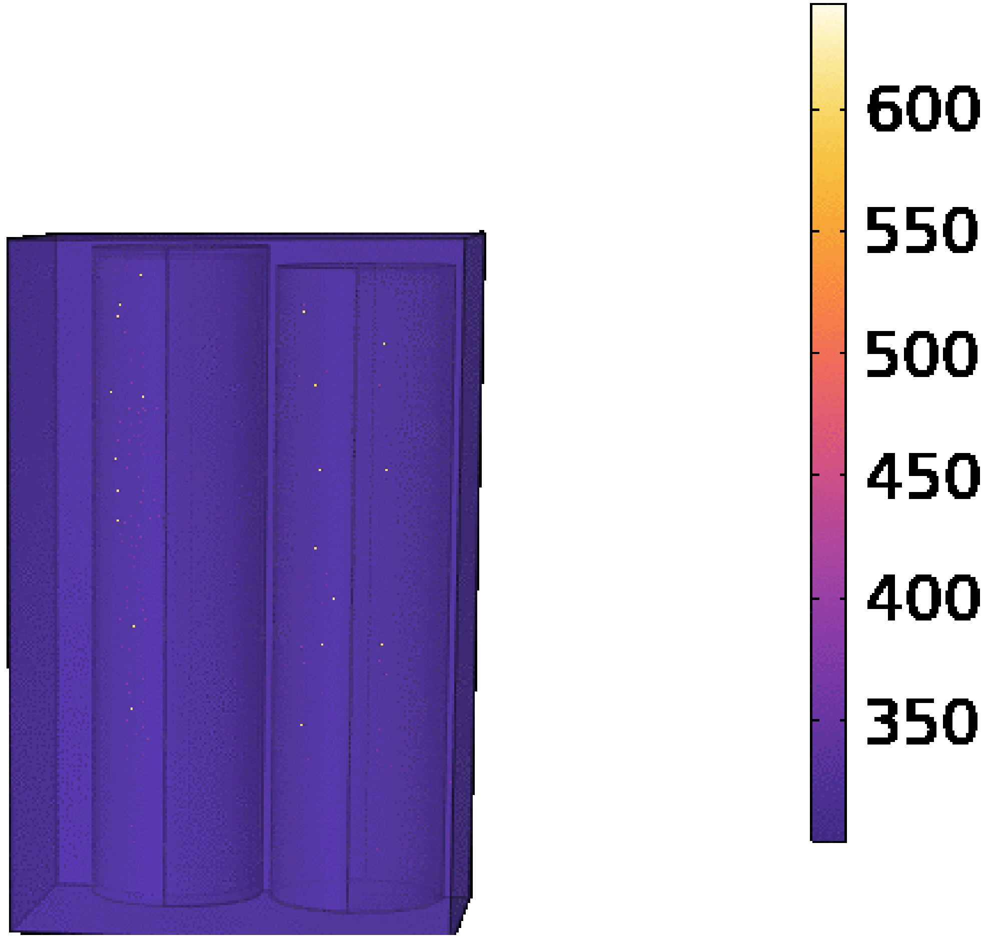


Two cells, multi body, conduction

Animations



Control volume convection, radiation



Control volume, flowing air, convection, radiation

Project direction

Trigger → Heat transfer → Cell response

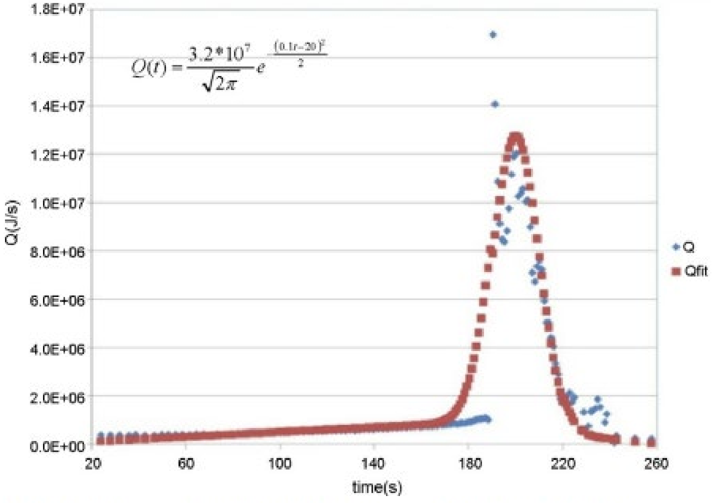


Fig. 3. Rate of heat generation per unit time based on measurements by ARC for Type 18,650 high power cells.

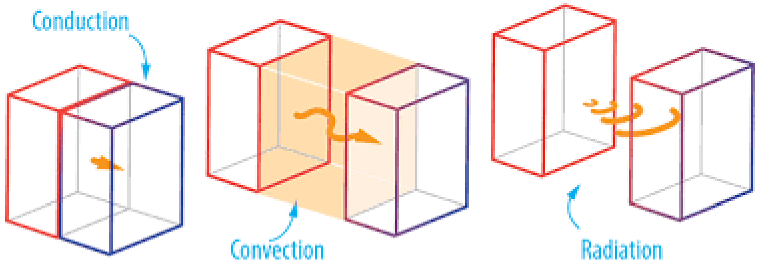
An alternative cooling system to enhance the safety of Li-ion battery packs

Trigger profile

- Calorimetry
- Bell curve

<u>Validation</u>

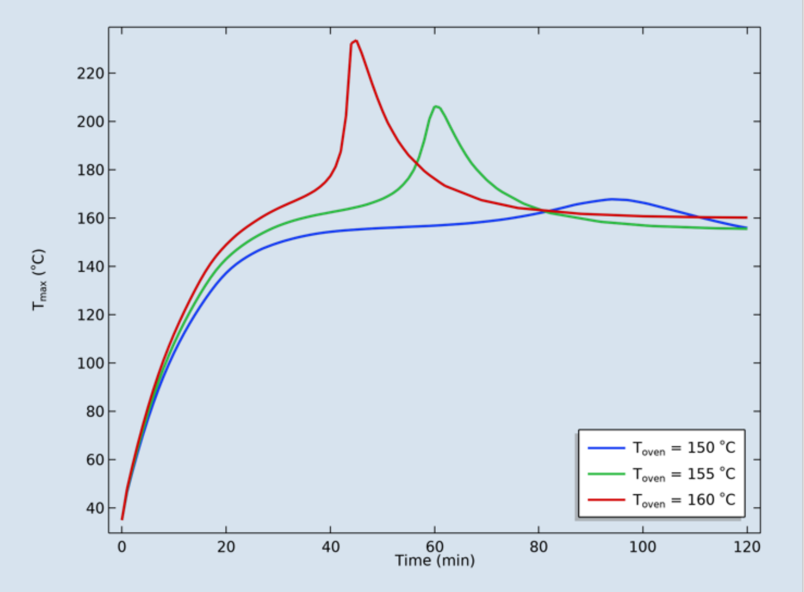
- Directly from test data



- Conduction
- Convection
- Radiation

<u>Validated</u>

- From low power cartridge physical test



Maximum battery temperature at different oven temperatures.

- Chemical kinetics

<u>Validated</u>

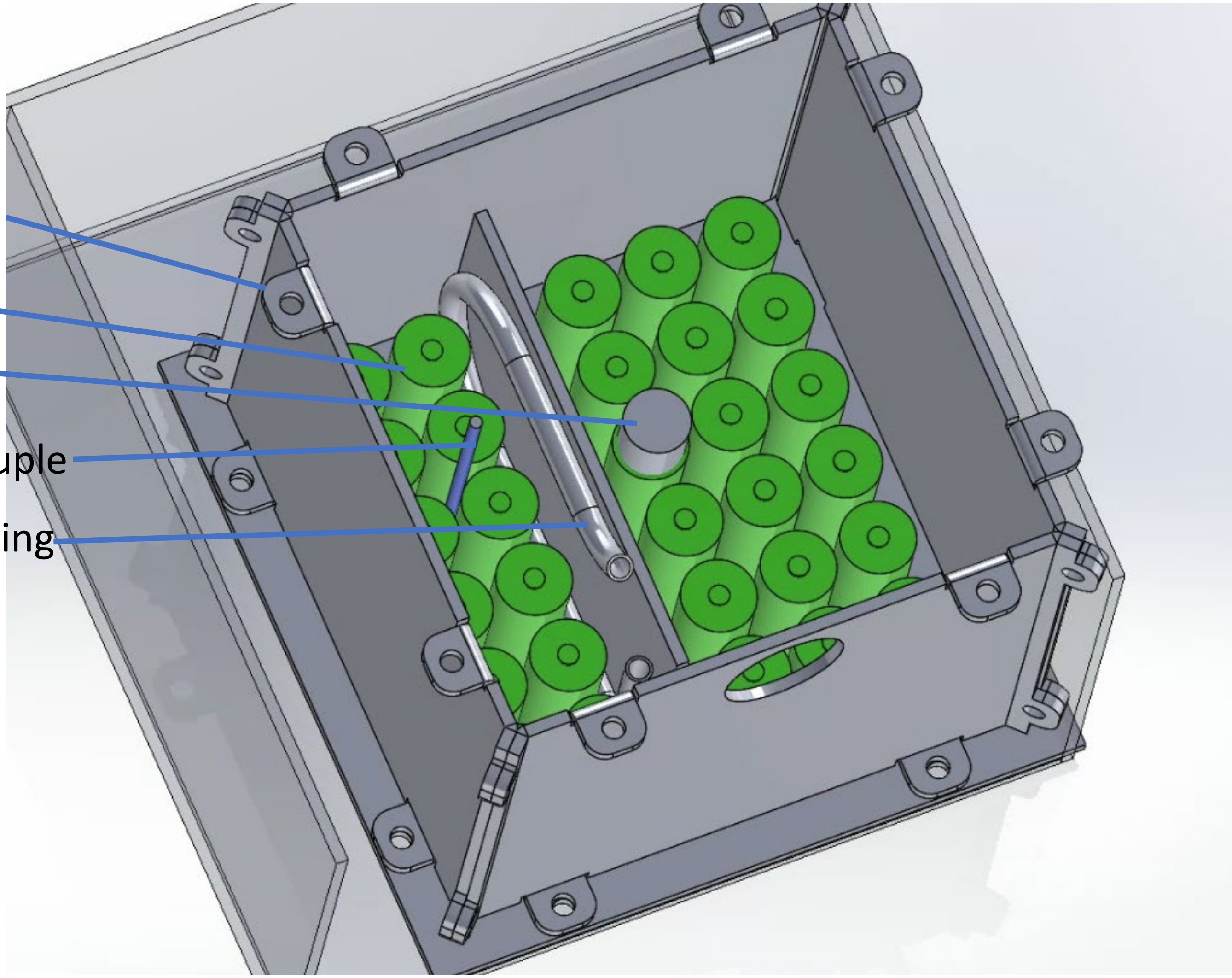
- From oven tests

Rig Design

Rig purpose

- Low power testing- COMSOL validation
- Rig for final full physical test

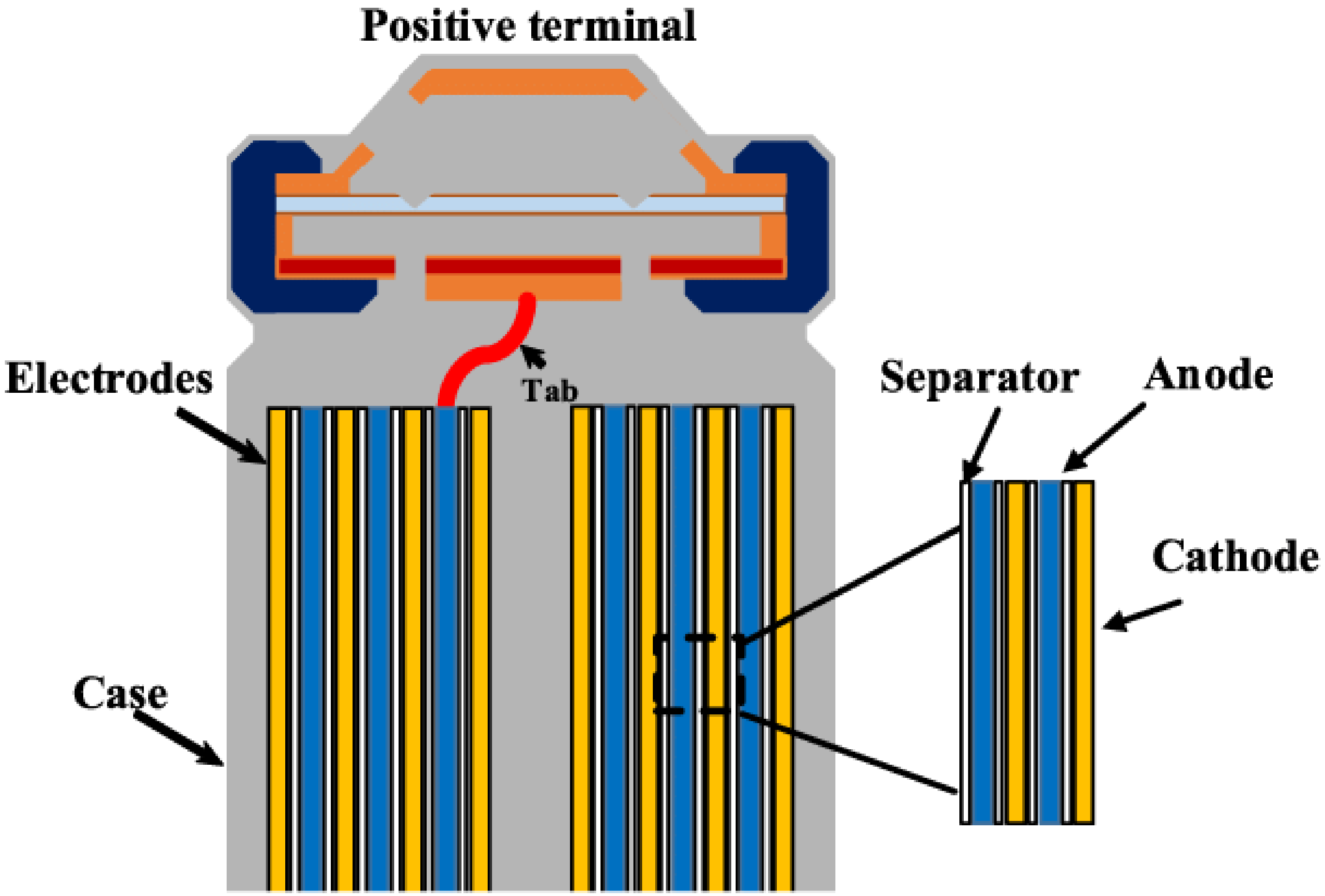
- Containing mock cells
- Liquid cooling
- Stainless steel enclosure
- Instrumented with thermocouples



Mock cell

- What to consider for this mock cell
- Components
  - Can
  - Jellyroll
  - Mandrel

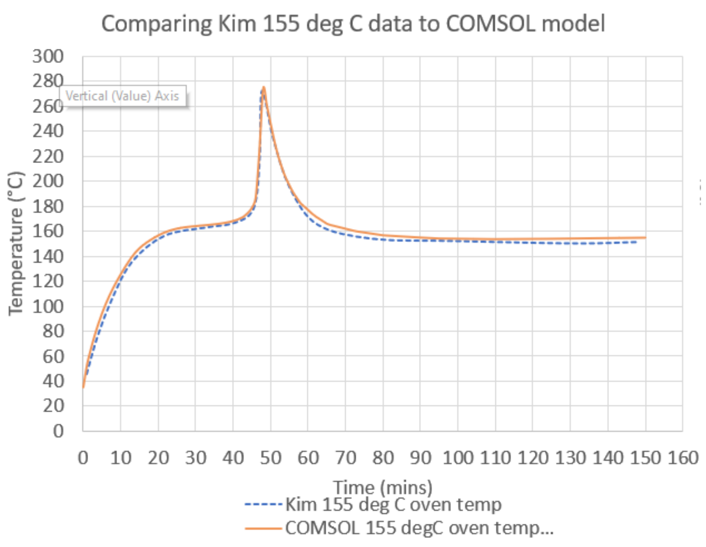
- Properties
  - Anisotropic thermal conductivity
  - Heat capacity
  - Dimensions
  - Cell density

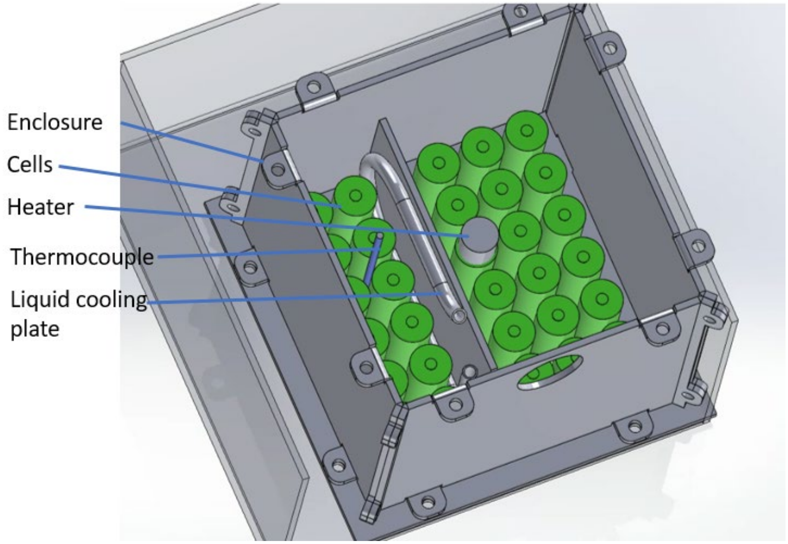


Summary

- 3D COMOSL model with chemical kinetics validated
- Full scale COMSOL model under development
  - Conduction
  - Radiation
  - Liquid cooling
  - Chemical kinetics

- Rig to validate full scale model mid development
- Cell analogue mid development.





Future work

Present

Develop cell analogue

Produce rig

Validate COMSOL Simulation

- Run a range of low power tests

Variables

- Multiple trigger profiles
- Flow rates
- Interstitial materials

Conduct novel simulations

- Sensitivity analysis
- Weight optimisation
- Volume optimisation
- Environmental affects

Final physical test/validation (time permitting)

November year 3

Acknowledgements

Supervisors:

- Dr. Glover
- Dr. Istrate
- Prof. Nockemann

Funding:

- Department for the Economy (DfE DTP)

Department for the Economy

Runaway reactions

$$q_{sei} = H_{sei} W_c R_{sei}$$

$$R_{sei}(T, C_{sei}) = A_{sei} \exp\left(\frac{-E_{a,sei}}{RT}\right) C_{sei}^{M_{sei}}$$

$$q_{ne} = H_{ne} W_c R_{ne}$$

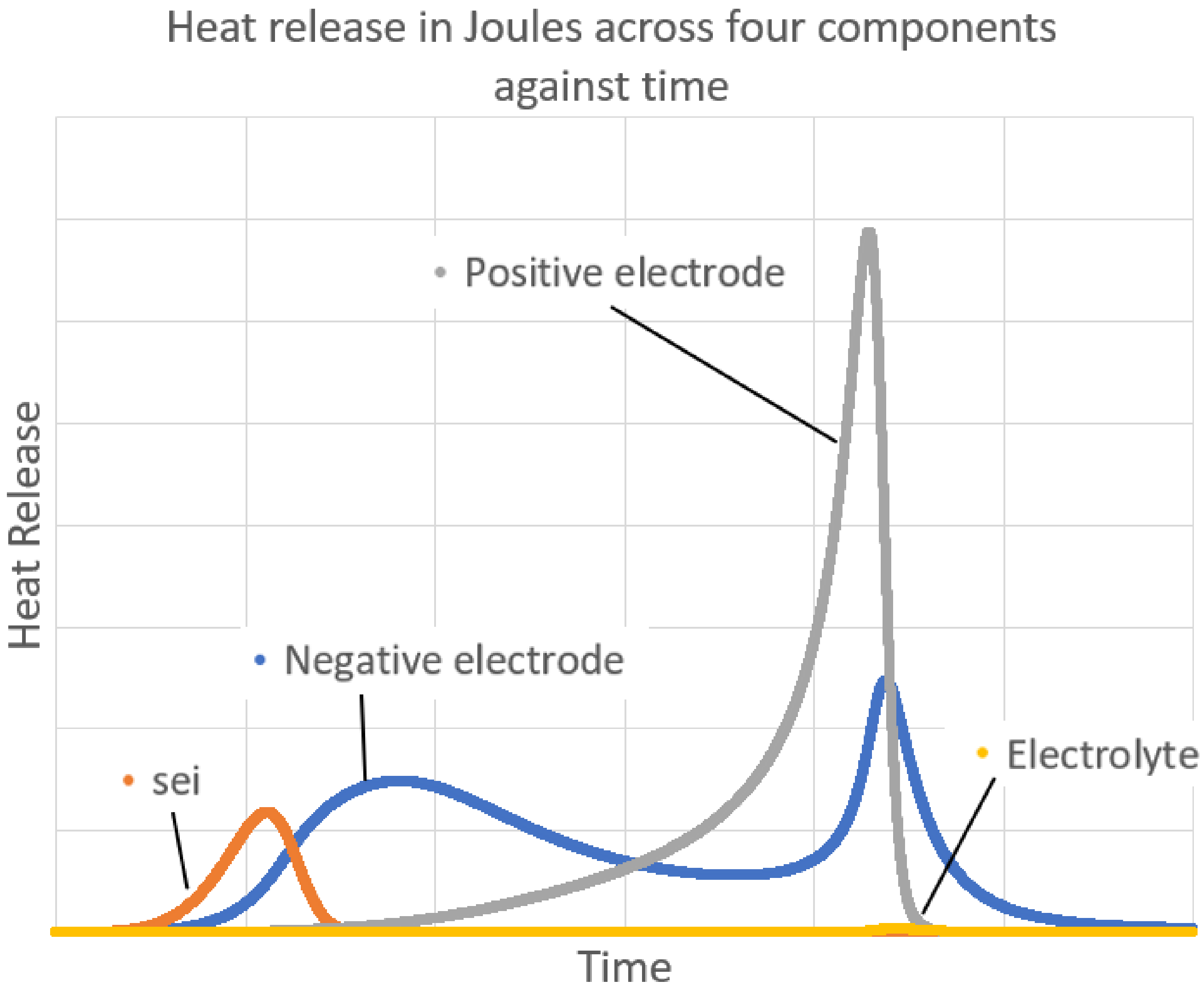
$$R_{ne}(T, C_{ne}, t_{sei}) = A_{ne} C_{ne}^{m_{ne}} \exp\left(\frac{-E_{a,ne}}{RT} - \frac{t_{sei}}{t_{sei0}}\right)$$

$$q_{pe} = H_{pe} W_p R_{pe}$$

$$R_{pe}(T, \alpha) = A_{pe} \alpha^{m_{pe}} (1 - \alpha)^{m_{pe}} \exp\left(\frac{-E_{a,pe}}{RT}\right)$$

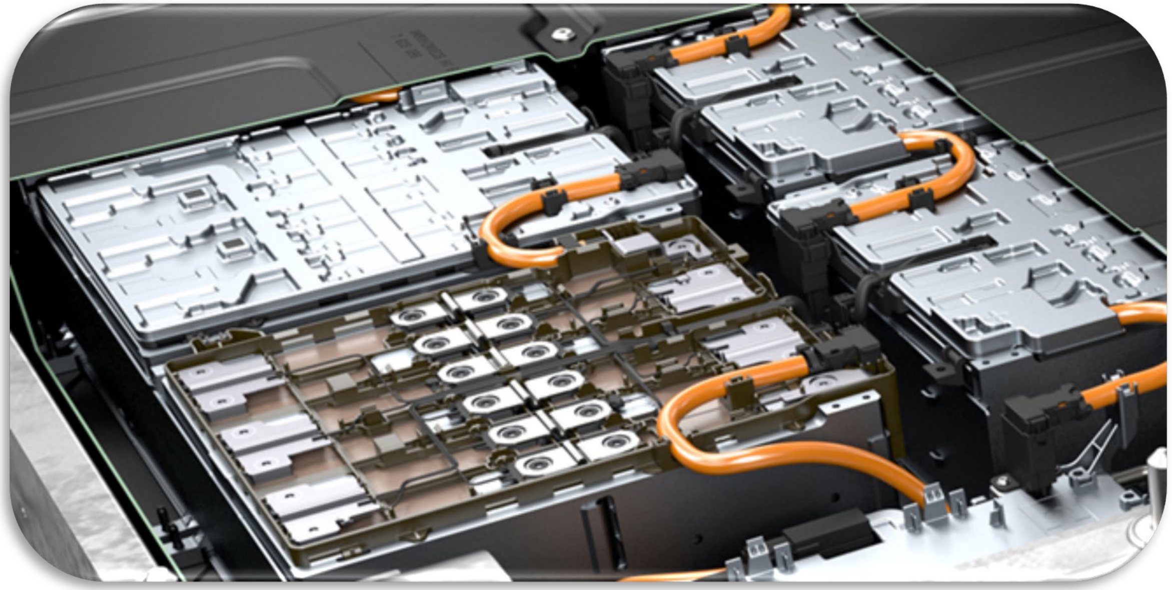
$$q_e = H_e W_e R_e$$

$$R_e(T, C_e) = A_e \exp\left(\frac{-E_{a,e}}{RT}\right) C_e^{m_e}$$



Li, Yuanmao, Liu, Guixiong, Li, Zuyu. Numerical modeling of thermal runaway in high-energy lithium-ion battery packs induced by multipoint heating. Case Studies in Thermal Engineering. 2022, vol. 38

Industry Trends



Consumers

- Tightly packed with increasing energy density
- Cell to pack and cell to car technology
- Liquid or air cooling employed

Policy

- Price parity of electrified vehicles are on the horizon

Tesla battery day event https://www.tesla.com
Volkswagen "Battery Day" Focuses On Scale https://insideevs.com/
Power Day https://www.volkswagen-newsroom.com/

Consumer demand

Energy density

Cell cost

Price parity

Consumer priorities for EV adoption, 2018 and 2020

Greater concerns are shown in orange.

2020 Global Auto Consumer Study												
	FRANCE		GERMANY		ITALY		UK		CHINA		US	
In your opinion, what is the greatest concern regarding all battery-powered electric vehicles?	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020	2018	2020
Driving range	31%	28%	35%	33%	4%	27%	26%	22%	25%	22%	24%	25%
Cost/price premium	32%	22%	22%	15%	19%	13%	24%	16%	9%	12%	26%	18%
Time required to charge	11%	15%	11%	14%	18%	16%	13%	16%	12%	15%	10%	14%
Lack of electric vehicle charging infrastructure	16%	22%	20%	25%	44%	32%	22%	33%	18%	20%	22%	29%
Safety concerns with battery technology	4%	11%	5%	10%	7%	10%	6%	12%	22%	31%	8%	13%
Others	6%	2%	7%	3%	8%	2%	9%	1%	14%	0%	10%	1%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Sample size	1,083	1,266	1,287	3,002	1,048	1,274	965	1,264	1,606	3,019	1,513	3,006

Source: Deloitte Global Auto Consumer Study[18]

Deloitte Insights | deloitte.com/insights

Electric vehicles Setting a course for 2030.

Past Data

Tesla Vehicle Safety Report

- 2012-2021 approximately one Tesla fire for every 210 million miles travelled
- 2012-2018 approximately one Tesla fire for every 170 million miles travelled
- NFPA shows in the US there is a vehicle fire for every 19 million miles travelled

Vehicle fires attended by the London Fire Brigade		
	Electric	Internal combustion
Fires in London 2019	54	1,898
Vehicles in London	27,000	2.56 million
Incident rate	0.194%	0.075%

Low incident rates and small data sets!
Difficult to draw reliable statistically significant conclusions from this data.

Fleming E. What percentage of cars in London are electric? . 2021. Available from: https://www.sidmartinbio.org/what-percentage-of-cars-in-london-are-electric/
Fires in Electric vehicles Bedfordshire Fire and Resuce Service. Available from: https://www.bedsfire.gov.uk/Community-safety/Road-safety/Fire-in-Electric-Vehicles.aspx
Tesla Vehicle Safety Report. 2020. Available from: https://www.tesla.com/en_GB/VehicleSafetyReport

Commercial and Research

Commercial

Nissan leaf
BMS -Air cooled battery pack

Commercial

Tesla model 3
BMS -Indirect liquid cooling with intumescent foam

Commercial

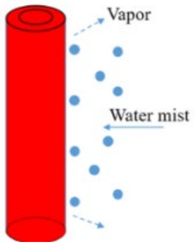
BMW
BMS -AC cooling system (refrigerant)

Research
Phase change materials

- Paraffin wax
- Rubitherm (RT15)

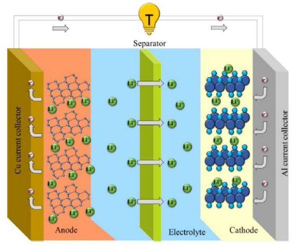
Research
Dedicated suppressants

- Water mist
- Dry powders
- CO_2



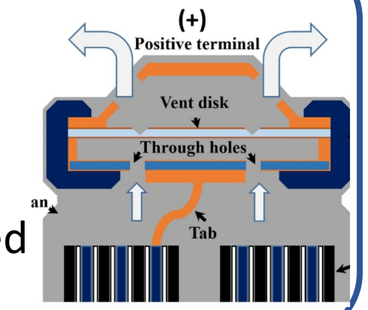
Research
Cell material modification

- Electrolyte
- Separator
- electrodes



Research
Early detection

- Vent gases
- Cell swelling
- Temperature based detection



- https://www.patentsencyclopedia.com/app/20100086844
- LaMonica M. MIT Technology Review . 2012. Available from: https://www.technologyreview.com
- Koch S, Birke KP, Kuhn R. Fast thermal runaway detection for lithium-ion cells in large scale traction batteries. Batteries. 2018;4(2):1–11.
- Kshetrimayum KS, Yoon YG, Gye HR, Lee CJ. Preventing heat propagation and thermal runaway in electric vehicle battery modules using integrated PCM and micro-channel plate cooling system. Appl Therm Eng . 2019;159(May):113797. Available from: https://doi.org/10.1016/j.applthermaleng.2019.113797
- Liu Y, Duan Q, Xu J, Li H, Sun J, Wang Q. Experimental study on a novel safety strategy of lithium-ion battery integrating fire suppression and rapid cooling. J Energy Storage . 2020;28(December 2019):101185. Available from: https://doi.org/10.1016/j.est.2019.101185

Future work/ areas for investigation

Areas for investigation

- Novel parameters
  - <u>Model based design</u>
    - Accumulator pack layout
    - Module walls
    - Multiple PCMs
    - 26650, 18650 (cell trends)
    - Environmental effects
    - Non uniform PCM
    - Directional calorimetry
    - Staggered cells vs in line
    - Thermal management
- Physical testing
- Correlation of model results to physical testing
- Characterisation of PCMs at QUB (flammability)
- Define required parameters of an ideal PCM (spider plot)

Present

Model development

Design of Experiments

Validation

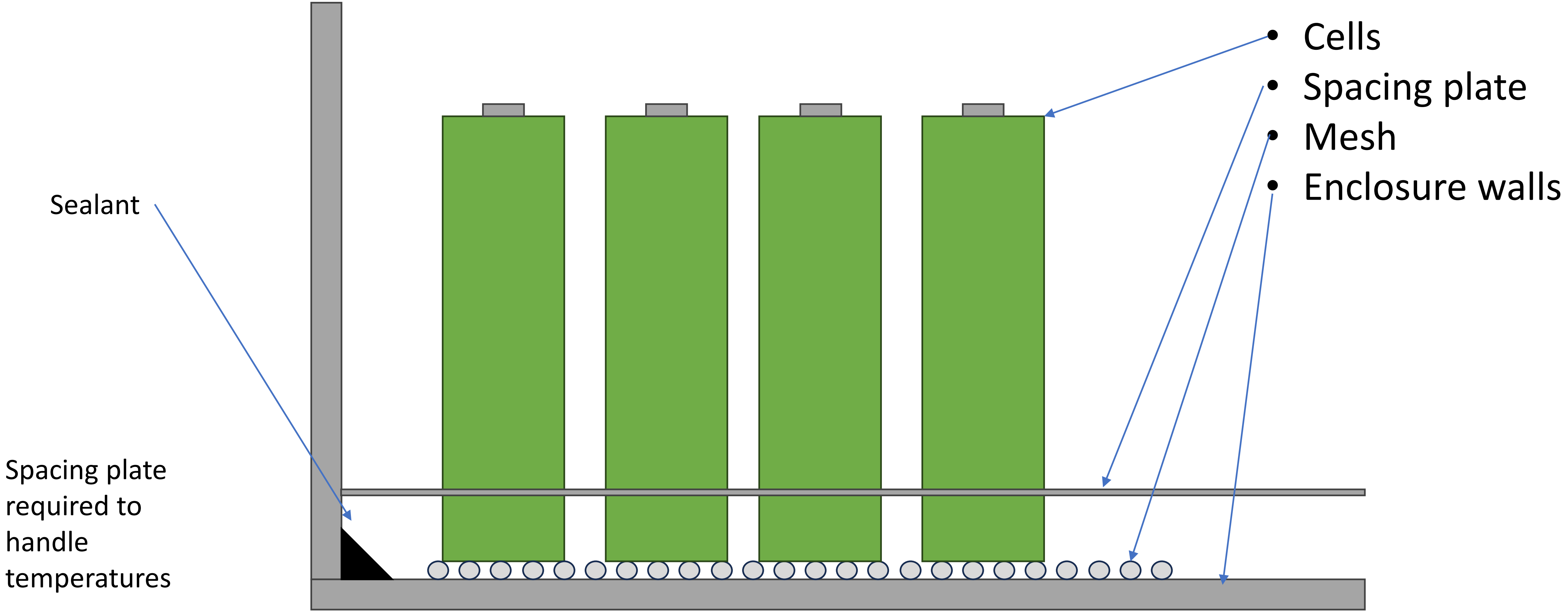
Software driven viable parametric change

Final physical test/validation (time permitting)

October year 3

33

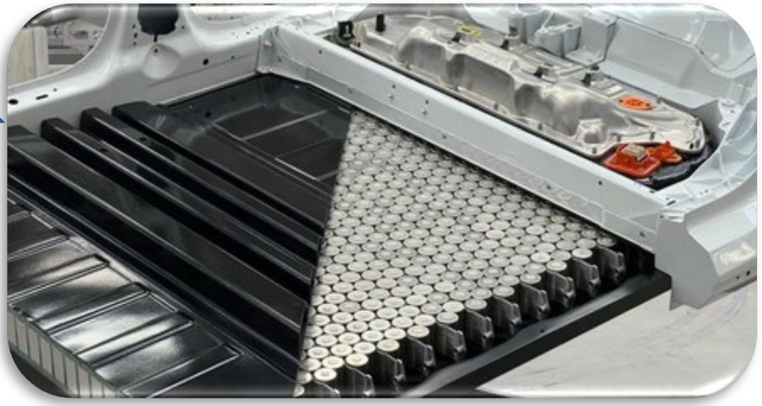
Enclosure design



Introduction

Industry Trends

- Energy density
- Cell cost
- Price parity



Past Data

Tesla Vehicle Safety Report

- 2012-2021 approximately one Tesla fire for every 210 million miles travelled
- 2012-2018 approximately one Tesla fire for every 170 million miles travelled
- NFPA shows in the US there is a vehicle fire for every 19 million miles travelled

- Inconsistent picture of the frequency of EV fires/runaway events
- Small data sets

Consumers

- Range demand
- Safety concerns

Consumer priorities for EV adoption, 2018 and 2020

Greater concerns are shown in orange.

2020 Global Auto Consumer Study

In your opinion, what is the greatest concern regarding all battery-powered electric vehicles?	FRANCE 2018	FRANCE 2020	GERMANY 2018	GERMANY 2020	ITALY 2018	ITALY 2020	UK 2018	UK 2020	CHINA 2018	CHINA 2020	US 2018	US 2020
Driving range	31%	28%	35%	33%	4%	27%	26%	22%	25%	22%	24%	25%
Cost/price premium	32%	22%	22%	15%	19%	13%	24%	16%	9%	12%	26%	18%
Time required to charge	11%	15%	11%	14%	18%	16%	13%	16%	12%	15%	10%	14%
Lack of electric vehicle charging infrastructure	16%	22%	20%	25%	44%	32%	22%	33%	18%	20%	22%	29%
Safety concerns with battery technology	4%	11%	5%	10%	7%	10%	6%	12%	22%	31%	8%	13%
Others	6%	2%	7%	3%	8%	2%	9%	1%	14%	0%	10%	1%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Sample size	1,083	1,266	1,287	3,002	1,048	1,274	965	1,264	1,606	3,019	1,513	3,006

Source: Deloitte Global Auto Consumer Study[18]

Deloitte Insights | deloitte.com/insigl

Research

Commercial

Nissan leaf
BMS -Air cooled battery pack

Commercial

Tesla model 3
BMS -Indirect liquid cooling with intumescent foam

Commercial

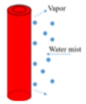
BMW
BMS -AC cooling system (refrigerant)

Research
Phase change materials

- Paraffin wax
- Rubitherm (RT15)

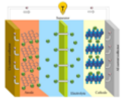
Research
Dedicated suppressants

- Water mist
- Dry powders
- CO_2



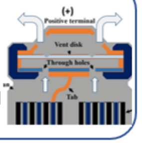
Research
Cell material modification

- Electrolyte
- Separator
- electrodes



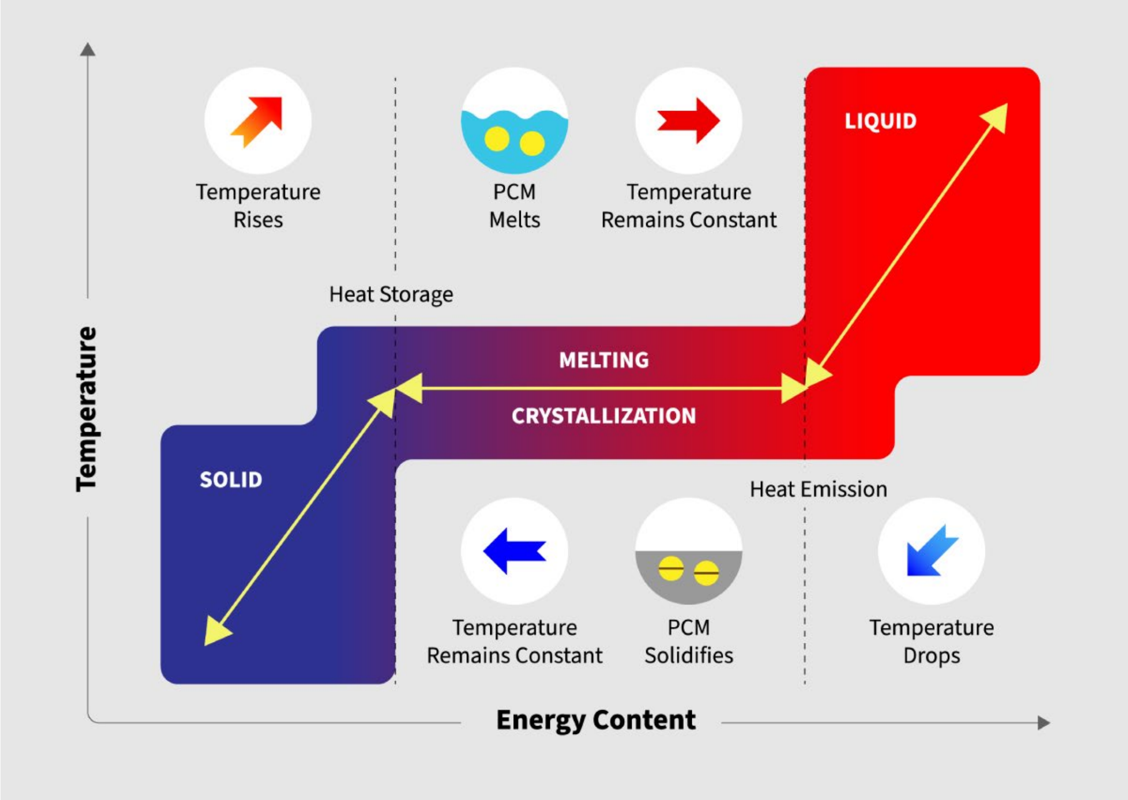
Research
Early detection

- Vent gases
- Cell swelling
- Temperature based detection

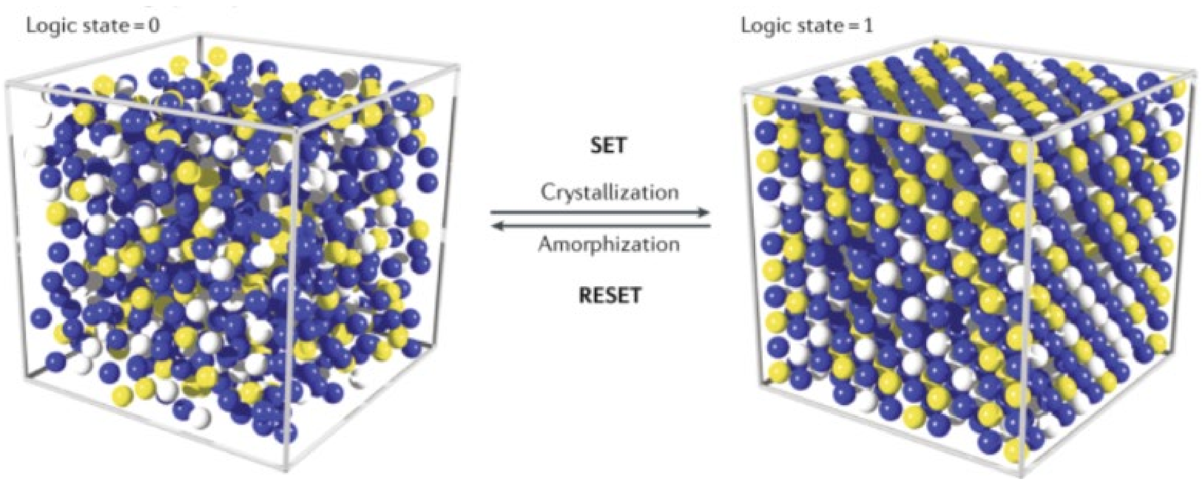


- https://www.patentsencyclopedia.com/app/20100086844
- LaMonica M. MIT Technology Review [Internet]. 2012. Available from: https://www.technologyreview.com
- Koch S, Birke KP, Kuhn R. Fast thermal runaway detection for lithium-ion cells in large scale traction batteries. Batteries. 2018;4(2):1–11.
- Kshetrimayum KS, Yoon YG, Gye HR, Lee CJ. Preventing heat propagation and thermal runaway in electric vehicle battery modules using integrated PCM and micro-channel plate cooling system. Appl Therm Eng [Internet]. 2019;159(May):113797. Available from: https://doi.org/10.1016/j.applthermaleng.2019.113797
- Liu Y, Duan Q, Xu J, Li H, Sun J, Wang Q. Experimental study on a novel safety strategy of lithium-ion battery integrating fire suppression and rapid cooling. J Energy Storage [Internet]. 2020;28(December 2019):101185. Available from: https://doi.org/10.1016/j.est.2019.101185

Phase change materials - PCM



Reproduced from reference



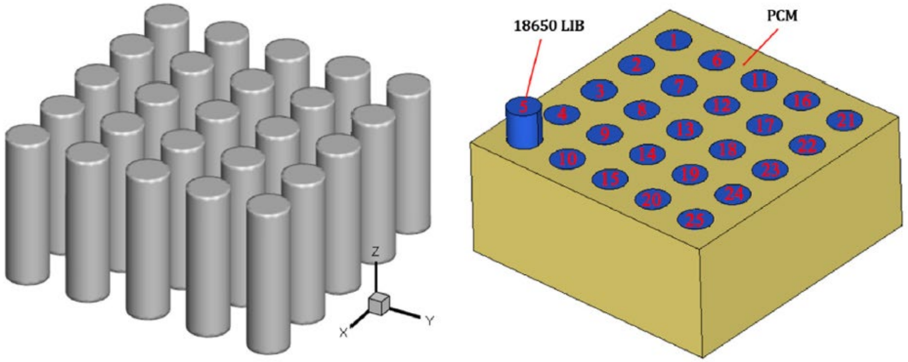
Reproduced from reference

Phase change material https://thermtest.com/phase-change-material-pcm

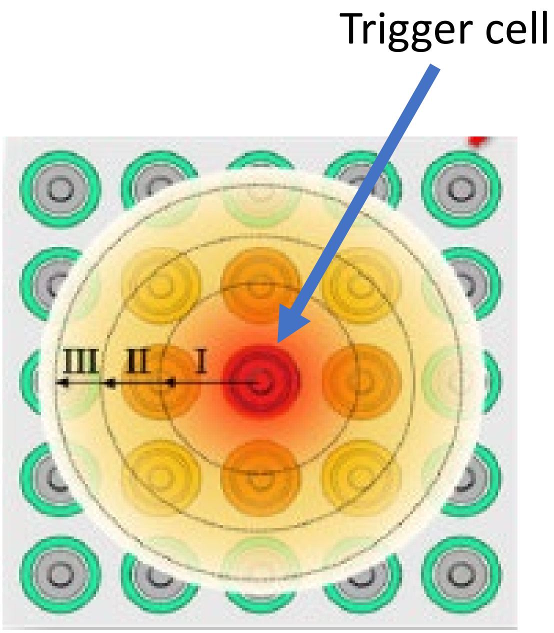
	Cp J/kgK	K radial W/mK	K axial W/mK	Density kg/m3	Cell chemistry	Source
Hatchard 2001	830	0.34		2580	18650 LiCoO2	Thermal model of cylindrical and prismatic Lithium-Ion cells
Abada 2018	1100	0.7	140	2231	18650 LFP	Combined experimental and modelling approaches of the thermal runaway of fresh and aged lithium-ion batteries
Jia				2580	18650 LCO	Thermal runaway propagation behaviour within 18650 lithium-ion battery packs: A modelling study
Coleman2016	1200	0.633	48	2222		Reducing cell-to-cell spacing for large format lithium ion battery modules with aluminium or PCM heat sinks under failure conditions
Zhang	1143	5	1	2800	18650 Samsung 33G	Non-uniform phase change material strategy for directional mitigation of battery thermal runaway propagation
~~Yuan~~	~~1143~~	~~5~~	~~1~~	~~2800~~	~~18650 Samsung 33G~~	~~Inhibition effect of different interstitial materials on thermal runaway propagation in the cylindrical lithium-ion battery module~~
N.Spinner (Analytical)	972+-92	0.55+-0.23	21.9+-1.7		LiCoO2	Analytical, Numerical and Experimental Determination of Thermophysical Properties of Commercial 18650 LiCoO2 Lithium-Ion Battery
~~Nieto 2014~~	~~1076~~	~~1.36~~	~~29.4~~	~~2382~~	~~NMC Pouch~~	~~Novel thermal management system design methodology for power lithium-ion battery~~
S.J Drake 2013	1720+-86	0.2+-0.01	30.4+-1.5	2362	18650 LFP	Measurement of anisotropic thermophysical properties of cylindrical Li-ion cells
Gumussu 2017	814-2400	0.219	28.05	2939	Panasonic NCR18650B	3-D CFD modeling and experimental testing of thermal behavior of a Li-Ion battery
Sabbah 2008	900	3	30	2663	18650 high power	Active (air-cooled) vs. passive (phase change material) thermal management of high power lithium-ion packs: Limitation of temperature rise and uniformity of temperature distribution
Jiang 2023		2.4	14.07	3020		Axial and radial thermal conductivity measurement of 18,650 Lithium-ion battery
Average	1123.57 (830-1200)	1.005 (0.2-5)	44.62 (30-140)	2599.7 (2200-2800)		

Experimental

- Strict safety concerns with provoking a module of cells.
- Cartridge heater as a cell analogue that can be controlled.
- Using thermal profiles from literature.
- Thermocouples to record temperature profiles.

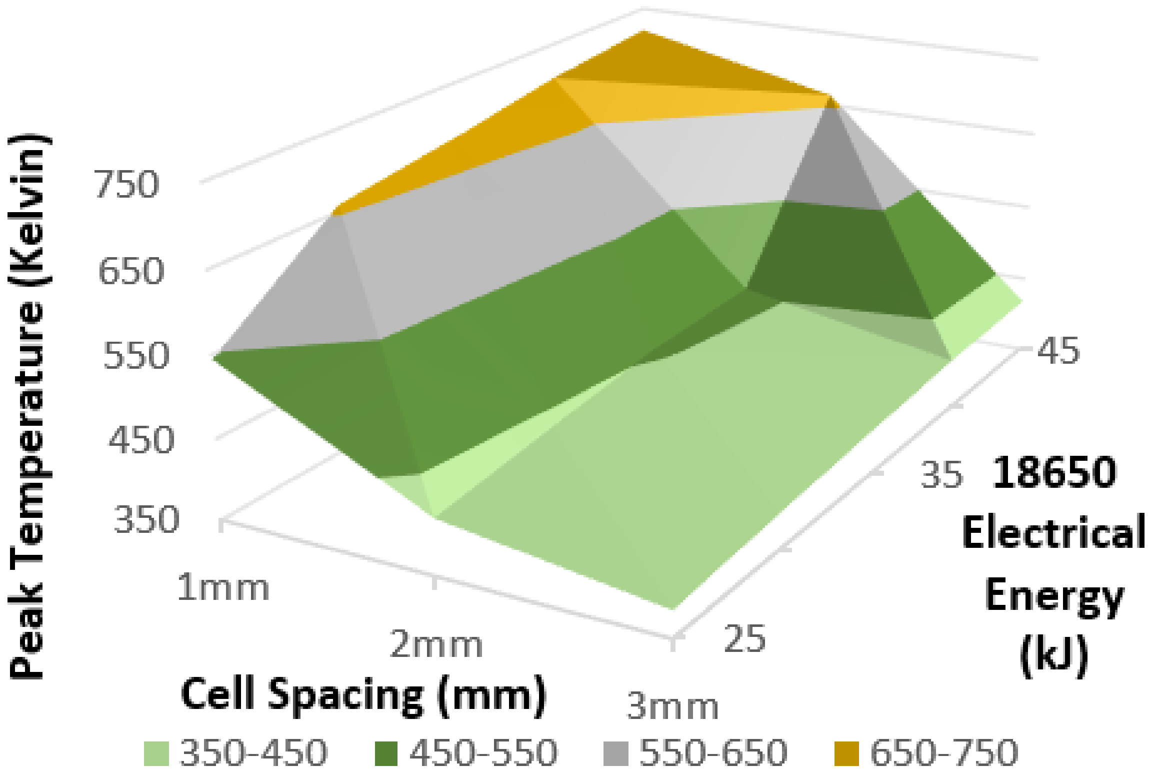


(a) (b)

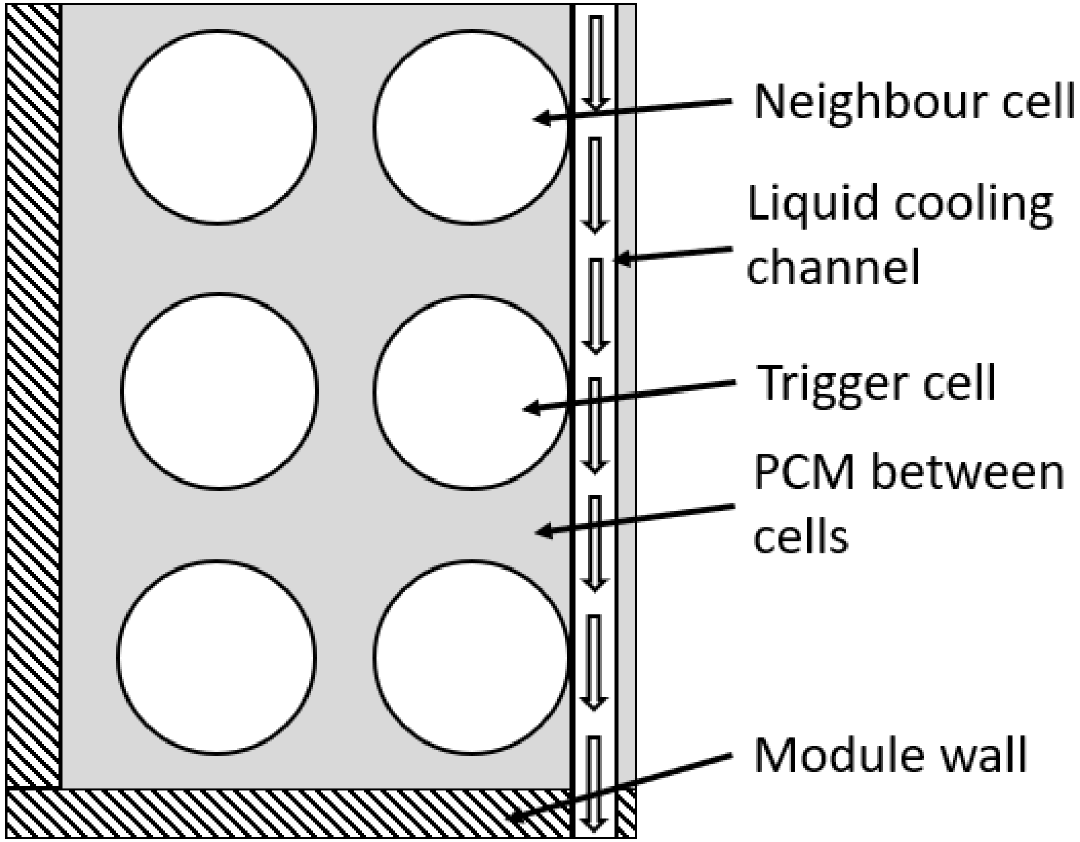


Wang Z, Li X, Zhang G, Lv Y, Wang C, He F, et al. Thermal management investigation for lithium-ion battery module with different phase change materials. RSC Adv. 2017;7(68):42909–18.

Combined model outputs – Cell spacing

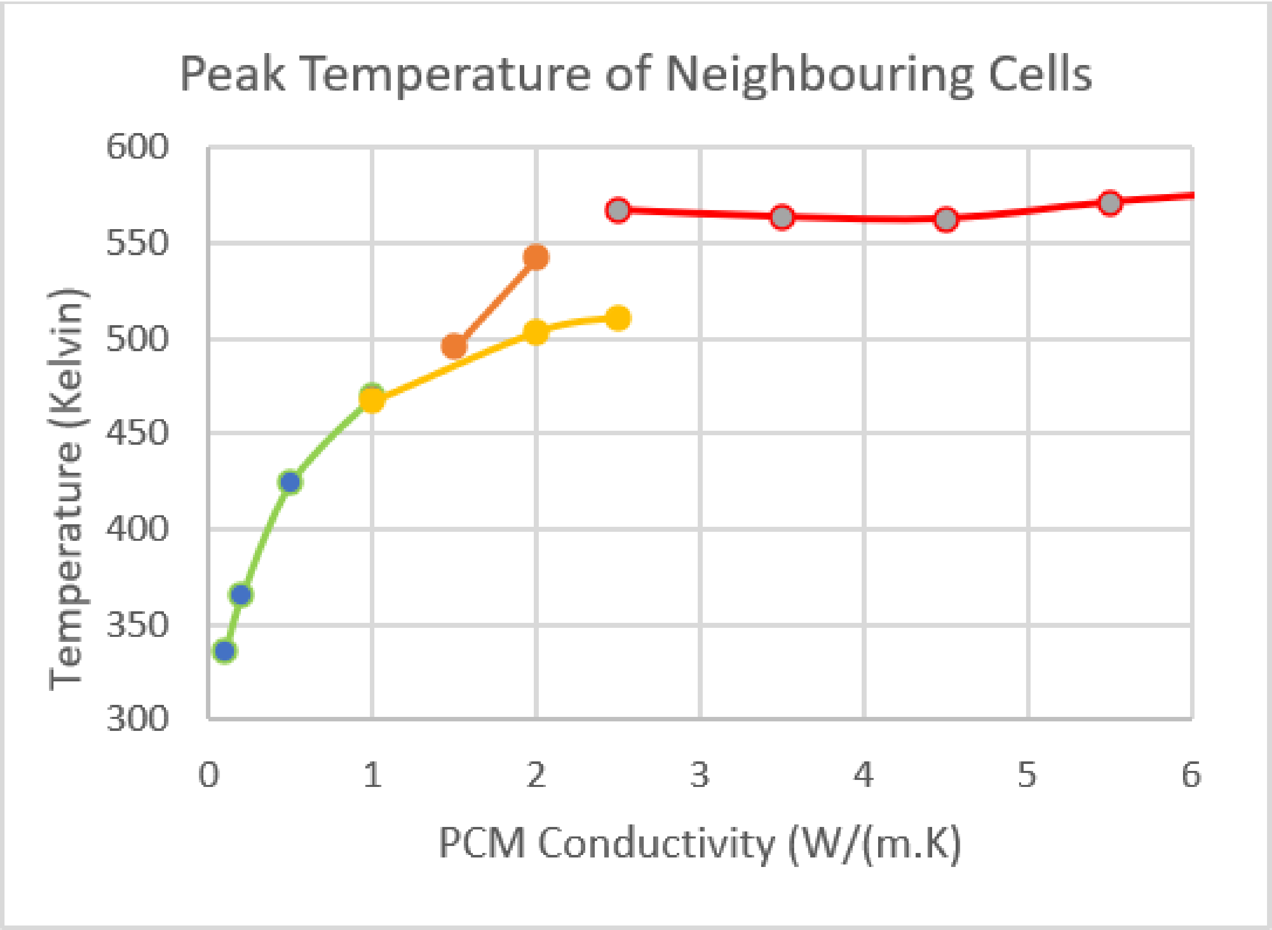


PCM paraffin (RT42)
K=0.2W/mK
Flash point 459K

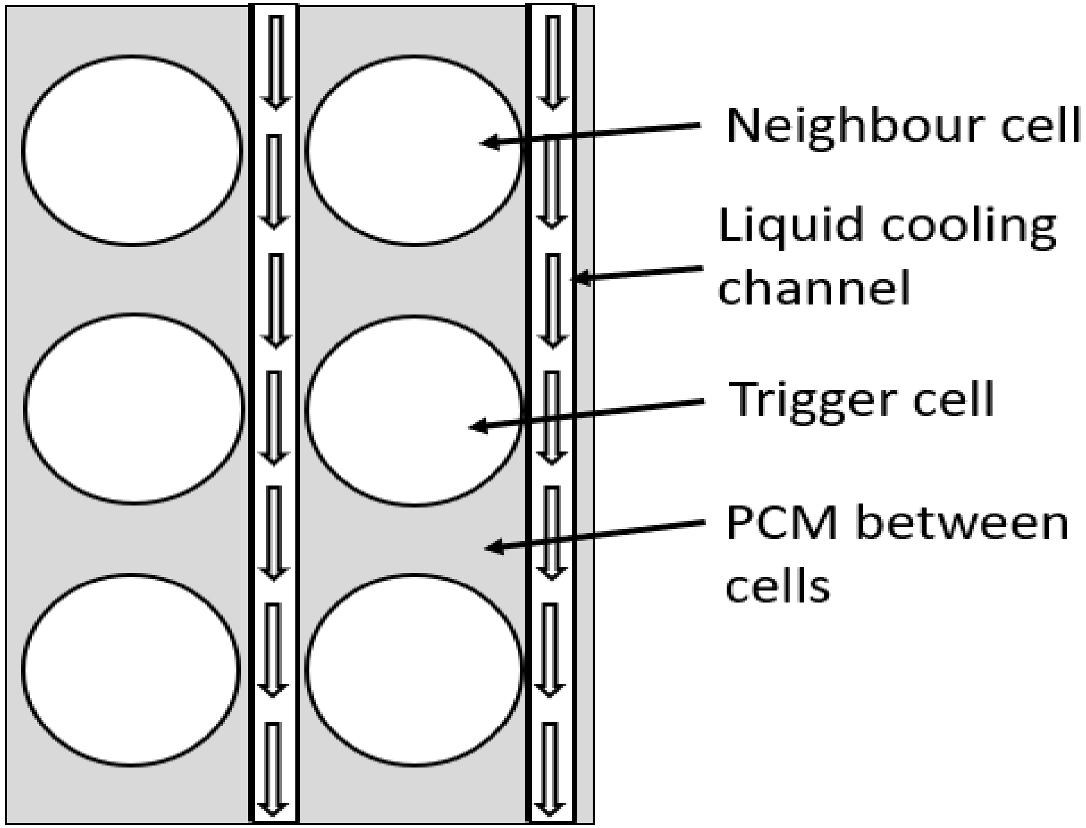


Module/pack periphery layout

Thermal conductivity impact



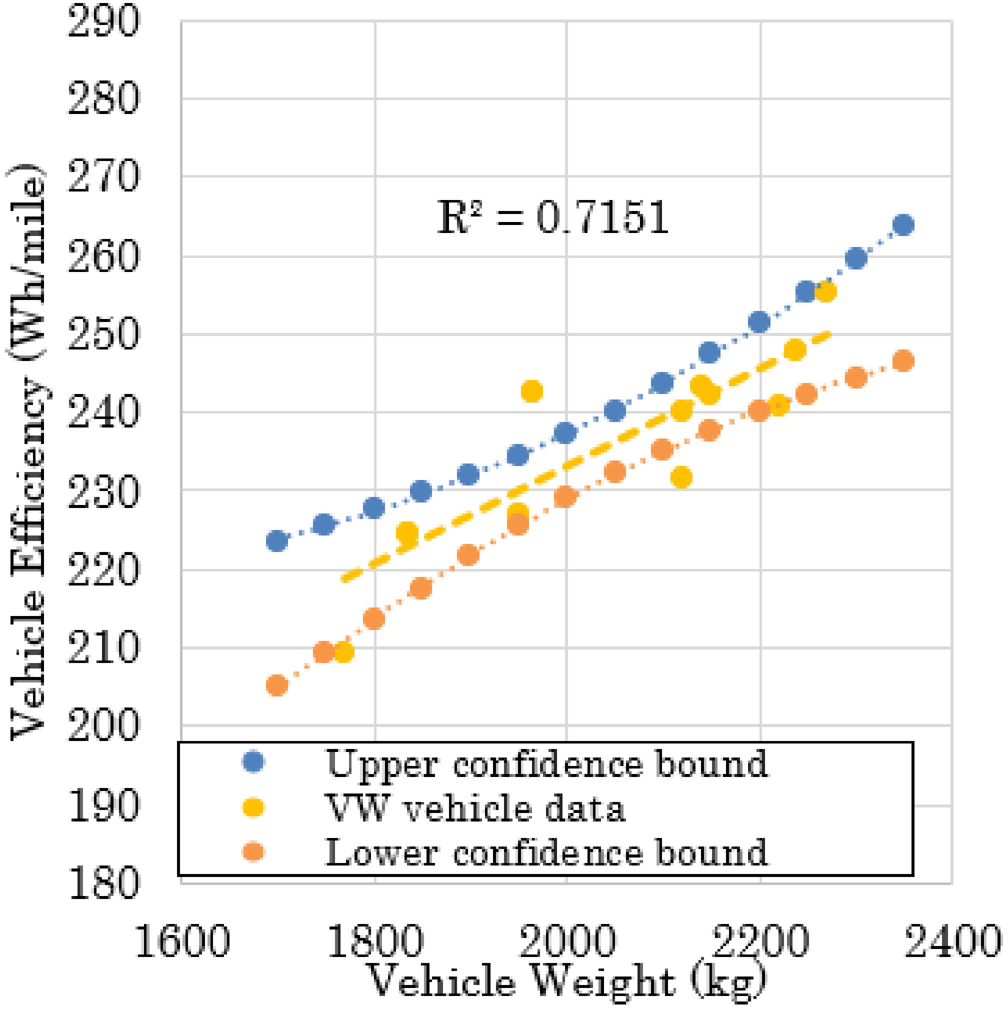
No propagation expected
Propagation expected
Transition region
No kinetics heating



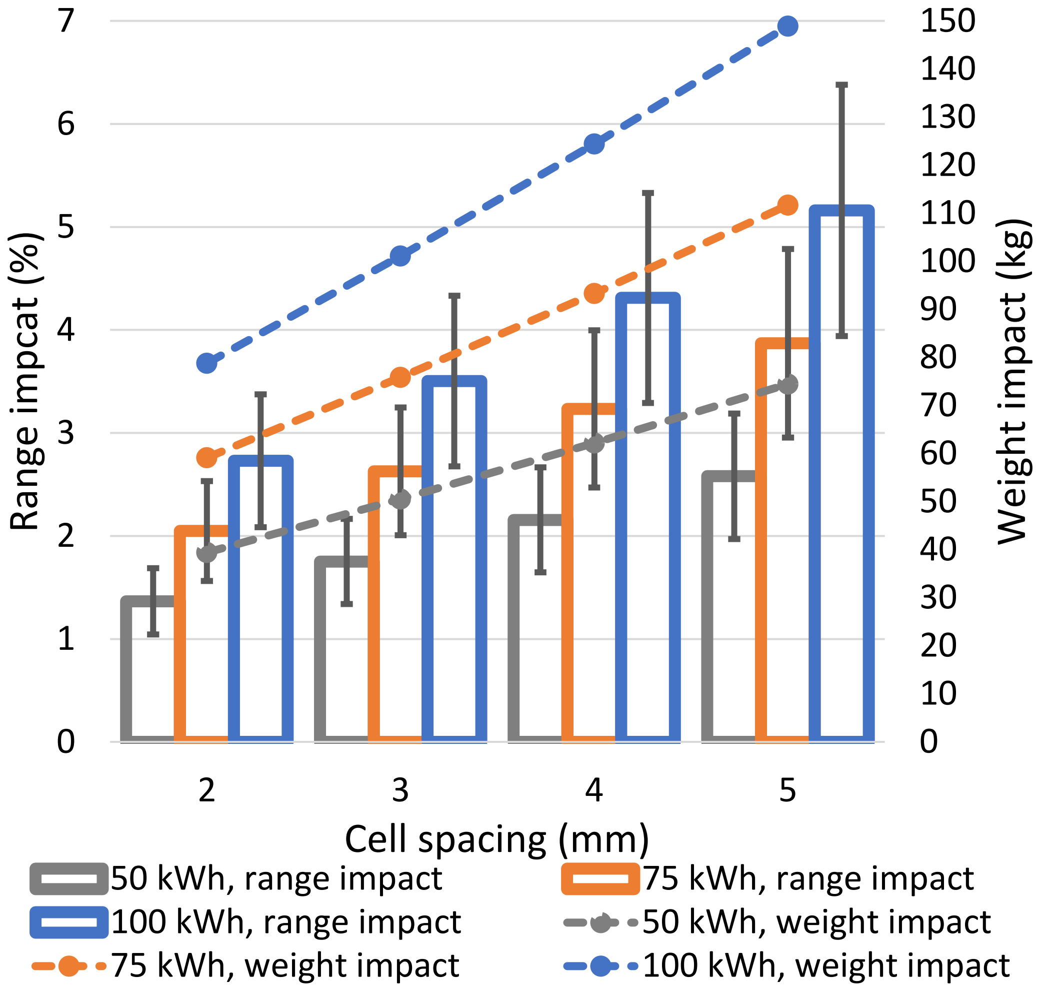
Module/pack interior layout

Weight impact

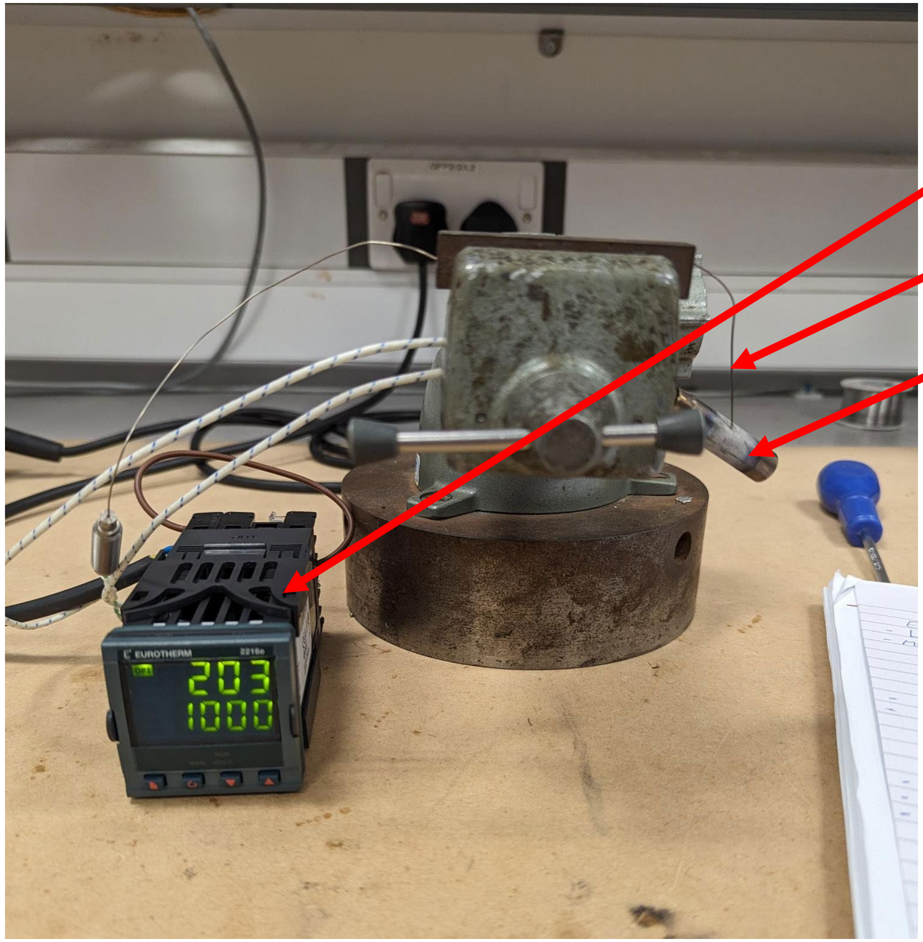
EV efficiency against vehicle weight (MEB platform)



Range and weight impact of cell spacing to accommodate PCM



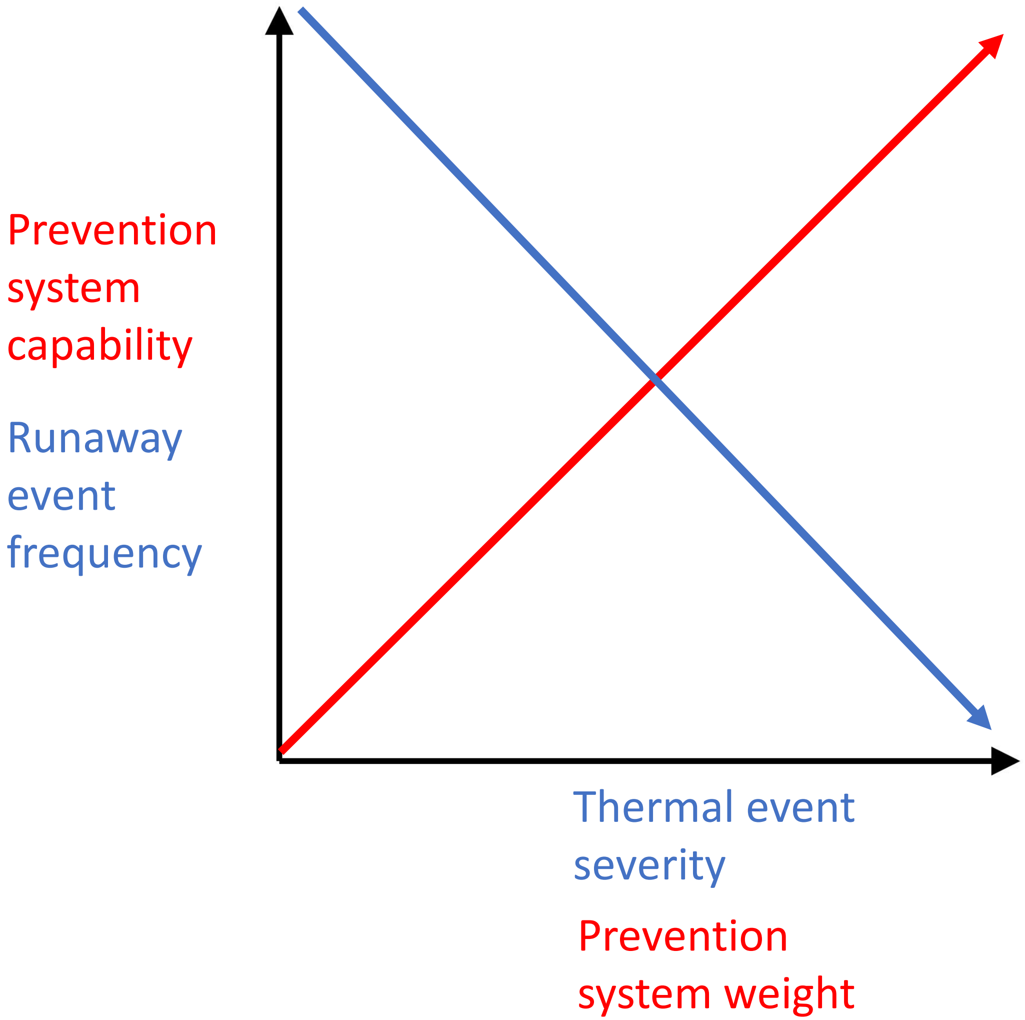
Heating loop



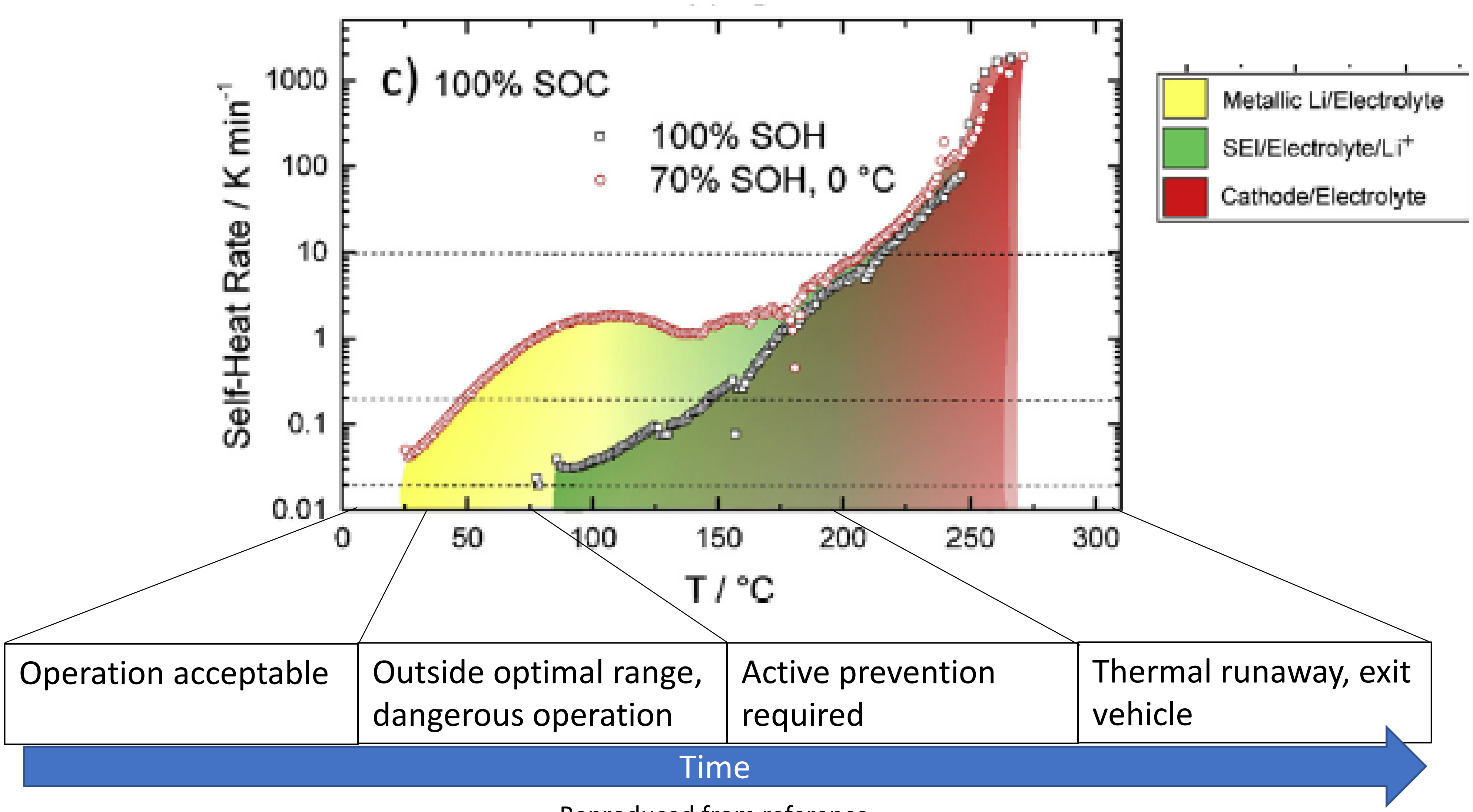
- PID controller
- Thermocouple
- Heater

- PID good for 1000 degrees
- 200W test heater in this case

Project objectives



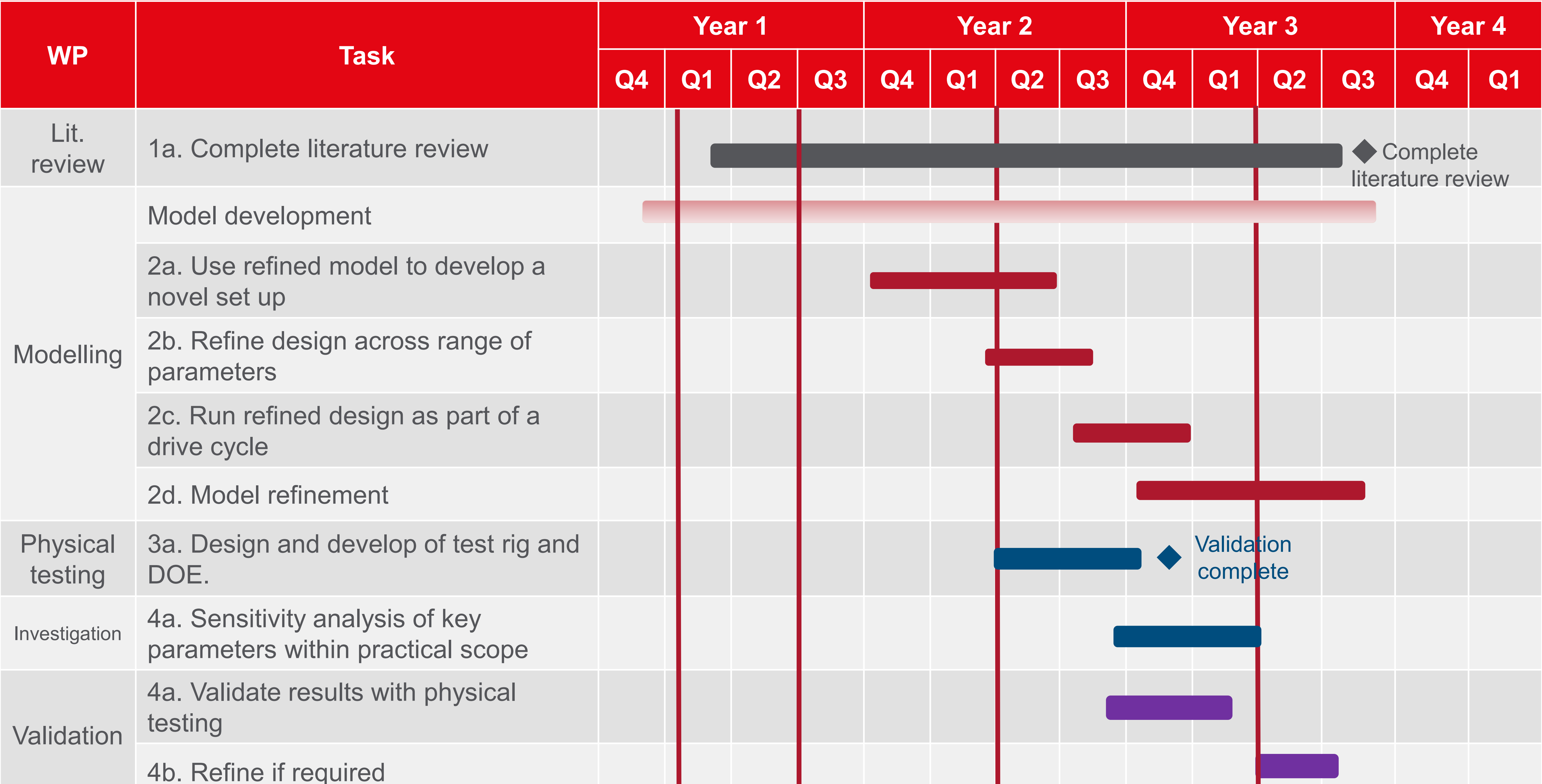
Time Sensitivity



Reproduced from reference

Impact of cycling at low temperatures on the safety behaviour of 18650-type lithium ion cells: Combined study of mechanical and thermal abuse testing accompanied by post-mortem analysis

Project Plan



Project Plan

QUEEN'S UNIVERSITY BELFAST

WP	Task
Lit. review	1a. Complete literature review
Modelling	Model development
	2a. Convert refined model to novel set up
	2b. Refine design across range of parameters
	2c. Run refined design as part of a drive cycle
	2d. Model refinement
Physical testing	3a. Design and develop of test rig and DOE.
Validation	4a. Validate results with physical testing
	4b. Refine if required
Thesis	5a. Write thesis