Fires On Zero Emission Buses (ZEB's)

Presented by Robert Dunster, July 27th 2024

KlineFire

Contents

- Do Fires Occur on Zero Emission Buses?
- Are they more or less frequent than for Diesel Vehicles?
- What are the similarities and differences in Fire Threats
- Risks on Zero Emission Vehicles
- Risk Mitigation
- Review of ongoing Research and Solutions

News Articles Following Fires on ZEB's

2021, Stuttgart, Germany - 25 Mercedes eCitaro electric buses, charging hub & depot destroyed when a 'technical fault triggered when bus was charging'. Image: Feuerwehr Stuttgart

Cause: Fire during Charging

Significant Event
25 Vehicles involved
Loss of facility

2023, July: Hydrogen Fuel Cell Bus: Bakersfield CA, USA

Cause: Fire during Refuelling

10 hydrogen vehicles taken out of service pending investigation

2022, Paris, France - Driver saw a 'wheel explode' & evacuated passengers before the e-bus became fully involved. Full footage on Twitter, credit JP News Photographer.

Cause: Energy storage system (ESS)
Events on 2 vehicles in a short time frame

300 Vehicles out of service
Until May 2024 – 2 years

Additional thermal protection
On battery packs

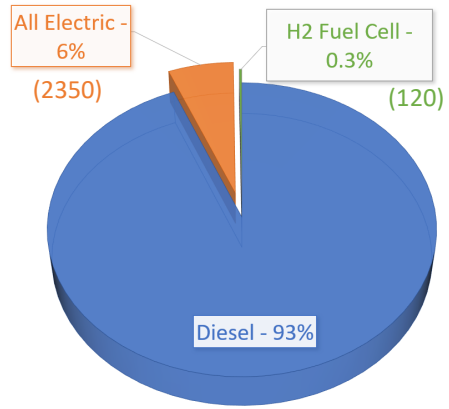
2024, London, UK – All Electric Double Dekker Bus caught fire at bus stop
3rd event to occur in 2 months.

Cause: HVAC system

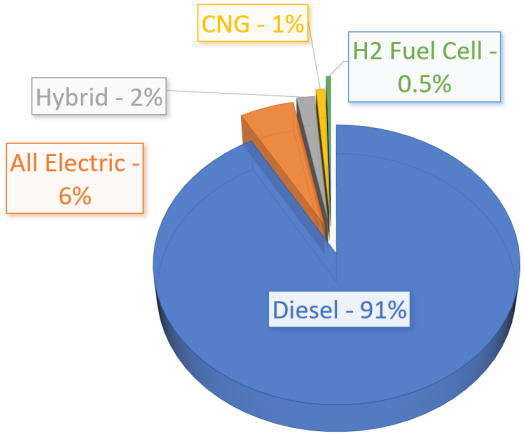
1 hybrid, 2 All Electric Batteries (ESS) not cause

Transport For London
Inspecting 1800
All Electric vehicles

Investigation of Fires on Buses (June 2023-24)

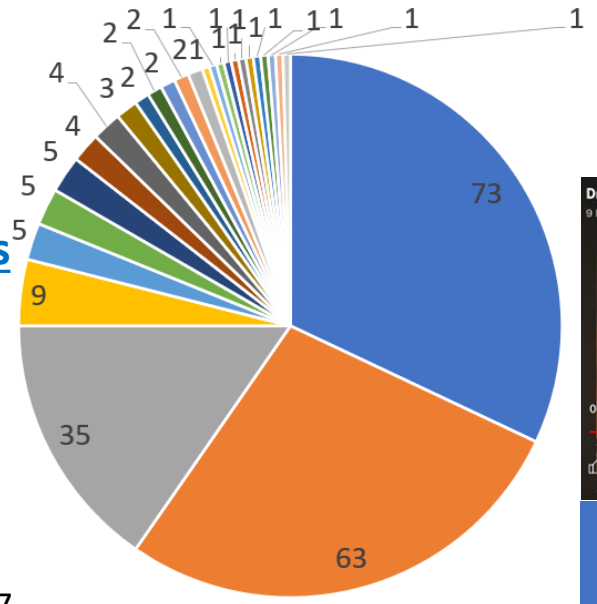


Transit Vehicles in UK - 39100



Total Events - 230 (1 every 40 hours)

Aus – 5 events



Countries - 27

USA	UK	India	Bangladesh	Australia
Canada	New Zealand	Ireland	Kenya	Cypress
Greece	Italy	Malaysia	Pakistan	Tailand
Algeria	Eygpt	Fiji	Ghana	Luxemburg
Philippinnes	Poland	Serbia	Spain	Tenerife
Uzbekistan	Vietnam			

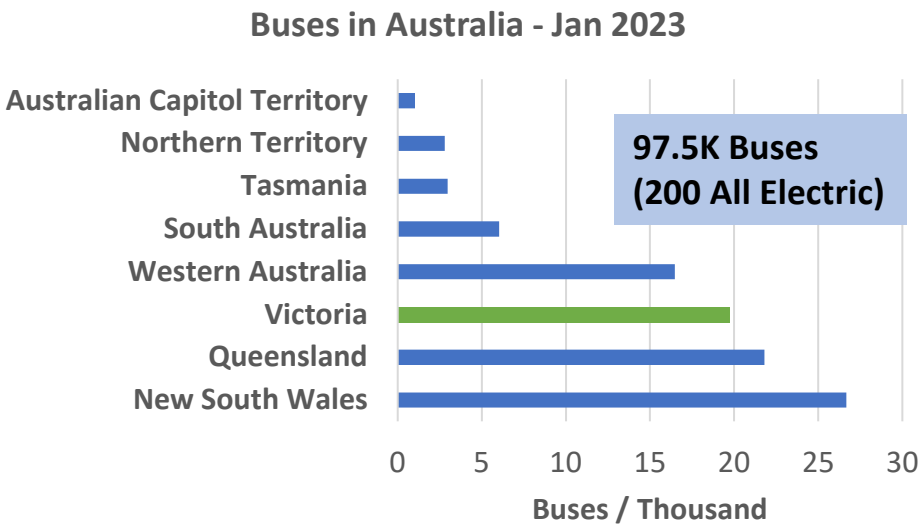
	Deaths	Injuries
Collisions - Fire	135	103
Fire	6	36

10/7/2023 – West Gate Bridge Melbourne, Engine Fire. No Injuries, 100% burned out
Note: No Engine Suppression System fitted

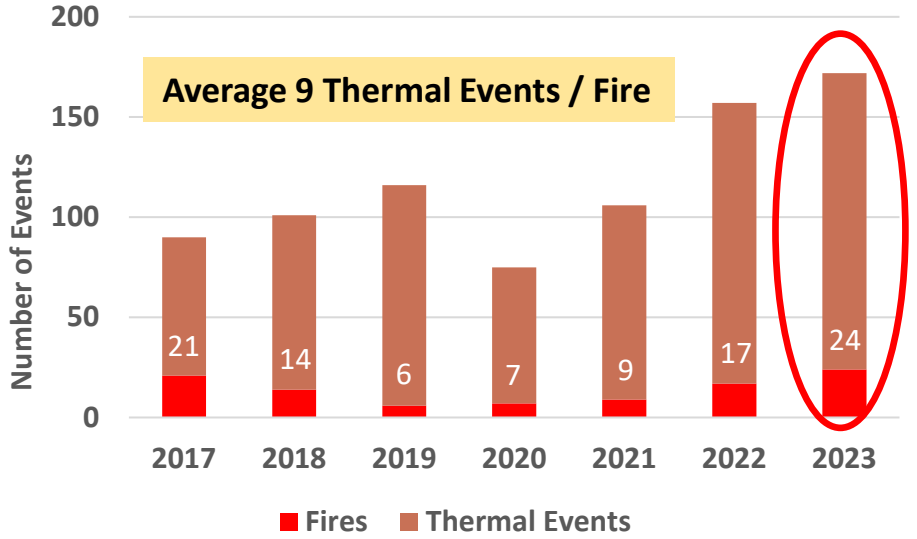
Investigation carried out using Google Alerts on "**Bus Fire English**"

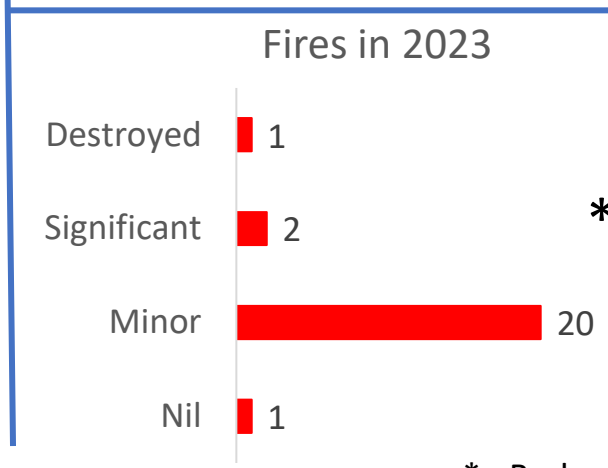
Fires on Buses – Australia

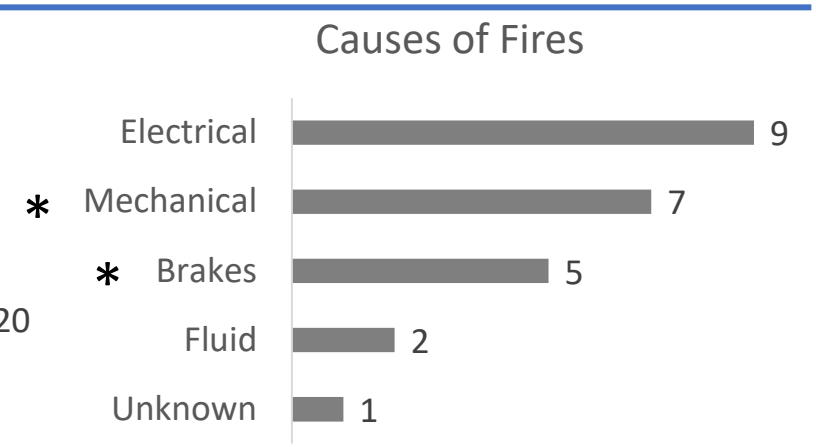
From: Bus Safety Report in NSW 2023: Office of Transport Safety Investigations (OTSI)



NSW – Electrification
2023 – 71 buses
2028 – 1200 buses
2040 – All Metropolitan
2047 – All Regional







* - Brakes (56%), Mechanical (23%) of Thermal Events

Fire suppression and extinguishing equipment and safety monitoring systems were critical in mitigating damage

Analysis of Fire on Buses 2023-24

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174 Vehicles (2 CNG)

Type of Vehicle	Cause Of Fire	Bus Location	Emergency Measures
• Transit Bus – 63% • School Bus – 21% • Coach - 16% • DD / ART. Bus – 13% • Cutaway / Midi – 2%	• Engine – 63% • Tyre - 6% • Arson – 6% • Electrical – 2% • Collision – 4% • Not recorded -19%	• In Service – 96% • Maintenance – 2% • Depot – 2%	 2000 L 2 Fire crews: 30 mins – 1.5 hr

13 Vehicles (1 FCEV)

Type of Vehicle	Cause Of Fire	Bus Location	Emergency Measures
• Transit Bus – 85% • DD / ART. Bus – 15%	• Electrical Fault (not Batt) – 42% • Batteries - 33% • Collision – 25%	• In Service – 62% • Maintenance – 8% • **Depot – 31%**	 30000 L 3-7 Fire crews: 4 hr– 12 hr (Re-Strikes)

Case Study – Event Timeline

Fire on Battery Electric Transit Bus, Hamden, Connecticut, USA

- **July 20th 2022**
  - Vehicle failed to power up after charging
    - Low coolant and temperature indicator on Energy Storage System (ESS)
  - Vehicle taken out of Service for Maintenance
- **July 22nd 2022**
  - 3:39am - Reports of smoke inside depot
  - 3:49 - 4:35am – Fire Brigade Attended
    - Heat detected in rear Li-Ion battery
    - Vehicle pulled outside to parking lot
  - 7:32 am – 8:30pm – Fire Brigade Attended 2nd Time
    - Vehicle fire fully involved
    - No further danger to personnel or structure – vehicle left to burn
    - Hamden Fire Crew (HFC) attempted to cool rear batteries for several hours – HFC cleared at 3:30 pm
    - Small team remained until 8:30 pm to monitor vehicle
- **July 25th 2022**
  - 3:31 am – 3:57 am – Fire Brigade attended
    - Smoke from ESS enclosure

Ref: US National Transport Safety Board Report HIR-24-03

2021: 7 New Flyer Xcelsior 40-foot BETBs - ~$1M ea

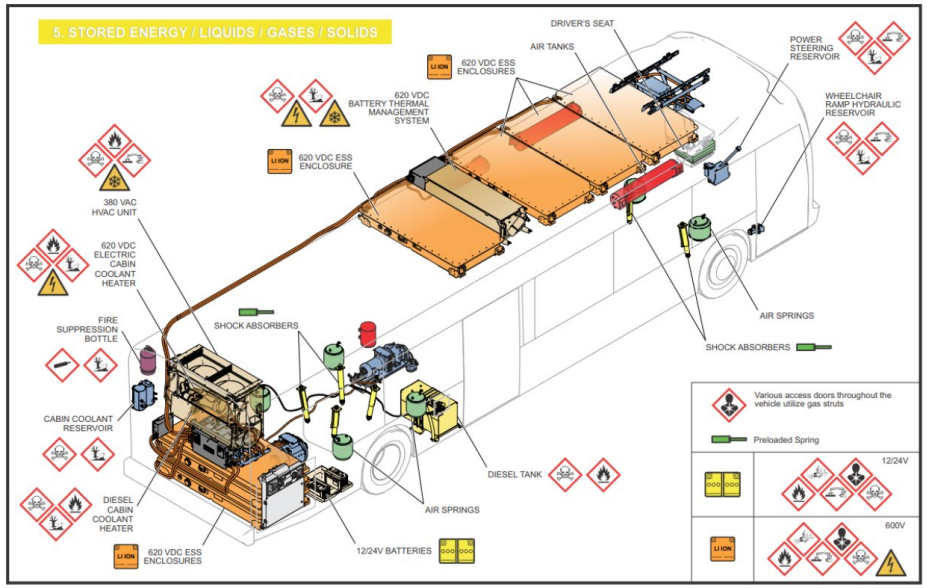
July 2022: Vehicle Fully involved

Aftermath

Case Study - Summary of Findings

- **Probable Cause**
  - Coolant from the Thermal Management System in one of the rear batteries (ESS) caused a short and thermal runaway
- **Infrastructure** –
  - 10 new charging stations fitted inside. 5 in use due to grid constraints
  - Depot fire suppression systems upgraded to handle larger volumes of water
- **Safety Risk Management**
  - Emergency response guide found in vehicle behind drivers seat.
  - Federal Transit Authority (FTA) does not require onboard fire suppression
  - Vehicle was fitted with detection and suppression outside ESS
- **Maintenance Personnel**
  - Good records kept of all vehicle charging – bus No, charger, SOC etc..
  - 30 min class on emergency procedures for BEB's
  - Vehicle under warranty – New Flyer field service personnel perform repairs on electric systems
- **First Responder Training**
  - 3 training sessions held at Hamden during Jan – Feb 2022 including train the trainer
  - HFC on-sight had all received this training

Probable Cause: Coolant leak in rear ESS



Emergency Response Guide (ERG)

Future Procurements

Aim- 100% ZEB's by 2035 ~ 600 buses
50 additional New Flyer – End 2024
142 more buses for completive bid

Facility Upgrades

150KW plug in charger
10 x 180KW Pantograph chargers
1 x 450KW fast charger
Upgrade suppression

Summary From Bus Fire Data

- Do Fires Occur on ZEB's? – **Yes**
- Are they more or less frequent than for ICEB's? – **Same**
- A few observations from Investigation
  - Create significant media interest – vehicle recalls etc..
  - Some fires in ZEB's similar to ICEB's – Collisions, External threats
  - Some fires challenges in ZEV's are different
  - Fires Occurring more often in depots – Vehicles not "off" when charging
  - Vehicles often new to properties – Battery systems can require offsite experts
  - Could early warnings have saved the Connecticut BETB?
  - Several good practices already in place
    - Emergency training for Transit teams and Fire Crew
    - Removed bus from depot. "Designated location" (SEPTA, Philadelphia – Nov 2022)
    - Emergency Response Guide – available and easy to access
    - Suppression system fitted – even though not required

Hybrid Bus – London, UK

All Electric Bus – Wichita, USA

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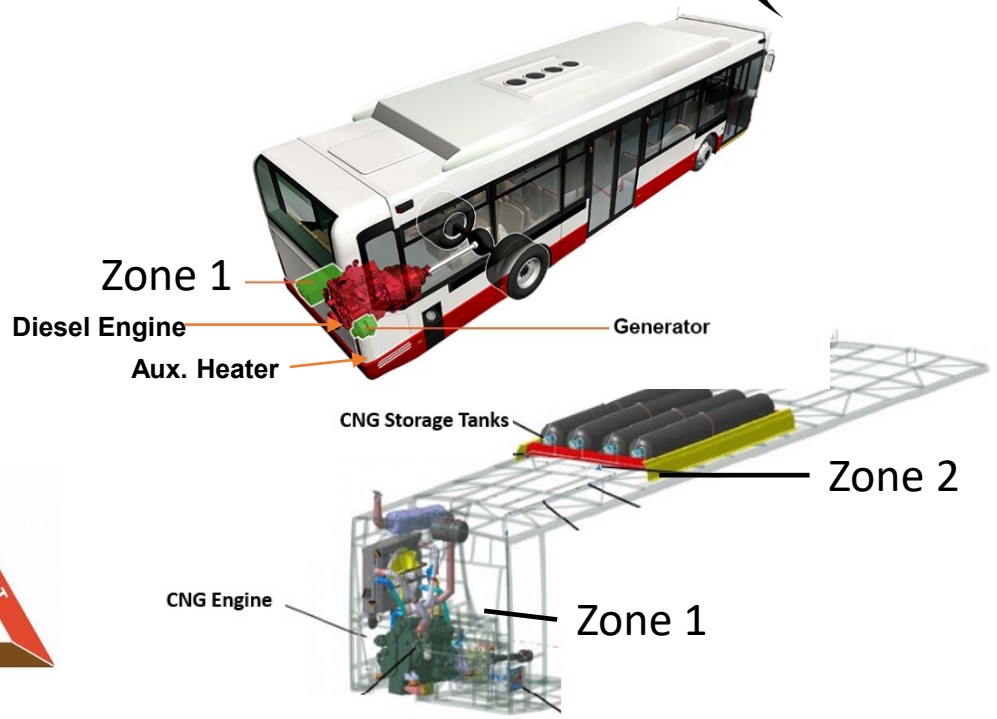
Bus Fire Research

Diesel and Gas Engines

- Diesel
  - 1 Zone
  - Early Detection – Thermal. Optical
  - Stop flow of Fuel
  - Suppress – re-strike protection
- Gas – CNG, LNG
  - 2 Zones
  - Early Detection – Gas
  - Turn off Gas valve
  - Detection & Suppression (As Diesel)



- Minimum Performance Standards
  - City Spec's – USA – From early 2000's
  - P-Mark – Global 2017
  - AS5062 – Australia – 2016 Sydney bus fire
  - UNECE R107 – Europe – Legal 2019-2021

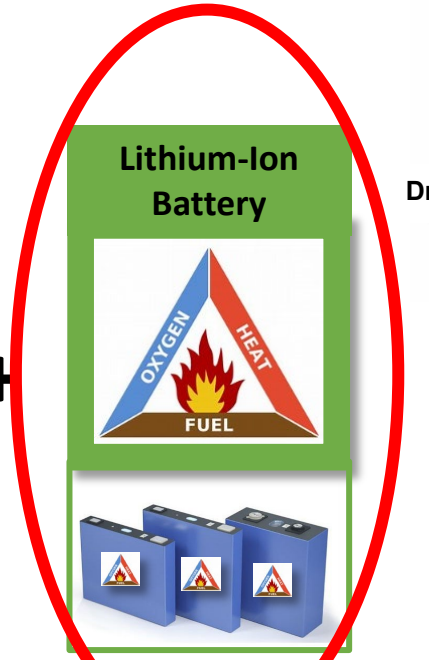
UNECE 107 – Fire Test

Zero Emission Vehicles

- All Electric
  - Threats in Multiple Zones
  - Lithium Ion Batteries – New Challenge
  - Many hazards similar to traditional vehicles

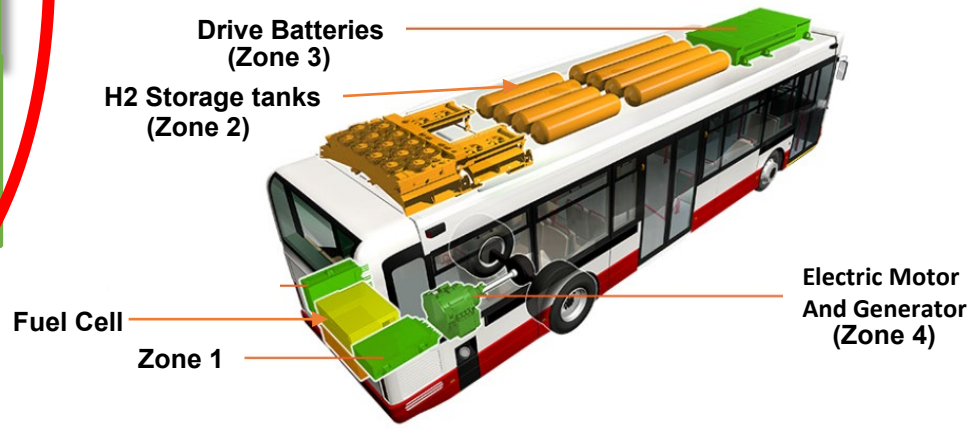
Other Threat - External	Fuels
• AC/DC Invertors	• Hydrogen
• Electric Drive Motors	• Hydraulics
• Compressors	• Lubricants
• Auxiliary Heater	• Coolants
• Steering units	• Fuels
• High Voltage Cabling/Connections	• Plastics
• Wheel bearings & Brake issues	• Tyres

+



Routes
Tunnels etc..

All Electric



Hydrogen Fuel Cell

Hydrogen Fuel Cell

- Threats in Multiple Zones
- Early Detection – Gas
- Turn off Gas valve
- Detection & Suppression (As Diesel)

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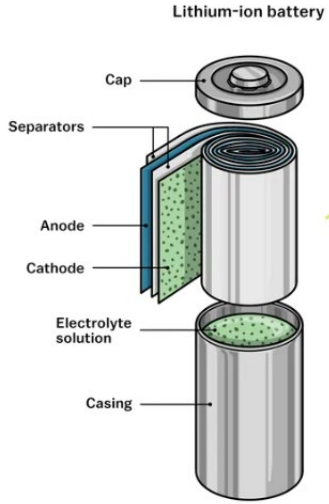
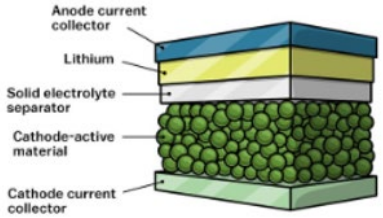
Information on Batteries

Lithium Ion Batteries - Variables



Liquid Electrolyte

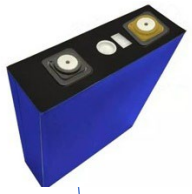


Solid “State” Electrolyte

Cell Design

Cells

Prismatic

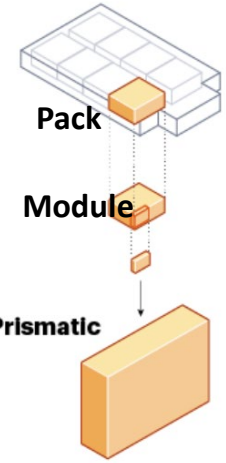


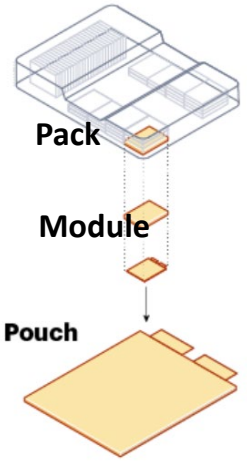
Pouch

Cell Type

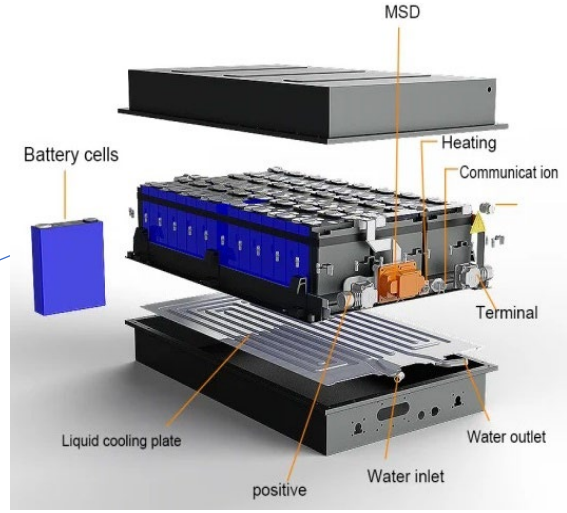
Parallel & Series
Volts & Capacity
(e.g. 600V, 150 kWh)

Module

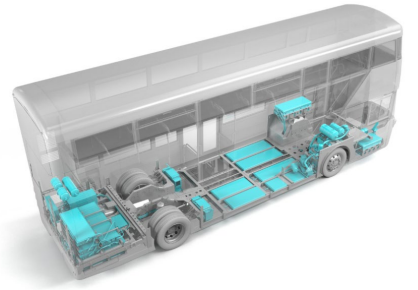


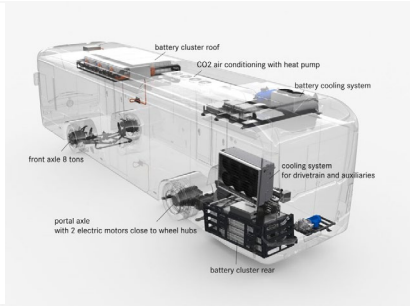


Pack



Battery Manufacturer



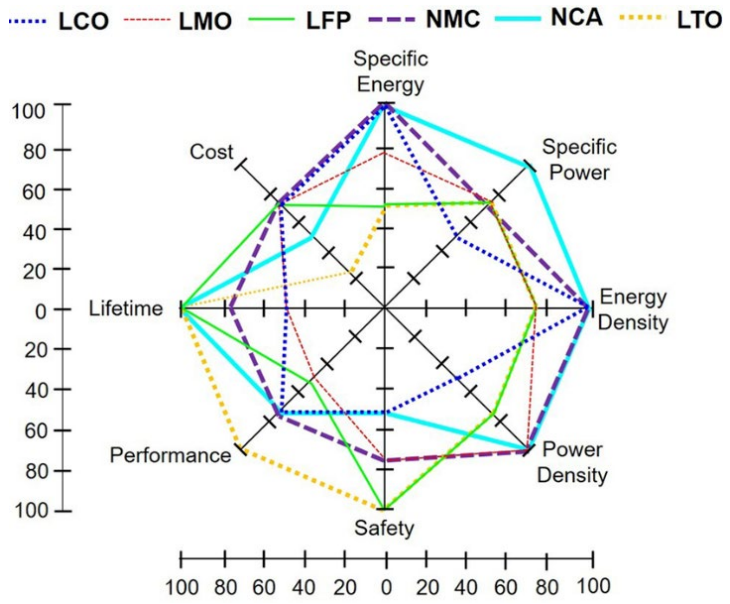


Integration into Vehicle - OEM

Chemistry

Abbreviation	Chemical Name	Chemical Forumula	Application
LCO	Lithium Cobalt Oxide	$LiCoO_2$ (60% Co)	High capacity for cell phones, cameras etc..
LMO	Lithium Manganese Oxide	$LiMn_2O_4$	e.g. Ford Focus (LMO,NMC blend)
LFP	Lithium Iron Phosphate	$LiFePO_4$	e.g. BYD (2010), Volvo 7900, Solaris 2024
NMC	Lithium Nickel Manganese Cobalt Oxide	$LiNiMnCoO_2$ (10% Co)	e.g. VW-E-Golf (2015), Honda Fit EV, Renault Zoe (2014), Daimler
NCA	Lithium Nickel Cobalt Aluminium Oxide	$LiNiCoAlO_2$ (9% Co)	e.g. Tesla (2012 - 2018)
LTO	Lithium Titanate	$Li_4Ti_5O_{12}$	e.g. Solaris Urbino, VDL Citea

Specific Energy: Battery capacity per unit of Weight (WH/kg)
Energy Density: Battery capacity per unit of volume (WH/m^3)
Specific Power: Rate of discharge per unit of weight (W/kg)
Power Density: Rate of Discharge per unit of volume (W/m^3)
Safety: Protection from abuse to minimise aging and extend life
Lifetime: Calendar life plus number & rate of charge cycles
Performance: The overall capability of a battery to supply energy effectively and reliably over a specific period.
Cost: Upfront, ongoing and end of life



Battery Management System

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Current

Voltage

Temperature

BMS

Algorithms

Communications

Driver

Engine Control Unit (ECU)

External??

Safety + Performance Optimisation

State of Charge (SOC)

100% 80% 60% 40% 20%

Capability Estimation

275 Miles

Cell Balancing

Over Voltage

Under Voltage

Cells Balanced

Thermal Management

< 10°C Slows Down

20°C – 40°C

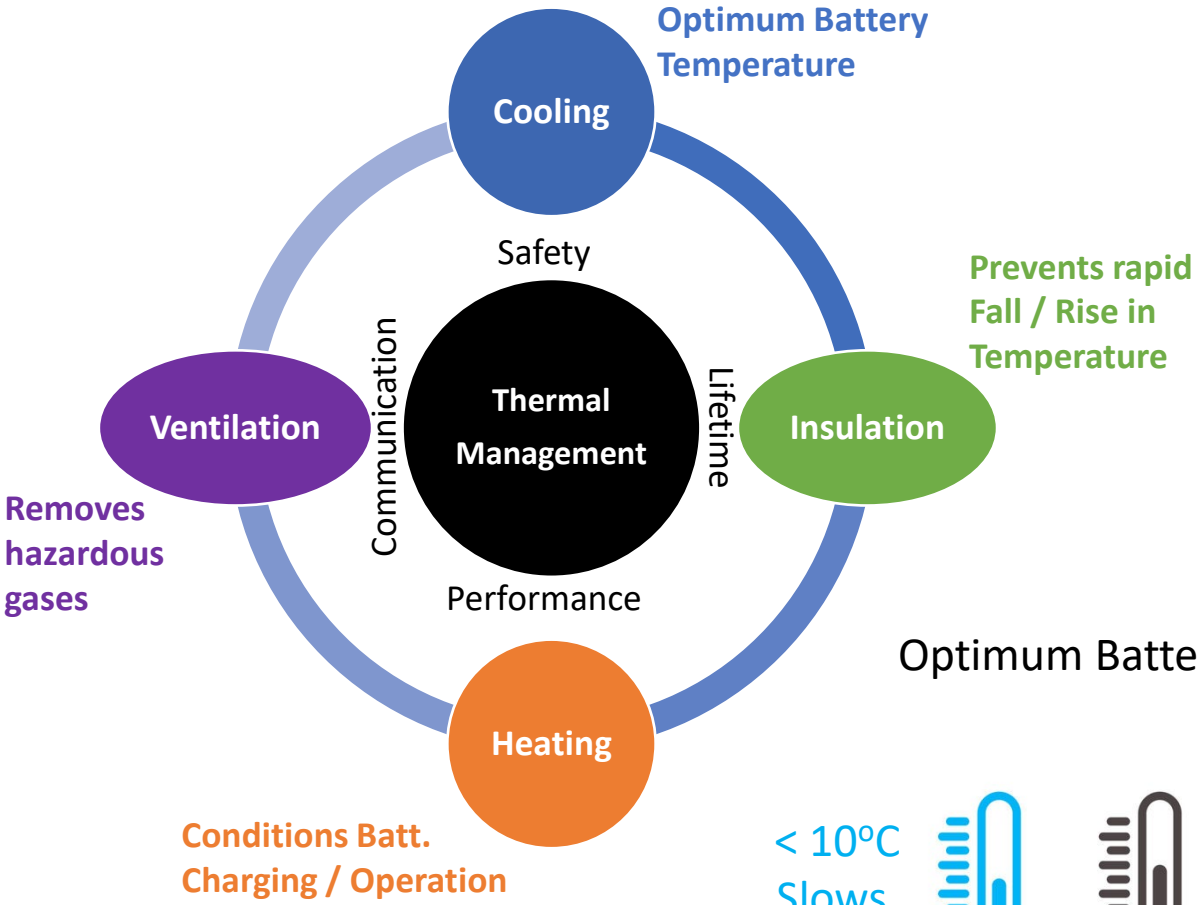
> 80°C Thermal Runaway

State of Health (SOH)

Status / fault codes / emergency disconnect

Stranded energy

Thermal Management System



Technologies of Battery Thermal Management System

- Air Cooling and Heating
- Phase Change Material Cooling
- Liquid Cooling and Heating
- Thermo- Electric Module
- Refrigerant Cooling
- Heat Pipe module

Optimum Battery Performance

< 10°C Slows Down

> 80°C Thermal Runaway

20°C – 40°C

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Information on EV Batteries

- Emerging Technology – Production Increasing
- Complex – Many Variables
- Evolving / Changing
- Experts in Different Sectors

EV Vehicles - Battery Failure Mechanisms

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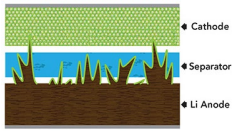


Dendrites

Particle

Separator Failure

Impact / Puncture

Internal Shorts

Water Ingress / Humidity

External Shorts

Overcharge

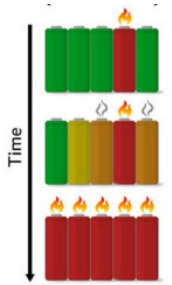
Over discharge

External Heating

Temperature Extremes

Causes

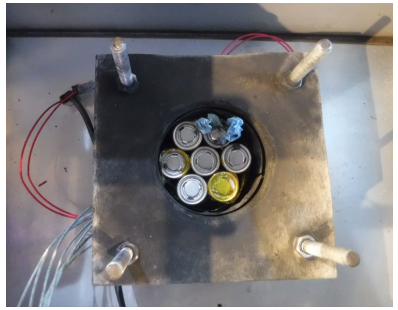
Stage 1 – Recovery possible	Stage 2 – Thermal Runaway in progress	Stage 3 – Battery Pack / Vehicle Fully Involved
 Safe Outcome	Cell Venting	Rupture 1st Cell
Heat Dispersion > Heat Generation	Thermal Runaway	Rupture Module
Elevated Temperature	Heat Dispersion < Heat Generation (Exothermic Reaction)	Explosion - Pack
BMS / TMS Other?		FIRE



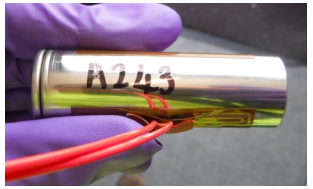
Indicators

Heat Generation · Swelling · Pressure in Pack · Gas Generation - External · Voltage drop · Gas Generation - Internal · Heat / Fire - External

Research into Battery Thermal Runaway

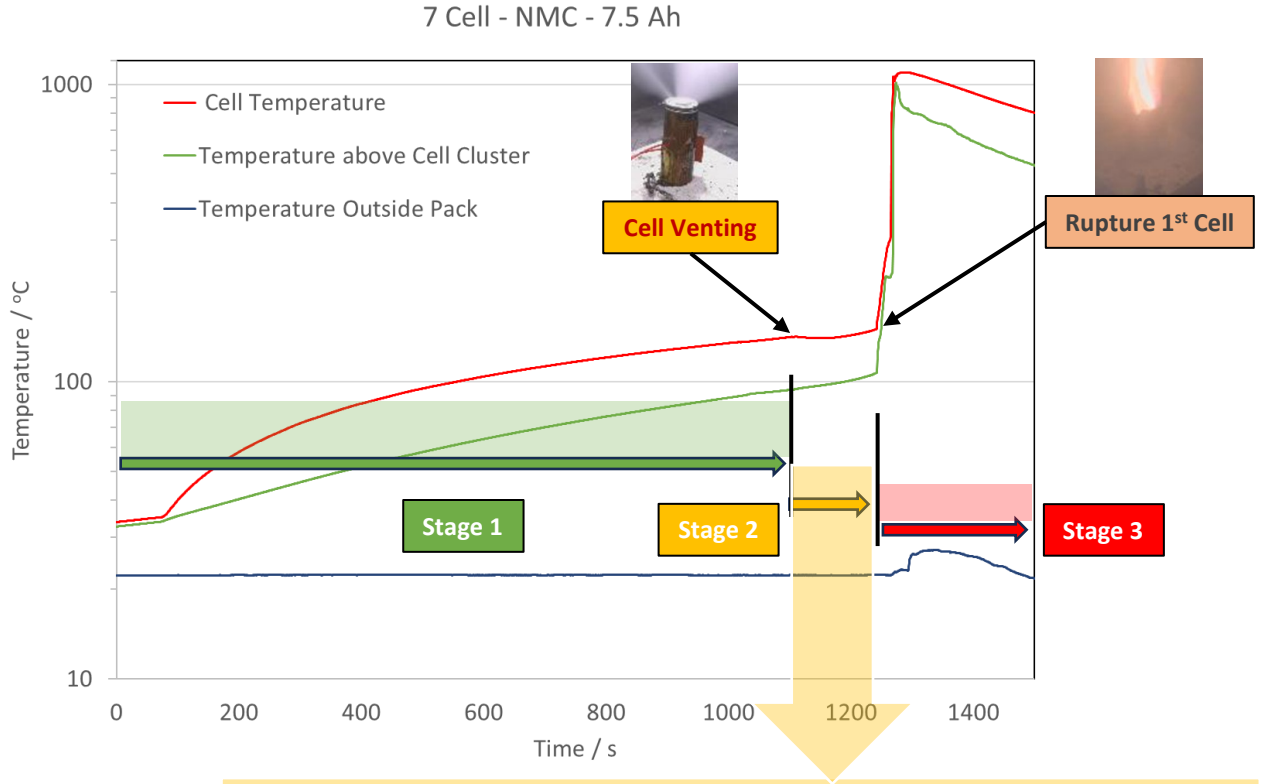


7 Cell Cluster

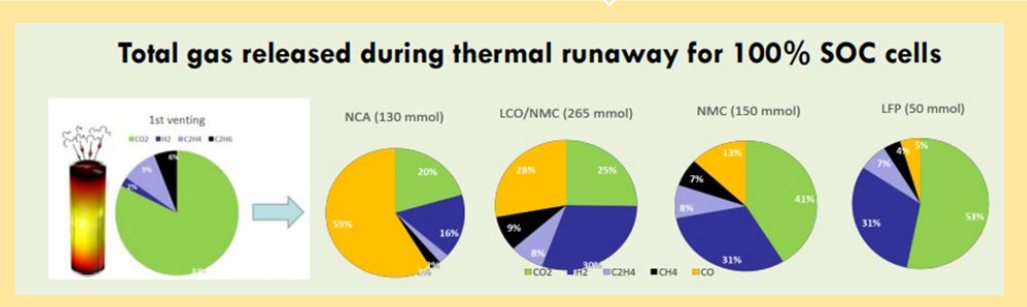


NMC Cell – 4Ah
(Heated)

Battery Pack and Sensors



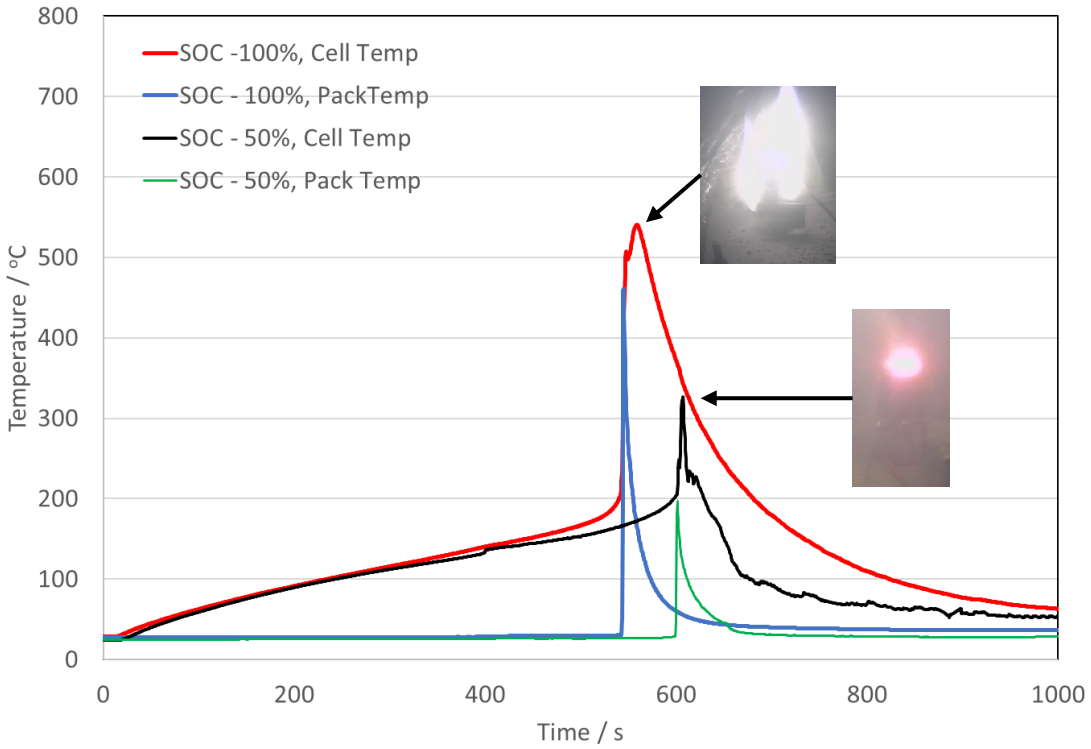
Acid Gases
HF, HCL
60 – 80%
more than ICEV's

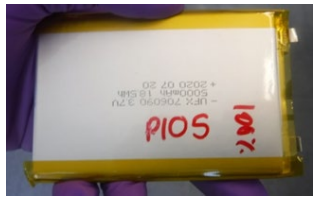


Thermal and Gases during testing on Battery Failures

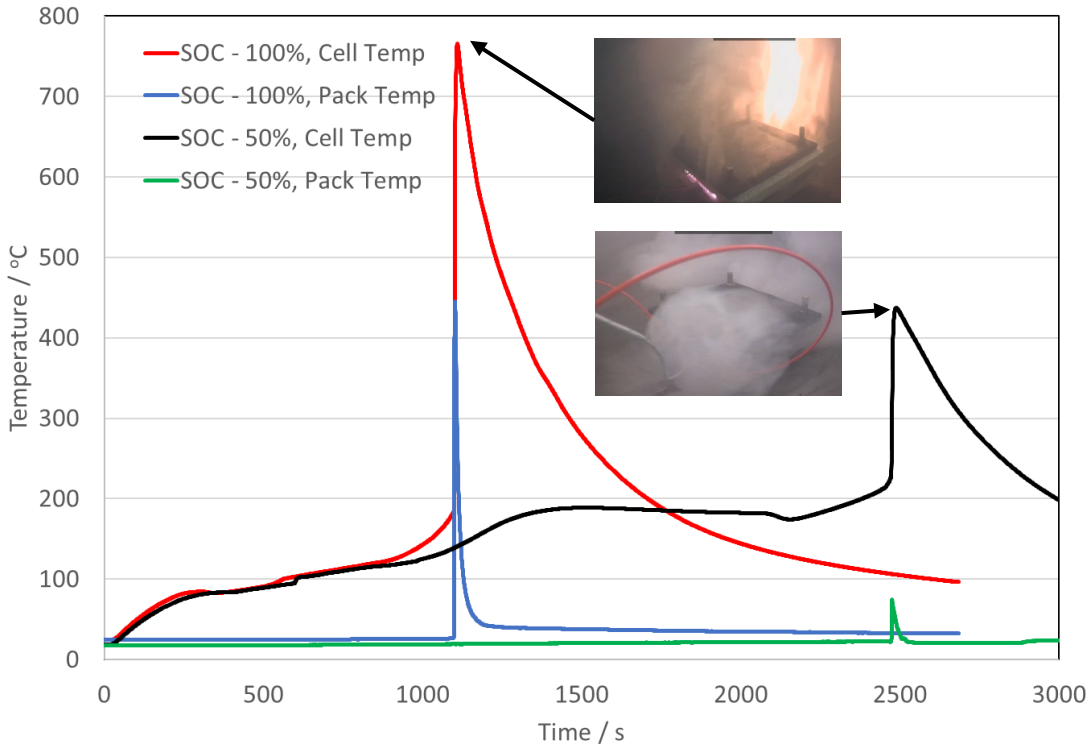
Research into State of Charge

Single Cell - NMC - 4 Ah



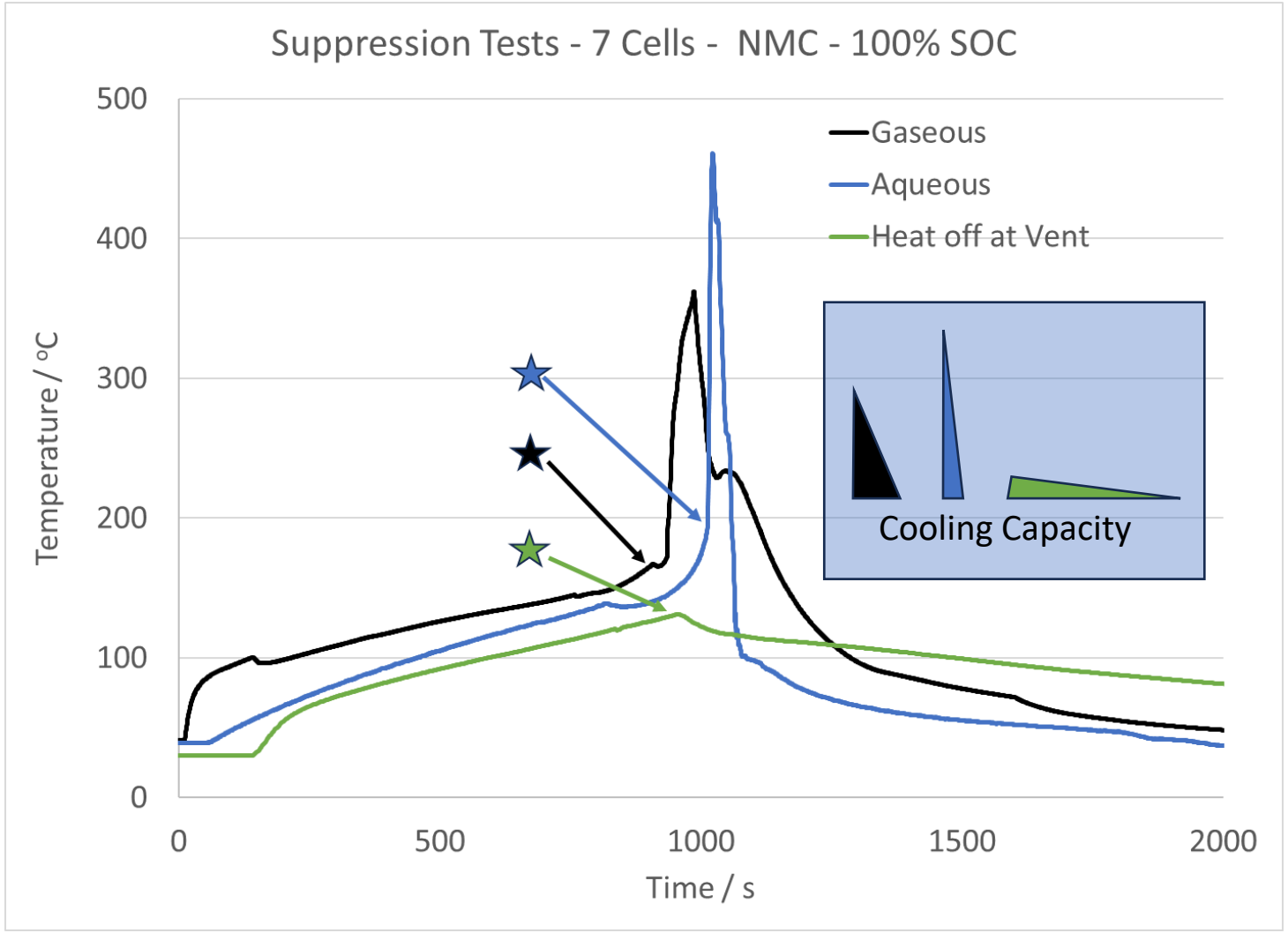


Single Pouch - NMC - 7.5 Ah



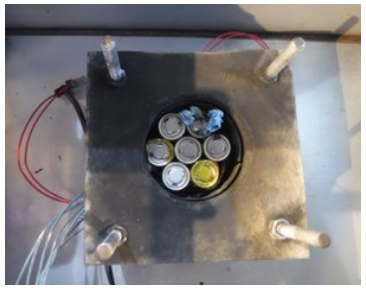
State of Charge reduces energy (e.g. Peak) during thermal runaway + Chemistry

Research into Prevention / Suppression



Gaseous

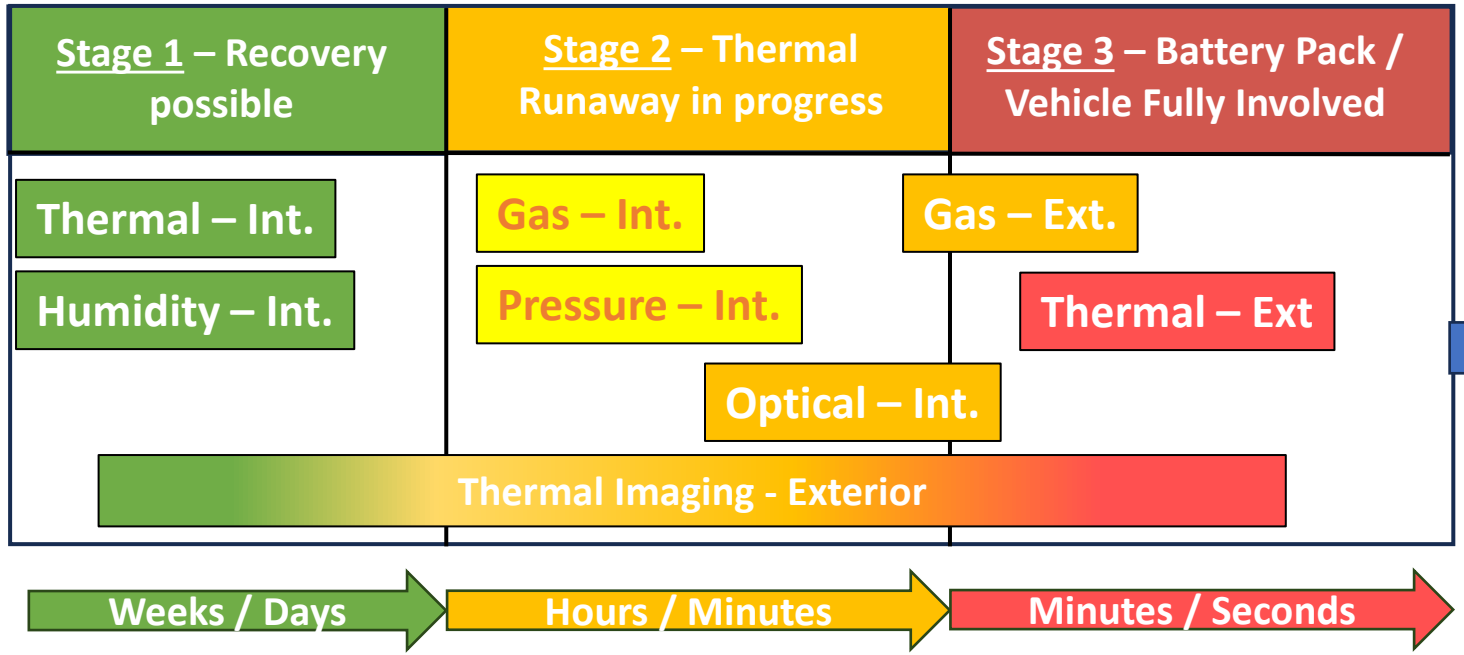
Aqueous



Heat off at Vent

More Research required on Cells (Different Fault modes) / Modules / Packs

Detection



Communication

- Driver
- Depot Personnel
- Maintenance
- Operators
- OEM's

Internal Detection (Int.)

External Detection (Ext.)

Early detection promotes prevention – minimises damage.

Risk Reduction / Suppression

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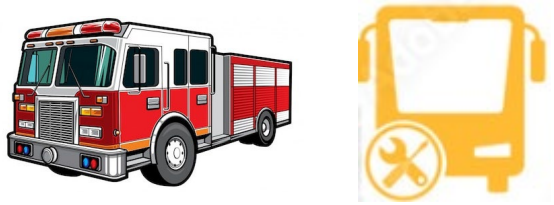
Stage 1: Prevention Detection: Pre-TR	Stage 2: Early on-set Detection: Early TR	Stage 3: Vehicle full involved Detection: TR in progress
1. Turn off Vehicle 2. Move Vehicle to “Safe” Location • Bunded • Toxic gases 3. Reduce SOC 4. Report Emergency Maintenance • Remove battery • Store in “safe” location for repair	1. Evacuate - Turn off Vehicle 2. Driver / On-site personnel • Be mindful of Toxic gases • Call Emergency Services 3. Move personnel to “Safe” Location 4. Emergency Service to monitor vehicle 5. Move vehicle to “Safe” location 6. Reduce SOC 7. Report Emergency Maintenance • Remove battery • Store in “safe” location for repair	1. Evacuate - Turn off Vehicle 2. Driver / On-site personnel • Be mindful of Toxic gases • Call Emergency Services 3. Move personnel to “Safe” Location 4. On board Suppression activates if fitted 5. Emergency Services Suppression 6. Move to “Safe” Location when suppressed 7. When fully extinguished assess for repair

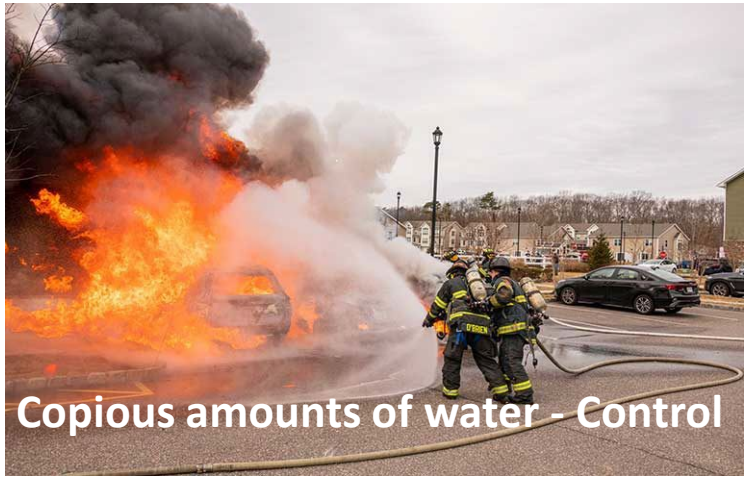
Weeks / Days

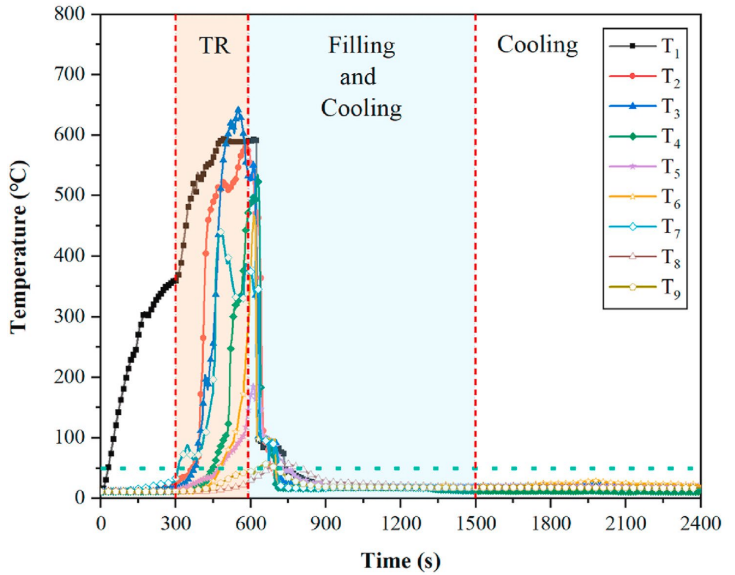


Hours / Minutes

Minutes / Seconds

Suppression – Fire Departments





<u>Fire Blankets</u> - Control / Suppress

Water Solutions -Suppress / Extinguish

Summary from Battery Fire Research

- Diesel and Gas vehicles
  - Detection / Suppression well understood
  - Minimum performance standards in place
- ZEB's
  - Hydrogen Fuel cell vehicles – Hydrogen leak detection similar to natural gas vehicles (differences: Gas Detector & Locations)
    - High Energy Batteries to be assessed as with All Electric
  - All Electric Vehicles
    - Assess fire challenges on vehicle – use detection / suppression on multiple high risk zones
    - High Energy Batteries
      - Many variables in battery types / locations / changes in Tech.
    - Who is Expert? – Training to educate local service teams
    - Emergency information where it is needed
    - Early Detection – Research & New products to drive detection from Stage 3/2 (current) to Stage 1
    - Emergency procedures – Local service teams / fire departments to work together
    - Suppression – Research & New products to improve on-board and fire department methods

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KlineFire

Thank You