





Automotive Battery Testing Capability and Best Practice

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UTAC - A UNIQUE & MARKET LEADING PROPOSITION DEDICATED TO THE AUTOMOTIVE SECTOR

- Full service proposition
- Market leading expertise
- Scale testing capability
- State of the art assets and capacity to anticipate upcoming needs
- Global reach

- Most of UTAC's battery testing in Europe is done at its Millbrook testing ground, near Bedford in the UK.



Contents

- Overview of battery types, voltages and applications
- Li-ion Safety
- Test methods and standards for abuse, performance and life
- How to split testing between cell, module and packs
- Conclusions



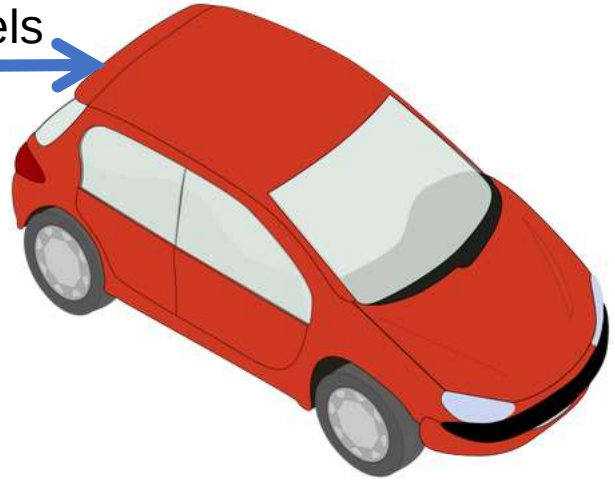
Vehicle Emissions – Well to Wheels





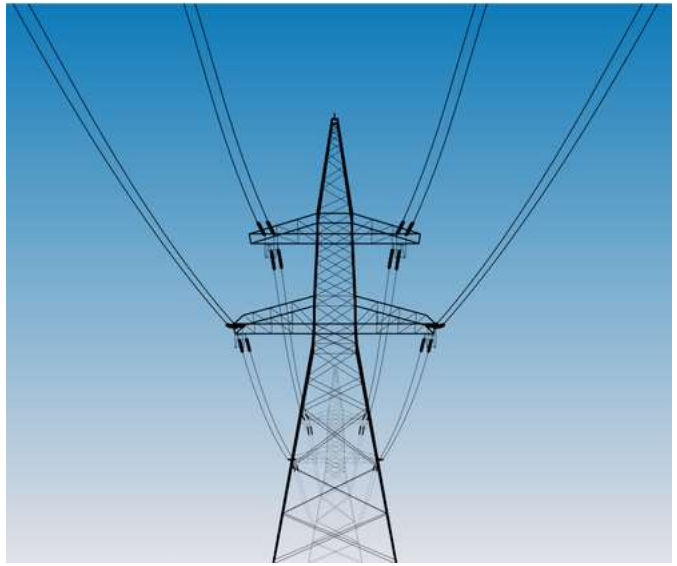
Well

Wheels





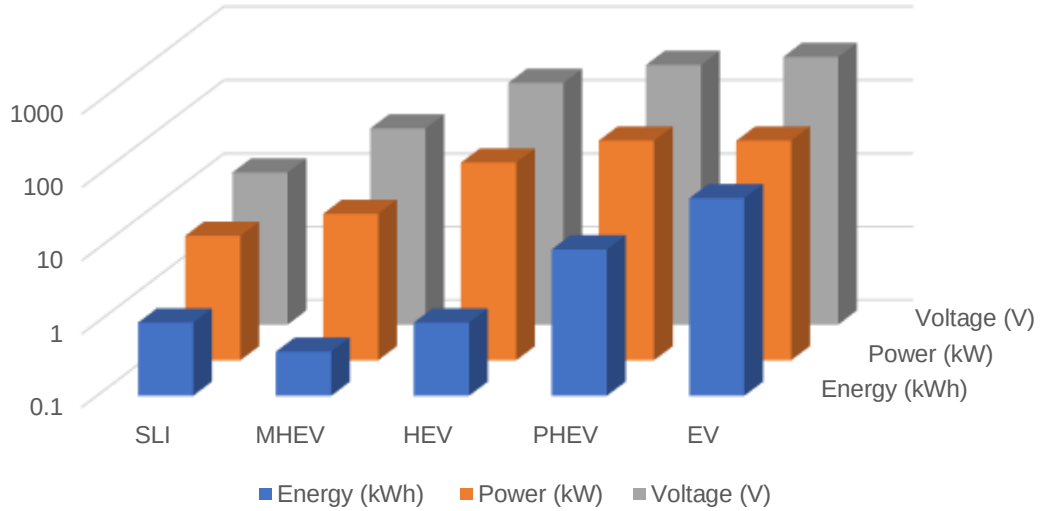




- The next slide gives "Well to Wheels" CO_2 equivalent emissions
  - This accurately reflects the emissions due to vehicle use.
- World average figures are used.
- In the longer term LCA (Life Cycle Analysis) will be used as this captures the total impact of the vehicle from raw /recycled materials, then manufacture to recycling including the use phase.

Overview of Battery Types, Voltages and Applications

- **SLI (Starting Lighting Ignition)**
  - The functionality now normally also includes idle-stop
  - Normally lead-acid batteries, but small penetration of (normally $LiFePO_4$) Lithium-ion
    - 12V, < 1kWh, 5-10kW peak (for starting) [202g/km CO_2 equiv. well to wheels]
- **Mild hybrid (MHEV)**
  - Either lead-acid or Lithium-ion , 300-500Wh, 5-30kW
    - 48V is becoming the standard for this functionality
    - Fuel economy gains of ~ 10% [~ 180g/km CO_2 well to wheels]
- **Full hybrid (HEV)**
  - Fuel cells or conventional combustion engines provide the main energy source
  - Either NiMH or Lithium-ion 1-2kWh , ~ 50kW
    - 100 to 250V battery
      - Toyota use a high voltage boost system to run their propulsion motors at up to 650V
  - Fuel economy gains of 20-30% [136g/km CO_2 well to wheels for petrol, 101 g/km CO_2 for fuel cell using steam reformed hydrogen]
- **PHEV**
  - Fuel cells or conventional combustion engines provide the main energy source
  - Lithium-ion battery 4-20kWh depending on Electric range, 100-200kW
    - 300-450V
    - Fuel economy gains depend heavily on usage/recharging (typically ~50%). [107g/km CO_2 well to wheels]
- **EV (BEV)**
  - Lithium-ion battery 30-90kWh depending on range, 100-200kW
    - 300-800V
  - No tail pipe emissions, but well-wheels emissions of 83g/km CO_2 equiv.
- CO_2 equiv. well to wheels values are world averages for cars, April 2021, from https://www.iea.org/data-and-statistics/charts/well-to-wheels-greenhouse-gas-emissions-for-cars-by-powertrains



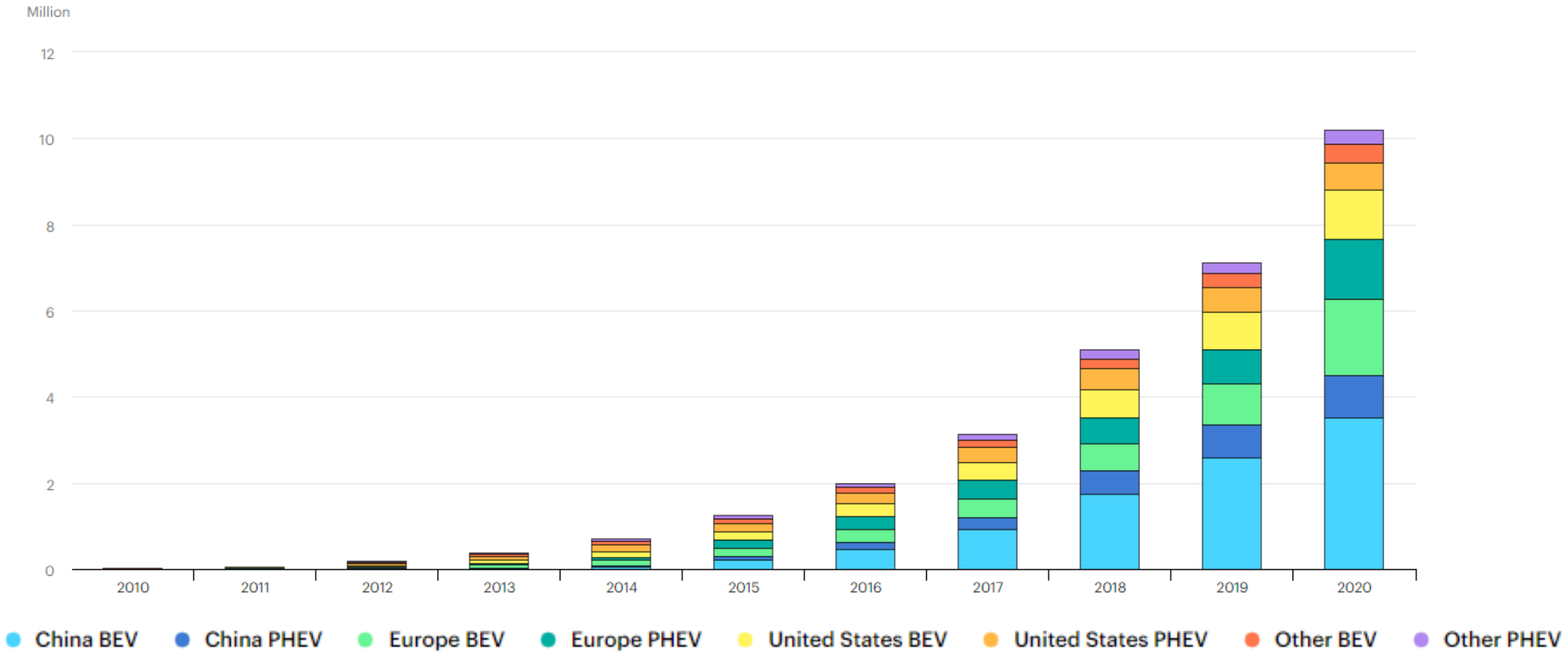
UK Sales Data to End of September 2021

	YTD 2021	YTD 2020	YTD 2019	Market share 2021 (%)	Market share 2020 (%)	Market share 2019 (%)
Diesel	117,605	209,093	478,147	8.9	16.8	25.7
Petrol	621,598	719,908	1,204,719	47.2	57.9	64.7
BEV	125,141	66,611	25,097	9.5	5.4	1.3
PHEV	87,040	42,277	23,015	6.6	3.4	1.2
HEV	120,283	83,993	77,679	9.1	6.8	4.2
MHEV diesel	85,171	44,351	21,731	6.5	3.6	1.2
MHEV petrol	120,283	77,423	31,883	12.1	6.2	1.7
Total	1,316,614	1,243,656	1,862,271	100.0	100.0	100.0

EU vehicle sales are similar to the UK, for example EU wide BEV's were 8.7% (ytd to end Sept 2021) and PHEV 8.6%.

Data provided by the SMMT

The World, EV and PHEV Car Stock



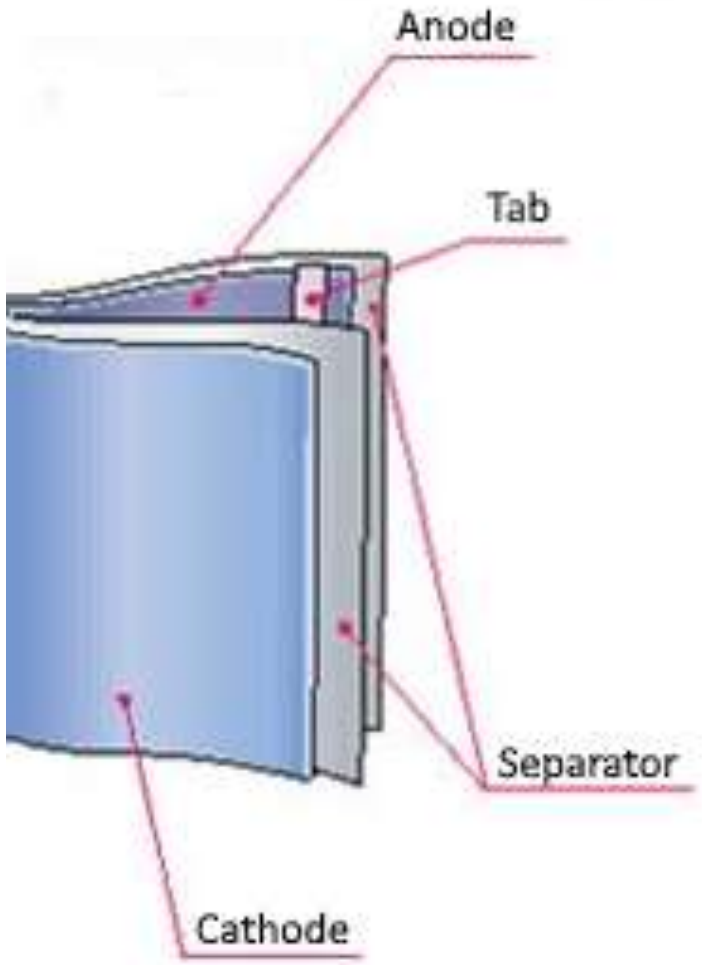
Global electric passenger car stock [IEA].

Lithium-ion Battery

A Lithium-ion cell consists of:

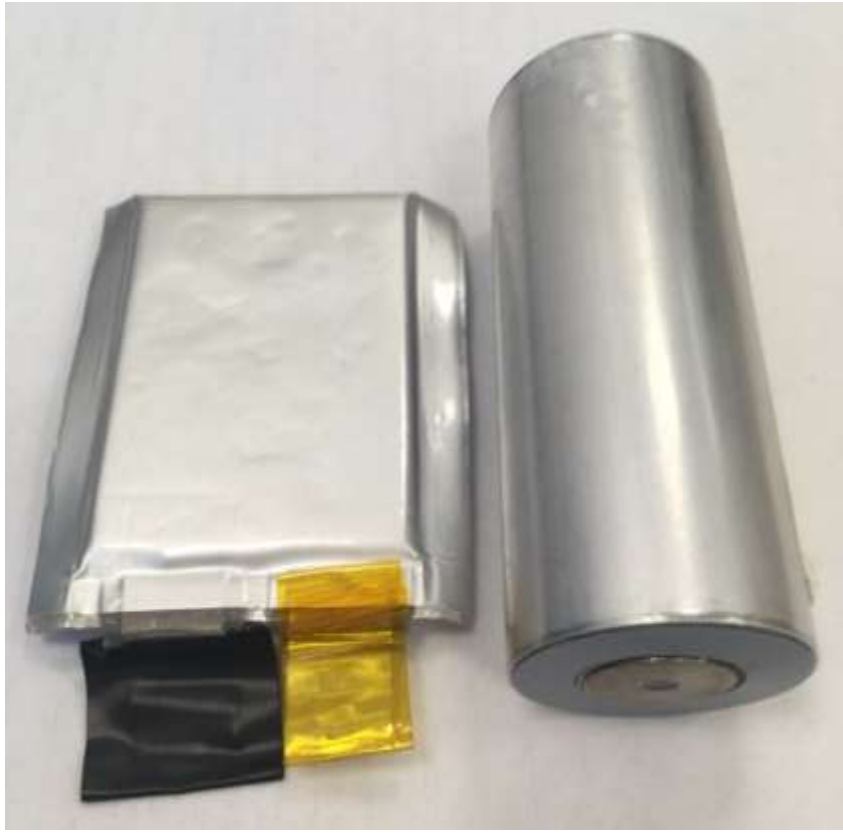
- Carbon (graphite) Anode
- Lithium metal oxide Cathode
  - Typically NMC
    Lithium-Nickel-Manganese-Cobalt-Oxide
- Porous, insulating separator which also holds the (flammable) electrolyte.

- The Anode and cathode have metal tabs attached to connect to the external terminals.



Cells, Modules and Packs

- A cell is a single electrochemical device
  - For most Lithium-ion chemistries it's ~ 3.7V and 2 to 100Ah (7.4 to 370 Wh)
- A module is normally a manufacturing convenience and contains a number of cells
  - Typically a module is 30-100V and 2-10kWh
  - It may contain 12-100 cells
  - A module may contain some thermal management and protection from external shocks and vibration.
- A pack is what's actually fitted in a vehicle.
  - A typical pack contains 5-20 modules



Pouch cell (left)
Cylindrical cell (right)

Physical sizes can vary significantly but the cylindrical cell shown is 18mm diameter and 65mm long.

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- As an example the BMW i3 pack (42kWh) contains
  - 96 cells each of 120Ah
  - Each module has 12 cells giving a nominal 48V
  - The pack has 8 modules
- The Tesla model S 85kWh pack contains
  - 7104 cells each of 3.2Ah
  - Each module has 444 cells (6s74p) giving a nominal 24V
  - The pack has 16 modules

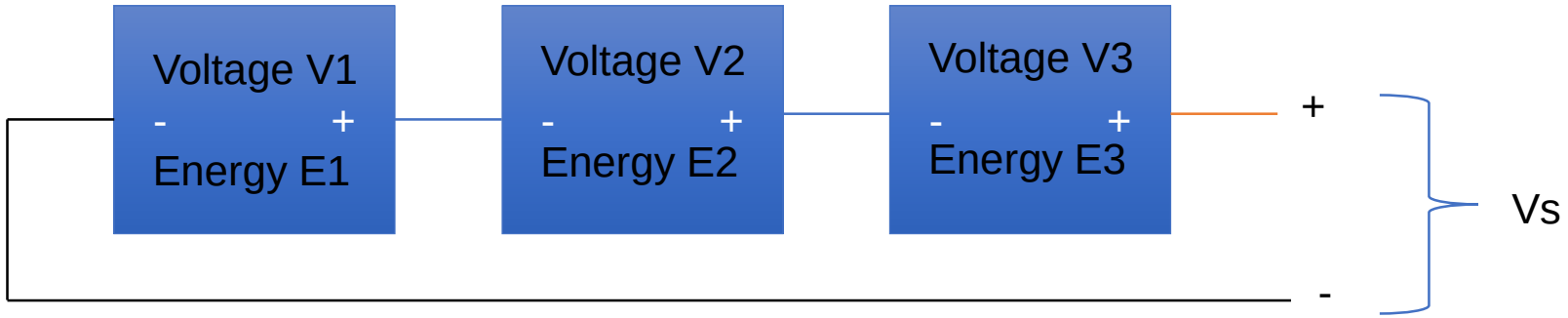


BMW i3 and Battery

Photo courtesy of BMW

https://www.press.bmwgroup.com/united-kingdom/article/detail/T0285468EN_GB/the-all-electric-bmw-i3-120ah?language=en_GB

Cells (or Modules) in Series



- The diagram above shows 3 cells (or modules) in series
  - The resultant voltage is Vs=V1+V2+V3
  - The total energy is 3* the smallest of (E1,E2,E3)
    - Because of this the packs capacity is limited by the “weakest cell”
      - in this case the cell with the smallest capacity (energy), but the same is true for power

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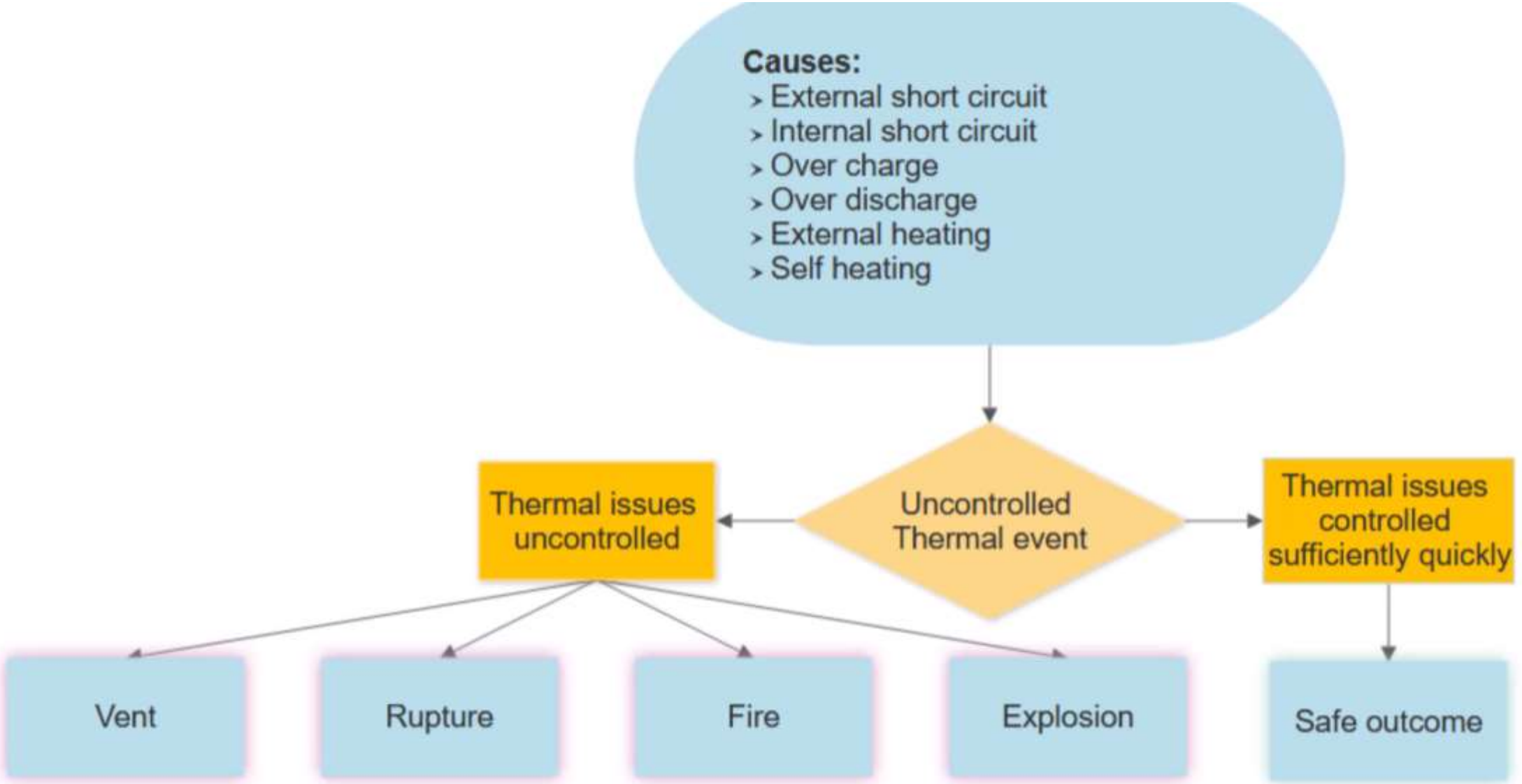
EV Fires



Lithium-Ion Safety : Causes and Hazards



EUCAR Hazard Levels

Hazard Level	Short Description	Long Description
0	No effect	No effect. No loss of functionality
1	Passive protection activated	No defect. Reversibly damaged. Repair of protection device needed (e.g. fuse replacing)
2	Defect/Damage	Irreversibly damaged. Repair needed
3	Leakage < 50%	Weight loss of < 50% of electrolyte weight
4	Leakage > 50%	Weight loss of > 50% of electrolyte weight
5	Fire or Flame	No flying parts
6	Rupture	Flying parts of active mass
7	Explosion	Explosion (disintegration)

Almost the same levels are defined in SAE J2464, IEC 62660-2 and FreedomCAR SAND 2005-3123.

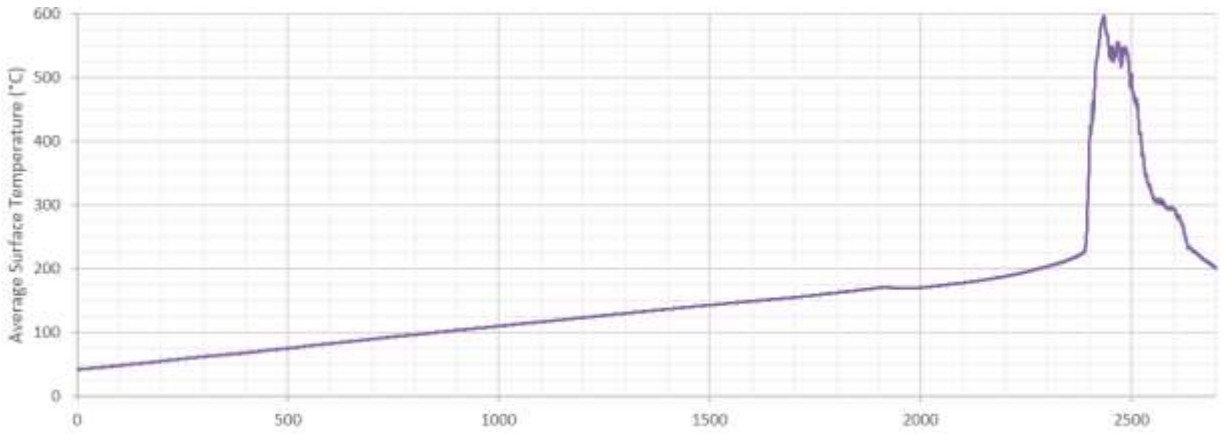
Thermal Runaway

The graph was obtained by slowly heating a NMC-811 lithium ion cell

- NMC is the most common lithium-ion chemistry currently in use in EVs

The cell vented at 1900 secs and went into thermal runaway at 2400 secs

- The gas vented (the electrolyte) is flammable – in the test above fire was seen and the jelly roll was expelled (see photograph on next page)
- Oxygen is also created by decomposition of the cathode making the resultant fire very difficult to put out



This testing was completed by Stephanie Morton who was an EngD student at WMG; she was sponsored by UTAC-Millbrook.

Thermal Runaway



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6	Rupture
7	Explosion

- The photograph above is of the remains of the cell after the test on the last slide

Fire of a Li-ion Pack





- This could happen when a Li-ion battery pack is severely damaged
  - Impossible to control with hand held extinguishers
  - It took nearly 15 minutes to completely extinguish the fire with water from a fire truck

Comparison to conventional vehicles

For this test the fuel tank was full (50 litres) and the battery fully charged at the start.

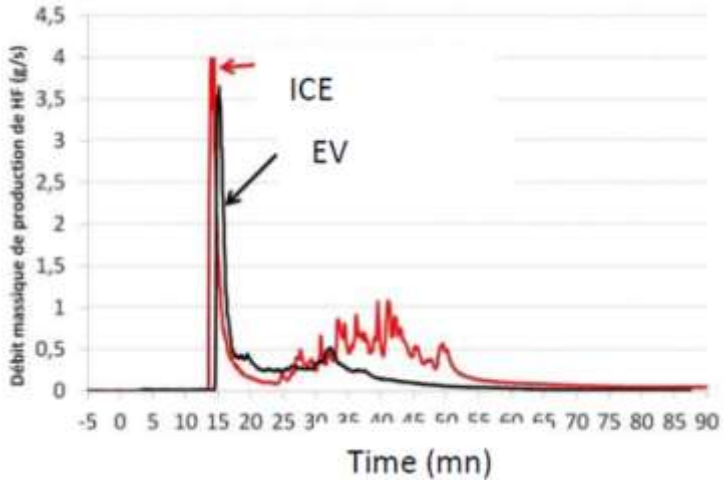
The vehicles were identical apart from the powertrain.

In most cases the EV emitted less hazardous gases than the conventional vehicle(ICE)

- For HF (the most hazardous gas listed) the EV emitted more than the ICE, but the peak value was earlier and higher on the ICE.

The fire maximal thermal power and the total energy released are lower for the EV than for ICE: respectively 4.7MW against 6.1 MW, and 8 500 MJ against 10 000 MJ

Emitted Gas (g)	Conventional Diesel Car (ICE)	Same Model Car as EV
CO_2	722,637	618,487
CO	15,732	11,700
HCl	2,139	1,933
NO	740	770
NO_2	410	349
HCN	178	148
HF	813	1472



Reference: "A PARTNERSHIP BETWEEN RENAULT AND FRENCH FIRST RESPONDERS TO ENSURE SAFE INTERVENTION ON CRASH OR FIRE-DAMAGED ELECTRICAL VEHICLES.", Paper Number 15-0252, ESV 2015 Congress, June 2015.

Hydrogen and Conventional Vehicle Fires

- The conventional vehicle leaked ~ 3 litres of petrol via a 1.5mm hole in the fuel line causing severe damage to the vehicle within 3.5 minutes.
- The hydrogen powered vehicle released 1.5kg of hydrogen (all that was in the tank) within 100 seconds when the tank pressure relief device (PRD) opened. This vehicle was not damaged by the fire.
- M. Swain, Fuel Leak Simulation, Miami: Proceedings of the 2001 DOE Hydrogen Program Review NREL/CP-570-30535, 2001



3 seconds

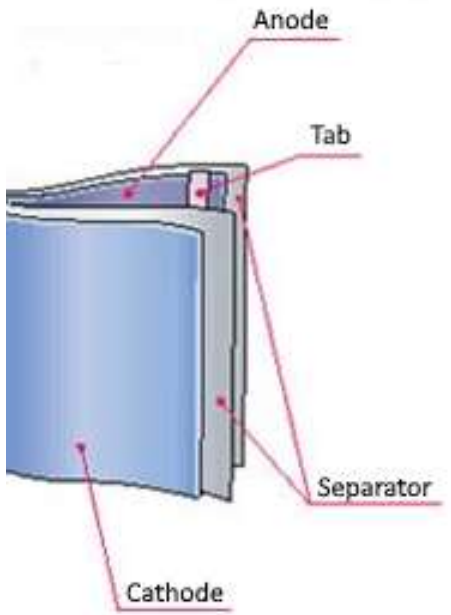


1 minute



2 minute 20 seconds, petrol vehicle only

GM Bolt Recall



2019 GM Bolt EV that caught fire on July 1, 2021 in a driveway.
Vermont State Police.



- The recent GM Bolt recall was caused by 13 vehicle (battery) fires.
  - No injuries or deaths have been linked to these fires.
  - This is about 10X better than the expected number of fires in conventional vehicles (~ 1 vehicle fire/year for every 1500 vehicles).
- The issue with the GM Bolt packs has been traced to 2 manufacturing defects inside a cell, which if they occurred together could lead to a short circuit inside the cell.
  - A tab on the anode was torn
  - The separator was folded
- The related (141,000 car) recall cost ~ $2 billion, LG Chem. (the cell manufacturers) are paying $1.9 billion of this.

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Test Methods for Abuse, Performance and Life

- The key legal regulations are:
  - UN 38.3 for transport of Li-ion batteries (any, not just automotive)
    - This covers almost every country in the world and transport in-between by air, sea and land
  - ECE Regulation 100
    - This is an automotive type approval test
    - This currently covers EU, Norway, Russia, Ukraine, Croatia, Serbia, Belarus, Kazakhstan, Turkey, Azerbaijan, Tunisia, South Africa, Australia, New Zealand, Japan, South Korea, Thailand and Malaysia
- These are both focused on safety / abuse



Summary of Legislative Tests for Automotive Battery Packs

Type of Test	UN 38.3	UN 38.3 Duration	Reg. 100.02	Reg. 100.02 Duration
Altitude	T1: 15000m	~6 hrs	n/a	
Thermal	T2:+72/-40ºC	~24 hrs	+60/-40ºC	~84 hrs
Vibration	T3:7-200Hz <=2g	~ 9hrs	7-50Hz <=1g	~3 hrs
Shock	T4: depends on weight e.g. 100kg pack ~17g	~24 hrs	Depends on vehicle type for cars <=28g	~ 2 hours
Short circuit	T5: <0.1 ohm	~ 7 hrs	<5mOhm	~ 2 hrs
Overcharge	T7: 1.2*rated voltage	~ 200hrs	To twice rated capacity	~ 1 hr
Crush	n/a		100kN	~ 4 minutes
Over discharge	n/a		Until 25% voltage	~ 1 hr
Over temperature	n/a		Use then heated in climatic chamber	~ 24 hrs
Fire resistance	n/a		Pack over burning fire	~2 mins

Best Practice

As EVs started moving into the mainstream, more and more people became involved in developing and working on EVs and it became clear that a way was required to spread best practice.

Innovate UK (a non-departmental public body) sponsored the development of three PASs (Publicly Available Specifications) from the British Standards Institution (BSI) and these have now been released:

- **PAS 7060:2021, Electric vehicles – Safe and environmentally-conscious design and use of batteries – Guide.**
  https://shop.bsigroup.com/ProductDetail?pid=000000000030411151
- **PAS 7061:2020 Batteries for vehicle propulsion electrification – Safe and environmentally-conscious handling of battery packs and modules – Code of practice.**
  https://shop.bsigroup.com/ProductDetail/?pid=000000000030430987
- **PAS 7062:2021, Electric vehicle battery cells – Health and safety, environmental and quality management considerations in cell manufacturing and finished cell – Code of practice.**
  https://shop.bsigroup.com/ProductDetail?pid=000000000030408624

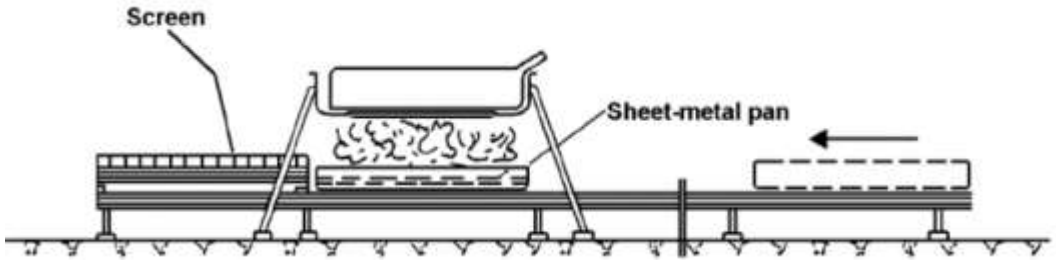
These documents are free to download from the above links.



Example Test: Regulation 100 Fire Resistance

This test is designed to simulate a crash between a conventional vehicle and an EV

- Petrol leaks from the conventional vehicle and catches fire underneath the EV
- This test is probably more severe than would actually be seen when the pack is mounted inside a vehicle
- Photograph shows a fire test in progress at UTAC's Millbrook testing ground.
    - UTAC can offer the new Reg. 100.3 tests including the LPG (gas burner) fire test and the new overcurrent test (Annex 9J)





Tests for Performance and Life

- Performance tests include power and energy and in particular how they vary with temperature
  - This testing is done to support the vehicles performance
    - Power → top speed and acceleration
    - Energy → range

- Life tests show how the batteries performance (power and energy) changes with both time and use.
  - This testing is mainly done to support warranty analysis, but its likely that life will soon become a legal requirement via the GTR EVE which is expected to come into force in 2023 in EU, USA , China, Japan, Canada, South Korea and Great Britain.
    - This will also require that accurate information about the health and remaining capacity of the battery is available to the vehicle owner.



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Split Testing Between Cell, Module and Pack: 38.3

Type	Number of items to be tested
Cells	40
Modules	8
Packs	8*

- For 38.3 (transportation) testing the number of items that need to be tested is shown in the table above
  - The actual tests were summarised in a previous slide and include altitude, thermal, vibration…
- For battery packs there are a number of options, including one which does not require any testing of the pack if its built from modules that have passed the 38.3 testing providing some other requirements are met.
  - Expert advice is recommended to select the best route to approval

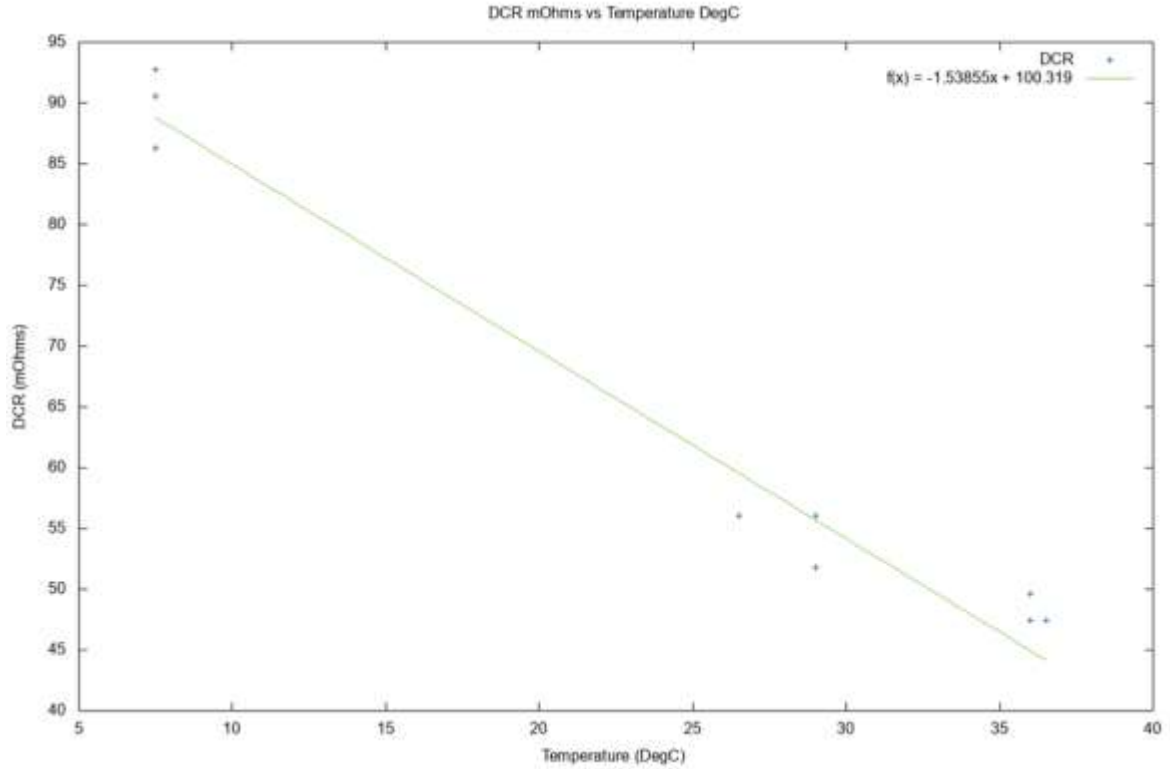
Performance Testing



Example of cell to cell variation.

- A large numbers of cells are normally tested which allows reasonable statistical information on the spread of the main cell parameters to be estimated.
  - The graph above shows two nominally identical cells exposed to the same current pulse, there is a 5.5% difference in these cells internal resistance.
    - This was the largest variation in the ~ 100 cells tested.

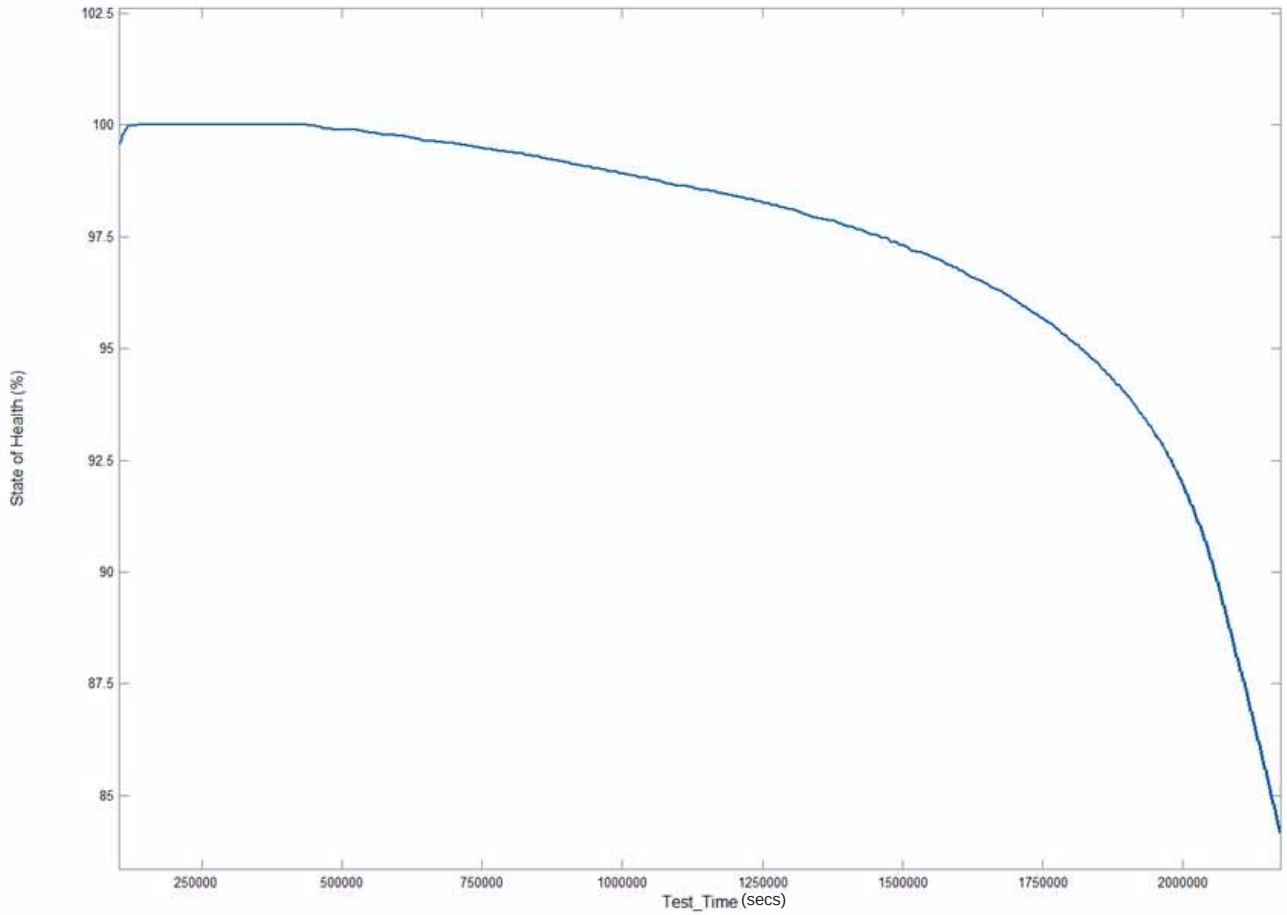
Performance Testing



Variation of cell internal resistance with temperature

- Module and pack performance testing can be easily extrapolated from cell test results
  - However, as temperature has a large impact on performance, testing is normally still done at module and pack level as the temperature distributions within these are difficult to accurately model.
  - As the weakest cell in a series chain defines the whole pack performance the cell level results can be used to predict the statistics for packs without needing to test a very large number of packs

Example (Cell) Life Test Data



- The above graph shows an example of cell capacity decaying under a repeated charge/discharge test
- Above graph is part of a Millbrook analysis of data at https://data.matr.io/ see Severson et al. Data-driven prediction of battery cycle life before capacity degradation. Nature Energy volume 4, pages 383–391 (2019)

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Conclusions

- A lot of testing is required on the cells and battery before they can be used in a car, and OEMs normally go well beyond what's required legally.
- The evidence from the field is that the industry is doing a very good job in creating safer vehicles for example xEVs have about 10X fewer fires per miles driven than combustion engine vehicles on average.
- Evidence is still mounting, but EV's fires overall are very similar to conventional vehicles.
  - For example on the 10th July this year the Austrian project "BRAFA – Fire Effects of Vehicles with Alternative Drive Systems", announced that their testing of 3 EV's and two diesel powered vehicles had shown that EV fires in Tunnels are not significantly different to those of conventional vehicles for people, the emergency services or in terms of damage to the tunnel itself.



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