HBM Prenscia Technology Day

Virtual Seminar Series

Automotive Battery Testing Capability and Best Practice

Presented by Dr. Peter Miller
Chief Engineer - Battery
Millbrook Proving Ground

Session #1: Electric Vehicle Battery Testing

Automotive Battery Testing Capability and Best Practice

Abstract

This presentation will start by giving an overview of the various automotive battery applications (from SLI to EV) and the battery requirements for each. It will then look at test methods and standards for automotive batteries for xEV's that cover abuse, performance and life and give some examples of these. Finally the split of testing between cells, modules and packs will be discussed.

About the presenter, Dr. Peter Miller

Peter joined Millbrook in 2018 as the Chief Engineer for Battery. At Millbrook, Peter provides expert knowledge and experience in the technical and practical aspects of battery technology. Peter played a key role in the preparation, set-up and launch of a brand new Battery Test Facility at Millbrook, which opened in 2019.

Previously he worked for Johnson Matthey Battery Systems for 6 years as Chief Electronics Technologist, prior to this he was Director - Electrical/Electronic Engineering at Ricardo a large automotive consultancy where he specialised in batteries.

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Automotive Battery Testing Capability and Best Practice

November 2020

Dr Peter Miller
Chief Engineer - Battery

"virtual" Prenscia Technology Day
3rd November 2020

www.millbrook.co.uk

Millbrook at a Glance

Millbrook is a leading global provider of independent and impartial test services and test systems.

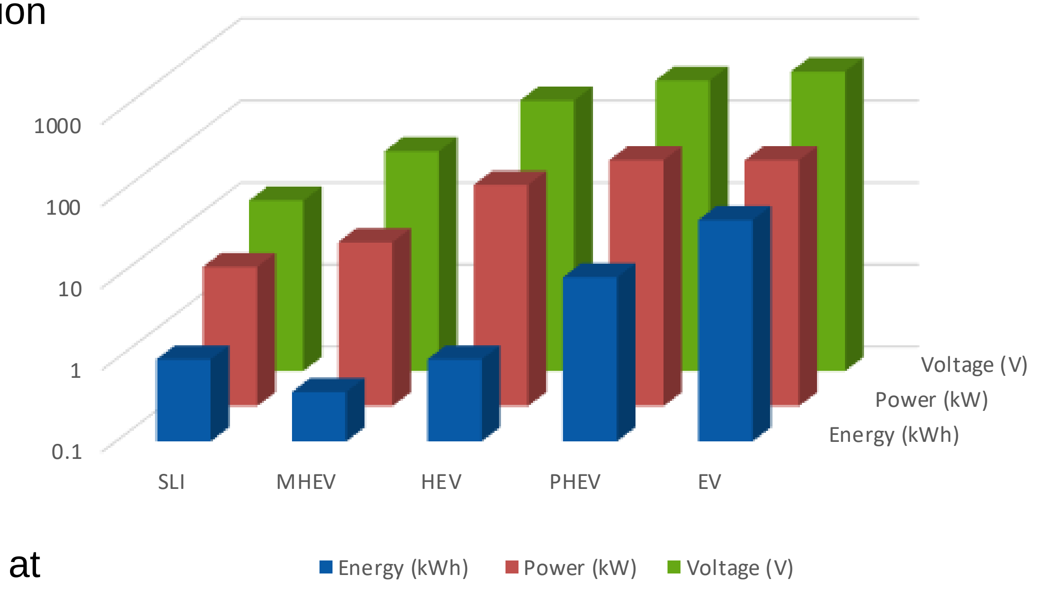
It is a leader in battery test techniques and facilities.

Overview

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

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)
- **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%
- **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%
- **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%).
- **EV (BEV)**
  - Lithium-ion battery 30-90kWh depending on range, 100-200kW
    - 300-800V



UK Sales Data to End of September 2020

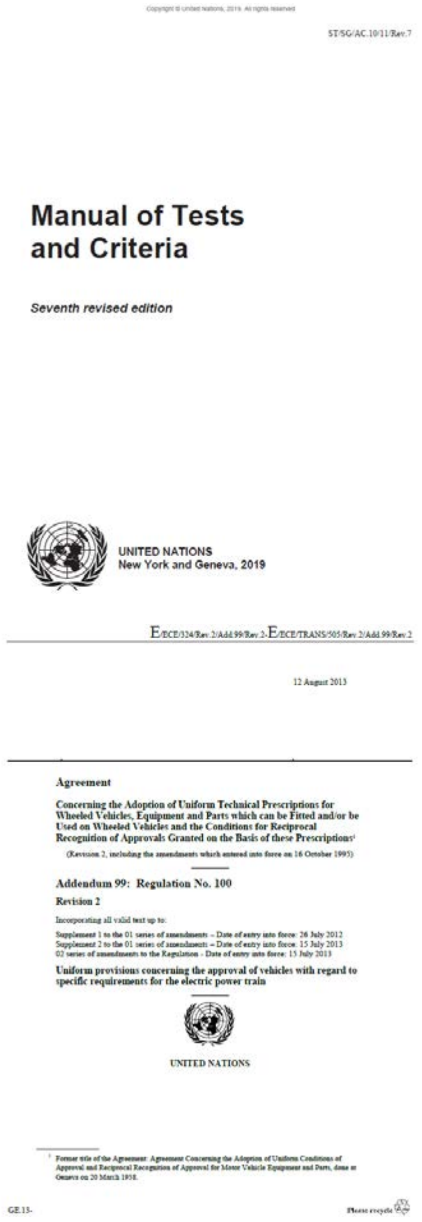
	YTD 2020	YTD 2019	% change	Market share 2020 (%)	Market share 2019 (%)
Diesel	209,093	478,147	-56.3	16.8	25.7
Petrol	719,908	1,204,719	-40.2	57.9	64.7
BEV	66,611	25,097	165.4	5.4	1.3
PHEV	42,277	23,015	83.7	3.4	1.2
HEV	83,993	77,679	8.1	6.8	4.2
MHEV diesel	44,351	21,731	104.1	3.6	1.2
MHEV petrol	77,423	31,883	142.8	6.2	1.7
Total	1,243,656	1,862,271	-33.2	100.0	100.0

Data provided by the SMMT

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


ST/SG/AC.10/11/Rev.7

Manual of Tests and Criteria

Seventh revised edition

UNITED NATIONS
New York and Geneva, 2019

E/ECE/324/Rev.2/Add.99/Rev.2−E/ECE/TRANS/505/Rev.2/Add.99/Rev.2

12 August 2013

Agreement

Concerning the Adoption of Uniform Technical Prescriptions for Wheeled Vehicles, Equipment and Parts which can be Fitted and/or be Used on Wheeled Vehicles and the Conditions for Reciprocal Recognition of Approvals Granted on the Basis of these Prescriptions

Addendum 99: Regulation No. 100

Revision 2

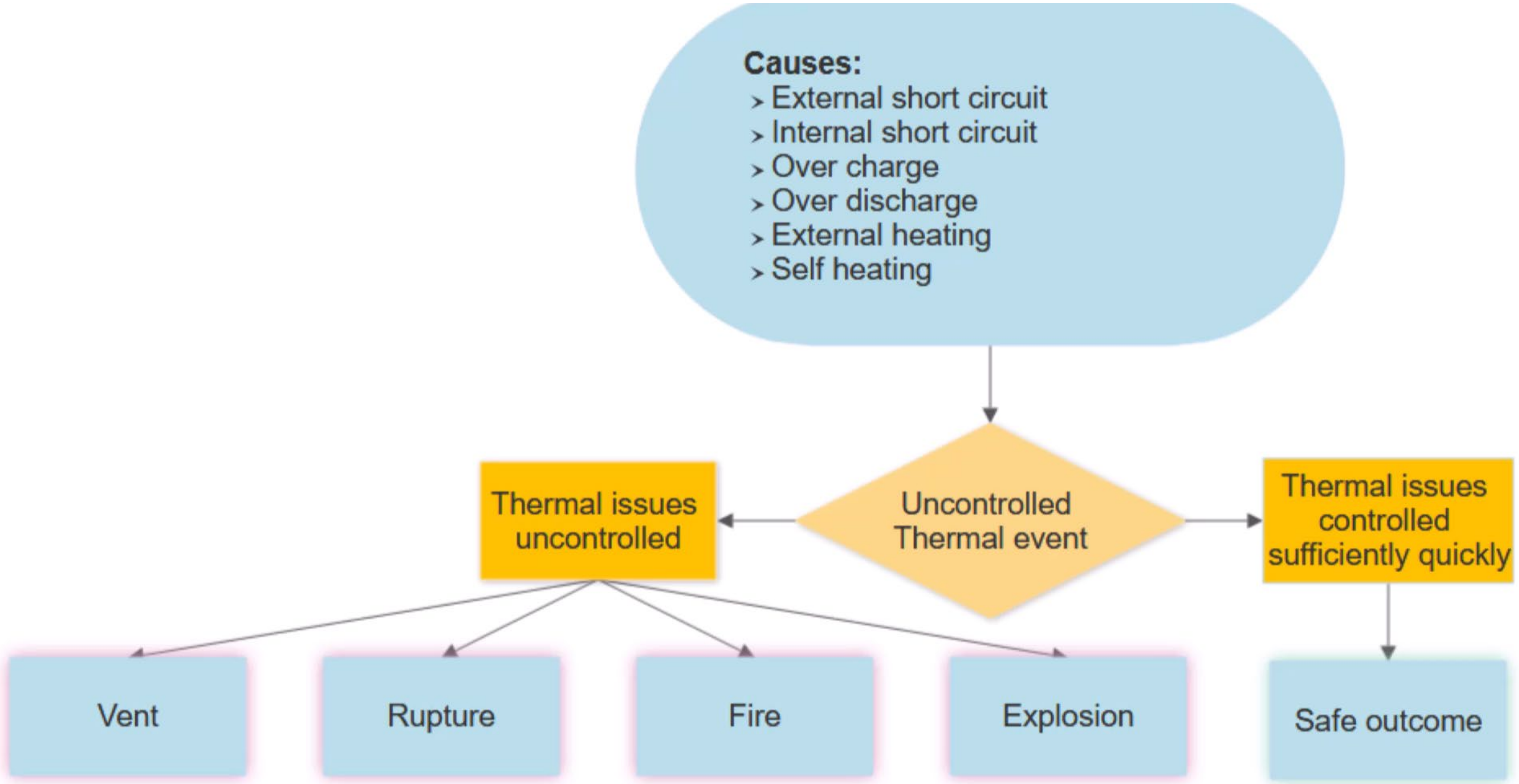
Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train

UNITED NATIONS

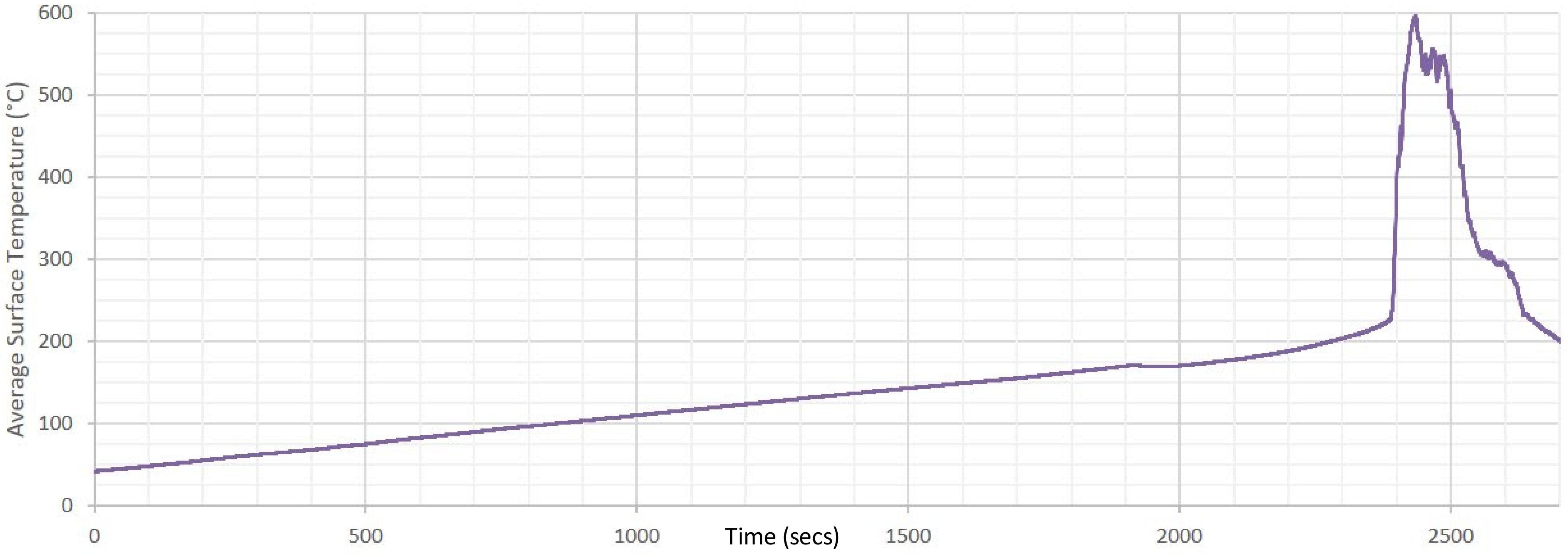
Summary of Legislative Tests for Automotive Battery Packs

Type of Test	UN 38.3	UN 38.3 Duration	Reg. 100	Reg. 100 Duration
Altitude	T1: 15000m	~6 hrs	n/a	
Thermal	T2:+72/-40^{o}C	~24 hrs	+60/-40^{o}C	~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

Lithium-Ion Safety : Causes and Hazards



Thermal Runaway



- The graph above was obtained by slowly heating a NMC lithium ion cell
  - NMC is the most common lithium-ion chemistry current 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 the photograph on the 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 Millbrook

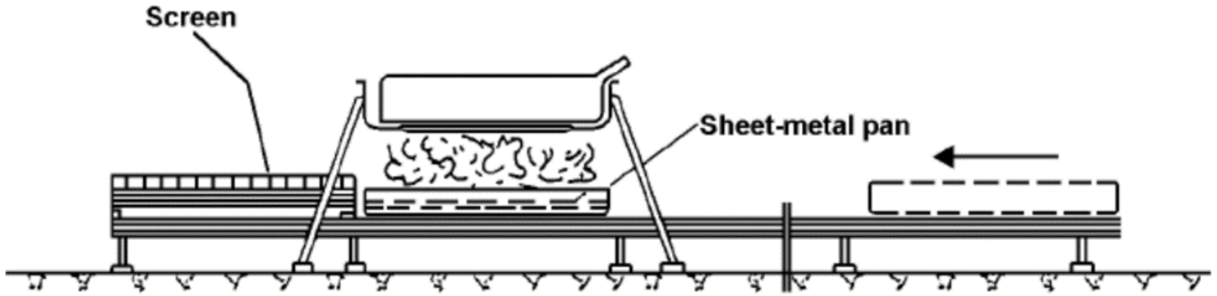
Thermal Runaway

- 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

Example Test: Regulation 100 Fire Resistance



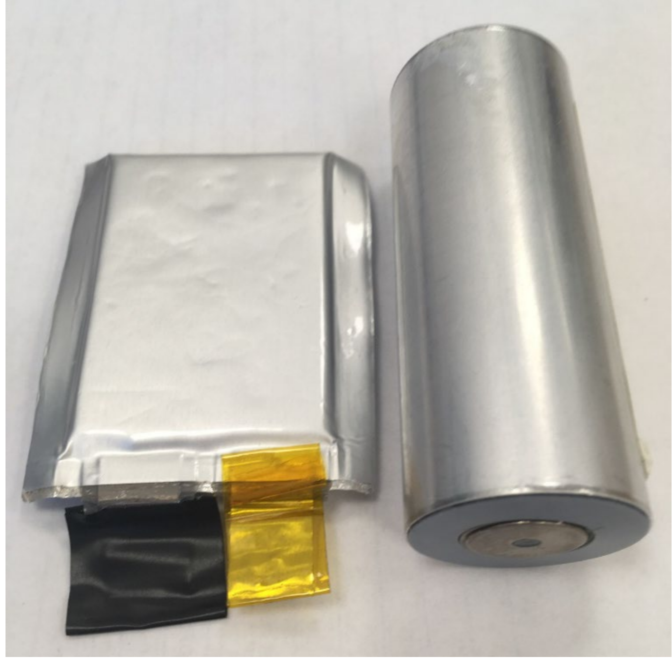
- This test is designed to simulate a crash between a conventional vehicle and an EV
    - Petrol leaks from the conventional vehicle and catches fire underneath the EV
- This test is probably more severe than would actually be seen when the pack is mounted inside a vehicle
- Photograph shows a fire test in progress at Millbrook

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

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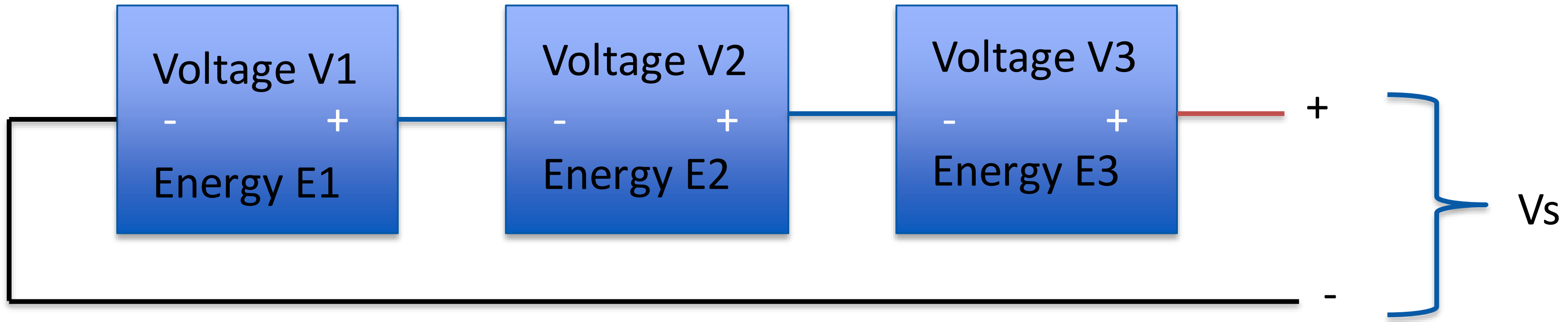
- As an example the BMW i3 pack (42kWh) contains
  - 96 cells each of 120Ah
  - Each module has 12 cells giving a nominal 48V
  - The pack has 8 modules
- The Tesla model S 85kWh pack contains
  - 7104 cells each of 3.2Ah
  - Each module has 444 cells (6s74p) giving a nominal 24V
  - The pack has 16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



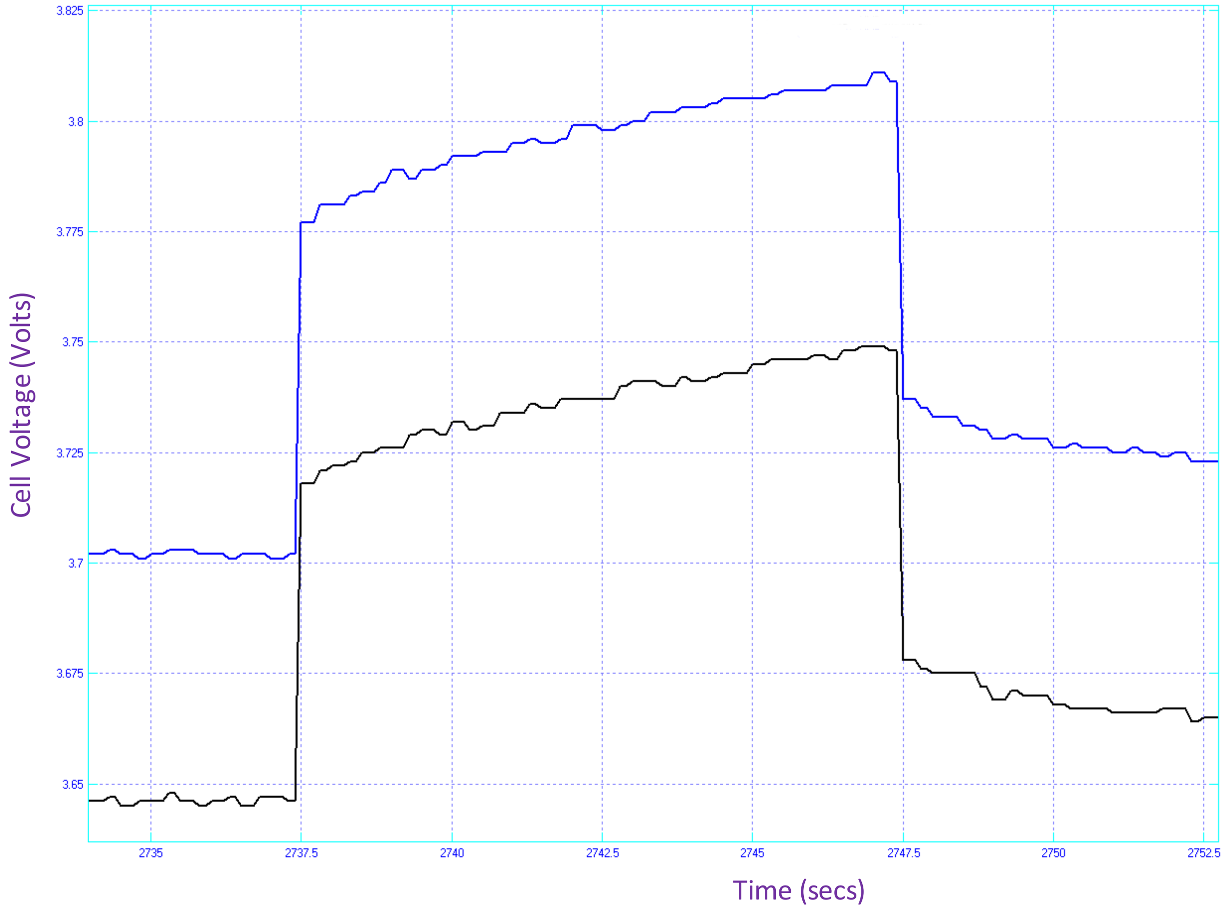
- The diagram above shows 3 cells (or modules) in series
  - The resultant voltage is Vs=V1+V2+V3
  - The total energy is 3* the smallest of (E1,E2,E3)
    - Because of this the packs capacity is limited by the "weakest cell"
      - in this case the cell with the smallest capacity (energy), but the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

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

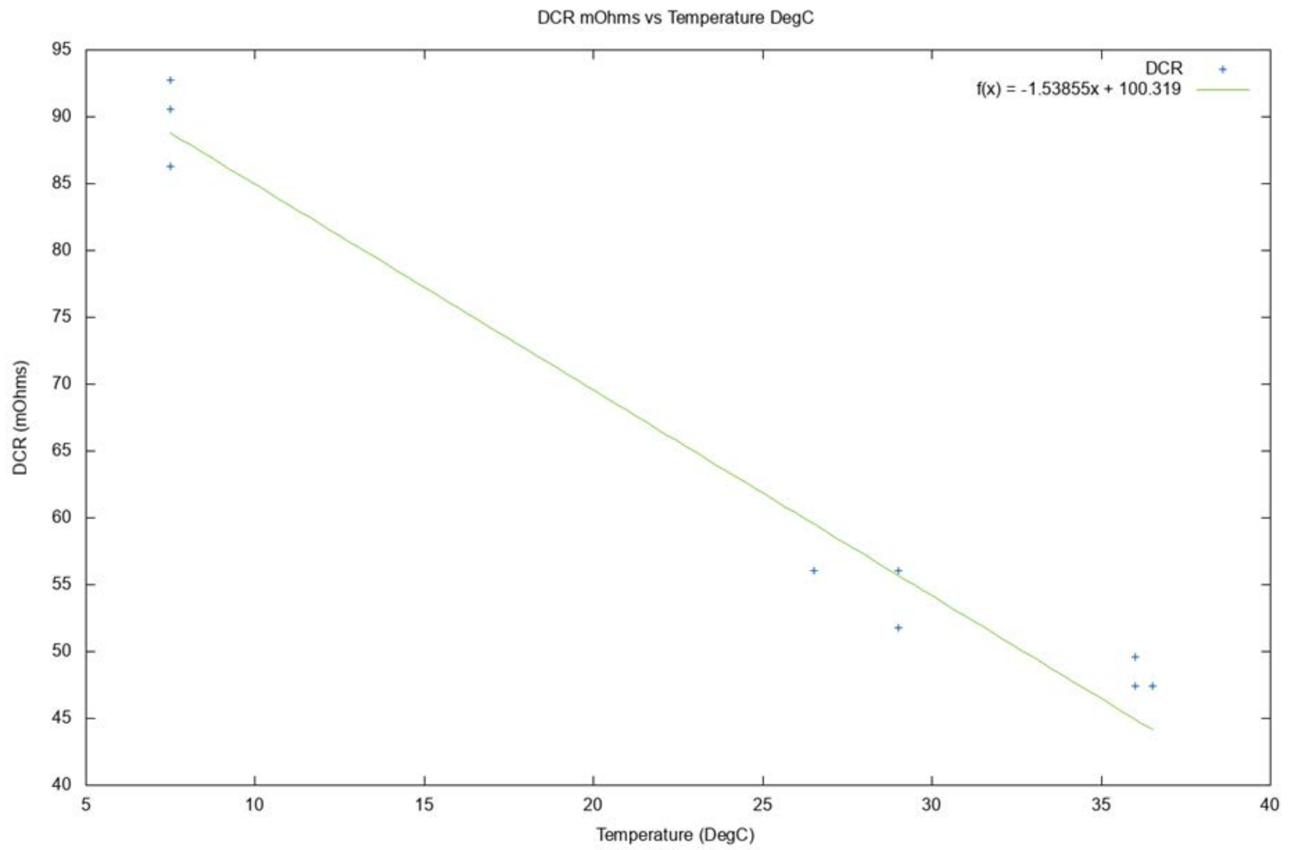
Performance Testing



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.

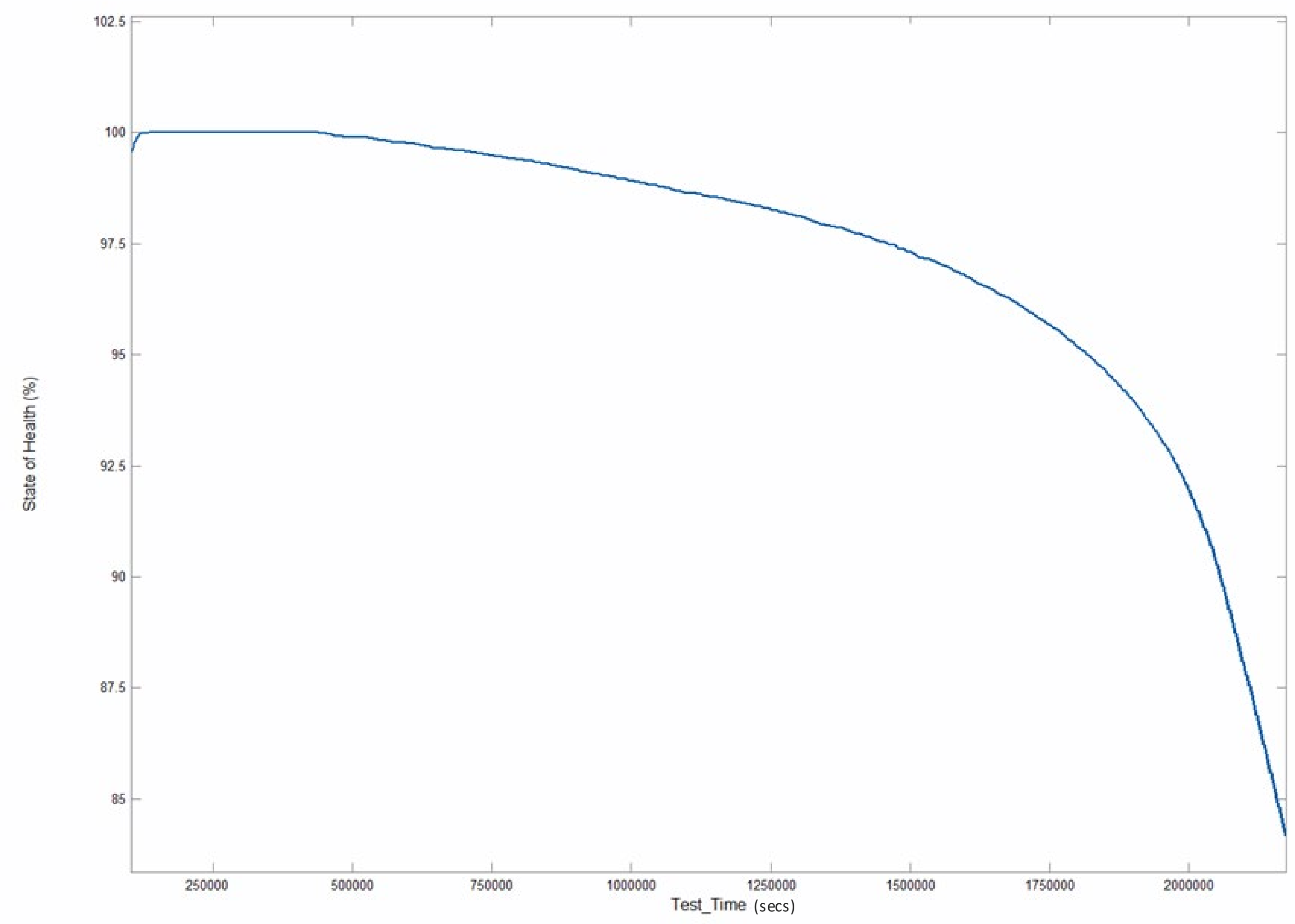
Performance Testing



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)

Conclusions

- Safety, performance and life testing is required for battery packs, but testing cells and modules allows this to be better defined
    - Life testing normally needs the most packs/testing time
    - A good test house (like Millbrook) can help you to develop and execute optimised test plans

- The evidence from the field is that the industry is doing a very good job in creating safer vehicles for example xEV's have about 10X fewer fires per miles driven than combustion engine vehicles on average.
- Evidence of adequate battery life will take longer to accumulate
    - In October 2019 Toyota extended its hybrid battery warranty to 10 years/150,000 miles (up from 8 years/100,000 miles), and this is extended to 15 years if you get your services at a Toyota dealer.
    - Hyundai's Ioniq Electric and the KONA Electric, Kia's Niro EV are all covered with lifetime warranties on batteries, regardless of mileage or year of purchase.

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www.millbrook.co.uk/ev-battery-testing

Q&A

- Mpho Lencwe (Transnet, South Africa)
  - How does Energy relate to range?
    - *Basically in an EV more energy means more range. Don't forget in an EV all energy comes from the battery so using a heater for example will reduce the available energy for propulsion.*
  - What standard do you use for cycle life testing?
    - *This depends on the application and the customer as normally life testing is not a legal requirement.*

- David Brown (Cummins Turbo Technologies, UK)
  - Is there an easy way to accelerate testing of batteries (e.g. temperature) ?
    - *There is no easy way, temperature can be used in a limited way but as the chemical reactions change with temperature this can give misleading results.*

- Prashant Tripathi (Mahindra Electric Mobility Limited, India)
  - What's new to have dynamic test more involved in battery pack testing including functions?
    - *Dynamic testing either based on vehicle simulations or real measurements is clearly a key part of functional testing.*
  - To get more information and failure, should we do high discharge on a battery pack like 3.5C discharge on cell?
    - *High discharge rates are not normally used to create a cell failure as its normally simpler to do this just by heating the cell.*

Q&A

- Muhammad Afzal (Omnicell, USA)
  - How do you quantify Reliability of EV battery for 10 years or 15 years?
    - *The same statistics apply as testing other things – you can work out the number of test hours needed. However as noted above its hard to get large acceleration factors by increasing the temperature which is what done with many other items. This means tests need to be automated and run 24/7/365.*
  - Commercially which OEM (Tesla VS. RIVIAN VS BMD) better?
    - *I am sorry this is commercially sensitive information.*

- Md Uddin (Central Queensland University, Australia)
  - What is the maintainability of the battery? – Is it generally discarded or repaired?
    - *For automotive applications the battery is designed to last the life of the vehicle. It is normally possible to do some repairs but this is a specialist operation. “2nd life” uses are also being investigated for battery packs that are no longer suitable for use in a vehicle.*

- Peter Arrowsmith (BOTE Consulting, Canada)
  - Please comment on life testing and test results: accelerating stress factors for an ALT (accelerated life test)?
    - *See question from Muhammad Afzal above.*
  - Is testing based on time to failure and/or degradation? What outputs are monitored for degradation?
    - *Its normally to a defined degradation in either power or energy. Typically 80% of initial energy is used.*

Q&A

- Derik Cloete (LEAP Consultancy, Australia)
  - What about battery life at extreme low temperatures?
    - *Most Li-ion Batteries don’t perform well at low temperatures (< 0). Charging at low temperatures could impact the life but normally that is managed at the system level.*

- Robert de Chazal (Arrival, UK)
  - How does fast charging effect a batteries life?
    - *This depends on the battery chemistry and design – in some cases it has no impact on life while in other it can have a big impact.*
  - How can you accelerate a fast charging test?
    - *Fast charging testing tests to be quite quick (compared to normal charging). Normally initial tests would be done at cell level which would confirm the chemistry was suitable and show what was required in the module/pack for good life.*

- Phil Irving (UK)
  - What is the variability battery to battery of the performance curves you have shown?
    - *It’s mainly due to manufacturing variability of the cells.*

Q&A

- Ata Toker (TOGG, Turkey)
  - Apart from regulative ones, do you conduct vibrational fatigue test that represents whole lifetime of the vehicle?
    - *Yes, in fact Millbrook has published some papers based on extrapolating real world usage into accelerated vibration profiles.*

- Jonas Rolfart (Husqvarna, Sweden)
  - We experience UN38.3 to be a bit extreme with regards to amplitude and frequency range. Do you have any information of any change in the standard?
    - *Most people would agree that 38.3 is quite harsh, but that's because it has to cover every possible situation that may be seen in transport.*

- Filmon Tsegai (AeroVironment, USA)
  - Do you accelerate thermal and vibration stresses together?
    - *It's still unusual to do this for battery packs, as its difficult to merge the different acceleration factors together in a way that guarantees the results will be valid.*

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Q&A

- Lazaro Luna (Innova, Columbia)
  - Any difference when testing battery banks for PV photovoltaic applications?
    - *Many of the tests are the same. Some tests would have different (normally lower) limits (eg vibration and you may not need shock tests.*

- Kieran Roberts-Bee (Dennis Eagle, UK)
  - Is there an equivalent approximate mileage life for an EV battery and how does this compare to the life of the other components in a vehicle vs an ICE powered vehicle?
    - *As with a conventional vehicle its as much about how the vehicle has been driven / used (charged in the case of an EV) as the mileage.*
  - Does there become a point where an EV will rapidly lose value due to high mileage?
    - *Normally "SOH" ("State of Health") is available on the dashboard and this gives an indication of the battery's remaining life. When the remaining life is low, especially if the car is quite old then its reasonable to expect the car will rapidly lose value. In general depreciation curves for EV's are improving and getting closer to conventional vehicles and that's a trend we expect to continue.*

- Pasquale Digesu (CNH Industrial, Italy)
  - What really happens inside the battery (which change) that reduce the life with thermal wrong use?
    - *The chemistry inside the battery is quite complex and still not fully understood. Google will find many papers that will help you better understand this.*

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Q&A

- Berk Ozoguz (TOGG, Turkey)
  - What should be the way of charging while running a vehicle level durability test?
    - *We would always recommend trying to duplicate real world usage as much as possible which is likely to involve a mixture of charging rates.*
  - There will be timing pressure to finish the testing asap but fast charging may affect the life/performance etc. - what is your advice?
    - *See answer above.*

- Dietrich Meyer (MAN, Germany)
  - For which tests do you use simulation tools for preparation?
    - *Most tests are well defined so can “just be done”. Crash tests at the pack level are one area where simulation may be useful before the test.*

Q&A

- Dheepanraj PV (KONE, India)
  - Can ultracapacitors be a replacement to Li-ion batteries?
    - *Ultracapacitors normally store much less energy that batteries so they are mainly used in high power low energy situations.*
  - Will it be the same performance when compared with batteries?
    - *See answer above. In a few specialized cases ultracapacitors can be combined with batteries to give higher powers than the batteries alone.*
  - Should we use ultracapacitors instead of batteries? - How can they be tested?
    - *It is not for me to say whether you should use ultracapacitors or batteries, you should determine what is appropriate for your application.*
    - *The tests for ultracapacitors are very similar to those for batteries, so Millbrook are able to test them if required*

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