# Battery Basics

4AT060 / 5AT010

Steven Wilkins, PhD
Assistant Professor , EPE – EE

Electrical Engineering, Electromechanics and Power Electronics Department

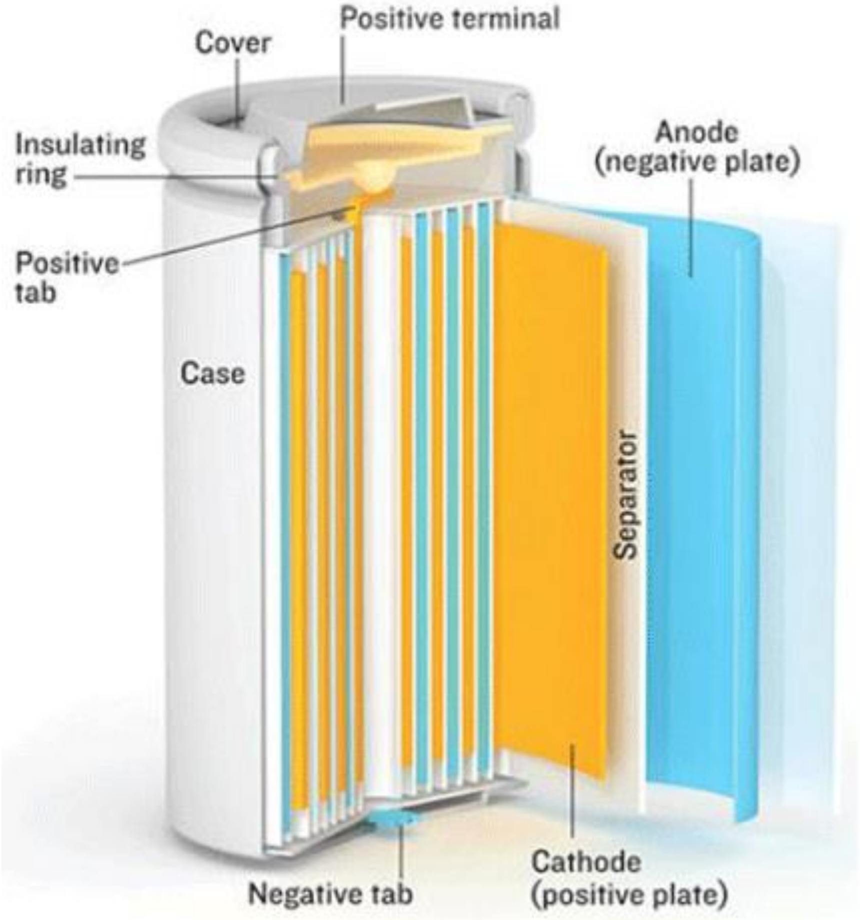
EINDHOVEN UNIVERSITY OF TECHNOLOGY

# Lecture Objectives

- Provide a basic overview of battery technology
- Provide understanding of the modelling of batteries
- Understand how to create basic thermal modelling
- Provide an overview of battery types and battery systems

# Battery Fundamentals

# Electrochemistry Fundamentals

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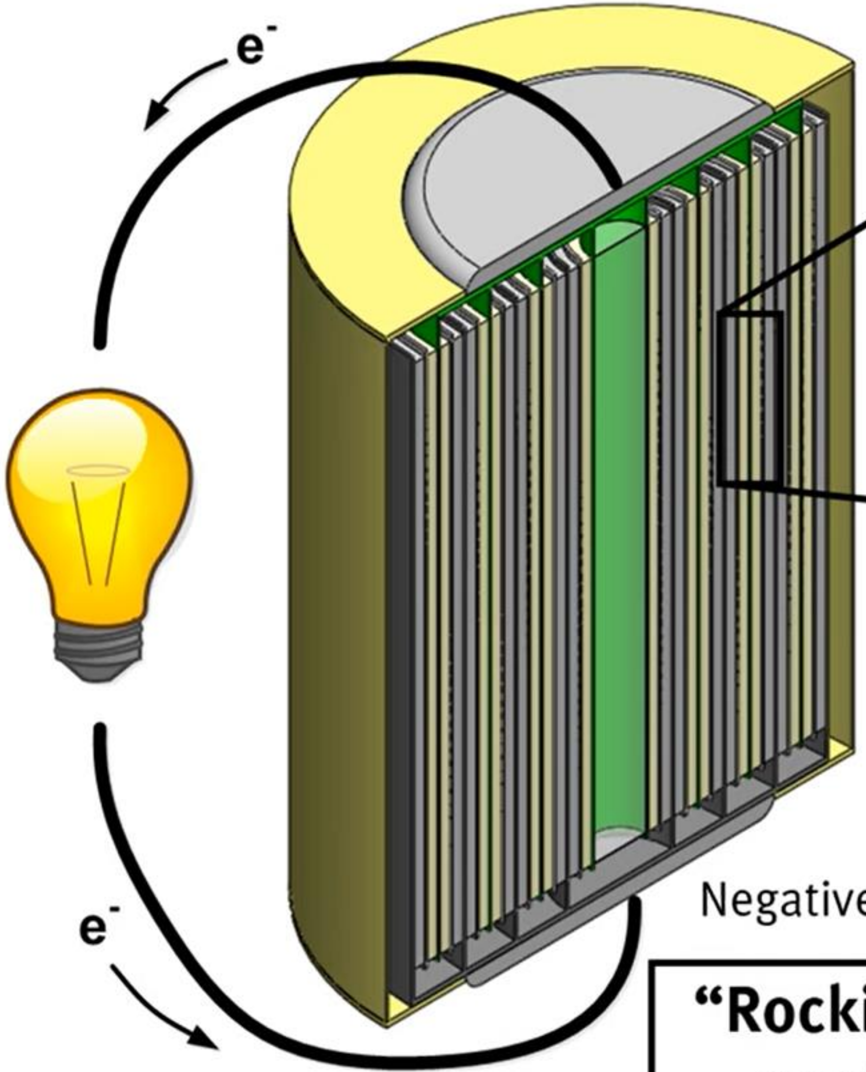
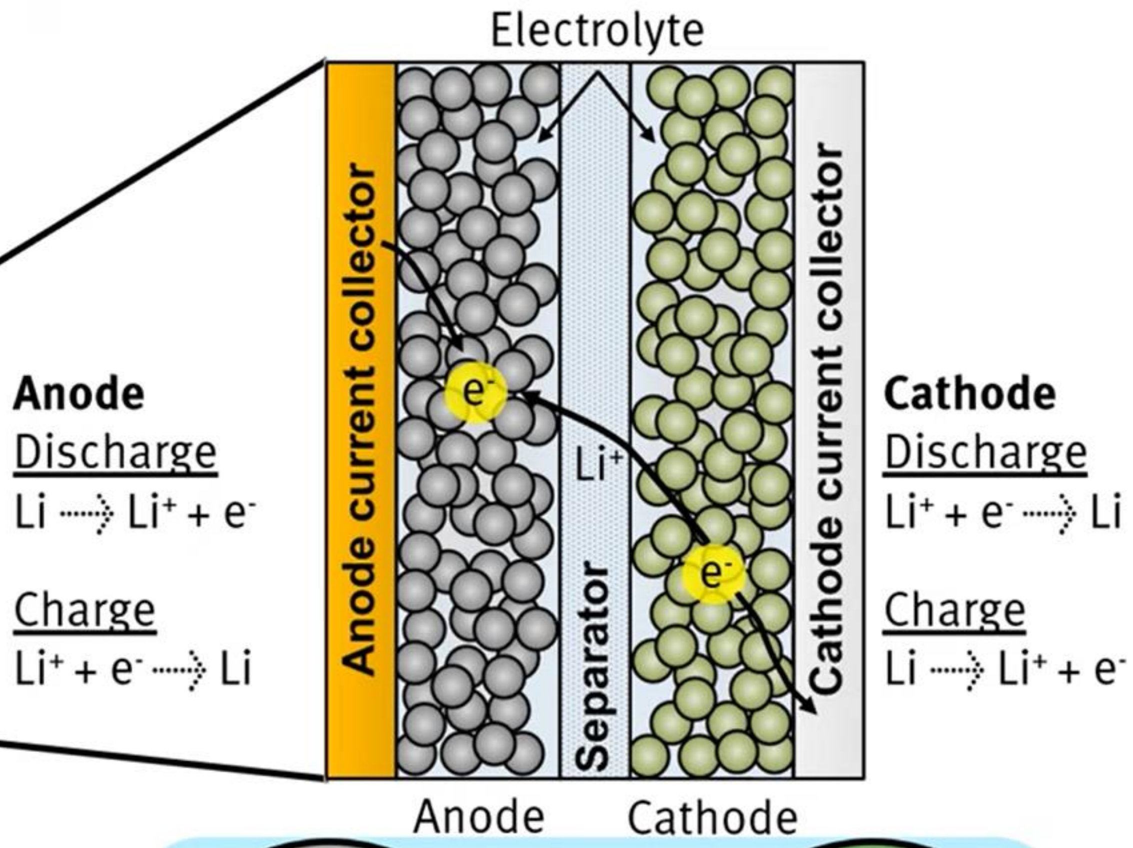
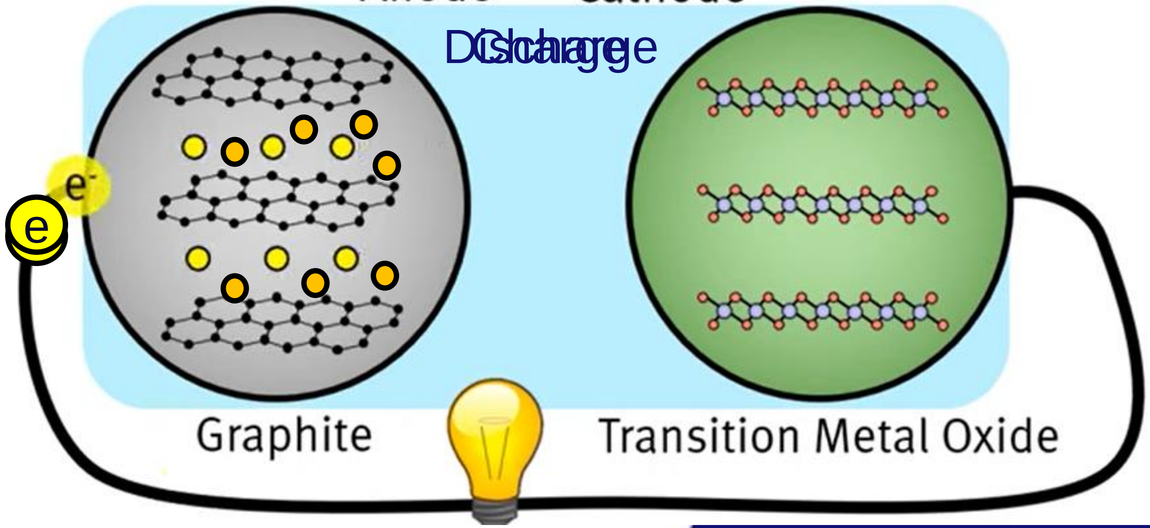
# How does a battery work?




**“Rocking chair” mechanism**

Adapted from Billy Wu

# Battery Fundamentals

**The negative electrode: Often a metal or an alloy.**

- During discharge, gives up electrons to external circuit, is oxidized (OIL: “Oxidation is Loss (of electrons)”).
- During charge, accepts electrons from external circuit, is reduced (RIG: “Reduction is Gain (of electrons)”).
- During discharge, it is the anode.

**The positive electrode: Often a metallic oxide, or sulfide**.

- During discharge, accepts electrons from circuit, is reduced.
- During charge, gives up electrons to external circuit, is oxidized.
- During discharge, it is the cathode.

# Basic Terminology

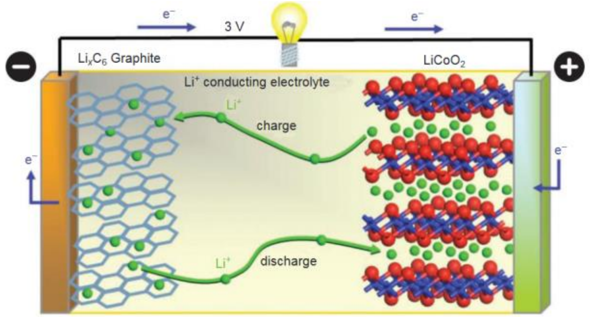
- **Irreversible reaction:** **"primary cell"**
- **Primary cell is discharged only once**

- **Reversible reaction:** **"secondary cell"**
- **Secondary cell can be charged and discharged in cycle**

- **Single use:** **"reserve cell"**
- **Requires activation procedure**

# Battery Fundamentals

- The electrolyte (the ionic conductor) provides the medium for internal ion charge transfer between the electrodes.
  - The electrolyte is typically a solvent containing dissolved chemicals
  - It must be an electronic insulator to avoid self discharge.
    - Cations are ions with net positive charge: during discharge they move through the electrolyte toward the positive electrode.
    - Anions are ions with net negative charge: during discharge they move through the electrolyte toward the negative electrode.
  - Cells using aqueous (containing water) electrolytes are limited to less than 2 V because the oxygen and hydrogen in water dissociate in the presence of higher voltages.
  - Lithium batteries use non-aqueous electrolytes as their overall voltages are above 2V.
- The separator electrically isolates the positive and negative electrodes to avoid self discharge of the cell.

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# Battery Fundamentals

The charge process

- In primary cells, this electrochemical reaction is not reversible. During discharge, the chemical compounds are permanently changed and electrical energy is released until the original compounds are completely exhausted. Primary cells can be used only once.
- In secondary cells, this electrochemical reaction is reversible. The original chemical compounds can be reconstituted by the application of an electrical potential between the electrodes, injecting energy into the cell.
- Such cells can be discharged and recharged many times. During charge, cations move from positive to negative electrode through electrolyte; electrons move from positive to negative electrode through external circuit.
- The energy “pumped” into the cell transforms the active chemicals back to their original state.

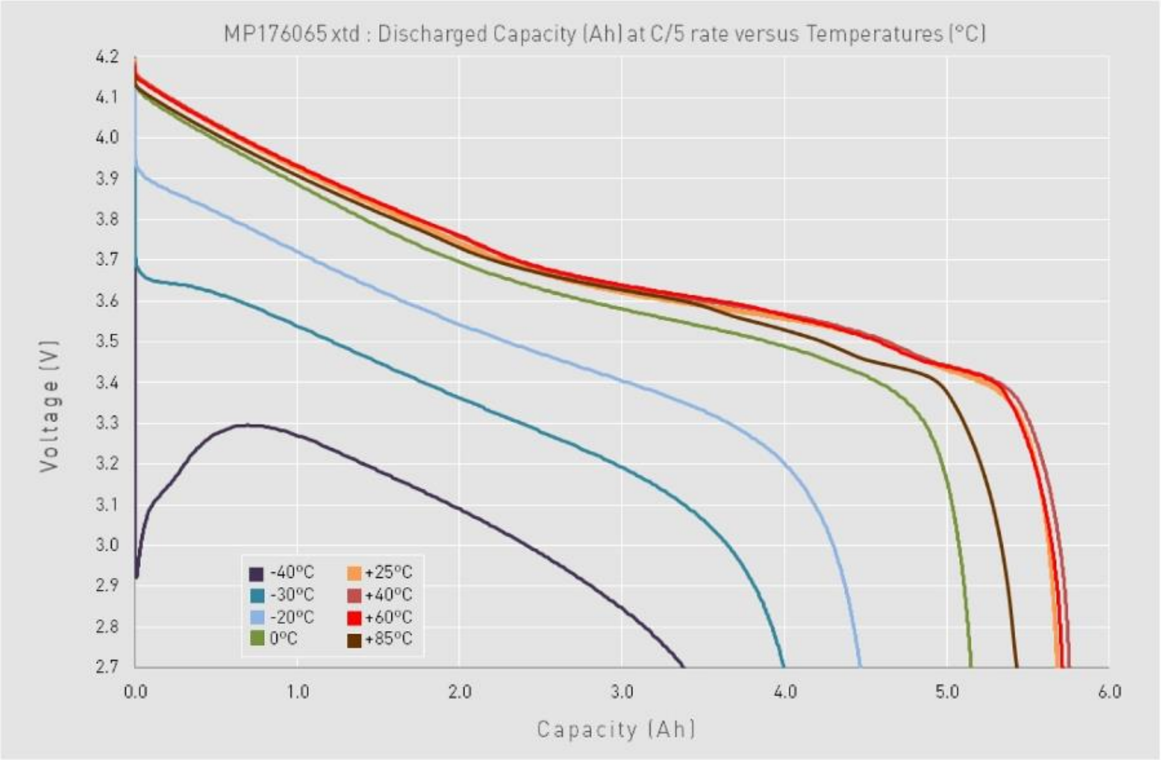
The discharge process

- Electrochemical potential energy at the negative electrode favors a chemical process that would release electrons into the external circuit and positively charged ions into the electrolyte.
- Also, electrochemical potential at the positive electrode favors a chemical process that would accept both electrons from the external circuit and positively charged ions from the electrolyte.
- The resulting electrical pressure or potential difference between the terminals is called the cell voltage or electromotive force (EMF).
- Cell performs work when an external circuit is completed, converting stored chemical potential energy into electrical energy on demand.

# Terminology

# Cell Potential

- **Potential (voltage) of the cell depends on type of oxidation-reduction reaction and varies on operating conditions**
- **Nominal voltage usually refers to (average) discharge voltage at specified load**
- **The voltage is based on the potential difference of the cathode and anode (see later)**
- **At rest state, based on SOC, and temperature**

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# Energy and Power per Unit Mass and Volume

- Specific Energy: E/m
- Units: Wh/kg
- Energy density (volumetric): E/v
- Units: Wh/l

Normally measured by discharge from full to empty state.

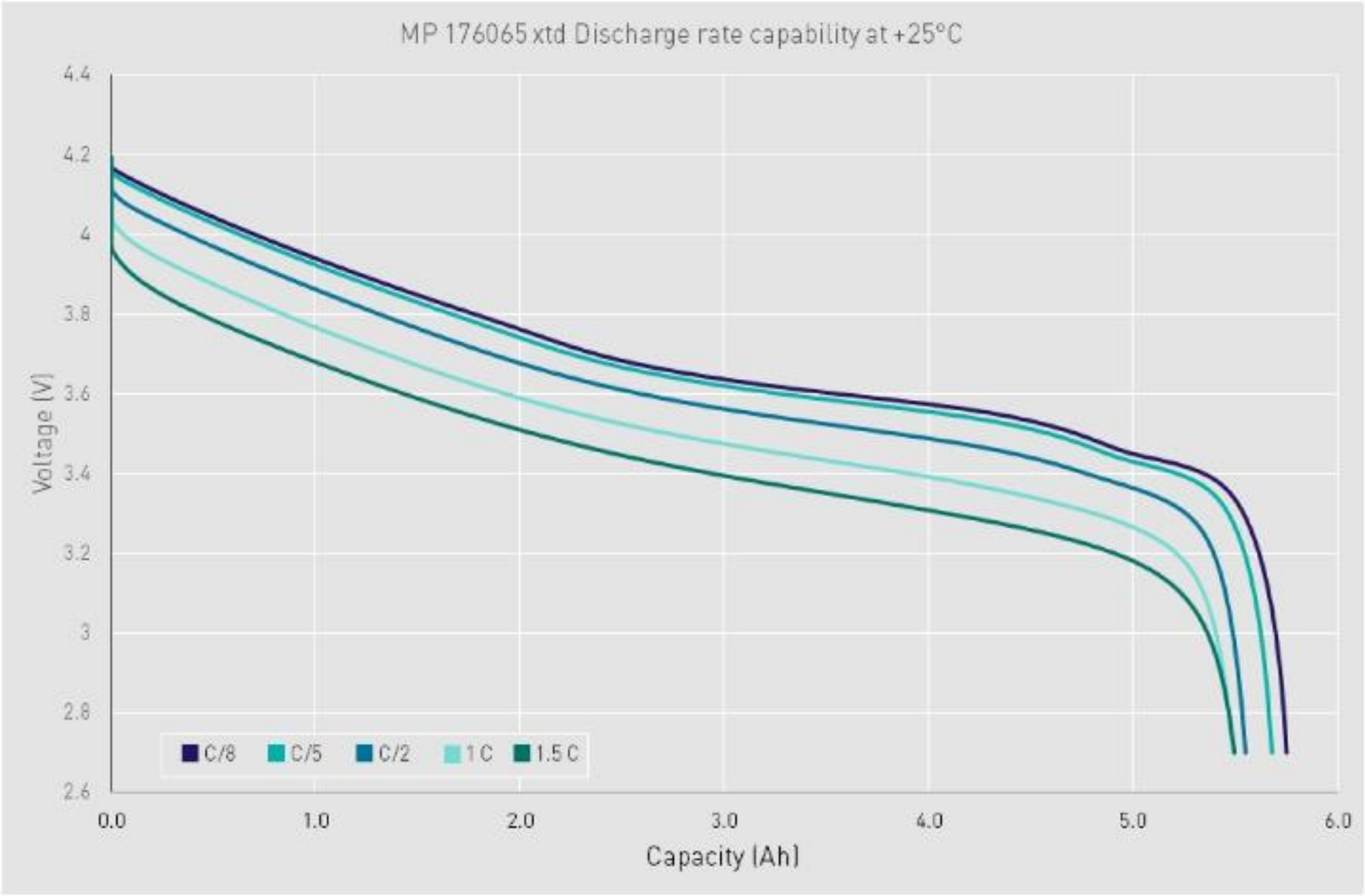
- Specific Power: P/m
- Units: W/kg
- Power density (volumetric): P/v
- Units: W/l

Normally measured by short pulse discharge and depends on state of charge.

# Specific Units of Measure

- **State of Charge (SoC)**
- **The fraction of the total electrical charge stored in a battery that is available for discharging at a certain point of time. Usually measured in percentages (fractions).**
- **Depth of Discharge (DoD):**
- **The fraction of the total electrical charge stored in a battery that had been extracted at a certain point of time. Usually measured in percentages (fractions).**
- **Depth of Charge (DoC):**
- **The fraction of the total electrical charge supplied to the battery up to a certain point of time. Usually measured in percentages (fractions). Note that charging current can be partially lost due to side reactions.**
- **Percentages mentioned above usually relate to nominal capacity, but exact terminology depends on context**
- **State of Energy (SoE)**
- **The fraction of the total electrical energy stored in a battery that is available for use at a certain point of time. Usually measured in percentages (fractions).** *NOTE: this is not the same as SOC, but can be proportional based on similar discharge powers

# Specific Units of Measure - SOE




The available energy is a function of the power of extraction – since the voltage is influenced by the current drawn

Higher power = less capacity

Lithium-ion batteries in use: 5 more tips for a longer lifespan | Saft | Batteries to energize the world (saftbatteries.com)

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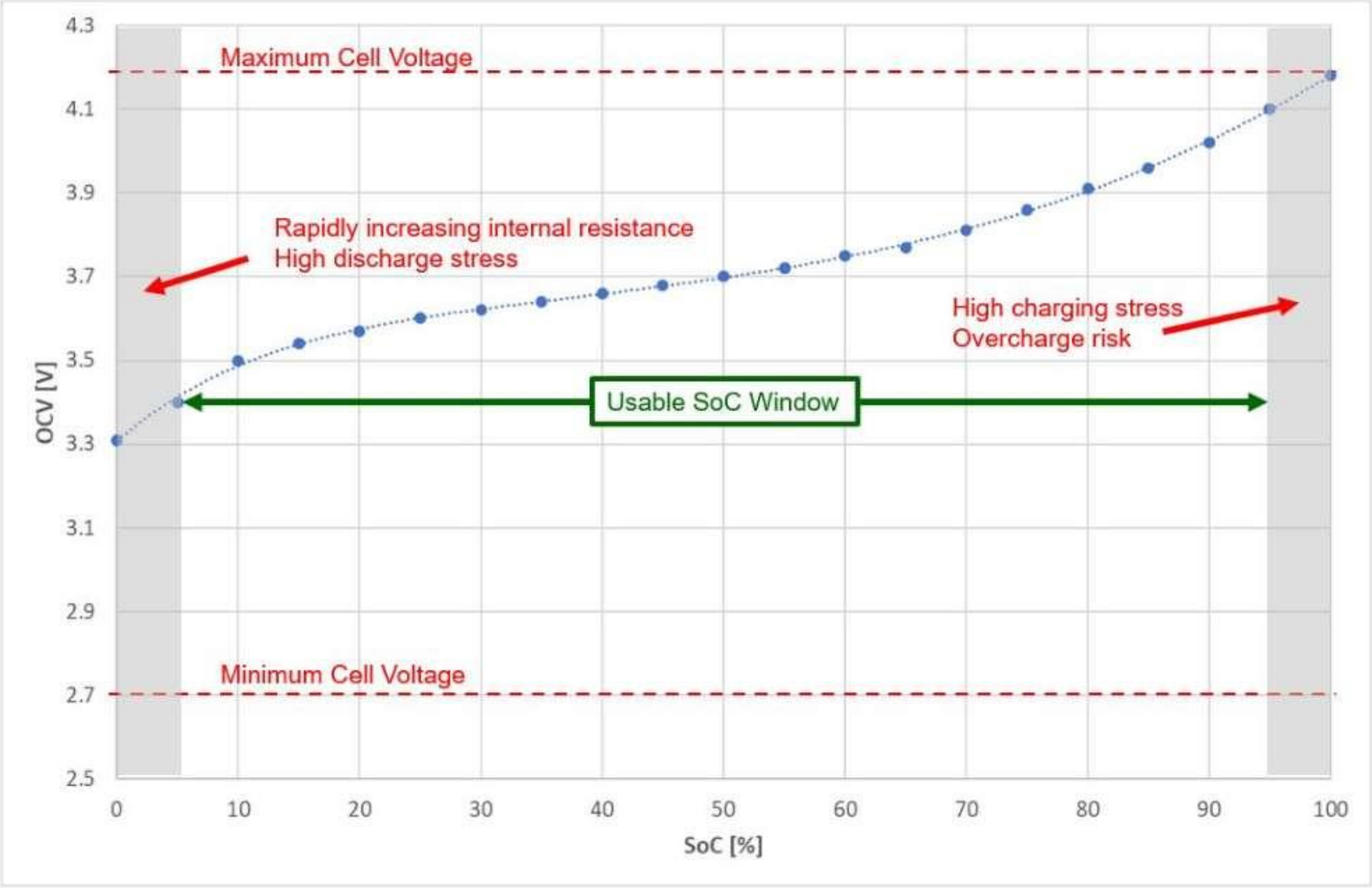
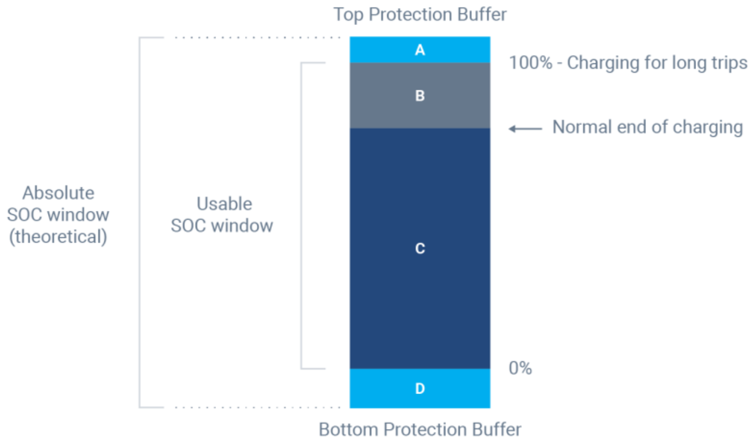
# Usable Window

- **For health and performance reasons, not all the capacity is available**




Also: operation in the region which can withstand Constant Current charging improves charging speeds (region C above)

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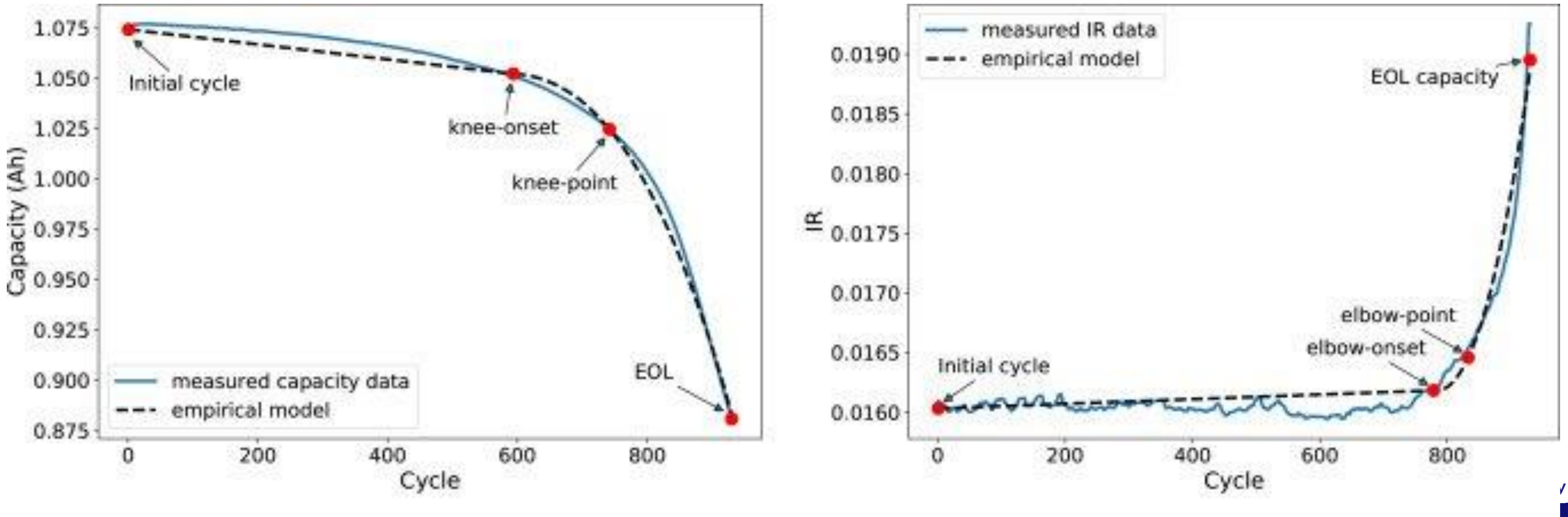
# Specific Units of Measure - SOH

- **State of Health (SOH)**
- **Typically the fraction of capacity relative to the original nominal capacity**
- **Can also relate to the resistance**
- **End of Life typically 80% of the original capacity (and/or 20% increase in impedance)**
- **NOTE: ageing of batteries can be often non-linear (elbows and knees!)**




(a) capacity (b) internal resistance

# Terminology – Packs, Modules, Cells

- Cells are the smallest individual electrochemical unit, and deliver a voltage that depends on the cell chemistry.
- There are primary (single use) and secondary (rechargeable) cells.
- A cell is different from a battery, but many people use the term “battery” to describe any electrochemical energy source, even if it is a single cell, and this can lead to confusion.

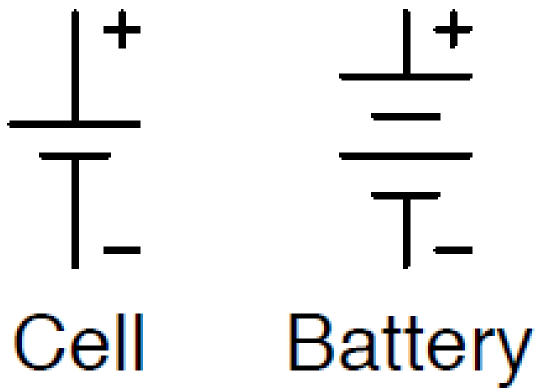
# Terminology

- **Cell**: combination of two electrodes immersed in the electrolyte, usually enclosed in single casing
- To reach desirable energy, voltage or power several separate cells are combined in (battery) **packs**
- It is common to use smaller packs to combine those into larger packs. In this case word **module** is used

- **Batteries and battery packs** are made up from groups of **cells**.
- Groups of cells are usually referred to as **modules.**
- Sometimes these are packaged in a single physical unit, as in 12V lead-acid batteries, which comprise six 2V cells in series, or in many high-capacity lithium-ion batteries, where a number of cells are wired in parallel in a single package.
- Other times, the connections are external to the cells.

# Terminology – Batteries/Cells

- We use schematic symbols to represent cells and batteries in a circuit diagram.
- Cell (nominal) voltage depends on the combination of active chemicals used in the cell.
  - For many nickel-based cells (e.g., NiCad, NiMH), this is 1.2V.
  - For many lithium-based cells, this is over 3V.



# Terminology – C-Rate

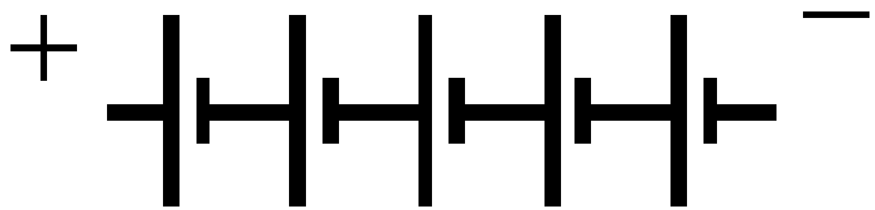
- Cell (nominal) capacity specifies the quantity of charge, in ampere hours (Ah), that the battery is rated to hold.
- The C rate is a relative measure of cell current. It is the constant current charge or discharge rate that the cell can sustain for one hour.
  - A 20Ah cell should be able to deliver 20A (“1C”) for 1h or 2A (“C/10”) for about 10 h (but, the relationship is not strictly linear).
  - If the cell is discharged at a 10C rate, it will be completely discharged in about six minutes.

# Terminology - kWh

- A cell stores energy in electrochemical form, which it can later release to do work.
- The total energy storage capacity of a cell is roughly its nominal voltage multiplied by its nominal capacity (Wh or kWh).
- The energy release rate is the cell's instantaneous power (W or kW).

# Terminology – Series Ah vs. kWh

- When cells are connected in series, the battery voltage is the sum of the individual cell voltages, but the capacity is the same for the chain since the same current passes through all of the cells.
  - A battery constructed from five 3V, 20Ah cells in series will have a voltage of 15 V, a capacity of 20 Ah, and energy capacity of 300 Wh.

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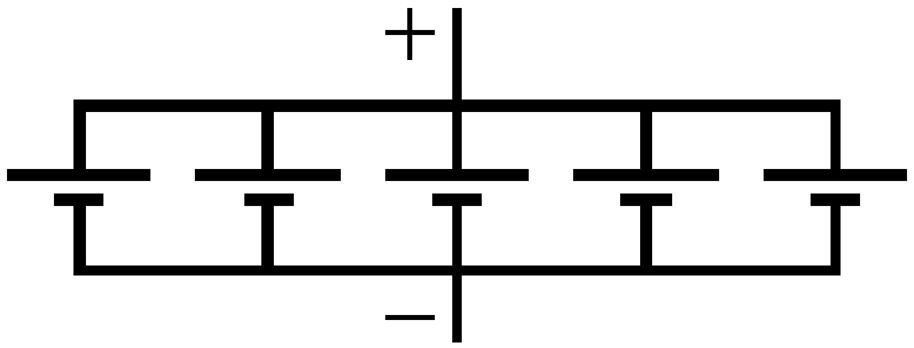
# Terminology – Parallel Ah vs. kWh

- When cells are connected in parallel, the battery voltage is equal to the cells' voltage, but the capacity is the sum of the cells' capacities, since the battery current is the sum of all the cell currents.
  - The battery will have a voltage of 3V, a capacity of 100Ah, and energy capacity of 300Wh.

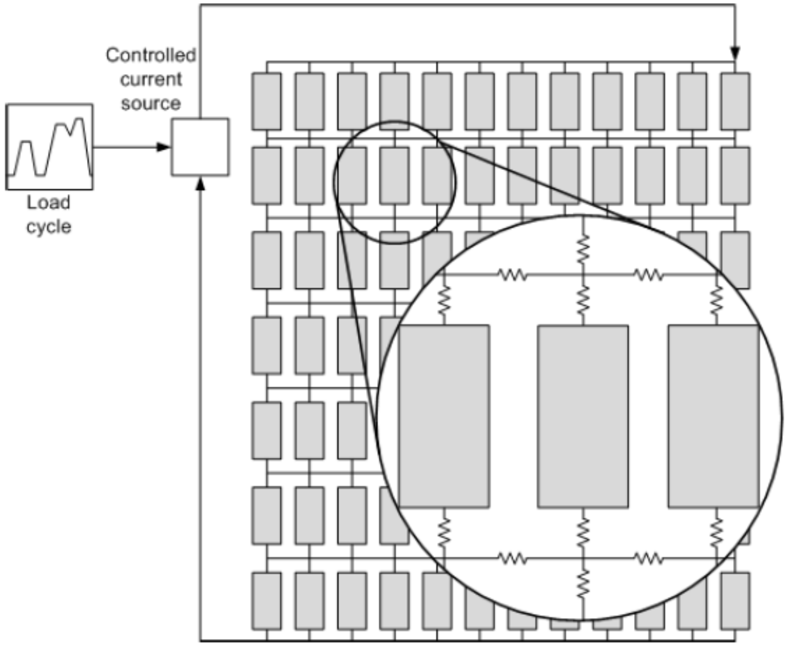


# Notation and Faults

- Configurations of cells are often referred to as 6s3p or similar, where s = series, and p = parallel

- Faults:
  - If a cell in series has a lower voltage, the whole string voltage is affected, and the cells will not try to re-balance
  - If a cell in parallel has a lower voltage, the cells will try to re-balance
  - Interconnection resistances can affect current paths

- Highly parallel cell strings can lead to uneven current paths

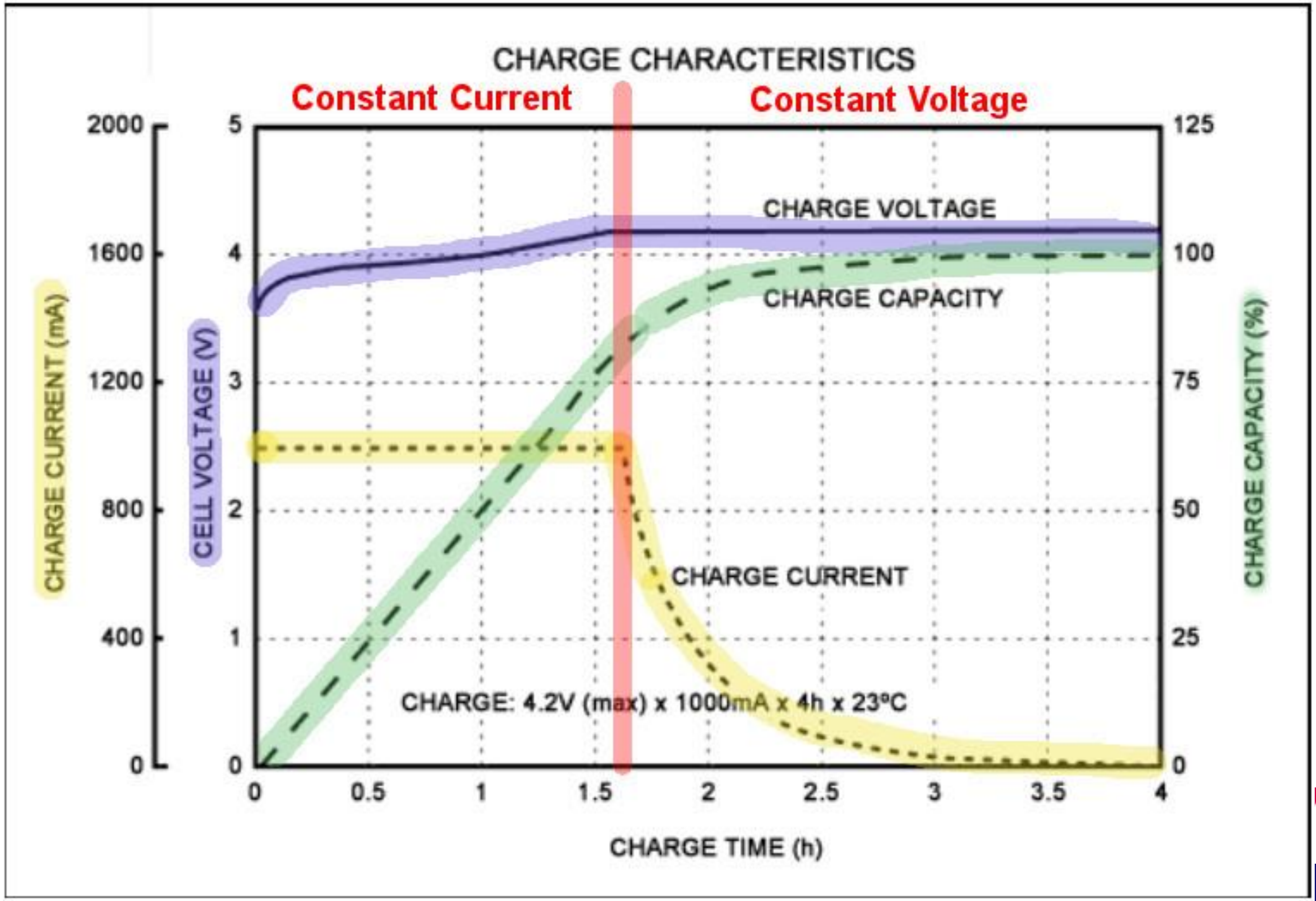


# Charging

# Charging Methods

- Cells are usually charged with CCCV
  - Cells are firstly charged with a constant current until a nominal voltage is reached
  - Cells are then charged at a constant voltage until the large current drops below a certain threshold
  - Balancing can occur during and usually at the end of the charging process

# CCCV Profile

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# Example Exercise

- **A battery pack consists of 40 modules in series, with each module of 6 20Ah cells connected in parallel. Each cell has a nominal voltage of 3.2V, and the vehicle has an average energy use of 0.1kWh/km. What is the expected range of the vehicle, given a SOC* lower limit of 20%?**

$6 \times 20 = 120\text{Ah}$

$40 \times 3.2 = 128\text{V}$

$120 \times 128 = 15.36\text{kWh}$

$0.8 \times 15.36\text{kWh} = 12.288\text{kWh}$

$\Rightarrow 122.88\text{km}$

* You can assume SOC = SOE

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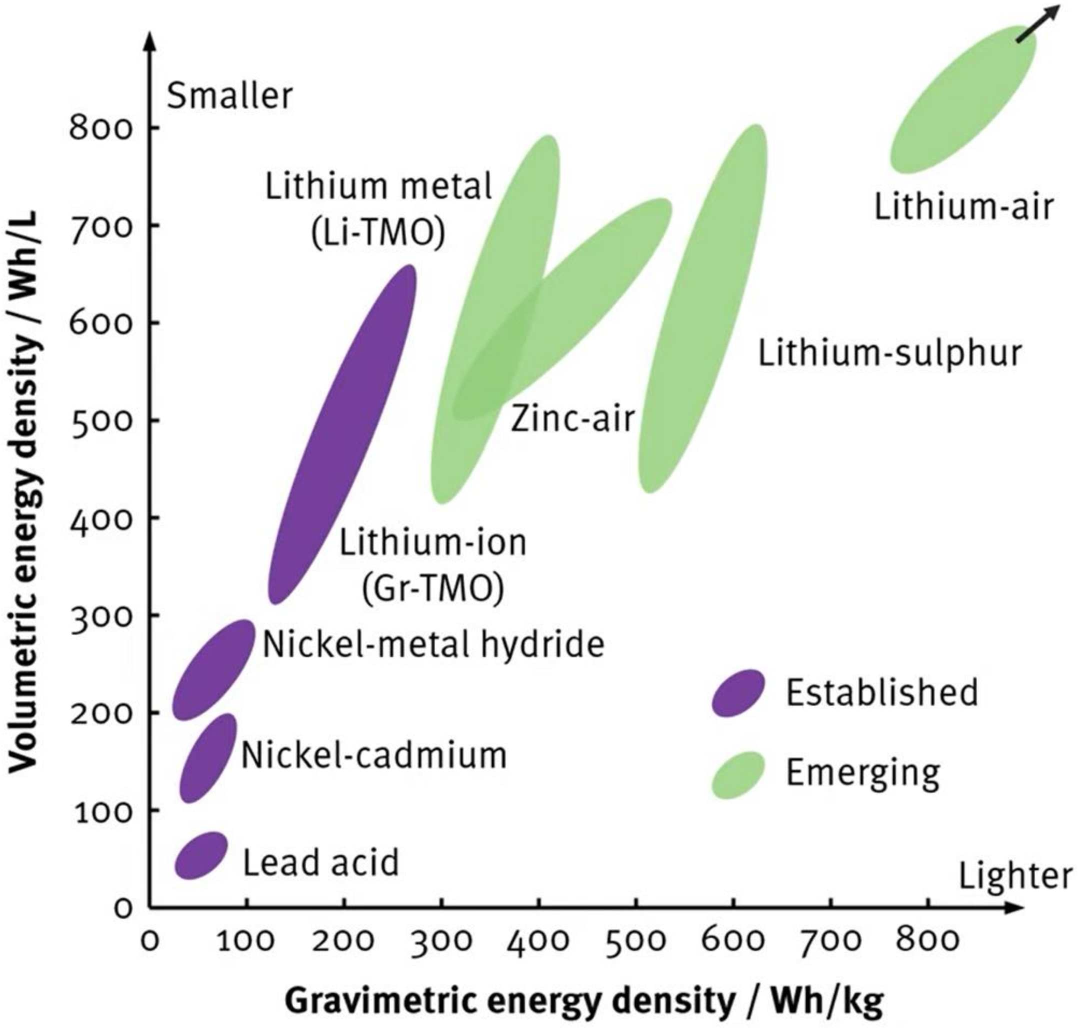
# Lithium Ion Chemistries

# Terminology – Energy Density

## Battery technologies

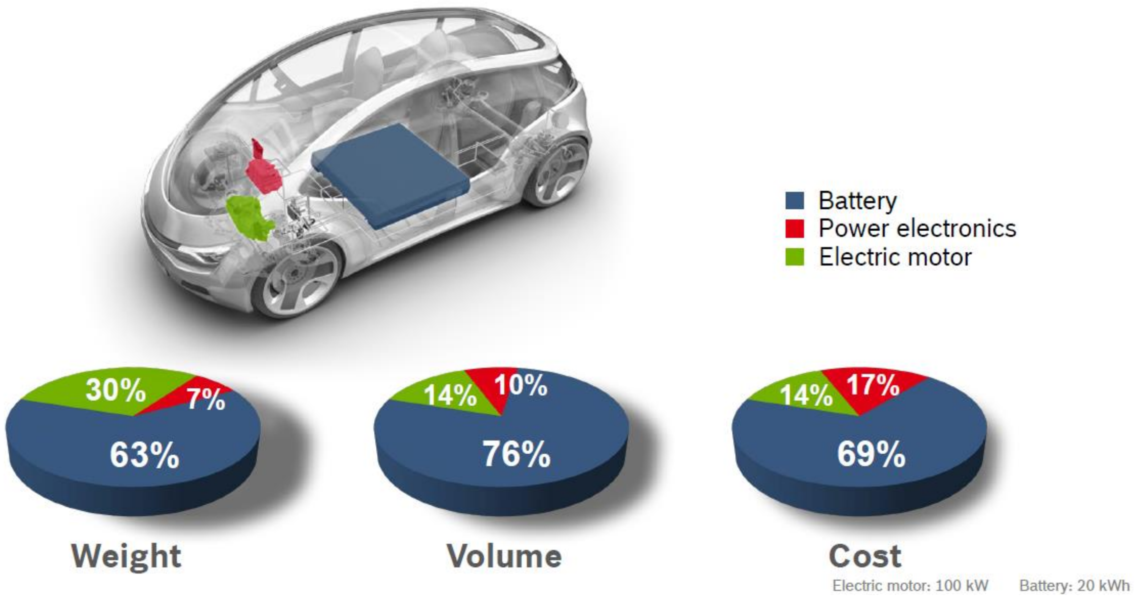
- **Petrol** ~9,500 Wh/L and ~12,800 Wh/kg
  - Engine efficiency ~25%
  - ~2,400 Wh/L and ~3,200 Wh/kg
- Lots of different chemistries which are defined by their cathode/anode materials
  - Lead acid
  - Nickel-cadmium
  - Nickel-metal hydride
  - Lithium-ion
    - Graphite-Transition Metal Oxide
  - Lithium metal
    - Lithium-Transition Metal Oxide
  - Lithium-sulphur
  - Metal-air




ount

# Terminology

- For a given weight, a higher specific energy cell chemistry will store more energy, and for a given storage capacity, a higher specific energy cell will be lighter.
- For a given volume, a higher specific energy density cell chemistry will store more energy, and for a given storage capacity, a higher energy density cell will be smaller.



# Terminology

- In general, higher energy densities and specific energies are obtained by using more reactive chemicals.
  - The downside is that more reactive chemicals tend to be unstable and may require special safety precautions.
  - The quality of the active materials used in cell construction matters.

- Impurities limit cell performance that can be achieved.
  - Cells from different manufacturers with similar cell chemistries and similar construction may yield different performance.

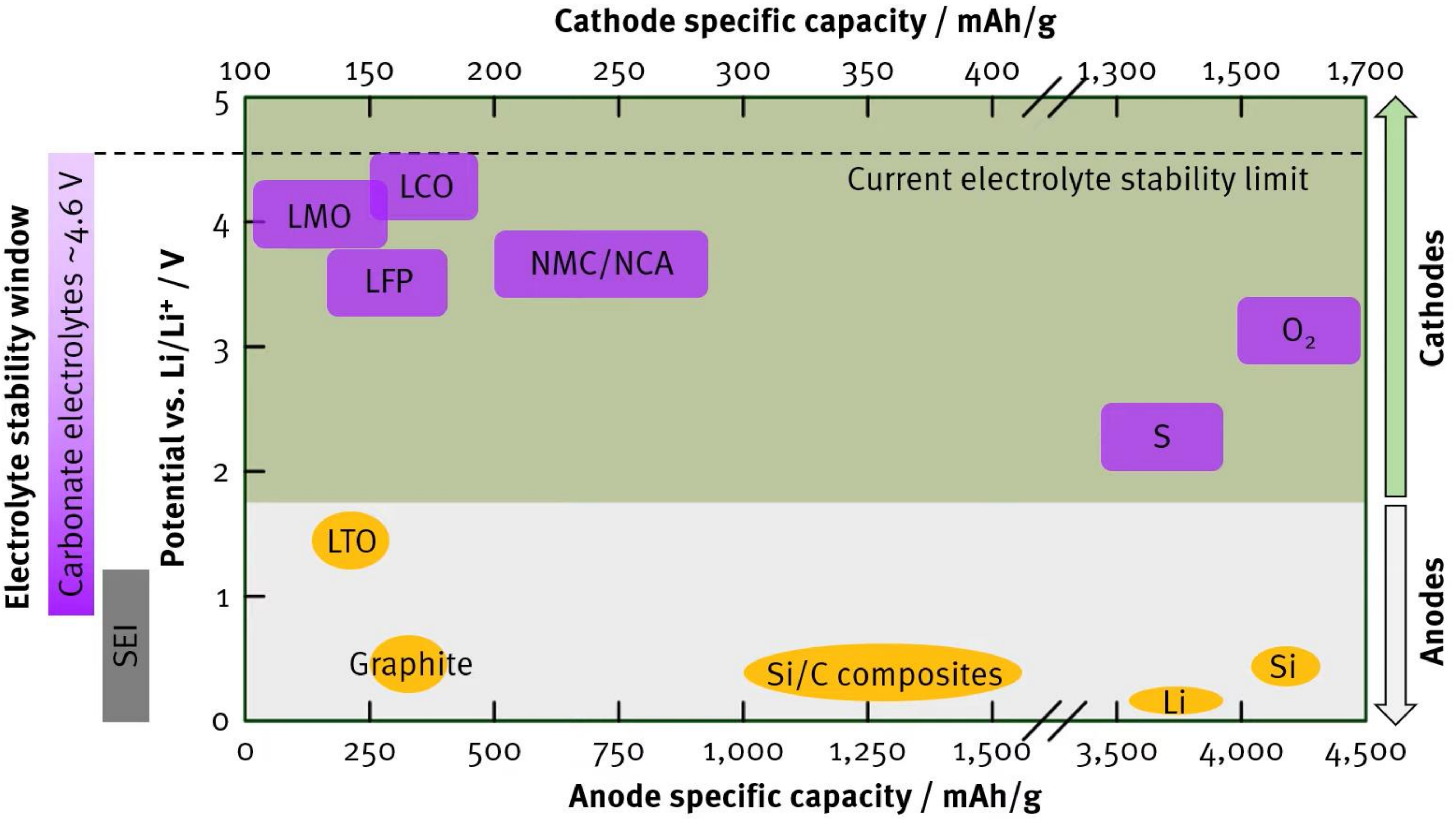
# Do we have good chemistry?

**Anode**
High capacity and low voltage

**Cathode**
High capacity and high voltage

**Electrolyte**
Large stability window

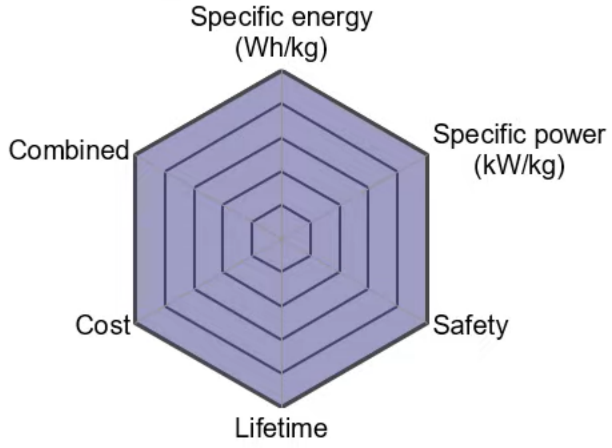
**All**
Cheap, mass produced, non-flammable



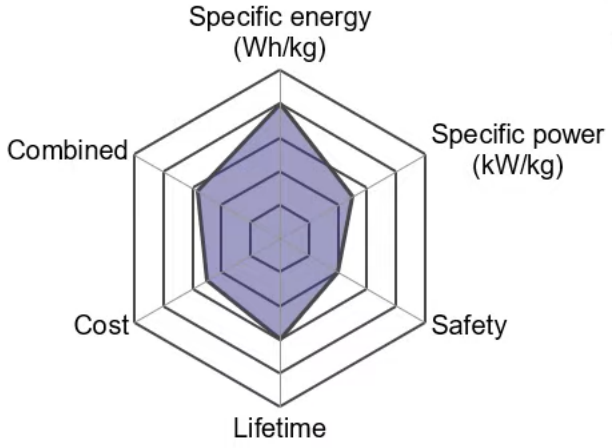
# Do we have good chemistry?

**Nickel = Capacity**
**Cobalt = Rate capability (power), stability**
**Manganese = Safety, cost**

### The perfect cathode

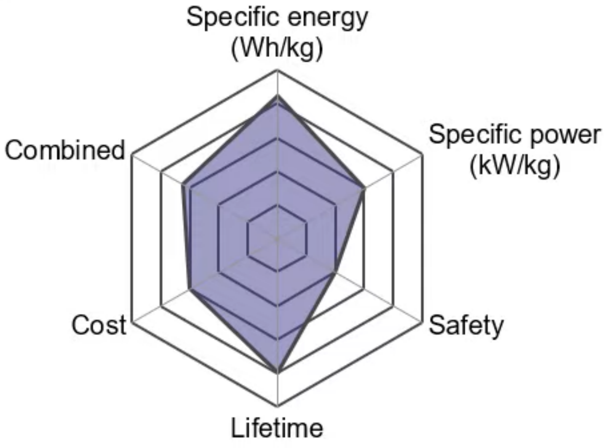



### NMC

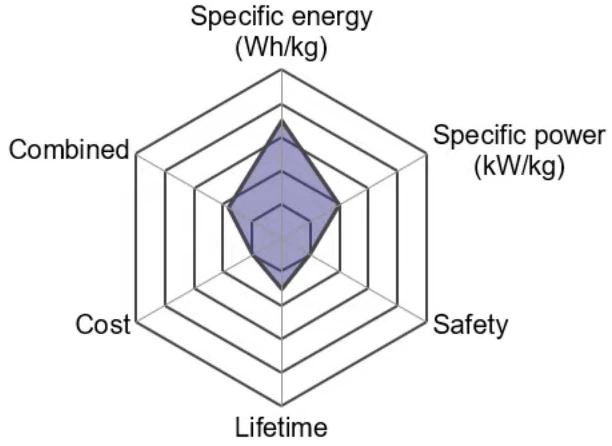



Increasing nickel content trend continues

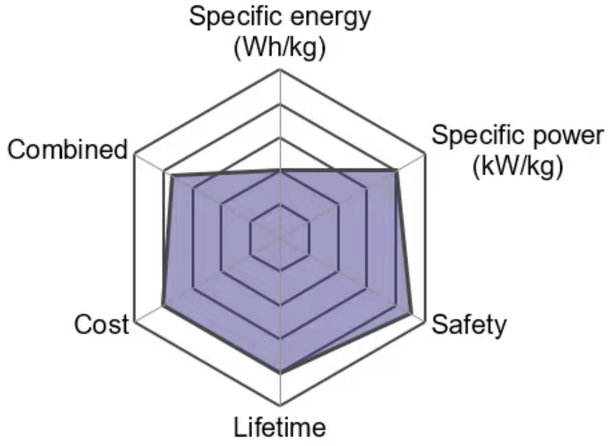
### NCA



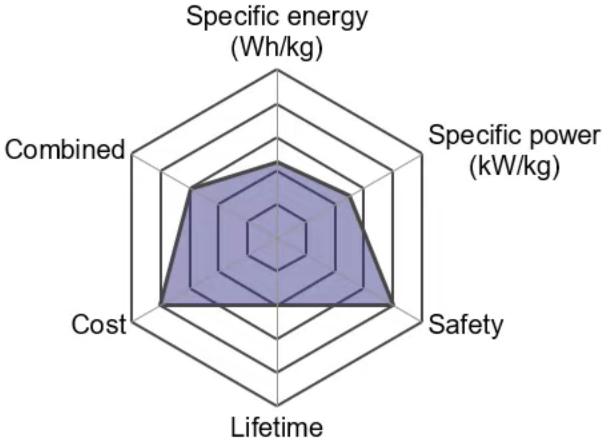

### LCO




### LFP




### LMO




*Not to scale

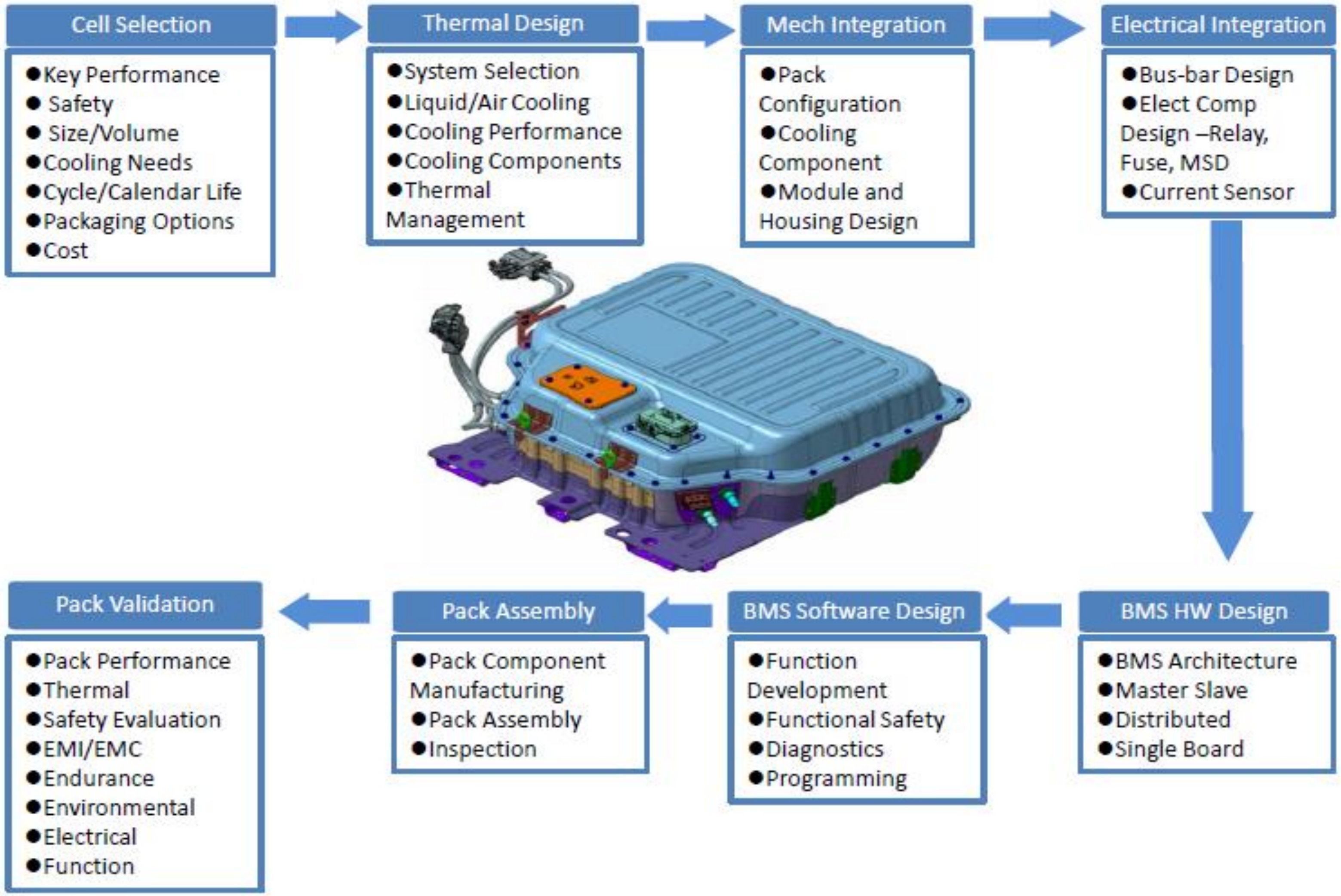
*adjusted for 2024

# Chemistries - Overview

| | Cell level energy density, Wh $kg^{-1}$ | Cell level energy density, Wh $l^{-1}$ | Durability cycle life, 100% DoD | Price estimate, US$ $Wh^{-1}$ | Power C-rate | Safety thermal runaway onset, °C | Potential, V | Temperature range in ambient conditions, °C |
|---|---|---|---|---|---|---|---|---|
| $LiCoO_2$ | 170–185 | 450–490 | 500 | 0.31–0.46 | 1 C | 170 | 3.6 | –20 to 60 |
| $LiFePO_4$ (EV/PHEV) | 90–190 | 130–300 | 2000-3500 | 0.1-0.3 | 5 C cont.<br>10 C pulse | 270 | 3.2 | –20 to 60 |
| $LiFePO_4$ (HEV) | 80–190 | 200–240 | 2000-3500 | 0.1-0.3 | 30 C cont.<br>50 C pulse | 270 | 3.2 | –20 to 60 |
| NCM (HEV) | 150-250 | 270–290 | 1500-2500 | 0.15-0.3 | 20 C cont.<br>40 C pulse | 215 | 3.7 | –20 to 60 |
| NCM (EV/ PHEV) | 155–250 | 330–365 | 1500-2500 | 0.15-0.3 | 1 C cont.<br>5 C pulse | 215 | 3.7 | –20 to 60 |
| Titanate *vs.* NCM/LMO | 65–100 | 118–200 | 12,000+ | 1–1.7 | 10 C cont.<br>20 C pulse | Not susceptible | 2.5 | –50 to 75 |
| Manganese spinel (EV/ PHEV) | 90–110 | 280 | >1000 | 0.45–0.55 | 3–5 C cont. | 255 | 3.8 | –20 to 50 |

# Battery Formats

# Battery Pack Design and Development Methodology

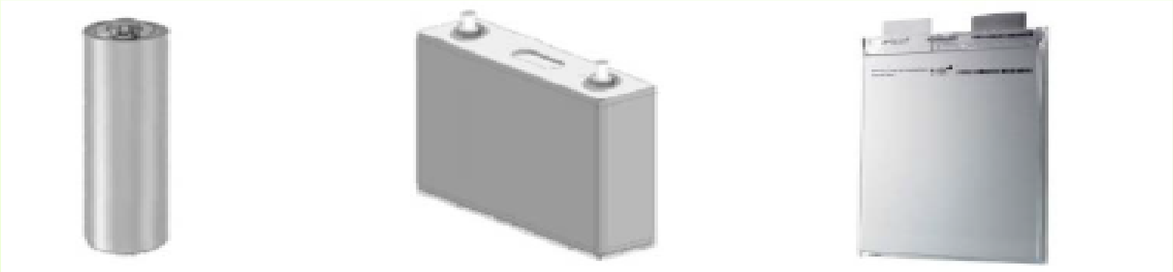


# Cell Selection and Design

| Challenge | Potential Solutions |
|---|---|
| High Energy/High Power | ❑ Improved Cell technology for high energy and high power application<br>❑ Improved Software to manage energy efficiently<br>❑ Efficient Thermal Management System for using high power |
| Efficiently Packaged | ❑ Utilizing the space efficiently with improved design to add extra space in car.<br>❑ Weight reduction measures without impacting structural strength and performance of pack.<br>❑ Using new and improved light weight material technology |
| Reasonable Cost | ❑ Analyzing material cost, development cost and manufacturing cost for all new developments.<br>❑ Using modular and scalable technology<br>❑ Reducing electronics cost by applying new architecture. |
| Service Life (10 Years/300,000km) | ❑ Life Estimation with real life load profile for battery pack operation.<br>❑ Optimum Set Point for SOC operation windows<br>❑ Improved Thermal Management to keep battery temperature in range least effect on cell ageing |
| Safety | ❑ Improved Thermal Management Control with fail safe design<br>❑ 4-Level Safety Concept<br>❑ Improved battery materials |

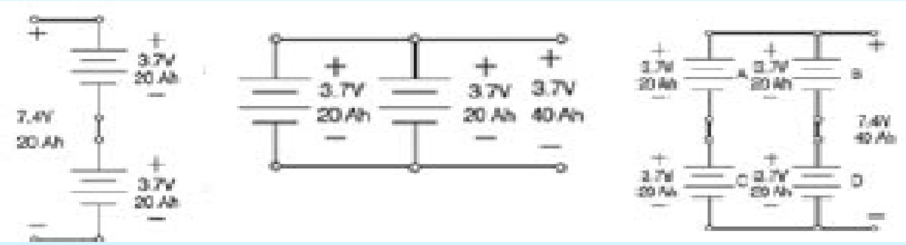
# Cell Selection and Battery Architecture

## Cylindrical Vs Prismatic Vs Pouch



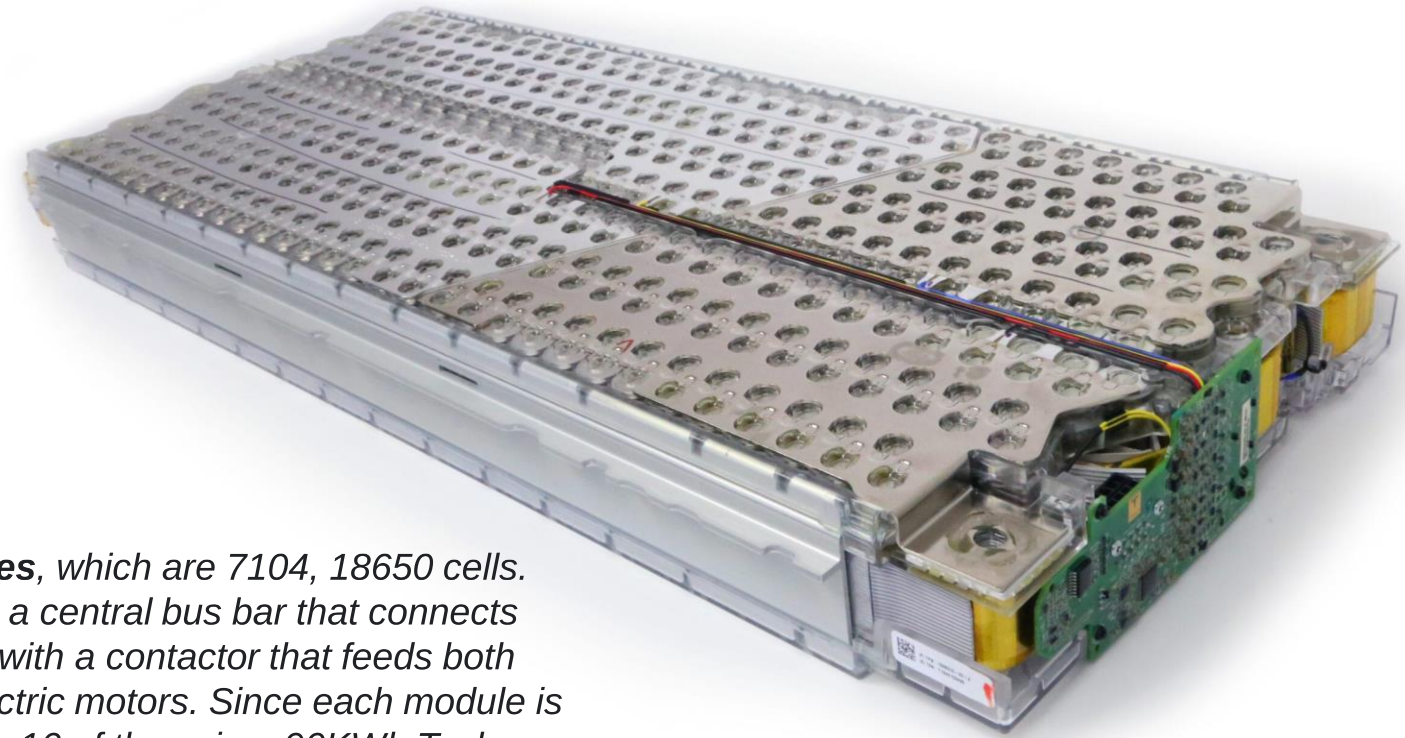
| Cylindrical | Prismatic | Pouch |
|---|---|---|
| ■Robust and strong structure<br>■Ease of processing<br>■low cost.<br>■Ability to maintain pressure to prevent safety events<br>■As size gets larger, the heat transfer ability goes down. | ■Rigid structure<br>■Controllable dimensions.<br>■Good life performance.<br>■Requires complex and specialized hardware.<br>■Costly<br>■Contains pressure build-up, under abuse<br>■Higher heat transfer surface area.<br>■Better volume efficiency. | ■Flexible structure<br>■Ease of processing<br>■Potential low cost.<br>■Requires careful seal design<br>■Life concern<br>■Vent activation is through seal breach<br>■Attention must be paid to preventing local stresses. |

## A Few Large Cells vs. Many Small Cells




- **Many small cells - Advantages**
  - ✓ Lower cell cost
  - ✓ Improved safety (faster heat rejection) and small magnitude of safety events.
  - ✓ Higher quality production.
- **Many small cells - Disadvantages**
  - ✓ Include many interconnects and much higher integration and assembly costs
  - ✓ Lower weight and volume efficiency
  - ✓ Lower reliability and costly electrical management.
- **Fewer large cells - Advantages**
  - ✓ Include lower assembly cost
  - ✓ Higher weight and volume efficiency
  - ✓ Higher reliability .
- **Fewer large cells - Disadvantages**
  - ✓ Higher cell cost
  - ✓ More difficult thermal management
  - ✓ Large magnitude of safety events.

# Cylindrical 18650 Cells
# Example Tesla (Model S)



*It contains **16 modules**, which are 7104, 18650 cells. The battery pack has a central bus bar that connects each battery module with a contactor that feeds both the front and rear electric motors. Since each module is 5.5 kWh and we have 16 of those in a 90KWh Tesla battery.* [ref]

Model S - Main Battery Pack Repair | Gruber Motors

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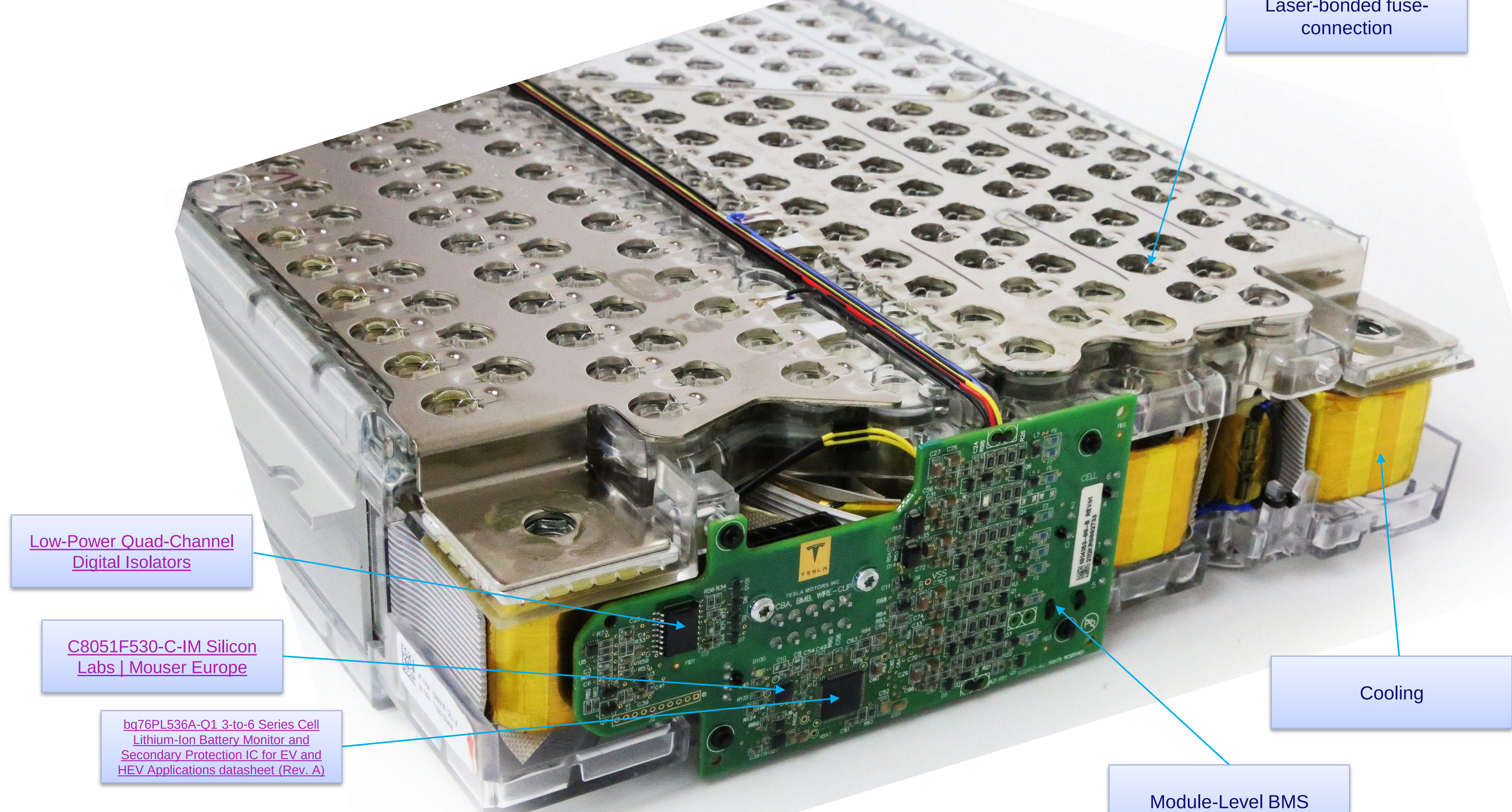
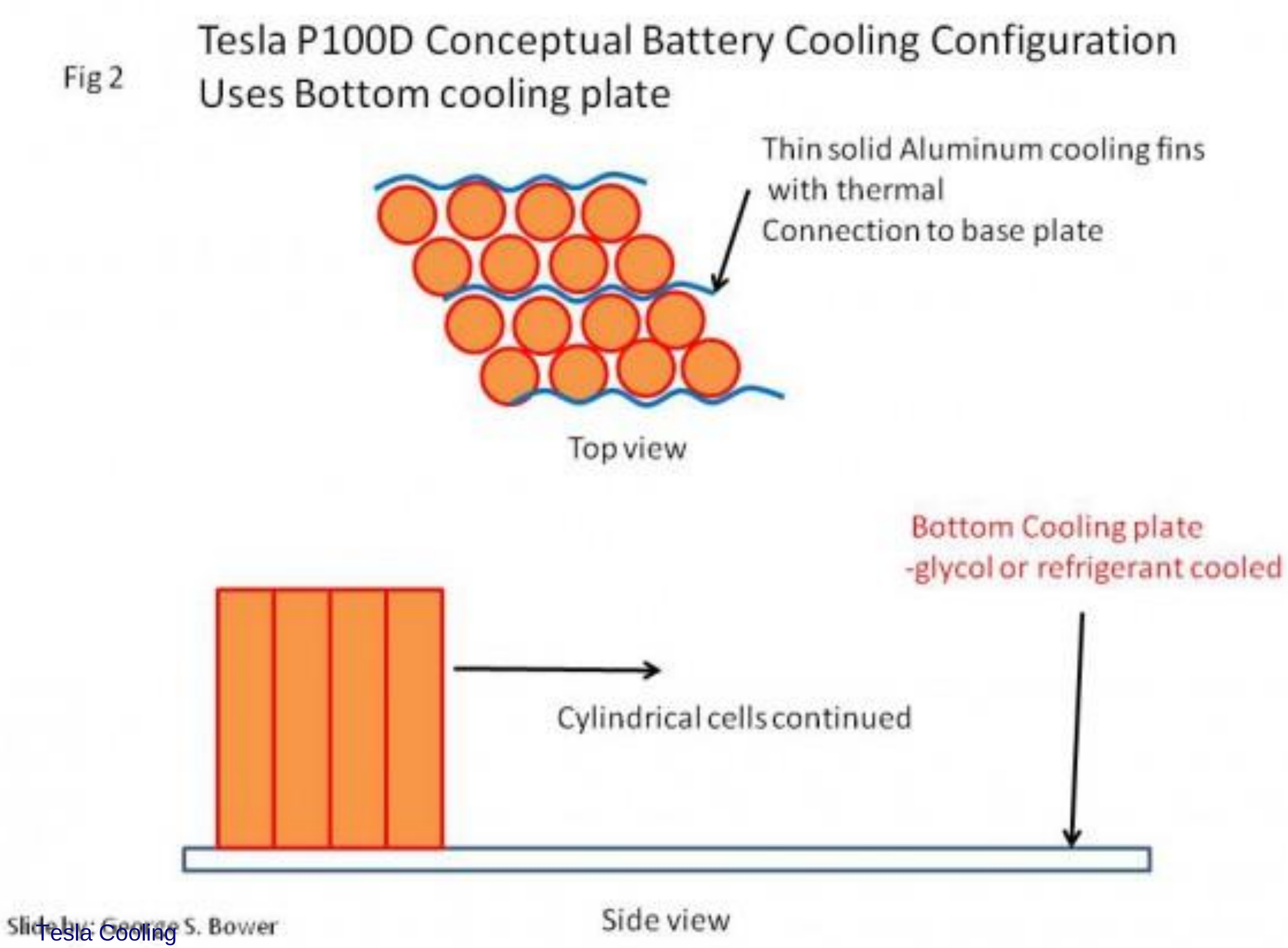
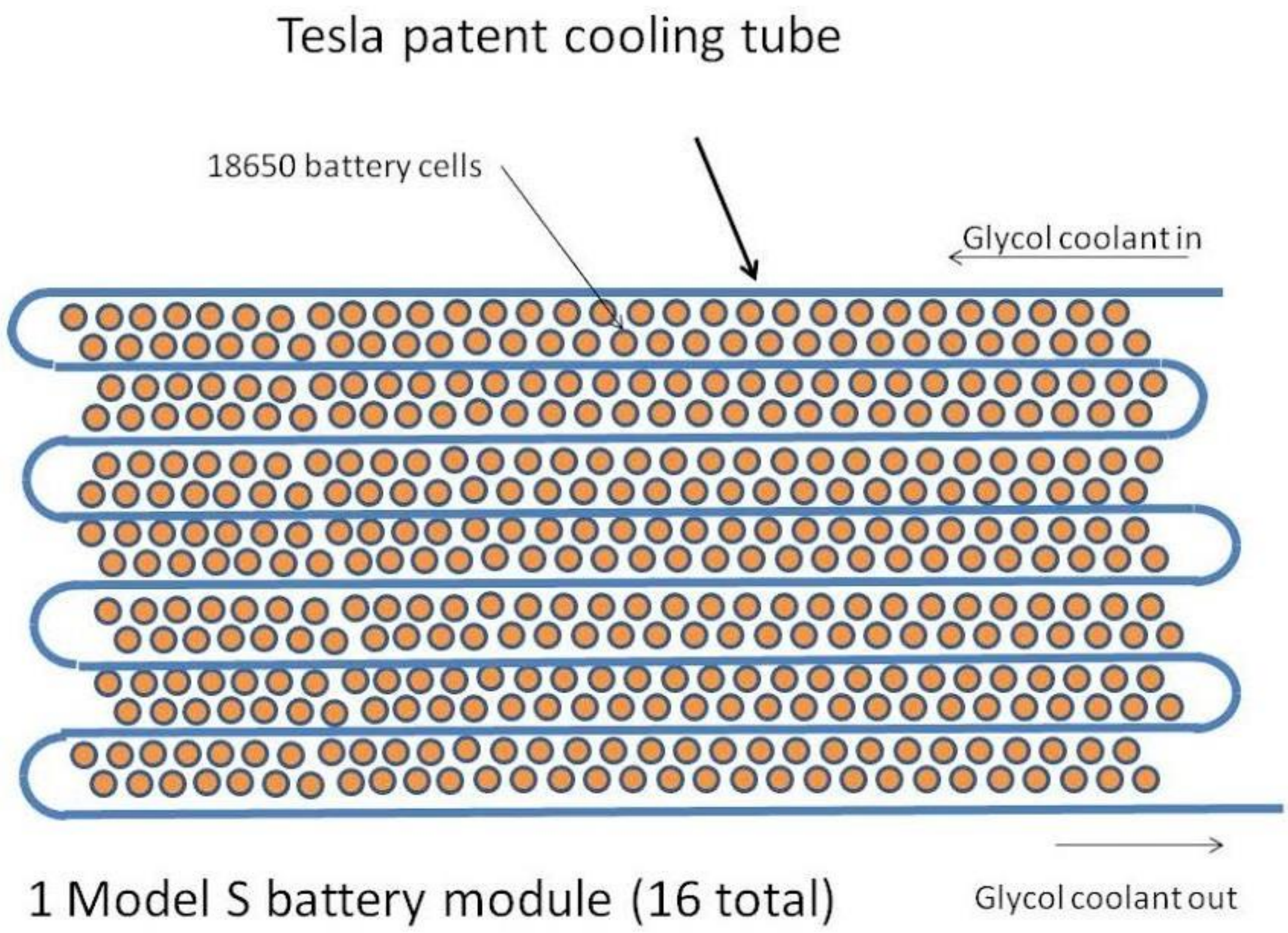


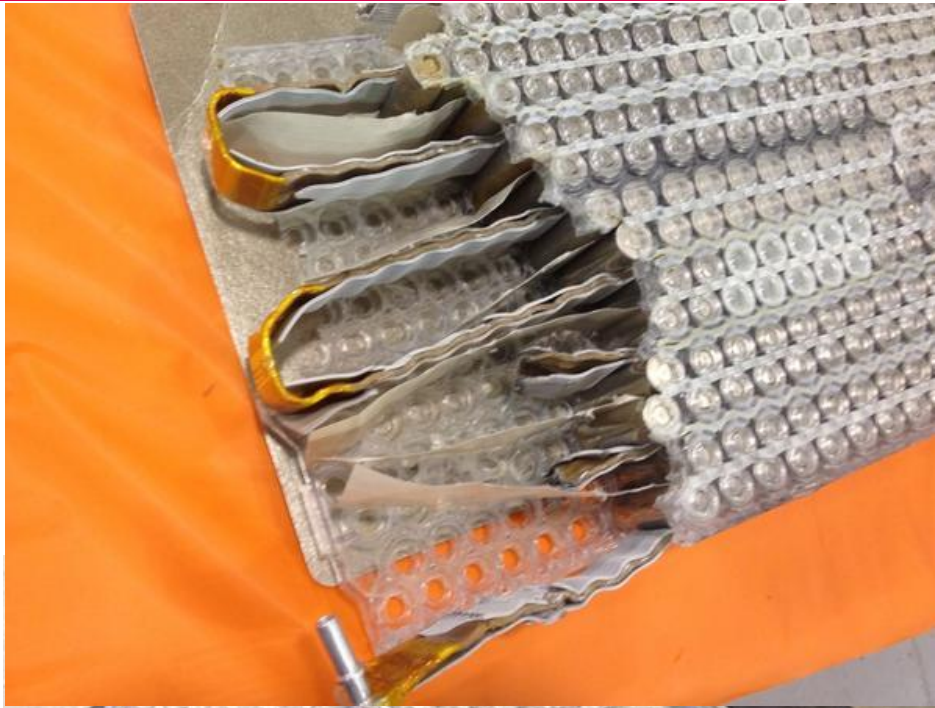

Model S - Main Battery Pack Repair | Gruber Motors

# Battery Cooling via interlaced cooling circuit and base plate



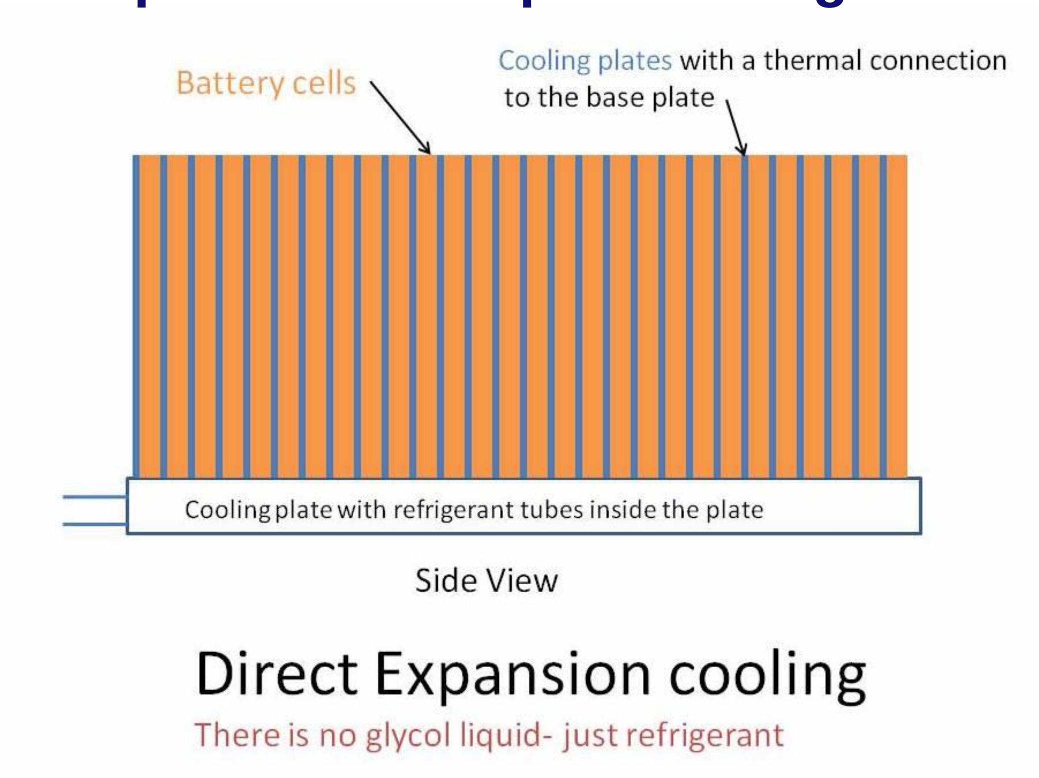

# Battery Cooling

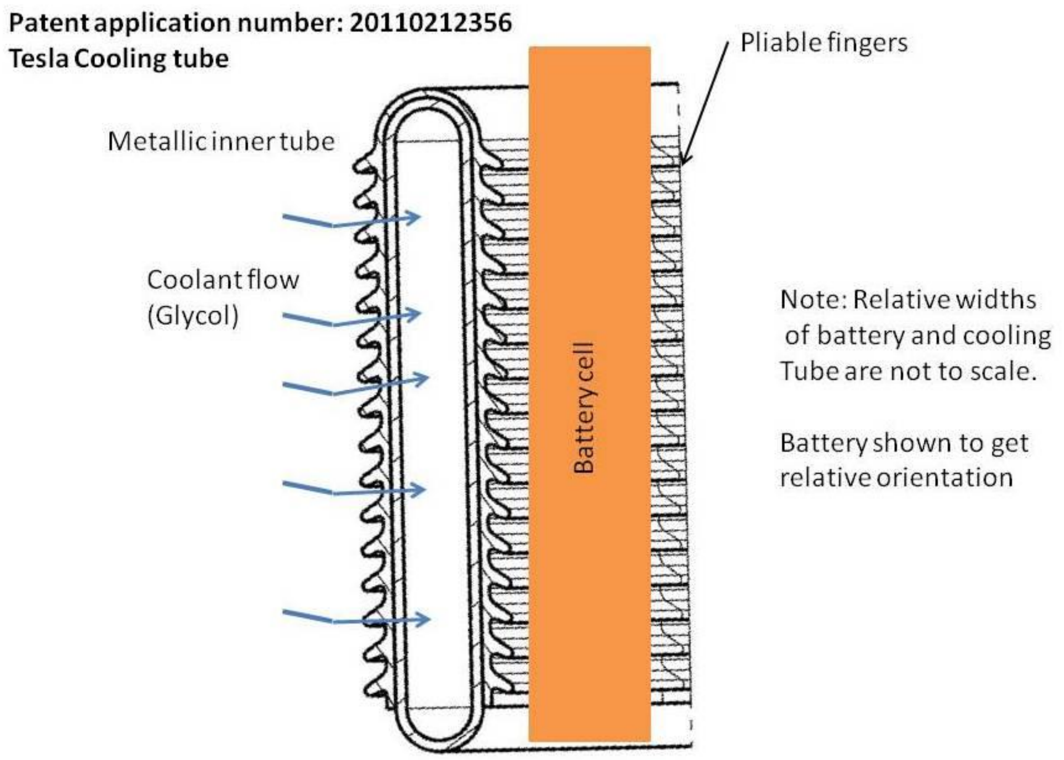


# Battery Cooling – Heat Fin

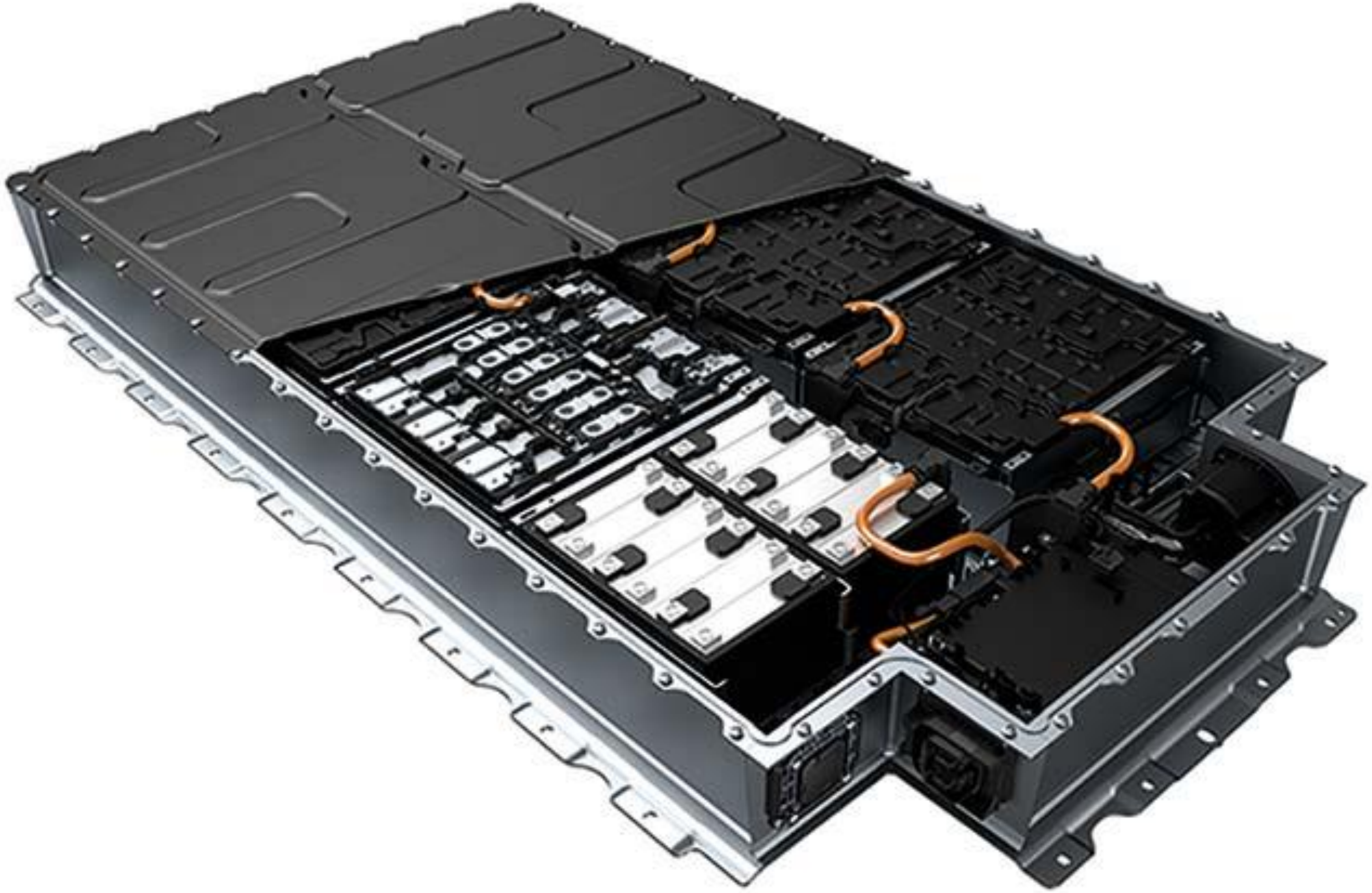
- **Applications for advanced cooling measures:**
  - **Integrated cooling**
  - **Significant space for innovation**
  - **Newer packs have liquid cooling**



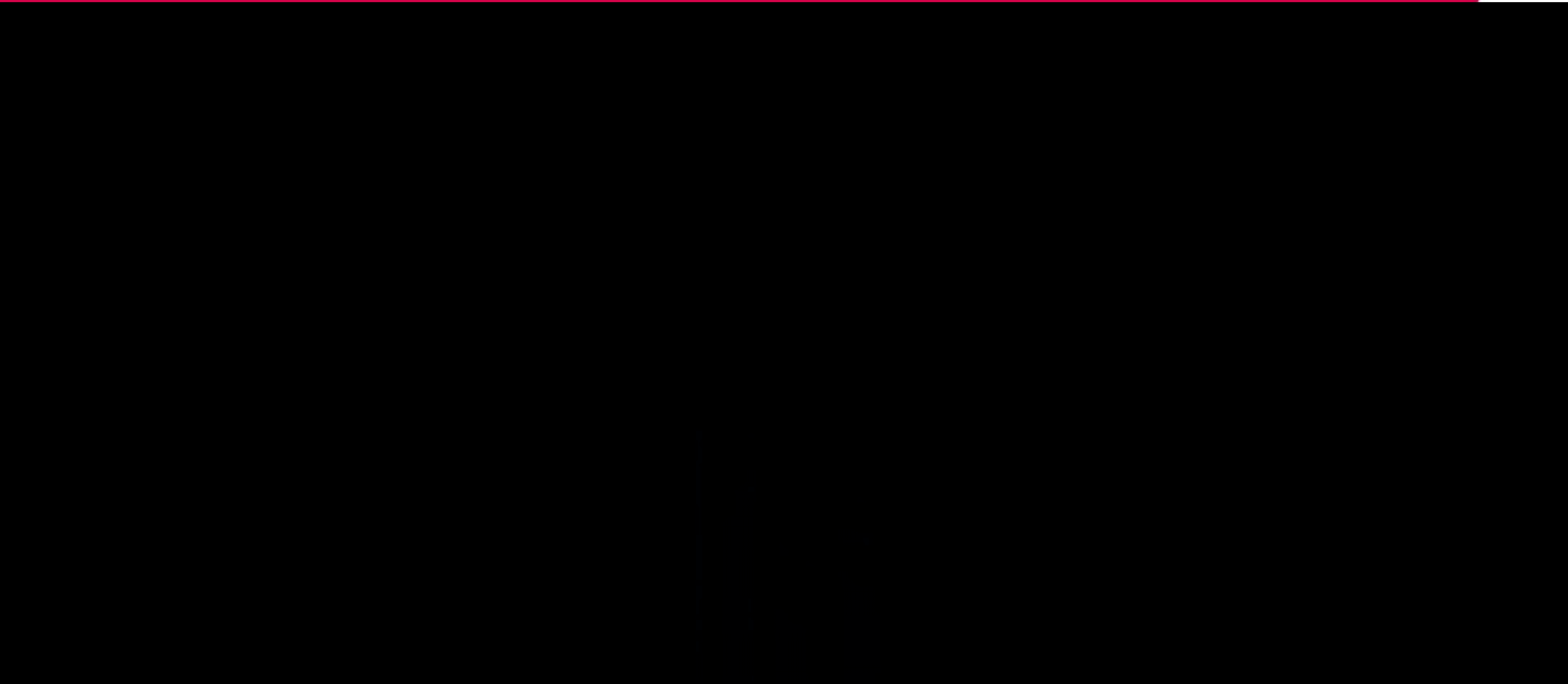

http://www.hybridcars.com/bmw-and-lg-chem-tru

# Prismatic
# Example: BMW i3



Technische Universiteit Eindhoven University of Technology

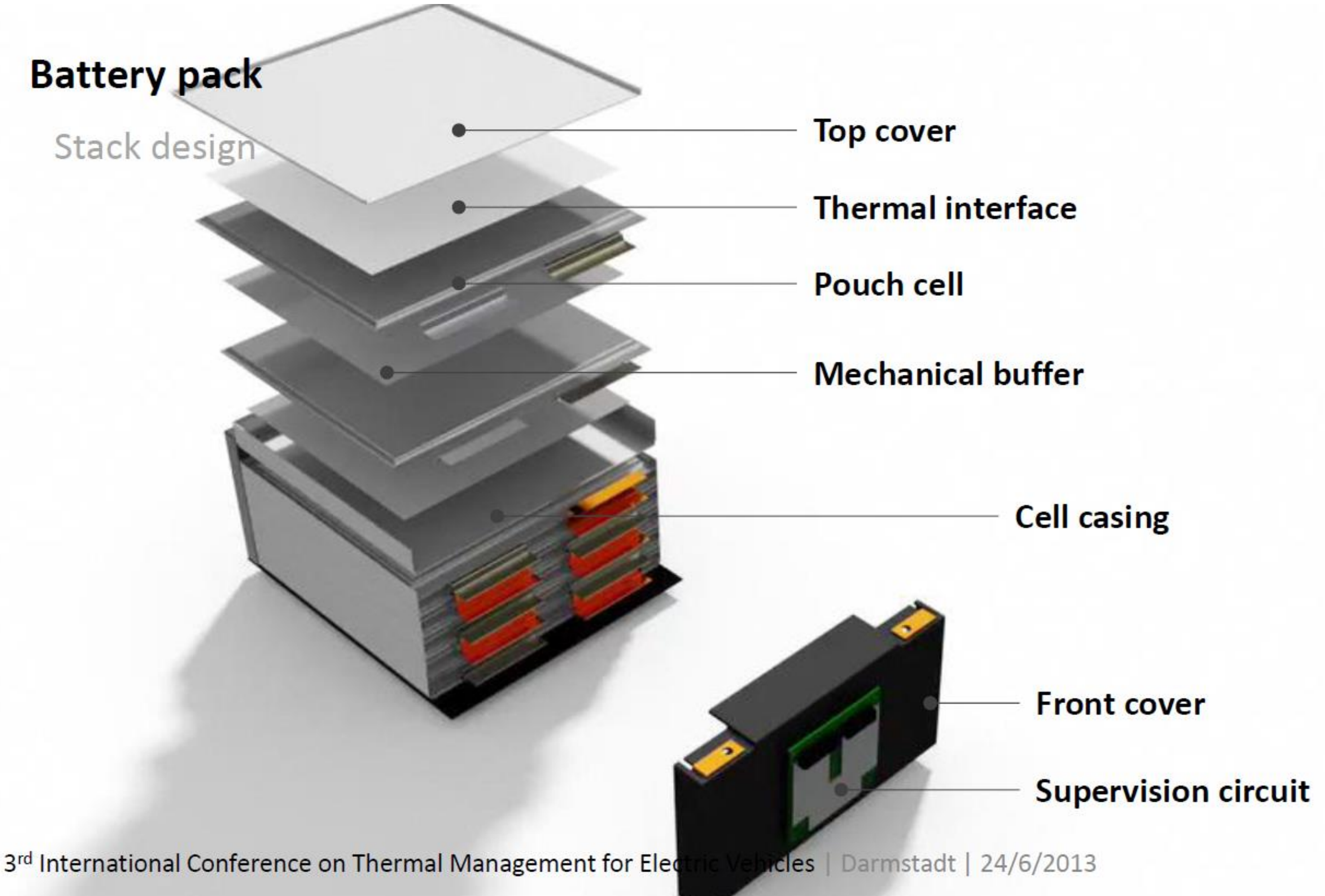
# BMW Production (Samsung Cells)



# BMW Production (Modules, Pack)

# Pouch Cells

- High packing density possible
- Tabs typically folded/clamped to PCB
- Grouped into modules with BMS PCB
- Will physically expand during use
- Cooling solutions integrated between pouches
  - Aluminium heat / structural plate
  - Air cooling channel
  - Liquid cooling channel (cooling fin)
  - Phase Change Materials (PCM)
- OEM examples: Nissan, Chevy Volt
- TU/e use: URE,



## Nissan Leaf

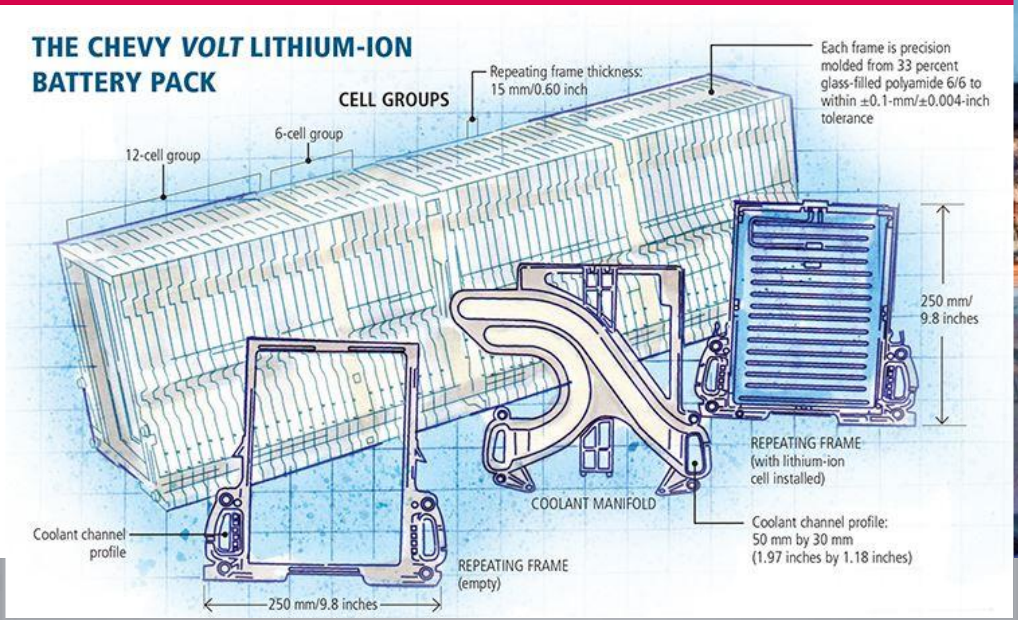
The original Nissan Leaf had 4 cells in a 2s2p configuration in each of the "sardine tin" modules.

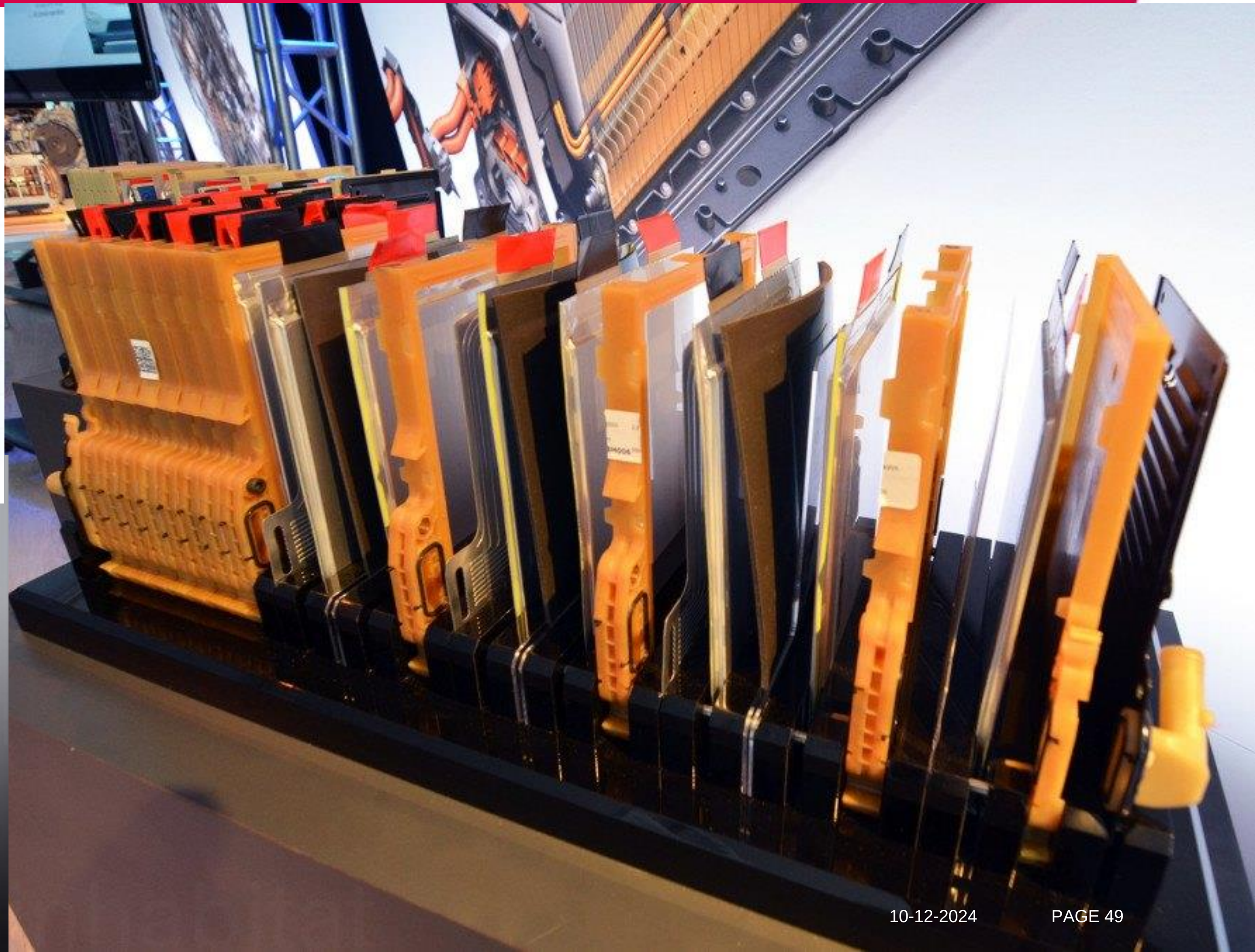
There is no cooling other than radiation and convection from the outer surface of the pack to the environment. Air flow cooling increases over the outside of the battery pack when the car is moving.

The pack also absorbs heat from the environment, radiated and reflected from road surfaces.

The pack is simple, but the downside is the performance is limited and lifetime is limited in very hot climates.

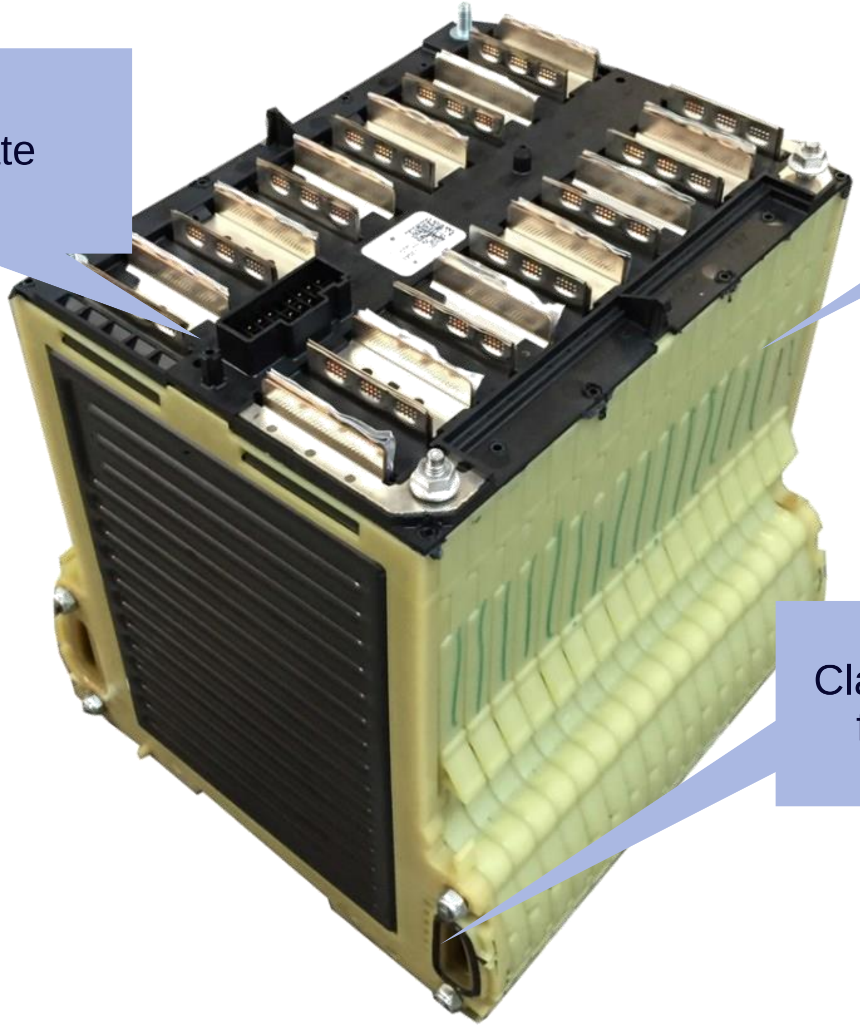
# Pouch-Cell Example (Chevy Volt)



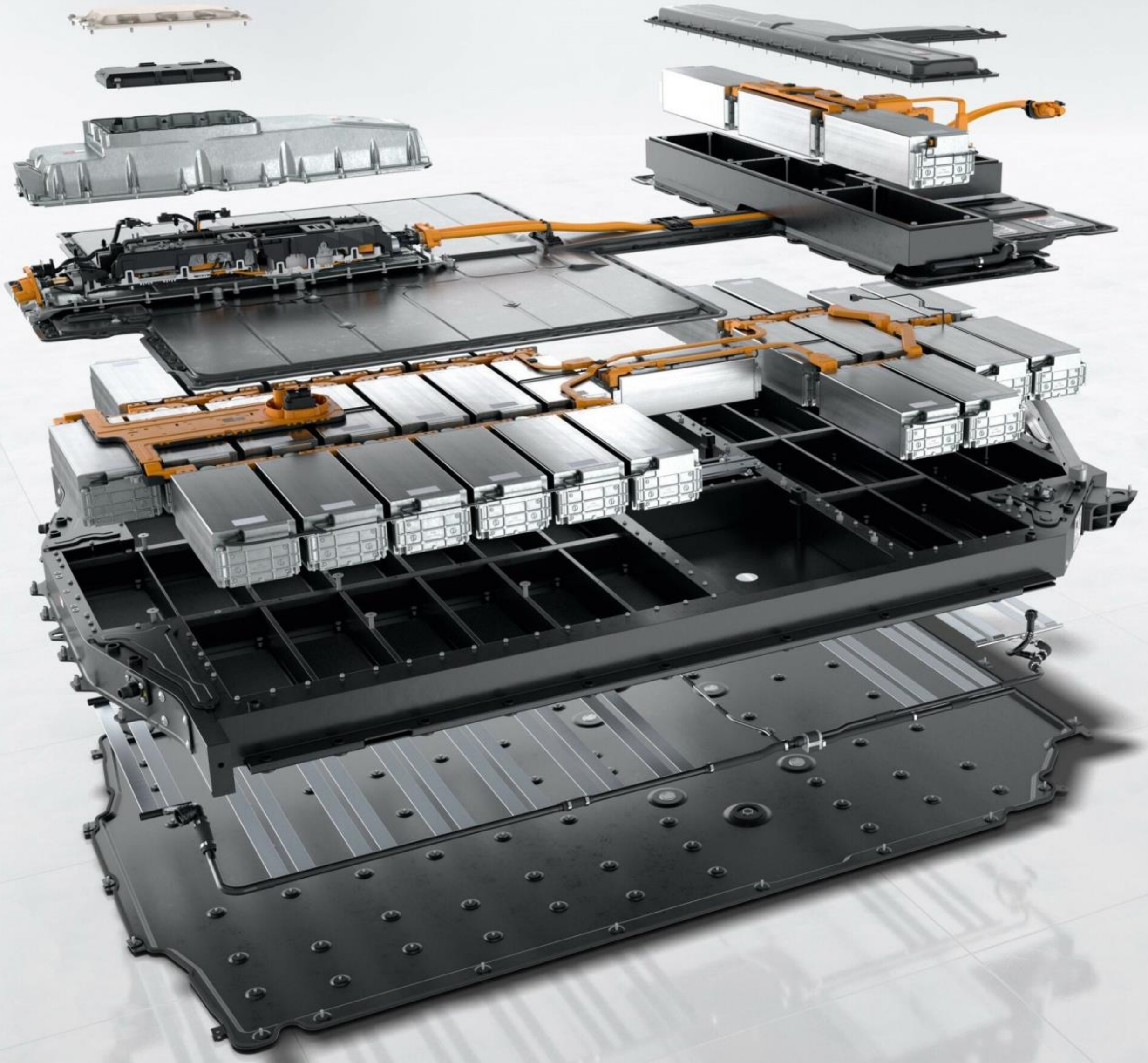
# Pouch-Cell
# Example (Chevy Volt)

Fixed plate



Tesselating sections

Clamping around fluid channel



# Pouch-Cell Example

**Porsche Taycan**

This is an 800V pack designed for fast charge and fast discharge.
The modules fit into a robust waterproof frame and the cooling elements are glued on underneath the bulkhead plate using heat conductive adhesive.
This approach is simple and robust in terms of it’s approach to possible coolant leaks, but it does reduce the overall thermal performance of the pack.

# Pouch-Cell
# Example (Porsche Taycan)


## Edge Cooling

Fundamentally pouch cells are made from multiple layers of active material all applied to copper and aluminium electrodes that are sandwiched and compressed together. The copper and aluminium electrodes have very good in-plane thermal conductivity and hence cooling along the longest edge of the cell makes perfect sense.

This is perhaps the most common approach to cooling pouch cells in automotive applications. The cells are held upright within a module (Audi e-tron module has 12 pouch cells) with one edge in contact with the bottom inner surface of the module.
These modules are then arrange on a larger cooling plate that will accommodate multiple modules.
This design has gradually been optimised to reduce cost, weight and improve the thermal connection between the cells and the cooling plate.

# Questions