Battery Management System (BMS): PART 1

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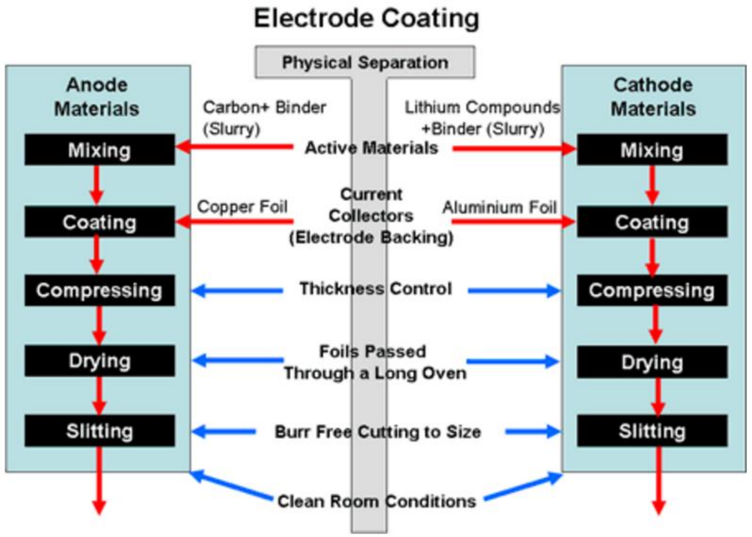
1. Lithium Battery Manufacturing
2. Lithium Battery failures
3. Battery Management System
4. State of Charge (SOC) and State of Health (SOH)

1. Lithium Battery Manufacturing

1. Lithium Battery manufacturing

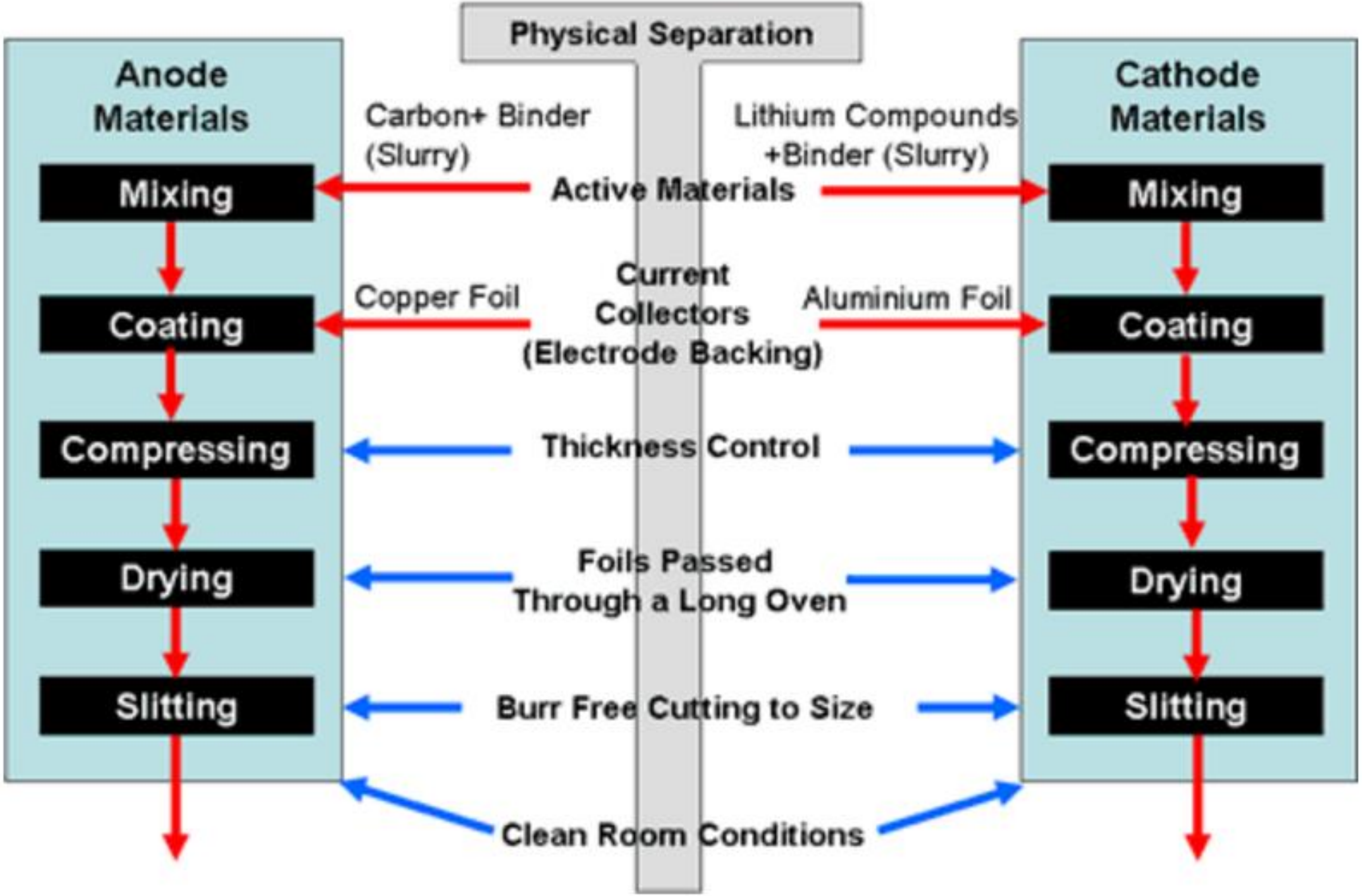
Electrode Coating

The anodes and cathodes in Lithium cells are of similar form and are made by similar processes on similar or identical equipment. The active electrode materials are coated on both sides of metallic foils which act as the current collectors conducting the current in and out of the cell. **The anode material is a form of Carbon and the cathode is a Lithium metal oxide. Both of these materials are delivered to the factory in the form of black powder and to the untrained eye they are almost indistinguishable from each other**. Since contamination between the anode and cathode materials will ruin the battery, great care must be taken to prevent these materials from coming into contact with each other. For this reason the anodes and cathodes are usually processed in different rooms.



http://www.mpoweruk.com/battery_manufacturing.htm

Electrode Coating



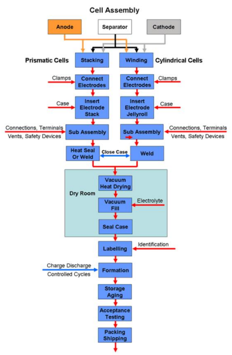
1. Lithium Battery manufacturing (contd.)

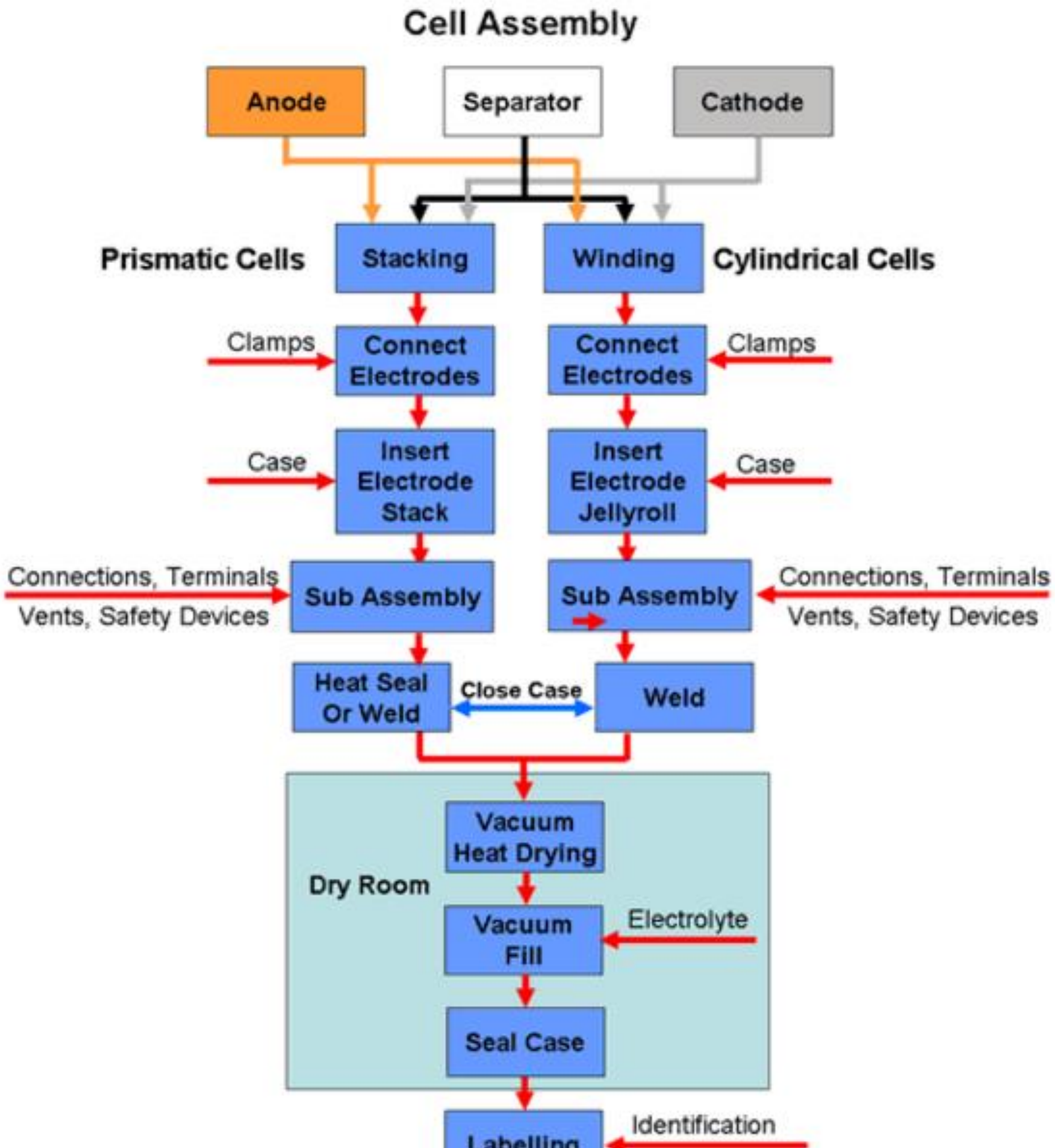
Cell Assembly

In the best factories cell assembly is usually carried out on highly automated equipment, however there are still many smaller manufacturers who use manual assembly methods.

The first stage in the assembly process is to build the electrode sub-assembly in which the separator is sandwiched between the anode and the cathode. Two basic electrode structures are used depending on the type of cell casing to be used, a ***stacked structure for use in prismatic cells and a spiral wound structure for use in cylindrical cells.***

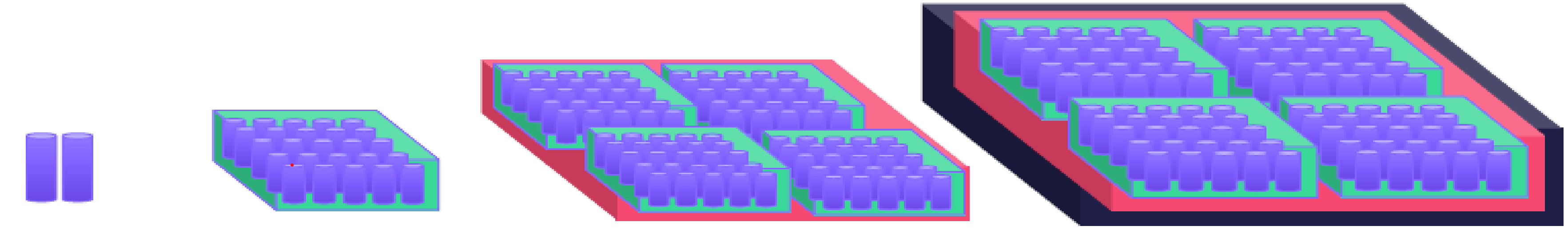
The assembly process for prismatic and cylindrical cells is illustrated in the following diagram.




Cell Assembly
Anode
Separator
Cathode
Prismatic Cells
Stacking
Winding
Cylindrical Cells
Clamps
Connect Electrodes
Connect Electrodes
Clamps
Case
Insert Electrode Stack
Insert Electrode Jellyroll
Case
Connections, Terminals
Vents, Safety Devices
Sub Assembly
Sub Assembly
Connections, Terminals
Vents, Safety Devices
Heat Seal Or Weld
Close Case
Weld
Dry Room
Vacuum Heat Drying
Vacuum Fill
Electrolyte
Seal Case
Identification

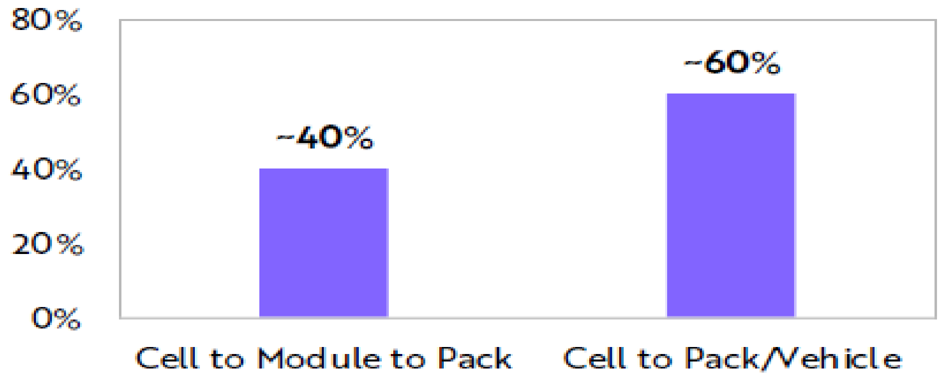
EV Assembly Process

How most EVs are manufactured today:

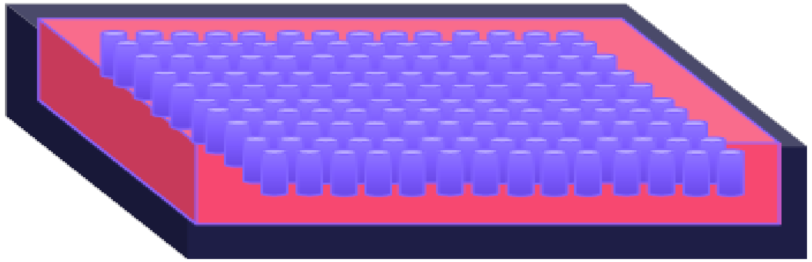


Battery Cells | Battery Cells in a Module | Battery Cells in Modules in a pack | Battery Cells in Modules in a Pack in the Vehicle

Battery as Percent of Volumetric Density



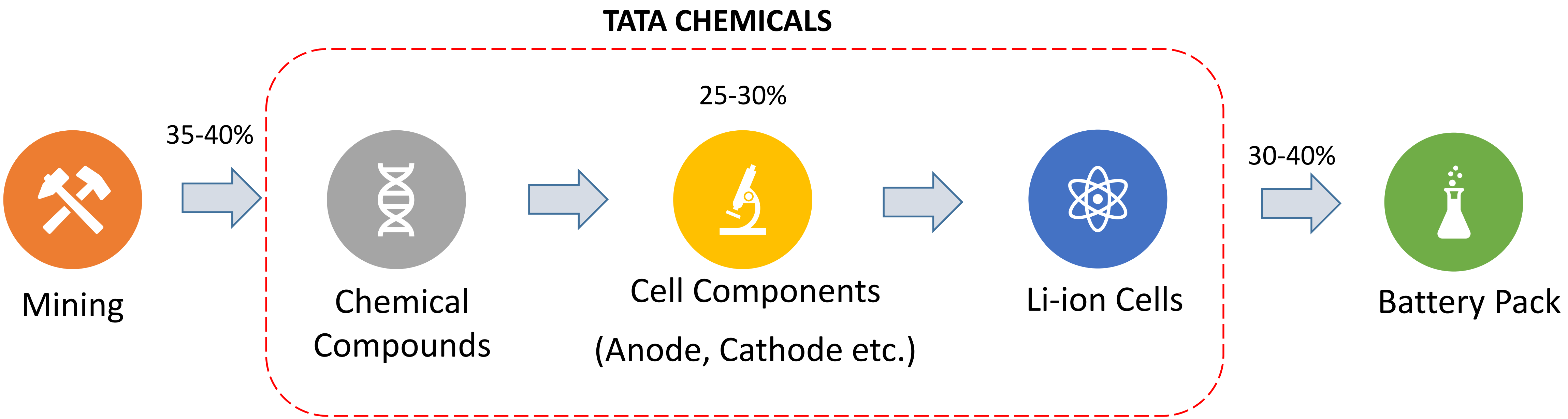
How leaders in the space are manufacturing EVs:



Cell-to-Battery Pack/Vehicle

Li-ion batteries make for the most expensive component of an electric vehicle, accounting for **40-50%** of the cost

Li-ion Cell Manufacturing Process



Lithium: Bolivia, Argentina, Chile
Cobalt: Australia, Congo
Nickel: Indonesia, Australia, Brazil
No mines in India

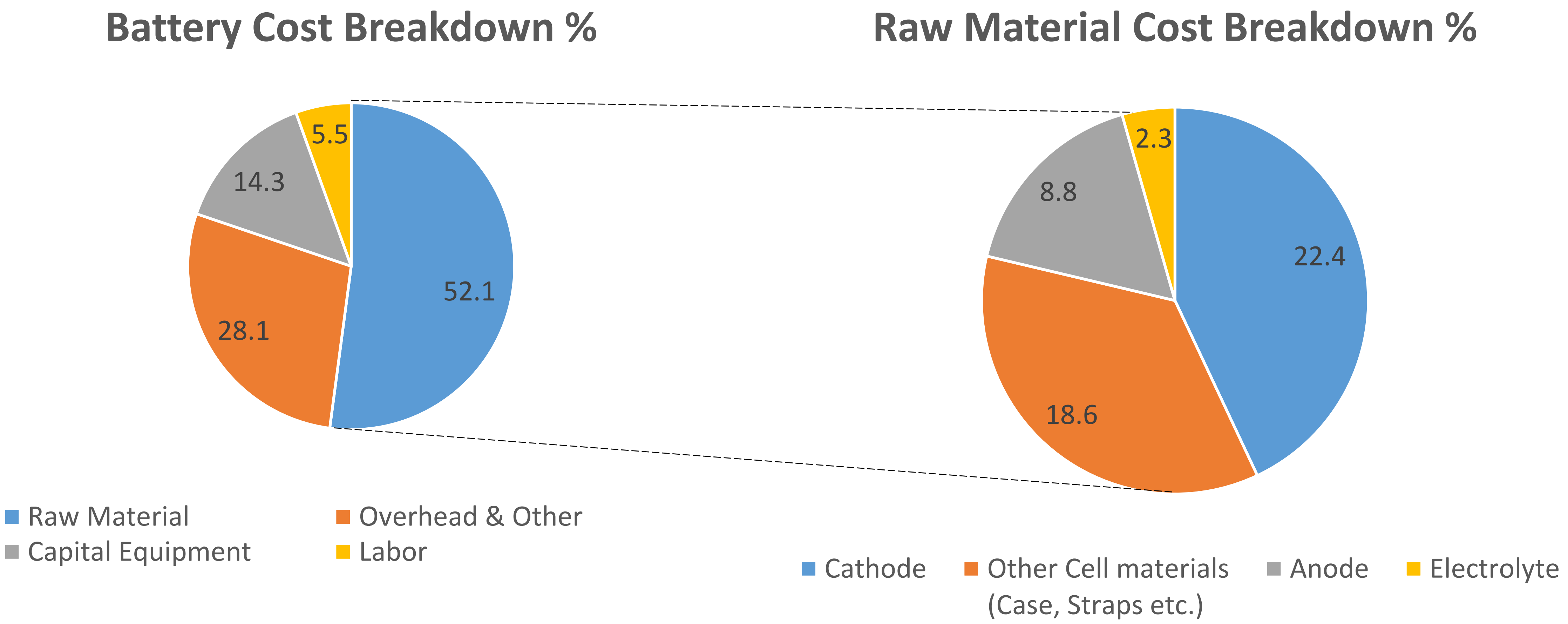
80% capacity in China
No capacity in India - Manikaran Power Ltd. from 2024

CATL, Panasonic, LG Chem, Tesla-Panasonic
India - Epsilon Advanced Materials

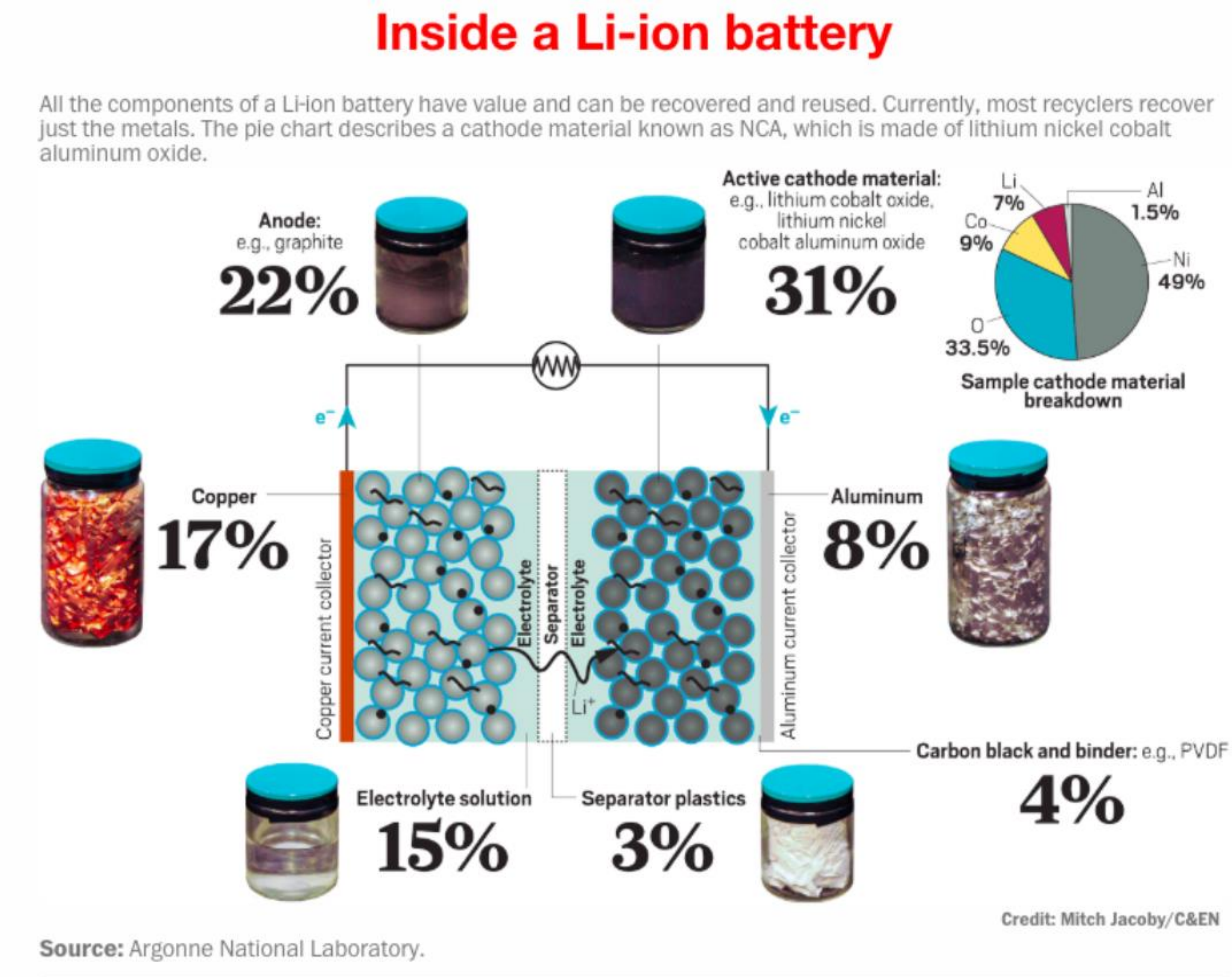
No present capacity in India
In Future - TDS, Li Energy, BHEL, Amara Raja, CUMI, Exicom, GOCL, Jyoti CNC, Thermax, Sukhbir Agro, NALCO

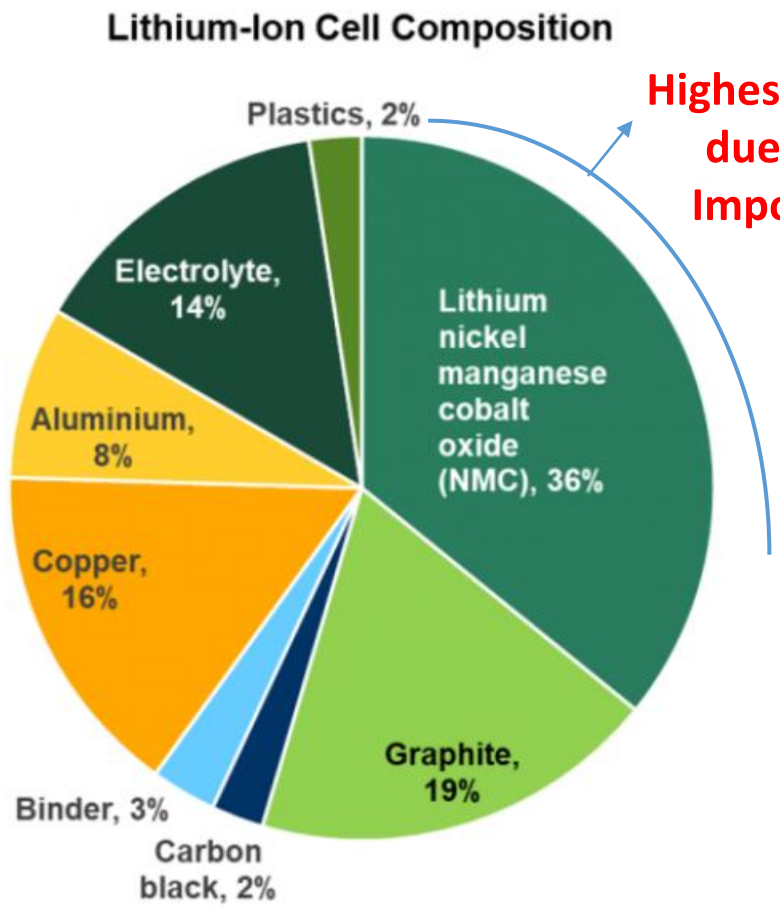
Presently - 1 GWh annual capacity
In Future - Exide, Amara Raja, Panasonic, Mahindra, Adani, Reliance, ATL, Hero

EV Battery Cost Breakdown



Li-ion Cell Diagram





Highest Cost due to Imports

Challenges in Battery Manufacturing

- Zero in-house availability of key raw materials: Lithium, Cobalt, and Nickel
- High Fixed Costs due to Large Capital Investment
- Cost Disadvantage vs Global Peers –
  - High Import Costs – No Li-ion battery components made in India
  - Li-ion battery costs can be reduced by up to 80% on larger volumes. 50GWh capacity to achieve global parity in costs
- Complex, Fast changing Cell Technology

Cost Improvement Areas

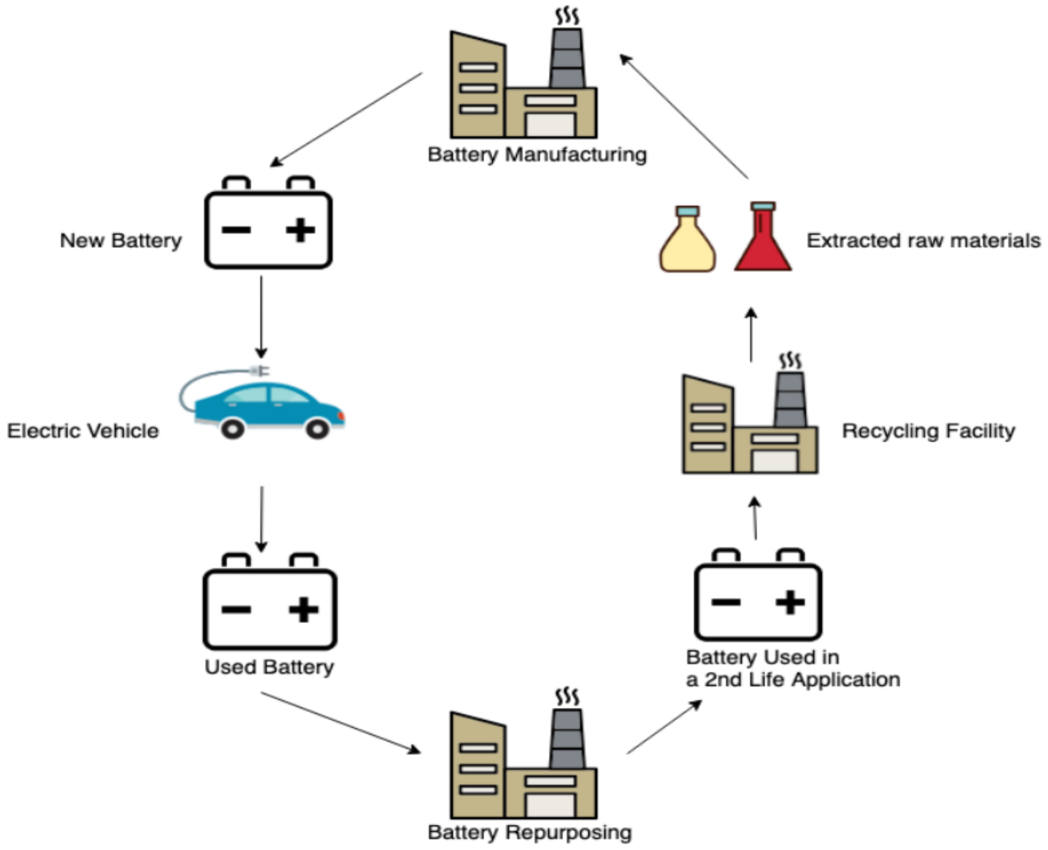
Cathode –

Cathode is the largest component of battery cost
3 oxide types in use - Nickel Cobalt Aluminum oxide, Nickel Manganese Cobalt oxide, Lithium Iron Phosphate

Cobalt is the most expensive material within the cathode, so formulations of these materials with less cobalt typically lead to cheaper batteries

Inactive cell materials –
Contribute nearly 36% of cell
Improving cell design to reduce inactive materials

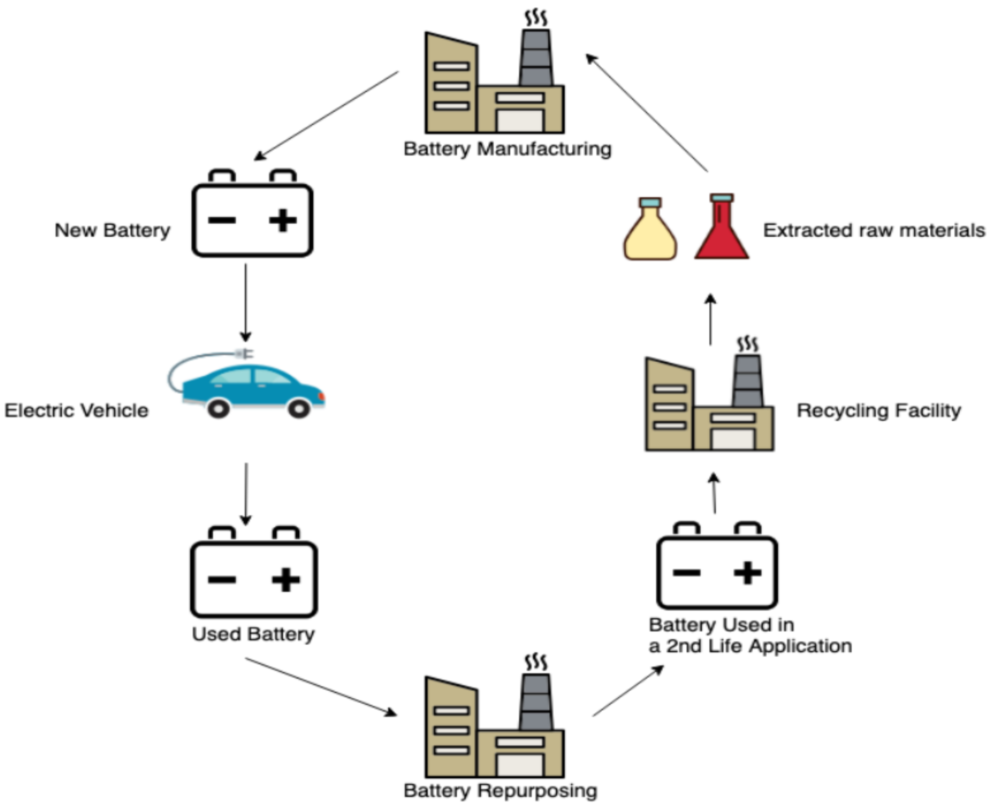
Recycling – to extract Li, Co & Ni



Lifecycle of a Lithium-ion Battery

Cost Improvement Areas (Contd.)

- Recycling – to extract Li, Co & Ni



Lifecycle of a Lithium-ion Battery

Cost Improvement Areas

- Cathode –
  - Cathode is the largest component of battery cost
  - 3 oxide types in use - Nickel Cobalt Aluminum oxide, Nickel Manganese Cobalt oxide, Lithium Iron Phosphate
  - Cobalt is the most expensive material within the cathode, so formulations of these materials with less cobalt typically lead to cheaper batteries
  - Nickel cobalt aluminum oxide has the lowest cost-per-energy-content and highest energy-per-unit-mass
- Inactive cell materials –
  - Contribute nearly 36% of cell
  - Improving cell design to reduce inactive materials

1. Lithium Battery manufacturing (contd.)

Prismatic Cells

Prismatic cells are often used for high capacity battery applications to optimise the use of space. These designs use a stacked electrode structure in which the anode and cathode foils are cut into individual electrode plates which are stacked alternately and kept apart by the separator. The separator may be cut to the same size as the electrodes but more likely it is applied in a long strip wound in a zig zag fashion between alternate electrodes in the stack.

While this case design makes optimum use of space when used in a battery pack, it has the disadvantage that it uses multiple electrode plates which need a clamping mechanism to connect all the anodes together

Cylindrical Cells

For cylindrical cells the anode and cathode foils are cut into two long strips which are wound on a cylindrical mandrel, together with the separator which keeps them apart, to form a jelly roll (Swiss roll in the UK). Cylindrical cells thus have only two electrode strips which simplifies the construction considerably.

A single tab connects each electrode to its corresponding terminal, although high power cells may have electrode strip to carry the higher currents.

Figure 2: Popular 18650 lithium-ion ce

The metallic cylinder measure 18mm in diameter and 65mm the length. The large 26650 cell measures 26mm in diameter.

Courtesy of Cadex


A123RC

Figure 2: Popular 18650 lithium-ion cell.

The metallic cylinder measure 18mm in diameter and 65mm the length. The larger 26650 cell measures 26mm in diameter.

Courtesy of Cadex

BMS: 3 sessions of 1h30 each:

- Introduction to Failures of Batteries: Mechanical, Thermal and Electrical
- Introduction to Battery Management System (BMS): Components and Functions
- Introduction to Battery models: Electrical; Mechanistic; Thermal and Electrochemical
- Lab visit to Battery Testing laboratory: Hands-on experience on use of battery management systems, cycling testing of batteries, etc.

1. Lithium Battery failures
2. Battery Management System
3. State of Charge (SOC) and State of Health (SOH)

Lithium Battery failures

Outcome Of Catastrophic Battery Failure

The New York Times

Dell Recalls Notebook Batteries

By REUTERS
Published: August 15, 2006

Filed at 10:37 a.m. ET

REUTERS

SAN FRANCISCO/TOKYO (Reuters) - Dell Inc. (DELL.O) said on Monday it will recall 4.1 million notebook computer batteries because they could overheat and catch fire, in the biggest recall in its 22-year history.

iTWire
IT and TELCO news
Australia's #1 Technology website
don't take our word for it >>

HP issues battery fire hazard recall number 3

By Stan Beer
Wednesday, 07 June 2006

Hewlett-Packard, appears to have a serious quality control problem with its battery powered systems. The giant computer maker has just issued its third major global product recall because of potential fire hazards to consumers within just nine months.

In its latest recall, the largest to date, HP has issued a public recall notice for 679,000 model R707 digital cameras sold between August 2004 and April 2006.

wcco.com

Laptop Fires Prompt Battery Recalls

May 29, 2006
8:28 am US/central
By David Schechter

Dave Brown

(WCCO) Nick Brown, 11, was playing on his Apple iBook laptop about one month ago when, like most children, he got distracted and left the room.

His mom, Cindy Brown, explains what happened next. "My husband and I were in the other room, heard a popping noise, came out and the room was filled with smoke," she said.

Source:http://ecow.engr.wisc.edu/cgi-bin/getbig/interegr/160/johnmurphy/3lectureno/archivedle/lecture15_walz.ppt#299,1,Energy Storage, Lithium

2. Lithium batteries

Since the late 1980s rechargeable lithium cells have come onto the market. **They offer greatly increased energy density in comparison with other rechargeable batteries**, though at greatly increased cost. It is a well-established **feature of the most expensive laptop computers and mobile phones that lithium rechargeable batteries are specified, rather than the lower cost NiCad or NiHM cells that we have been considering earlier.**

The lithium batteries are of following types:
1. Lithium polymer batteries
2. Lithium ion batteries

2. Lithium batteries (contd.)

The lithium polymer battery:

The lithium polymer battery uses **lithium metal for the negative electrode** and a **transition metal intercalation oxide for the positive**. In the resulting chemical reaction the lithium combines with the metal oxide to form a lithium metal oxide and release energy. When the battery is recharged the chemical reaction is reversed. The lithium is thus both a reactant and the mobile ion that moves through the electrolyte. The overall chemical reaction is:

$$xLi + M_yO_z \leftrightarrow Li_xM_yO_z$$

2. Lithium batteries (contd.)

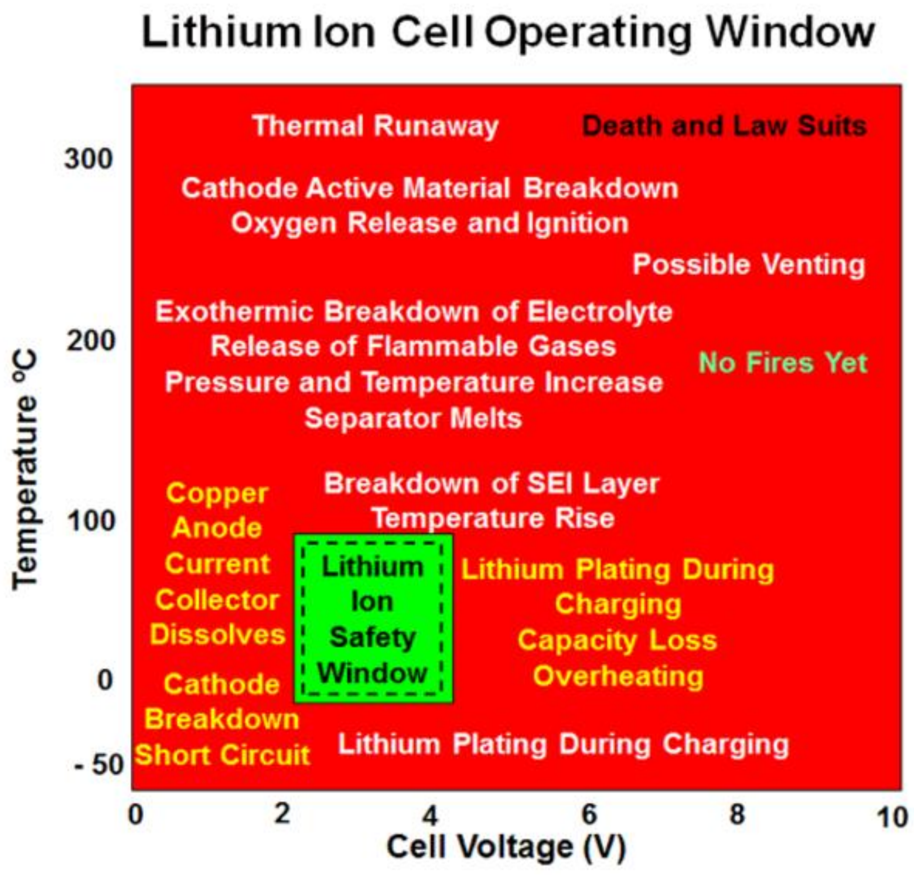
The lithium ion battery:

The lithium ion battery was introduced in the early 1990s and it uses a **lithiated transition metal intercalation oxide for the positive electrode** and **lithiated carbon for the negative electrode**. **The electrolyte is either a liquid organic solution or a solid polymer**. Electrical energy is obtained from the combination of the lithium carbon and the lithium metal oxide to **form carbon and lithium metal oxide**. The overall chemical reaction for the battery is:

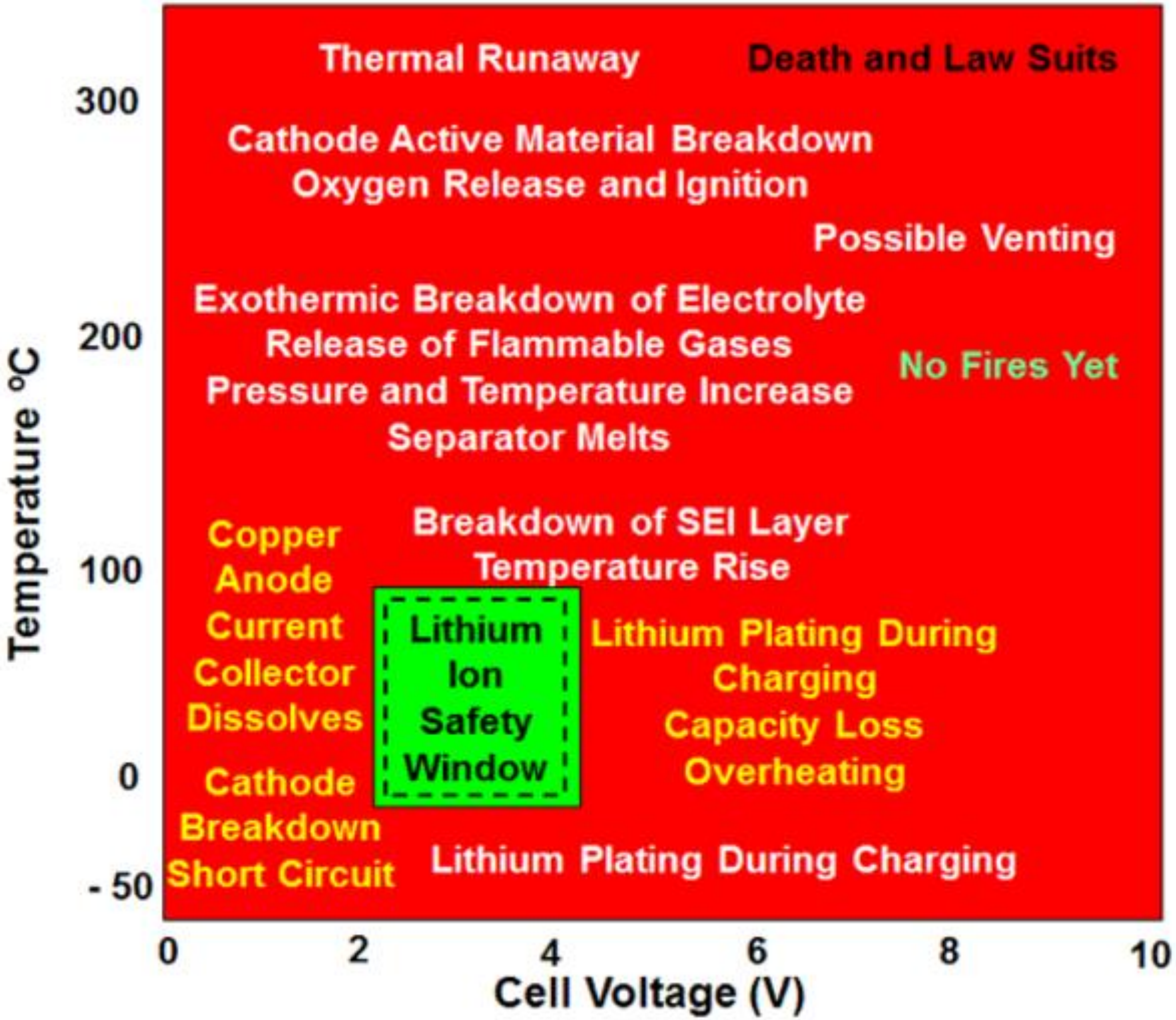
$$C_6Li_x + M_yO_z \leftrightarrow 6C + Li_xM_yO_z$$

2. Lithium Battery failures

The performance of Lithium Ion cells is dependent on ***both the temperature and the operating voltage***. The diagram below shows that, at all times, the cell operating voltage and temperature must be kept within the limits indicated by the green box. Once outside the box permanent damage to the cell will be initiated.



Lithium Ion Cell Operating Window



2. Lithium Battery failures (contd.)

1. Voltage Effects

•Over-Voltage

If the charging voltage is increased beyond the recommended upper cell voltage, typically 4.2 Volts, excessive current flows giving rise to two problems.

- **Lithium Plating**

With excessive currents the Lithium ions can not be accommodated quickly enough between the intercalation layers of the carbon anode and Lithium ions accumulate on the surface of the anode where they are deposited as metallic Lithium. This is known as Lithium plating. The consequence of this is a reduction in the free Lithium ions and hence an irreversible capacity loss and since the plating is not necessarily homogeneous, but dendritic in form, it can ultimately result in a short circuit between the electrodes.

Another major cause of Lithium plating is low temperature operation and it can also be caused by non-uniformities in the cell elements due to manufacturing defects or abuse. See below.

- **Overheating**

Excessive current also causes increased Joule heating of the cell, accompanied by an increase in temperature.

•Under-voltage / Over-discharge

Rechargeable Lithium cells suffer from under-voltage as well as over-voltage. Allowing the cell voltage to fall below about 2 Volts by over-discharging or storage for extended periods results in progressive breakdown of the electrode materials.

- **Anodes**

First the anode copper current collector is dissolved into the electrolyte. This increases the self discharge rate of the cell however, as the voltage is increased again above 2 volts, the copper ions which are dispersed throughout the electrolyte are precipitated as metallic copper wherever they happen to be, not necessarily back on the current collector foil. This is a dangerous situation which can ultimately cause a short circuit between the electrodes.

- **Cathodes**

Keeping the cells for prolonged periods at voltages below 2 Volts results in the gradual breakdown of the cathode over many cycles with the release of Oxygen by the Lithium Cobalt Oxide and Lithium Manganese Oxide cathodes and a consequent permanent capacity loss. With Lithium Iron Phosphate cells this can happen over a few cycles .

2. Lithium Battery failures (contd.)

2. Temperature Effects
Heat is a major battery killer, either excess of it or lack of it, and Lithium secondary cells need careful temperature control.

2.1 Low temperature operation

Chemical reaction rates decrease in line with temperature. The effect of reducing the operating temperature is to reduce rate at which the active chemicals in the cell are transformed. This translates to a reduction in the current carrying capacity of the cell both for charging and discharging. In other words its power handling capacity is reduced.

Futhermore, at low temperatures, the reduced reaction rate (and perhaps contraction of the electrode materials) slows down, and makes makes more difficult, the insertion of the Lithium ions into the intercallation spaces.

2.2 High temperature operation

Operating at high temperatures brings on a different set of problems which can result in the destruction of the cell. In this case, the Arrhenius effect helps to get higher power out of the cell by increasing the reaction rate, but higher currents give rise to higher I^2R heat dissipation and thus even higher temperatures. This can be the start of positive temperature feedback and unless heat is removed faster than it is generated the result will be **thermal runaway**.

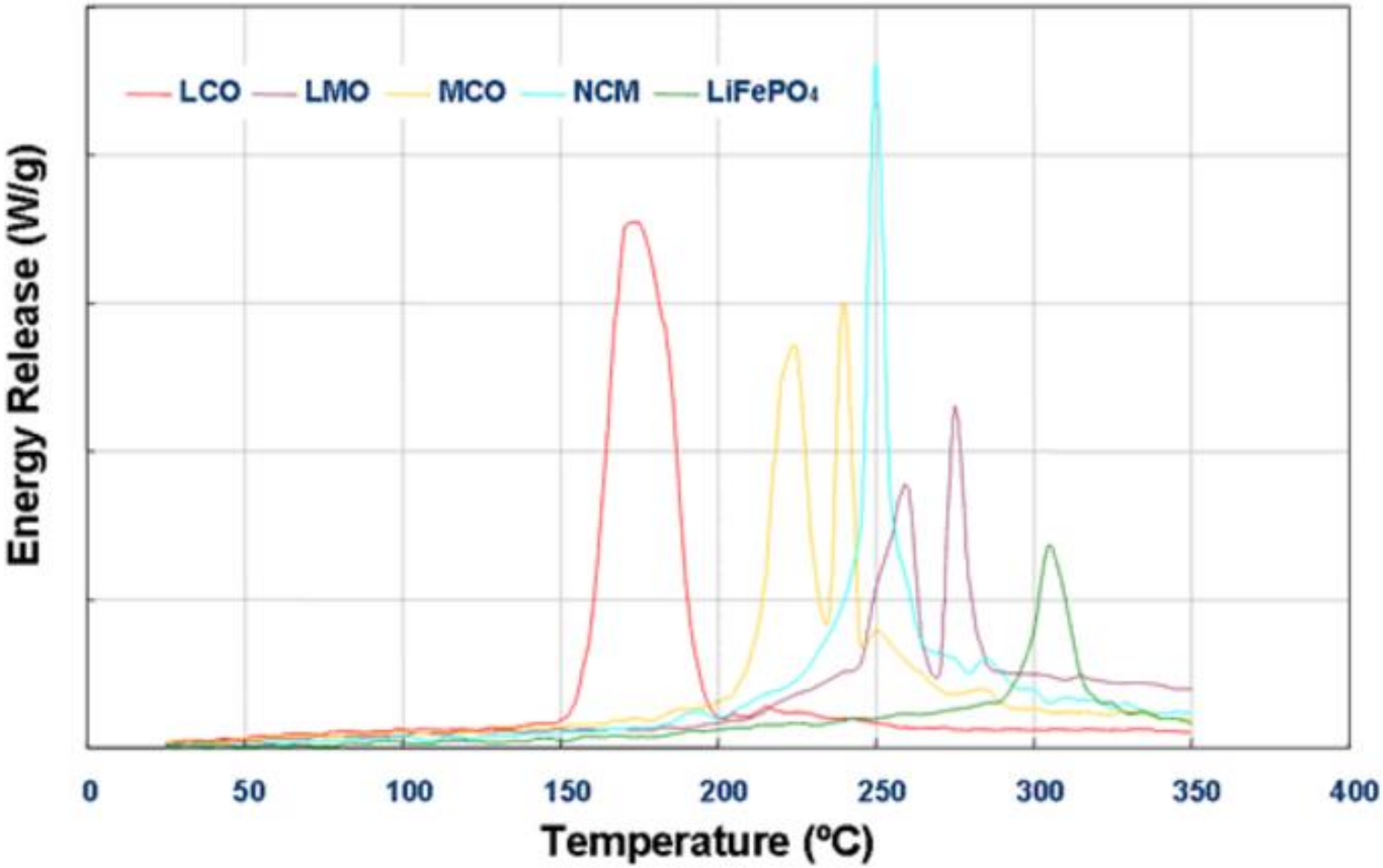
2. Lithium Battery failures (contd.)

2.2.1 Thermal runaway

Several stages are involved in the build up to thermal runaway and each one results in progressively more permanent damage to the cell.

- The **first stage** is the **breakdown of the thin layer on the anode, due to overheating or physical penetration**. The initial overheating may be caused by excessive currents, overcharging or high external ambient temperature. The breakdown of the layer starts at the relatively low temperature of 80ºC and once this layer is breached the electrolyte reacts with the carbon anode at a higher, uncontrolled, temperature. This is an exothermal reaction which drives the temperature up still further.
- **As the temperature builds up, heat from anode reaction causes the breakdown of the organic solvents used in the electrolyte releasing flammable hydrocarbon gases (Ethane, Methane and others) but no Oxygen**. This typically starts at 110 ºC but with some electrolytes it can be as as low as 70ºC. The gas generation due to the breakdown of the electrolyte causes pressure to build up inside the cell. Although the temperature increases to beyond the flashpoint of the gases released by the electrolyte, the gases do not burn because there is no free Oxygen in the cell to sustain a fire.
- **The cells are normally fitted with a safety vent which allows the controlled release of the gases to relieve the internal pressure in the cell avoiding the possibility of an uncontrolled rupture of the cell - otherwise known as an explosion, or more euphemistically, "rapid disassembly" of the cell. Once the hot gases are released to the atmosphere they can of course burn in the air**.
- At around 135 ºC the polymer separator melts, allowing the **short circuits between the electrodes.**
- **Eventually heat from the electrolyte breakdown causes breakdown of the metal oxide cathode material releasing Oxygen which enables burning of both the electrolyte and the gases inside the cell.**
- **The breakdown of the cathode is also highly exothermic sending the temperature and pressure even higher. The cathode breakdown starts at around 200 ºC for Lithium Cobalt Oxide cells but at higher temperatures for other cathode chemistries.**

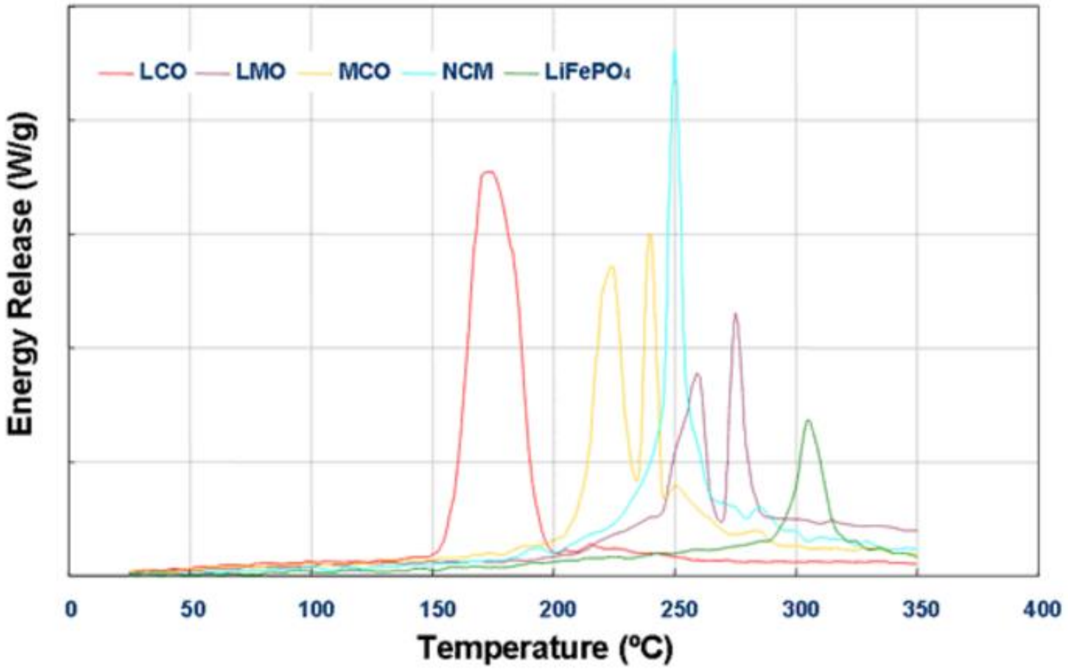
By this time the pressure is also extremely high and it's time to run for the door.


LCO
LMO
MCO
NCM
LiFePO4
Energy Release (W/g)
0
50
100
150
200
250
300
350
400
Temperature (ºC)

2. Lithium Battery failures (contd.)

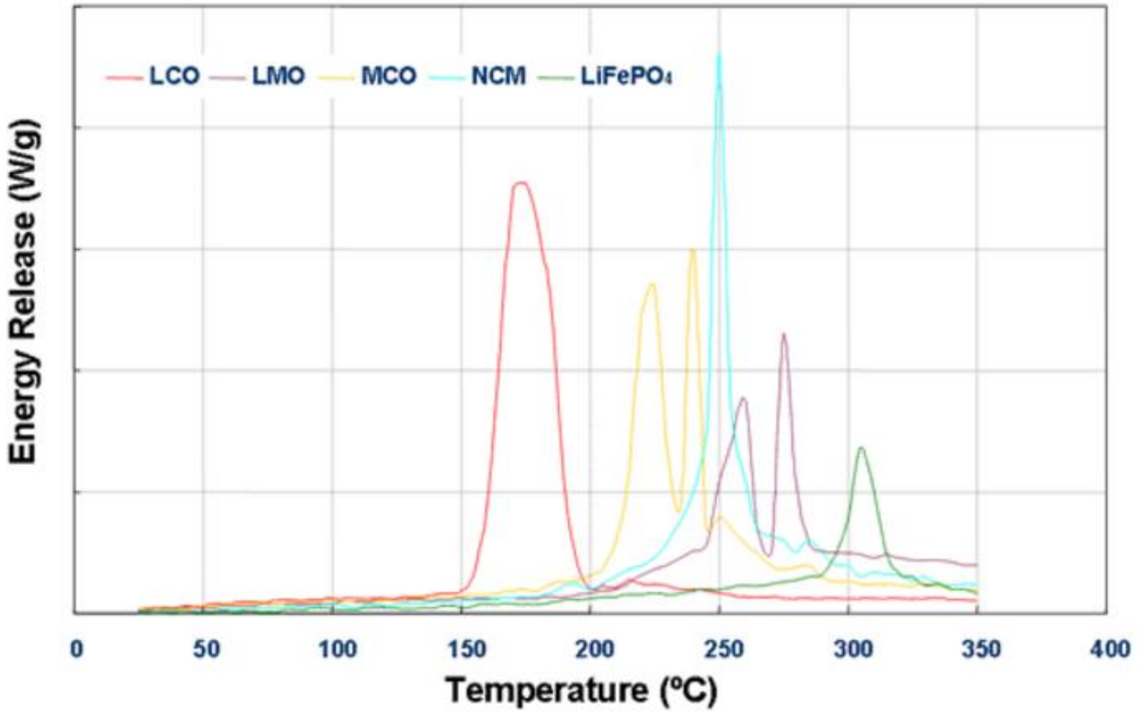
3. Alternative Lithium cathode chemistries

Lithium Cobalt Oxide *was the first material used for the cathodes in Lithium secondary cells but safety concerns were raised for two reasons*. **The onset of chemical breakdown is at a relatively low temperature and when the cathode breaks down, large amounts of energy are released. For that reason alternative cathode materials have been developed. The diagram below shows the breakdown characteristics of several alternative cathode materials.**

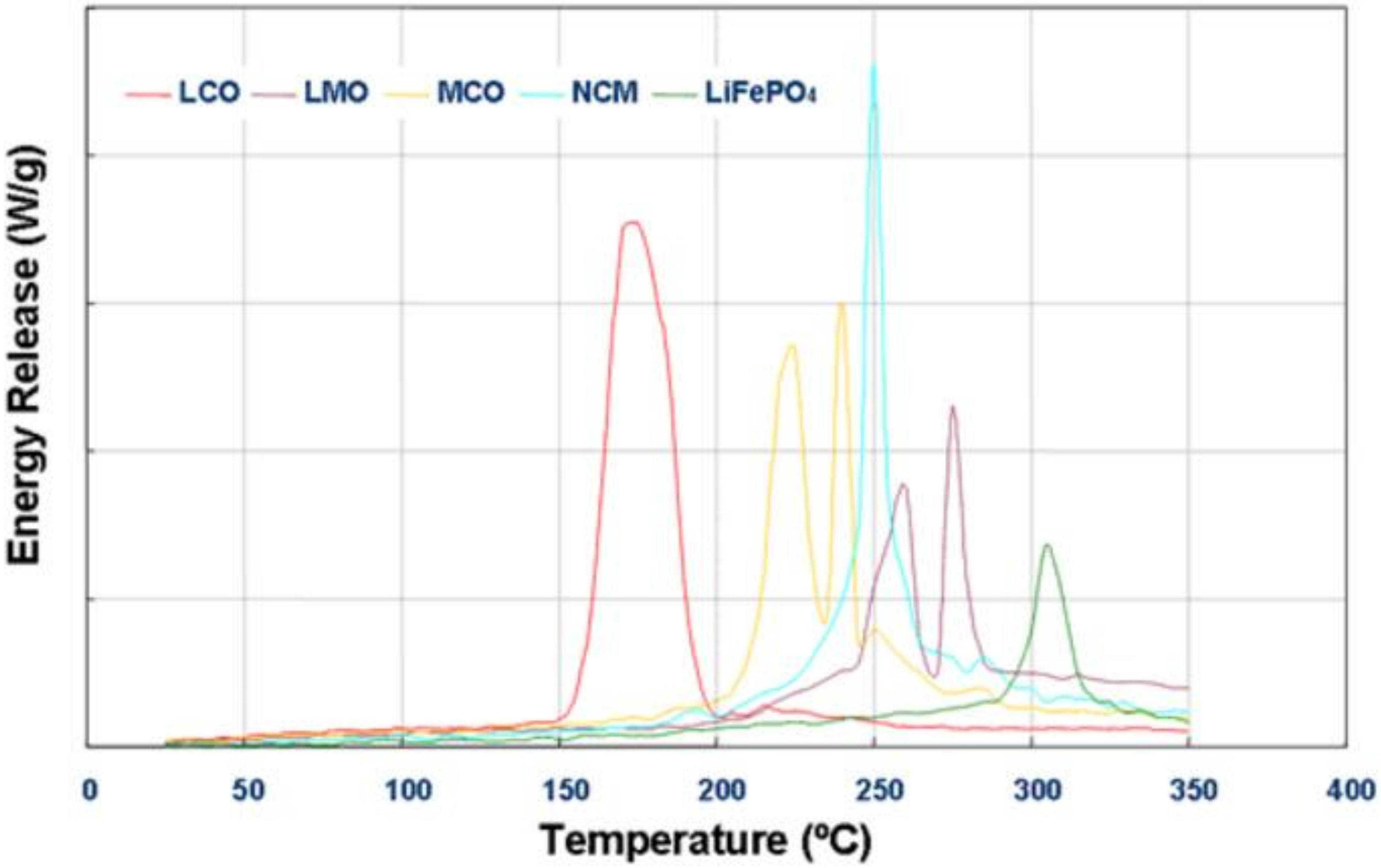


2. Lithium Battery failures (contd.)

The graph above shows that ***Lithium Iron Phosphate cathodes*** do not break down ***with the release of oxygen until much higher temperatures and when they do, much less energy is released***. The reason is that the Oxygen molecules in the Phosphate material have a much stronger valence bond to the Phosphorus and this is more difficult to break. **The other cathode chemistries are based on Lithium metal oxides which have much weaker valence bonds binding the Oxygen to the metal and these are more easily broken to release the Oxygen.**



Note that consumer concern about the safety of Lithium batteries tends to be focussed on the Lithium cathode materials, whereas in reality, thermal runaway is initiated at the anode, NOT the cathode.



LCO
LMO
MCO
NCM
LiFePO4
Energy Release (W/g)
0
50
100
150
200
250
300
350
400
Temperature (ºC)

2. Lithium Battery failures (contd.)

4. Non-Uniformities

Non-uniform current flow due to **localised defects in the region of the interface between the separator and the anode surface can also give rise to Lithium plating**. Examples of such defects are:

Why Manufacturing Defects?

- Mechanical deformation of the components
- Blockage or deformation of the separator pores
- Uneven anode coating
- Non-uniform contact between the separator and the anode
- Delamination of the current collector
- Contamination of the active chemicals
- Local electrolyte drying

Abuse

- Physical damage
- Copper deposition as a result of prolonged over discharge

While the bulk current through the cell may not be excessive, these defects can cause an uneven current density in the flow of Lithium ions and the corresponding high concentrations of Lithium ions give rise to Lithium plating.

2. Lithium Battery failures (contd.)

5. Mechanical Fatigue

The electrodes of Lithium cells expand and contract during charging and discharging due to the effect of the intercalation of the Lithium ions into and out of the crystal structure of the electrodes. **The cyclic stresses on the electrodes can eventually lead to cracking of the particles making up the electrode resulting in increased internal impedance as the cell ages, or in the worst case, a breakdown of the anode layer which could lead to overheating and immediate cell failure.**

A similar process, possibly augmented by the accumulated release of small amounts of gas due to the slow deterioration of the electrolyte each time it is heat cycled, **could result in swelling of the cell and ultimately rupture of the cell casing.**

2. Lithium Battery failures (contd.)

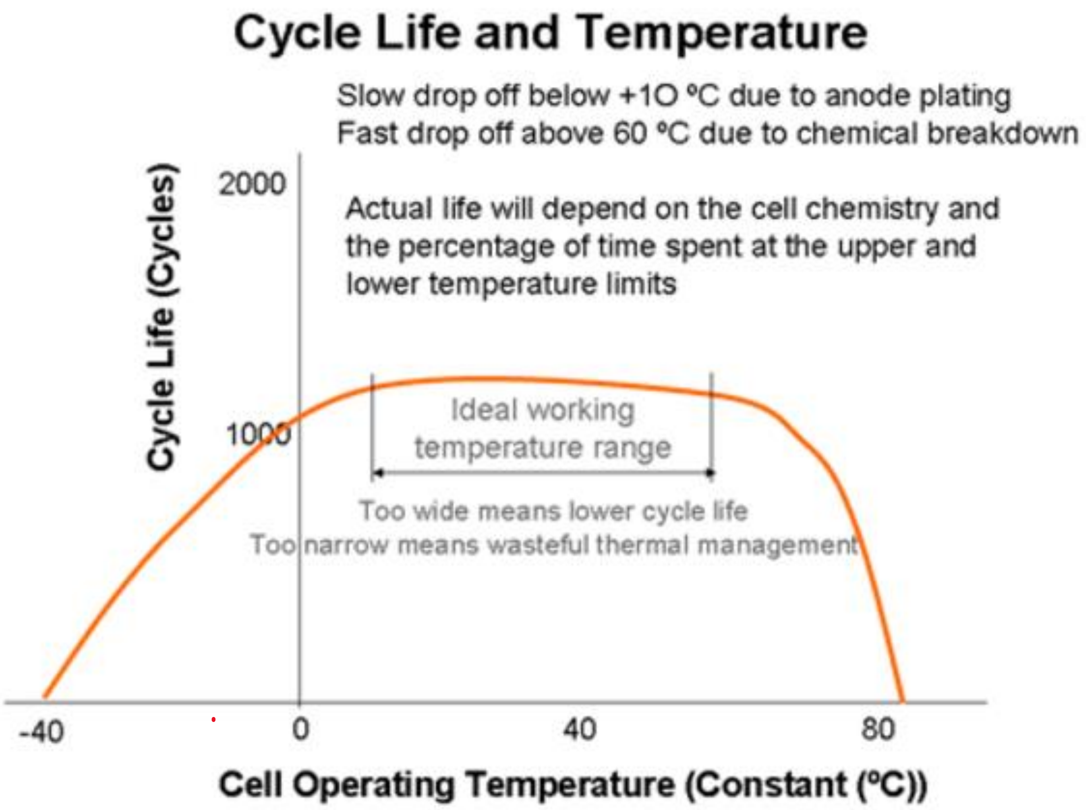
6. Cycle Life

The effects of voltage and temperature on cell failures tend to be immediately apparent, but their effect on cycle life is less obvious. We have seen above that excursions outside of the recommended operating window can cause irreversible capacity loss in the cells. The graph above shows that starting at about 15 ºC cycle life will be progressively reduced by working at lower temperatures. Operating slightly above 50 ºC also reduces cycle life but by 70 ºC the threat is thermal runaway.

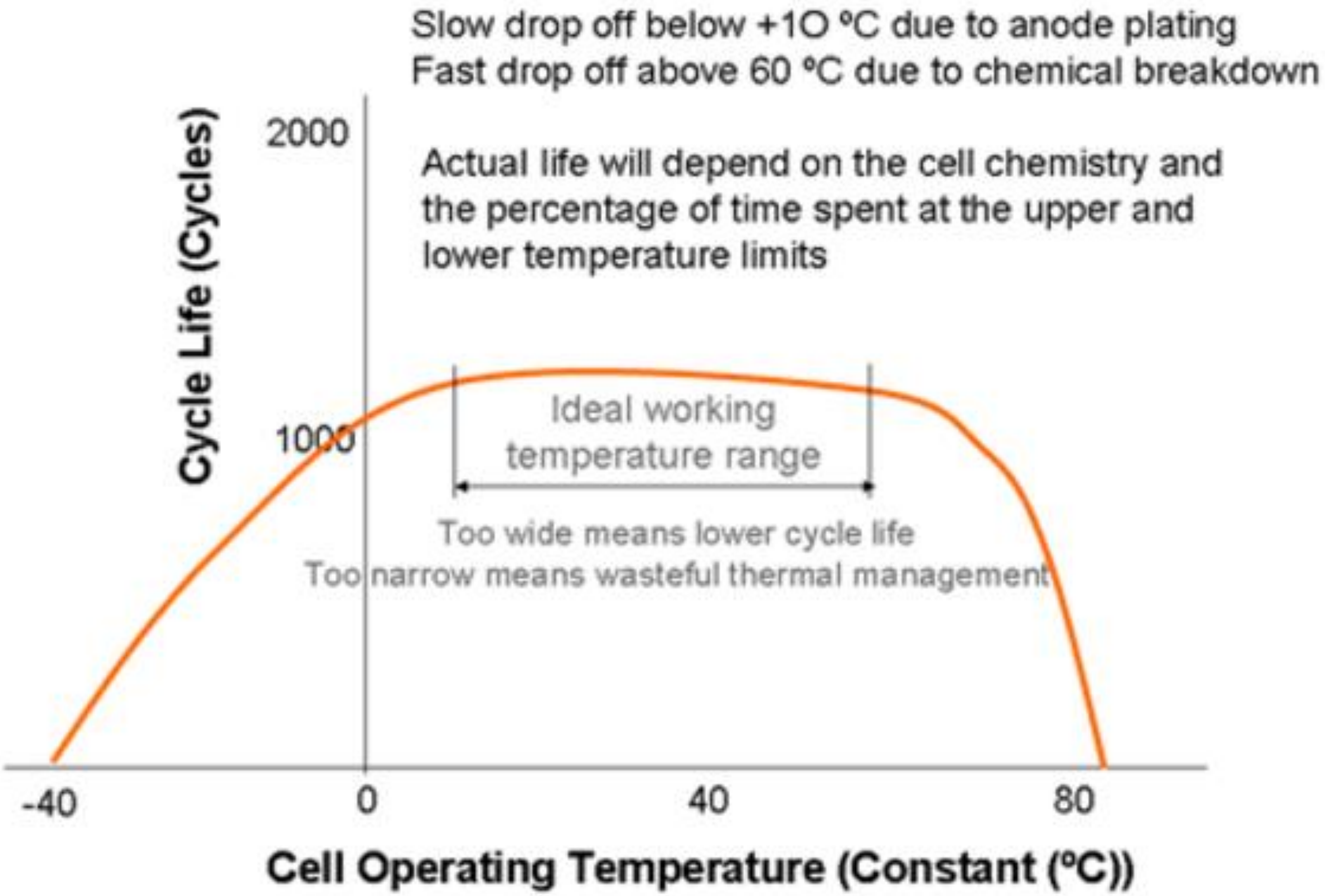
Battery Cycle Life is defined as the number of complete charge - discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity. Key factors affecting cycle life are time **t** and the number **N** of charge-discharge cycles completed.

Battery Calendar Life is the elapsed time before a battery becomes unusable whether it is in active use or inactive. There are two key factors influencing calendar life, namely temperature and time, and empirical evidence shows that these effects can be represented by two relatively simple mathematical dependencies.

A rule of thumb derived from the Arrhenius Law describes how the rate at which a chemical reaction proceeds, doubles for every 10 degrees rise in temperature, in this case it applies to the rate at which the slow deterioration of the active chemicals increases. Similarly the $\mathbf{t^{1/2}}$ (or $\sqrt{\mathbf{t}}$) relationship represents how the battery internal resistance also increases with time **t**. The graph below illustrates these effects.



Cycle Life and Temperature



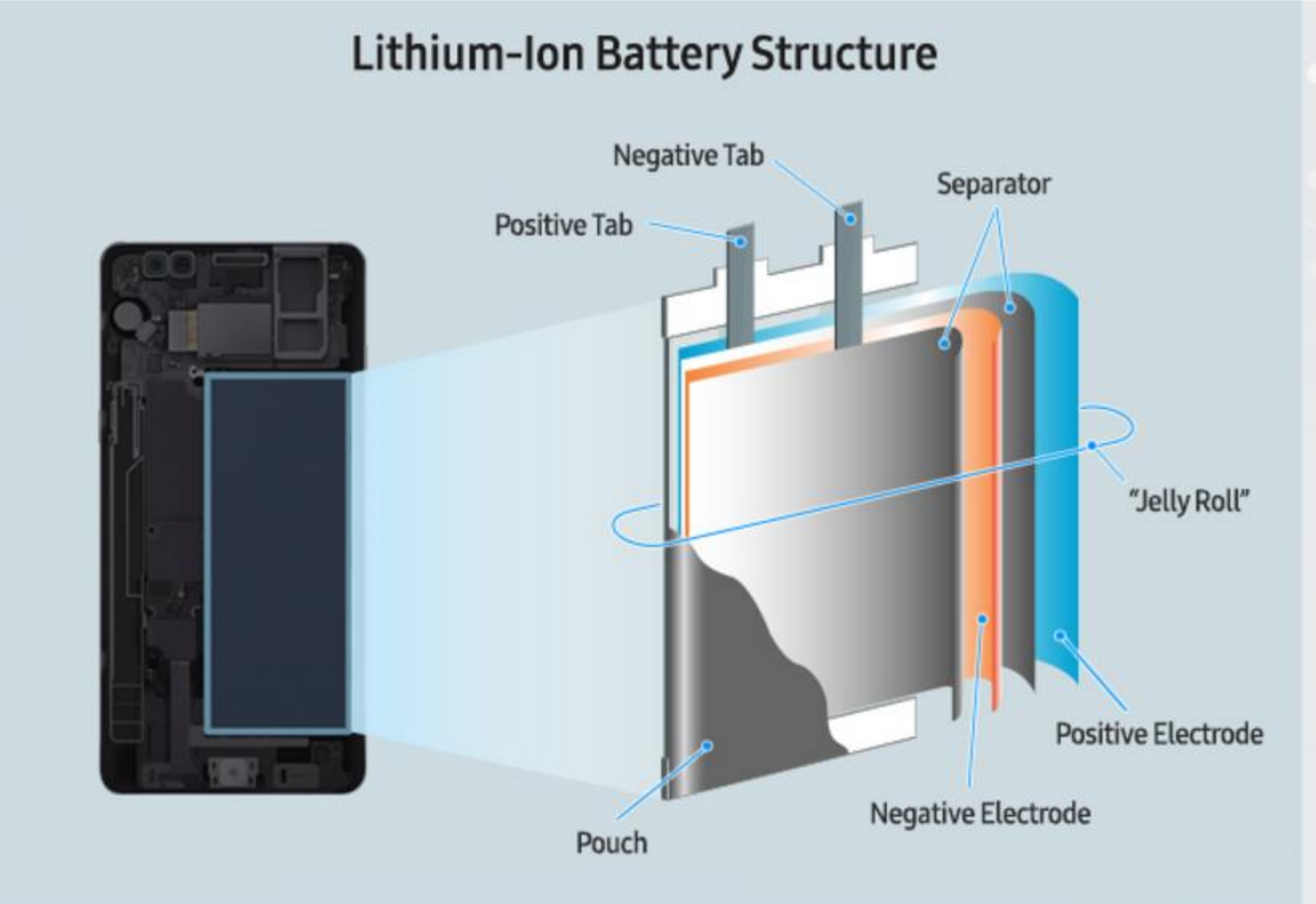
Samsung 2016 Battery Failures

Source : Samsung Galaxy Note 7 failure investigation press conference, Jan 2017. All Information in public domain

Samsung Galaxy 2016 Failures

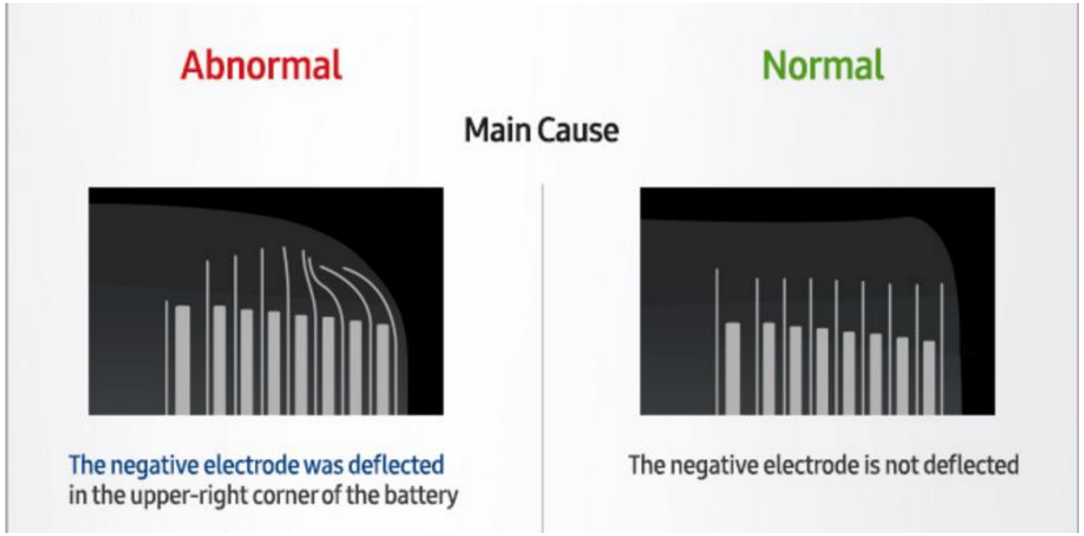
- Galaxy Note 7 fires were reported within a few weeks of the product launch.
- Samsung recalled affected phones, and pointed to a manufacturing error from its battery supplier Samsung SDI.
- Replacement phones that were supposed to be "fixed" also started to catch on fire.
- Samsung scrapped the entire product line. 2.5 million phone recalls prior. Cost Samsung $5 Billion

Flattened Jellyroll Pouch Cell Design



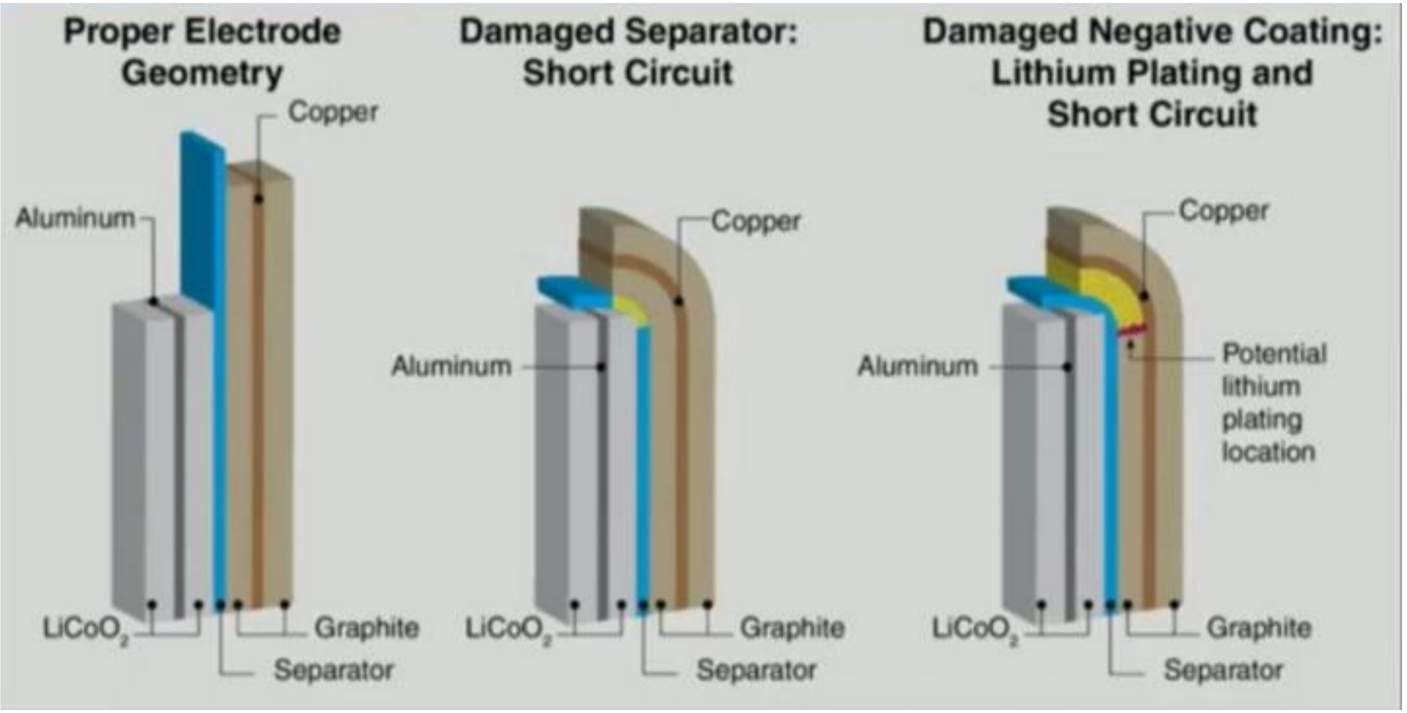
Manufacturer A Root Cause

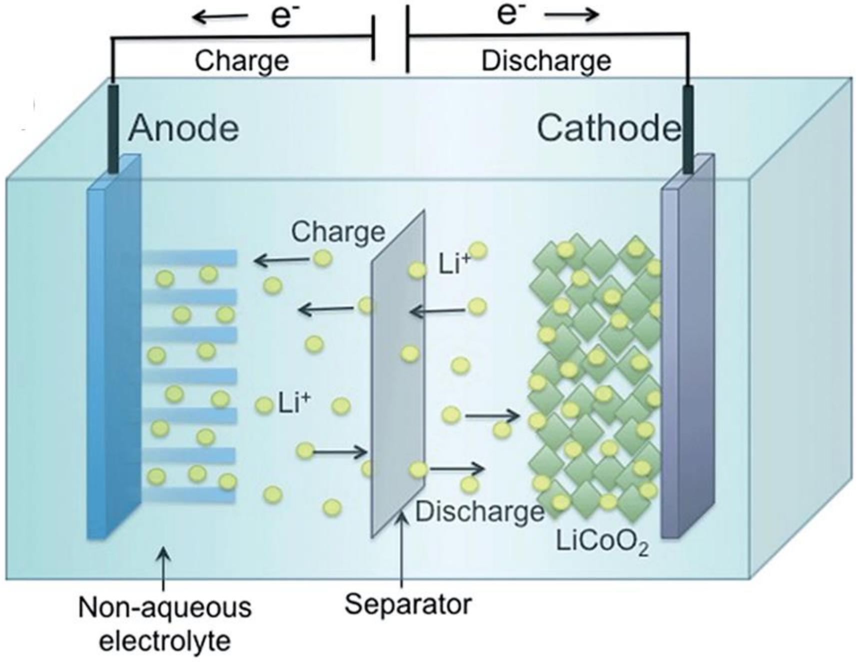
- Damage to the negative electrode windings caused by deflection by a pouch design that did not provide sufficient volume to accommodate the electrode assembly.
- Curvature of pouch causes deflection of the negative electrodes.



Negative Electrode Deflection

- Negative electrode damage provides multiple pathways to cell internal short circuit and thermal runaway under normal cycling conditions
  - Damage to the separator
  - Lithium plating

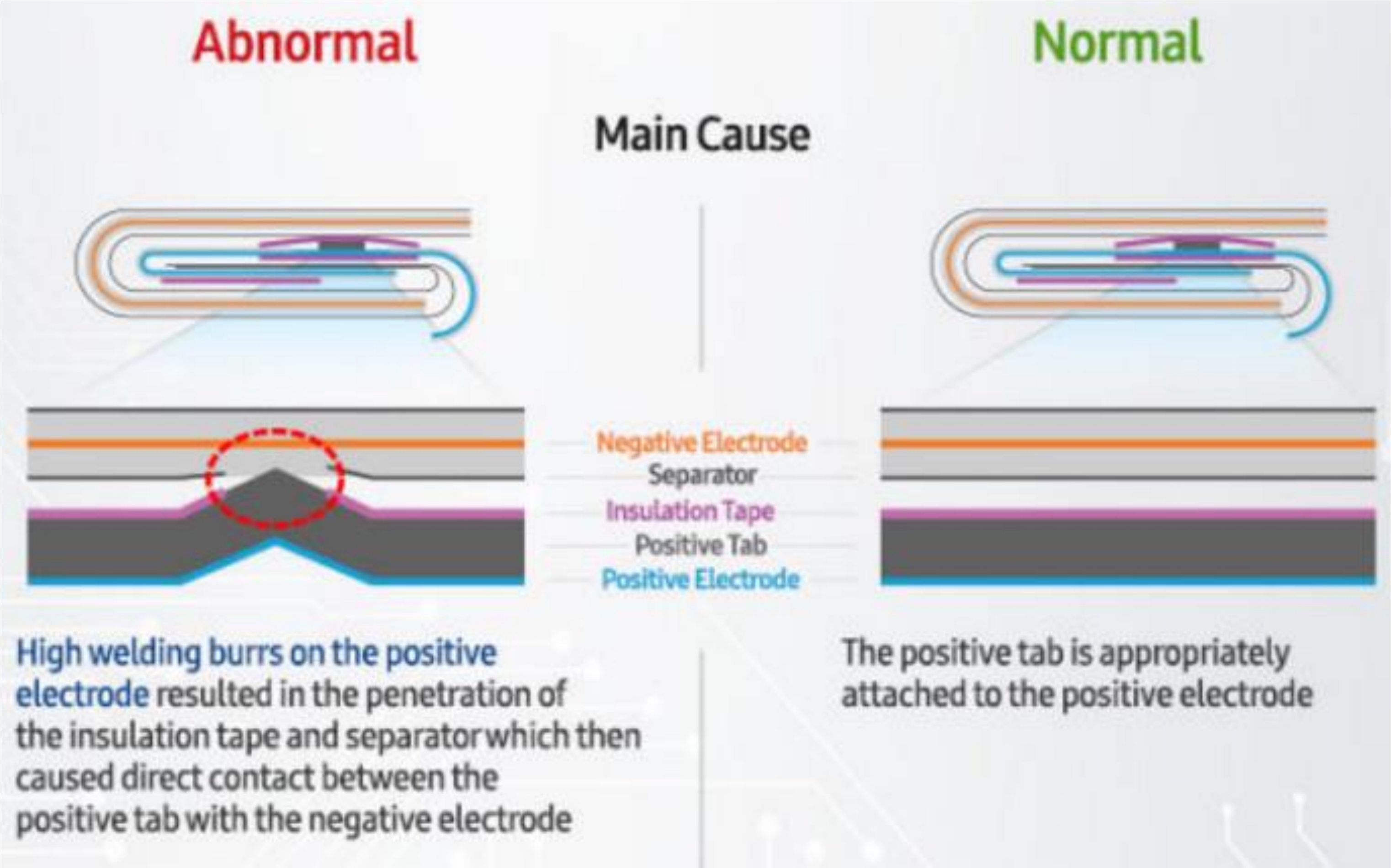




Manufacturer B Root Cause

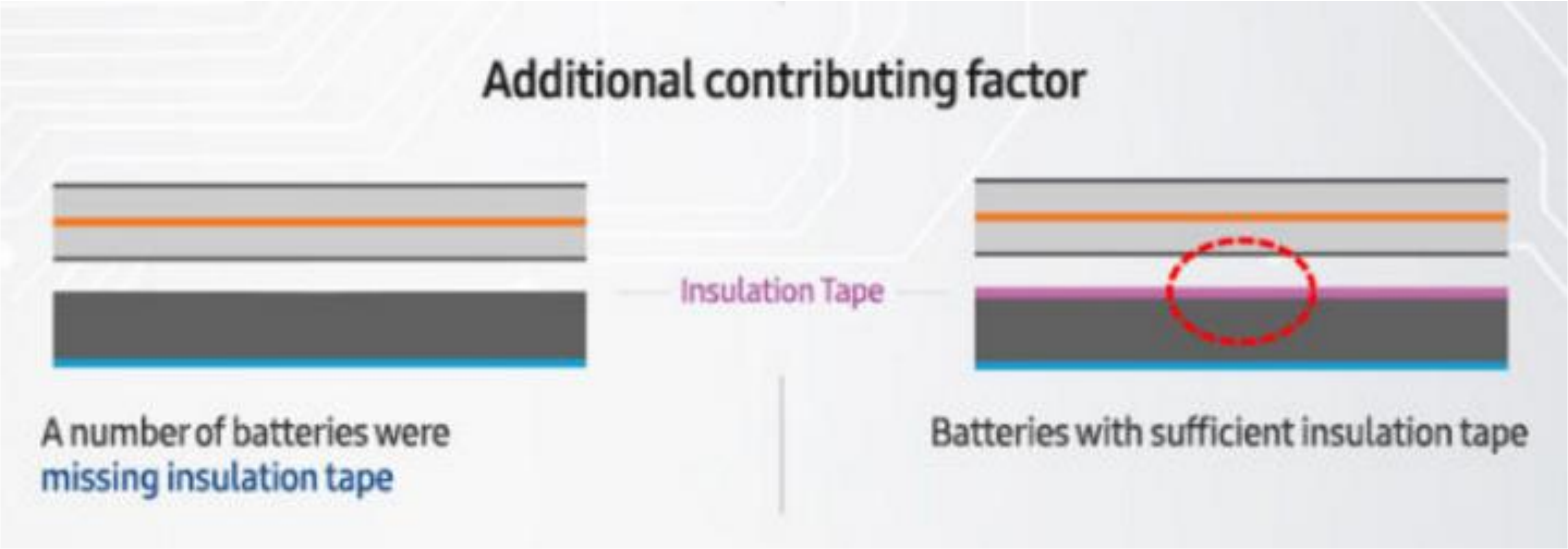
- Tab welding defect created an internal short

- Poorly controlled welding process - Burr height 80 µm in some cases
- Normal swelling and contraction occurs during charge-discharge cycling



Manufacturer B Root Cause

- Some batteries were missing the insulation tape!!
- Samsung blames the flaws on its factories trying to get production started too quickly to counteract lost sales.
- There are simply no short cuts when it comes to lithium ion battery manufacturing process control



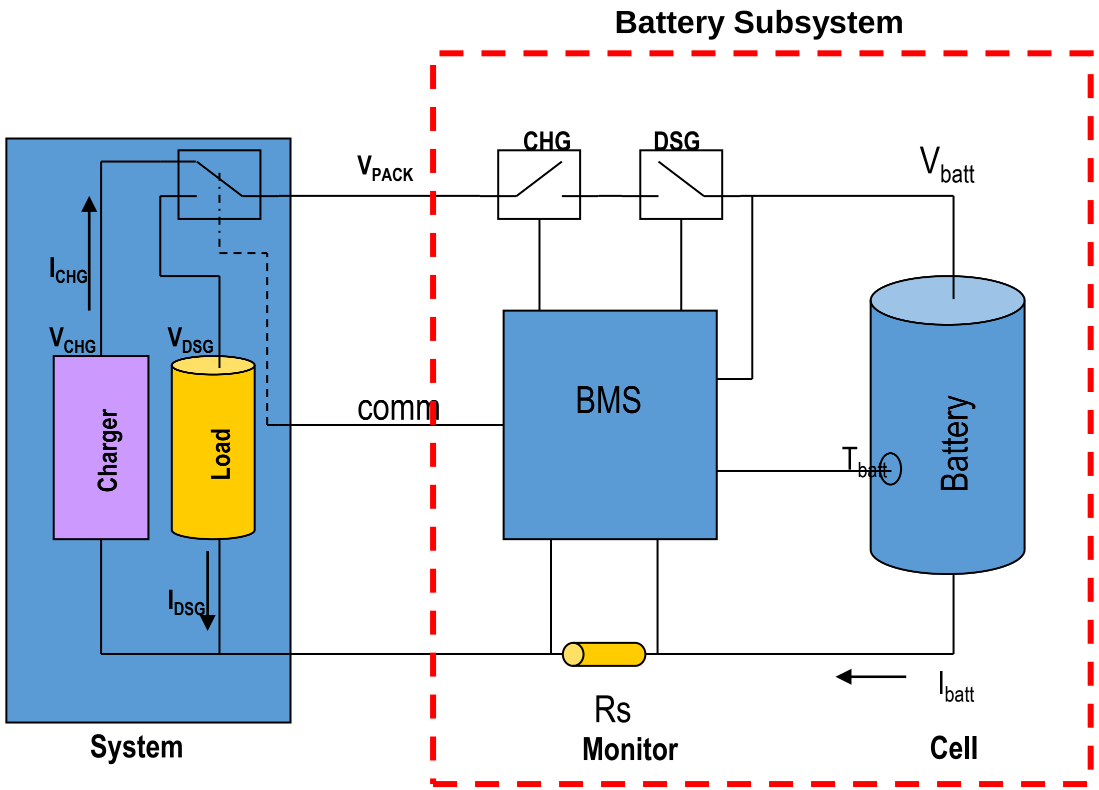
Thank you

Battery Monitoring Basics

Section 1 – Basic Concepts

- What does a battery monitor do?
- How to estimate battery capacity?
  - Voltage lookup
  - Current integration
- Factors affecting capacity estimation
- Other functions
  - Safety and protection
  - Cell balancing
  - Charging support
  - Communication and display
  - Logging

What does a battery monitor (BMS) do?



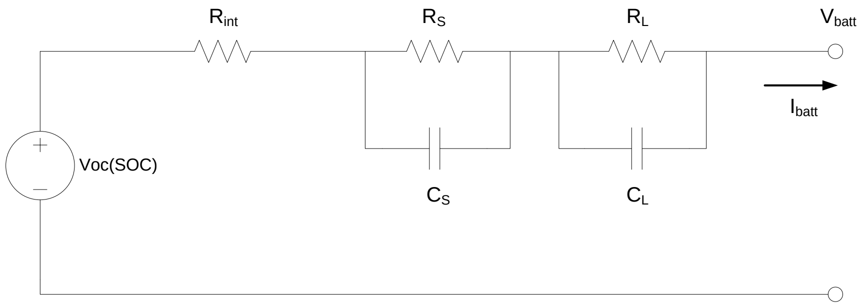
- Capacity estimation
- Safety/protection
- Charging support
- Communication and Display
- Logging
- Authentication

How to estimate battery capacity?

- Measure change
  - Voltage lookup
  - Coulomb counting

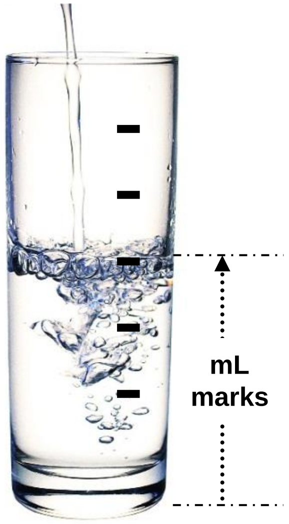
DC model

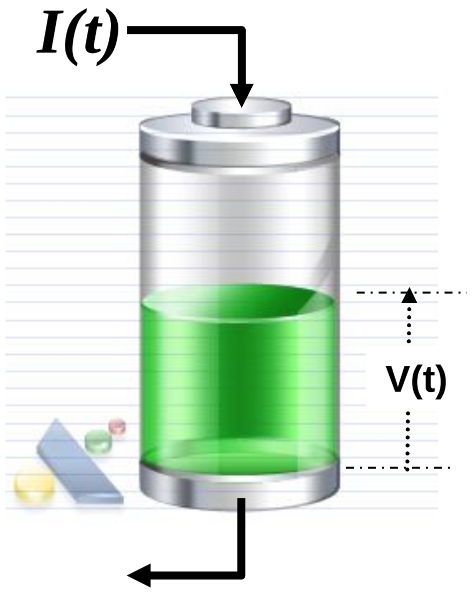
- Develop a cell model
  - Circuit model
  - Table Lookup



Voltage lookup

- One can tell how much water is in a glass by reading the water level
  - Accurate water level reading should only be made after the water settles (no ripple, etc)
- One can tell how much charge is in a battery by reading well-rested cell voltage
  - Accurate voltage should only be made after the battery is well rested (stops charging or discharging)



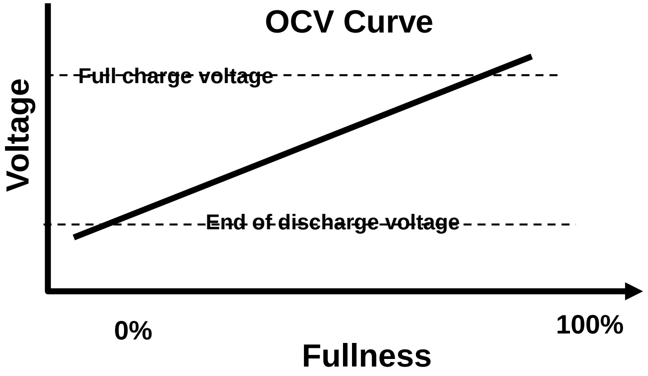


OCV curve

Level
rises
same rate

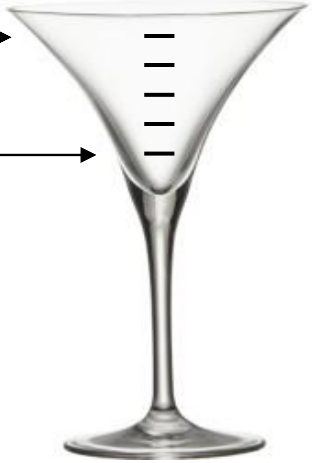
Level
rises
same rate

Capacitor

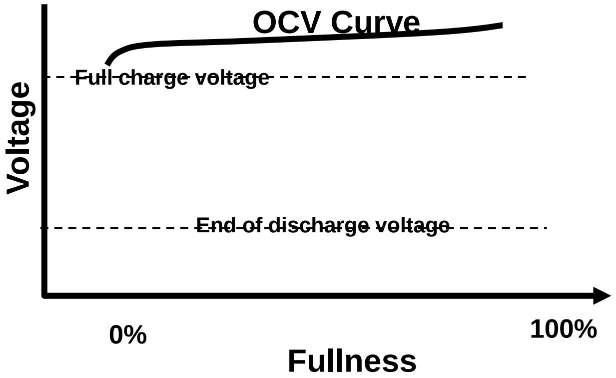


Level rises
slower

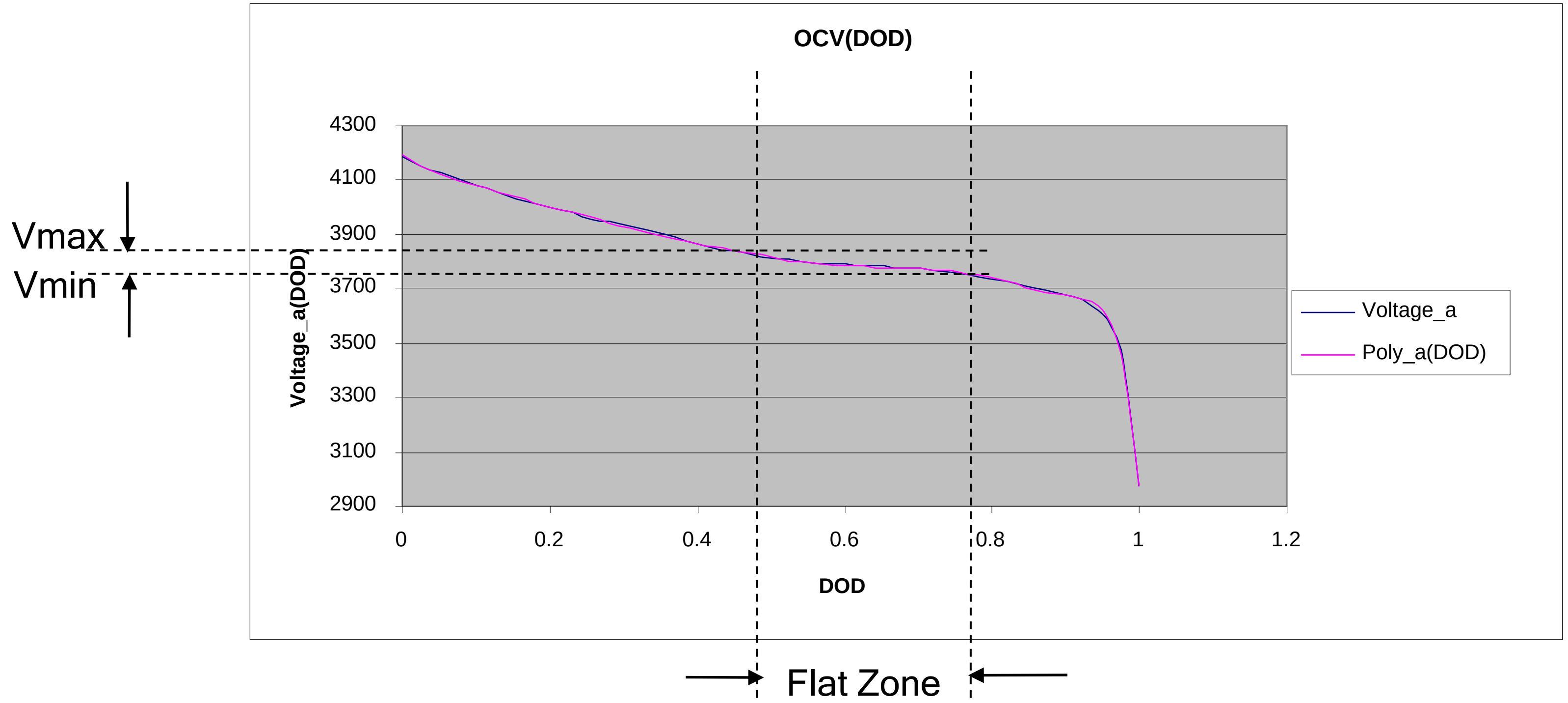
Level rises
faster



Battery



OCV voltage table: DOD representation



DOD = Depth of Discharge
SOC = State of Charge
DOD = 100% - SOC
SOC = 100%-DOD

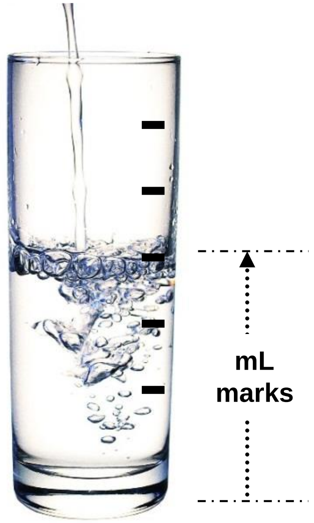
Current integration

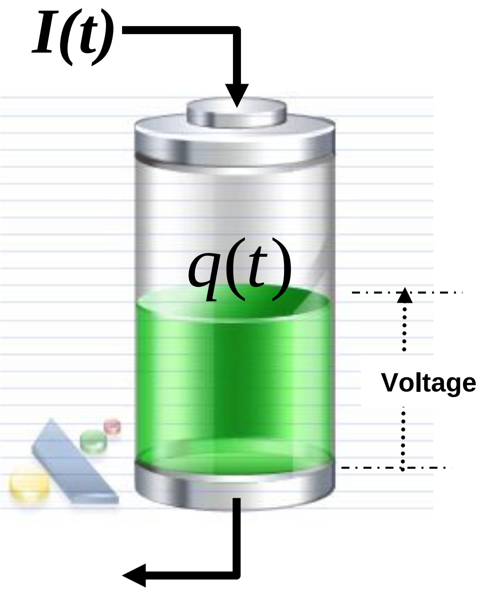
- One can also measure how much water goes in and out
- In batteries, battery capacity <u>*changes*</u> can be monitored by tracking the amount of electrical charges going in/out

$$q(t) = q_0 + \int I(t) \cdot dt$$

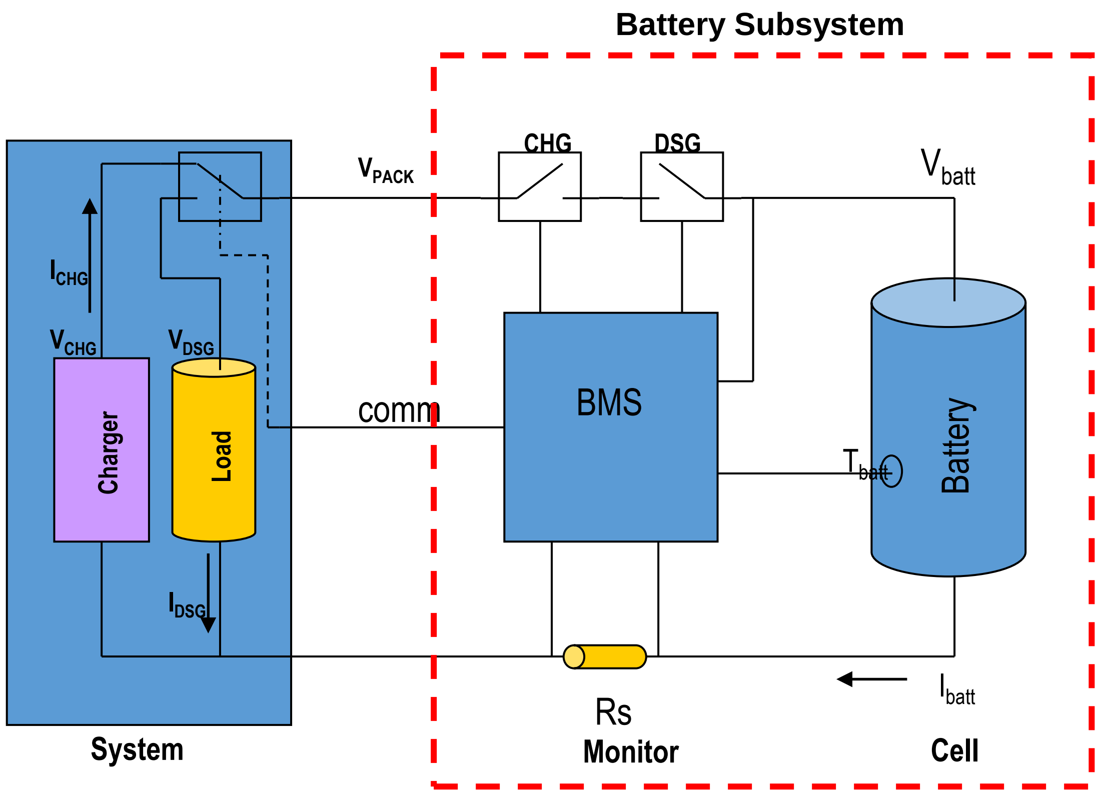
$$q_k = q_0 + \Delta t \cdot \sum_k I_k$$

- But how do you know the amount of charge, q_0, already in the battery at the start?
- How do you count charges accurately?



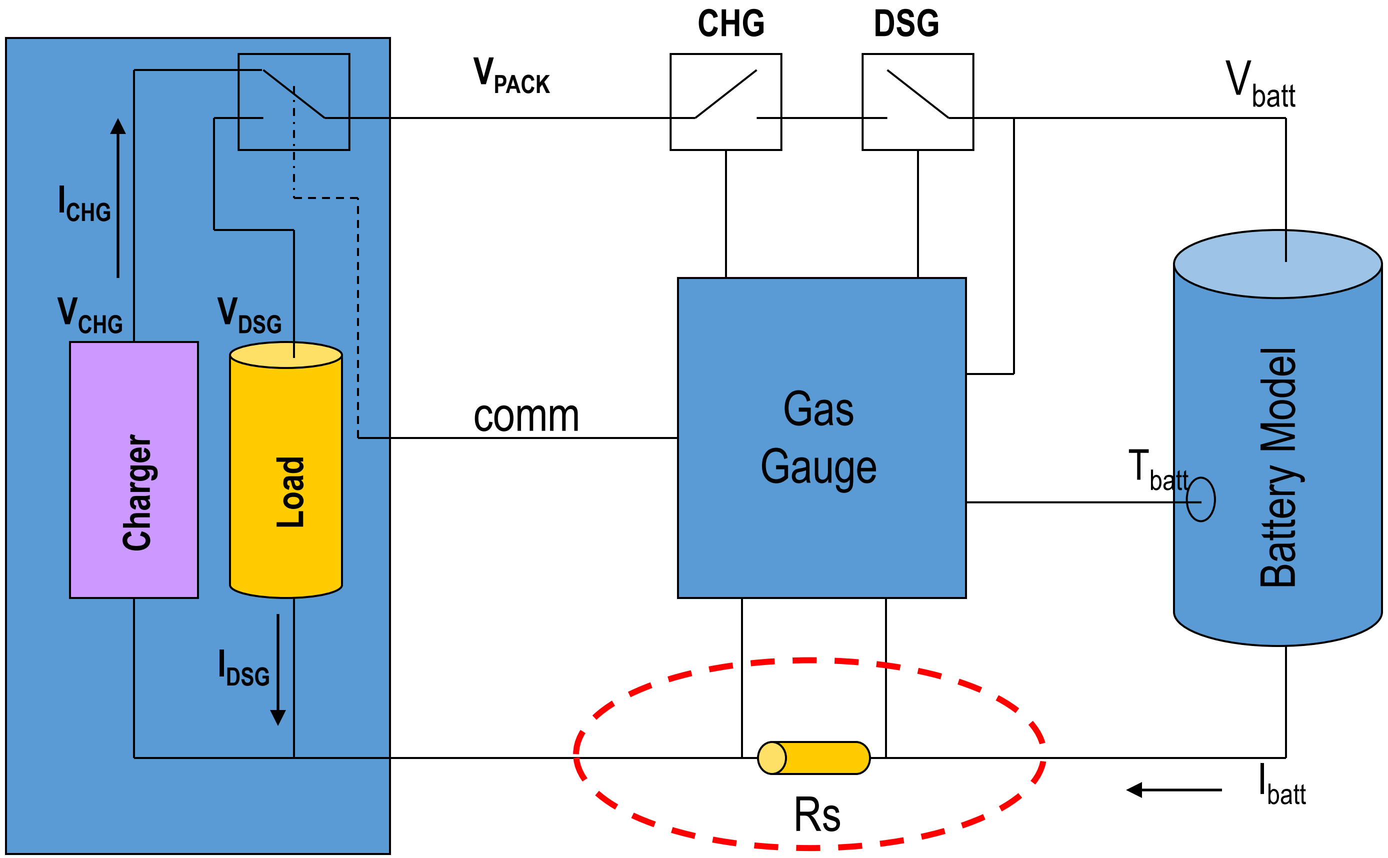


What does a battery monitor do?



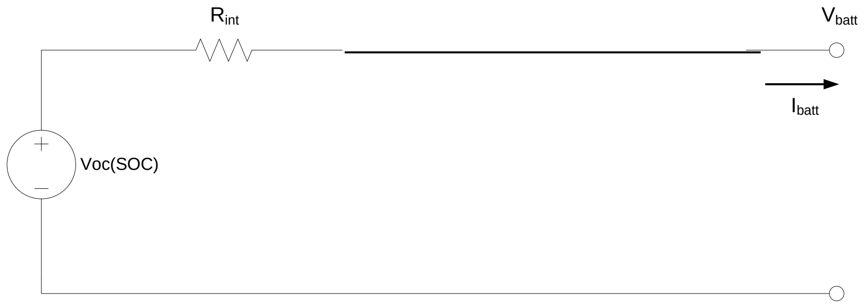
- Capacity estimation
- Safety/protection
- Charging support
- Communication and Display
- Logging
- Authentication

Basic Smart Battery System

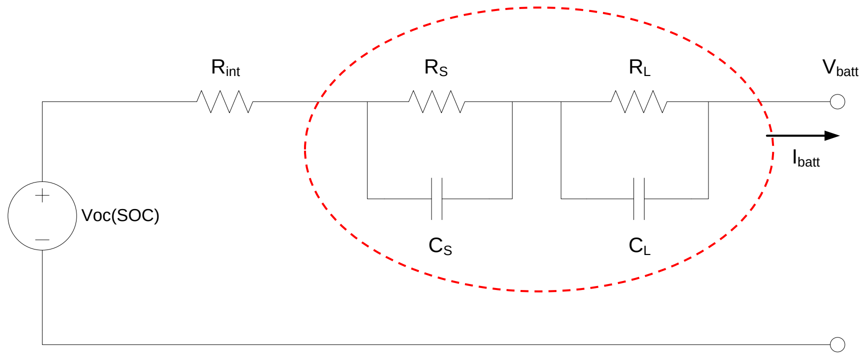


$$q_k = q_0 + \Delta t \cdot \sum_k I_k$$

Circuit model



DC model



Transient model

- V_{OC} a function of SOC
- R_{int} is internal resistance
- R_s and C_s model the short term transient response
- R_L and C_L model the long term transient response
- V_{batt} and I_{batt} are the battery voltage and current
- All parameters are function of temperature and battery age

Table lookup

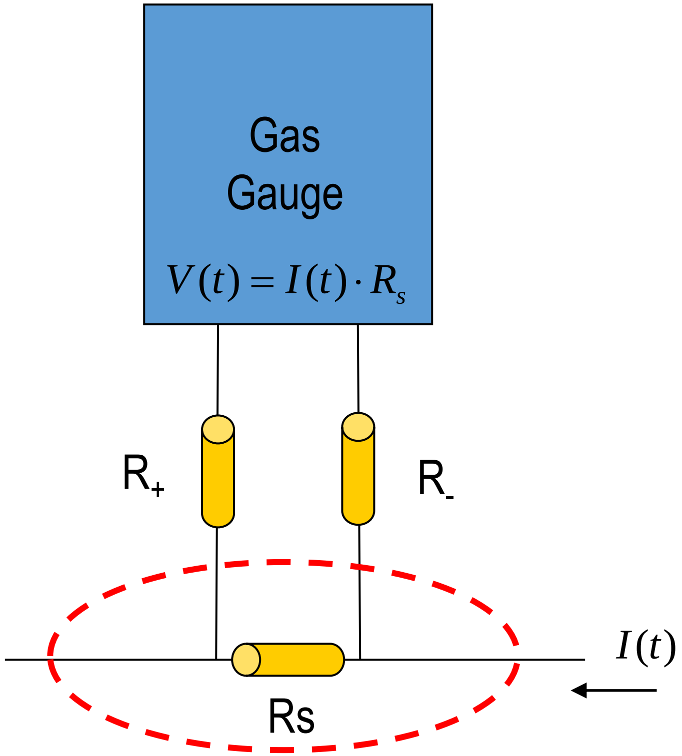
- Large, multi-dimensional table relating capacity to
  - Voltage
  - Current
  - Temperature
  - Aging
- No cell model
- Apply linear interpolation to make lookup “continuous”
- Memory intensive

Factors affecting capacity estimation

- PCB component accuracy
- Instrumentation accuracy
- Cell model fidelity
- Aging
- Temperature

PCB component accuracy

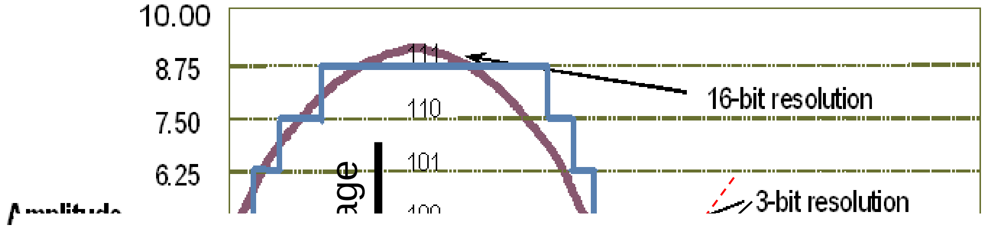
- Example
  - Current sensing resistor
  - Trace length (resistance)

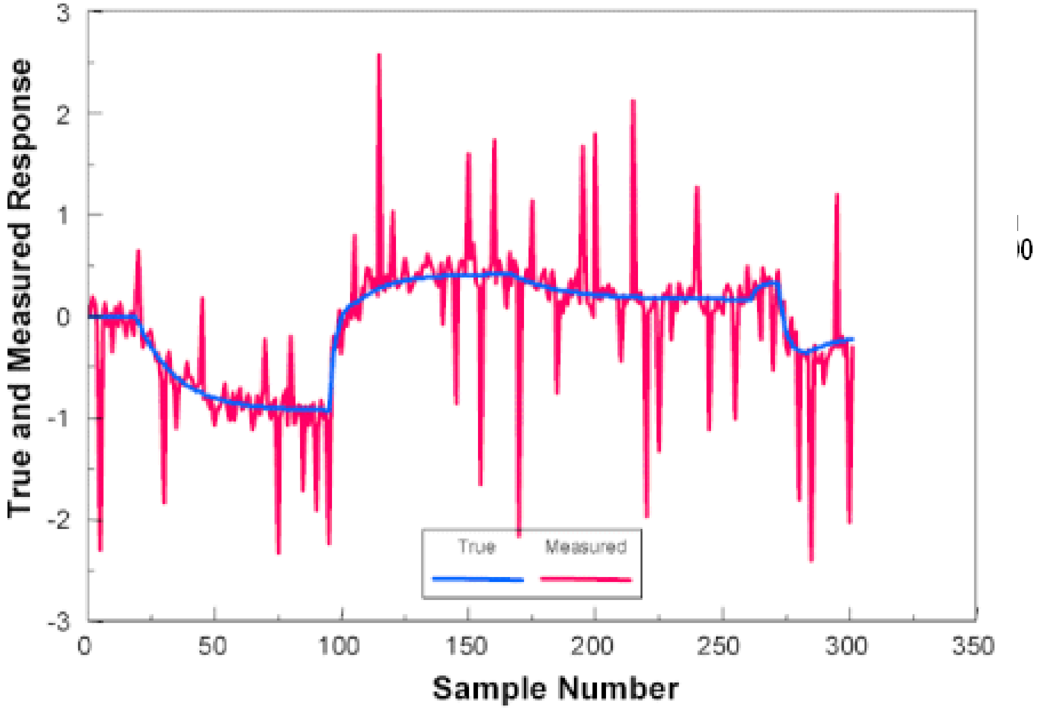


$$I(t) = \frac{V(t)}{R_s \pm \varepsilon_r}$$

Instrumentation accuracy

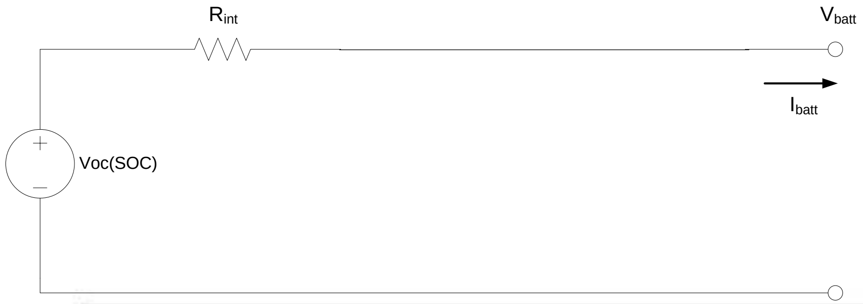
- ADC Resolution
- Sampling rate
- Voltage drift / calibration
- Noisy immunity

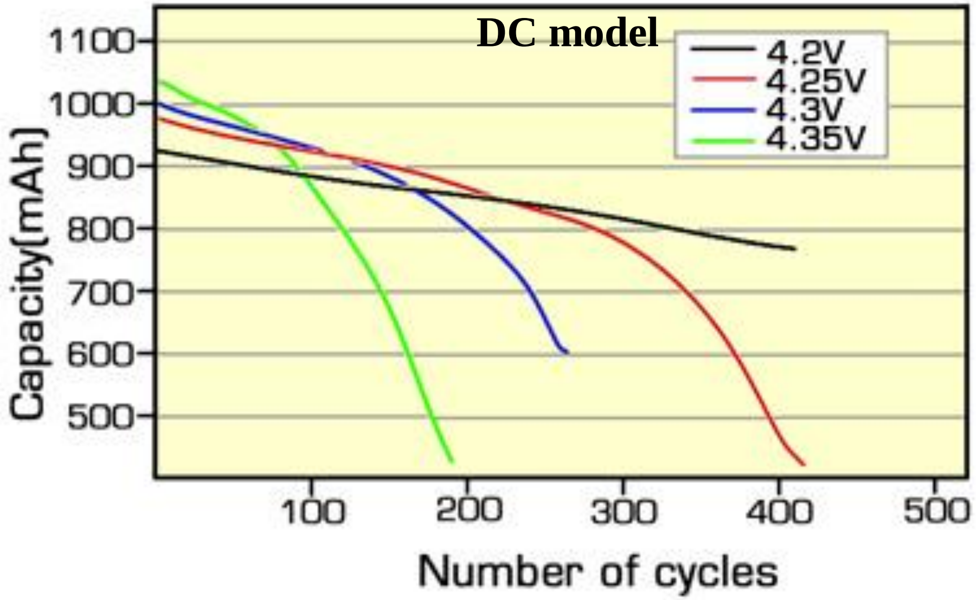




Battery model fidelity

- Steady-state (DC)
- Transient (AC)
- Capacity degradation
  - Aging
  - Overcharge



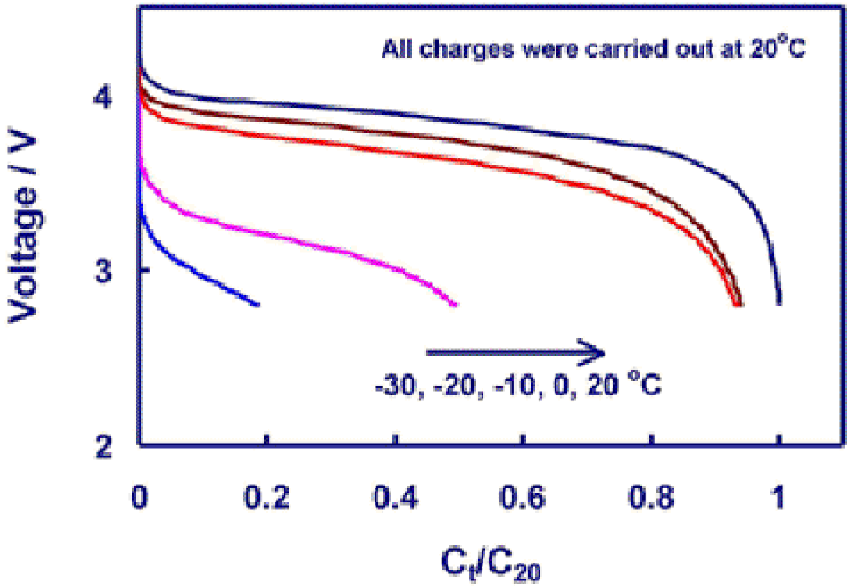


Model parameter extraction

- Extract battery model parameter values using actual collected battery data
  - Open circuit voltage (OCV)
  - Transient parameters (RC)
  - DC parameters (Ri)
- Least square minimization
- Extraction process can be hard and time consuming

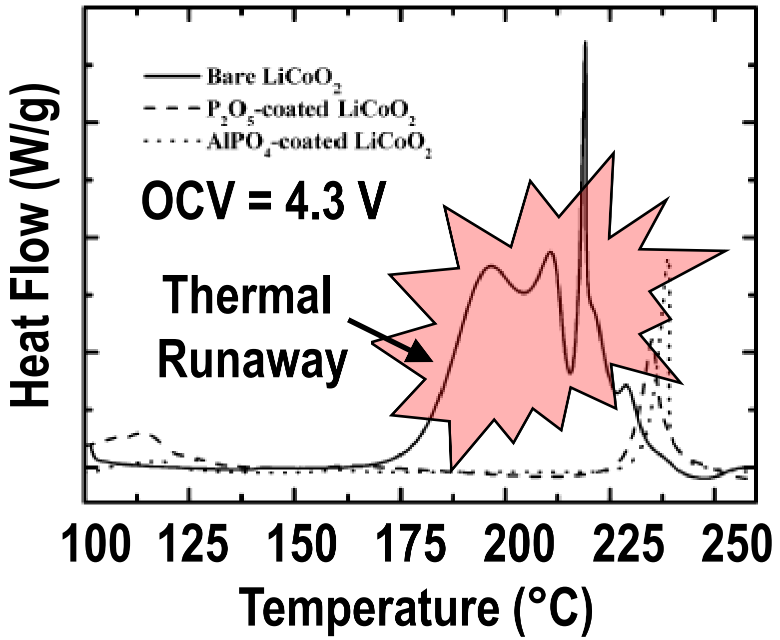
Temperature

- Temperature is important for
  - Capacity estimation
  - Safety
  - Charging control
- Temperature impacts model parameters
  - Resistance
  - Capacitance
  - OCV
  - Max capacity



Safety

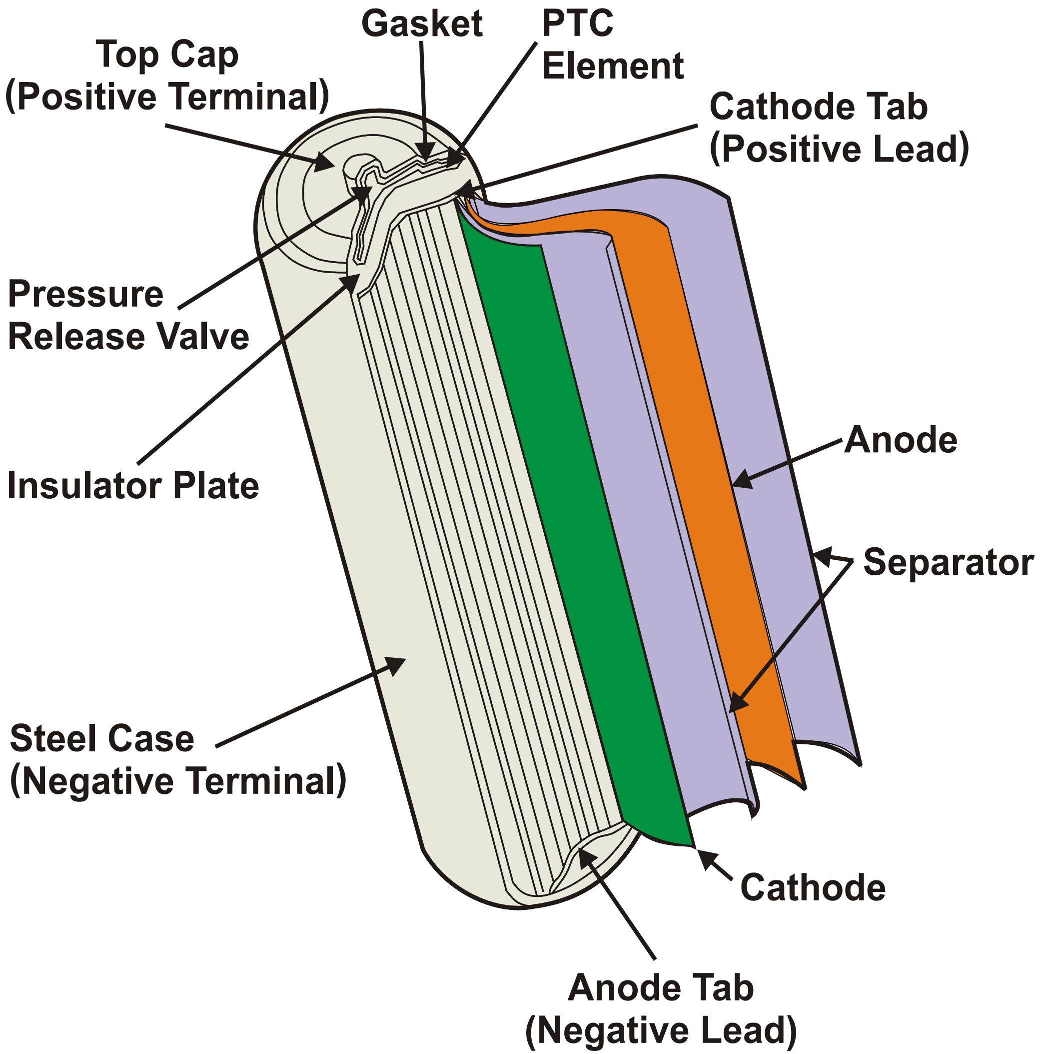
- High operating temperature
    - Accelerates cell degradation
    - Thermal runaway and explosion
- $LiCoO_2$ – Cathode reacts with electrolyte at 175°C with 4.3 V
- Cathode coatings help considerably
- $LiFePO_4$ shows huge improvement! Thermal runaway is > 350°C



Cell Safety

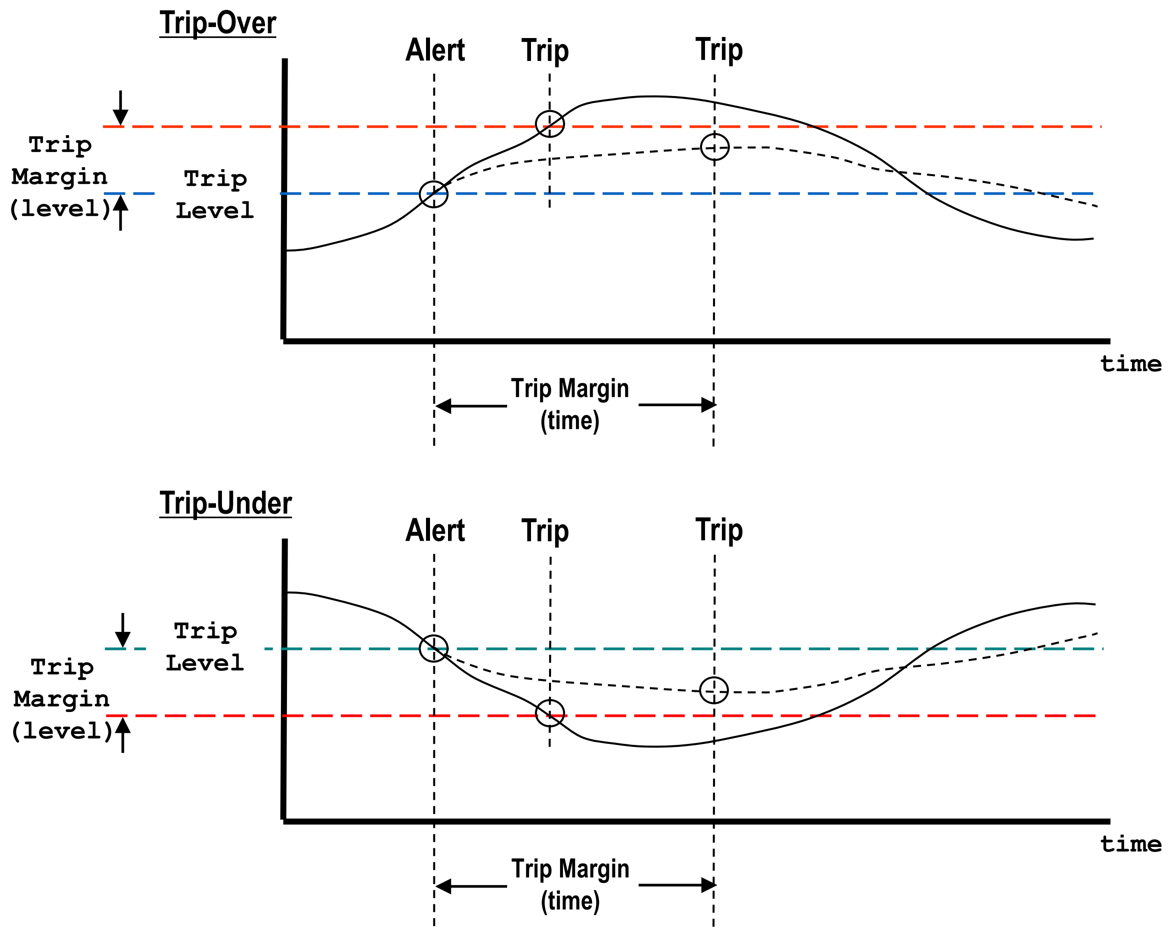
Safety Elements

- Pressure relief valve
- PTC element
- Aluminum or steel case
- Polyolefin separator
    - Low melting point (135 to 165°C)
    - Porosity is lost as melting point is approached
    - Stops Li-Ion flow and shuts down the cell
- Recent incidents traced to metal particles that pollutes the cells and creates microshorts



Safety and protection

- Short circuit
- Over/under (charge/discharge) current
- Over/under voltage
- Over temperature
- FET failure
- Fuse failure
- Communication failure
- Lock-up
- Flash failure
- ESD
- Cell imbalance



4. State of Charge (SOC) and State of Health (SOH)

4. State of Charge (SOC)

Knowing the amount of energy left in a battery compared with the energy it had when it was full gives the user an indication of how much longer a battery will continue to perform before it needs recharging.

It is a measure of the short term capability of the battery. Using the analogy of a fuel tank in a car, State of Charge (SOC) estimation is often called the "Gas Gauge" or "Fuel Gauge" function.

The preferred SOC reference should be the **rated capacity of a new cell rather than the current capacity of the cell**. This is because the cell capacity gradually reduces as the cell ages. For example, towards the end of the cell's life its actual capacity will be approaching only 80% of its rated capacity and in this case, even if the cell were fully charged, its SOC would only be 80% of its rated capacity

Rated capacity: 4200 Ah (fresh new cell) (travel 200 km)
Current capacity: 3000 Ah (during cycle no. 60) (travel : 142.8 km maximum)
Full capacity (current): 3600 Ah (cycle no. 50) (travel: (200/4200)*3600 = 171.42 km)

SoC_1: (3000/3600)*100 = 83.33%; SoC_2: (3000/4200)*100 = 73.33% aka. SoH (State of health);

4. State of Charge (SOC, contd.)

Methods of Determining the State of Charge

Several methods of estimating the state of charge of a battery have been used. Some are specific to particular cell chemistries. Most depend on measuring some convenient parameter which varies with the state of charge.

Direct Measurement

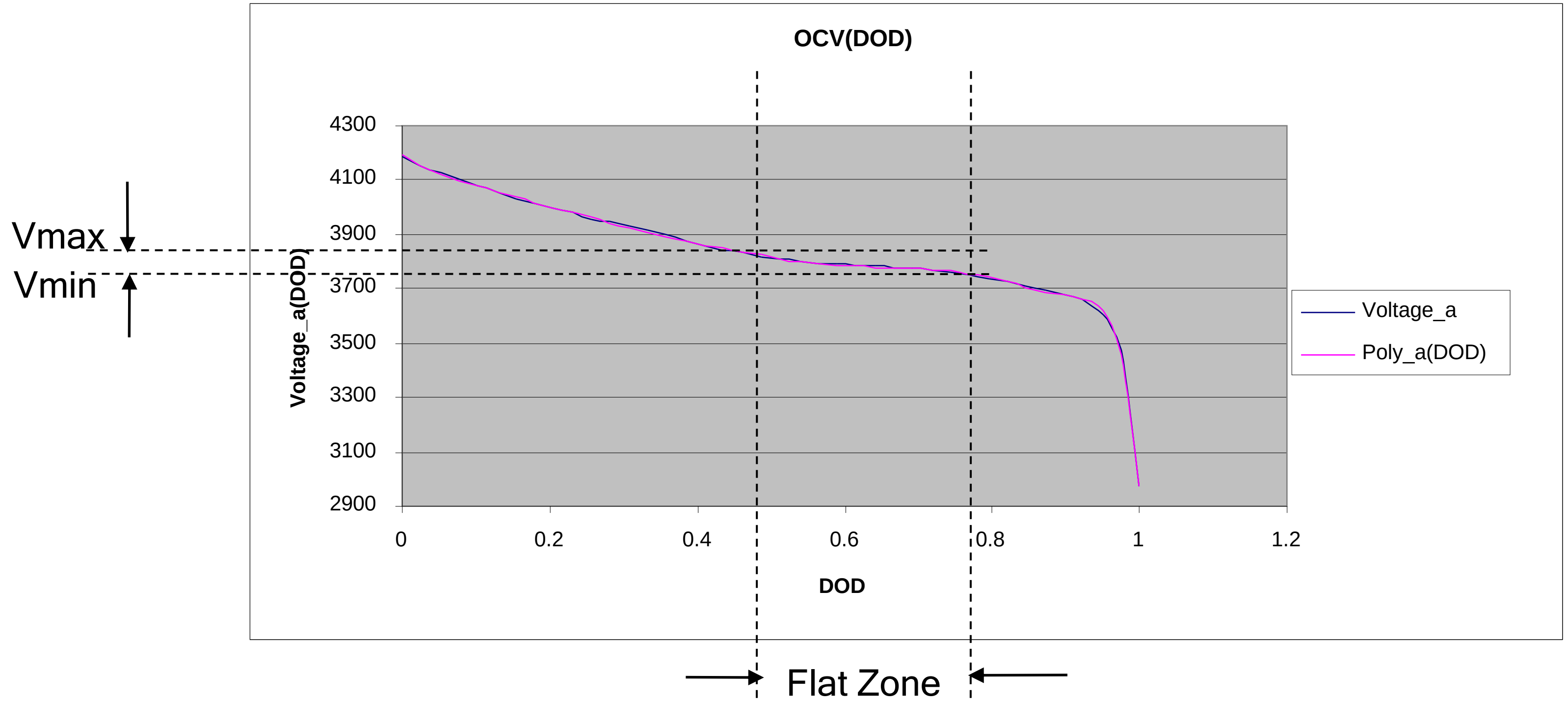
This would be easy if the battery could be discharged at a constant rate. The charge in a battery is equal to the current multiplied by the time for which it flowed. Unfortunately there are two problems with this. In all practical batteries, the discharge current is not constant but diminishes as the battery becomes discharged, usually in a non-linear way. Any measurement device must therefore be able to integrate current over time. Secondly, this method depends on discharging the battery to know how much charge it contained. In most applications except perhaps in qualification testing, the user (or the system) needs to know how much charge is in the cell without discharging it.

It is not possible either to measure directly the effective charge in a battery by monitoring the actual charge put into it during charging. This is because of the Coulombic efficiency of the battery. Losses in the battery during the charge - discharge cycle mean that the battery will deliver less charge during discharge than was put into it during charging.

Voltage Based SOC Estimation

This uses the voltage of the battery cell as the basis for calculating SOC or the remaining capacity. Results can vary widely depending on **actual voltage level, temperature, discharge rate and the age of the cell and compensation** for these factors must be provided to achieve a reasonable accuracy.

OCV voltage table: DOD representation



DOD = Depth of Discharge
SOC = State of Charge
DOD = 100% - SOC
SOC = 100%-DOD

4. State of Health (SOH)

The **State of Health is a "measurement" that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery**. It takes into account such factors as charge acceptance, internal resistance, voltage and self-discharge. It is a measure of the long term capability of the battery and gives an "indication" not an absolute measurement, of how much of the available "lifetime energy throughput" of the battery has been consumed, and how much is left.

Unlike the SOC which can be determined by measuring the actual charge in the battery there is no absolute definition of the SOH. ***It is a subjective measure in that different people derive it from a variety of different measurable battery performance parameters which they interpret according to their own set of rules. It is an estimation rather than a measurement***. This is fine so long as the estimate is based on a consistent set of rules but it makes comparisons between estimates made with different test equipment and methods unreliable.

4. State of Health (SOH, contd.)

How is the SOH determined?

Any parameter which changes **significantly with age, such as cell impedance or conductance**, can be used as a basis for providing an indication of the SOH of the cell. Changes to these parameters will normally signify that other changes have occurred which may be of more importance to the user. **These could be changes to the external battery performance such as the loss of rated capacity or increased temperature rise during operation or internal changes such as corrosion.**

In practice some people estimate the SOH from a single measurement of either the cell impedance or the cell conductance.

1. Capacity (relative to fresh/new cell)
2. Impedance (relative to fresh/new cell)
3. Stack stress (self discharge) (relative to fresh/new cell)
4. Diffusion coefficient/Li-ions concentration (relative to fresh/new cell)

Assignment:

To find out which parameter is mostly used capacity or impedance ? Or is there any parameter that combines both together to estimate SoH.

3. Prevention of Battery Failures by design of Battery Management System (BMS)

EV Bus Failure

- EV electric bus caught fire during charging (Excessive Charging current will lead to higher heat generation (Heat generation: i^2*R))

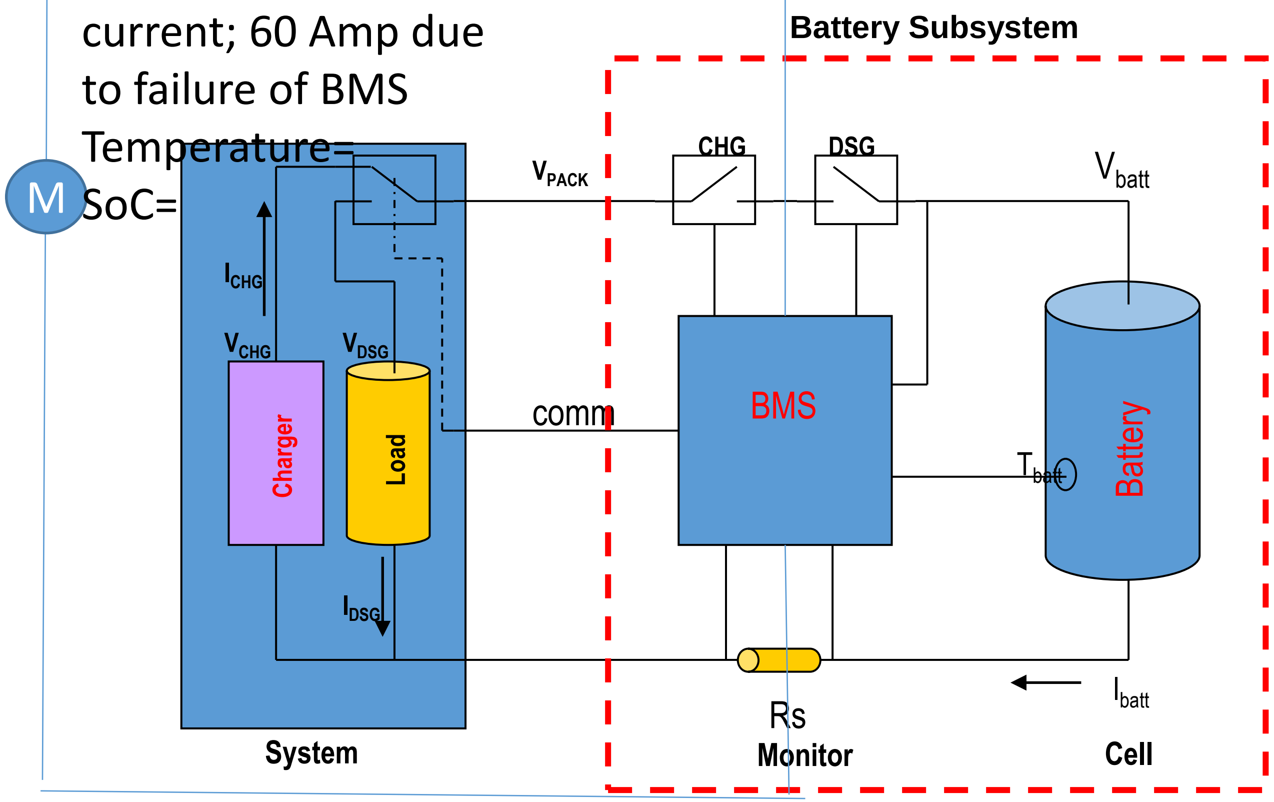
- BMS Failure (Over current sensing failure; Over Temperature)

- Without a BMS, there is no

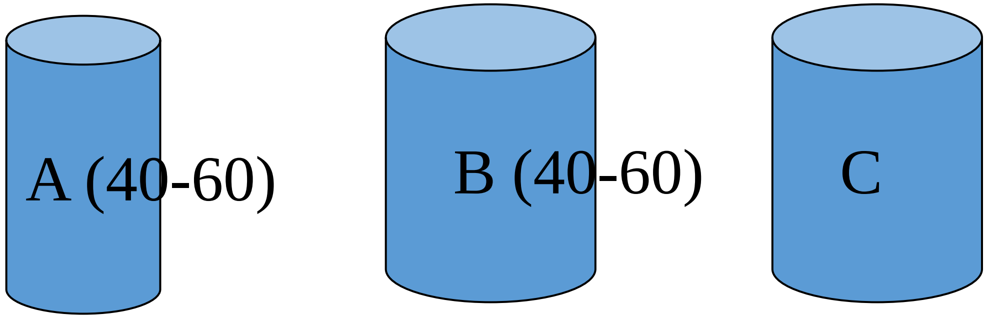
  safe lithium ion battery

What does a battery monitor do?

I = 40 Amp/50 discharge Amp current; 60 Amp due to failure of BMS
Temperature=
SoC=



- Capacity estimation
- Safety/protection
- Charging support
- Communication and Display
- Logging
- Authentication



- Data sheet:
- Parameters for Battery B: Rating (2000 mAh; 6V (Two Batt
- Test results:

1. Voltage Discharge curves based on different temperatures
2. Voltage discharge curves based on different C rate
3. Capacity vs Cycles based on different C rate
4. Safe Temperature range limits
5. Safe charging/discharging current limits

Data sheet:

Parameters for Battery A: Rating (2000 mAh; 3V; 2C)

Test results:

1. Voltage Discharge curves based on different temperatures
2. Voltage discharge curves based on different C rate
3. Capacity vs Cycles based on different C rate
4. Safe Temperature range limits
5. Safe charging/discharging current limits

3. Battery Management System (BMS)

BMS means different things to different people. To some it is simply ***Battery Monitoring, keeping a check on the key operational parameters during charging and discharging such as voltages and currents and the battery internal and ambient temperature. The monitoring circuits would normally provide inputs to protection devices which would generate alarms or disconnect the battery from the load or charger should any of the parameters become out of limits.***

Battery Management System (BMS)
One of the main functions of the BMS is to keep the cells operating within their designed operating window (the green box above). This is not too difficult to achieve ***using safety devices and thermal management systems***. As an additional safety factor some manufacturers set their operating limits to more restricted levels indicated by the dotted lines.
There is however very little the BMS can do to protect against an internal short circuit. The only prevention action that can be taken is strict process control of all the cell manufacturing operations.

Lithium Charged but Not Guilty?
The cause of many fires has been attributed to Lithium batteries and there is a fear of Lithium because of its well known vigorous reaction with water. Under normal circumstances, most (but not all) batteries do not contain any free Lithium. The Lithium content is combined into other compounds which do not react with water. The amount of Lithium deposited during the Lithium plating when cells are damaged as described above is very small and not usually responsible for the fires which have occurred. ***Furthermore, many of the reported fires are due to burning electrolyte rather than the Lithium compounds.***

3. Battery Management System (BMS) (Contd.)

Designing a BMS

In order to control battery performance and safety it is necessary to understand **what needs to be controlled and why it needs controlling.** This requires an in depth understanding of the fundamental cell chemistries, performance characteristics and battery failure modes particularly Lithium battery failures. The battery can not simply be treated as a black box.

BMS Building Blocks

There are three main objectives common to all Battery Management Systems

1. Protect the cells or the battery from damage
2. Prolong the life of the battery
3. Maintain the battery in a state in which it can fulfil the functional requirements of the application for which it was specified.

3. Battery Management System (BMS) (Contd.)

To achieve these objectives the BMS may incorporate one or more of the following functions. (Follow the links to see how these functions are implemented.)

Cell Protection Protecting the battery from out of tolerance operating conditions is fundamental to all BMS applications. In practice the BMS must provide full cell protection to cover almost any eventuality.

Charge control This is an essential feature of BMS. More batteries are damaged by inappropriate charging than by any other cause.

Demand Management While not directly related to the operation of the battery itself, demand management refers to the application in which the battery is used. Its objective is to minimise the current drain on the battery by designing power saving techniques into the applications circuitry and thus prolong the time between battery charges.

SOC Determination *Many applications require a knowledge of the State of Charge (SOC) of the battery or of the individual cells in the battery chain. This may simply be for providing the user with an indication of the capacity left in the battery, or it could be needed in a control circuit to ensure optimum control of the charging process.*
SOH Determination *The State of Health (SOH) is a measure of a battery's capability to deliver its specified output. This is vital for assessing the readiness of emergency power equipment and is an indicator of whether maintenance actions are needed.*

Cell Balancing In multi-cell battery chains small differences between cells due to production tolerances or operating conditions tend to be magnified with each charge / discharge cycle. Weaker cells become overstressed during charging causing them to become even weaker, until they eventually fail causing premature failure of the battery. Cell balancing is a way of compensating for weaker cells by equalising the charge on all the cells in the chain and thus extending battery life.

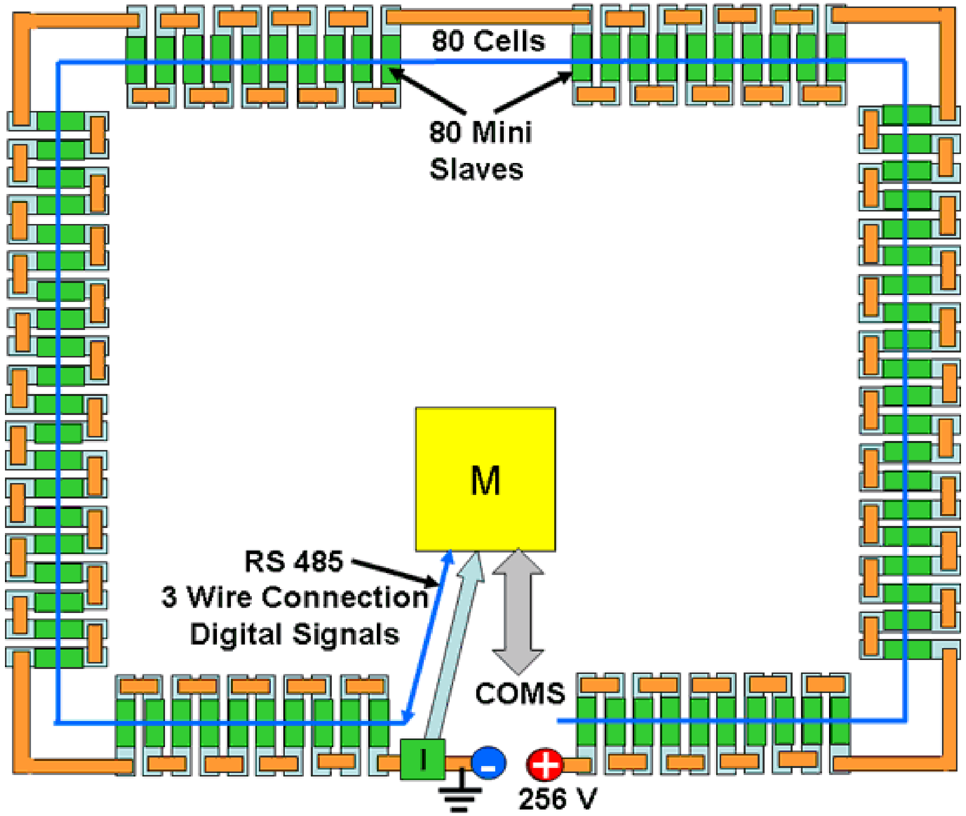
History - (Log Book Function) Monitoring and storing the battery's history is another possible function of the BMS. This is needed in order to estimate the State of Health of the battery, but also to determine whether it has been subject to abuse. Parameters such as number of cycles, maximum and minimum voltages and temperatures and maximum charging and discharging currents can be recorded for subsequent evaluation. This can be an important tool in assessing warranty claims.

ENTER THE LITHIUM BMS

- Many thoughts and discussions on what constitutes a Battery Management System (BMS):
  - Monitor and Detect Cell Over-Charge, and cut off charger
  - Monitor and Detect Cell Over-discharge and alert operator, or cut off system power.
  - Cell Balance for string charging
  - Temperature Monitoring
  - Remaining State of Charge determination
- This is done in your cell phone & laptop, why not in your car?
  - High voltages and high currents make it difficult
- Sparse BMS technology availability has held up Lithium conversion projects.

BMS Topology: Distributed

- Put voltage monitor and discharge balancer on each cell, with digital communications for charger cutoff and status.

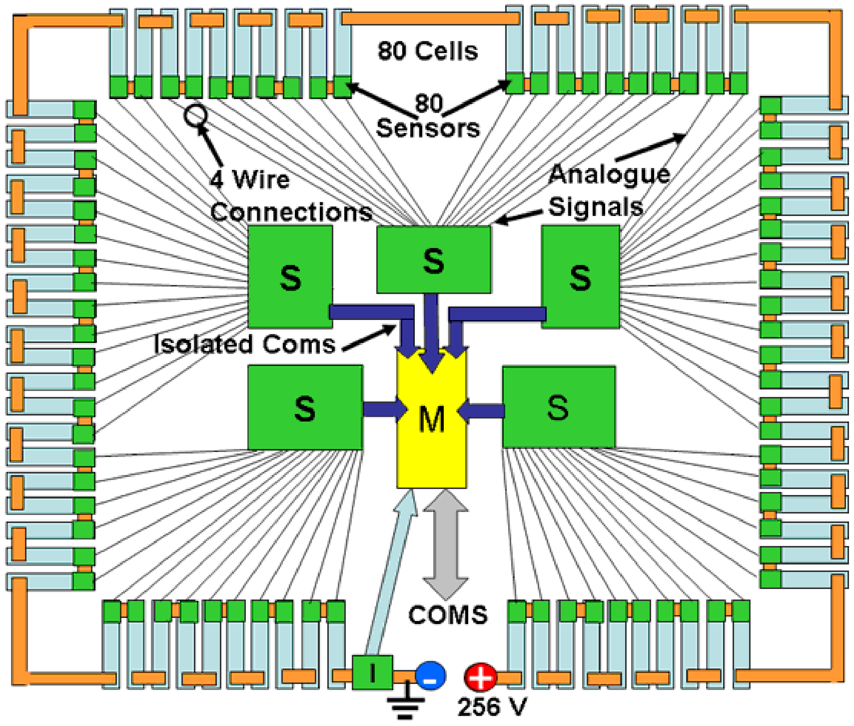


Advantages: Simpler design and construction and its potential for higher reliability in an automotive environment.

Disadvantages: Large number of mini-slave printed circuit boards which are needed and the difficulty of mounting them on some cell types.

BMS Topology: Modular

- Several Slave controllers consolidate data to a master

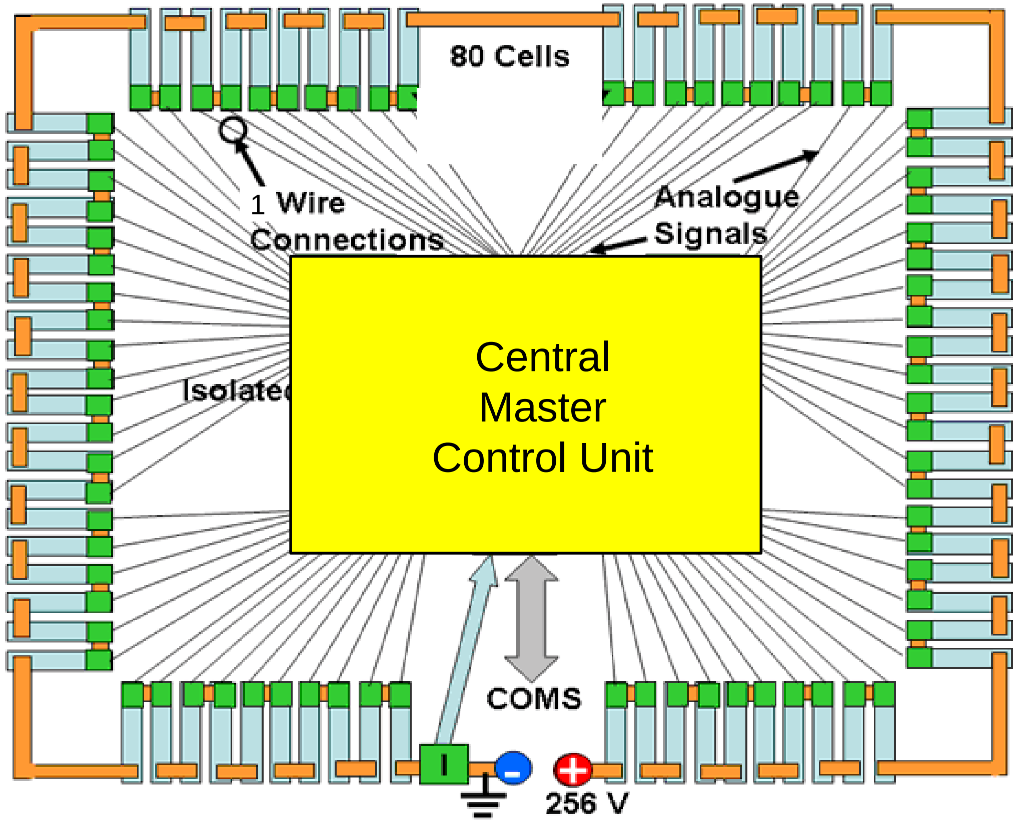


Advantages: Does not need printed circuit boards connected to individual cells.

Disadvantages: Master-Slave isolated communications can be challenging in an EV.

BMS Topology: Centralized

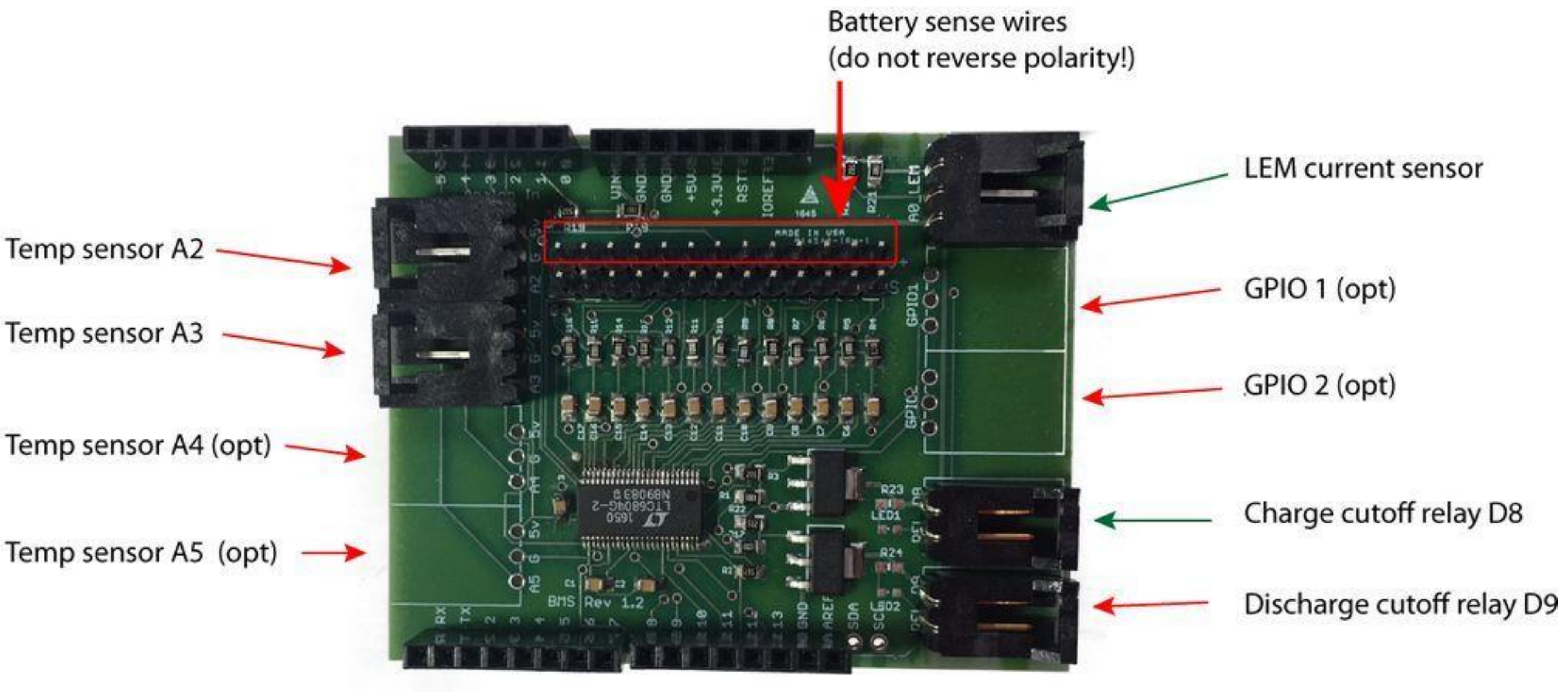
- Centralized Master Control Unit



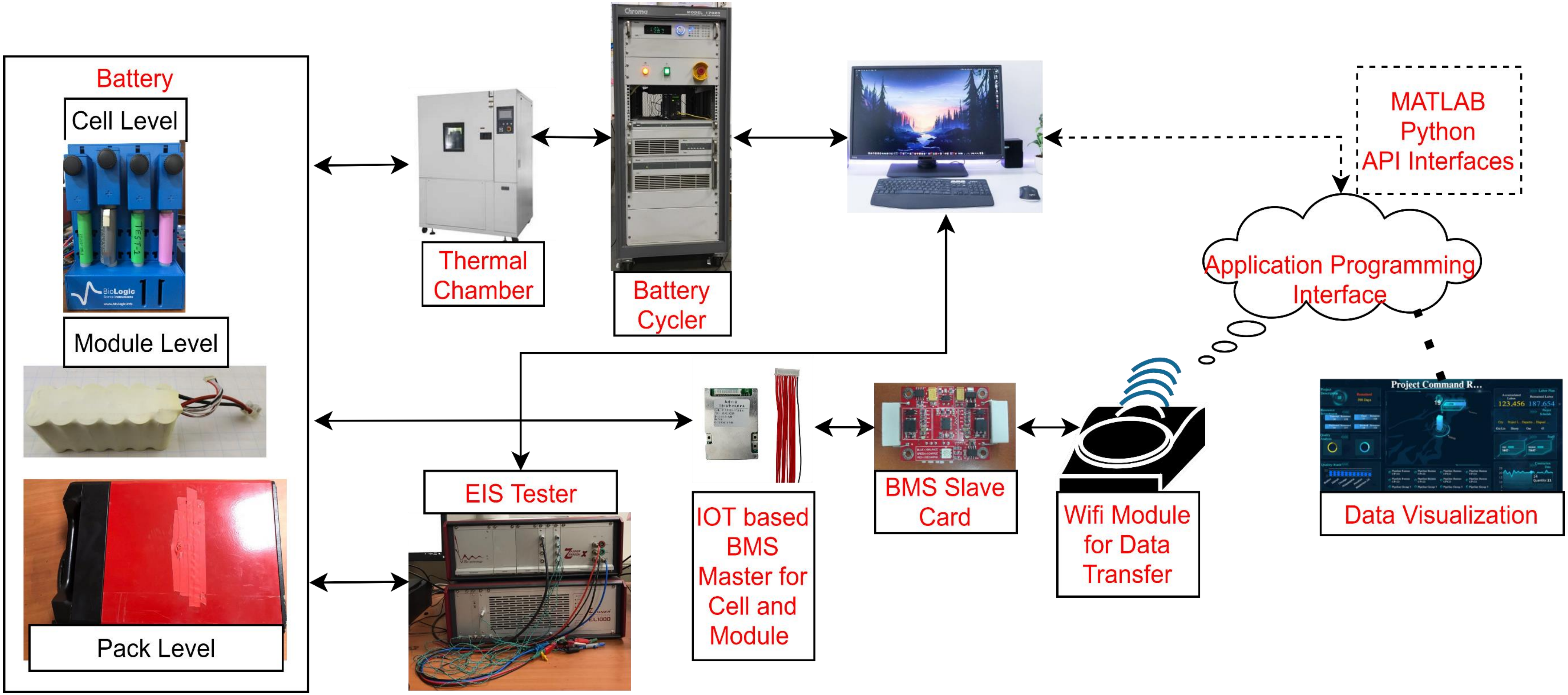
Advantages: Single installation point. No complex inter-vehicle communications

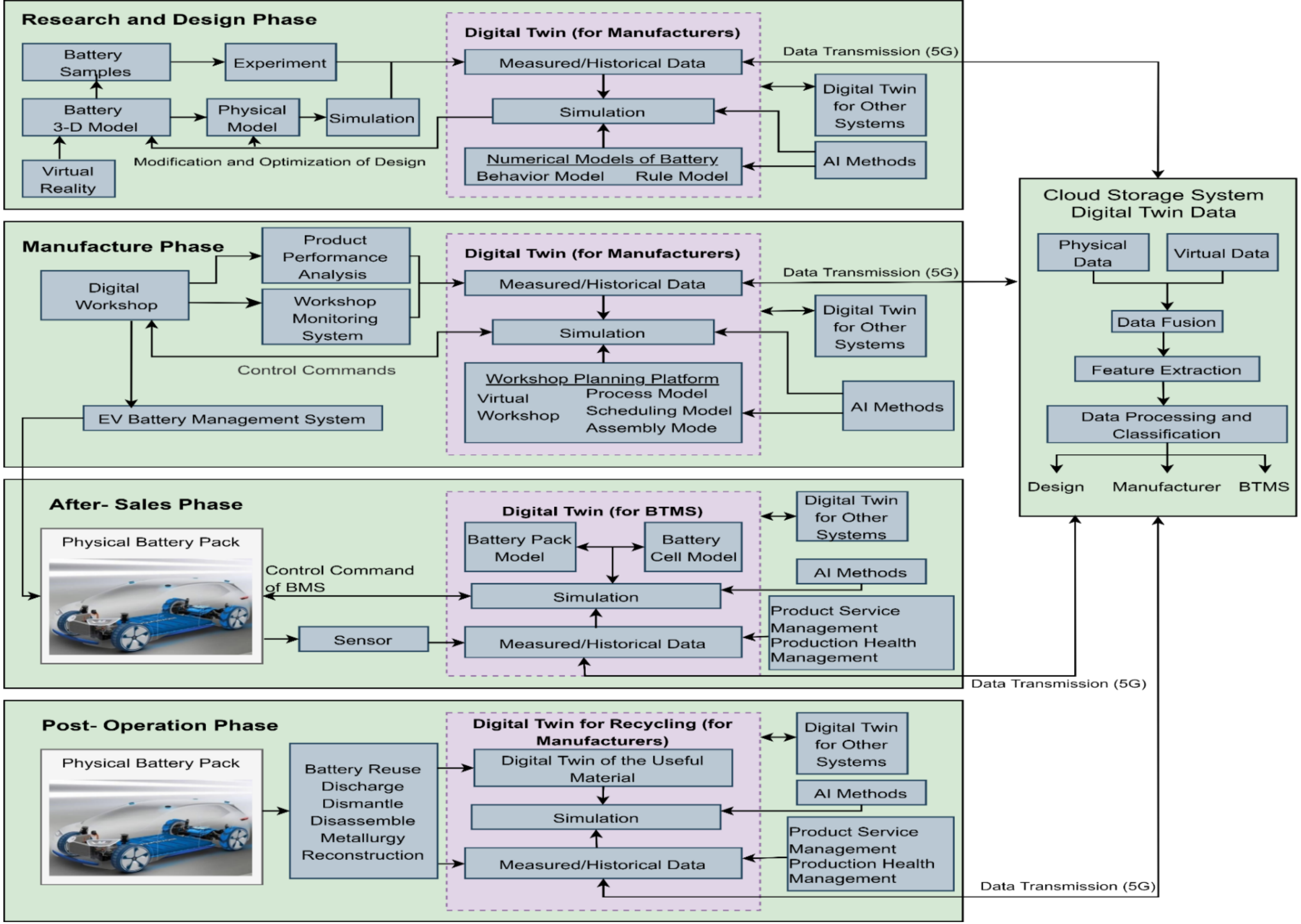
Disadvantages: Typical EV batteries are distributed in the vehicle, requiring wiring to a central location.
Single source for balancer heat generation.

Arduino LTC6804 BMS - Part 1: Main Board



Experiment Setup




Research and Design Phase
Battery Samples
Experiment
Battery 3-D Model
Physical Model
Simulation
Virtual Reality
Modification and Optimization of Design
Digital Twin (for Manufacturers)
Measured/Historical Data
Simulation
Numerical Models of Battery
Behavior Model
Rule Model
Data Transmission (5G)
Digital Twin for Other Systems
AI Methods
Manufacture Phase
Digital Workshop
Product Performance Analysis
Workshop Monitoring System
Control Commands
EV Battery Management System
Digital Twin (for Manufacturers)
Measured/Historical Data
Simulation
Workshop Planning Platform
Virtual Workshop
Process Model
Scheduling Model
Assembly Mode
Data Transmission (5G)
Digital Twin for Other Systems
AI Methods
Cloud Storage System Digital Twin Data
Physical Data
Virtual Data
Data Fusion
Feature Extraction
Data Processing and Classification
Design
Manufacturer
BTMS
After- Sales Phase
Physical Battery Pack
Control Command of BMS
Sensor
Digital Twin (for BTMS)
Battery Pack Model
Battery Cell Model
Simulation
Measured/Historical Data
Digital Twin for Other Systems
AI Methods
Product Service Management
Production Health Management
Data Transmission (5G)
Post- Operation Phase
Physical Battery Pack
Battery Reuse
Discharge
Dismantle
Disassemble
Metallurgy
Reconstruction
Digital Twin for Recycling (for Manufacturers)
Digital Twin of the Useful Material
Simulation
Measured/Historical Data
Digital Twin for Other Systems
AI Methods
Product Service Management
Production Health Management
Data Transmission (5G)

Thank you

If you have any doubts, kindly contact me!!