Introduction to Lithium-Ion Battery Systems

Lecture 8 - Part 2, TSFS11

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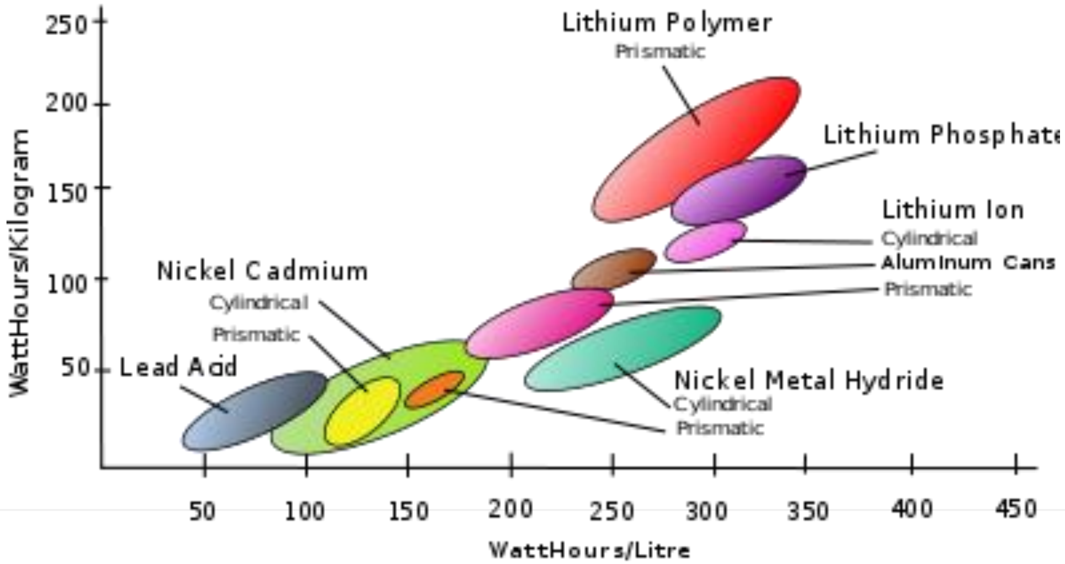
Battery Packs and Battery Management

- Comparison with other chemistries
- Lithium-ion batteries
  - Safety
  - Modeling
  - Efficiency
  - Aging
- Battery management
  - Discharging/charging
  - Balancing
  - State of charge estimation

Battery Chemistries

Comparison of different cell chemistries.

Chemistry	V	Wh/kg (pack)	W/kg	Cycles	Efficiency
Lead-acid	2	40(30)	180	600	70-92%
Nickel-cadmium	1.2	50(47)	120	1500	70-90%
Nickel-metal hydride (Ni-MH)	1.2	70(55)	200	1000	66%
Lithium-ion (Li-ion)	3.6	130(90)	430	1200	> 90%



Li-ion performs well, but only if treated well.

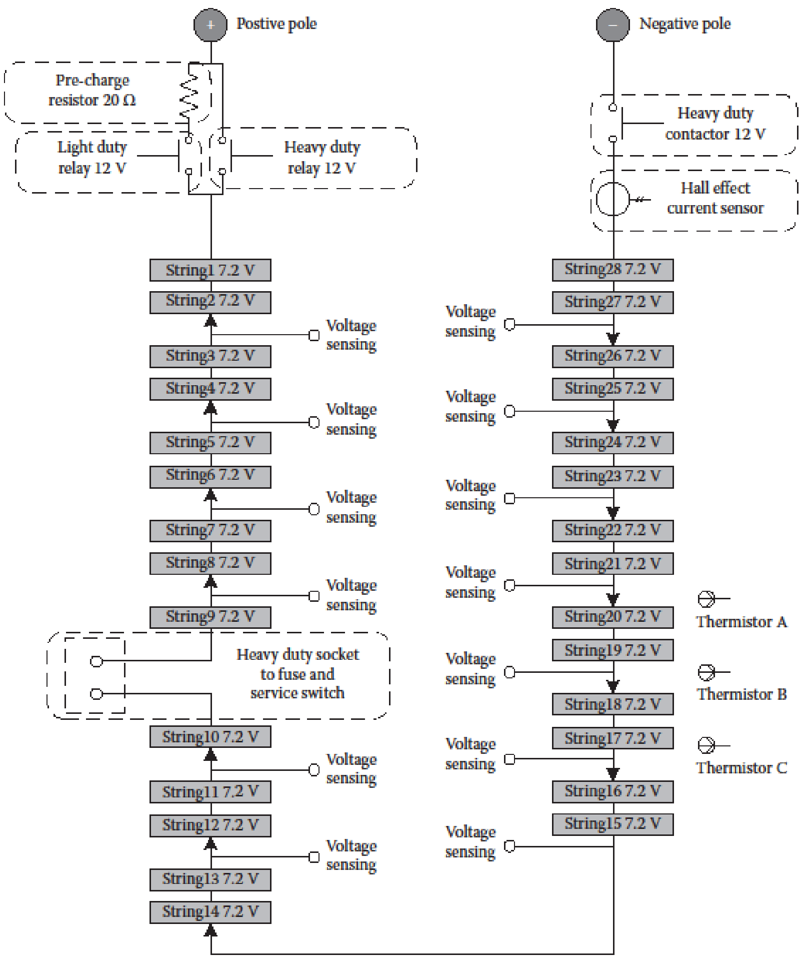
Toyota Prius Hybrid Battery Pack Configuration

Batteries

- 201.6 V, 1.31 kWh (38%-82%)
- Ni-MH cells of 1.2 V, 6.5 Ah
- 168 cells = 28 modules · 6 cells
- Module: 46 Wh/kg, 1.3 kW/kg
- no charge balancing

Sensors

- 1 current sensor
- voltage sensor every second string
- 3 thermistors



85 kWh Tesla Model S Battery Pack

Pack specs:

- 85 kWh (540 kg)
- 400 V
- 7104 cells: 16 modules in series

Module specs:

- Module: 6 groups in series of 74 cells in parallell

Cell specs:

- 18650 Li-ion cells
- 3.6 V, 3.2 Ah, 48.5 g, 243 Wh/kg

Lithium Ion
Panasonic NCR18650B

Features & Benefits

- High energy density
- Long stable power and long run time
- Ideal for notebook PCs, boosters, portable devices, etc.

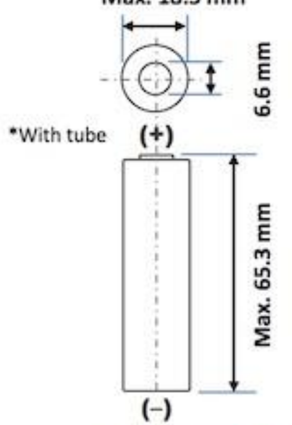
* At temperatures below 10°C, charge at a 0.25C rate.

Specifications

Rated capacity[1]	Min. 3200mAh
Capacity[2]	Min. 3250mAh Typ. 3350mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1625mA, 4.20V, 4.0 hrs
Weight (max.)	48.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density[3]	Volumetric: 676 Wh/l Gravimetric: 243 Wh/kg

[1] At 20°C [2] At 25°C [3] Energy density based on bare cell dimensions

Dimensions



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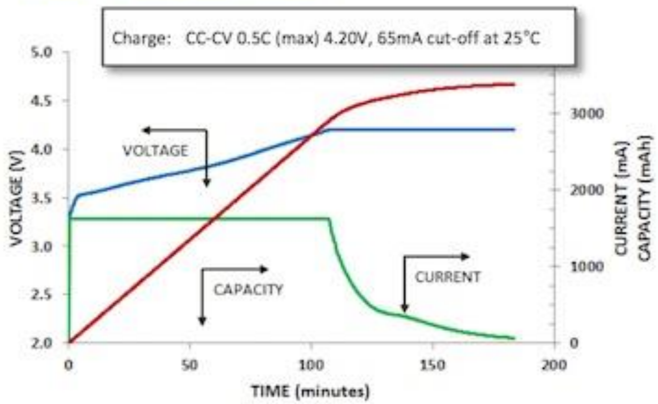
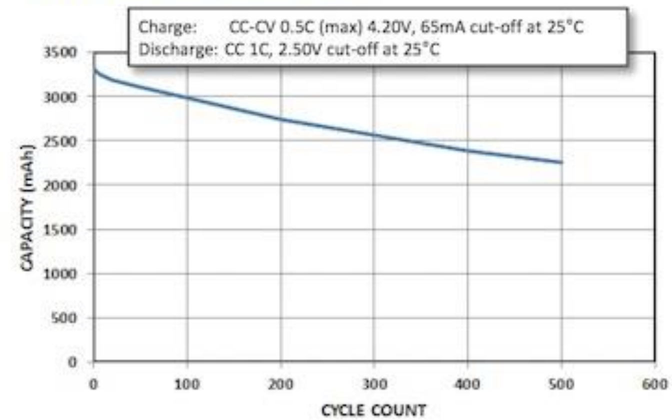
Charge Characteristics



Cycle Life Characteristics



Discharge Characteristics (by temperature)

Discharge Characteristics (by rate of discharge)

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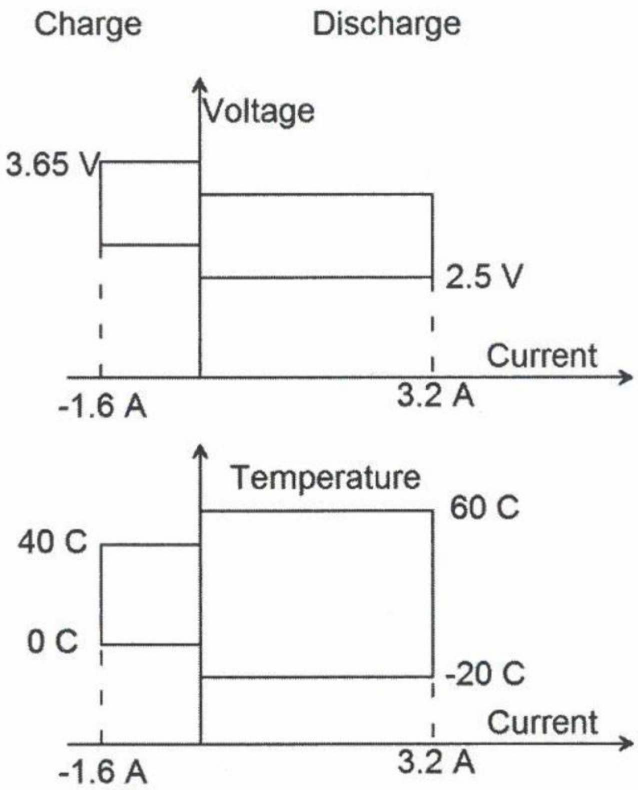
Safety

Reduction or damage to cell

- Over-discharge
- Charging, discharging outside certain temperature bounds
- Charging, discharging with high currents

Dangerous abuse

- Overheating cause by over-current, over-voltage, over-charging, or external heat.
- Piercing, crushing

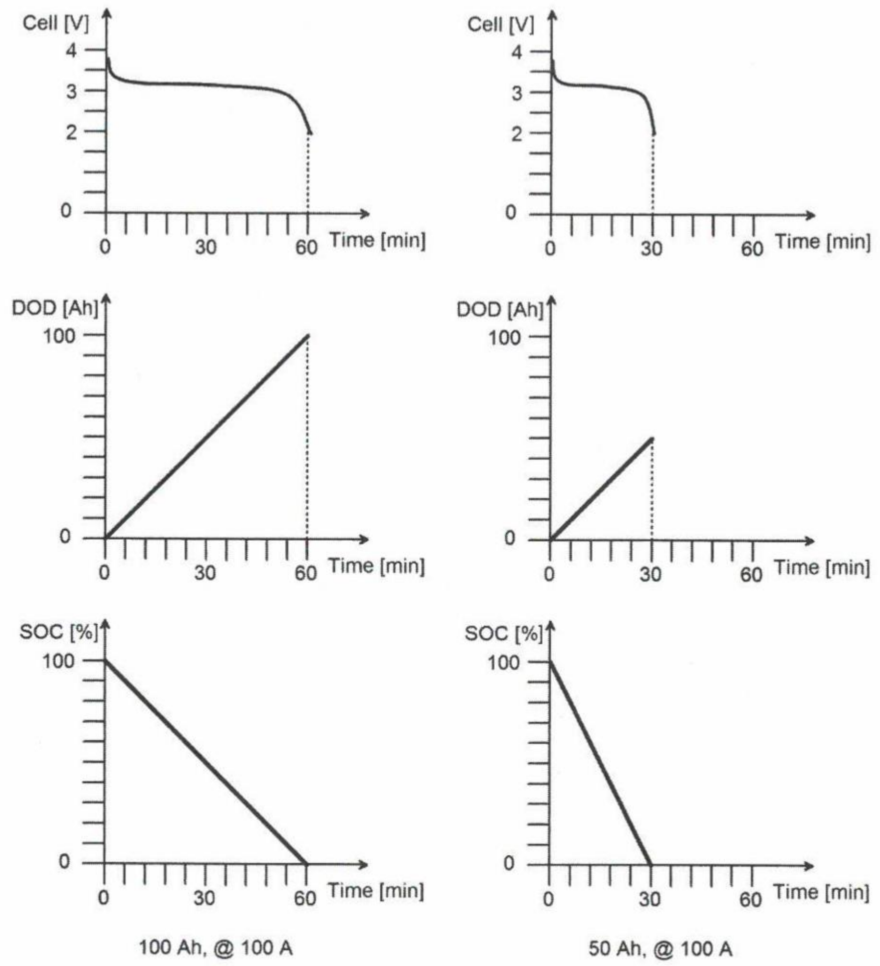


Battery and cell properties

- 1C current = current able to discharge the nominal battery in 1h
- Depth of discharge (DOD)
  - Ah discharge from full battery
- State of charge (SOC)
  - Procentage of charge in the battery/cell
  - 100% full
  - 0% empty

Nominal battery
Capacity = 100 Ah
Discharge rate =1C

Degraded battery
Capacity = 50 Ah
Discharge rate = 1C



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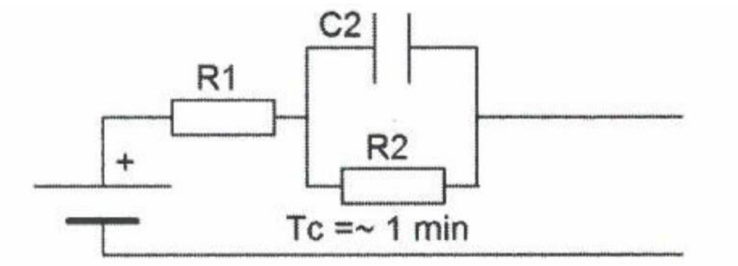
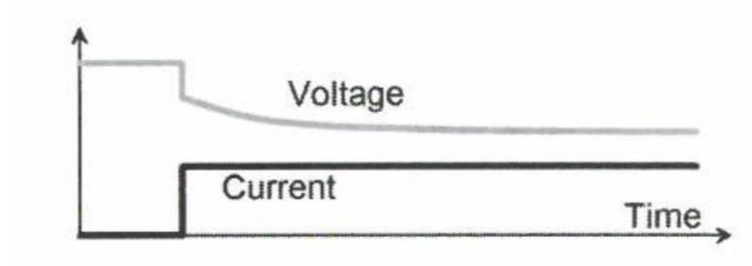
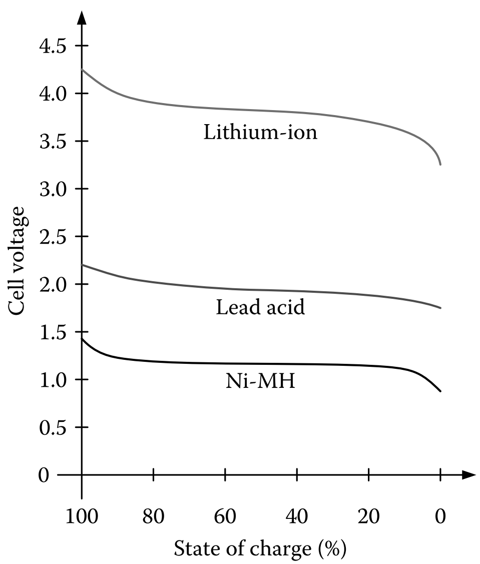
Modeling

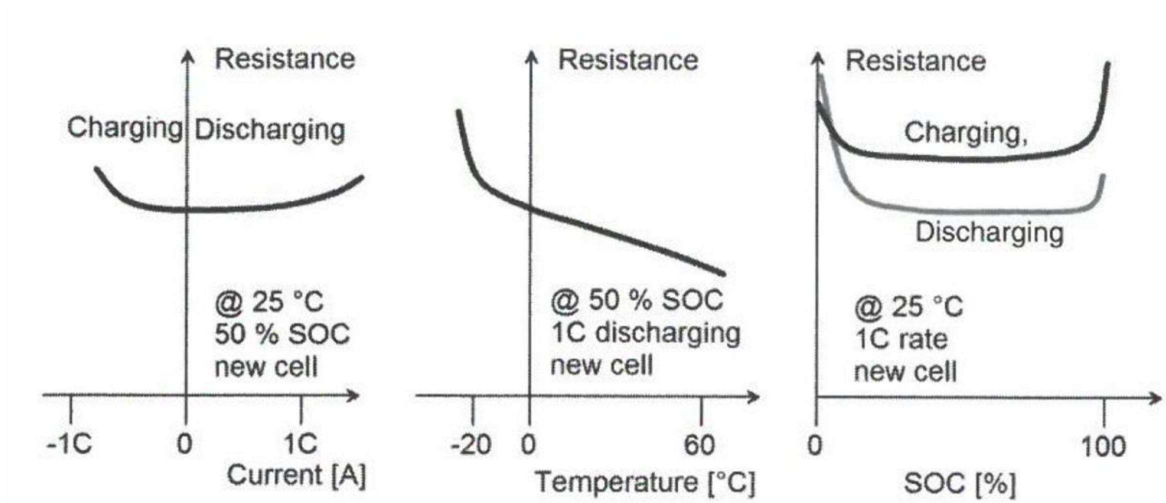




Open Circuit Voltage (OCV) [V]

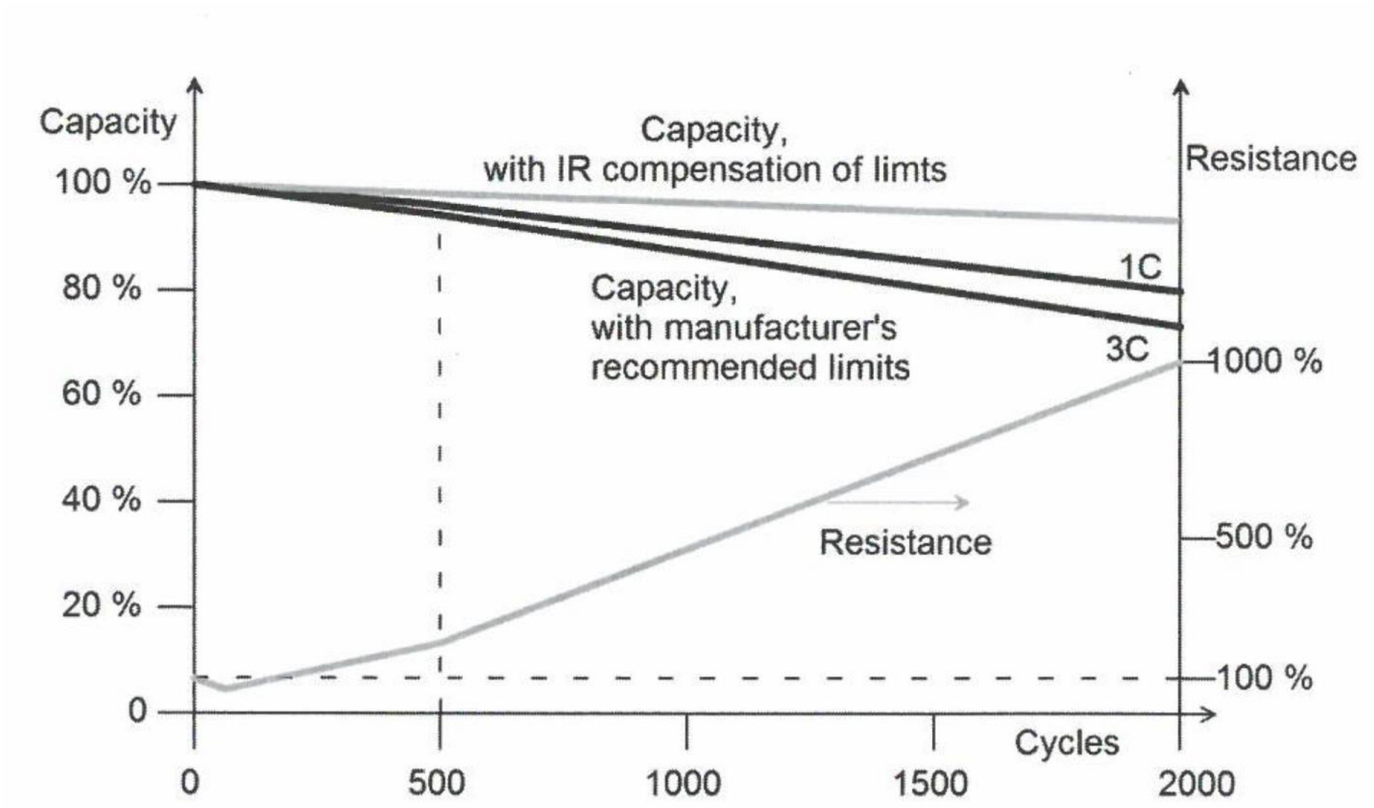


State of Charge (SOC) [%]



Aging

Capacity decreases and internal resistance increases for increasing number of charging/discharging cycles.



Discharging

Constant current discharge until a specified cut-off voltage is reached.

The available capacity depends on the required current (discharge rate)

Peukert's law:

C_p- capacity [Ah] at 1 A

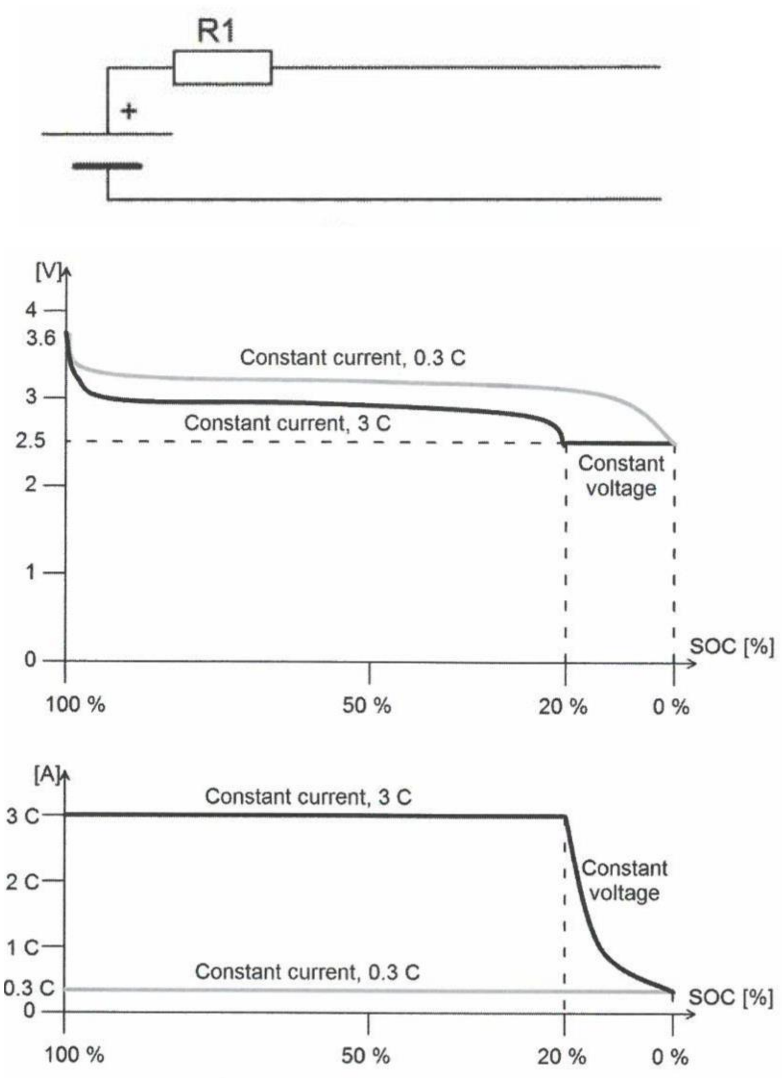
– actual discharge current [A]

- discharge time [h]

– Peukert constant > 1

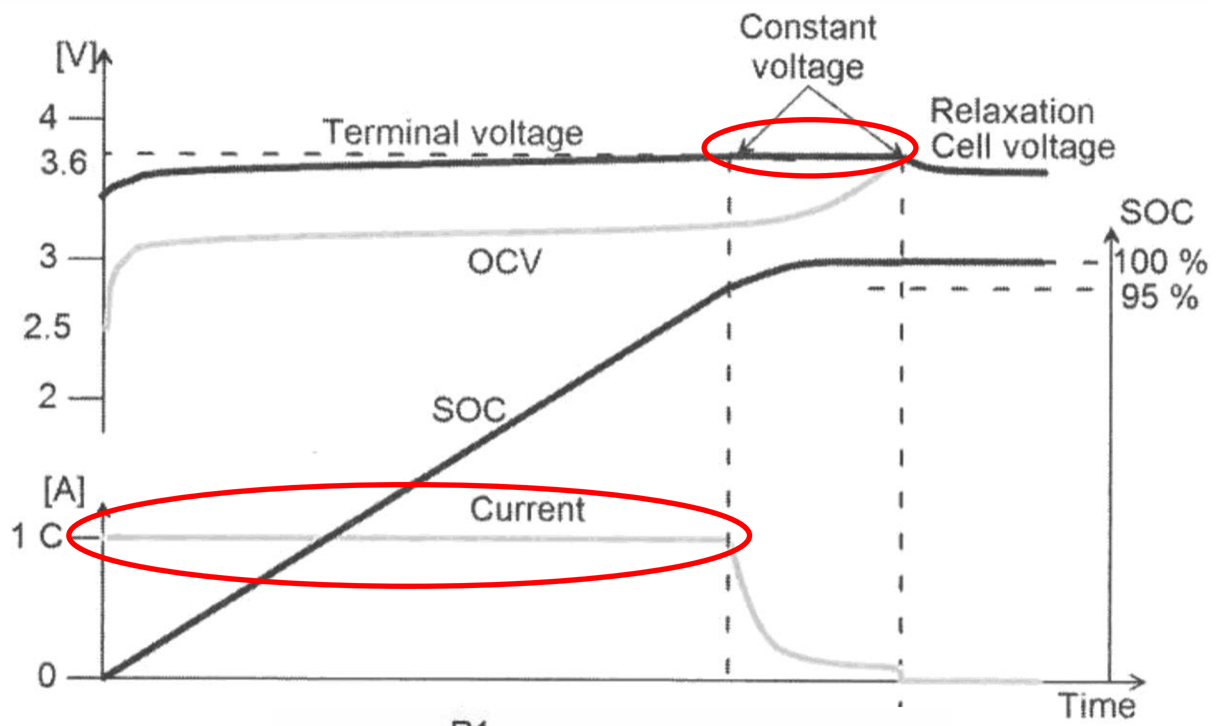
Ex: Capacity at 2 A when k = 1,2:

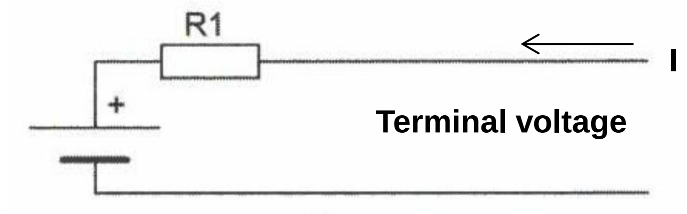
$1 = 1^{1,2} \cdot 1 = 2^{1,2} \cdot 0,43 > 2 \cdot 0,43 = 0,86$



Charging algorithm CCCV

Constant current constant voltage (CCCV) charging





I = (Terminal voltage – OCV)/R1

OCV

Terminal voltage

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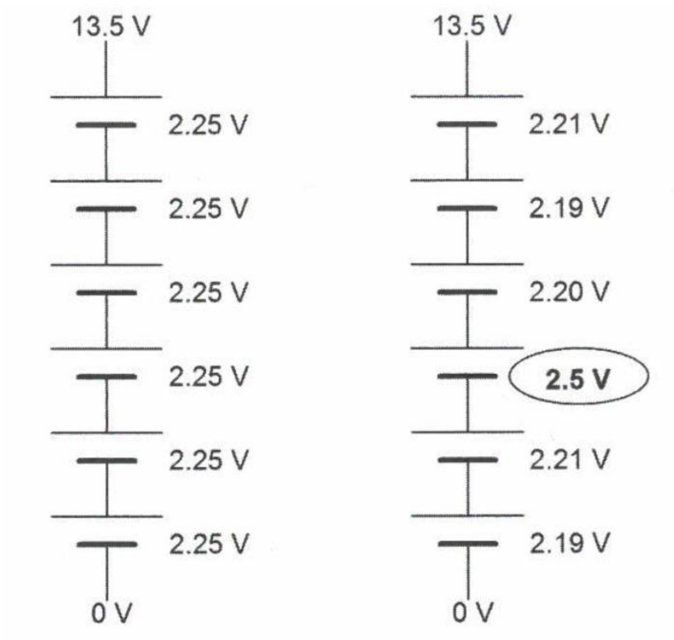
Unequal Voltages in Series Strings

Consider charging of balanced and unbalanced cells.

Starter lead acid battery



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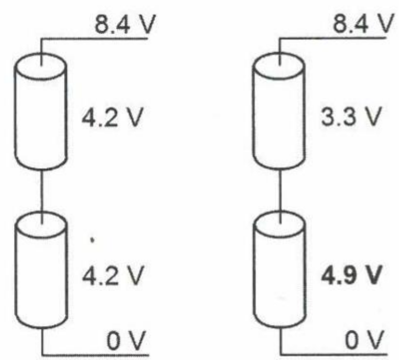
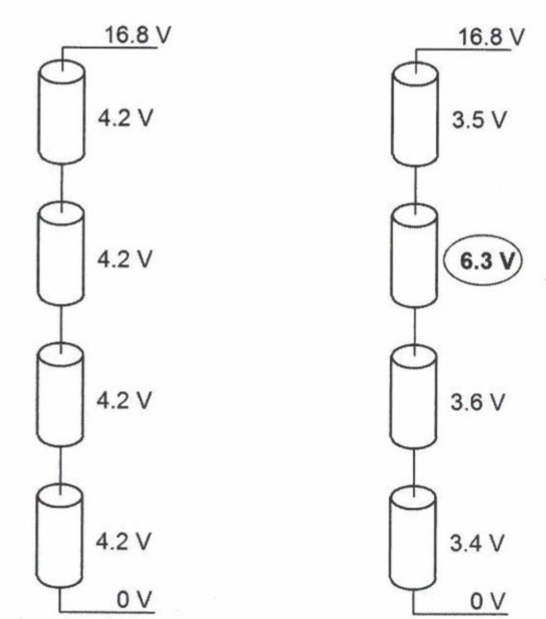
Small LiPo battery



Cell damage

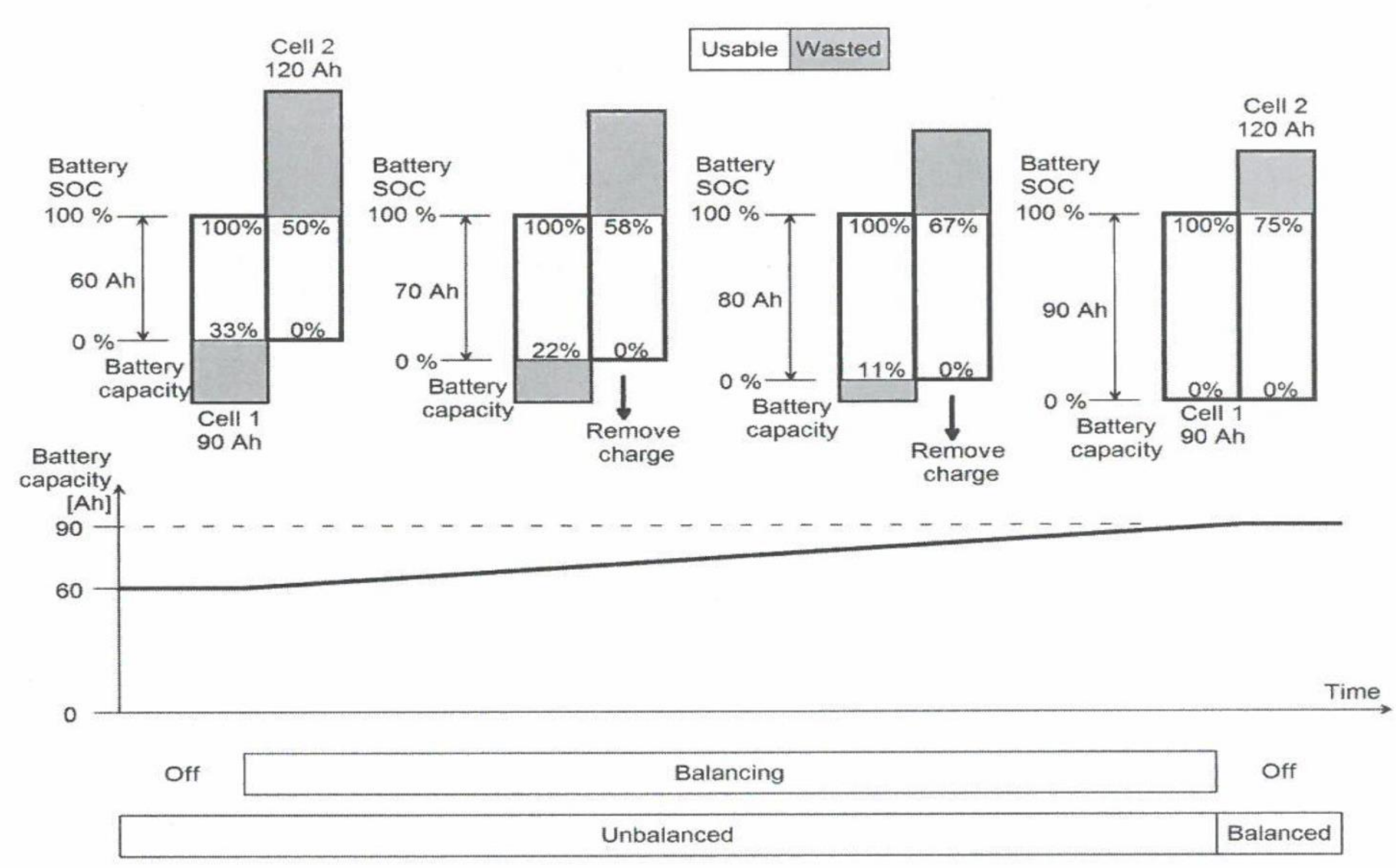
Four cell Li-ion battery



Thermal runaway

Balancing

Balancing increases battery capacity.
Battery capacity = min(cell capacity) = 90 Ah



Redistribution also handles capacity unbalance.
Battery capacity = mean(cell capacity) = 105 Ah

SOC estimation

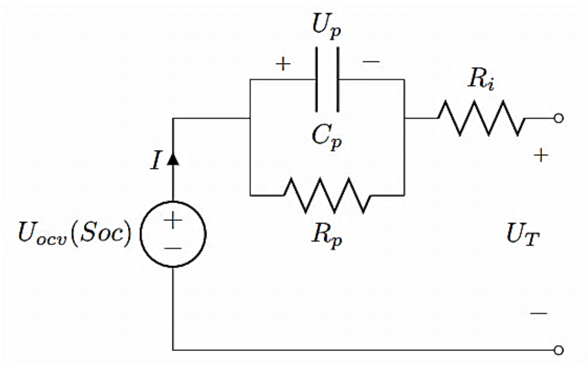
Why?

- Damage control - Keep SOC within given range
- Range prediction
- Degradation estimate

SOC estimation

How?

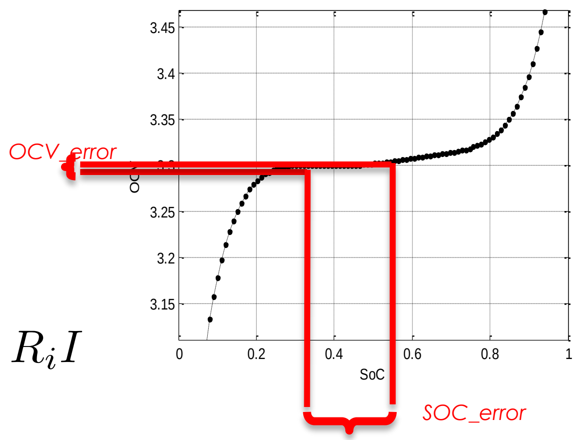
- Coulumb counting – integrate measured current $Q = \int I dt$
- OCV-SOC curve - inaccurate $OCV = f(SOC)$
- Combine these in a filter (Kalman, particle)



$$\dot{\mathrm{SOC}} = \frac{\eta I}{Q_{\mathrm{Batt}}}$$

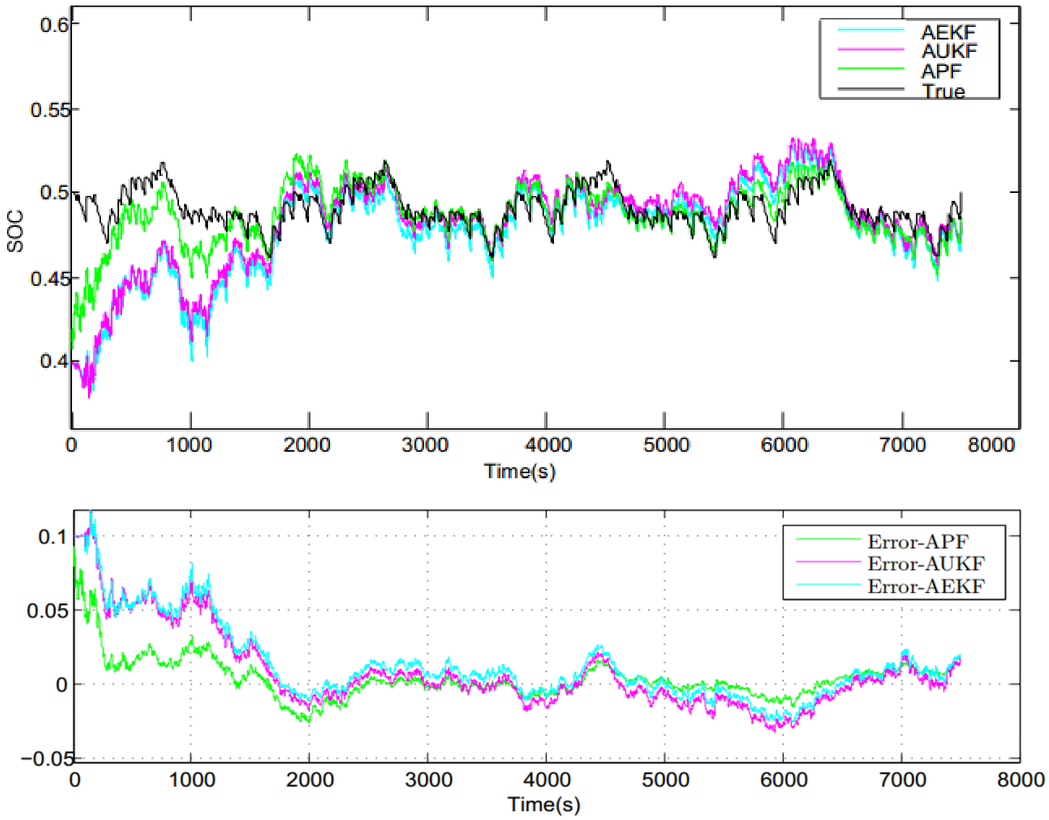
$$\dot{U}_p = \frac{I}{C_p} - \frac{R_p U_p}{C_p}$$

$$U_T = U_{\mathrm{OCV}}(\mathrm{SOC}) - U_p - R_i I$$



SOC-estimation using different filters

HEV operation with a SOC close to 0.5



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