Lecture Note #8 (Spring, 2022)

Battery Applications: Cell and Battery Pack Design

1. Battery design
2. Battery layout using a specific cell design
3. Scaling of cells to adjust capacity
4. Electrode and cell design to achieve rate capability
5. Cell construction
6. Charging of batteries
7. Battery management system (BMS)

*battery > cell. e.g. two or more cells connected together form a battery, of course, a single cell as a battery possible

Fuller & Harb (textbook), ch.8

Battery design

Table 8.1 Important Battery Requirements

Requirement	Units	Comments
Discharge time	hours	Nominal operation time for application, inversely proportional to rate capability
Nominal Voltage maximum, and minimum voltages	V	Output voltage of the battery string, not an individual cell
Energy	W·h	Capacity of the battery. Linked to average power and discharge time
Weight or mass	kg	Closely related to energy stored in battery
Volume	m^3	Closely related to energy stored in battery
Peak power	W	Power for a short pulse of fixed time, 30 seconds, for instance
Cycle life	–	Number of charge/discharge cycles before capacity or power capability is reduced by 20%, for example
Temperature of operation, minimum, maximum	°C	Expected nominal, minimum, and maximum environmental temperatures
Calendar life	years	Beyond the scope of this text

-Critical design specifications: discharge time, nominal voltage, energy e.g. lithium-ion battery for an electric vehicle

A discharge time of 2 h, 24 kWh of energy, targeted battery voltage of 360 V, 3.75 V of nominal single-cell voltage (depends on the cell chemistry),

number of cells in series = m = V_{batt} / V_{cell} = 360/3.75 = 96

→ a minimum of 96 cells in series is needed

(cells connected in series "string")

If two parallel strings, n = 2

Total number of cells, N_c = mn = 96 x 2 = 192

m: number of cells in series,

n: number of cell strings connected in parallel

Energy of an individual cell, $E_{cell} = Q_{cell} \cdot V_{cell}$

Total energy of the battery, $E_{batt} = N_c E_{cell}$

→ $Q_{cell} = E_{cell} / V_{cell} = E_{batt} / (N_c \cdot V_{cell})$ = 24000 / [(192)(3.75)] = 33 Ah

→ total 192 cells, each with a capacity of 33 Ah

Illustration 8.1

Two cases (series & ;parallel): energy is same

series: higher voltage & lower capacity

parallel: lower voltage & higher capacity

Battery layout

A battery (or battery pack, cells in a module) consists of a collection of cells that are electrically connected with series and parallel combinations

→ mS-nP : m cells in series & n of these series strings in parallel

The total number of cells $N_c = m \times n$

→ many layouts of the cells → the best way to combine cells?

→ voltage requirement (in previous page),

battery resistance (a crucial impact on its peak power)

If open-circuit voltage of each cell, V_{ocv}, internal resistance, R_{int}

Total resistance of the battery,

$$R_{tot} = (m/n)R_{int}$$

-series connections (m) increase the resistance of the battery, and parallel connections (n) reduce the resistance of the battery)

-m (series connections) causes the battery voltage to increase, and n (parallel connections) increase the capacity and current

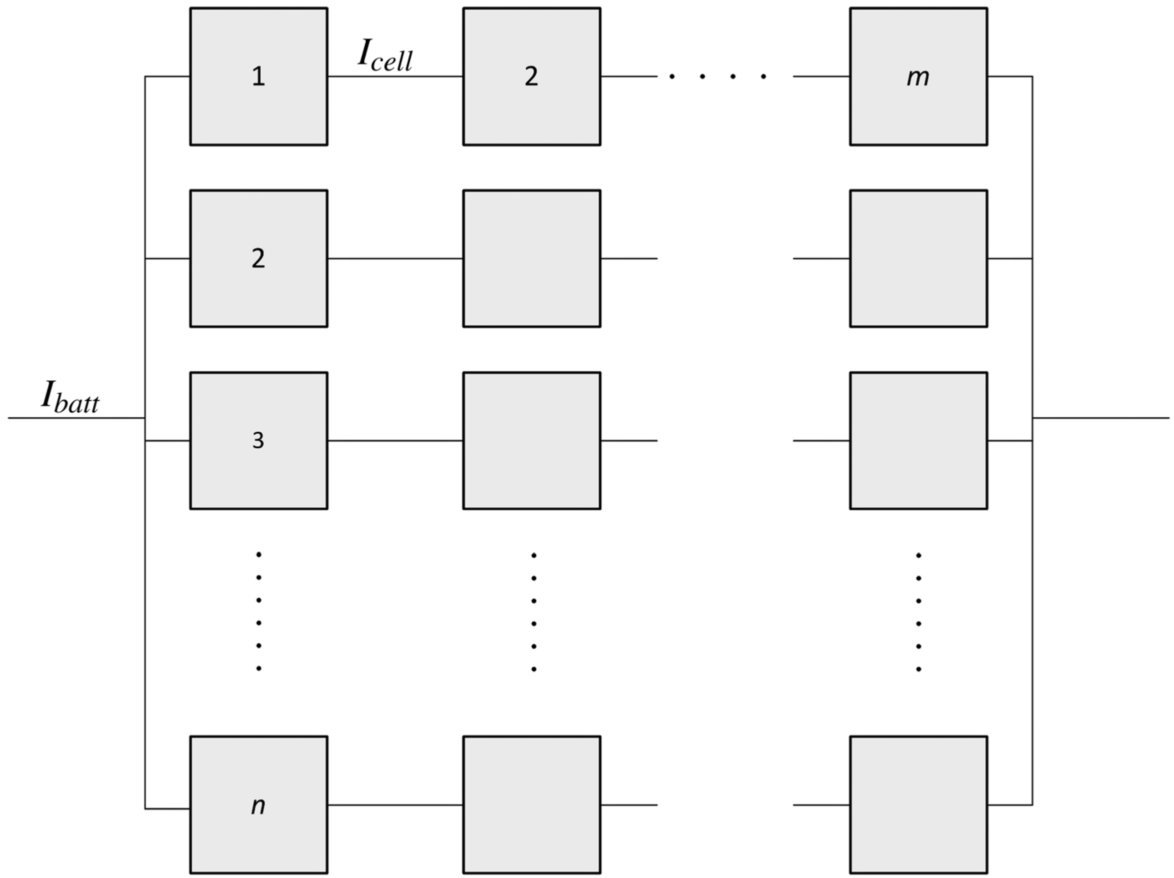


Figure 8.1 Possible series–parallel layout for a total of *mn* cells.

$$V_{batt} = mV_{cell}, \qquad I_{batt} = nI_{cell}$$

Assuming that the battery is ohmically limited

$$V_{batt} = m(V_{ocv} – I_{cell}R_{int}]$$

Power from the battery,

$$P_{batt} = I_{batt}V_{batt} = mnI_{cell}[V_{ocv} – I_{cell}R_{int}]$$

→ the power from the battery is just the power from an individual cell x the number of cells, and is independent of how the cells are connected together

If resistance in wires and contact resistance (external resistance, R_{ext})

$$R_{tot} = R_{ext} + (m/n)R_{int} \sim [R_w(1 + m)/n] + (m/n)R_{int}$$

R_w: the combined wire and connection resistance between each cell and on each end of the string

→ the lower the external resistance, the higher the maximum power and the greater the energy obtained from the battery

→ vary according to the battery layout

Illustration 8.2

Illustration 8.2

Maximum power goes up slightly as # of cells in series increases
Battery current becomes very large as cells are arranged in parallel

Module:

e.g. 24 kWh device where 192 cells were combined to form the battery, with two strings in parallel (96S-2P arrangement)

→ in practice, cells would be grouped into modules

→ e.g. 4 cells could be combined to form a module, where each module is 2S-2P and housed together in a single case with one pair of terminals → 48 modules are strung in series to form the battery

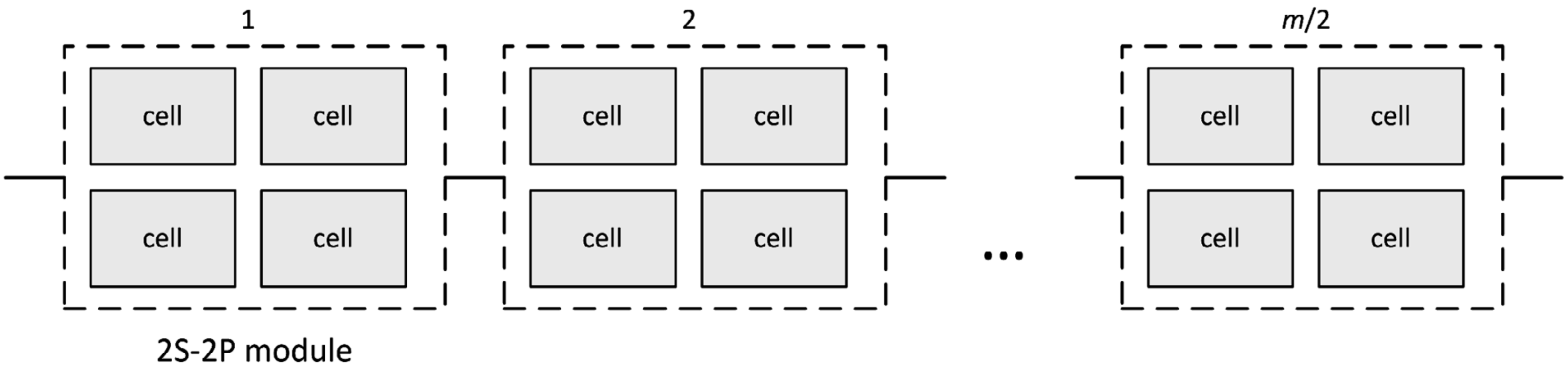


Figure 8.2 Creation of a battery from modules. Each module consists of four cells combined, two in series and two in parallel.

Electrochemical Engineering, First Edition. Thomas F. Fuller and John N. Harb.

Companion Website: www.wiley.com/go/fuller/electrochemicalengineering

Scaling of cells to adjust capacity

Consider each cell to increase capacity (to decrease # of cells in battery pack):

e.g. a primary lithium thionyl chloride battery

$$4Li(s) + 2SOCl_2 \rightarrow 4LiCl(s) + S(s) + SO_2(g)$$

Positive electrode: porous carbon, LiCl & S deposit on (+)electrode

Negative electrode: lithium metal foil

→ total cell volume

$$\mathbf{V_{cell}} = V_- + V_+ + V_s + V_{-cc} + V_{+cc} + V_{ex}$$

→ for a given capacity Q [Ah]

→ negative electrode (lithium) volume is given by Faraday's law

$$V_- = (3600QM_{Li}f_a) / (F\rho_{Li})$$

3600 converts Ah to coulombs

f_a: design factor (excess Li)

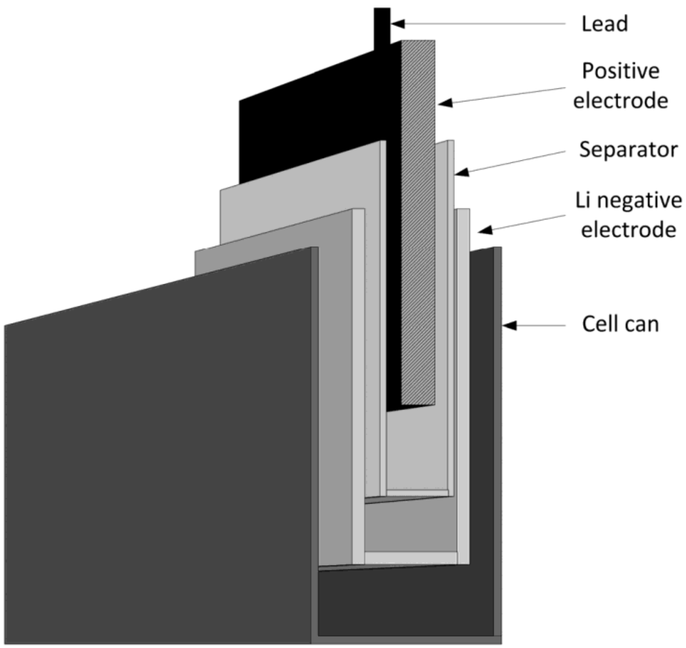


Figure 8.3 Construction of $LiSOCl_2$ cell.

→ positive electrode (porous carbon) volume: initial pore volume + excess solids volume of sulfur & lithium chloride

→ volume of solid products = $3600Q[M_{LiCl}/(F\rho_{LiCl}) + M_S/(4F\rho_S)]$

$$V_+ = (\text{volume of solid products}\cdot f_a)/\varepsilon$$
$$= (3600Qf_a)/\varepsilon)\ [M_{LiCl}/(F\rho_{LiCl}) + M_S/(4F\rho_S)]$$

ε: the initial void volume fraction of the positive electrode

f_c: design factor for additional porous volume

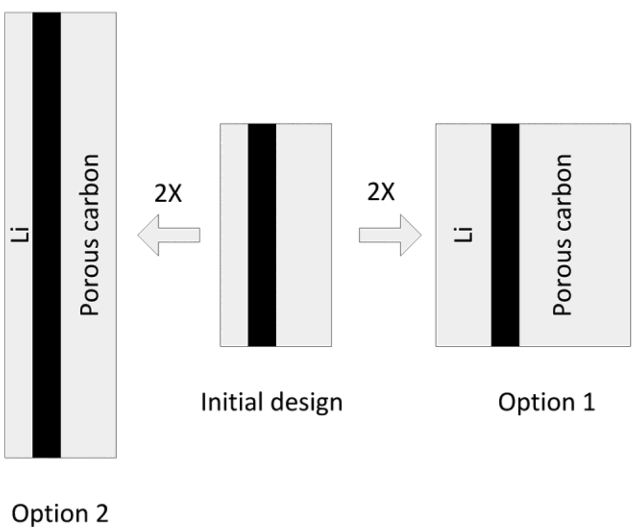
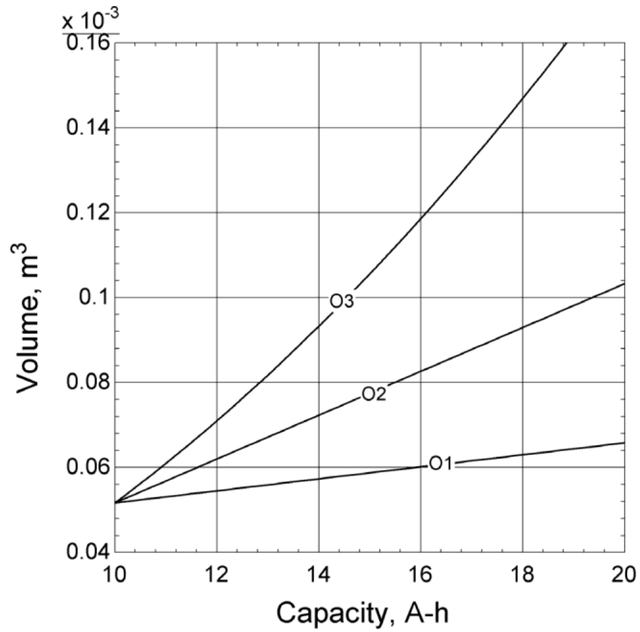


Figure 8.4 Two methods to increase capacity of a cell by a factor of 2.



Option 3

Option 2

Option 1
(polarization↑)

Figure 8.5 Three approaches to the scaling of 10 A·h thionyl chloride primary cell.

Option 3:
Current collector↑

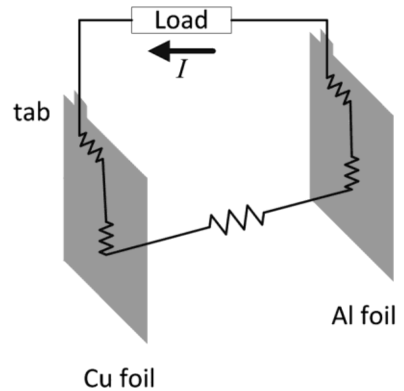


Figure 8.6 Resistance of the current collectors for lithium-ion cell.

Another option to increase capacity : stack

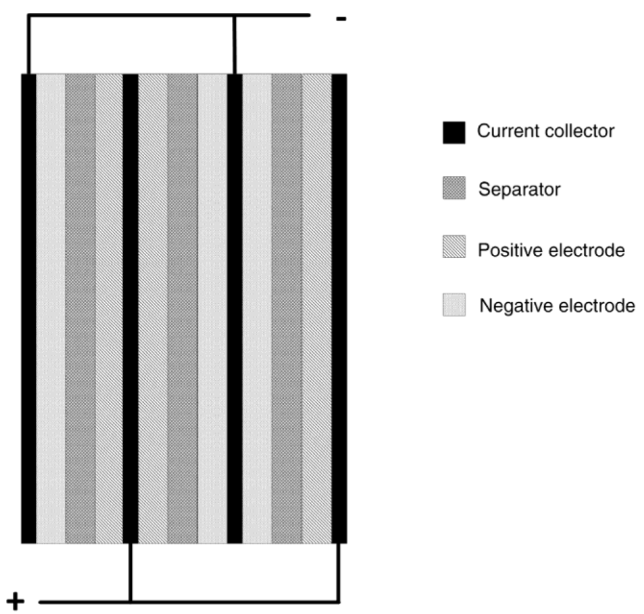


Figure 8.7 Stacked assembly of plates or cells, connected in parallel.

Electrode & cell design to achieve rate capability

Impact of cell design on rate capability or power of a cell:
→ For a given cell capacity, the current and current density are inversely proportional to the time of discharge

$$I_{cell}[A] = Q_{cell} / t_d \text{ and } I_{cell}[A/m^2] = Q_{cell} / A_s t_d$$

long discharge times → low-rate capability
e.g. lead-acid cell :
-SLI(starting-lighting-ignition) battery → high power needed for a short time, total capacity less important (~60Ah capacity)
-back-up power → a large change of SOC, operate at a lower power, high capacity needed → high-capacity or deep-cycle cells

Table 8.2 Design Parameters for SLI and Deep-Cycle Cells

Feature	Existing deep-cycle cell	Deep-cycle cell scaled for SLI capacity	Desired SLI cell
Nominal voltage [V]	2	2	2
Capacity [A·h]	1700	60	**60**
Discharge time	10 hours	30 seconds	**30 seconds**
Cold cranking amps	NA	71	**560**
Mass [kg]	125	4	16
Internal resistance [mΩ]	0.4	11.3	1.4
Cycle life	500 (50% SOC)		2000 (3% SOC)

Quantities in bold are fixed for the SLI cell.

Scale the existing deep-cycle cell from its capacity (1700 Ah) to the desired capacity (60 Ah) of the SLI battery using the cell area → decrease cell area in proportional to the capacity

-Internal resistance scales,

$$R_{int}^{SLI} = R_{int}^{dc}(\text{capacity of the deep cycle / capacity of the SLI})$$
$$= 0.4(1700 / 60) = 11.3\ m\Omega$$

→ the resistance increases with decreasing cell area since a higher voltage drop is required to drive the same current in the smaller cell

-the mass of the cell will scale directly with the capacity or area

$$m_{SLI} = m_{dc}(\text{capacity of the SLI / capacity of the deep cycle})$$
$$= 125(60 / 1700) = 4.4\ kg$$

A strategy for increasing the power at constant capacity is to make the individual electrodes or plates thinner (the amount of active material is the same) → increase the rate capability of the cell (thinner electrode (i) easier to access the active material. (ii) Increased cell area) by resistance↓

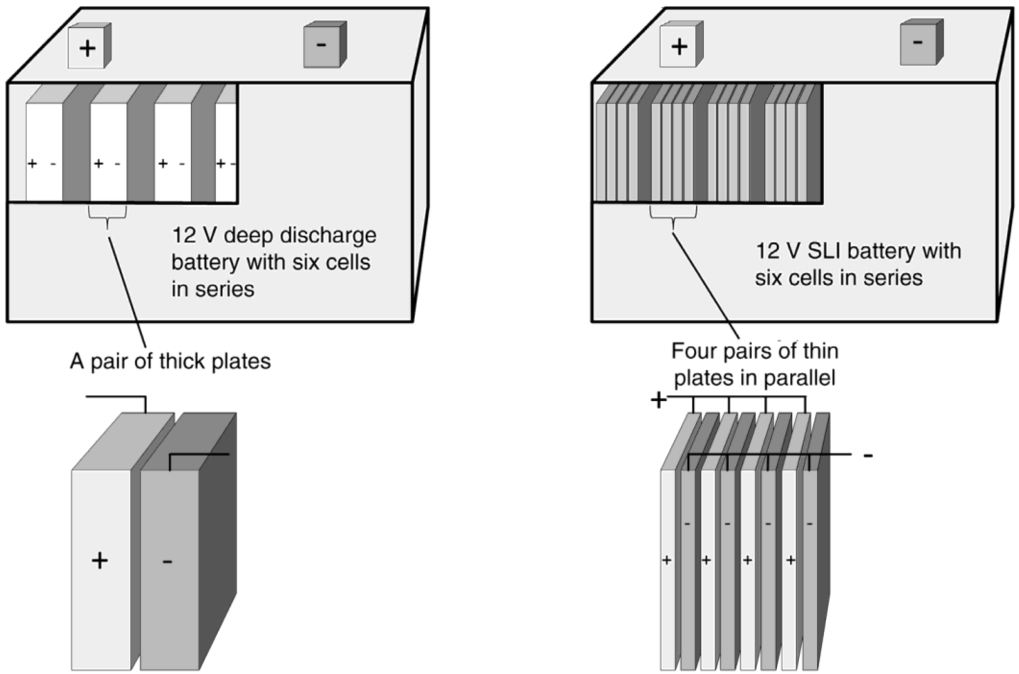


Figure 8.8 Comparison showing the internals of a deep discharge and an SLI lead–acid battery. Both are 12 V and have the same amount of active material. The electrodes for the SLI battery are thinner, with multiple plates connected in parallel to reduce the internal resistance of the cell.

Electrochemical Engineering, First Edition. Thomas F. Fuller and John N. Harb.

Companion Website: www.wiley.com/go/fuller/electrochemicalengineering

Cell construction

Cell types: prismatic, plate designs, cylindrical, and coin

Prismatic: pack efficiently → preferred where space is limited, stack

Cylindrical: familiar structure (alkaline battery), wind electrodes. Convenient to manufacture

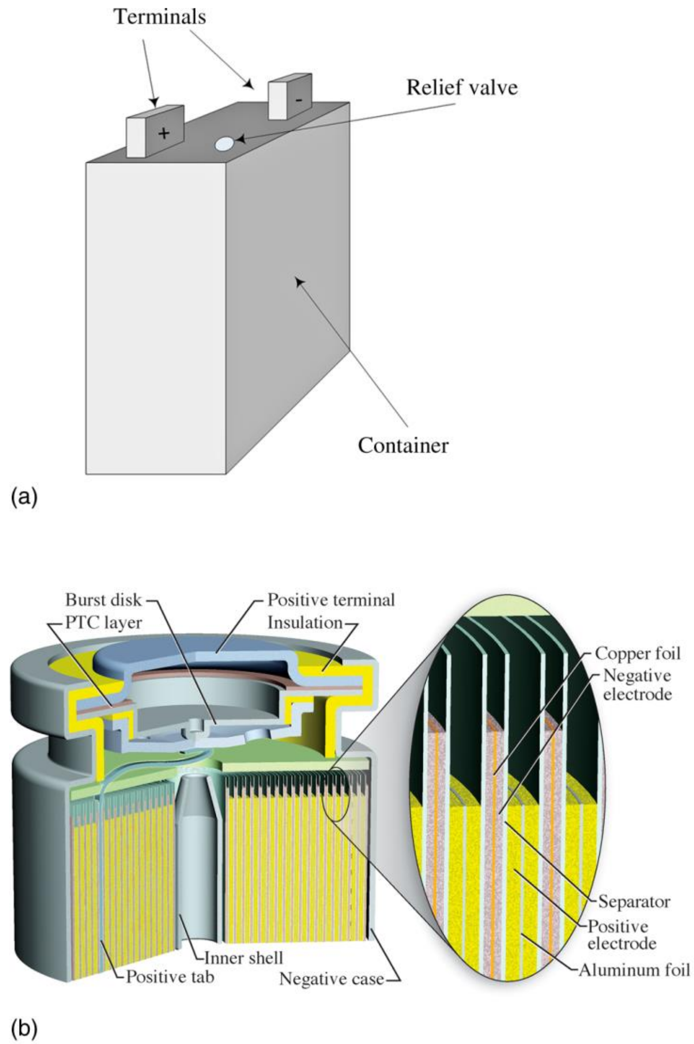


Figure 8.9 Cell configurations (a) A prismatic cell showing terminals and relief valve. (b) Spirally wound cylindrical cell.

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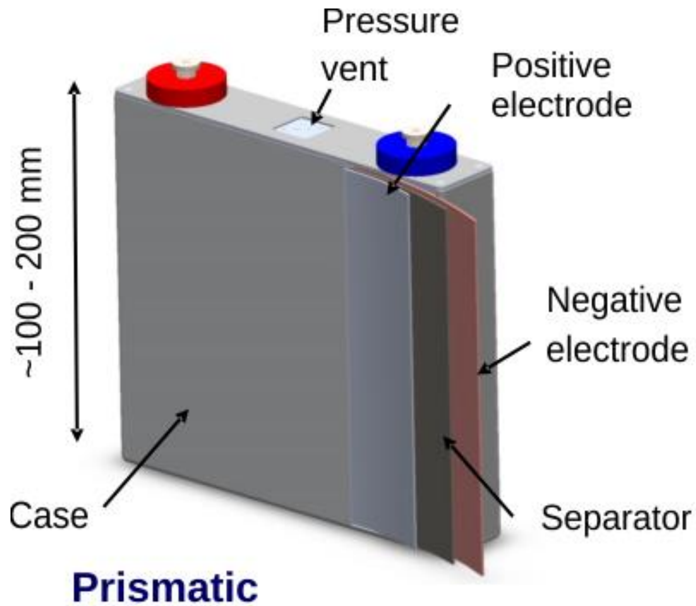
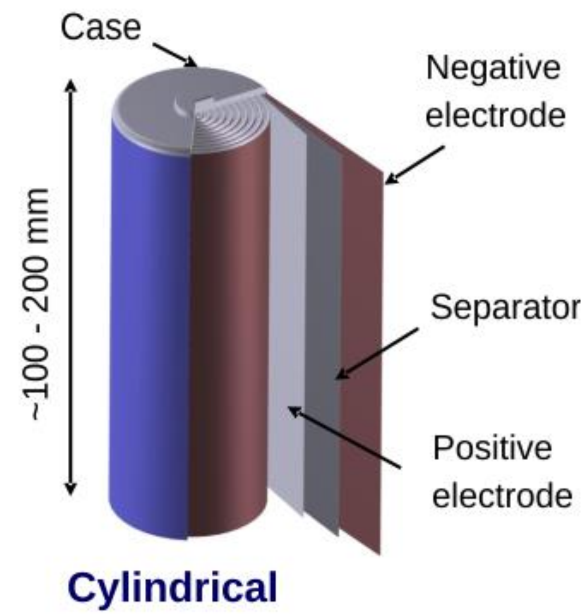
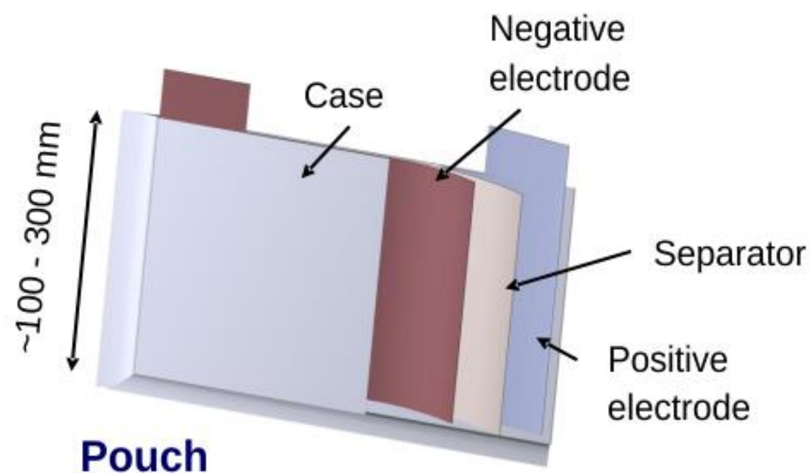
Lithium battery types

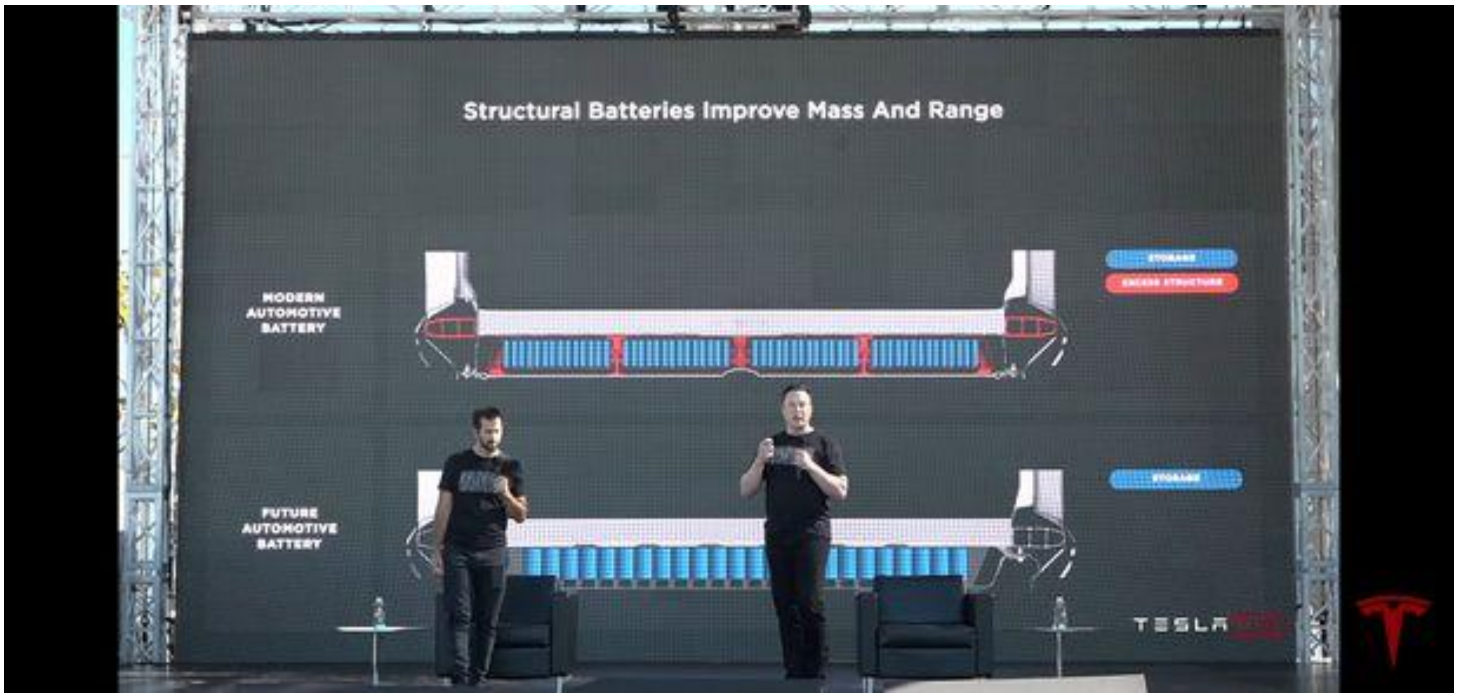






Cell to chassis technology

Cell to chassis (CTC) technology **integrates the battery cell with the vehicle body, chassis, electric drive, thermal management as well as various high and low voltage control modules**, extending driving range to over 1,000 km. (Google)



테슬라가 개발 중인 '셀 투 섀시(cell to chassis)' 기술. 작년 배터리데이 때 처음 공개됐다. 위쪽은 현재 전기차의 차체 모습으로, 배터리 중간에 지지대가 탑재돼 차체를 지탱한다. 아래는 개발중인 차체로 배터리 셀이 차체를 지지하도록 형태를 바꿨다. 당시 일론 머스크는 "배터리 탑재공간을 넓힐 수 있어, 자연히 효율이 높아진다"고 설명했다. /테슬라 배터리데이 영상 캡처 (조선일보 21.1.28)

Charging of batteries

Charge coefficient =
coulombs passed to fully recharge / coulombs drawn during discharge
$= 1 / \eta_{coul}$

→ charge coefficient is related to the coulombic efficiency
→ batteries with a coulomic efficiency less than 100% will have a charge coefficient greater than 1

-Two basic methods of adding charge
i) charging at constant current (CC): charged at constant rate (C/2 ~ C/8 depending on the battery) → during the charge, the potential of the cell rises, and charging is allowed to continue until a specified voltage is reached
ii) charging at constant voltage (CV): seldom used as the sole means of charging a cell because very large currents are possible at the beginning of the charge if the voltage is held constant at its final value
→ often, these two basic methods are combined: constant current charge followed by a constant voltage charge (CCCV)

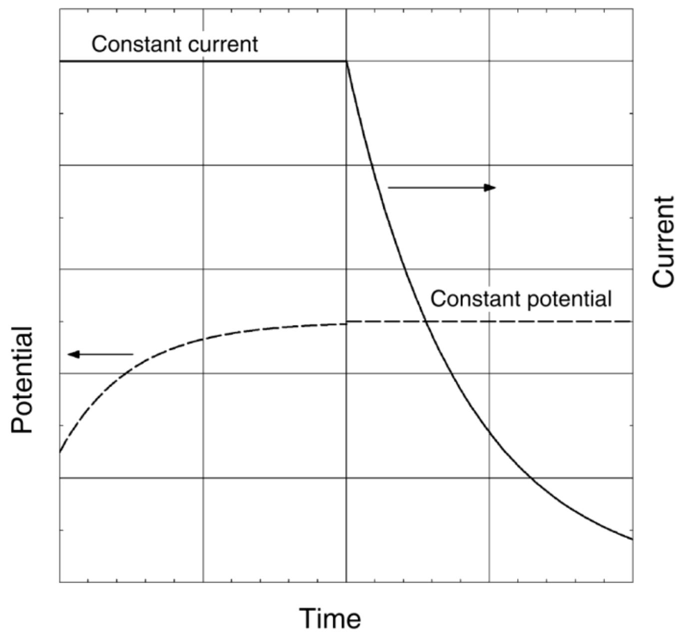


Figure 8.10 Constant current–constant voltage charge (CCCV).

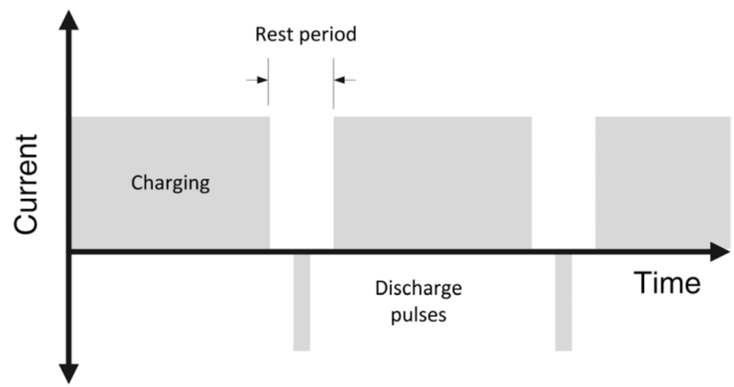


Figure 8.11 Pulse charging.

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-pulse-charging: widely applied to different cell chemistries. More rapid charging and a reduced extent of sulfation for lead-acid cells

Use of resistance to characterize battery performance

Health of the battery: a measure of the condition of the battery relative to its initial "full performance" state → use of resistance to provide health of the battery

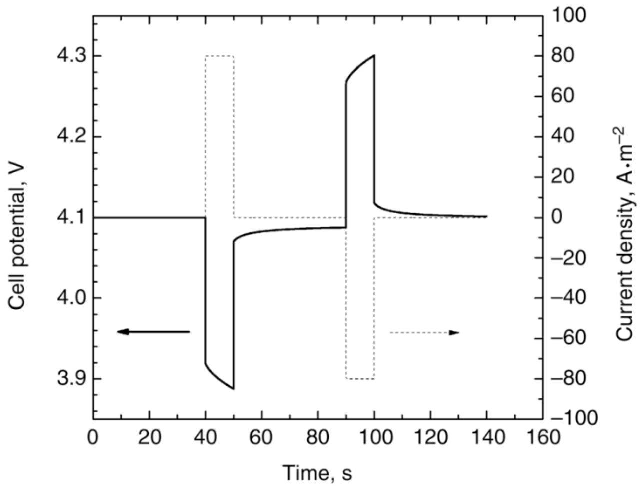


Figure 8.12 Pulse power test.

The concept and its relationship to the ohmic resistance (Fig. 8.12)
→ after a period of rest, two short current pulses are applied, one for discharging and one for charging → during discharge, the potential drops instantaneously and then decrease with time → the immediate drop represents the ohmic resistance, further decrease from t_0 to t_1 is due to activation and concentration polarization

Battery resistance,

$$R_{cell}^{d} = \Delta V / \Delta I = [V(t_0) - V(t_1)] / \Delta I \qquad (8.21)$$

A resistance of charging, R_{cell}^{c}

The cell voltage, $V_{cell} = V_{ocv} – IR_{cell}^{d}$ (8.22)

Power is equal to IV_{cell},

Current at maximum power, $I(\text{max power}) = V_{ocv} / 2R_{cell}^{d}$

And maximum power, $P_{max} = (V_{ocv})^2 / 4R_{cell}^{d}$ (8.23)

→ relationship between the power and the cell resistance

→ resistance examine the power or rate capability → resistance is a convenient way of characterizing battery performance, and the change in resistance with time as the battery is cycled provides a measure of the state of health (SOH) of the battery

SOH = present capability / design capability (8.24)

“as received” SOH = 100% → degrade with time → cause an increase in the cell resistance

Battery management system (BMS)

BMS: in order to get the most out of the battery and to ensure safe operation, current flow in and out of the cells that make up that battery must be carefully monitored and controlled

→ BMS uses measurements of current, potential, and temperature to control charging and discharging, and to estimate the SOC and SOH

The importance of and the sophistication required in the BMS depend on the cell chemistry, the size of the battery, and the application

One of the most important issues in the management of a multicell battery is keeping the individual cells in balance

Illustration 8.3: one weak cell (low coulomb efficiency) fails to contribute power and consumes power and can be damaged

→ BMS

passive balancing: energy is dissipated in a shunt resistor for cells with excess SOC (to avoid any cell exceed a voltage limit, some current bypasses the cell through a shunt resistor)

Active balancing: energy from a cell with a high SOC is moved to a cell with a lower SOC. Active balancing requires more complicated electric circuitry, but has greater energy efficiency

Battery management system (BMS)

A **battery management system** (**BMS**) is any electronic system that manages a rechargeable battery (cell or battery pack), such as by protecting the battery from operating outside its safe operating area, monitoring its state, calculating secondary data, reporting that data, controlling its environment, authenticating it and / or balancing it.

A battery pack built together with a battery management system with an external communication data bus is a smart battery pack. A smart battery pack must be charged by a smart battery charger.

A BMS may monitor the state of the battery as represented by various items, such as:

•Voltage: total voltage, voltages of individual cells, or voltage of periodic taps

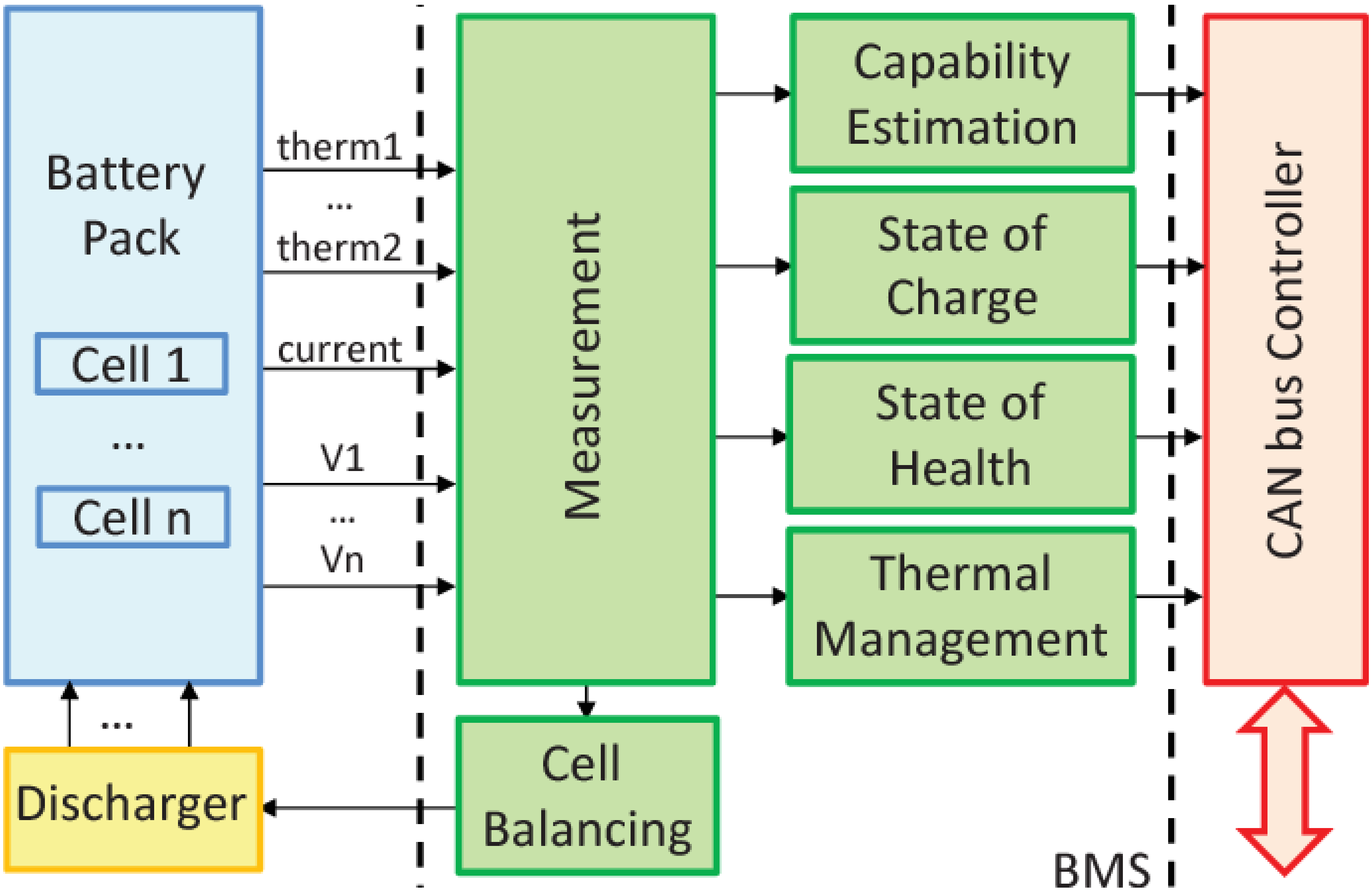
•Temperature: average temperature, coolant intake temperature, coolant output temperature, or temperatures of individual cells

•Coolant flow: for air or fluid cooled batteries

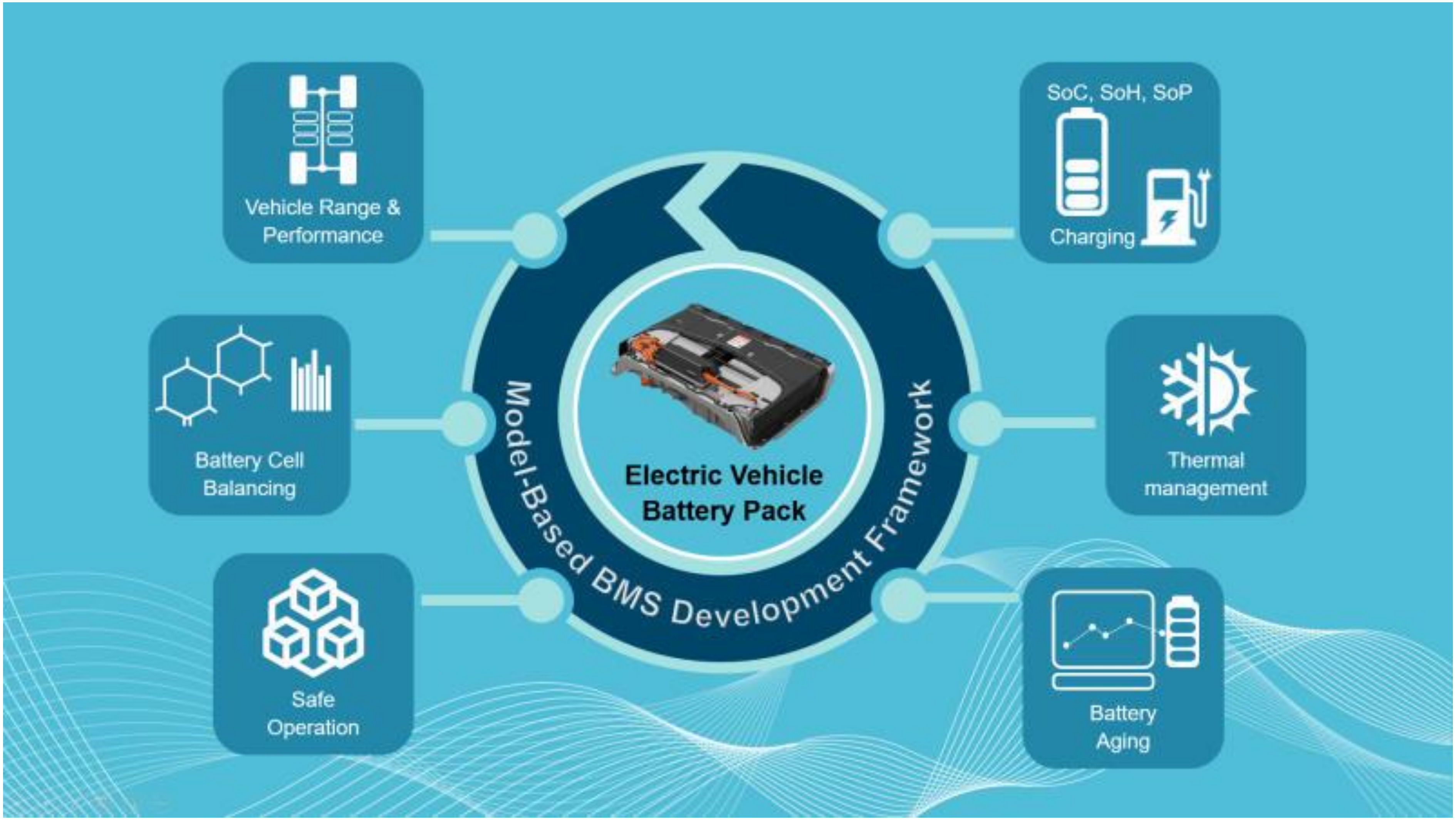
•Current: current in or out of the battery

…….

https://en.wikipedia.org/wiki/Battery_management_system



[Why is a Battery Management System needed in Electric Vehicles? • EVreporter]

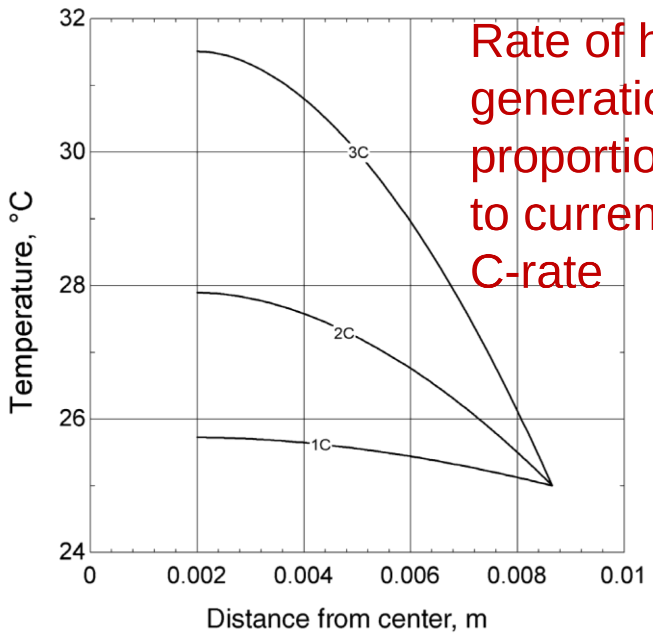


[Siemens Software]

Thermal management system

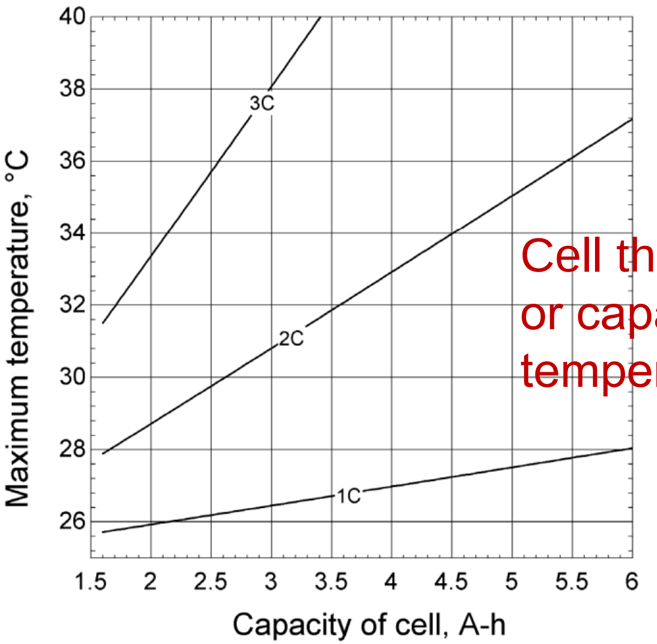
Heat generation during operation in the cell
Energy balance,

q: rate of heat generation, k_{eff}: effective thermal conductivity



Rate of heat generation is proportional to current or C-rate

Figure 8.13 Temperature profile in cell with C-rate as a parameter. Cell capacity is 1.6 A·h.



Cell thickness or capacity↑ → temperature↑

Figure 8.14 Effect of rate and capacity on maximum temperature.

Mechanical considerations

Mechanical effects are important in battery design and operation

-Volume changes by Li intercalation (negative electrode 10%, positive electrode 2%) and temperature

-Mechanical stability by vibration, shock

e.g. 2 tons battery in submarine