TERMS, DEFINITIONS AND PARAMETERS

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An Introduction to Battery Technologies
Lecture#3

1

CAPACITY, POWER, ENERGY

Capacity: The capacity of a battery is the amount of electrical charge that can be stored and released by the cell.

$$E = C \times V$$

E = Energy content [Wh]
C = Capacity [Ah]
V = Voltage [V]

ENERGY
The energy content of an energy storage device is a measure of its ability to store a specific amount of energy

POWER
P = I.V
It states how much energy can be released per unit of time
the power of the device is a measure of its internal resistance. A system with small internal resistance can provide lots of energy in a very short period.

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ENERGY OPTIMIZED VS POWER OPTIMIZED

ENERGY OPTIMIZED
Focus: Prioritizes storing and delivering maximum energy for a given size and weight.

Characteristics: High energy density, suitable for applications requiring long runtime or infrequent charging.

Electric vehicles (range), portable electronics (long battery life), energy storage systems (grid-scale).

POWER OPTIMZED
Focus: Delivers high power output quickly, even for short bursts.

Characteristics: High power density, capable of handling large current demands.

Electric vehicles (acceleration), power tools, hybrid vehicles (engine start-stop), uninterruptible power supplies (UPS)

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SPECIFIC VALUES AND DENSITY

Specific Energy: The quantity of energy stored per unit of mass. (Wh/kg)

Energy Density: The quantity of energy stored per unit of volume. (Wh/L)

Specific Power: The battery power stored per unit of mass. (W/kg)

Power Density: The battery power stored per unit of volume. (W/L)

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SPECIFIC VALUES AND DENSITY

For a 18650 **Lithium cell** with 50 g mass and C = 3250 mAh capacity, calculate the Specific Energy and Energy Density.

$$E = C \times V = 3250\ \text{mAh} \times \frac{1\ \text{A}}{1000\ \text{mA}} \times 3.6 = 11.7\ \text{Wh}$$

$50\ \text{g} = 0.05\ \text{kg}$

Therefore:

Specific energy is :

$$\text{Specific Energy} = \frac{11.7}{0.05} = 234\ \frac{\text{Wh}}{\text{Kg}}$$

According to IEC , 18650 batteries have 18 mm diameter and 65 mm length

$$\forall = \pi \frac{1.8^2}{4} \times 6.5 = 16.54\ \text{cm}^3$$

$$\text{Energy Density} = \frac{E}{\forall} = \frac{11.7\ \text{Wh}}{16.54\ \text{cm}^3} = 0.7073\ \text{Whcm}^{-3} = 707.3\ \text{WhL}^{-1}$$

STATE OF CHARGE AND DEPTH OF DISCHARGE

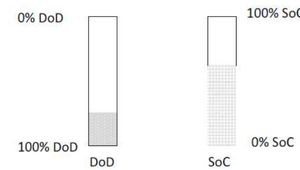
Each battery cell has a specific capacity. This means that the cell cannot store more energy than its capacity. When the cell is discharged, the capacity of the cell decreases.

$$\text{SoC} = \frac{C_{\text{avaliable}}}{C_{\text{nominal}}}$$

When the cell is fully charged, SoC = 1, and when the cell is completely discharged, SoC = 0.

the depth of discharge or DoD is defined as the amount of used energy of a cell. In other words, when the cell is fully charged, DoD = 0, and when the cell is fully discharged, we have DoD = 1.

DoD = 1 - SoC



sometimes the state of charge can erroneously be measured relative to the previous cycle capacity. Knowing that the capacity of a battery decreases with the number of cycles it is obvious that referencing the state of charge to the latest cycle does not give the correct information about the capacity.

EXAMPLE

A Lithium-ion battery with a total capacity of 150 Ah is cycled through various loads over a day:

Load 1: 10 A for 4 hours

Load 2 : 20 A for 2 hours

Load 3 : 5 A for 6 hours

(a) Calculate the total capacity consumed in Ah over the day

(b) Determine the remaining capacity after these discharges

(c) Calculate the DoD and SoC based on the remaining capacity

EXAMPLE SOLUTION :

(a)

$$\text{Total Energy Consumed} = (\text{Load1} \times \text{Time}) + (\text{Load2} \times \text{Time}) + (\text{Load3} \times \text{Time})$$
$$10 \times 4 + 20 \times 2 + 5 \times 6 = 40 + 40 + 30 = 110\ \text{Ah}$$

(b)

$$\text{Remaining Capacity} = \text{Total Capacity} - \text{Total Energy Consumed}$$
$$150\ \text{Ah} - 110\ \text{Ah} = 40\ \text{Ah}$$

(c)

$$\text{DoD}(\%) = \frac{(\text{Total Capacity} - \text{Remaining Capacity})}{\text{Total Capacity}} \times 100 = \frac{150-40}{150} \times 100 = 73\%$$

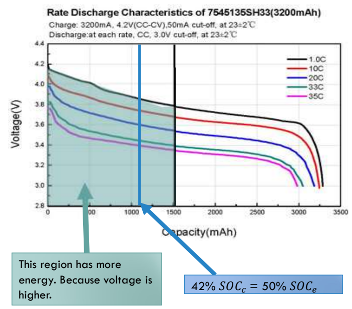
$$\text{SoC}(\%) = 100\ \% - \text{DoD}(\%) = 100 - 73 = 27\%$$

STATE OF CHARGE AND DEPTH OF DISCHARGE

Actually we got 2 type of SOC, one is based on capacity which was previously mentioned and the other is based on energy.

Coulomb Counting:

$$SOC(t) = SOC_{\text{initial}} + \frac{i(t)}{C_{\text{initial}}}\Delta t$$



STATE OF HEALTH

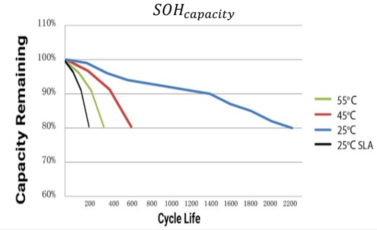
The state-of-health (*SoH*) of a battery describes the difference between a battery being studied and a fresh battery and considers cell aging.

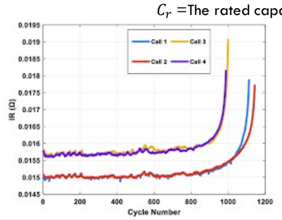
It is defined as the ratio of the maximum battery charge to its rated capacity.

$$SoH = \frac{C_{max}}{C_r}$$

C_{max} = The maximum charge available of the battery
C_r =The rated capacity (Beginning of life)

$SOH_{capacity}$





$SOH_{impedance}$

EXAMPLE

A Lead-acid battery originally rated at 200 Ah. The degradation rate is expected to be linear at approximately 10% per year.

(a) Estimate the capacity after three years if the degradation continuous at the same rate

(b) if you want to maintain at least 80% *SoH*, how may years can you continue to use this battery?

EXAMPLE SOLUTION

(a)

$$\text{Future Capacity} = \text{Current Capacity} - (\text{Degradation rate} \times \text{Year})$$
$$200 \text{ Ah} - (200 \times 0.1 \times 3) = 140 \text{ Ah}$$

(b)

Target Capacity:

$$200 \times 0.8 = 160 \text{ Ah}$$

$$\text{Years until SoH drops Below Target} = \frac{(\text{Current Capacity} - \text{Target Capacity})}{\text{Degradation Rate}}$$

$$\frac{200-160}{0.1 \times 200} = 2 \text{ years}$$

BATTERY CURRENT (C-RATE)

The current used to charge or discharge a battery is typically expressed as a multiple of a so-called **C-rate**, which is the capacity of a battery. For example, a 1 C current is the current expressed in amperes (A) that has equal numerical value to the battery capacity in Ah, i.e., it represents the current that would charge or discharge a battery in 1 h.

$$I(\mathrm{A}) = M \times C$$

What is the C-rate if a current of 300 mA is used to discharge a cell with a rated capacity of 1200 mAh?

$$M = I/C = 300\ \mathrm{mA}\ /\ 1200\ \mathrm{mAh} = 0.25\mathrm{C}$$

What is the battery capacity if it is fully charged using C/10 current of 250 mA?

$$C = I/(C/10) = 250\ \mathrm{mA} \times 10 = 2500\ \mathrm{mAh}$$

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EXAMPLE

A battery rated at 180 Ah is charged with 90 A.

(a) Calculate C-rate during charging

(b) Determine how long it will take to charge from an initial SoC of 30% to full charge.

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EXAMPLE SOLUTION

(a)

$$\mathrm{C-rate} = \frac{\text{Charge Current}}{\text{Battery Capacity}}$$

$$\mathrm{C-rate} = \frac{90\mathrm{A}}{180\mathrm{Ah}} = 0.5\mathrm{C}$$

(b)

$$\text{Time of Full Charge} = \frac{(\text{Target } SoC - \text{initial } SoC) \times \text{Battery Capacity}}{\text{Charge Current}}$$

$$\frac{(1 - 0.3) \times 180\mathrm{Ah}}{90\mathrm{A}} = 1.4\mathrm{h}$$

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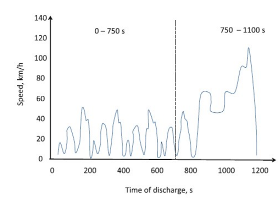
MODES OF DISCHARGE

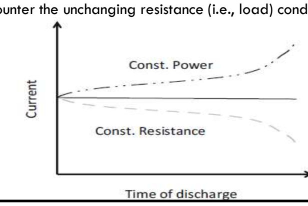
Modes of discharge :

1-Constatnt current
2-Constant load or resistance
3-Constant power

It is totally realistic to expect variable currents or loads such as automotive load regime:



The current itself will be constant for the constant current discharge;
For the constant power mode, current increases with progression of discharge because voltage decreases.
For constant load current decreases with voltage decrease to counter the unchanging resistance (i.e., load) conditions.



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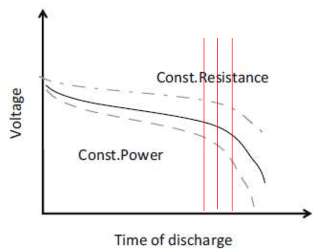
MODES OF DISCHARGE

In each case, the shape of curve is similar, but useful capacity is exhausted and **sharp voltage drop** takes place at different times.

This point is reached the soonest in the case of constant power.

It is followed by a longer discharge time for constant current (solid line)

constant resistance takes the longest time to reach the full discharge because the current adjusts with the voltage drop to, keep the load constant hence both voltage and current decrease means that the discharge slows down near the end of the process.



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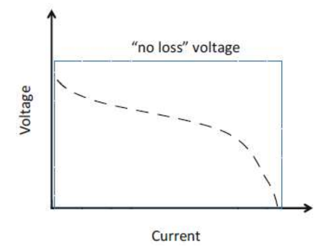
DISCHARGE CURRENT EFFECT ON VOLTAGE

It is obvious that the higher the discharge current, the lower is the voltage.

The theoretical assumption is that only after active mass is completely used in a reaction will the voltage drop to zero.

Practical voltage is, however, very different. In the first region, even at small current densities, the voltage is lower than the open circuit or thermodynamic, i.e., theoretical voltage. The reason for this is a voltage drop described as activation overpotential.



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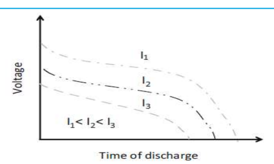
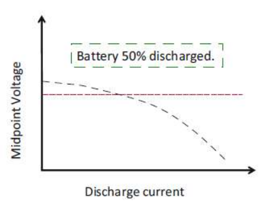
DISCHARGE CURRENT EFFECT ON VOLTAGE

As current increases, the resistive losses become significant and dominate the voltage loss for the majority of the curve. At the highest current densities for a specific battery, the voltage sharply drops because of the inability of a system to provide reactants fast enough. At that point, there are really no reactants left, which means that everything is converted to products. So, the concentration or availability of anode approaches zero and causes a voltage drop, which leads to the end of discharge reaction.

Below this nominal current, the midpoint voltage is higher and above the nominal current the midpoint voltage is lower. For current higher than the nominal, the midpoint voltage value is lower.





A midpoint voltage is the **nominal voltage** of a battery and is measured when a battery is discharged to 50% of the capacity.

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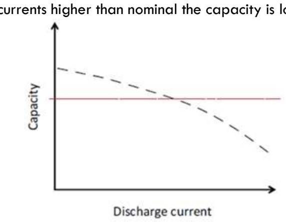
DISCHARGE CURRENT EFFECT ON CAPACITY

As we know:

Battery capacity is the total number of ampere-hours(Coulombs) that a battery can deliver under specified or nominal discharge current and temperature. (declared by manufacturer)

Since nominal capacity is given for a certain discharge current, it must be that the capacity changes with the value of the discharge current. The nominal capacity is obtained for certain, nominal discharge current and is indicated by the horizontal line. For currents lower than the nominal discharge current, capacity higher than nominal or 100% is obtained, while for currents higher than nominal the capacity is lower.



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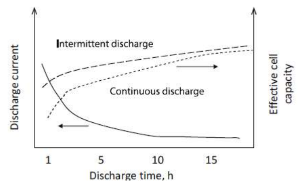
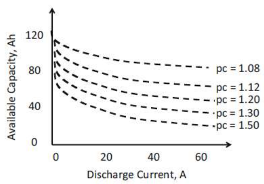
DISCHARGE CURRENT EFFECT ON CAPACITY

The Peukert equation gives the means to calculate capacity for a specific current if capacity is known for another current.

$$Q_2 = Q_1\left(\frac{I_1}{I_2}\right)^{pc-1}$$



The calculated capacity Q2 is mainly dependent on the Peukert coefficient (pc), which is related to internal resistance of the cell and varies not only by battery systems but also by design of the same battery chemistry, temperature of operation, and age of a battery.



Battery system/type	pc
Lead–acid, flooded	1.2–1.4
Lead–acid, VRLAB	1.15–1.25
Ni–Cd	1.10–1.20
Ni–MH	1.05–1.15
Li–ion	1.05–1.1
Ideal battery	1.0

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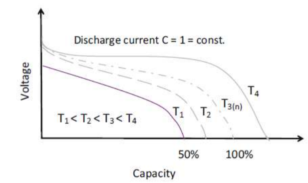
THE EFFECT OF TEMPERATURE ON BATTERY PERFORMANCE

For all reactions : Temperature ↑ ⟹ Rate of reaction ↑

For batteries: Temperature ↑ ⟹ cell voltage and capacity ↑

One hundred percent capacity should be obtained at the nominal temperature of 25 C (curve 3). At higher temperatures, higher capacity is obtained and at lower temperature, lower capacity.

Lower temperatures and higher C rates result in lower cell voltages; and higher temperatures and lower C-rates lead to higher cell voltages.



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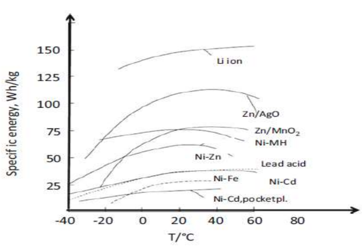
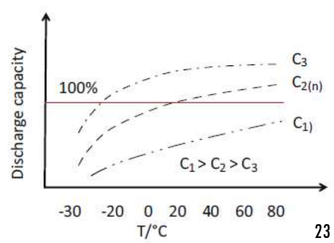
THE EFFECT OF TEMPERATURE ON BATTERY PERFORMANCE

When capacity versus temperature is plotted for different C-rates a trend revealed is an increase in capacity from lower to higher temperature and for lower C rates. The dashed line represents nominal capacity at a certain C rate, typically C/12 and nominal temperature, typically 20°C. For higher C-rates and lower temperatures, the capacity is lower and for lower C rates and higher temperature the capacity is higher than nominal.





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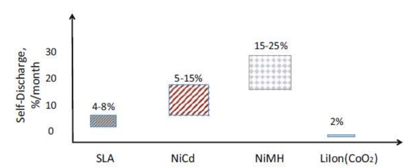
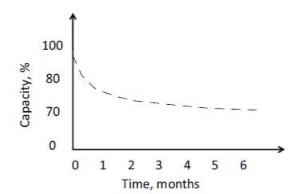
SELF-DISCHARGE

refers to a loss of capacity through involuntary reaction during the battery storage and when battery is not connected to a load. The reactions are mainly caused by thermodynamic instabilities between active masses and cell components, resulting in consumption of active masses.





The rate of self-discharge is dependent on the battery type. Each battery system has different rate of self-discharge.

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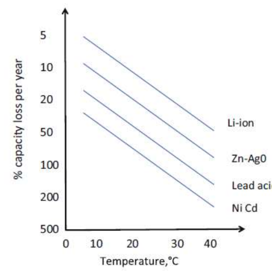
SELF-DISCHARGE

Storing batteries at high temperatures is detrimental to their capacity retention since self-discharge reaction rates increase. Note that the capacity loss per year can be larger than 100%, which means that a battery capacity will be completely lost in less than a year.

Battery chemistry	Rechargeable	Typical self-discharge or shelf life
Lithium metal	No	10 years shelf life
Alkaline	No	5 years shelf life
Zinc–carbon	No	2–3 years shelf life
Lithium–ion	Yes	2–3% per month
Low self-discharge NiMH	Yes	As low as 0.25% per month
Lead–acid	Yes	4–6% per month
Nickel–cadmium	Yes	15–20% per month
Nickel–metal hydride (NiMH)	Yes	30% per month



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CYCLIC LIFE

cyclic life:

It determines how many times a battery will be able to deliver charge–discharge cycles without its capacity dropping below a certain level, typically 80% of the original capacity.

The problem with battery cycle life is that it can only be estimated based on general empirical information and not absolutely determined.

Battery	Calendar	Cycle life
Lead–acid, SLI	3–6 months	200–700
Sealed NiCd (FNC)	5–20 months	500–10,000
Nickel metal hydride	2–5 months	300–600
Nickel iron	8–25 months	2000–4000
Zinc–silver oxide	2 months	50–100
Lithium cobalt oxide	/	300–1000

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CYCLIC LIFE

Why is it hard to determine battery end of life?

1-Experimental determination of the battery cycle life require a very long test time and a large number of batteries would need to be tested to failure.
2-higher C-rates and different load are experienced by the electronic device
3-The interconnectedness of numerous battery design parameters and operational factors such as voltage, current, self-discharge, internal resistance, and temperature
4-batteries employed in actual applications could be operating in very different conditions of temperature and actual depth of discharge

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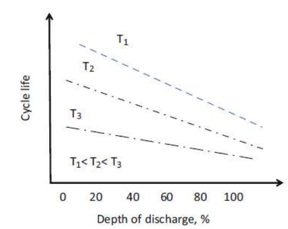
CYCLIC LIFE

How DoD effects battery life?

The greater the depth of discharge, the shorter or lower the cycle life. Battery cycle life depends on the battery chemistry, construction, and **materials used**; and a nominal cycle life will be determined assuming that all active electrode masses are going to be engaged in charge and discharge reactions in every cycle. But, if a battery is not fully discharged on every cycle some of the active masses are not involved in the reaction and this has a positive effect on the battery life.



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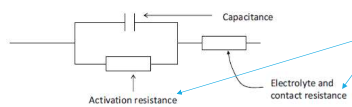
INTERNAL RESISTANCE

The internal battery resistance determines how much current can pass through a cell. The internal resistance is one of the best indicators of battery health. It deteriorates gradually during the life of a battery and it sometimes shows early signs of reactions that contribute to its increase.

Equivalent circuit model:



Primarily exists

Over the lifetime of a battery, additional resistive and capacitive components may develop as a result of processes that produce passive layers or deposits. The appearance of those additional battery interfaces usually increases the internal resistance, reduces the rate of electrochemical reaction, increases resistance and ohmic losses, and slows down diffusion of species to electrode active sites.

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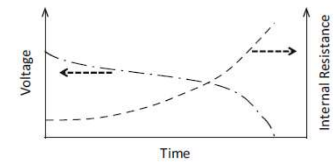
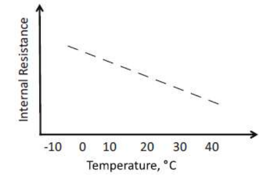
INTERNAL RESISTANCE

During discharge of a battery, the internal resistance increases. This is mainly because of the changes in the electrolyte as in lead–acid batteries or as a result of formation of passivating layers through which the reactants have to diffuse.

As temperature increases, the internal resistance decreases. It is also obvious that ionic electrolyte conductivity increases with temperature increase due to higher ionic mobility.





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SIDE REACTIONS

Side Reaction:

Side reactions are unwanted chemical processes that occur within a battery, competing with the primary charge-discharge reactions. These reactions can significantly impact a battery's performance, lifespan, and safety.

Common side reaction:

Electrolyte Decomposition: Electrolyte molecules can break down, forming gases (like hydrogen or oxygen) or solid-electrolyte interface (SEI) layers on the electrode surface.

Electrode Material Degradation: The active materials in the electrodes can undergo chemical changes, leading to capacity loss and power fade.

Dendrite Formation: In certain battery chemistries, metallic dendrites can grow on the electrode surface, causing short circuits and safety hazards.

Gas Evolution: The production of gases within the battery can cause swelling, pressure build-up, and potential explosions.

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MEMORY EFFECT

If a NiCd or NiMH battery was repeatedly charged after only partial discharge, it would "remember" this pattern. Over time, the battery would become less capable of holding a full charge, as if it had "learned" to stop charging at a lower capacity.

This effect was linked to the formation of certain crystalline structures within the battery during the charging process. These structures could interfere with the battery's ability to fully charge.

Modern lithium-ion batteries do not suffer from memory effect. This is one of the many advantages of lithium-ion technology.

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