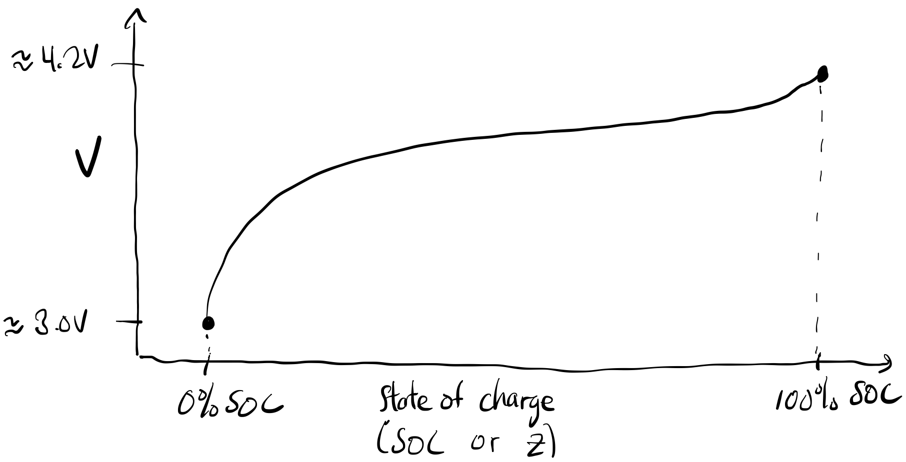
Battery Performance Metrics

Oct 12, 2021

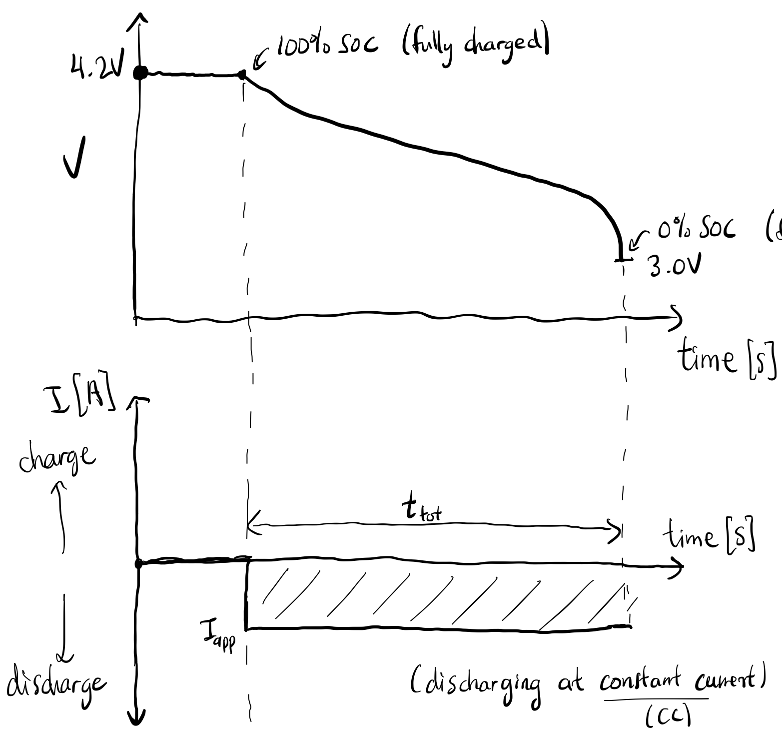
Start with the open-circuit voltage (OCV) curve: (a.k.a open circuit potential (OCP) or V_{OC})



→ Voltage limits depend on chemistry and are set by the manufacturer.

→ OCV = $f(z)$ is usually measured; it is a characteristic curve of a battery.

⇒ Consider a fully charged cell. Start discharging it using a constant current:



- I_{app} : Applied current [A]
- Q : Capacity [Ah] (Amp-hours)
- $Q = \int I_{app}(\tau)\, d\tau$
- $Q = I_{app} \cdot t_{total}$ (for constant current operation)

When dealing with batteries, we speak alot about capacity and energy, so let's get familiar with these units:

Capacity

- Capacity is usually measured in [Ah]
- Other common metrics include gravimetric capacity [Ah/g]
  volumetric capacity [Ah/L]
- $1\,[A] = \dfrac{1\,[\text{Coulomb}]}{1\,[\text{second}]} \Rightarrow 1\,[Ah] = 1\,\dfrac{[\text{coulomb}]\,[\cancel{\text{hour}}]}{[\cancel{\text{second}}]} \times \dfrac{3600\,[\cancel{\text{seconds}}]}{[\cancel{\text{hours}}]}$

$$\Rightarrow 1\,[Ah] = 3600\,[\text{coulombs}].$$

Energy

- Energy is obtained by considering $E = \int P(\tau)\,d\tau$

energy [Wh]   power [W]

- $P = I^{*}V \Rightarrow E = \int I(\tau)\,V(\tau)\,d\tau$

For constant current operation, $E = I_{app} \times \int V(\tau)\,d\tau \times \dfrac{t_{tot}}{t_{tot}}$

$$E = I_{app} \times t_{tot} \times V_{avg}$$

[A]   [h]   [V]

$1\,[W] = 1\,\dfrac{[\text{Joule}]}{[\text{second}]} \Rightarrow 1\,[Wh] = 1\,\dfrac{[J]\,[\cancel{h}]}{[\cancel{s}]} \times \dfrac{3600\,[\cancel{s}]}{[\cancel{h}]}$

$$1\,[Wh] = 3600\,[J].$$

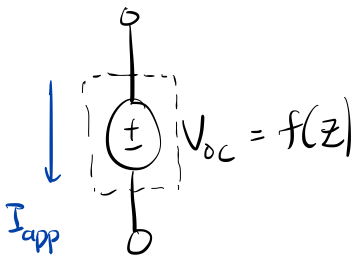
- Gravimetric energy $\Rightarrow$ [Wh/kg]
- Volumetric energy $\Rightarrow$ [Wh/L]

"C-rate": a convenient way to talk about current.

$1C\,[h^{-1}] \triangleq \dfrac{\text{Current } [A]}{\text{Capacity } [Ah]}$

Eg. for a 5Ah cell: $1C = 5A$
$2C = 10A$
$0.5C = 2.5A$

So far, our battery model looks like this:



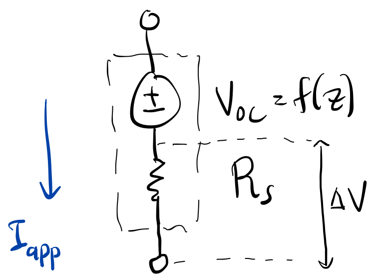
V_{OC}: open circuit voltage

z : state of charge. $z \in [0,1]$

I_{app} : Applied current.

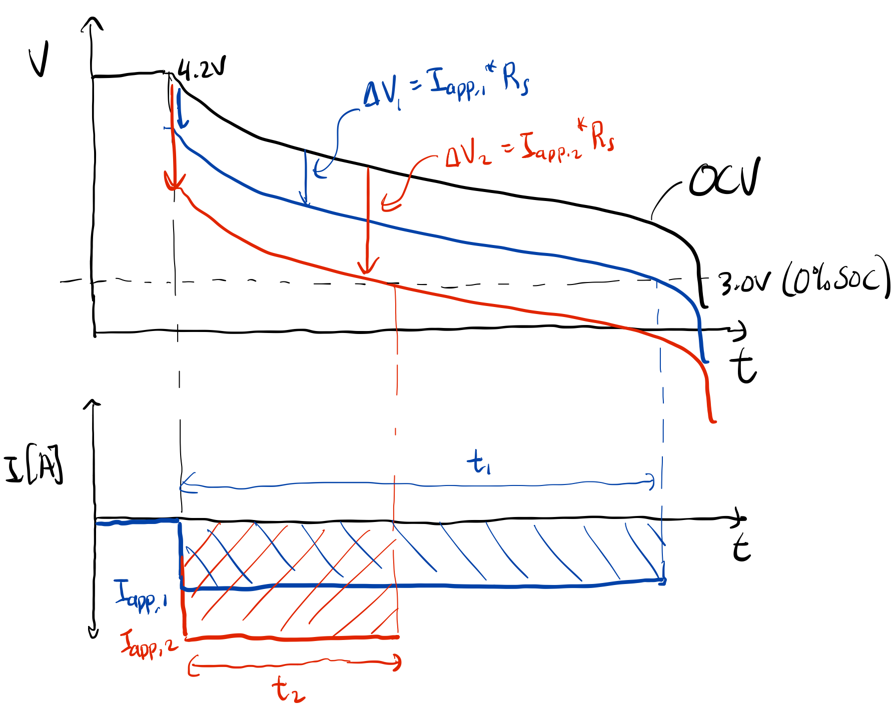
Here, a battery is simply a <u>voltage source</u>.

Let's add <u>another</u> element to make the model more realistic.



R_s: a series resistance: represents the internal resistance of the battery.

ΔV : an additional <u>voltage drop</u> due to R_s. ΔV will cause the cell to finish discharging more quickly.

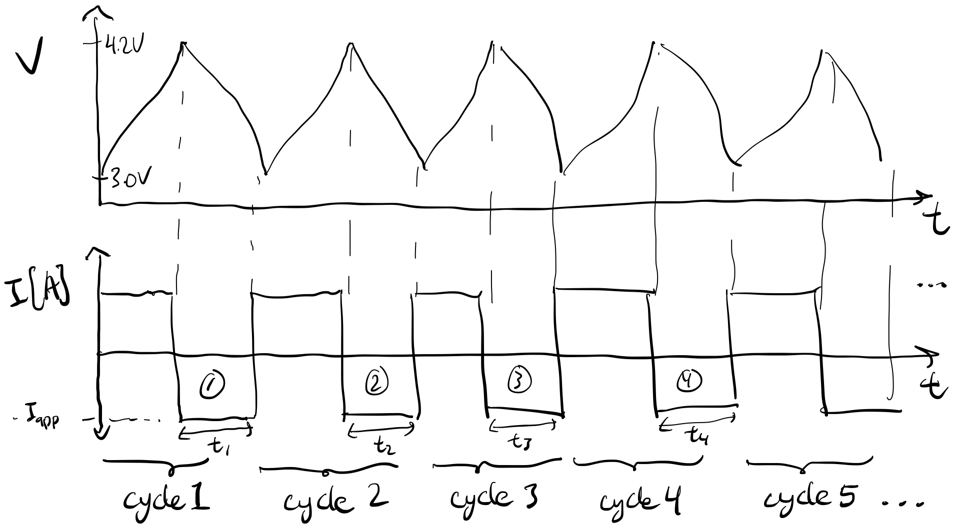


$Q_1 = I_{app,1} * t_1$

$Q_2 = I_{app,2} * t_2$

Cycle Life Characterization

1 cycle ≙ 1 charge and 1 discharge

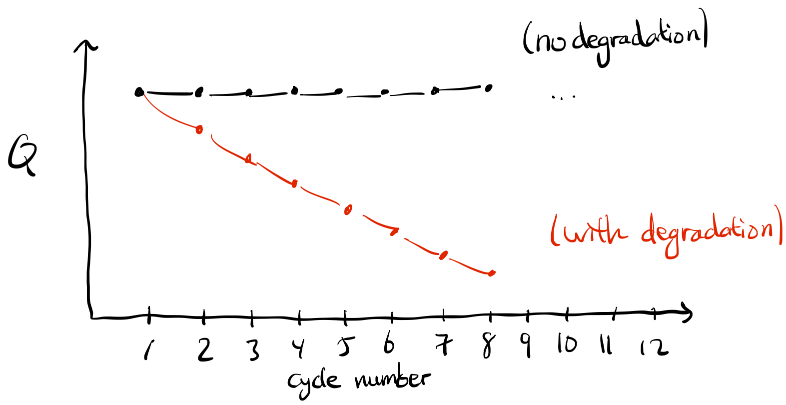


①: $Q_1 = |I_{app}| * t_1$

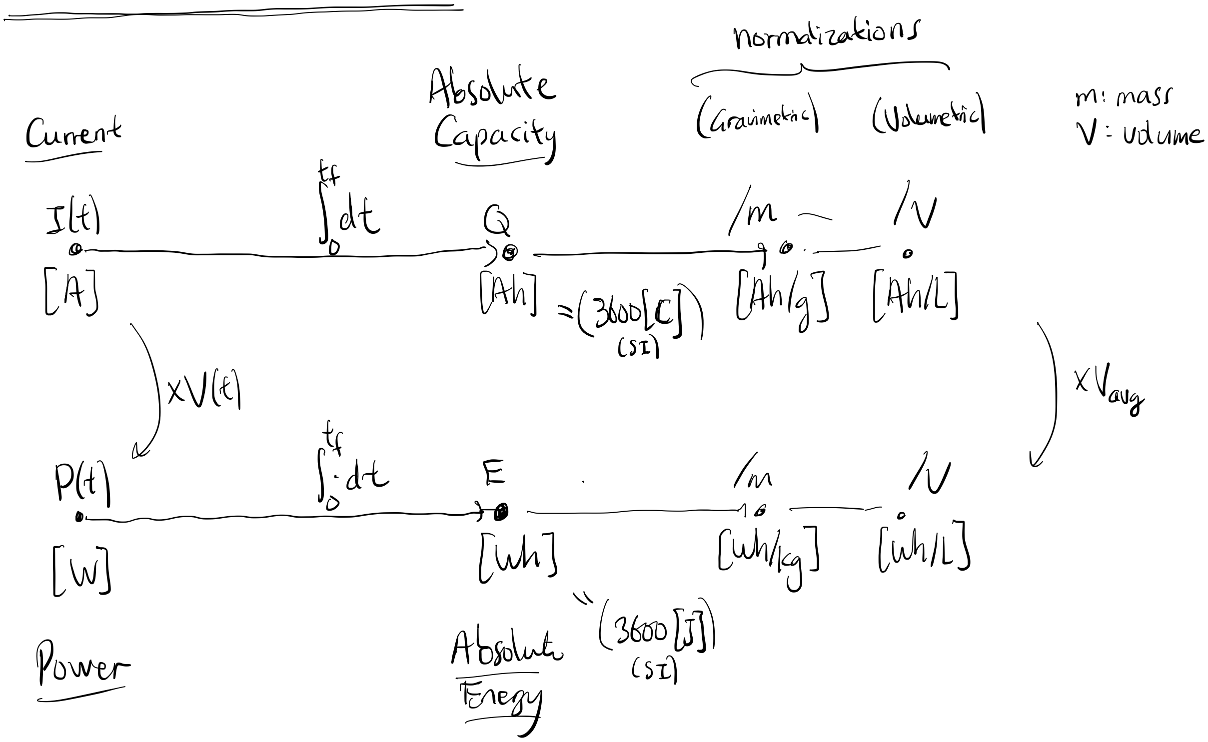
②: $Q_2 = |I_{app}| * t_2$

⋮

↳ plot the Q's against cycle number



"Units" Cheat Sheet



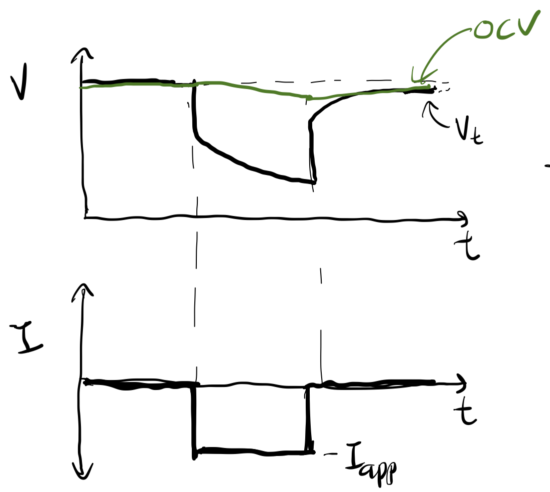
- State of charge : $z = \frac{1}{\underset{[Ah]}{3600\,Q}} \int_0^{t_f} I(\tau)\, d\tau \xrightarrow{\text{constant current}} \frac{\overset{[A]}{I} \cdot \overset{[s]}{t_f}}{3600 \cdot \underset{[Ah]}{Q}}$

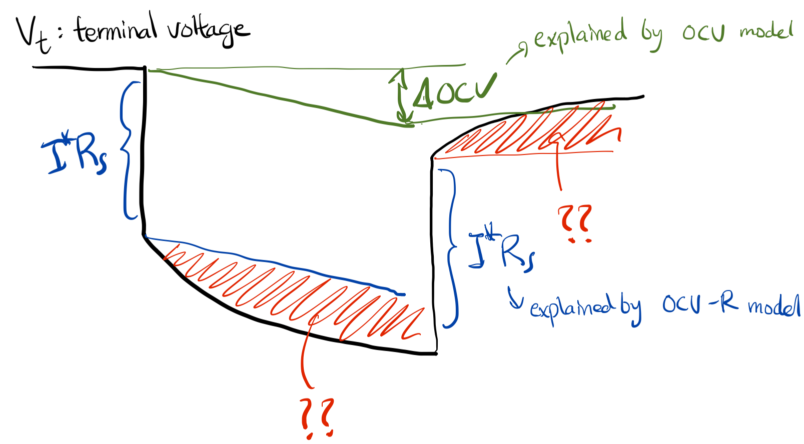
- C-rate : $[h^{-1}] = \frac{I}{Q}$ (for constant-current (CC) operation)

- E-rate : $[h^{-1}] = \frac{P}{E}$ (for constant-power (CP) operation)

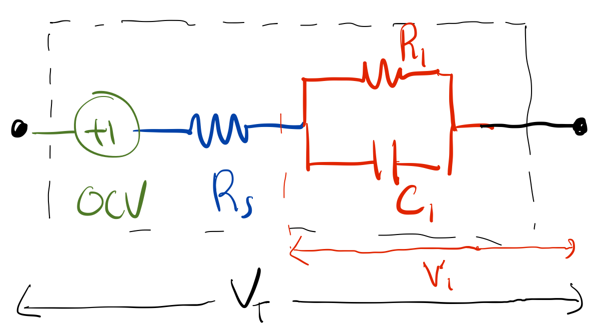
(Preview)

Let's look at the battery voltage response slightly more carefully.





OCV-R-RC model



To be continued...