14-Battery Voltage and Current Characteristics

Off-Grid Electrical Systems in Developing Countries

Chapter 8.5

Learning Outcomes

At the end of this lecture, you will be able to:

✓define the nominal voltage of a battery

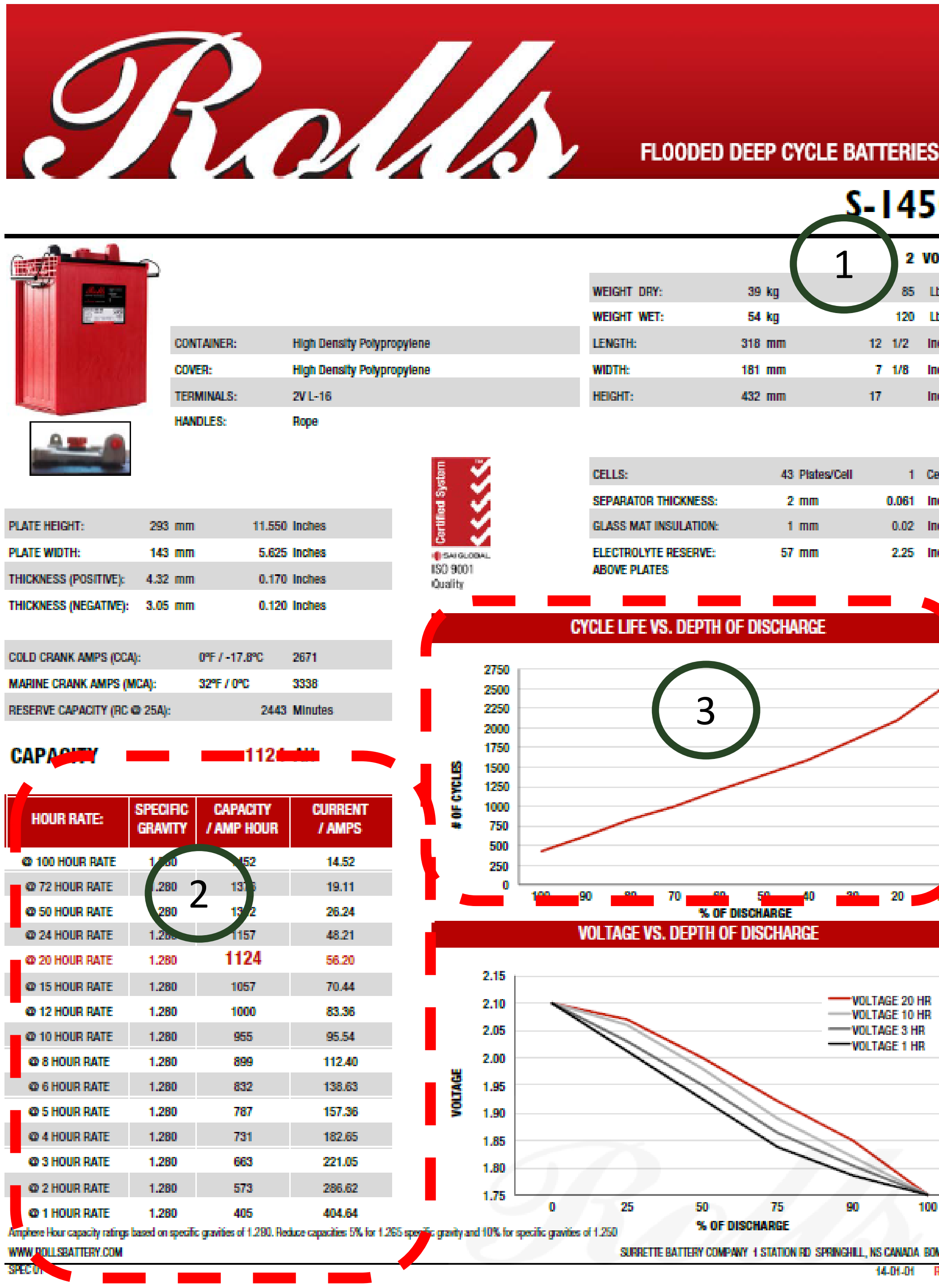
✓describe the I-V curve of a battery and explain why it is non-linear

✓develop and apply a circuit model for a battery

Battery Specification Sheets

- Provide technical information on battery characteristics and performance
- Not always easy to interpret
- Most important characteristics
  1. Nominal Voltage
  2. Capacity
  3. Cycle life

We will discuss these in a later lecture


Rolls FLOODED DEEP CYCLE BATTERIES

S-145

1

2 VO

CONTAINER:	High Density Polypropylene	
COVER:	High Density Polypropylene	
TERMINALS:	2V L-16	
HANDLES:	Rope	

WEIGHT DRY:	39 kg	85 Lb
WEIGHT WET:	54 kg	120 Lb
LENGTH:	318 mm	12 1/2 In
WIDTH:	181 mm	7 1/8 In
HEIGHT:	432 mm	17 In

Certified System, SAI GLOBAL ISO 9001 Quality

CELLS:	43 Plates/Cell	1 Ce
SEPARATOR THICKNESS:	2 mm	0.061 In
GLASS MAT INSULATION:	1 mm	0.02 In
ELECTROLYTE RESERVE: ABOVE PLATES	57 mm	2.25 In

PLATE HEIGHT:	293 mm	11.550 Inches
PLATE WIDTH:	143 mm	5.625 Inches
THICKNESS (POSITIVE):	4.32 mm	0.170 Inches
THICKNESS (NEGATIVE):	3.05 mm	0.120 Inches

COLD CRANK AMPS (CCA):	0°F / -17.8°C	2671
MARINE CRANK AMPS (MCA):	32°F / 0°C	3338
RESERVE CAPACITY (RC @ 25A):		2443 Minutes

CAPACITY 1124 AH

2

HOUR RATE:	SPECIFIC GRAVITY	CAPACITY / AMP HOUR	CURRENT / AMPS
@ 100 HOUR RATE	[illegible]	[illegible]	14.52
@ 72 HOUR RATE	1.280	[illegible]	19.11
@ 50 HOUR RATE	[illegible]	[illegible]	26.24
@ 24 HOUR RATE	[illegible]	1157	48.21
@ 20 HOUR RATE	1.280	1124	56.20
@ 15 HOUR RATE	1.280	1057	70.44
@ 12 HOUR RATE	1.280	1000	83.36
@ 10 HOUR RATE	1.280	955	95.54
@ 8 HOUR RATE	1.280	899	112.40
@ 6 HOUR RATE	1.280	832	138.63
@ 5 HOUR RATE	1.280	787	157.36
@ 4 HOUR RATE	1.280	731	182.65
@ 3 HOUR RATE	1.280	663	221.05
@ 2 HOUR RATE	1.280	573	286.62
@ 1 HOUR RATE	1.280	405	404.64

Ampere Hour capacity ratings based on specific gravities of 1.280. Reduce capacities 5% for 1.265 specific gravity and 10% for specific gravities of 1.250

CYCLE LIFE VS. DEPTH OF DISCHARGE

3

OF CYCLES

% OF DISCHARGE

VOLTAGE VS. DEPTH OF DISCHARGE

VOLTAGE 20 HR
VOLTAGE 10 HR
VOLTAGE 3 HR
VOLTAGE 1 HR

VOLTAGE

% OF DISCHARGE

WWW.ROLLSBATTERY.COM

SURRETTE BATTERY COMPANY 1 STATION RD SPRINGHILL, NS CANADA

SPEC 01

14-01-01

Nominal Voltage

- Nominal voltage: approximately equal to the average battery voltage during a charge and discharge cycle
  - Not: open-circuit voltage when fully charged or discharged
- Lead-acid batteries typically have nominal voltages of 2V, 6V, 12V or 24V
- Nominal voltage of a lithium-ion cell typically between 3.2V and 3.8V (depending on the chemistry used)
- Open-circuit voltage for a fully-charged lead-acid cell is approximately 2.10 V

Nominal Voltage

A lead-acid battery with 24V nominal voltage (12 cells in series) will have a fully-charged open-circuit voltage of approximately 12 x 2.11 = 25.32V

Open-circuit cell voltage	Approximate state-of-charge (%)										
	0	10	20	30	40	50	60	70	80	90	100
Flooded (V/cell) (V/cell)	1.90	1.92	1.94	1.96	1.99	2.01	2.03	2.05	2.07	2.09	2.11
AGM (V/cell)	1.94	1.96	1.98	2.00	2.02	2.04	2.06	2.08	2.10	2.12	2.14

Open-Circuit Voltage

- Open-circuit voltage refers to the voltage between the positive and negative terminals of a cell, battery, or battery bank
- Remember that batteries exhibit non-linear, temperature-dependent behavior, and have long time constants (before steady-state is reached)

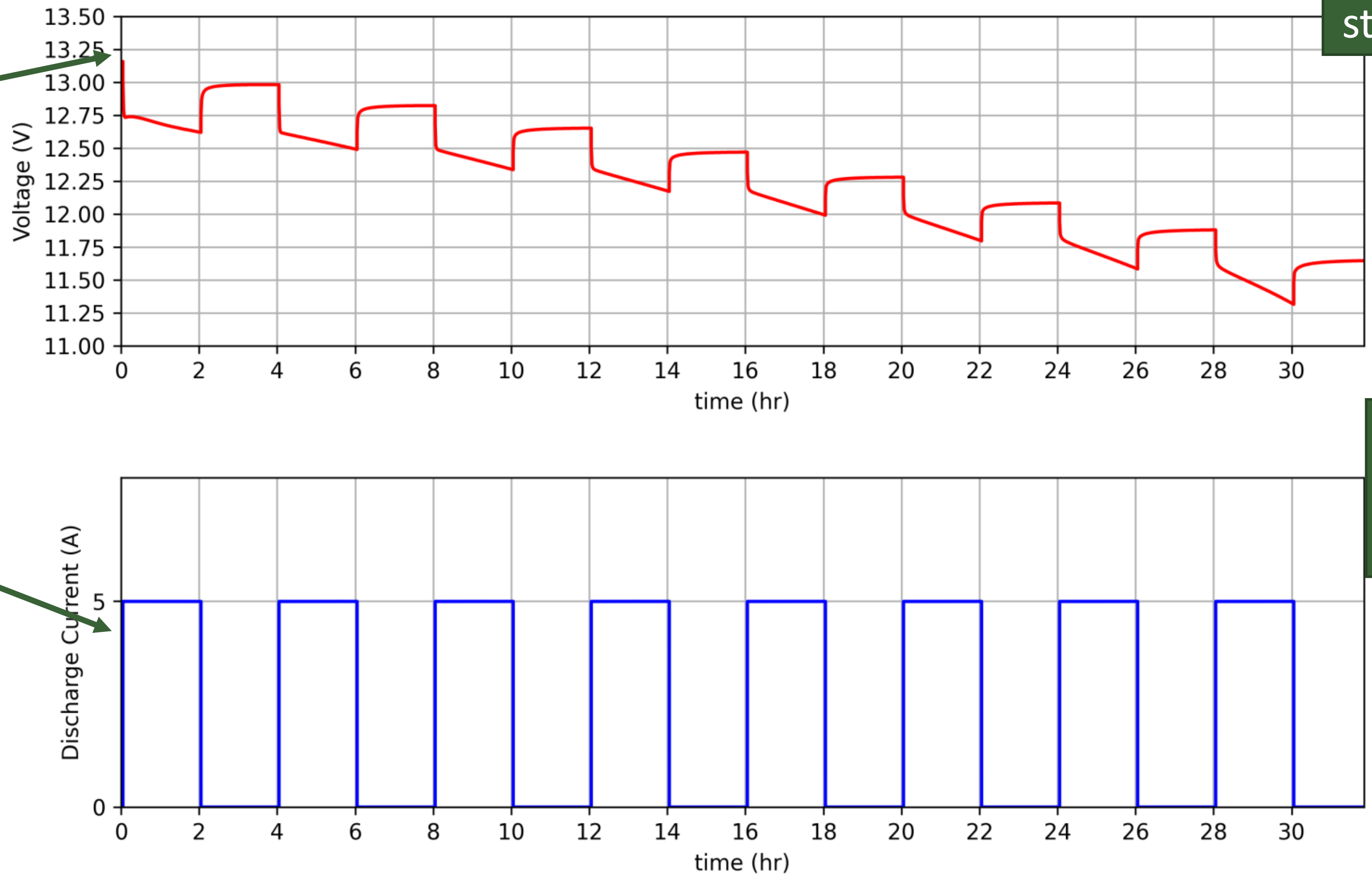
Open-Circuit Voltage

- Open-circuit voltage can only reliably be used to estimate state-of-charge if the battery has been open-circuited, not hot or cold, and given enough time to "rest"
  - Resting allows the chemicals within the battery to mix/re-distribute, avoiding localized concentrations which affect voltage
  - Resting time required can be several minutes to several hours

Open-Circuit Voltage

Battery Open-circuit voltage decreases with state of charge

Open-circuit voltage at 100% state of charge is 13.15 V (2.19 V/cell)



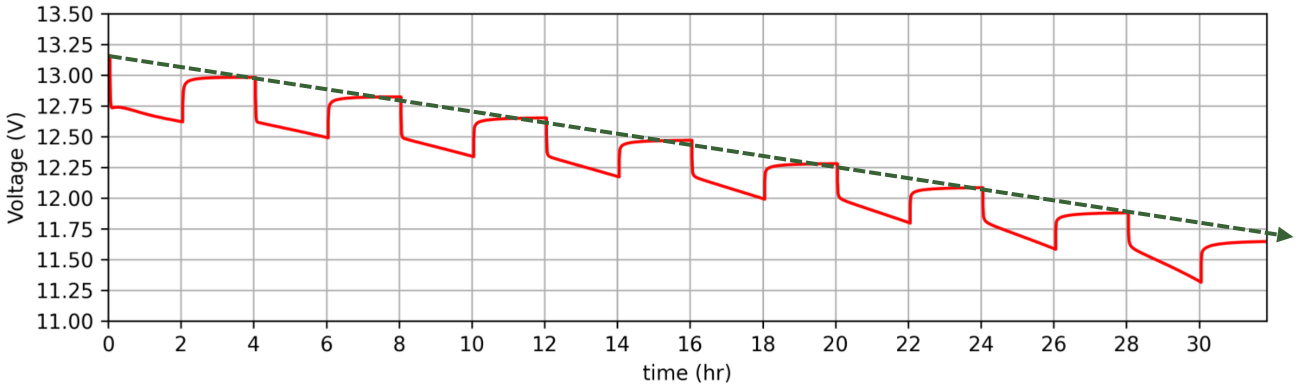
Battery rests for 2 hours between pulses

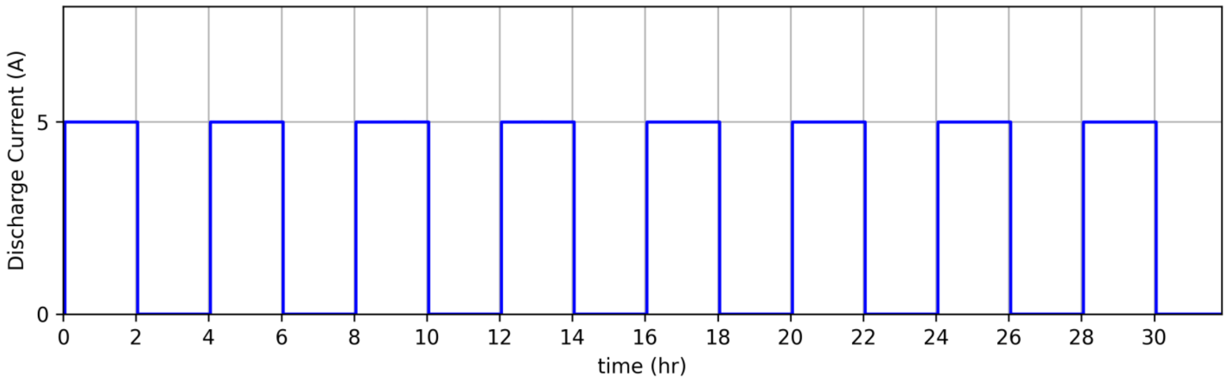
Each pulse reduces state of charge by 10%

(12V, 100 Ah, AGM Battery)

Open-Circuit Voltage

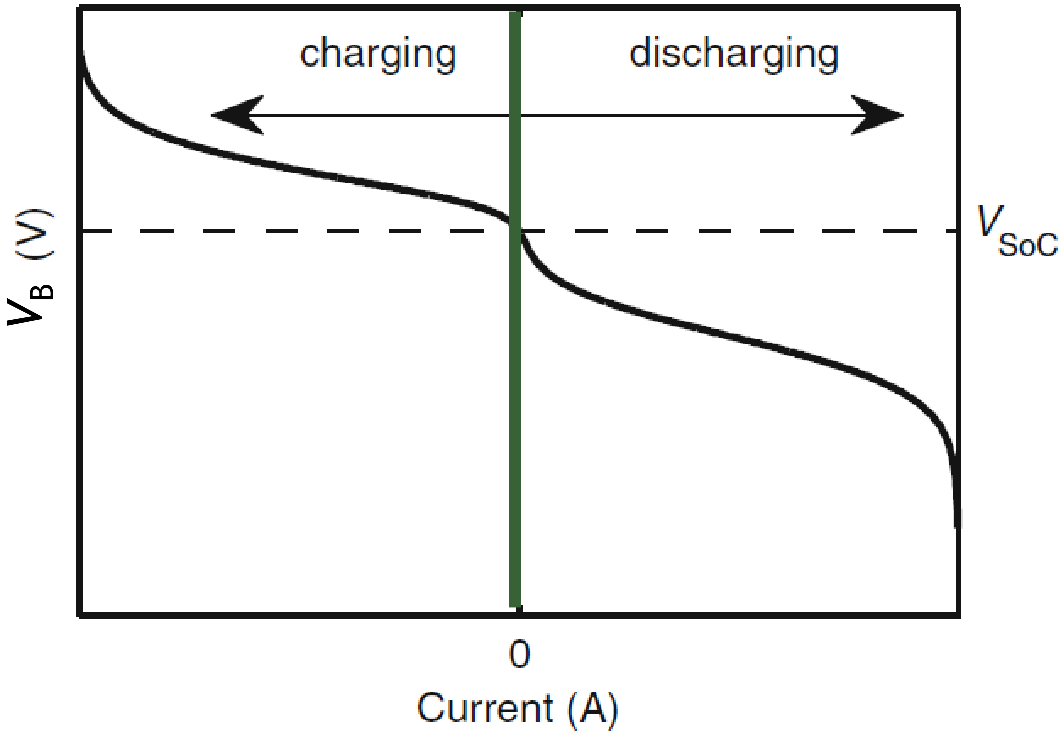
State of Charge	20%	30%	40%	50%	60%	70%	80%	90%	100%
Voltage (V/cell)	1.94	1.98	2.01	2.05	2.08	2.11	2.14	2.16	2.19





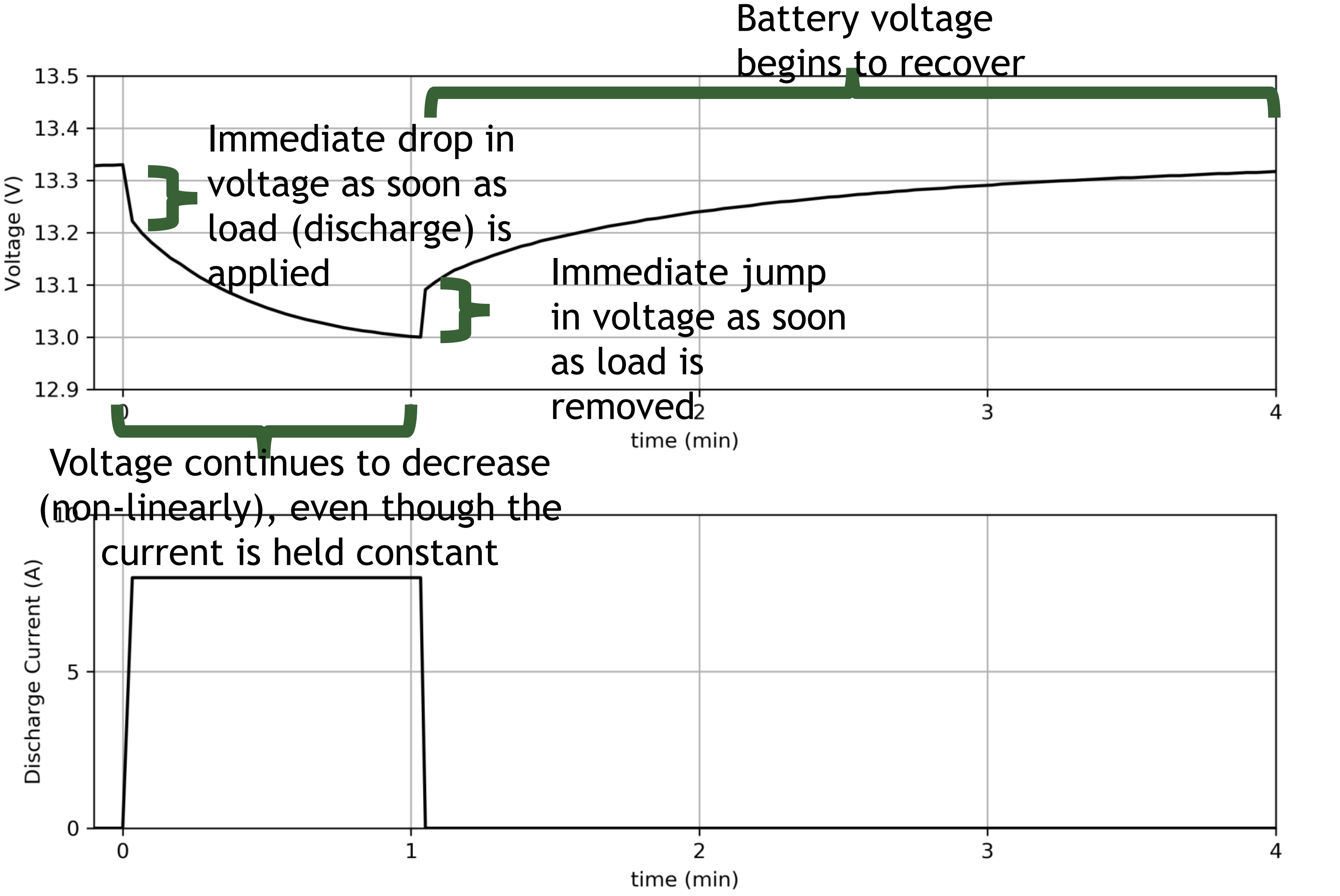
I-V Characteristic

- I-V characteristic shows how the *terminal* voltage (V_B) of the battery (cell) varies with charge/discharge current
- Note:
  - plot assumes the state-of-charge is constant at each point along the curve
  - non-linear dependence of terminal voltage with current
  - Asymmetry

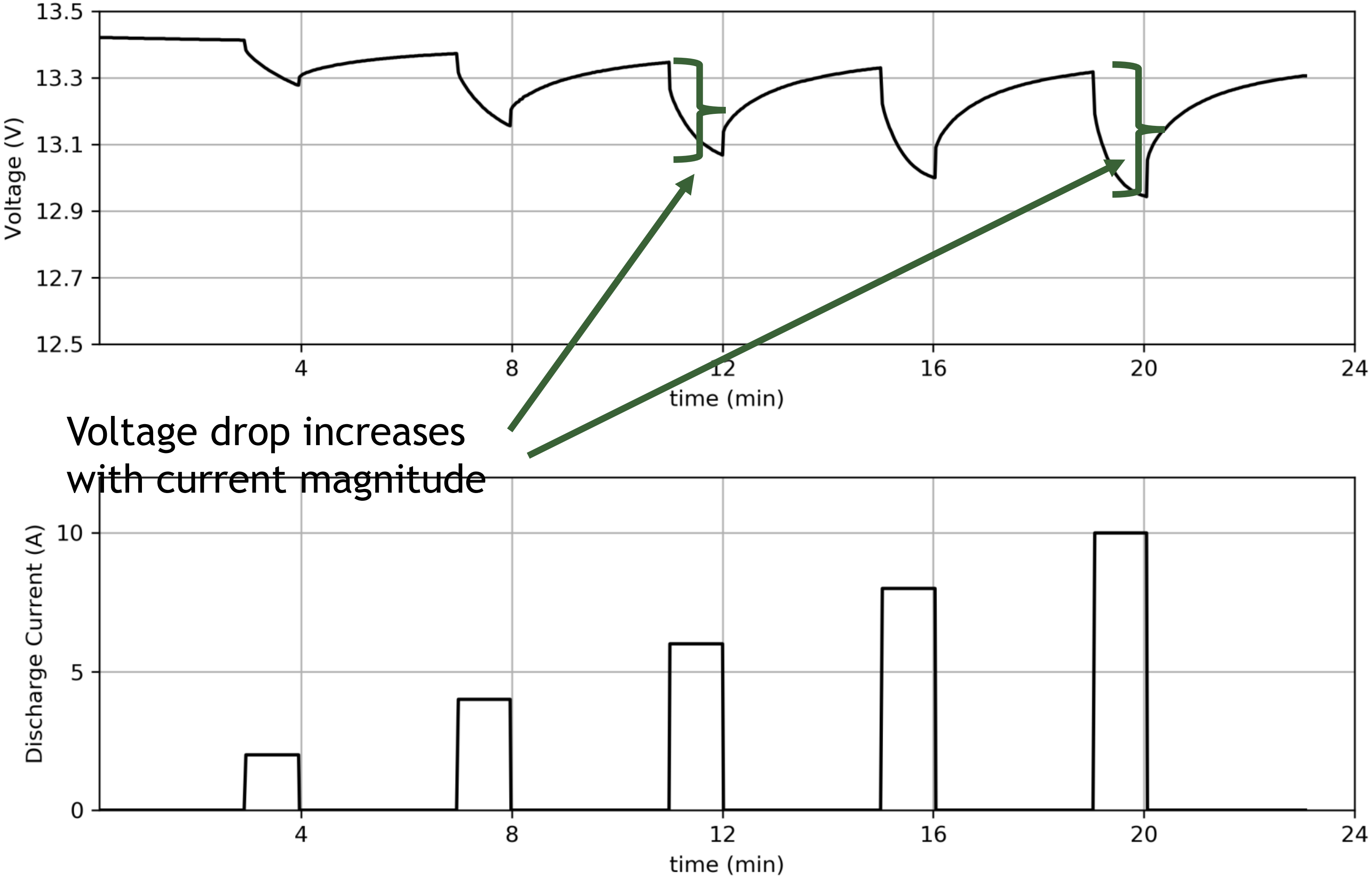


V_{SoC}: open-circuit voltage (State-of-Charge)

Don’t confuse the x-axis with time



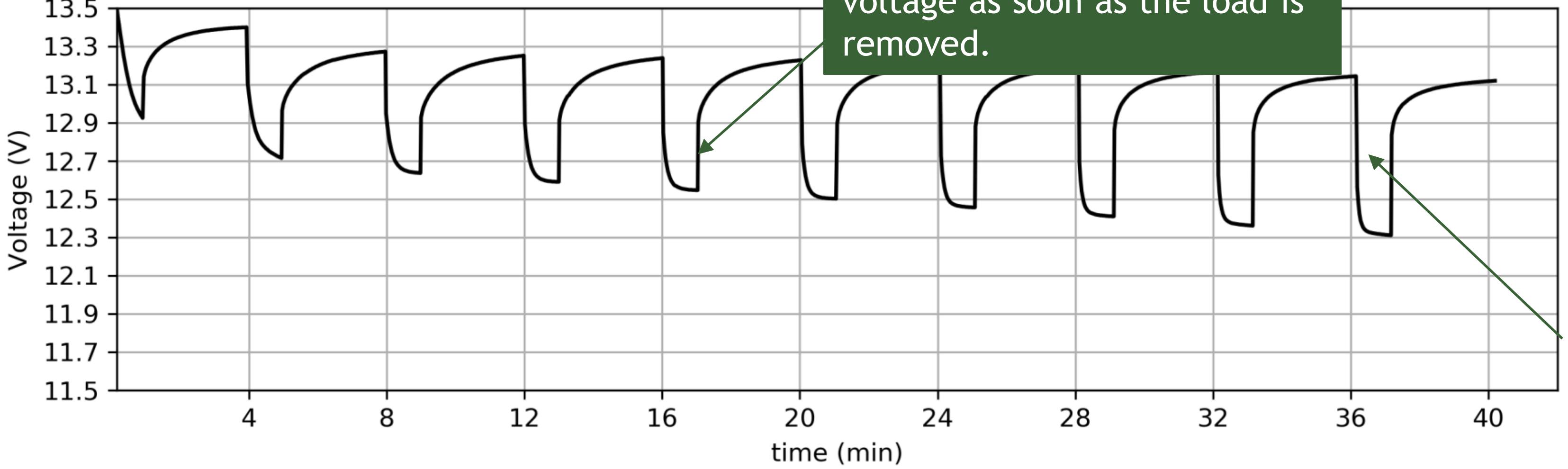
Battery voltage before and after a load of 8A is drawn from the battery (12V, 100 Ah, AGM Battery)



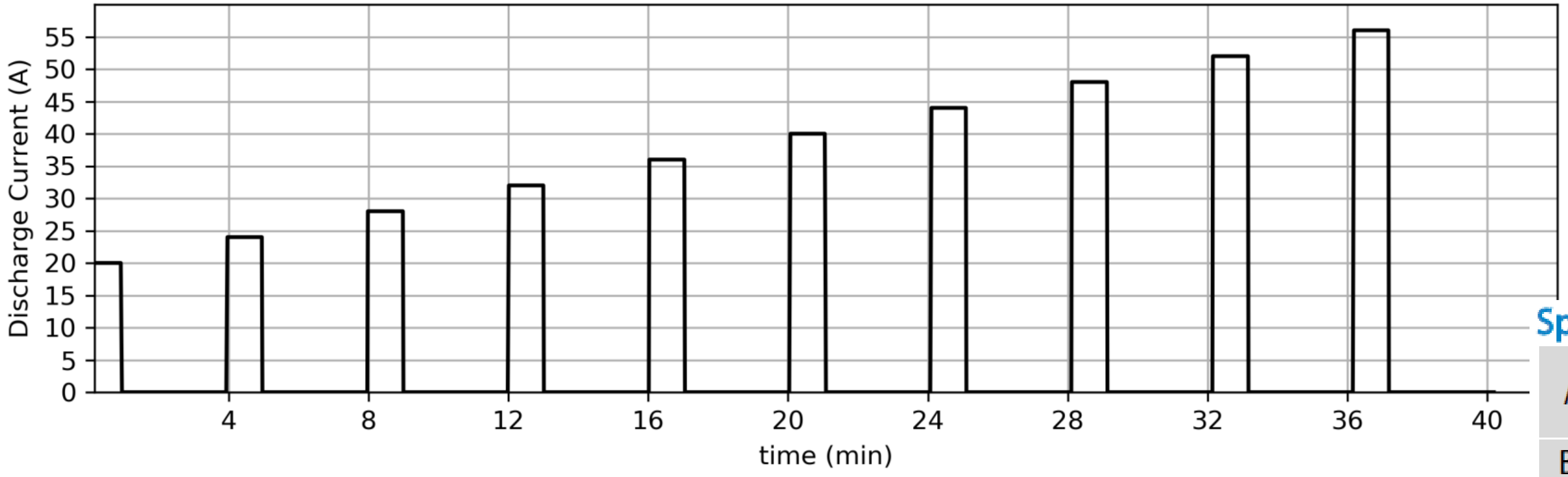
Battery voltage as succession of larger discharge current with 1 minute rest in between is applied
(12V, 100 Ah, AGM Battery ~75% SoC)

Discharge cycling of battery.
Pulses of load current increasing from 20A to 56 A for 1 min., with approx. 3 min. rest in between.

Notice the large rebound in voltage as soon as the load is removed.



Magnitude of voltage drop and rebound increase with load current

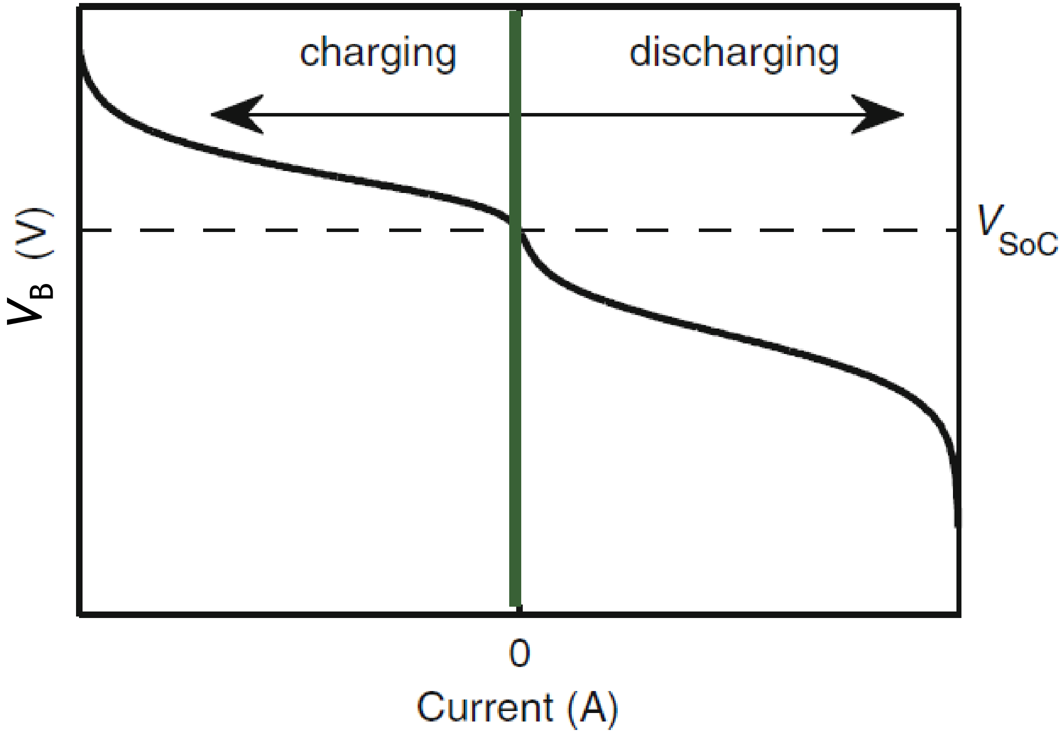


Specifications

Article number	V	Ah C5 (10,8V)	Ah C10 (10,8V)	Ah C20 (10,8V)
BAT412110081	12	82	90	100

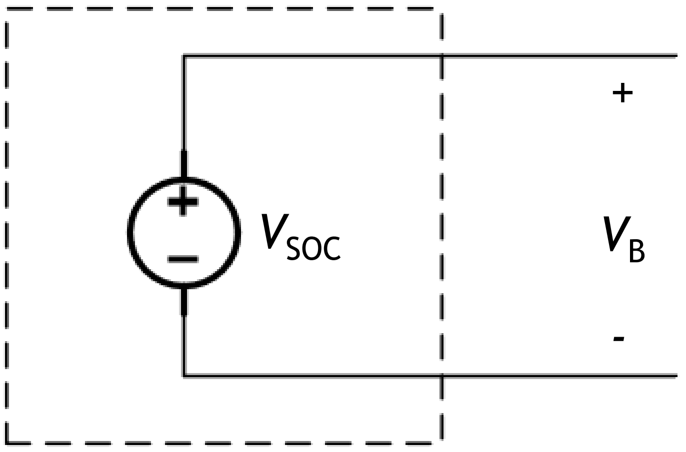
I-V Characteristic

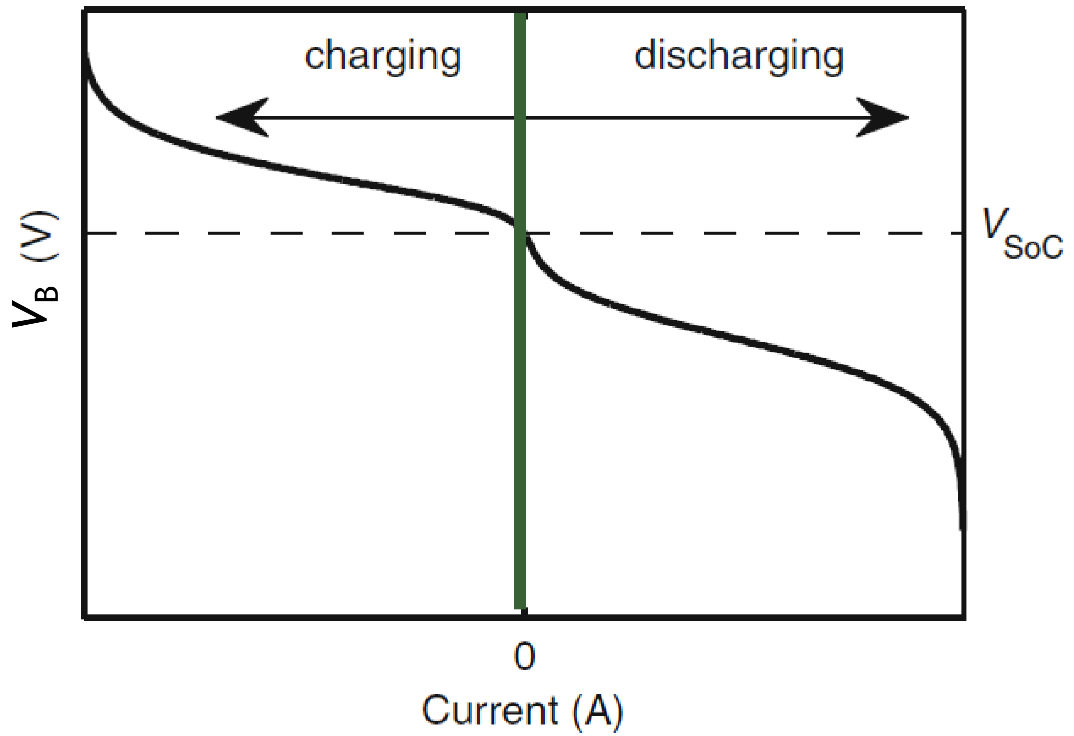
- Important:
  - Charging: terminal voltage is increased from open-circuit
  - Discharging: terminal voltage is decreased from open-circuit voltage



How can we explain the I-V curve?

What about this model?





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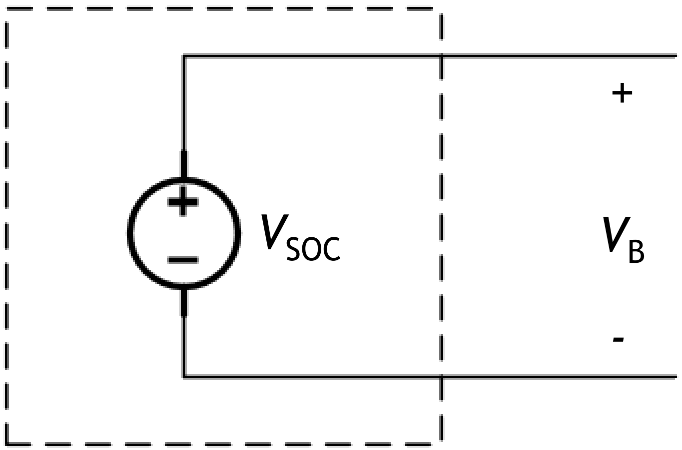
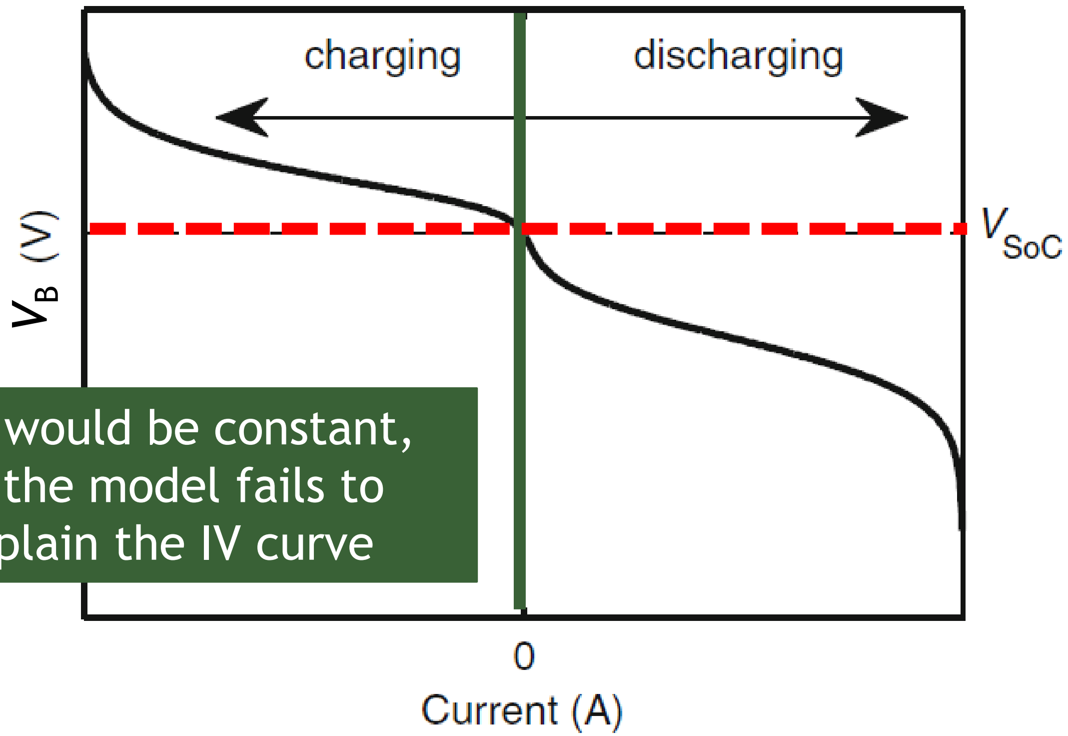


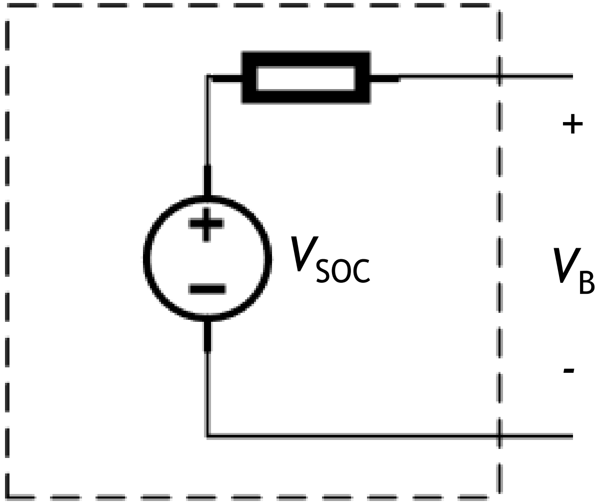


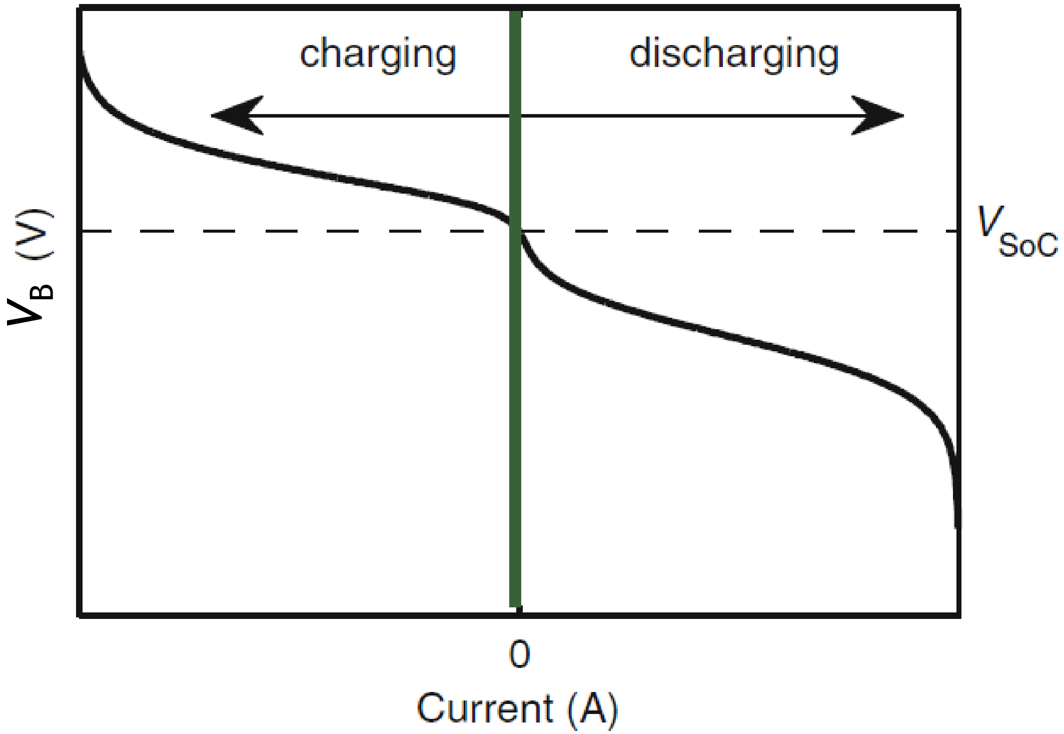
V_B would be constant, so the model fails to explain the IV curve

How can we explain the I-V curve?

What about this model?

Sketch the I-V curve.

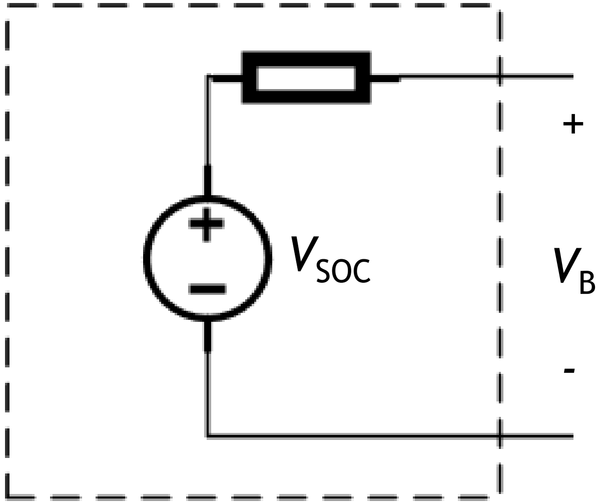


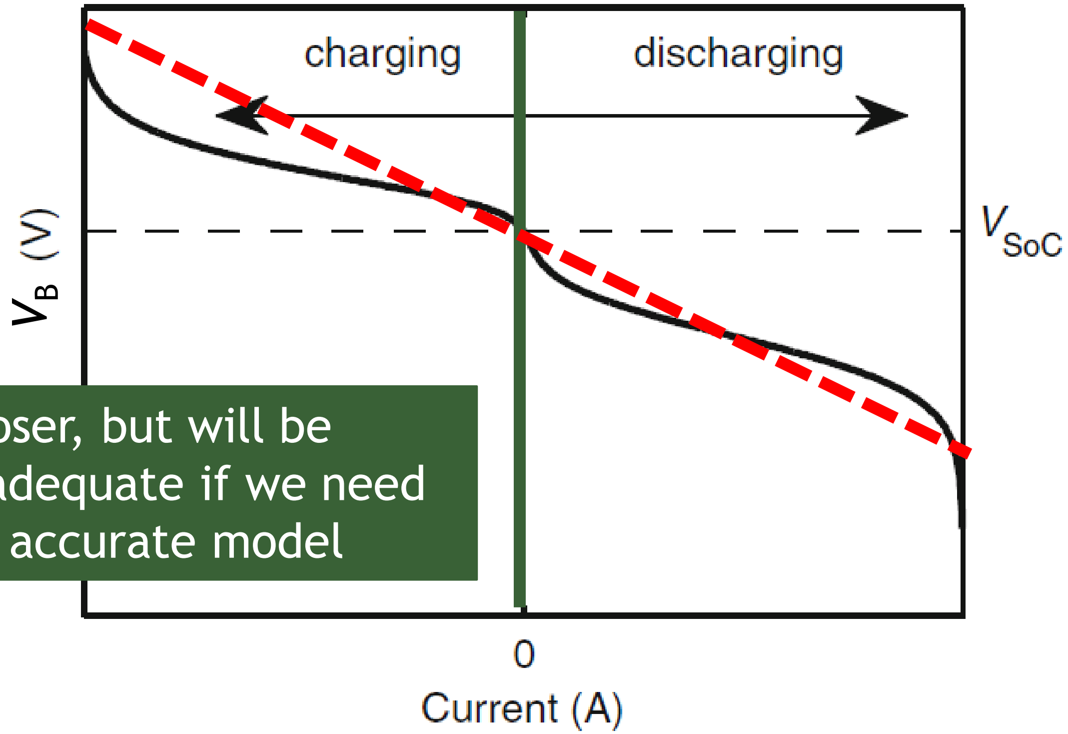


How can we explain the I-V curve?

What about this model?

Sketch the I-V curve.



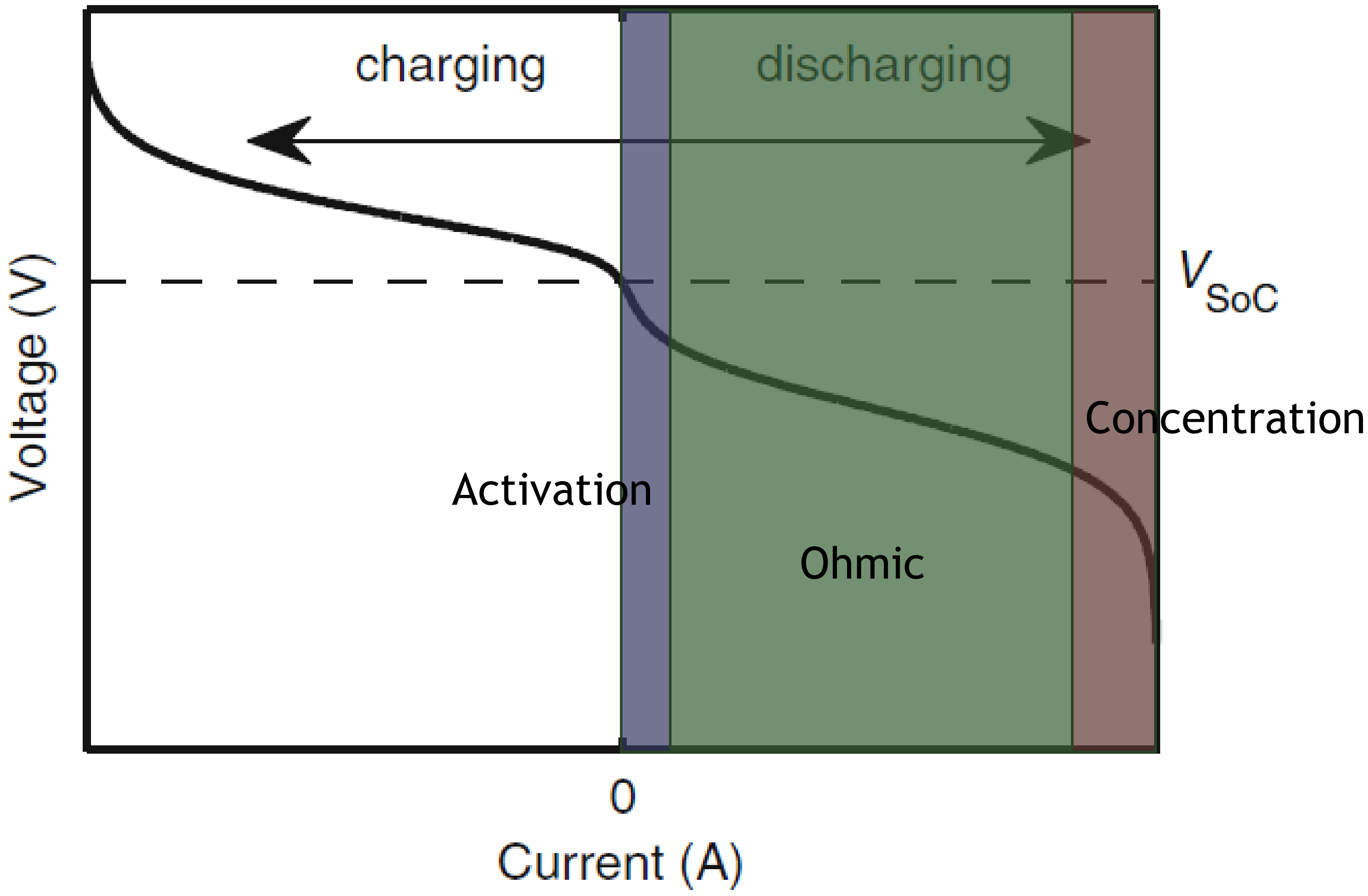


Closer, but will be inadequate if we need an accurate model

Polarization

- Non-linearity of I-V curve can be attributed to three mechanisms (*polarizations*)
- *Ohmic*: voltage drop caused by the battery current passing through the electrode resistance and electrolyte resistance (difficulty of ions moving through electrolyte)
- *Activation*: related to the kinetics of the reactions, for there to be current the equilibrium balance of chemical and electrostatic potential must be upset (decreased voltage when discharging, increased when charging)
- *Concentration*: at higher current, localized depletion or accumulation of ions can occur, which, per the Nernst equation will affect the cell voltage

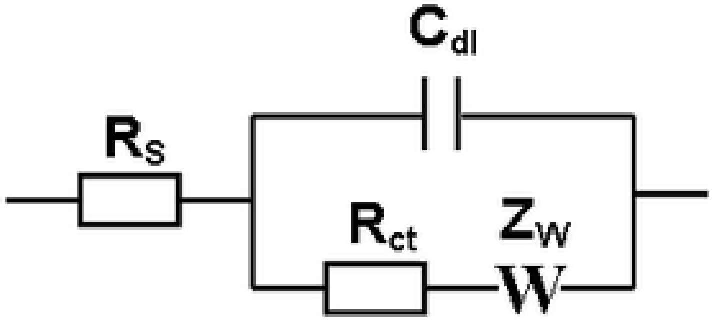
Polarizations

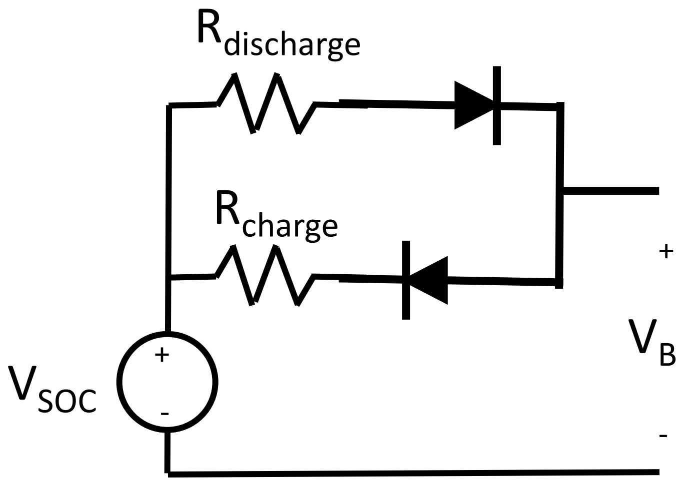


Only discharging shown, but analogous effects are present when charging

Cell Circuit Model

- Several circuit models of battery cells have been proposed and used
- Selection depends on what characteristics are of interest (e.g. steady-state, dynamics, etc.)



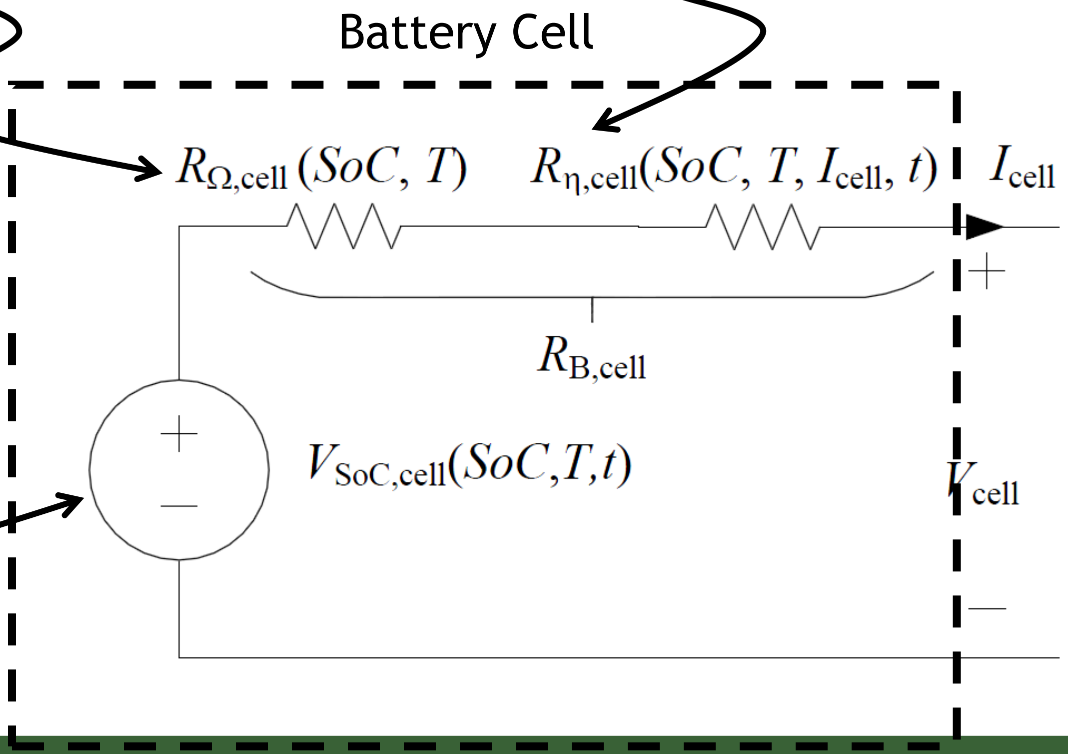


Circuit Model of a Battery Cell

Ohmic polarization, dependent on: state-of-charge, temperature

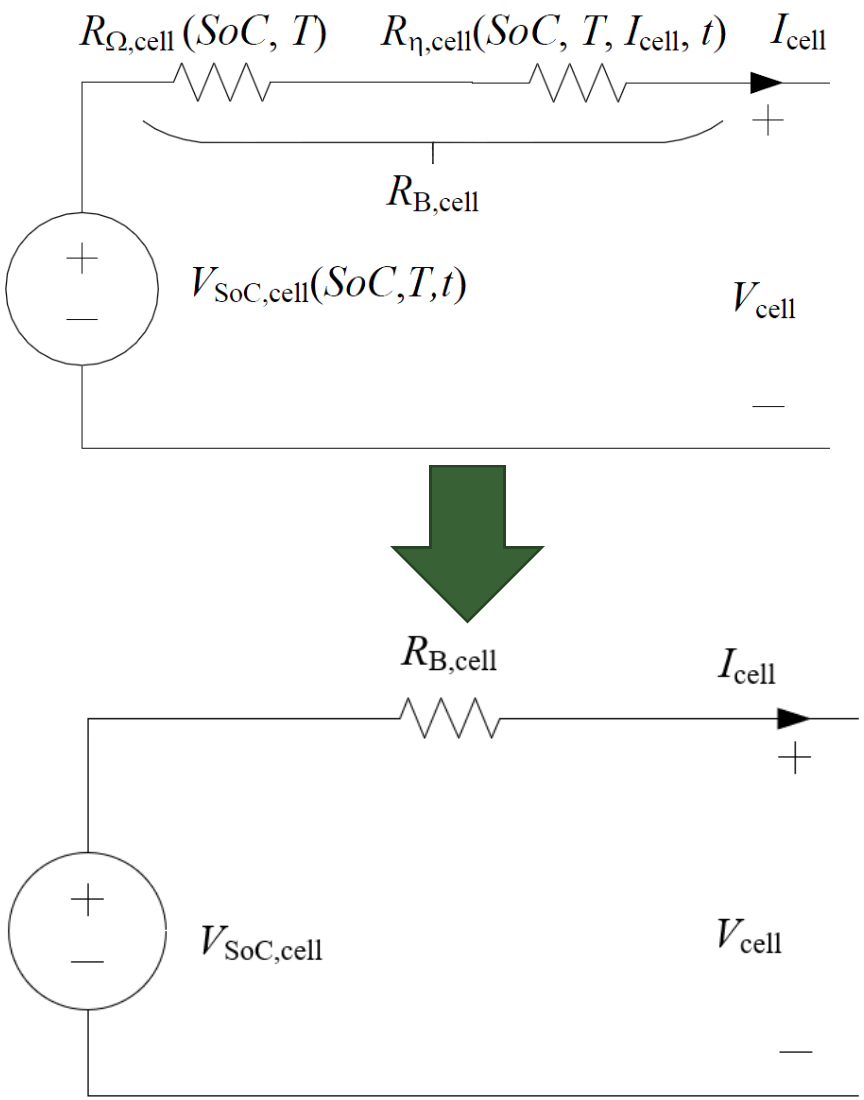
Activation and concentration polarization dependent on: state-of-charge, temperature, current magnitude and polarity, time (since charged/discharged)

State-of-charge voltage, dependent on: state-of-charge, temperature, time (since discharged/charged)



Cell Circuit Model

- Combine the resistances into a single quantity $R_{B,cell}$ which we will call the "battery resistance"
- Keep in mind:
  - $R_{B,cell}$ models the Ohmic, activation and concentration polarizations
  - $R_{B,cell}$ depends on many factors, and so there is no single $R_{B,cell}$ for a battery, rather we assume that $R_{B,cell}$ refers to the resistance at the present state of the battery
  - $R_{B,cell}$ is not the "internal resistance" sometimes reported on spec sheets, the reported value is usually the Ohmic resistance only

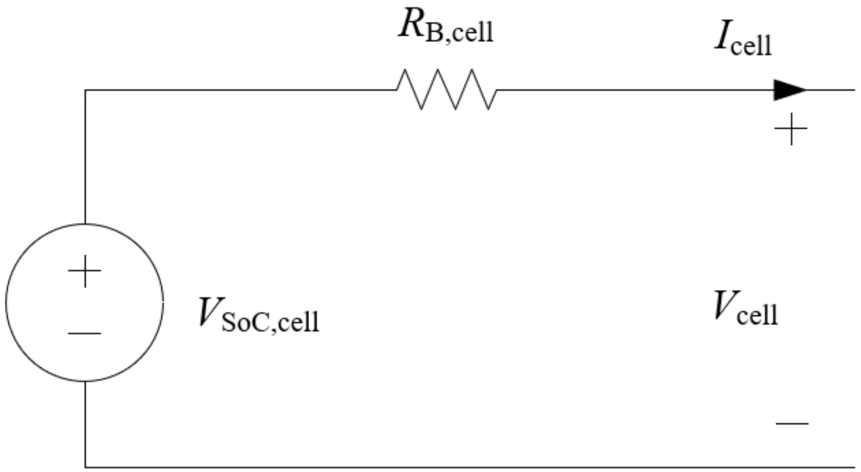


Cell Circuit Model

- Analysis via KVL:

$$V_{\text{cell}} = V_{\text{SoC,cell}} - I_{\text{cell}} R_{\text{B,cell}}$$

- Voltage drop associated with $R_{\text{B,cell}}$ causes the terminal voltage to greater than $V_{\text{SoC,cell}}$ when charging, and lower than $V_{\text{SoC,cell}}$ when discharging



Battery Circuit Model

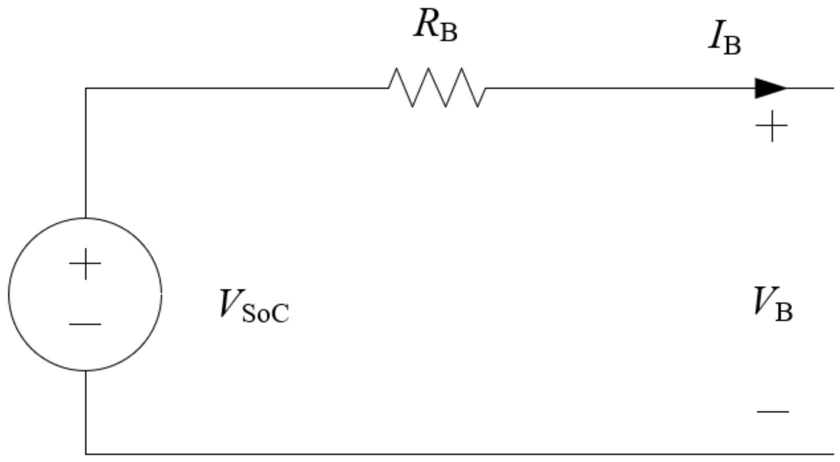
Extension of model to a battery with two or more series connected cells is straightforward

$$R_B = N_{cells} \times R_{B,cell}$$

$$I_B = I_{cell}$$

$$V_{SoC} = N_{cells} \times V_{SoC,cell}$$

$$V_B = V_{SoC} - I_B R_B$$



Exercise

The equilibrium open-circuit cell voltage of a 24 V lead-acid battery is 24.96 V. An external circuit is connected to the battery that draws 21 A. Assume the battery resistance R_B under these conditions is 0.060 Ω. Compute the terminal voltage.

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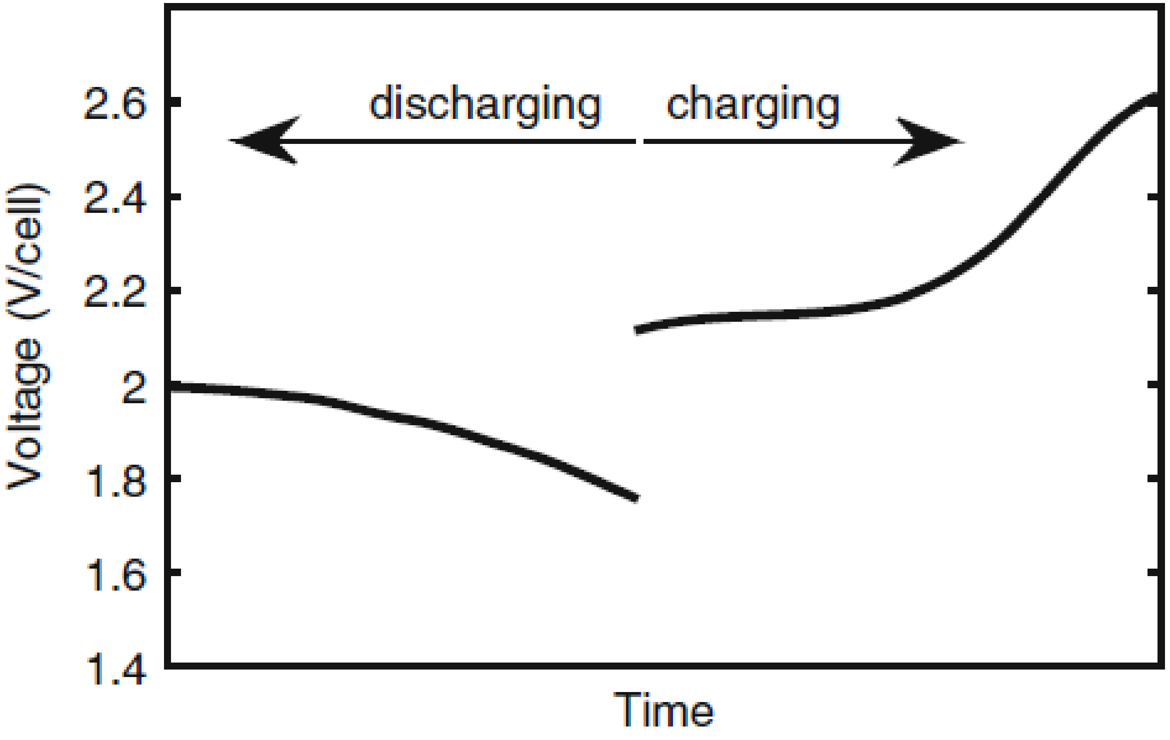
The equilibrium open-circuit cell voltage of a 24 V lead-acid battery is 24.96 V. An external circuit is connected to the battery that draws 21 A. Assume the battery resistance R_B under these conditions is 0.060 Ω. Compute the terminal voltage.

$$V_B = V_{SoC} - I_B R_B$$

$$V_B = 24.96 - 21.0 \times 0.060 = 23.70\,\mathrm{V}$$

Cell Voltage During Discharging/Charging

Curves are influenced by the dual effects of increasing V_{SoC} and changes
In the polarizations as function of state-of-charge



Current magnitude is kept constant throughout

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