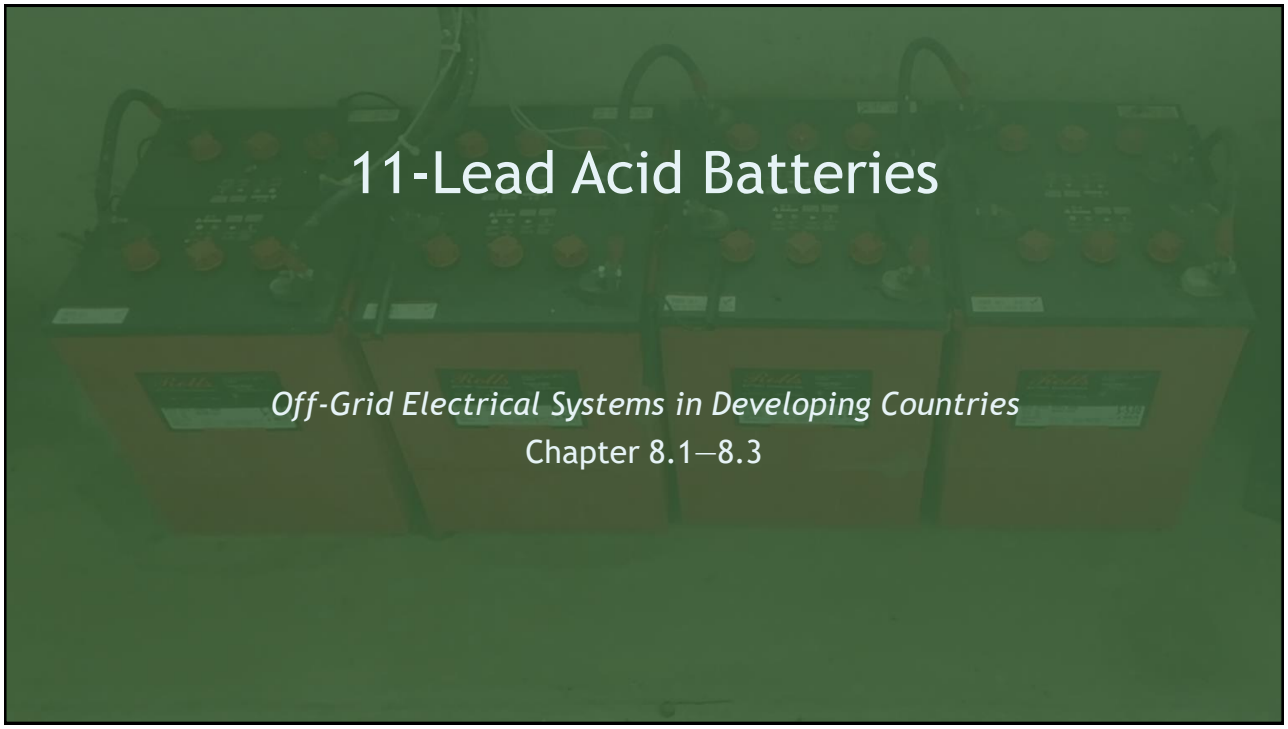


11-Lead Acid Batteries

Off-Grid Electrical Systems in Developing Countries

Chapter 8.1—8.3

1

Learning Outcomes

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

- ✓understand the basic components of lead acid batteries
- ✓describe the chemical reactions that occur when a lead acid battery charges and discharges
- ✓identify the commonly used types of lead-acid batteries
- ✓describe the side-reactions that occur in lead-acid batteries and their implications

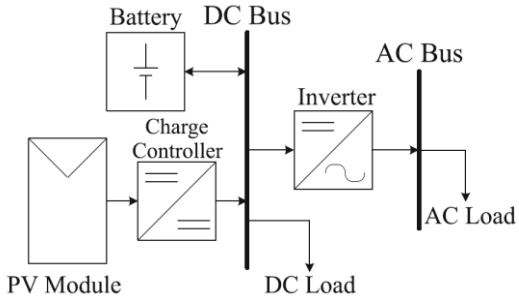
2

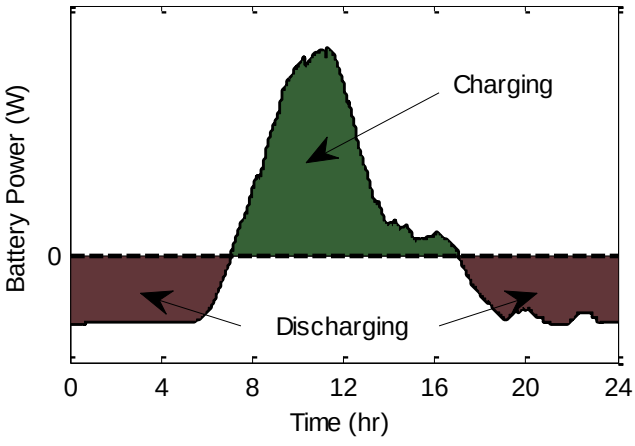
2

Off-Grid Batteries

- Battery bank is crucial in establishing the DC bus voltage in DC- and AC—DC-coupled systems
- Batteries are among the most expensive and shortest-lived components in off-grid systems
  - Lead-acid: $150 to 500/kWh
  - Lithium-ion: $500 to $3000/kWh
- How a system is designed and operated can lengthen or shorten battery lifespan

3





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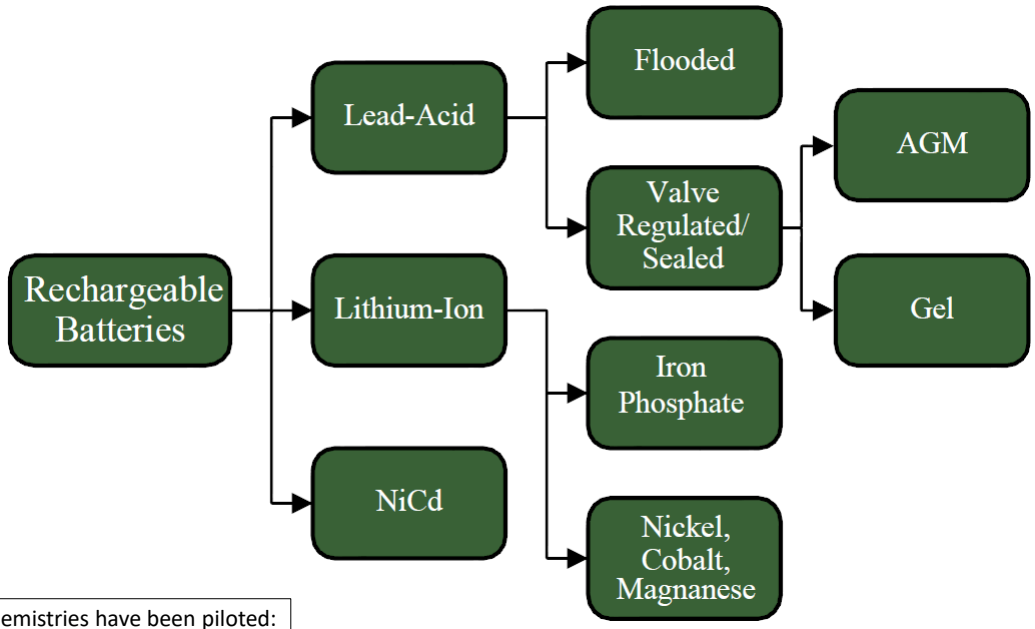


Other chemistries have been piloted:
See Zinc-Air battery by NantEnergy

5

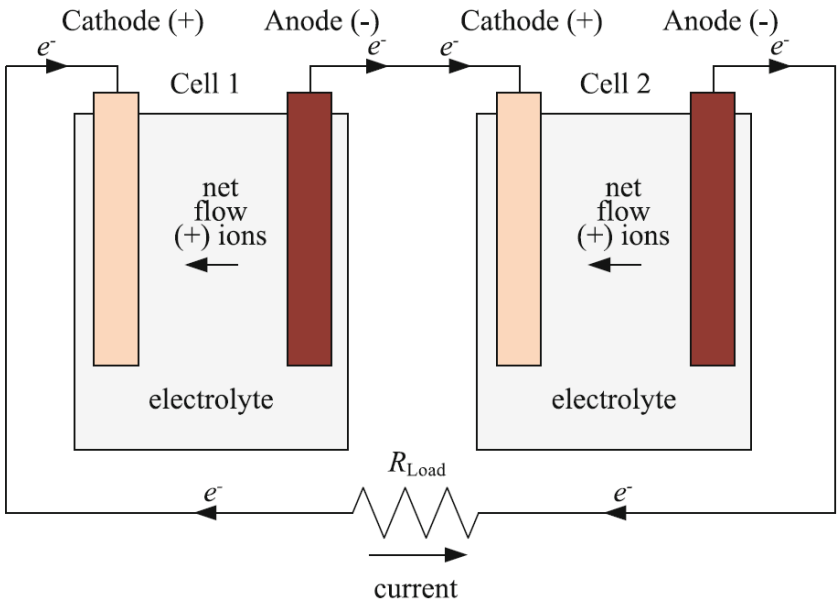
Electrochemistry (more on this in the next lecture)

- Batteries rely on chemical reactions to create a separation of charge between the electrodes and electrolyte
- A voltage is associated with a separation of charge
- Open-circuit voltage depends (non-linearly) on:
  - Chemicals involved
  - State of the chemicals (activities/concentrations, temperature)
- Voltage is an *intrinsic* property of the battery
- Chemicals and their state change during charge and discharging, and so the voltage changes as well

6

Active Materials

- *Active material*: substances within a battery that participate in the charge or discharge reactions
  - electrodes, but sometimes the electrolyte as well
- When active material is depleted or prevented from reacting, the battery is no longer able to provide charge



This battery consists of two cells in series

Lead-Acid Battery

- Invented by Gaston Planté in 1859
- Lead-acid batteries are usually designed for specific purposes
- Examples:
  - Automotive (starting, lighting, ignition---SLI)
  - Fork lifts
  - Marine
  - Off-grid systems (deep cycle)

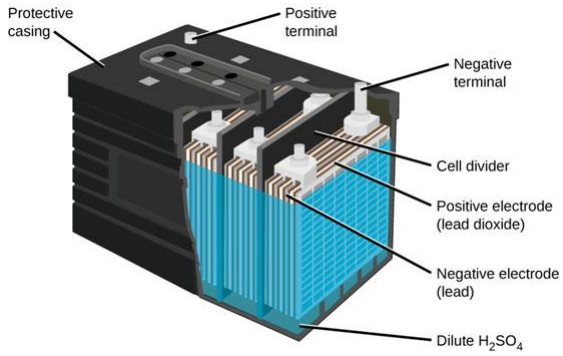
Informal Battery Recharging

Do not use SLI batteries in off-grid systems

Courtesy P. Dauenhauer

Electrodes

- Electrodes formed around metallic grids to improve conductivity and mechanical strength
- Anode: lead (Pb) that resembles a sponge (to increase surface area and interaction with electrolyte)
- Cathode: lead dioxide (PbO_2)



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11

11

Electrolyte

- Sulfuric acid (H_2SO_4) diluted in pure water
- Concentration of sulfuric acid in a fully-charged lead acid battery is typically 6 moles per liter
  - Recall that a "mole" is a measurement of the amount of a substance
  - The particles in 1 mole of a substances is 6.022×10^{23} (Avogadro's constant)
- As a battery is discharged, the concentration decreases to about 1 to 2 moles per liter when "fully discharged"
- Change in electrolyte concentration is important in understanding the voltage characteristics of lead-acid batteries

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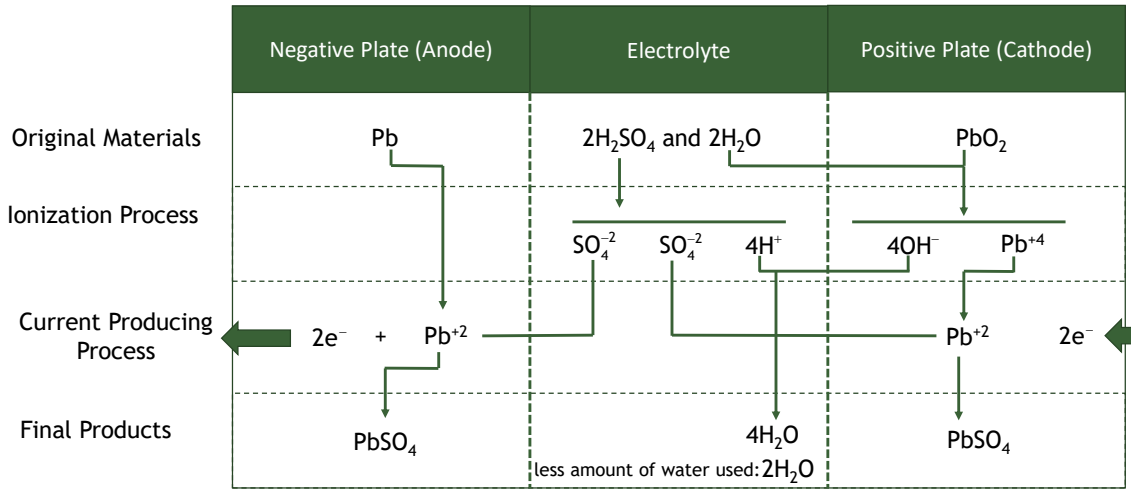
Discharge Process



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Note: there are somewhat different explanations of the sequence of reactions

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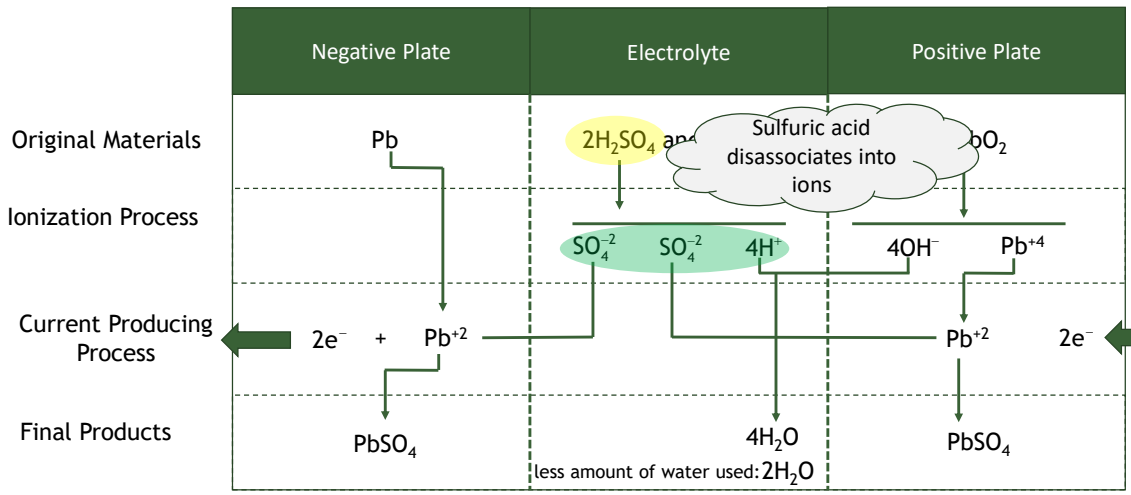
Discharge Process



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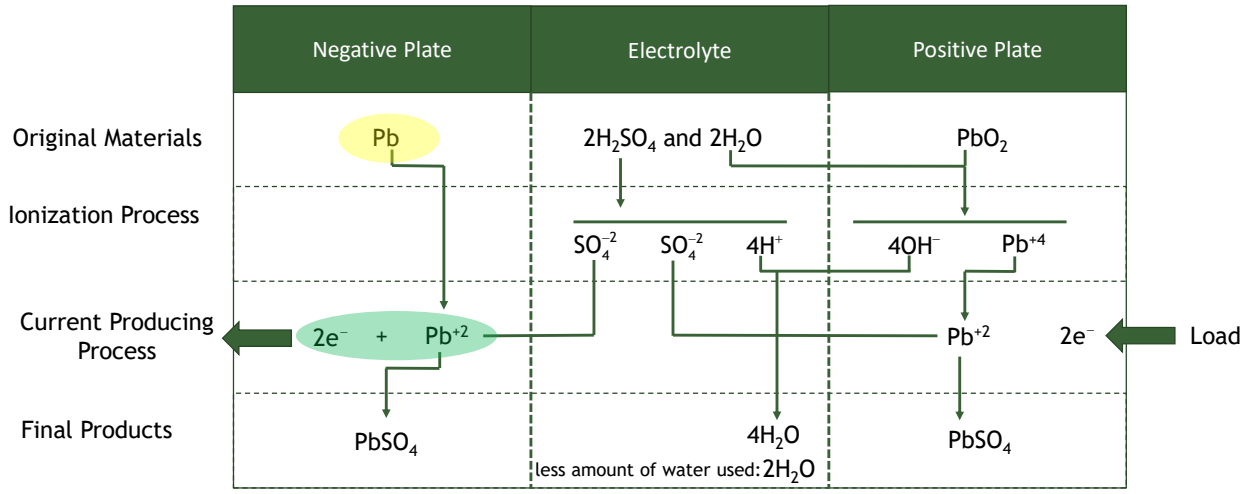
Discharge Process



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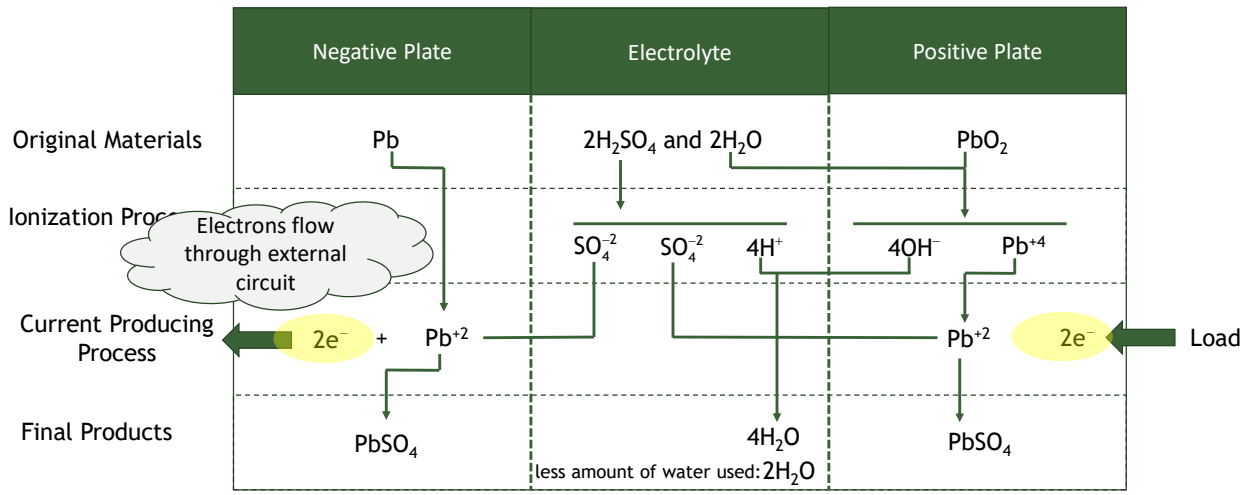
Discharge Process



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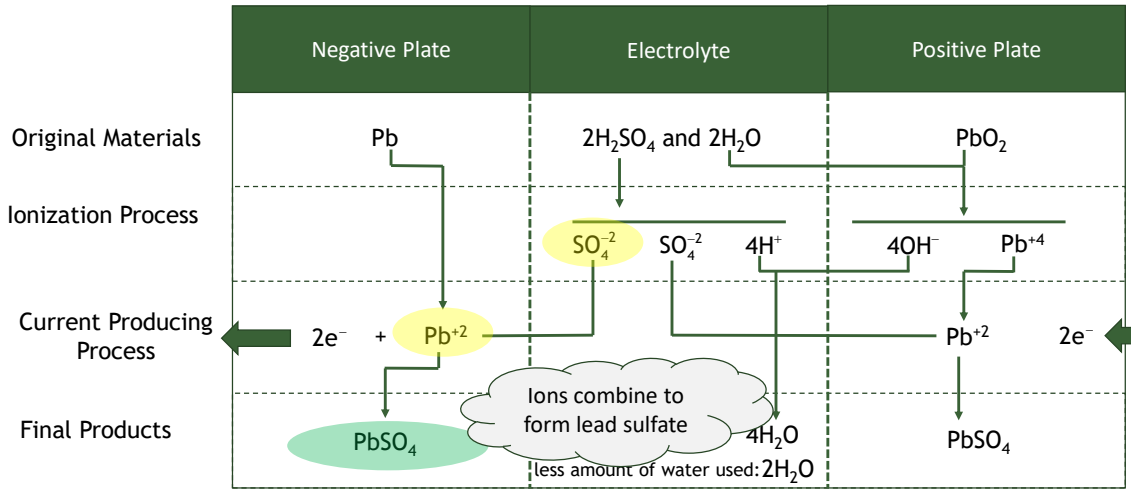
Discharge Process



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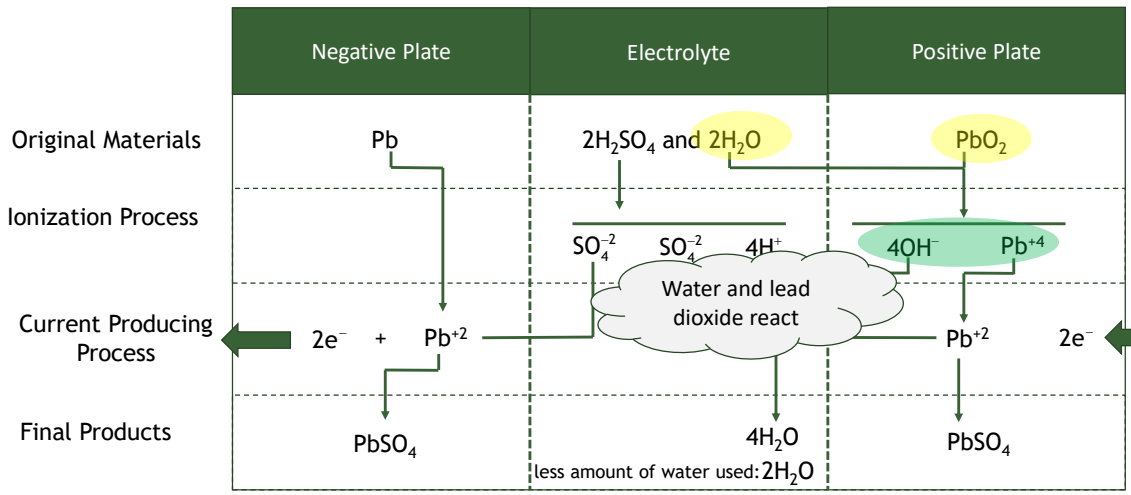
Discharge Process



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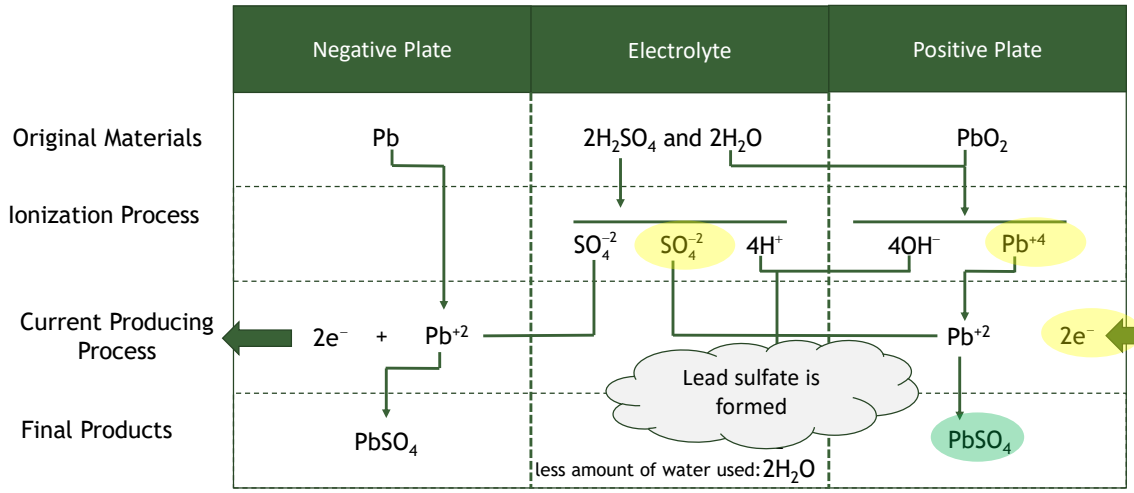
Discharge Process



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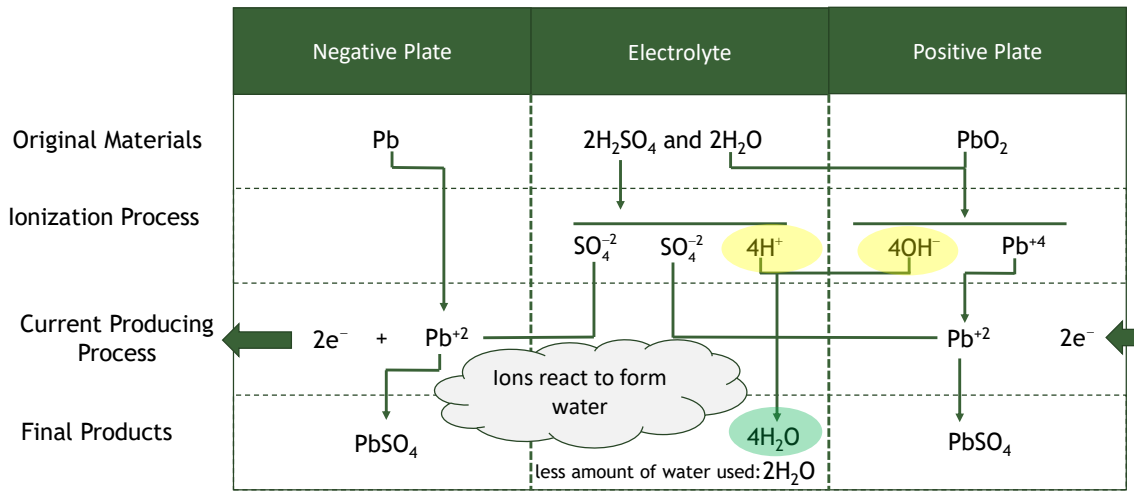
Discharge Process



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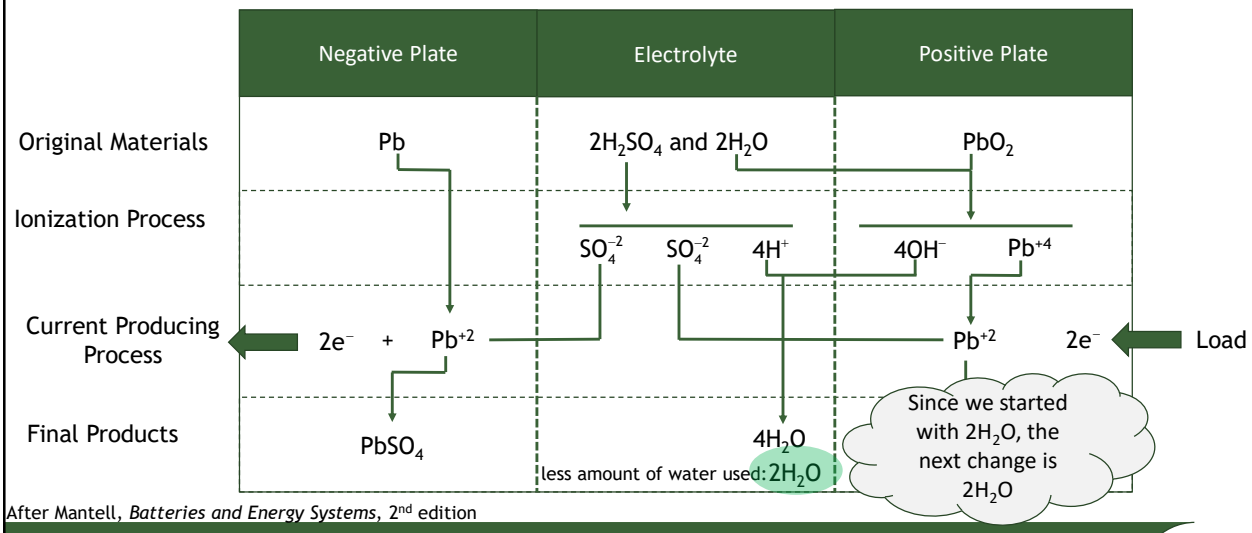
Discharge Process



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Discharge Reactions

Cathode (+ Terminal)

$$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$$

Anode (- Terminal)

$$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

Complete Reaction

$$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$$

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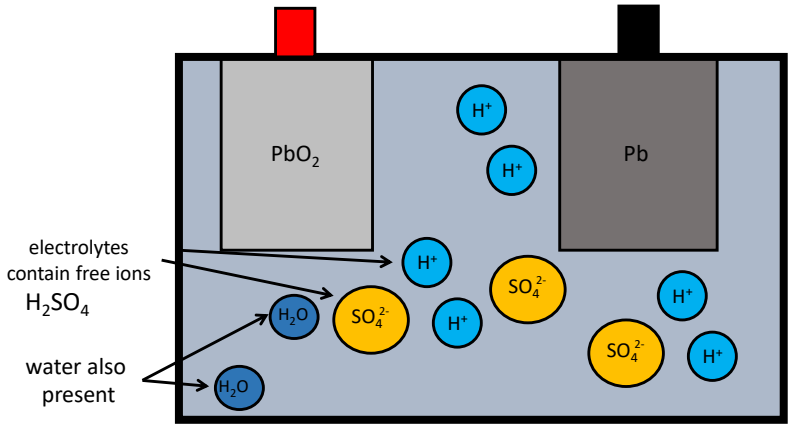
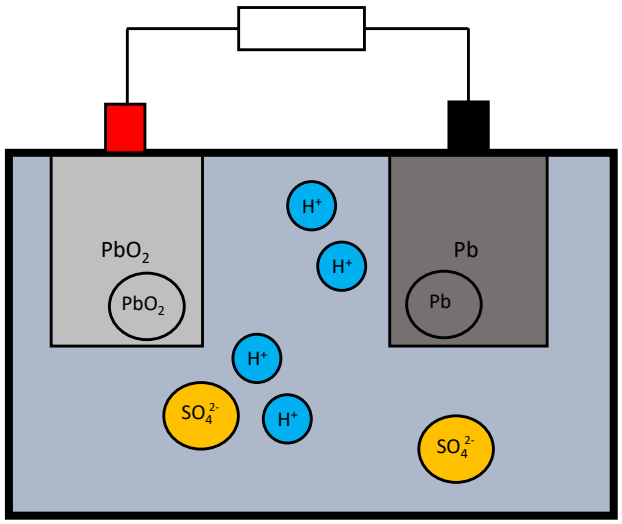
Fully-Charged, Open Circuit

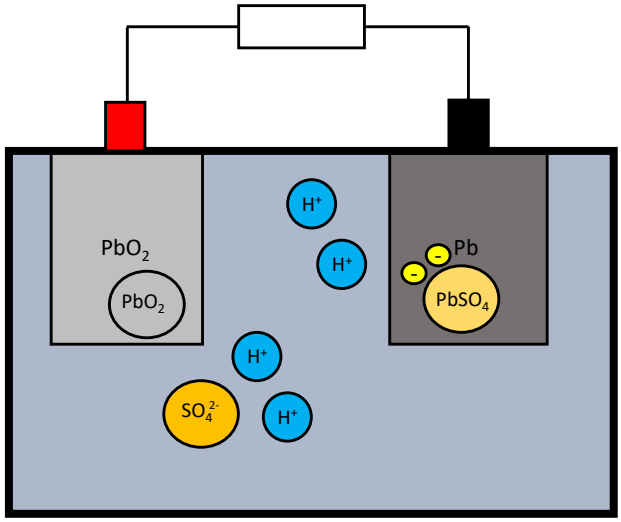


Concentration of sulfuric acid: ~6 moles

Discharging



Discharging



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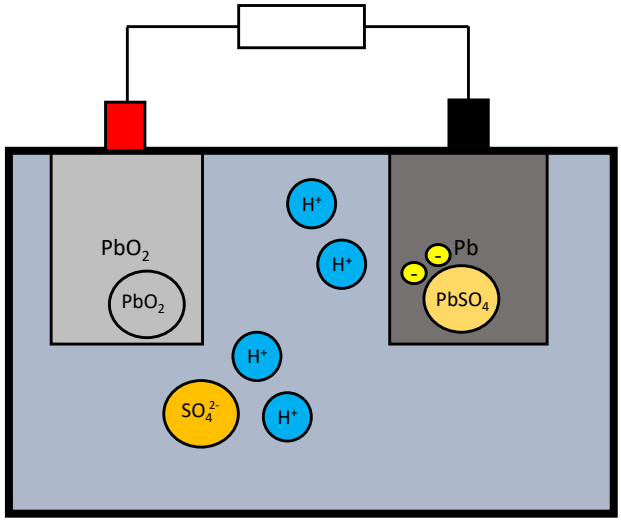
Discharging



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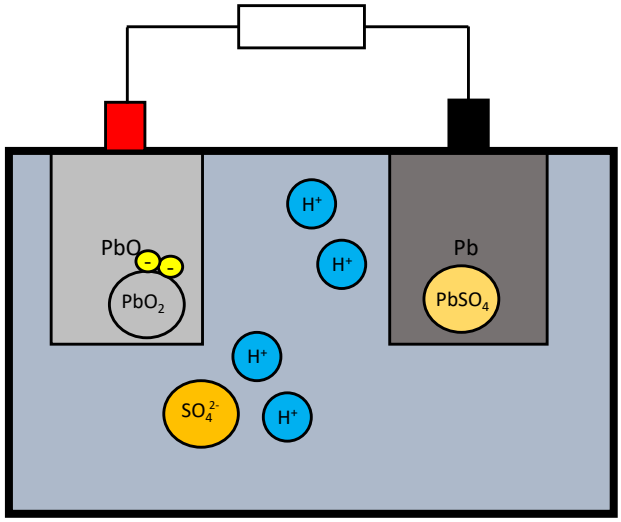
Discharging



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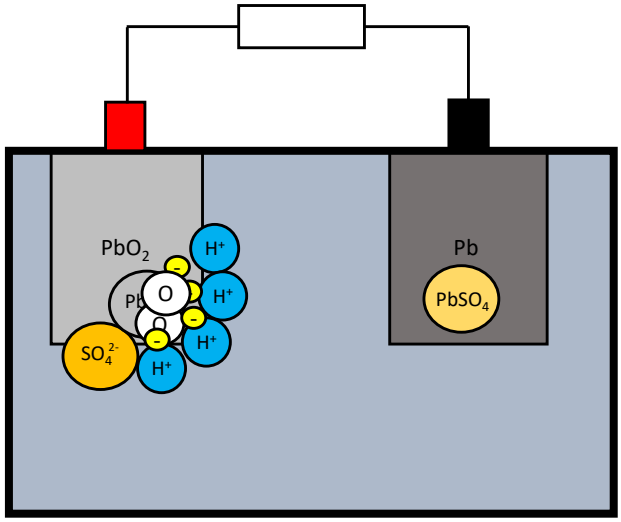
Discharging



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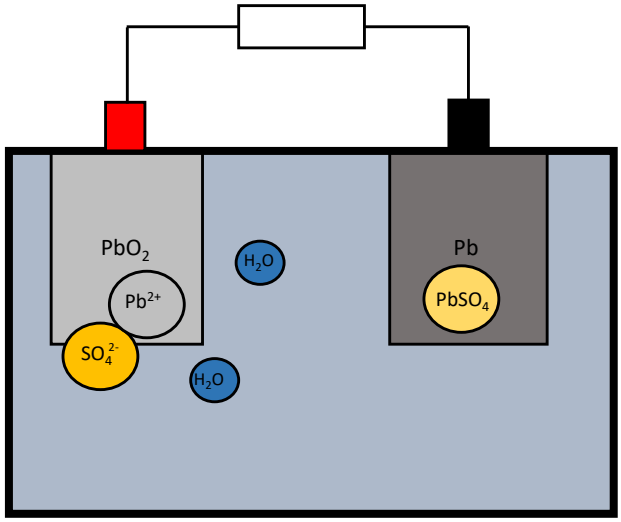
Discharging



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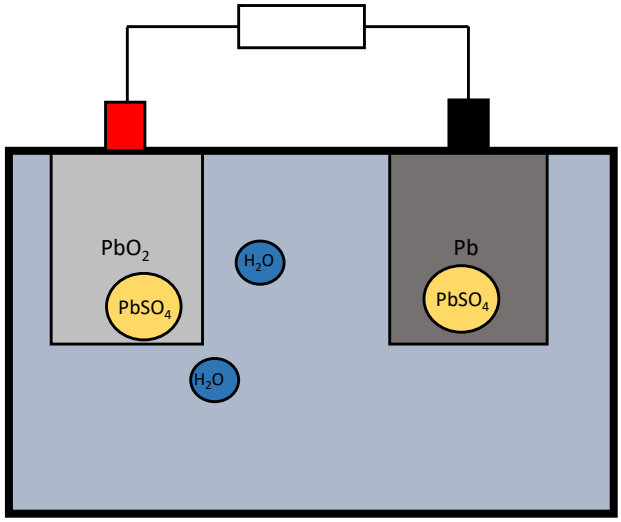
Discharging



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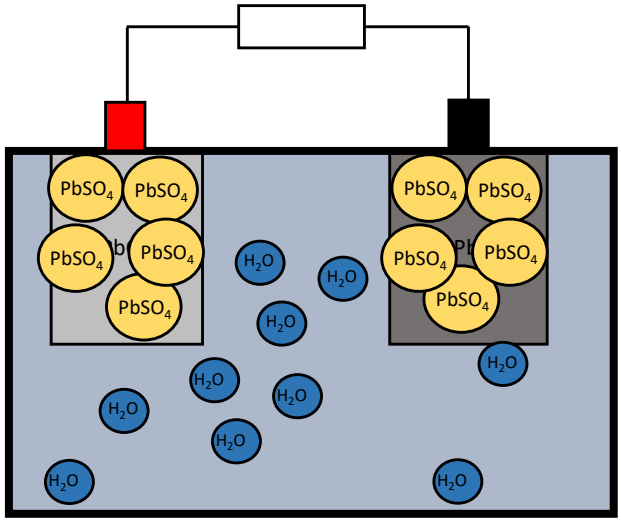
Discharging



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Charge Process

	Negative Plate	Electrolyte	Positive Plate
Original Materials	$PbSO_4$	$4H_2O$	$PbSO_4$
Ionization Process	Pb^{+2} SO_4^{-2}	$2H^+$ $4OH^-$ $2H^+$	SO_4^{-2} Pb^{+2}
Current Producing Process	$2e^-$		Pb^{+4} $2e^-$ charger
Final Products	Pb	$2H_2O$ H_2SO_4 H_2SO_4	PbO_2

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Charge Reactions

Cathode (+ Terminal)

$$PbSO_4 + 2H_2O \rightarrow PbO_2 + SO_4^{2-} + 4H^+ + 2e^-$$

Anode (- Terminal)

$$PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}$$

Complete Reaction

$$2PbSO_4 + 2H_2O \rightarrow PbO_2 + Pb + 2H_2SO_4$$

Charge reactions are the opposite of the discharge reactions

Exercise

Explain why/how the specific gravity (ratio of its density to the density of pure water) of the electrolyte in a lead acid battery can be used to estimate its state-of-charge.

Exercise

Explain why/how the specific gravity (ratio of its density to the density of pure water) of the electrolyte in a lead acid battery can be used to estimate its state-of-charge.

The specific density of sulfuric acid is not 1.0 (it is about 1.84). As the battery discharges, the specific gravity of the electrolyte will decrease since the concentration of sulfuric acid also decreases.

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courtesy Outback Power

Types of Lead-Acid Batteries

Flooded Lead-Acid ("wet cell"):

- Most common and mature lead-acid battery type
- Battery is not permanently sealed
- Electrolyte can be sampled and re-filled with pure water (never add sulfuric acid!)
- Less expensive
- Requires maintenance
- Can spill

Sealed Lead-Acid (Valve-regulated lead-acid)

- Absorbed Glass Mat (AGM)
- Gel

Also OPzV (Ortsfest PanZerplatte Verschlossen) tubular electrodes, common in Europe

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Swelling & Shedding

- As lead-acid batteries charge and discharge, the electrodes chemically change (electrodes swell and contract)
- Change in electrode shape and electrolyte volume can cause the battery to mechanically fail, causing short-circuits or active material to separate from the electrodes (shedding)
- The reactions in practice are not completely reversible and so the shape of the electrode changes over time

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Other Reactions

Reactions within the lead-acid battery are always occurring, even when not being charged or discharged

- Reactions when over-discharged
- Reactions when over-charged
- Corrosion
- Self-discharge reactions

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Over-discharge

- Deeply discharging a lead-acid battery can cause the lead sulfate that forms on the electrodes to turn into hard, dense crystals (*sulfation*)
- Crystals prevent interaction of electrode and electrolyte
- Amount of charge that can be provided is permanently reduced (battery is de-rated)

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Avoiding Sulfation

Ways to avoid sulfation:

- ✓Never deeply discharge the battery
- ✓Avoid leaving batteries at a low state of charge for prolonged periods of time (apply a "top up" charge every so often)
- ✓Avoid operating or storing battery at high temperatures

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Discussion

What are the important considerations in selecting a lead-acid battery type for an off-grid system?

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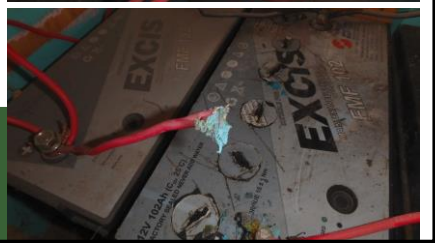
Corrosion

- Corrosion can occur on lead-acid battery terminals
  - Can weaken connections, increasing resistance or even cause an open-circuit
- Cause: electrolyte escapes (seeps or vents) and reacts with the terminals
- Depending on the terminal connections, either lead sulfate or hydrated copper sulfate
- Can prevent by greasing the terminals



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Self-Discharge

- Lead-acid will spontaneously discharge even when not connected to an external circuit
  - Lead and lead dioxide will naturally react with the electrolyte (i.e. the system is not thermodynamically stable)
- Reactions at the anode and cathode are different from the charge/discharge reactions, and are independent from each other, but each result in the evolution of lead sulfate and reduction of capacity

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Self-Discharge Reactions

- Cathode Reaction:

  $PbO_2(s) + H_2SO_4(aq) \rightarrow PbSO_4(s) + H_2O(\ell) + 0.5O_2(g)$
- Anode Reaction:

  $Pb(s) + H_2SO_4(aq) \rightarrow PbSO_4(s) + H_2(g)$

Each produce a gas, which if vented from the battery reduces the amount of water that can be reformed.

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Self-Discharge

- Anode self-discharge reaction occurs more rapidly than the cathode
- Self-discharge varies, but is often around 5% per month

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Over-Charging

- As the battery increases in charge, its voltage increases
- Higher voltages promotes other reactions in the battery
  - Anode:

$$2H^+(aq) + 2e^- \rightarrow H_2(g)$$

  - Cathode:

$$H_2O(\ell) \rightarrow 0.5O_2(g) + 2H^+(aq) + 2e^-$$

this is electrolysis

Both reactions produce hydrogen gas, which is explosive if concentrated.

If gases are vented from the battery, it limits the amount of water that can be reformed

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Over-Charging

- Ways to prevent/reduce over-charging:
  - Use a charge controller (3-stage)
  - Use sealed---AGM or gel---batteries (which prevent venting and allow gases to reform)
- Mitigating the effects of over-charging
  - Make sure flooded batteries are installed in rooms with adequate ventilation
  - Do not mount inverters or other controllers above flooded batteries
  - Monitor electrolyte level and add distilled water in flooded batteries

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Contact Information

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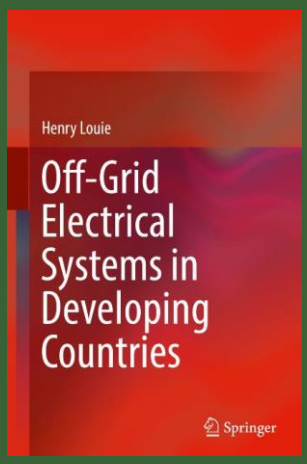

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