

ECEN 4517/5517

Power Electronics and Photovoltaic Power Systems Laboratory

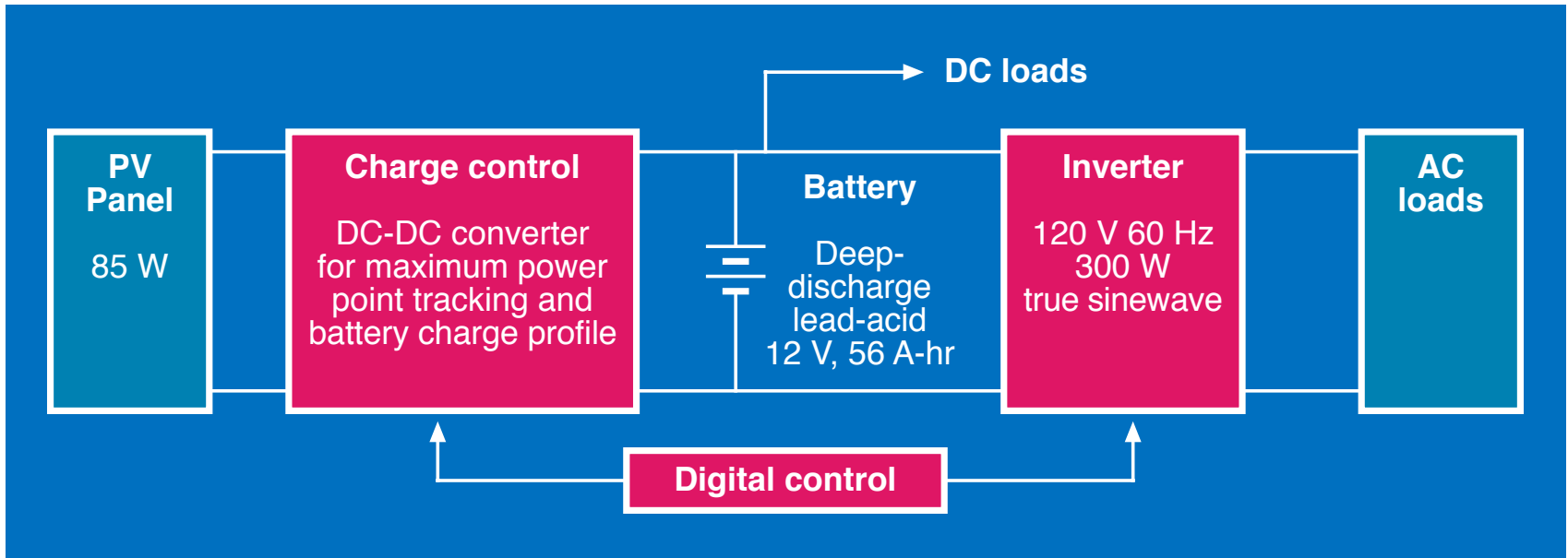
Lecture 6

Lead Acid Batteries

Announcements

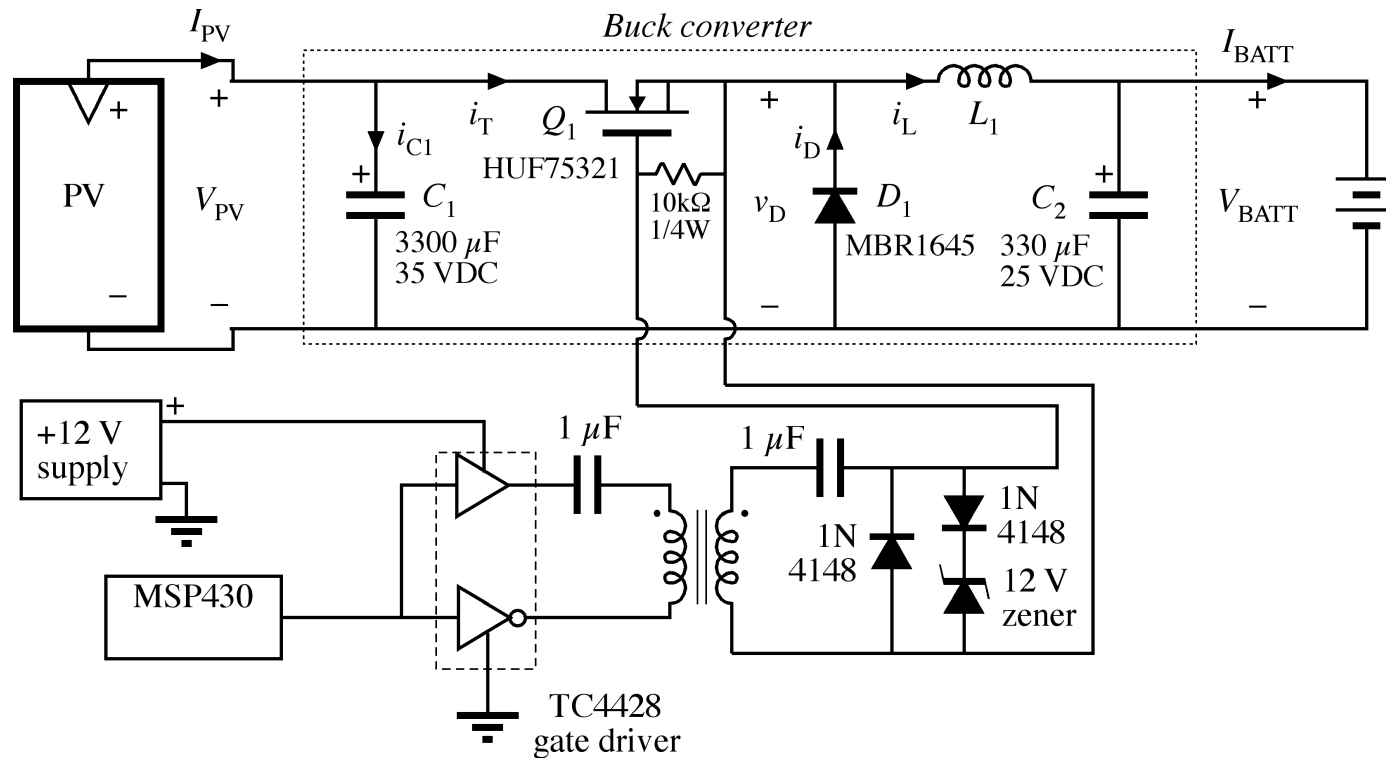
- Exp 3-1 Lab Report due by 11:59 pm (MT) on Friday February 24, 2017
- This week's lab: Start Experiment 3-2
 - Have 2 weeks to work on Experiment 3-2
 - Exp 3-2 Lab Report due by 11:59 pm (MT) on Friday March 10, 2017
- Following this: Experiment 4
 - Experiment 4 has a pre-lab (due 11:59 pm on Friday March 3, 2017)
 - Have 3 weeks to work on Experiment 4
 - Exp 4 Lab Report due by 11:59 pm (MT) on Friday April 7, 2017
- Quiz 1: Monday, February 27, 2017 (in class)
 - Closed book/notes, calculator allowed
 - Coverage:
 - Exp 1 to Exp 3-1 material
 - PWM Converter Steady State Analysis

Experiments



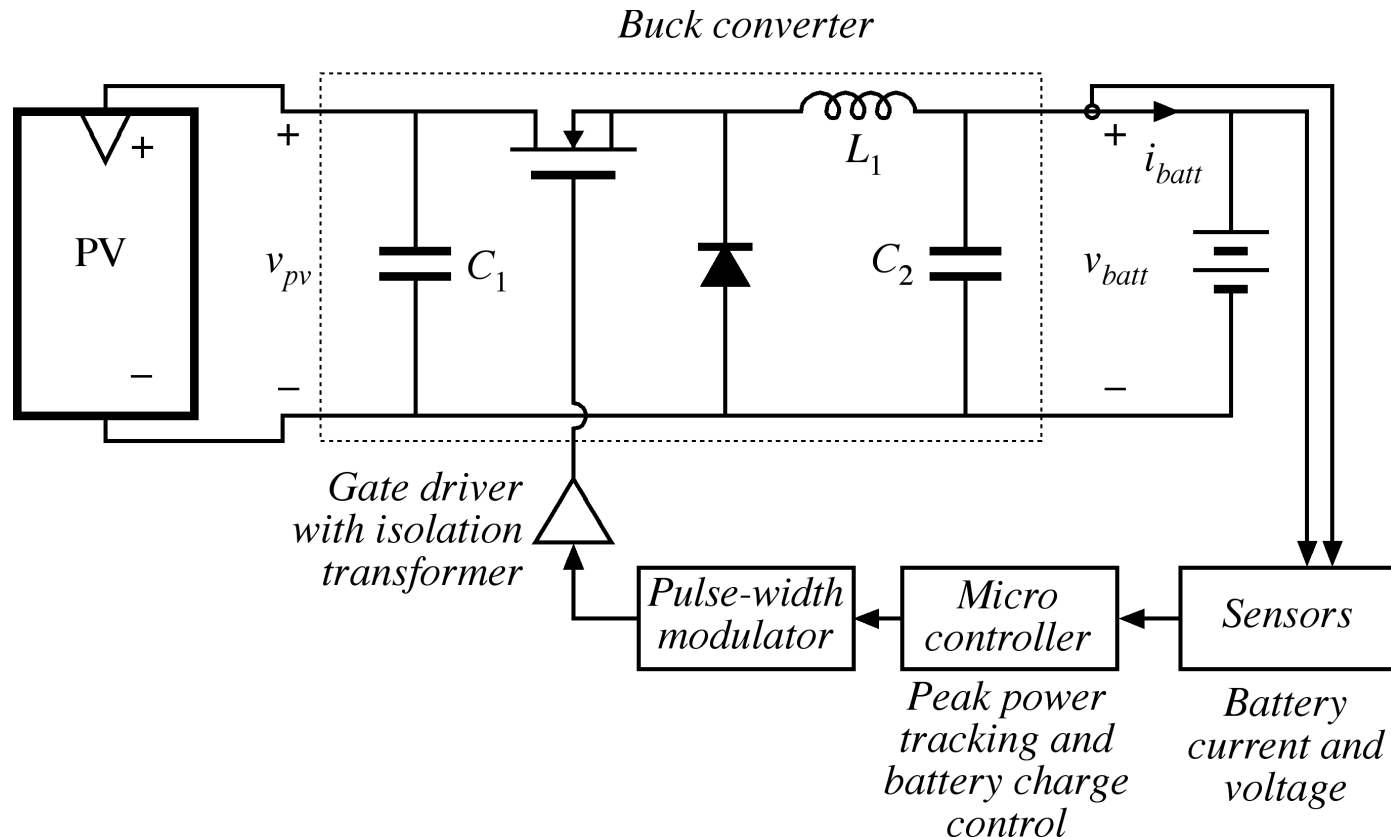
- [Exp 1](#) – PV panel and battery characteristics and direct energy transfer
- [Exp 2](#) – TI MSP430 microcontroller introduction
- [Exp 3-1, 3-2](#) – Buck dc-dc converter for PV MPPT and battery charge control
- [Exp 4](#) – Step-up 12V-200V dc-dc converter
- [Exp 5](#) – Single-phase dc-ac converter (inverter)
- [Expo](#) – Complete system demonstration

Experiment 3-1



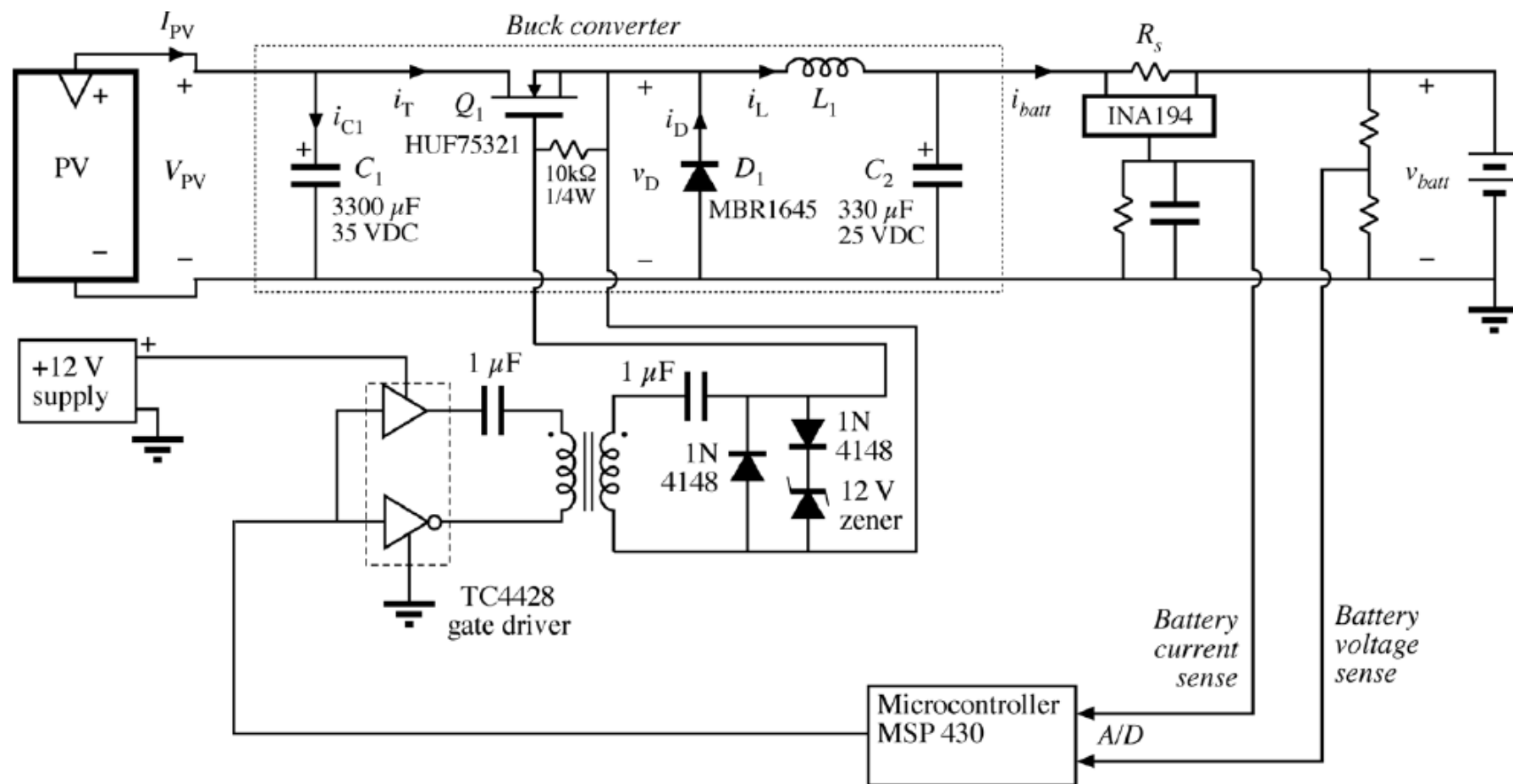
- Demonstrate dc-dc converter power stage operating open loop, driven by MSP430 PWM output:
 - Inside, with input power supply and resistive load
 - Outside, between PV panel and battery
- Compare experimental results with simulation

Experiment 3-2



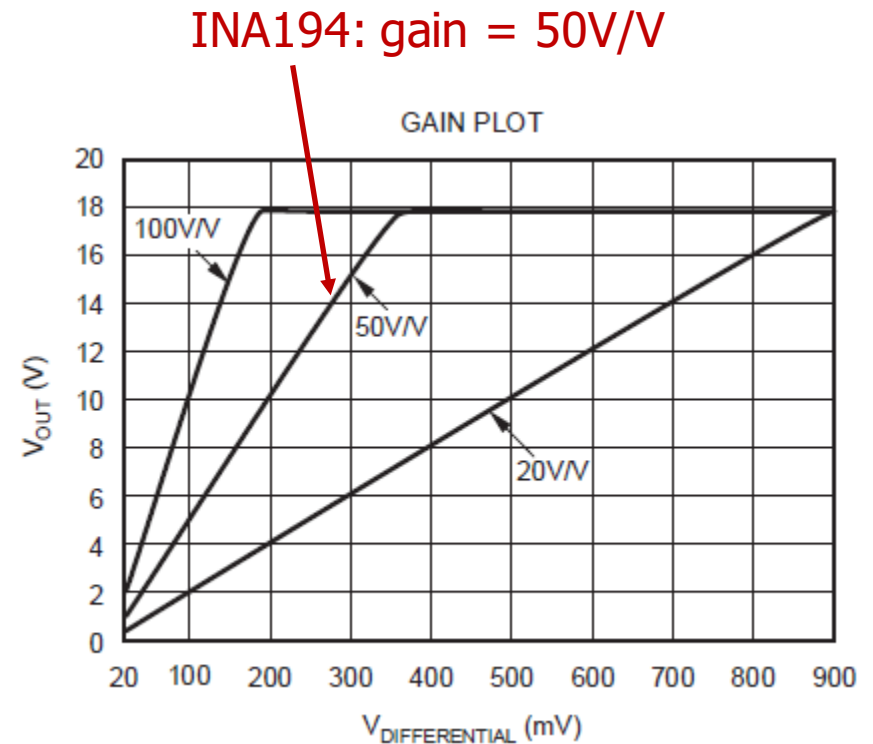
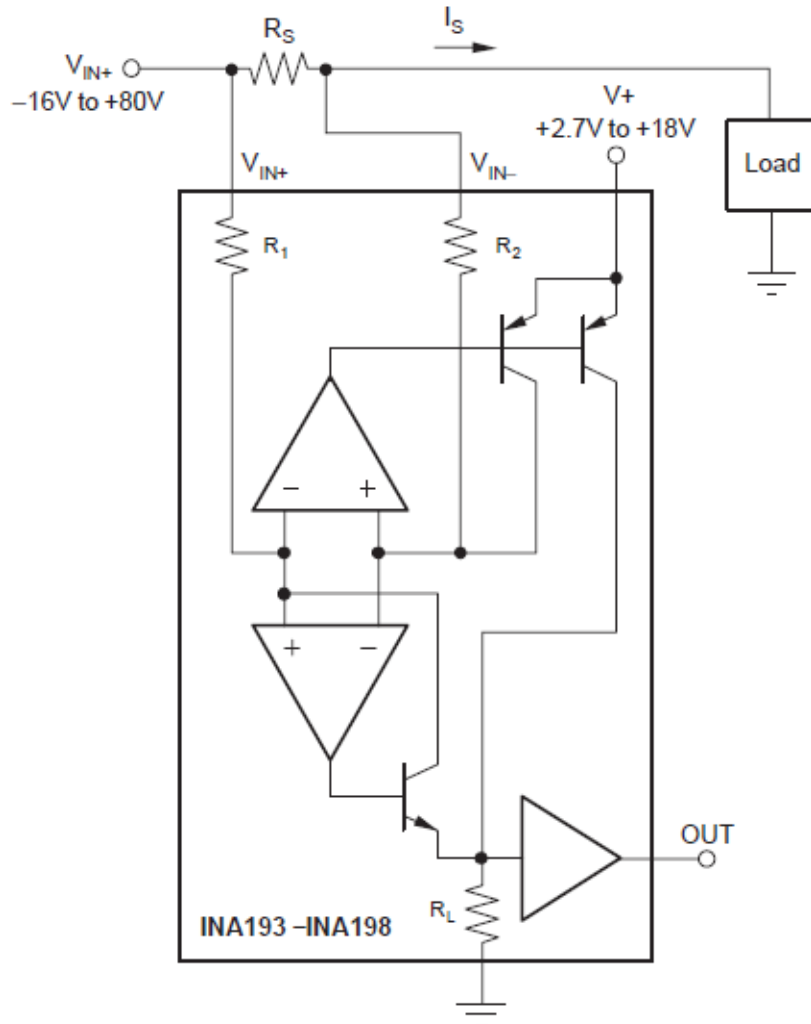
- Demonstrate working sensor circuitry, interfaced to microcontroller
- Demonstrate maximum power point tracking algorithm, outside with converter connected between PV panel and battery

Battery Current and Voltage Sensing Circuit



- Use INA194 current sense IC to measure current
- Use voltage divider to measure voltage

INA194 High-Side Current Sense IC



- INA194 datasheet contains useful application notes

Setting up ADC10

```
// Configure ADC10
ADC10CTL0 = ADC10SHT_2 + ADC10ON;           // sample time of 16 clocks, turn on
                                              // use internal ADC 5 MHz clock
ADC10CTL1 = ADC10SHP + ADC10CONSEQ_0;        // software trigger to start a sample
                                              // single channel conversion
ADC10CTL2 = ADC10RES;                        // use full 10 bit resolution
ADC10MCTL0 = ADC10SREF_1 + ADC10INCH_5;    // ADC10 ref: use VREF and AVSS
                                              // input channel A5 (pin 10)

// Configure internal reference VREF
while(REFCTL0 & REFGENBUSY);                 // if ref gen is busy, wait
REFCTL0 |= REFVSEL_0 + REFON;                // select VREF = 1.5 V, turn on
_delay_cycles(75);                           // delay for VREF to settle
```

The above code sets up the 10-bit ADC with A5 as its only input, with 1.5 V giving a reading of $2^{10} - 1$, and 0 V giving a reading of 0. Each reading will employ a sampling window of 16 ADC clocks = 3.2 μ sec.

Sampling the ADC10 Input

```
ADC10CTL0 |= ADC10ENC + ADC10SC;           // sampling and conversion start
while(ADC10CTL1 & ADC10BUSY);                // wait for completion
X = ADC10MEM0;                               // ADC10MEM0 contains result
```

The above code is simple and a good start. See CCS5 code examples for use of interrupts that do not require the processor to wait during the conversion time.

Code to Sample Two Inputs of ADC10

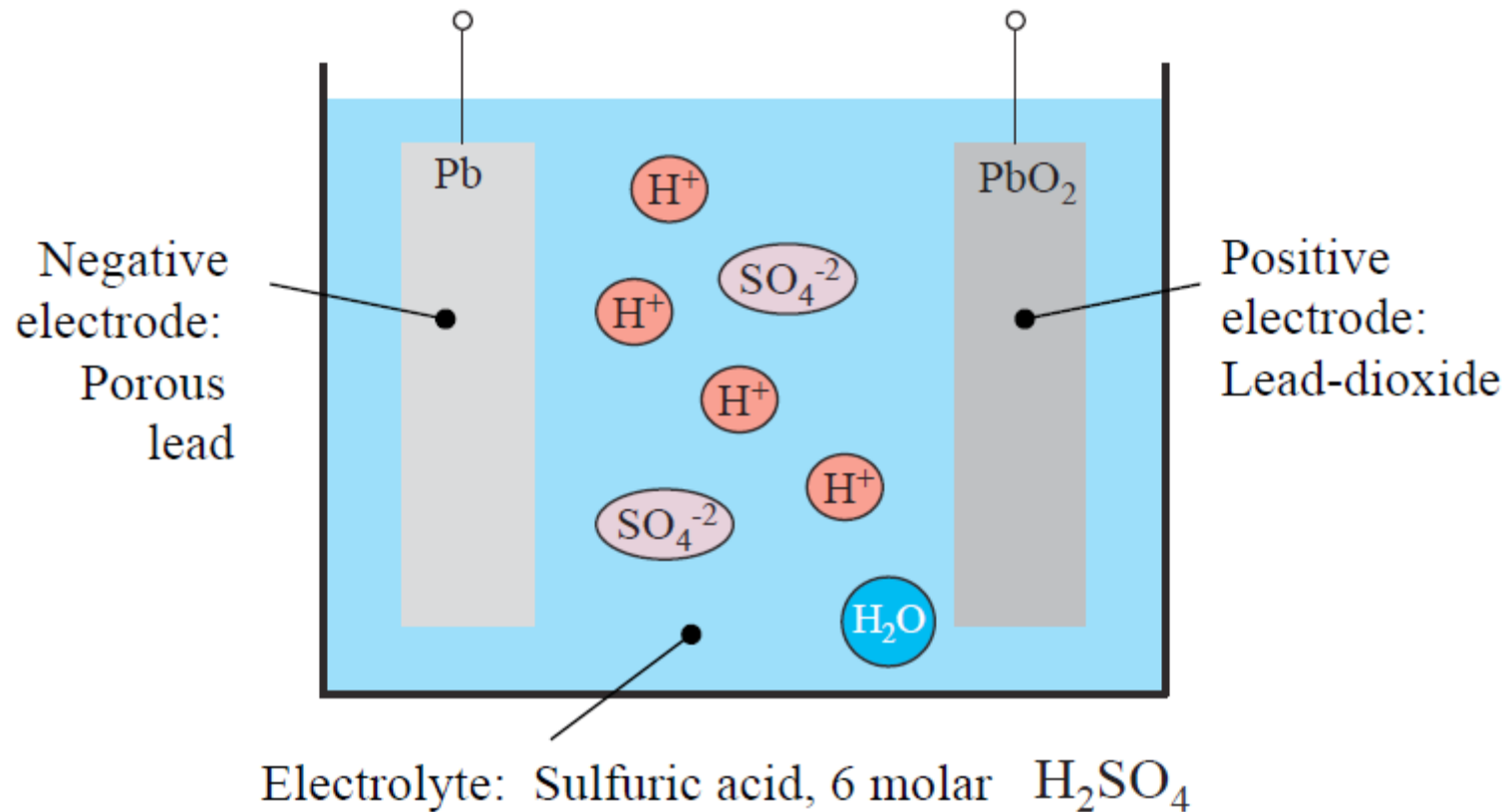
```
for (;;)
{
    __delay_cycles(25000);

    ADC10MCTL0 |= ADC10INCH_2 + ADC10SREF_1; // A2 ADC input select;
    ADC10CTL0 |= ADC10ENC + ADC10SC; // Sampling and conversion start
    while(ADC10CTL1 & ADC10BUSY); // wait for completion
    vbat = ADC10MEM0;
    ADC10CTL0 &= ~ADC10ENC; // Disable ADC

    ADC10MCTL0 |= ADC10INCH_1 + ADC10SREF_1; // A1 ADC input select;
    ADC10CTL0 |= ADC10ENC + ADC10SC; // Sampling and conversion start
    while(ADC10CTL1 & ADC10BUSY); // wait for completion
    ibat = ADC10MEM0;
    ADC10CTL0 &= ~ADC10ENC; // Disable ADC

    pout=ibat*vbat;
}
```

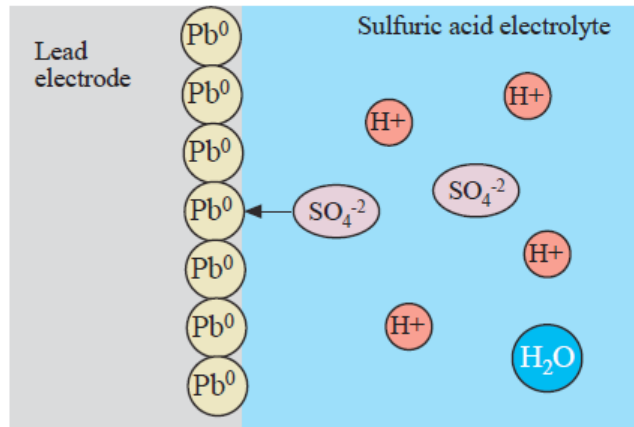
Lead Acid Battery – Cell Chemistry



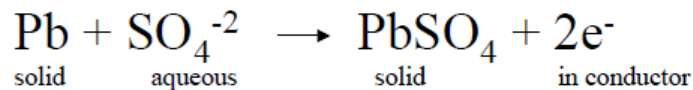
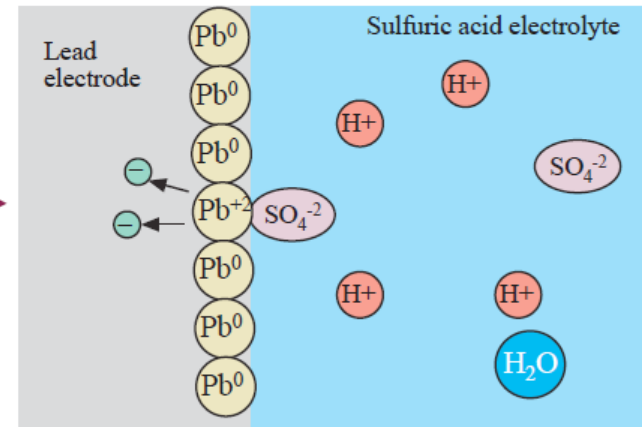
- Lead and lead-dioxide are good electrical conductors
- The electrolyte contains aqueous ions (H⁺ and SO₄⁻²); conduction within the electrolyte is via migration of ions via drift and diffusion

Reaction at Negative (Pb) Electrode

Charged sulfate ion approaches uncharged lead electrode surface, dipole attraction kicks in on close approach



Lead atom becomes ionized and forms ionic bond with sulfate ion. Two electrons are released into lead electrode



This reaction releases net energy

$$E^0 = 0.356 \text{ eV}$$

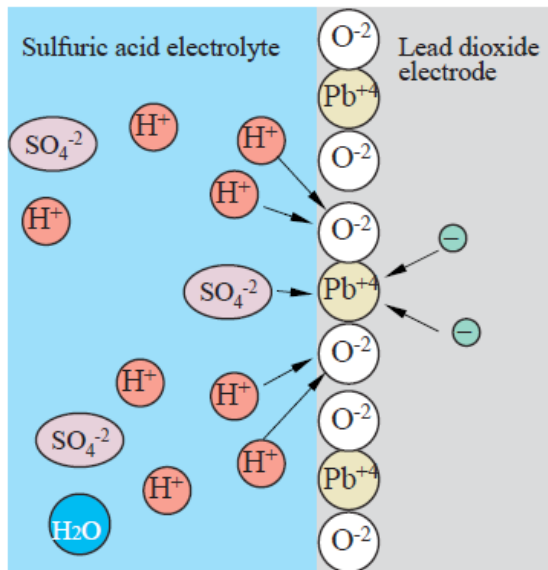
under standard conditions

(T = 298°K, 1 molar concentration)

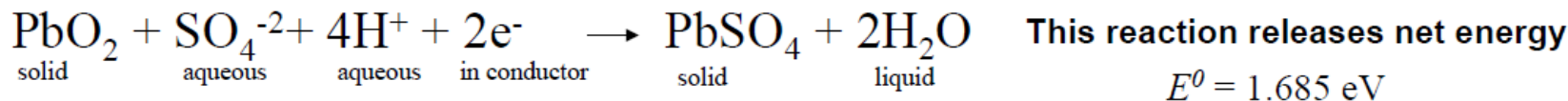
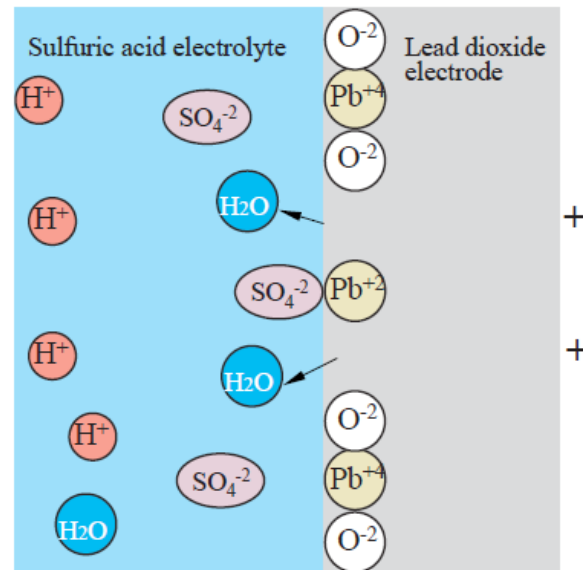
- **Release of two conducting electrons gives lead electrode a net negative charge**
- **As electrons accumulate they create an electric field which attracts hydrogen ions and repels sulfate ions, leading to a double-layer near the surface. The hydrogen ions screen the charged electrode from the solution which limits further reactions unless charge is allowed to flow out of electrode.**

Reaction at Positive (PbO_2) Electrode

Charged sulfate and hydrogen ions approach lead-dioxide molecule (net uncharged) on surface of electrode

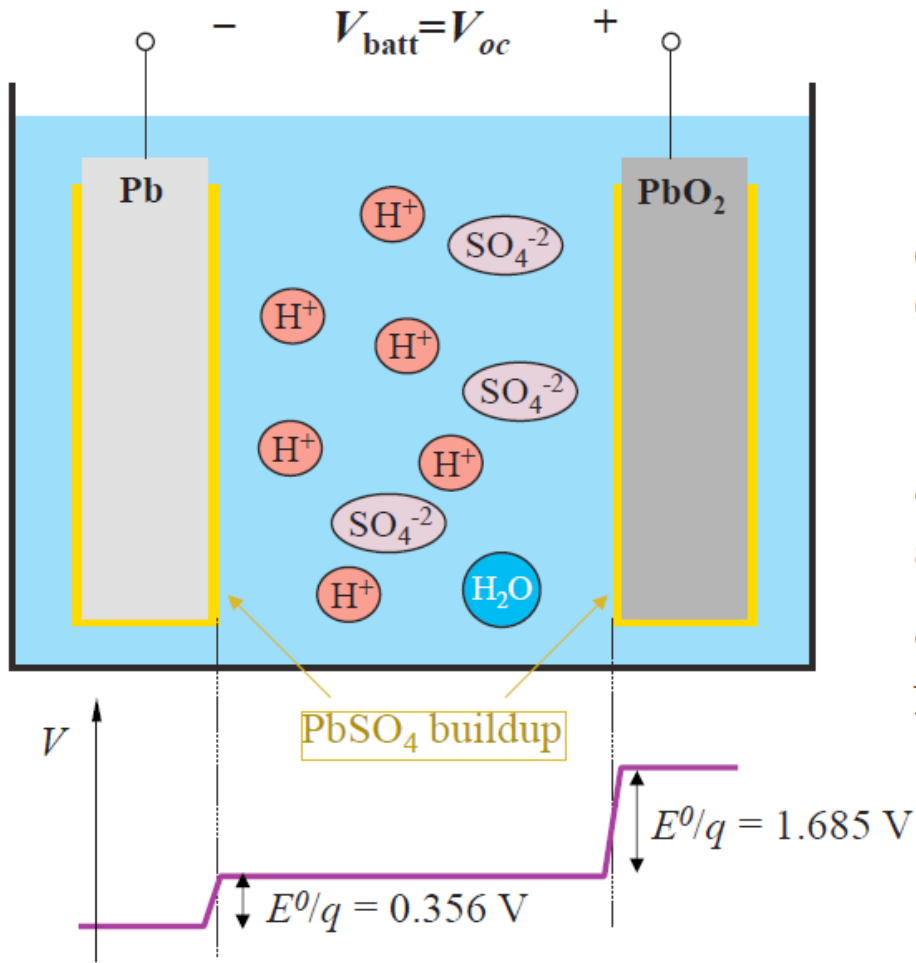


Lead atom changes ionization and forms ionic bond with sulfate ion. Two water molecules are released into solution



- As positive charge accumulates an electric field is created which will attract sulfate ions and repel hydrogen ions (charge screening) limiting further reaction unless charge is allowed to flow out of electrode.
- Note: Both half reactions cause the electrodes to become coated with lead sulfate (a poor conductor) and reduce the concentration of the acid electrolyte

Battery in Equilibrium (Zero Current)



As described in earlier slides, reactions at electrodes lead to opposite charge buildup on electrodes and hence a voltage difference

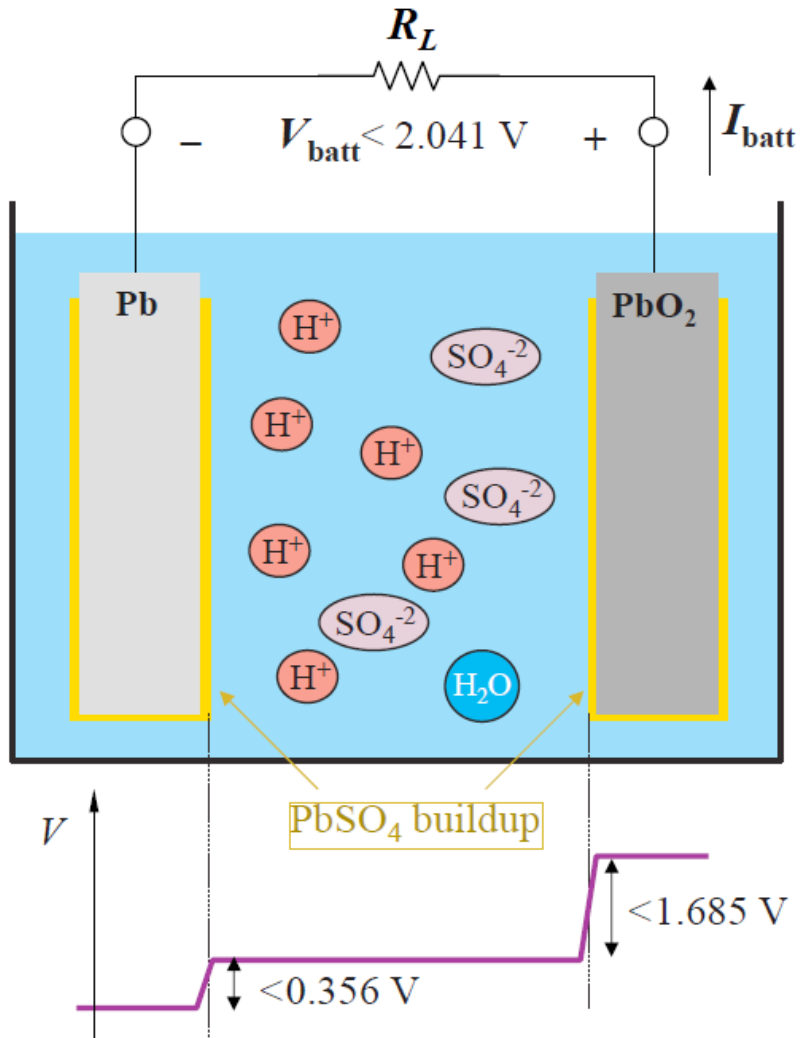
Open-circuit voltage under standard conditions ($T = 298^\circ\text{K}$ and 1 molar acid electrolyte) is

$$V_{\text{oc}} = 0.356 + 1.685 = 2.041 \text{ V}$$

“Sulfation” of electrodes and double-layers at surfaces limits further reactions

Temperature plays an important role (see Nernst equation later)

Battery Discharging through External Load



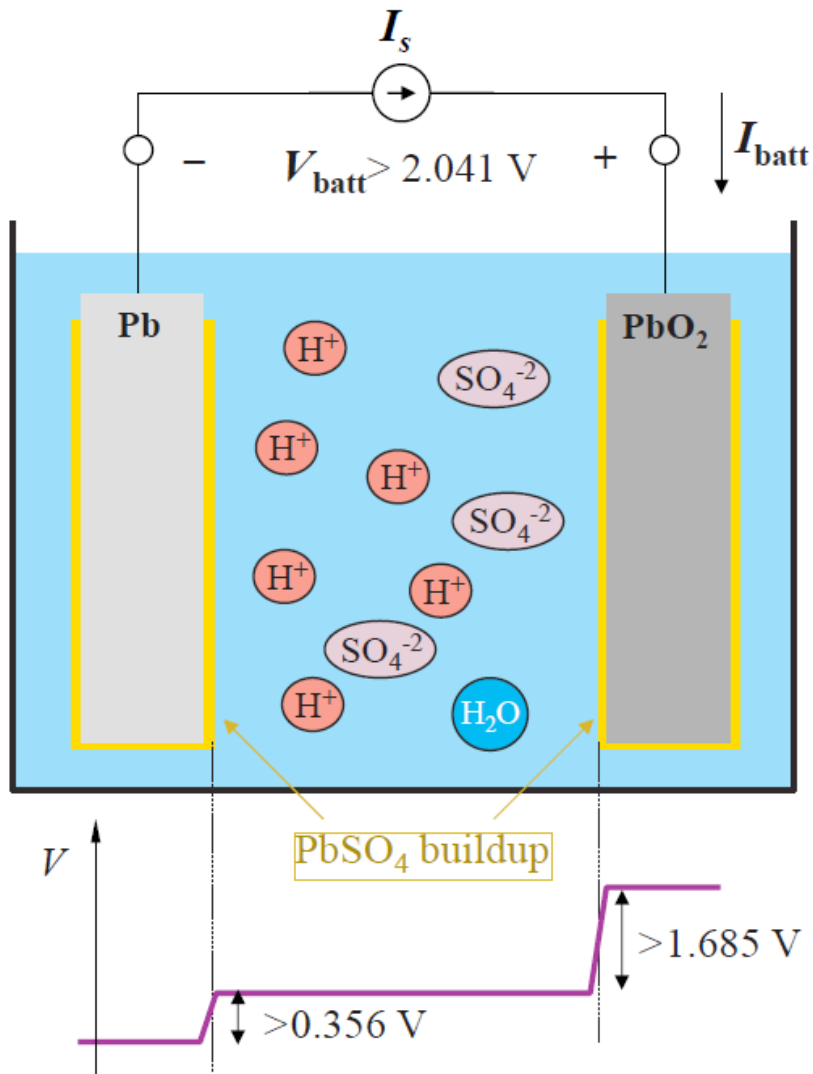
External load allows electrons to flow and chemical reactions to proceed

As battery is discharged, additional sulfation of electrodes occurs and acid electrolyte becomes weaker, lowering the terminal voltage

Note that current must flow through electrolyte to complete the circuit (combination of drift & diffusion currents)

The conductivity of electrolyte and the contact resistance of sulfated electrodes contribute to internal resistance of battery. Strong function of temperature and the state-of-charge of the system

Battery Charging from External Source



External source forces electrons to flow from positive to negative terminals

The chemical reactions are driven in the reverse direction, converting electrical energy into stored chemical energy

As the battery is charged, the lead sulfate coating on the electrodes is removed, and the acid electrolyte becomes stronger

Battery Charging from External Source

	Full Charged	Completely Discharged
State of charge (SOC)	100%	0%
Depth of discharge (DOD)	0%	100%
Electrolyte concentration, Q	~6 molar	~2 molar
Electrolyte specific gravity	~1.3	~1.1
No-load voltage, V_{oc} , @ 25C	12.7 (2.12V/cell)	11.7 (1.95 V/cell)

SOC (%) vs. OCV

An easy method to estimate the State of Charge (SOC) of the battery is by measuring its Open Circuit Voltage (OCV). This measurement should be made after the battery has been at rest for a minimum of four hours with the battery shut off from its charging source and load. The voltage is listed as Volts/cell and for a 12V (6 cell) battery at 25°C (77°F).

State of Charge (%)	OCV per cell	OCV per 12V battery
100	2.13 or greater	12.8 or greater
75	2.08	12.5
50	2.03	12.2
25	1.98	11.9
0	1.93 or less	11.6 or less

These voltage levels are approximate and give an indication of the state of charge of a battery at rest. As the battery ages these voltage measurements will be lower.

Voltage versus Electrolyte Concentration

The **Nernst** equation relates the chemical reaction energy to electrolyte energy:

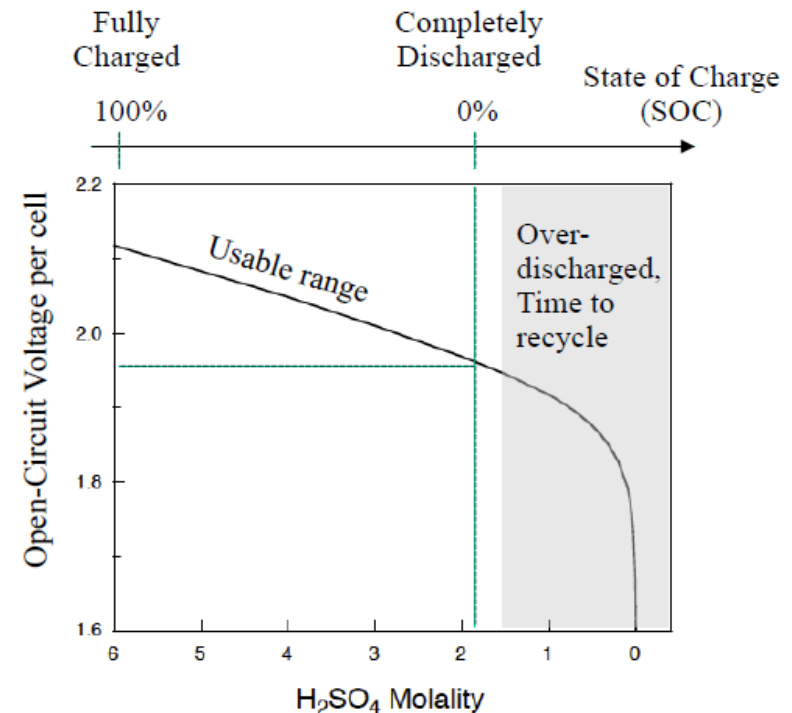
$$E = E^0 + \frac{kT}{q} \ln Q$$

where: E = energy at a given concentration
 E^0 = energy at standard 1 molar concentration
 Q = molar concentration
 $kT/q = 26$ mV at 298 °K

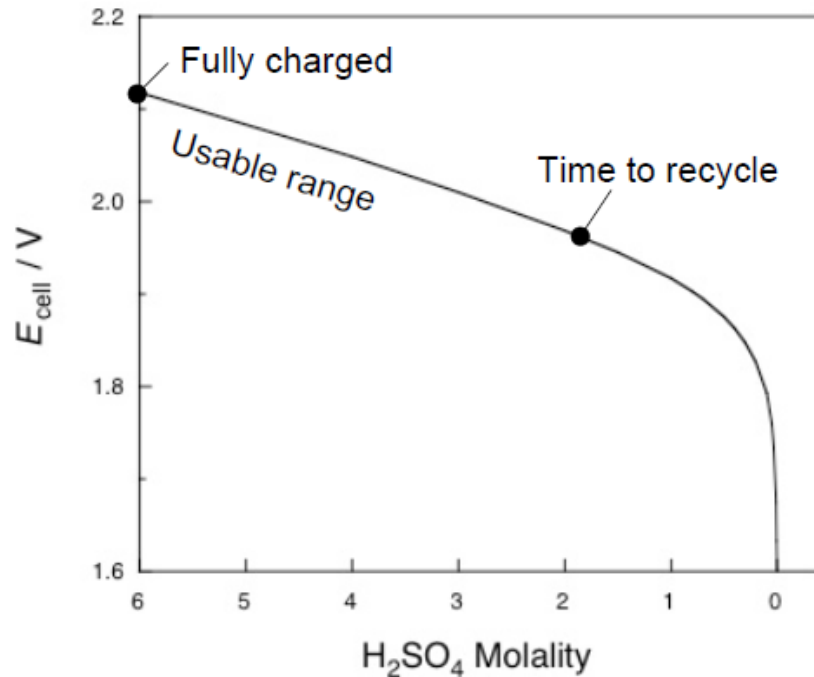
This is just an approximation for a real cell but gives some useful insight:

- At fully charged state (>6 molar), the cell voltage is a higher than E^0/q under standard conditions (1 molar)
- As the cell is discharged, the H_2SO_4 molality decreases so the open-circuit voltage decreases
- Voltage is temperature dependent (!)

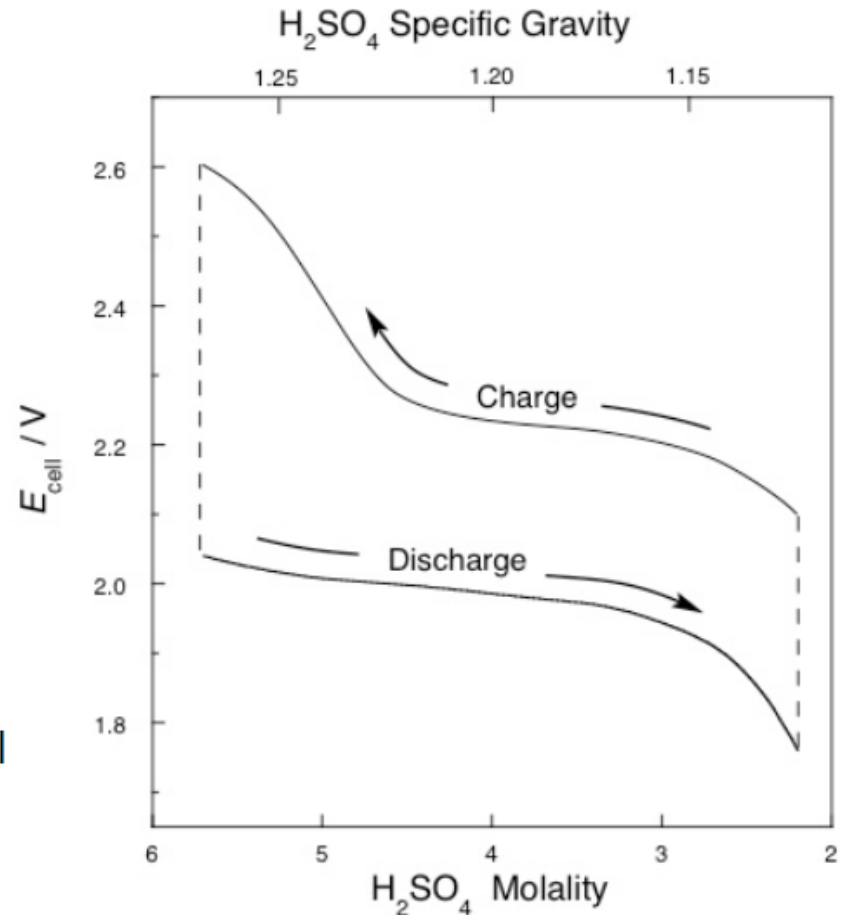
At some point of discharge the electrode sulfation builds to a point where it becomes difficult to recharge the battery. This “over-discharge” regime should be avoided. Battery manufacturers will specify “complete discharge” at some cell voltage



Voltage versus Electrolyte Concentration



Voltage of lead-acid electrochemical cell vs. electrolyte concentration, as predicted by Nernst equation



R. S. Treptow, "The lead-acid battery: its voltage in theory and practice," *J. Chem. Educ.*, vol. 79 no. 3, Mar. 2002

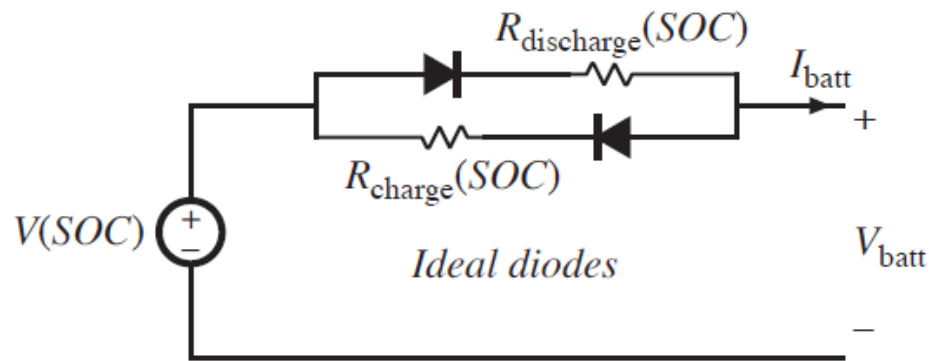
Mechanisms Effecting Terminal Voltage

1. Equilibrium voltage changes with electrolyte concentration (as described above – Nernst equation)
2. With current flow, there are resistive drops in electrodes, especially in surface lead-sulfate
3. With current flow, there is an electrolyte concentration gradient near the electrodes. Hence lower concentration at electrode surface; Nernst equation then predicts lower voltage
4. Additional surface chemistry issues: activation energies of surface chemistry, energy needed for movement of reacting species through electrodes
5. Physical resistance to movement of ions through electrodes

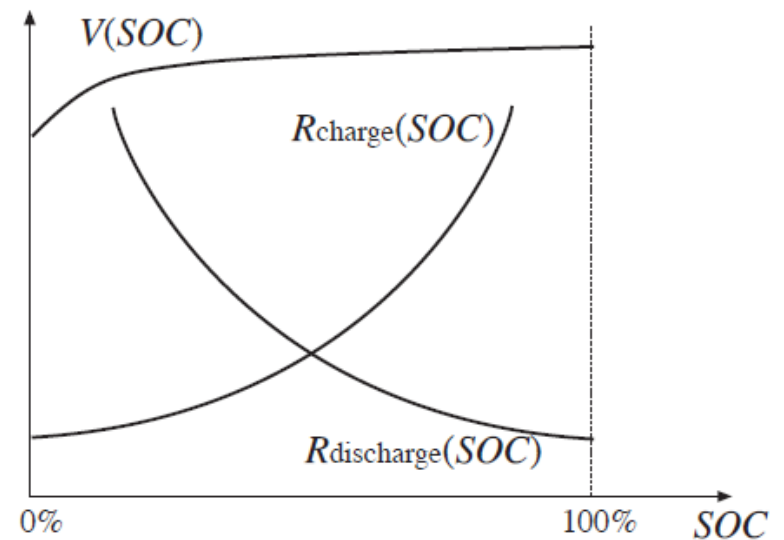
(2) - (5) can be modeled electrically as resistances

Basic Battery Model

Basic model



Dependence of model parameters on battery state of charge (SOC)



Types of Lead Acid Batteries

1. Car battery

- “SLI” - starter lighting ignition

- Designed to provide short burst of high current

 - Maybe 500 A to crank engine

- Cannot handle “deep discharge” applications

 - Typical lifetime of 500 cycles at 20% depth of discharge

2. Deep discharge battery

- More rugged construction

 - Bigger, thicker electrodes

 - Calcium (and others) alloy: stronger plates while maintaining low leakage current

 - More space below electrodes for accumulation of debris before plates are shorted

3. “Golf cart” or “forklift” batteries

- Similar to #2

- Bigger, very rugged

- Low cost — established industry

- Antimony alloy

 - Strong big electrodes

 - But more leakage current than #2

- Can last 10-20 years

Battery Capacity

The quantity C is defined as the current that discharges the battery in 1 hour, so that the battery capacity can be said to be C Ampere-hours (units confusion)

If we discharge the battery more slowly, say at a current of $C/10$, then we might expect that the battery would run longer (10 hours) before becoming discharged. In practice, the relationship between battery capacity and discharge current is not linear, and less energy is recovered at faster discharge rates.

Peukert's Law relates battery capacity to discharge rate:

$$C_p = I^k t$$

where C_p is the amp-hour capacity at a 1 A discharge rate

I is the discharge current in Amperes

t is the discharge time, in hours

k is the Peukert coefficient, typically 1.1 to 1.3

Battery Capacity Example

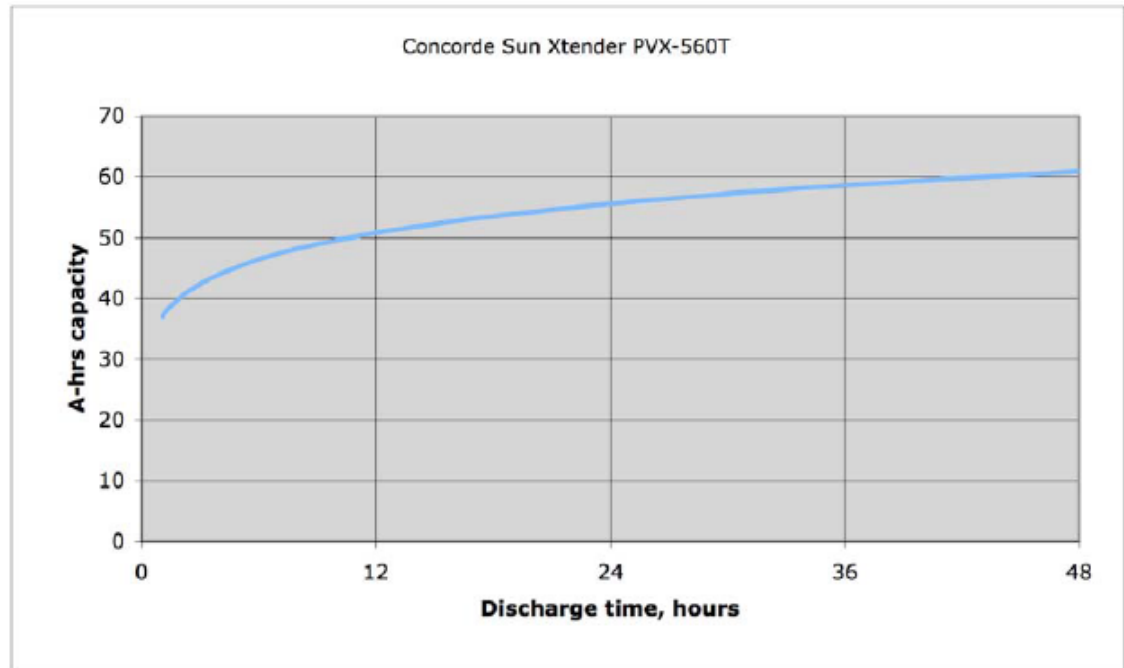
Our lab batteries

$$k = 1.15$$

$$C = 36 \text{ A}$$

$$C_p = 63 \text{ A-hr}$$

Prediction of Peukert equation is plotted at left



What the manufacturer's data sheet specified:

Nominal capacity: A-hrs @ 25°C to 1.75 V/cell				
1 hr	2 hr	4 hr	8 hr	24 hr
36 A-hr	45 A-hr	46 A-hr	49 A-hr	56 A-hr

Battery Efficiency

$$\text{Efficiency } \eta = E_D / E_C$$

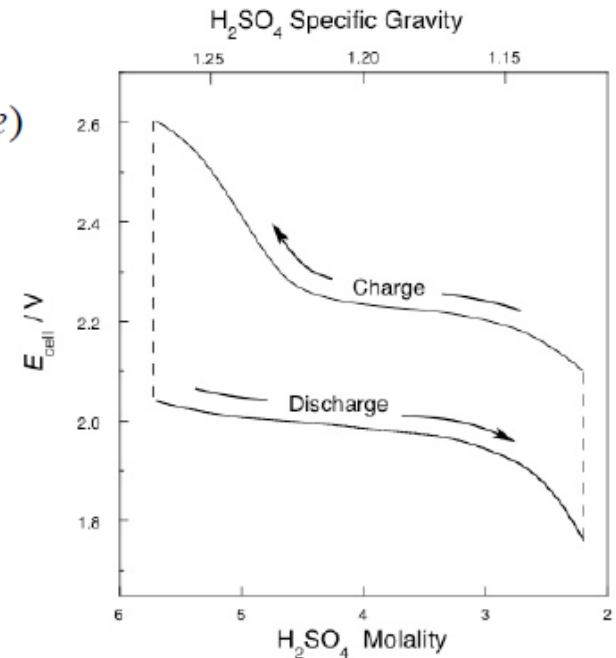
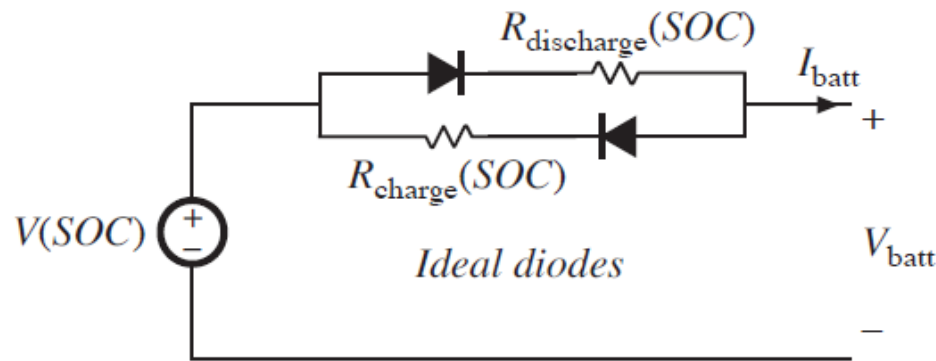
$$E_C = \text{Total energy during charging} = \int v_{\text{batt}} (-i_{\text{batt}}) dt \approx V_C I_C T_C$$

$$E_D = \text{Total energy during discharging} = \int v_{\text{batt}} i_{\text{batt}} dt \approx V_D I_D T_D$$

$$\text{Energy efficiency} = \left(\frac{V_D}{V_C} \right) \left(\frac{I_D T_D}{I_C T_C} \right) = \left(\text{voltage efficiency} \right) \left(\text{coulomb efficiency} \right)$$

$$\text{Coulomb efficiency} = (\text{discharge A-hrs}) / (\text{charge A-hrs})$$

$$\text{Voltage efficiency} = (\text{discharge voltage}) / (\text{charge voltage})$$



Battery Efficiency Example

Energy is lost during charging when reactions other than reversal of sulfation occur

At beginning of charge cycle, coulomb efficiency is near 100%

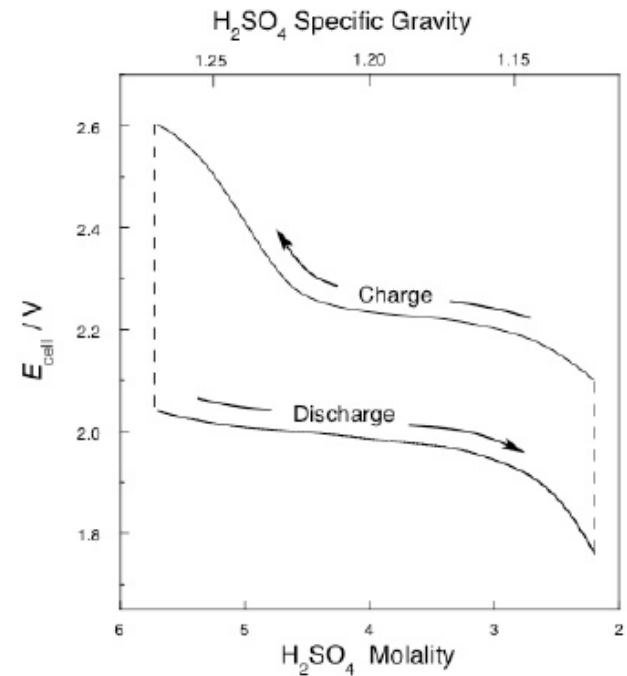
Near end of charge cycle, electrolysis of water reduces coulomb efficiency. Can improve this efficiency by reducing charge rate (taper charging)

Typical net coulomb efficiency: 90%

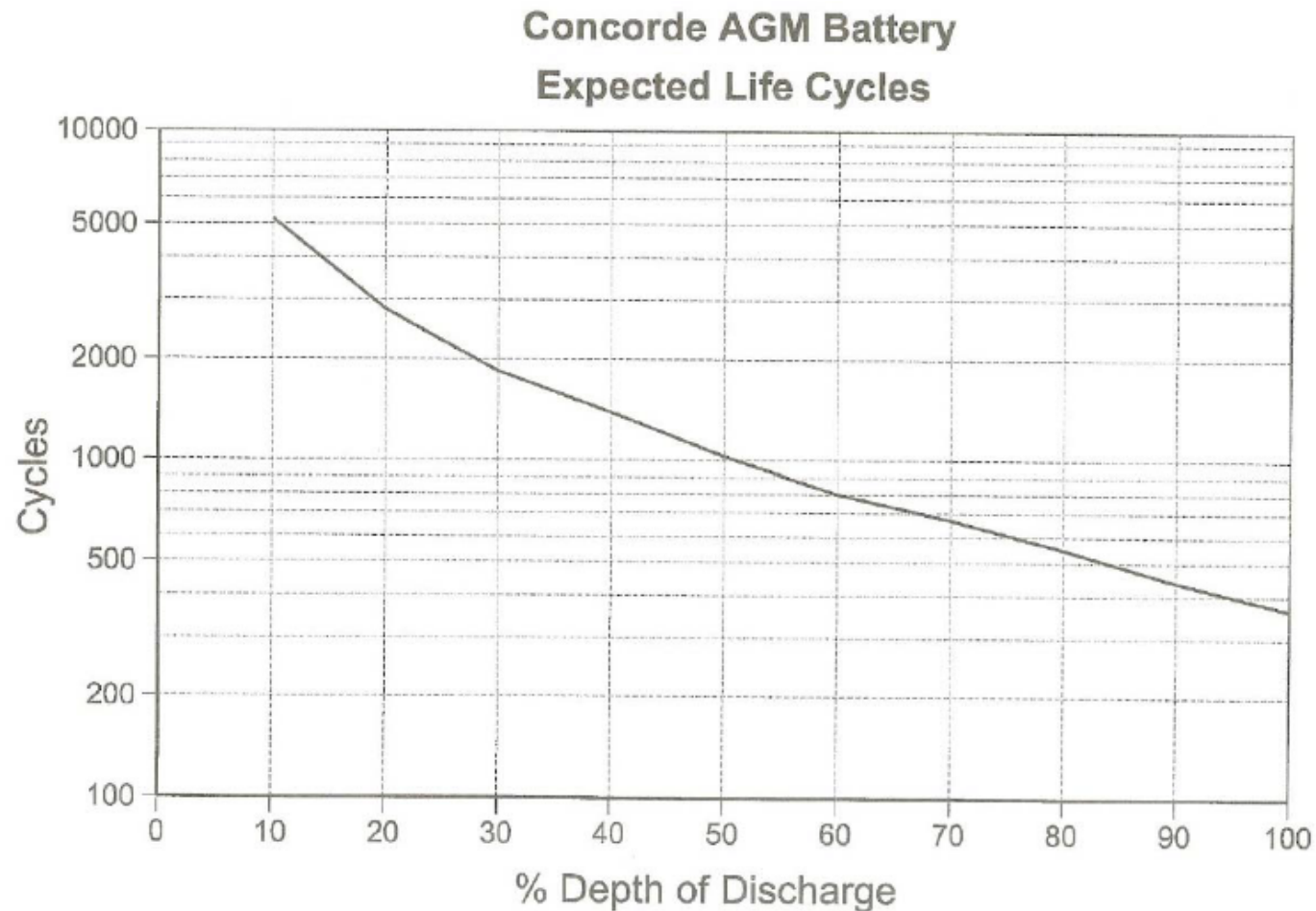
Approximate voltage efficiency: $(2V)/(2.3V) = 87\%$

Energy efficiency = $(87\%)(90\%) = 78\%$

Commonly quoted estimate: 75%



Battery Life



Test Conditions:

1. Discharge Voltage=1.75 Volts/Cell 2. Charge Voltage=2.40 Volts/Cell 3. DOD=100 % 4. Battery Temperature=25°C 5. End of Life=80 % of Capacity

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Concorde Battery Corporation, 2009 San Bernardino Rd, West Covina, CA, 91790 www.concordebattery.com Phone: 626-813-1234

Battery Charge Management

Over-discharge leads to “sulfation” and the battery is ruined. The reaction becomes irreversible when the size of the lead-sulfate formations become too large

Overcharging causes other undesirable reactions to occur

- Electrolysis of water and generation of hydrogen gas

- Electrolysis of other compounds in electrodes and electrolyte, which can generate poisonous gasses

- Bulging and deformation of cases of sealed batteries

Battery charge management to extend life of battery:

- Limit depth of discharge

- When charged but not used, employ “float” mode to prevent leakage currents from discharging battery

- Pulsing to break up chunks of lead sulfate

- Trickle charging to equalize charges of series-connected cells

Battery Charge Profile

A typical good charge profile:

Bulk charging at maximum power

Terminate when battery is 80% charged
(when a voltage set point is reached)

Charging at constant voltage

The current will decrease

This reduces gassing and improves
charge efficiency

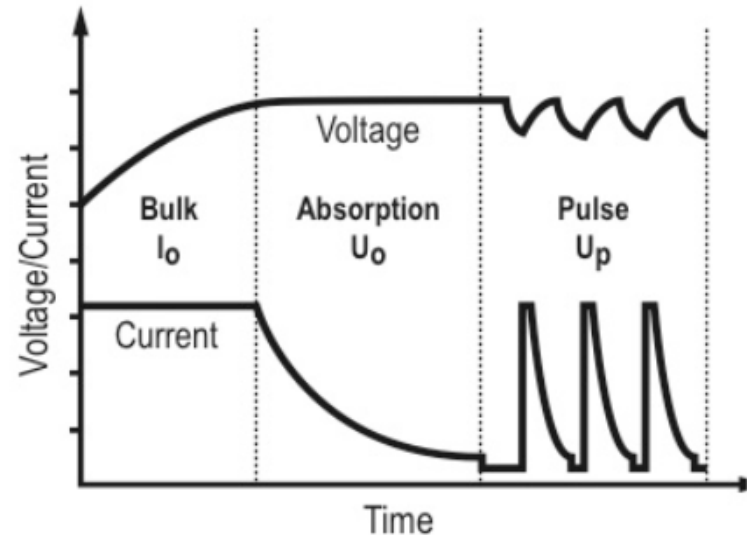
“Absorption” or “taper charging”

Trickle charging / float mode

Equalizes the charge on series-connected
cells without significant gassing

Prevents discharging of battery by
leakage currents

Occasional pulsing helps reverse sulfation
of electrodes



The three-step charge profile used
by the chargers in our power lab