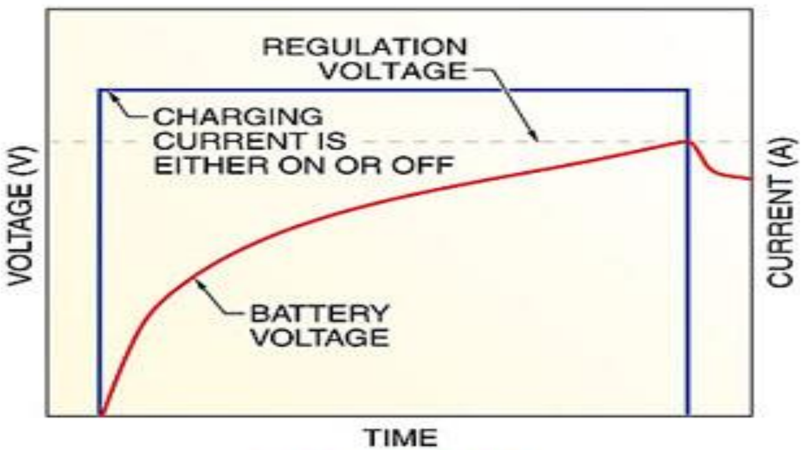
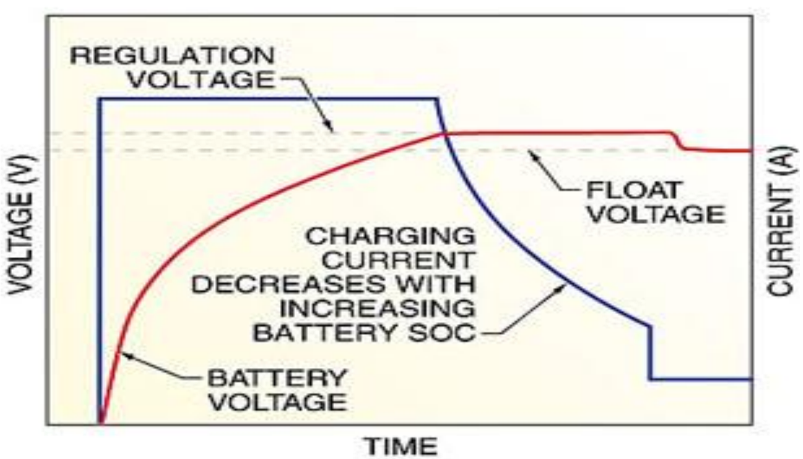
T8

PV Batteries

Charging



SINGLE-STAGE

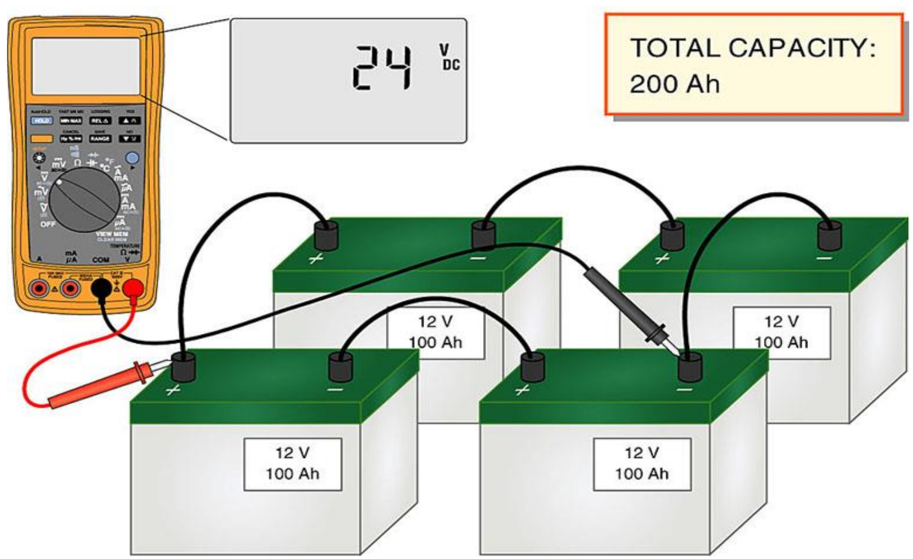


MULTISTAGE

Batteries

East Penn Manufacturing Co., Inc.

Batteries in Series and Parallel



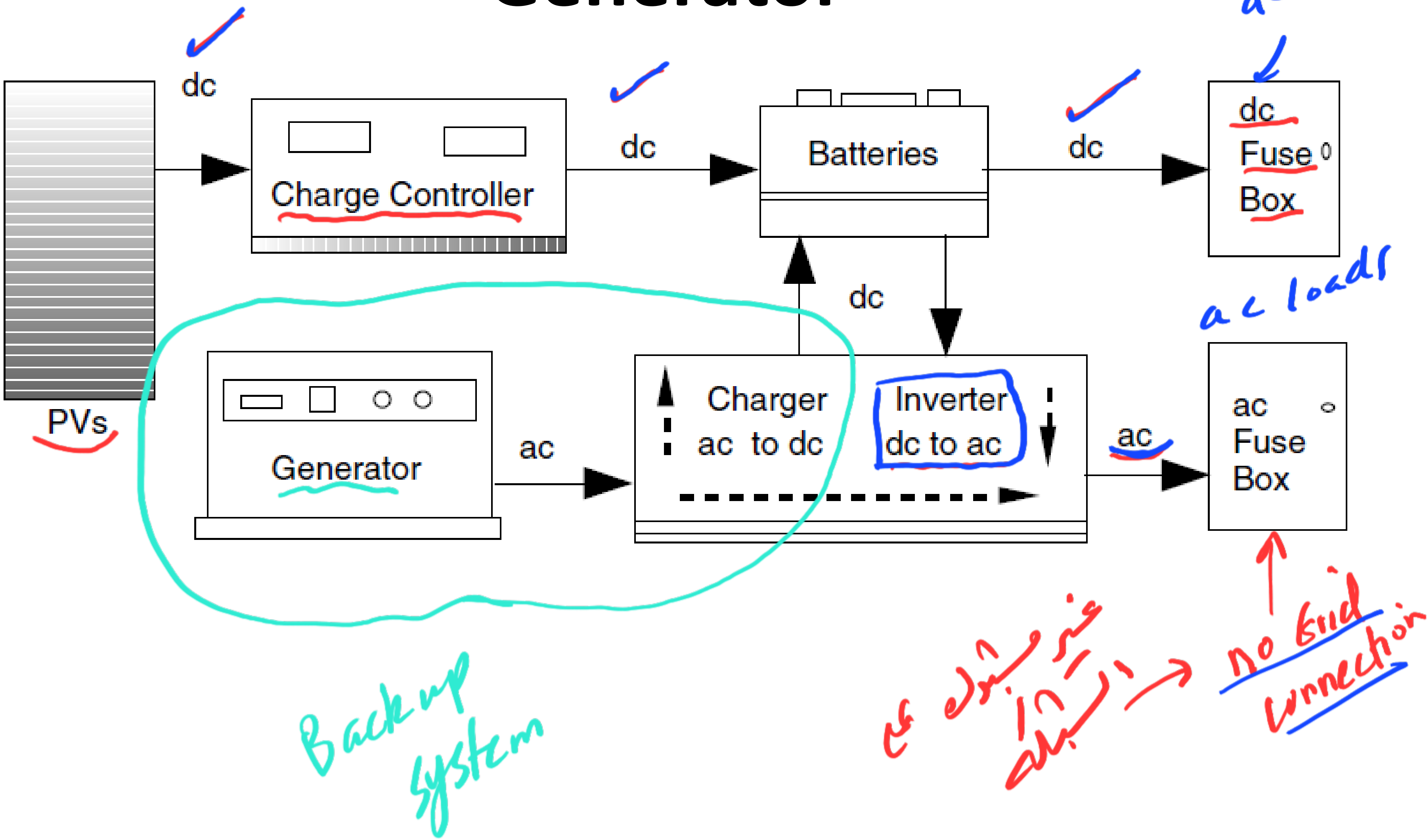
ENEE5307

2021

Outline

- Battery Principles
- Battery Types
- Battery Systems

Standalone PV System with Backup Generator



Batteries

- Stand-alone systems need a method to store energy gathered during good times to be able to use it during the bad.
- Lead-acid batteries are presently the most commonly used type in PV systems.
- In addition to energy storage, batteries provide several other important energy services for PV systems, :
- 1) the ability to provide surges of current that are much higher than the instantaneous current available from the array,
- 2) Controlling the output voltage of the array so that loads receive voltages that are within their own range of acceptability.

Batteries Classifications

1. Primary Batteries- cannot be recharged

2. Secondary batteries: can be recharged

- Batteries are divided into classes based on discharge and cycle characteristics.
- **Secondary batteries are often classified as**: traction; starting, lighting, and ignition (SLI); or stationary batteries.
- The differences in their design and materials result in different discharge and cycle characteristics

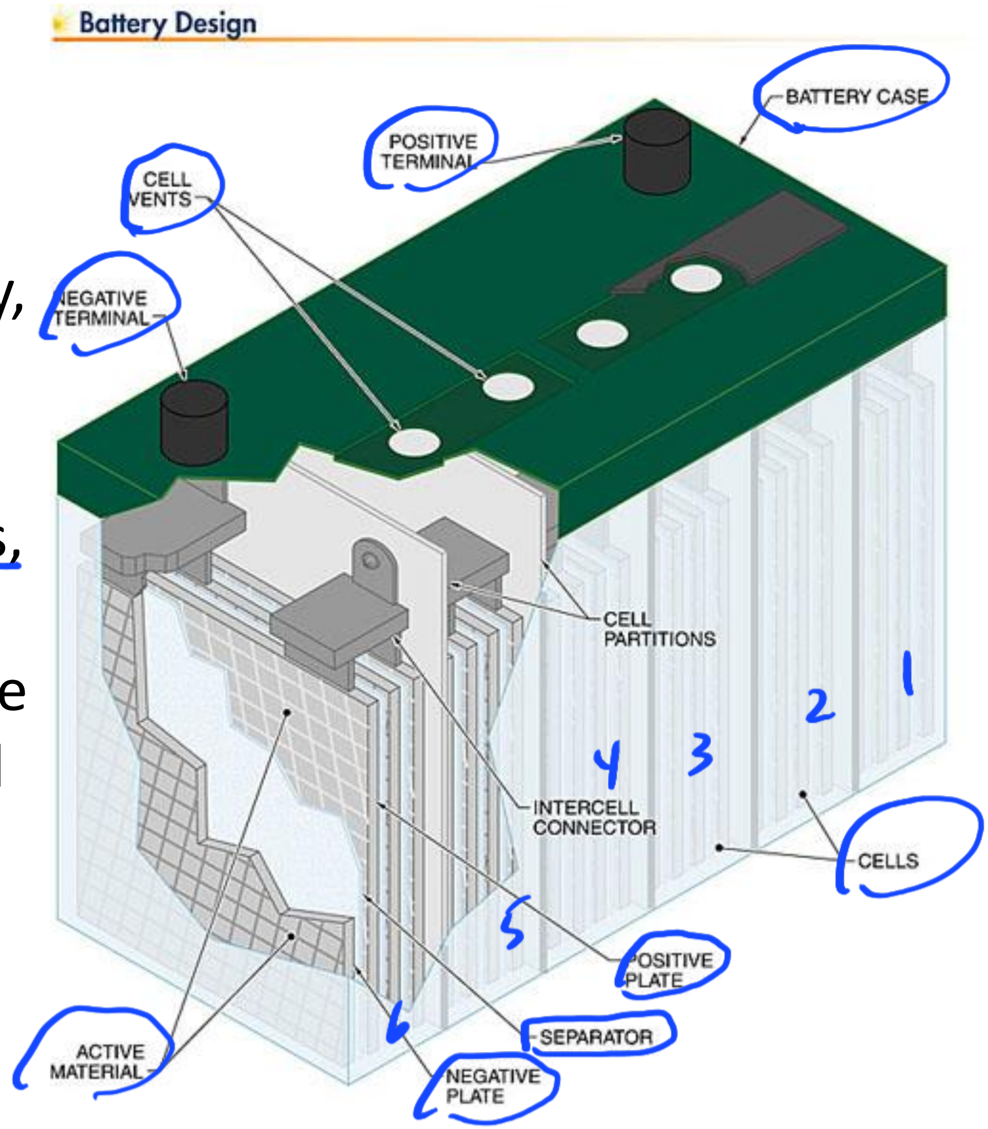
Battery Classifications

TRACTION BATTERIES

SLI BATTERIES

STATIONARY BATTERIES

- **Many components are common to various battery types.**
- **In each cell**, there can be a single pair or, more commonly, **several pairs of positive and negative plates.**
- When there are multiple pairs, all the positive plates are connected together and all the negative plates are connected together.
- ***Electrolyte*** is the conducting medium that allows the transfer of ions between battery cell plates.
- Electrolyte may be in a liquid or gelled form.



- **Thicker plates** tolerate deeper discharges over long periods while maintaining good adhesion of the active material to the grid, resulting in longer battery life.
- Thicker plates and larger cases mean that these batteries are big and heavy.
- A single 12-V deep-discharge battery can weigh several hundred pounds.
- They are designed to be discharged repeatedly by 80% of their capacity without harm, although such deep discharges result in a lower lifetime number of cycles
- **Thinner plates** allow more pairs per cell, maximizing surface area for delivering high currents.

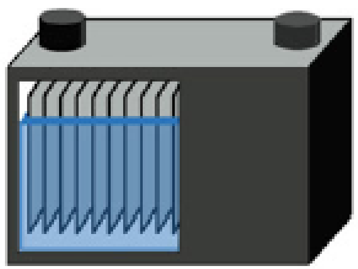


Figure 1: Starter battery

The starter battery has many thin plates in parallel to achieve low resistance with high surface area. The starter battery does not allow deep cycling.

Courtesy of Cadex

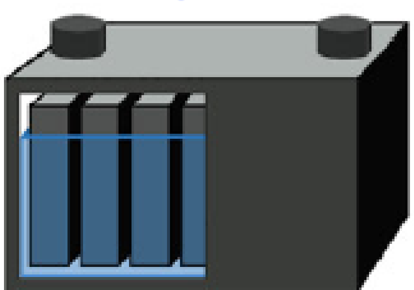


Figure 2: Deep-cycle battery

The deep-cycle battery has thick plates for improved cycling abilities. The deep-cycle battery generally allows about 300 cycles.

Courtesy of Cadex

Types of Batteries for PV Systems

- Lead-acid batteries are the most common type of batteries used in PV systems.
- Lead-acid batteries are generally inexpensive and widely available in many capacities from 10 Ah to over 1000 Ah.
- Their deep-cycle characteristics make them ideal for PV applications, **but they do not tolerate extreme temperatures well and may require frequent maintenance**
- The characteristics of lead-acid batteries vary between different designs.

Lead-Acid Battery Characteristics

	TYPE	COST	AVAILABILITY	DEEP-CYCLE PERFORMANCE	TEMPERATURE TOLERANCE	MAINTENANCE
Flooded electrolyte	Lead-antimony	low	very good	good	good	high
	Lead-calcium open-vent	low	very good	poor	poor	medium
	Lead-calcium sealed-vent	low	very good	poor	poor	low
	Lead-antimony/lead-calcium	low	limited	good	good	medium
Captive electrolyte	Lead-calcium sealed-vent	medium	limited	fair	poor	low
	Lead-antimony/lead-calcium	medium	limited	fair	poor	low

Types of Batteries for PV Systems

- Competitors to conventional lead-acid batteries include:

(1) nickel–cadmium,

(2) nickel–metal hydride,

(3) lithium–ion,

(4) lithium–polymer,

(5) and nickel–zinc technologies.

- Of these, only nickel–cadmium "Nicads" are even barely competitive with lead-acid batteries, but this may change in the near future due to the surge of interest and development in new battery technologies for electric and hybrid vehicles.
- Table (next slide) summarizes typical values of some of the important characteristics of these battery technologies. **(research on Battery Types and new Technologies)**

TABLE 9.14 Rough Comparison of Battery Characteristics[a]

Battery	Max Depth Discharge	Energy Density (Wh/kg)	Cycle Life (cycles)	Calendar Life (years)	Efficiencies Ah %	Efficiencies Wh %	Cost ($/kWh)
Lead-acid, SLI	20%	50	500	1–2	90	75	50
Lead-acid, golf cart	80%	45	1000	3–5	90	75	60
Lead-acid, deep-cycle	80%	35	2000	7–10	90	75	100
Nickel–cadmium	100%	20	1000–2000	10–15	70	60	1000
Nickel–metal hydride	100%	50	1000–2000	8–10	70	65	1200

[a] Actual performance depends greatly on how they are used.

- Lead-acid batteries are listed in three categories:

1)conventional automobile batteries for engine starting, vehicle lighting, and engine ignition (SLI);

2)low-cost, deep-cycle batteries typically used in golf carts; and

3) longer-lifetime, true deep-cycle batteries.

- Two other battery types are shown, nickel–cadmium (or Nicads) and nickel–metal hydride batteries, which are beginning to be used in some hybrid-electric vehicles.

- As can be seen, lead-acid batteries are by far the least expensive option, they have the highest efficiencies, and the more expensive ones, when used properly, can last nearly as long as their competitors.

TABLE 9.14 Rough Comparison of Battery Characteristics[a]

Battery	Max Depth Discharge	Energy Density (Wh/kg)	Cycle Life (cycles)	Calendar Life (years)	Efficiencies Ah %	Efficiencies Wh %	Cost ($/kWh)
Lead-acid, SLI	20%	50	500	1–2	90	75	50
Lead-acid, golf cart	80%	45	1000	3–5	90	75	60
Lead-acid, deep-cycle	80%	35	2000	7–10	90	75	100
Nickel–cadmium	100%	20	1000–2000	10–15	70	60	1000
Nickel–metal hydride	100%	50	1000–2000	8–10	70	65	1200

[a] Actual performance depends greatly on how they are used.

Basics of Lead-Acid Batteries

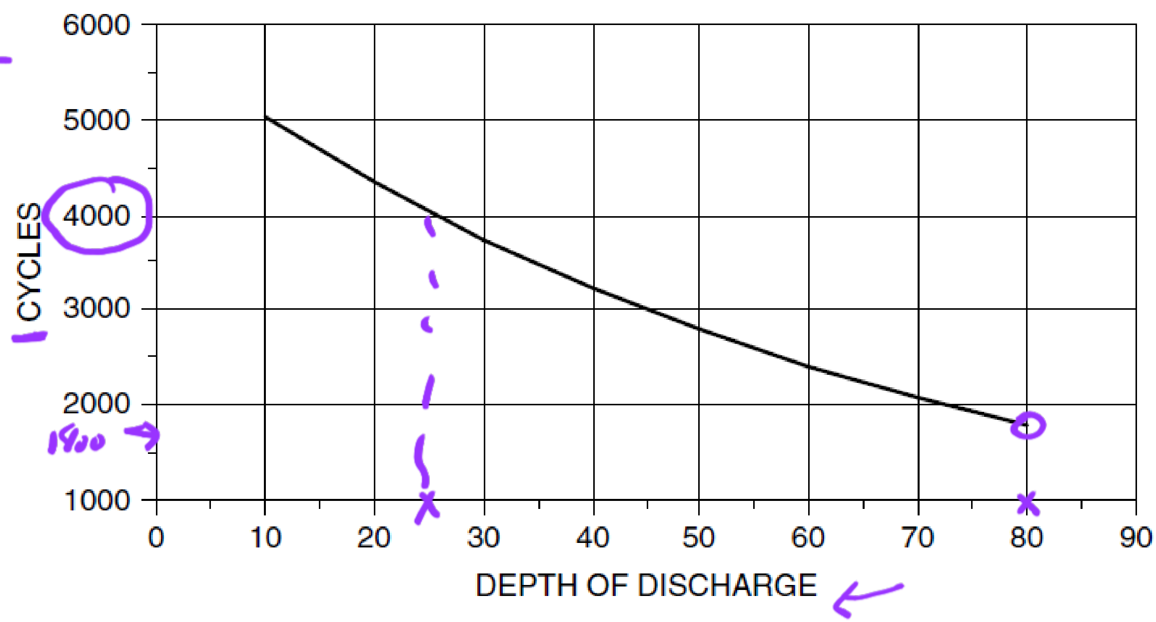
- Lead-acid batteries date back to the 1860s when inventor Raymond Gaston Plant´e fabricated the first practical cells
- Many advances since then have lead to a global market that now **exceeds $30 billion in annual retail sales**, with about three-fourths of that being starting, lighting, and ignition (SLI) automobile batteries.
- The largest Battery bank is found **in Chino, California**, is capable of **delivering 4 h of 10 MW power** (5000 A at 2000 V) into the grid.
- Automobile SLI batteries have been highly refined to perform their most important task, which is to start your engine.
- To do so, they have to provide short bursts of very high current (400–600 A!).
- Once the engine has started, its alternator quickly recharges the battery, which means that under normal circumstances the battery is almost always at or near full charge.

20% discharge only

Lead-Acid Batteries (حمض الرصاص)

- SLI batteries are not designed to withstand deep discharges, and in fact they will fail after only a few complete-discharge cycles.
- This makes them inappropriate for most PV systems, in which slow, but deep, discharges are the norm.
- If they must be used, as is sometimes the case in developing countries where they may be the only batteries available, daily discharges of less than about 20% can yield approximately 500 cycles, or a year or two of operation.
- In comparison with SLI batteries, deep discharge batteries have thicker plates, which are housed in bigger cases that provide greater space both above and beneath the plates.
- Greater space below allows more debris to accumulate without shorting out the plates, and greater space above lets there be more electrolyte in the cell to help keep water losses from exposing the plates

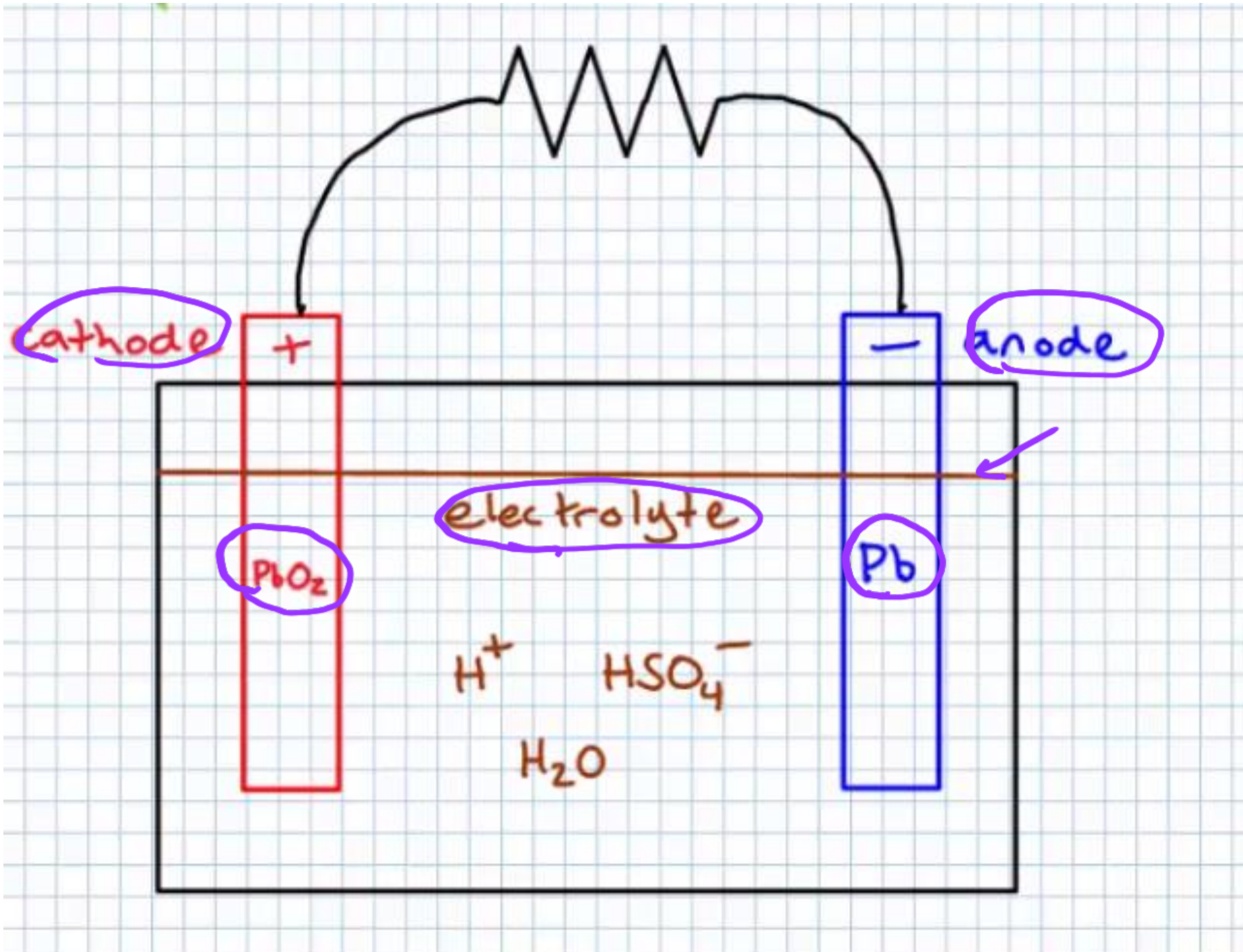
- Figure below suggests that a typical deep-cycle, lead-acid battery can be cycled about 4000 times when discharged by 25% of its rated capacity, which would give it a lifetime of over 10 years.
- At a daily discharge of 80%, about 1800 cycles could be expected, which suggests a lifetime of around 5 years.
- Other factors, including quality of battery, frequency of maintenance, charge rates, and final charging cut-off vo



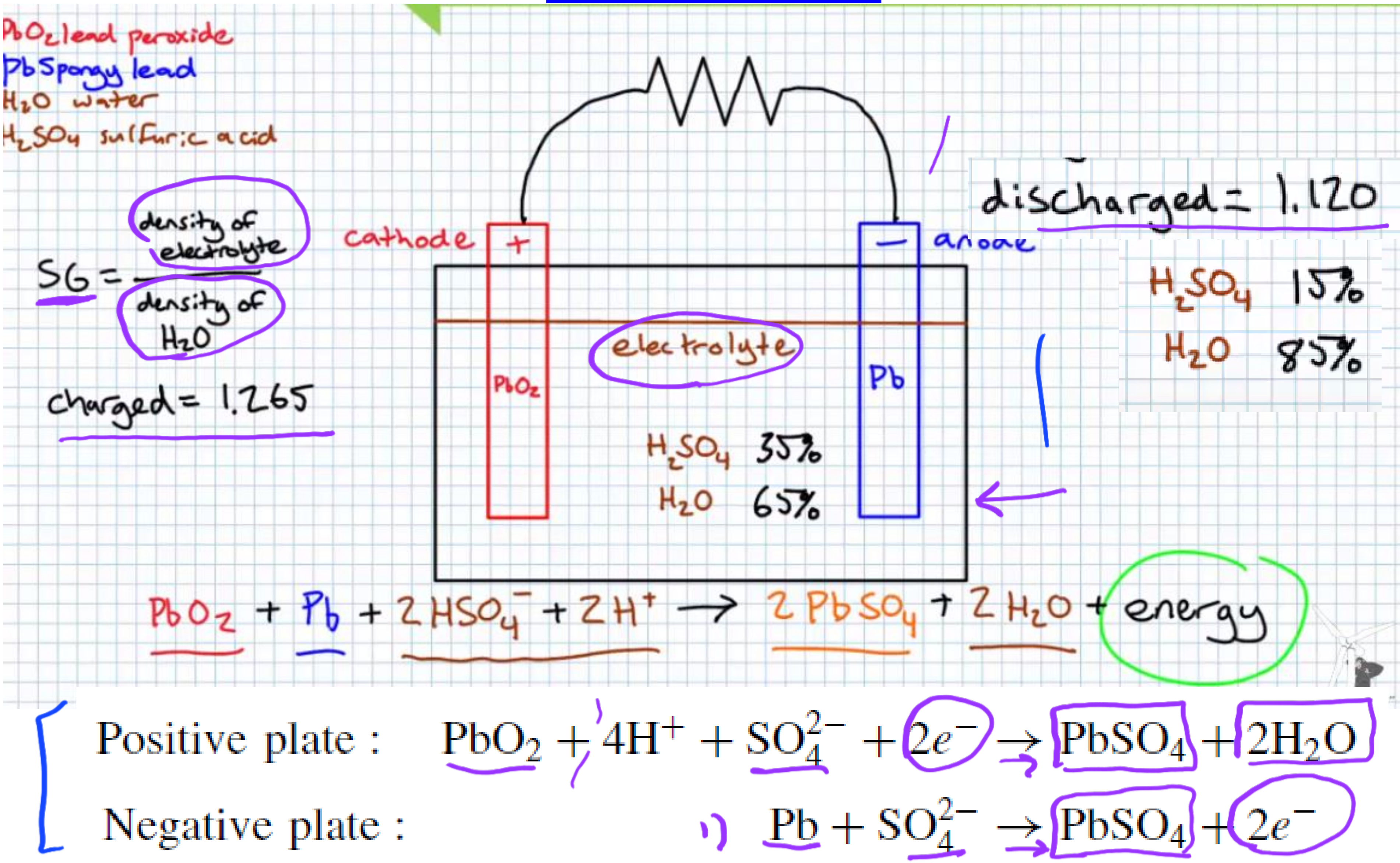
Impact of depth of discharge on the number of cycles a typical deep-cycle lead-acid battery might be able to provide. An automobile SLI battery delivers only around 500 cycles at 20% discharge.

Battery Chemistry (self Study)

- To understand some of the subtleties in sizing battery systems, we need a basic understanding of their chemistry.
- Very simply, an individual 2-V cell in a lead-acid battery consists of a positive electrode made of lead dioxide **(PbO_2)** and an negative electrode made of a highly porous (مسامية عالية), metallic lead (Pb) structure, both of which are completely immersed (مغموره تماما) in an electrolyte consisting of a dilute solution of **sulfuric acid** (حمض الكبريتيك)and water.
- Thin lead plates are structurally very weak and would not hold up well to physical abuse unless **alloyed** with a strengthening material.
- Automobile SLI batteries use **calcium for strengthening**, but calcium does not tolerate discharges more than about 25 percent very well.
- Deep discharge batteries use **antimony Sb** (الاثمد من اشباه المعادن عدده الذري 51)instead, and so are often referred to as lead-antimony batteries.


cathode
+
PbO2
electrolyte
H+
HSO4−
H2O
−
anode
Pb

https://www.youtube.com/watch?v=ZRruGTRHqiw



Chemical Reactions (self study)

- The chemical reactions taking place while the battery **discharges** are as follows:

SO4 كبريتات او سلفات

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

$$\text{Negative plate: } Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

- It is, by the way, simpler to refer to the terminals by their charge (positive or negative) rather than as the anode and cathode.
- Strictly speaking, the anode is the electrode at which oxidation occurs, which means that during discharge the anode is the negative terminal, but during charging the anode is the positive terminal.
- As can be seen from equation 2, during discharge the electrons are released at the negative electrode, which then flow through the load to the positive plate where they enter into the reaction given by equation 1 above

Chemical Reactions - Discharging

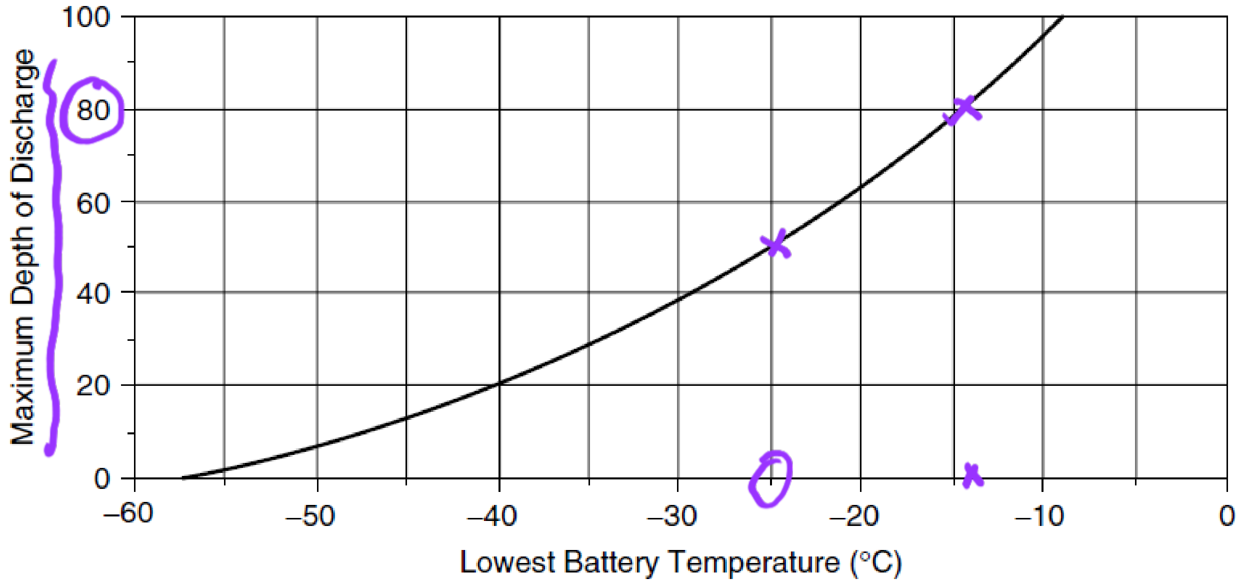
Positive plate : $PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$

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

- The key feature of both reactions is that sulfate ions (SO_4^{2-}) that start out in the electrolyte when the battery is fully charged end up being deposited onto each of the two electrodes as lead sulfate ($PbSO_4$) during discharge.
- **This lead sulfate, which is an electrical insulator, blankets the electrodes, leaving less and less active area for the reactions to take place.**
- **As the battery approaches its fully discharged state, the cell voltage drops sharply while its internal resistance rises abruptly** , SG is reduced

- During discharge the specific gravity of the electrolyte drops as sulfate ions leave solution, providing an accurate indicator of the battery's state of charge (SOC)
- The battery is more vulnerable to freezing in its discharged state since the anti-freeze action of the sulfuric acid is diminished when there is less of it present.
- A fully discharged lead-acid battery will freeze at around −8∘C (17∘F), while a fully charged one won't freeze until the electrolyte drops below −57∘C (−71∘F).
- In very cold conditions, concern for freezing may limit the maximum allowable depth of discharge, as shown below.

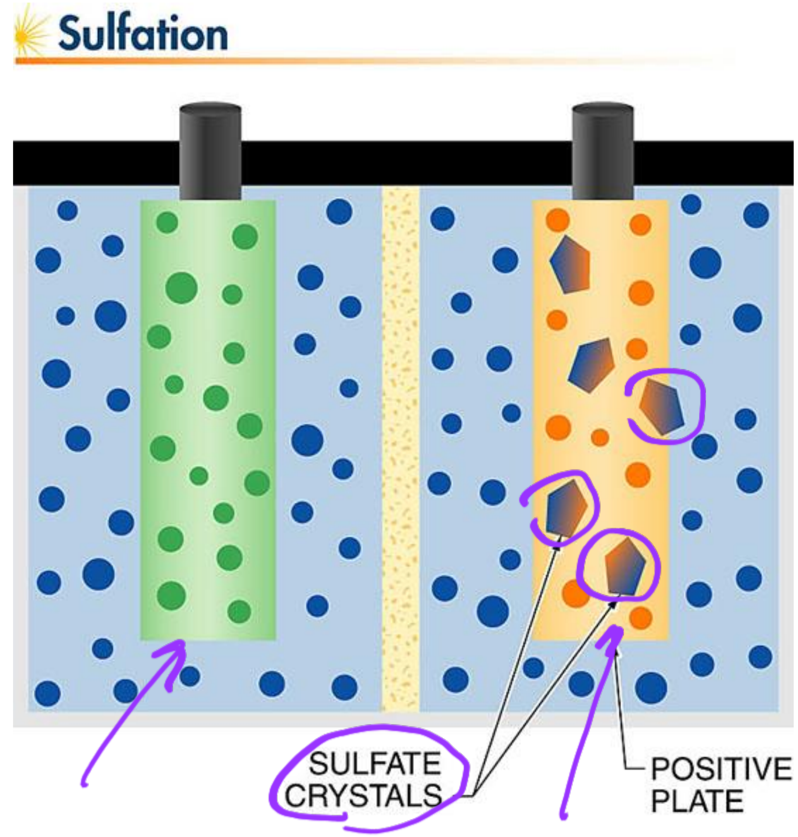
Concern for battery freezing may limit the allowable depth of discharge of a lead-acid battery.



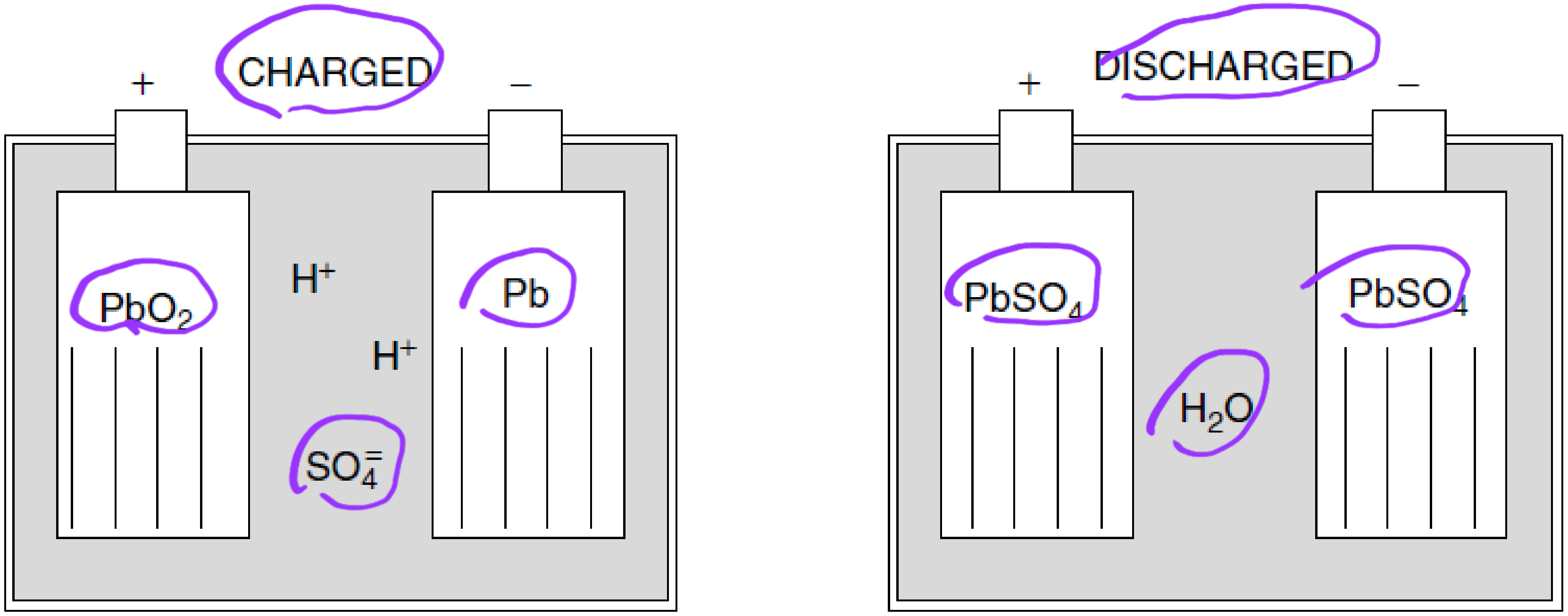
Chemical Reactions - Charging

- The opposite reactions occur during charging.
- Battery voltage and specific gravity rise, while freeze temperature and internal resistance drop.
- Sulfate is removed from the plates and reenters the electrolyte as sulfate ions
- Unfortunately, not all of the lead sulfate returns to solution, and each battery charge/discharge cycle leaves a little more sulfate permanently attached to the plates.
- **This sulfation is a primary cause of a battery's finite lifetime.**

- **Sulfation:** The amount of lead sulfate that permanently bonds to the electrodes depends on the length of time that it is allowed to exist, **which means that for good battery longevity it is important to keep batteries as fully charged as possible and to completely charge them on a regular basis.**



- Sulfation reduces the capacity of a lead-acid cell by locking away active material as crystals.



A lead-acid battery in its charged and discharged states.

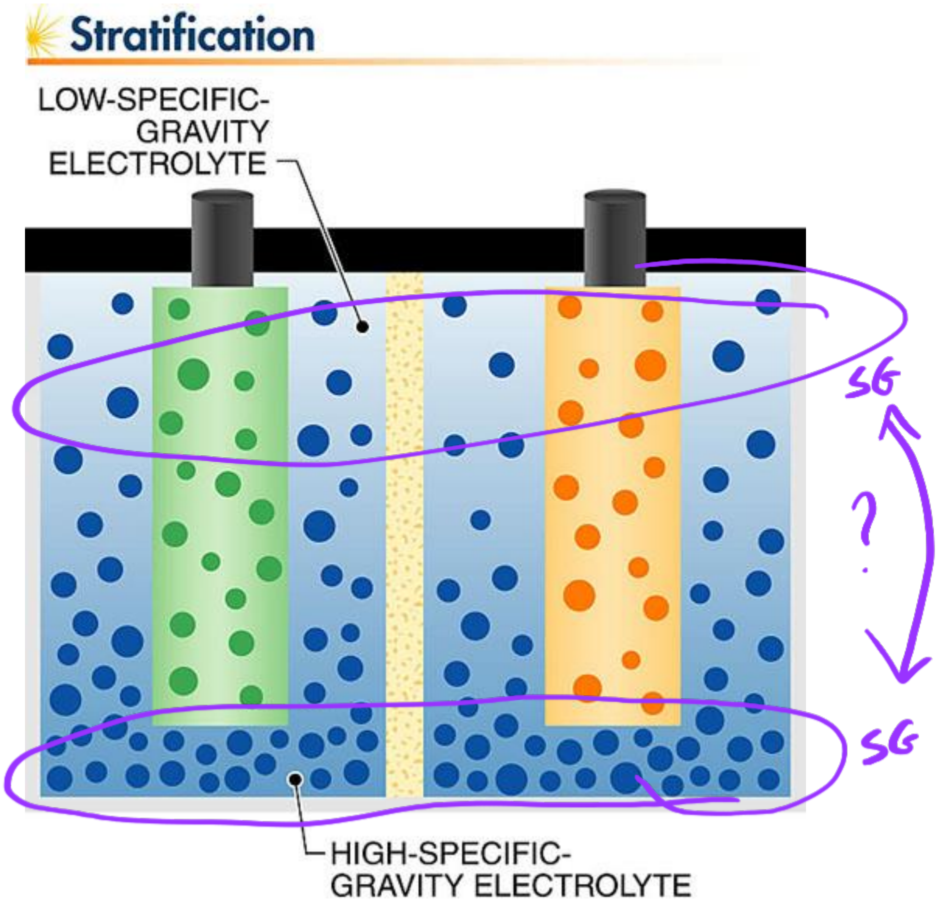
$$\text{Positive plate}: \quad PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O$$

$$\text{Negative plate}: \quad Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-$$

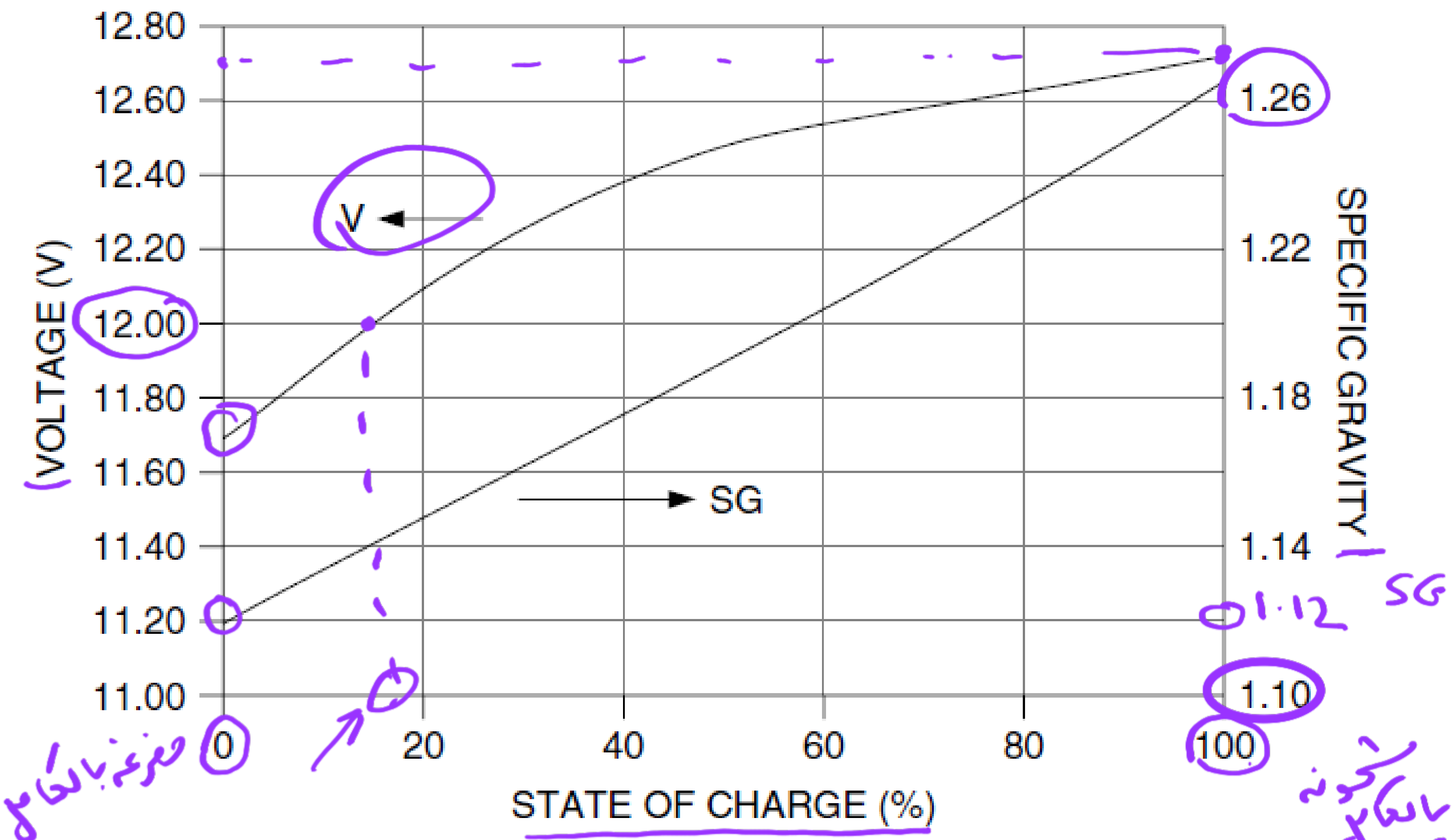
See movie

- As batteries cycle between their charged and partially discharged states, the voltage as measured at the terminals and the specific gravity of the electrolyte changes.
- While either may be used as an indication of the state of charge (SOC) of the battery, both are tricky to measure correctly.
- **To make an accurate voltage reading, the battery must be at rest, which means that at least several hours must elapse after any charging or discharging.**
- Specific gravity is also difficult to measure since **stratification of the electrolyte means that a sample taken from the liquid above the plates may not be an accurate average value.**
- **Stratification (ترسب)** results when the specific gravity of the electrolyte is higher at the bottom of a cell than at the top.

- During charging, electrolyte acid ions form on the plates and gradually descend to the bottom of the cell.
- Over time, the electrolyte can develop a greater acid concentration at the bottom of the cell than at the top.



Stratification is generally the result of low charge rates or undercharging, which does not produce the gassing needed to agitate the electrolyte



Bearing those complications in mind, Figure above shows voltage for a nominal lead-acid 12-V battery at rest along with the specific gravity for a well-mixed electrolyte, as a function of the state of charge.

It is interesting to note that a 12-V battery is only about 20% charged when its terminal voltage is 12 V.

Battery Storage CAPACITY

- *Capacity* is the measure of the electrical energy storage potential of a cell or battery.
- Several **physical factors** affect the capacity, including the quantity of active material; the number, design, and dimensions of the plates; and the electrolyte concentration.
- **Operational factors** affecting capacity include discharge rate, charging method, temperature, age, and condition of the cell or battery.
- Capacity is commonly expressed in ampere-hours (Ah), but can also be expressed in watt-hours (Wh). For example, a battery that delivers 5 A for 20 hr has delivered 100 Ah.
- If the battery averages 12 V during discharge, the capacity can also be expressed as 1200 Wh (100 Ah x 12V = 1200 Wh).

Battery Storage Capacity

- Energy storage in a battery is typically given in units of amp-hours (Ah) **at some nominal voltage and at some specified discharge rate.**
- A lead-acid battery, for example, has a nominal voltage of 2 V per cell (e.g., 6 cells for a 12-V battery), and manufacturers typically specify the amp-hour capacity at a discharge rate that would drain the battery down over a specified period of time at a temperature of 25◦C.
- For example, a fully charged 12-V battery that is specified to have a 10-h, 200-Ah capacity could deliver 20 A for 10 h, at which point the battery would be considered to be fully discharged

Extra Resources

- https://www.youtube.com/watch?v=sM2ss-EvAco

- https://www.youtube.com/watch?v=ZRruGTRHqiw
- Battery Charging Detailed
- https://www.youtube.com/watch?v=B9XLbuvq9As
- https://www.youtube.com/watch?v=A6mKd5_-abk

Battery Capacity and Discharge Rate

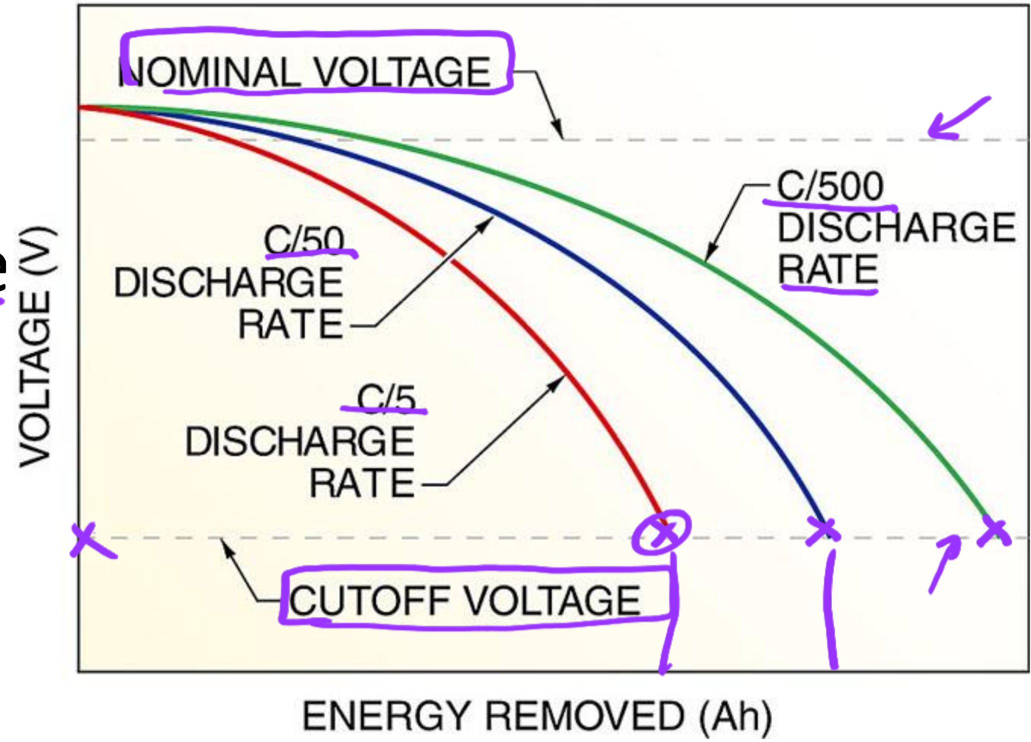
- Notice how tricky it would be to specify how much energy the battery delivered during its discharge.
- Energy is volts × amps × hours, but since voltage varies throughout the discharge period, we can't just say 12 V × 20 A × 10 h = 2400 Wh.
- To avoid that ambiguity, almost everything having to do with battery storage capacity is specified in amp-hours rather than watt-hours.

Battery Capacity and Discharge Rate

- A 200-Ah battery that is delivering 20 A is said to be discharging at a *C*/10 rate, where the *C* refers to Ah of capacity and the 10 is hours it would take to deplete (*C*/10 = 200 Ah/10 h = 20 A).
- That same 200-Ah battery won't be able to deliver 50 A for a full 4 h (*C*/4), however, and it will actually deliver 10 A for more than 20 h (*C*/20).
- In other words, the amp-hour capacity depends on the rate at which current is withdrawn. Rapid draw-down of a battery results in lower Ah capacity, while long discharge times result in higher Ah capacity

- Capacity is directly affected by the rate of discharge.
- Lower discharge rates are able to remove more energy from a battery before it reaches the cutoff voltage.
- Higher discharge rates remove less energy before the battery reaches the same voltage

Discharge Rate



C = 500Ah

1A

10A

100A

Discharge Rate

- Deep-cycle batteries intended for photovoltaic systems are often specified in terms of their 20-h discharge rate ($C/20$), which is more or less of a standard, as well as in terms of the much longer $C/100$ rate that is more representative of how they are actually used.
- Table 9.15 provides some examples of such batteries, including their $C/20$ and $C/100$ rates as well as their voltage and weight.

TABLE 9.15 Example Deep-Cycle Lead-Acid Battery Characteristics

BATTERY	Voltage	Weight (lbs)	Ah @ $C/20$	Ah @ $C/100$
Concorde PVX 5040T	2	57	495	580
Trojan T-105	6	62	225	250
Trojan L16	6	121	360	400
Concorde PVX 1080	12	70	105	124
Surette 12CS11PS	12	272	357	503

454 gram

- **The amp-hour capacity of a battery is not only rate-dependent, but also depends on temperature.** Figure 9.42 captures both of these phenomena by comparing capacity under varying temperature and discharge rates to a reference condition of *C*/20 and 25◦C.
- **These curves are approximate for typical deep-cycle lead-acid batteries,** so specific data available from the battery manufacturer should be used whenever possible.
- As shown in Fig. 9.42, battery capacity decreases dramatically in colder conditions. At −30◦C (−22◦F), for example, a battery that is discharged at the *C*/20 rate will have only half of its rated capacity.

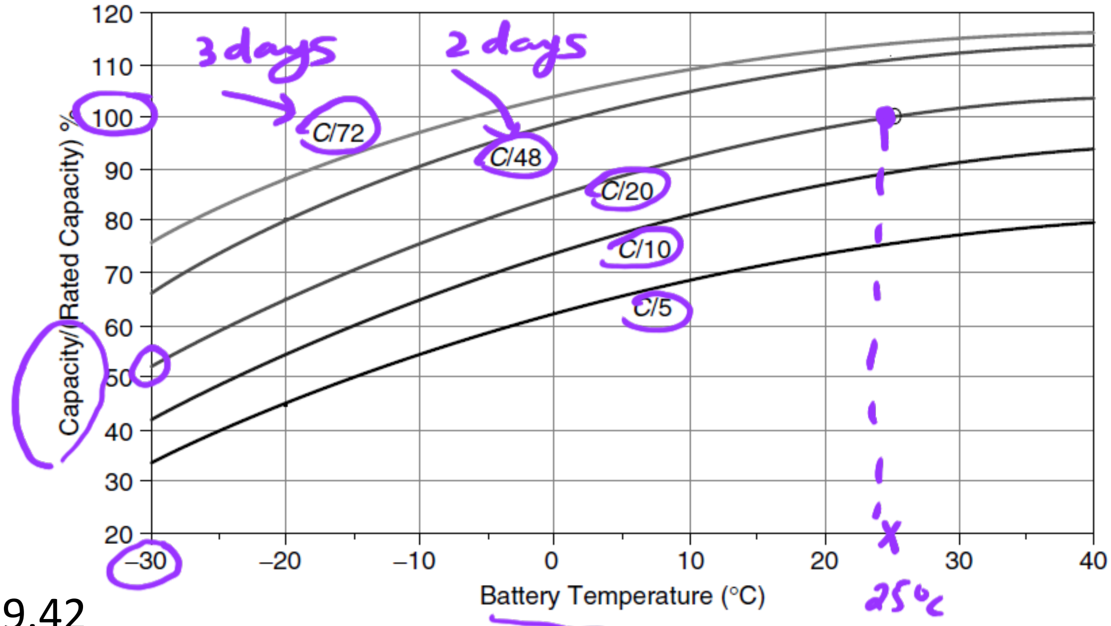
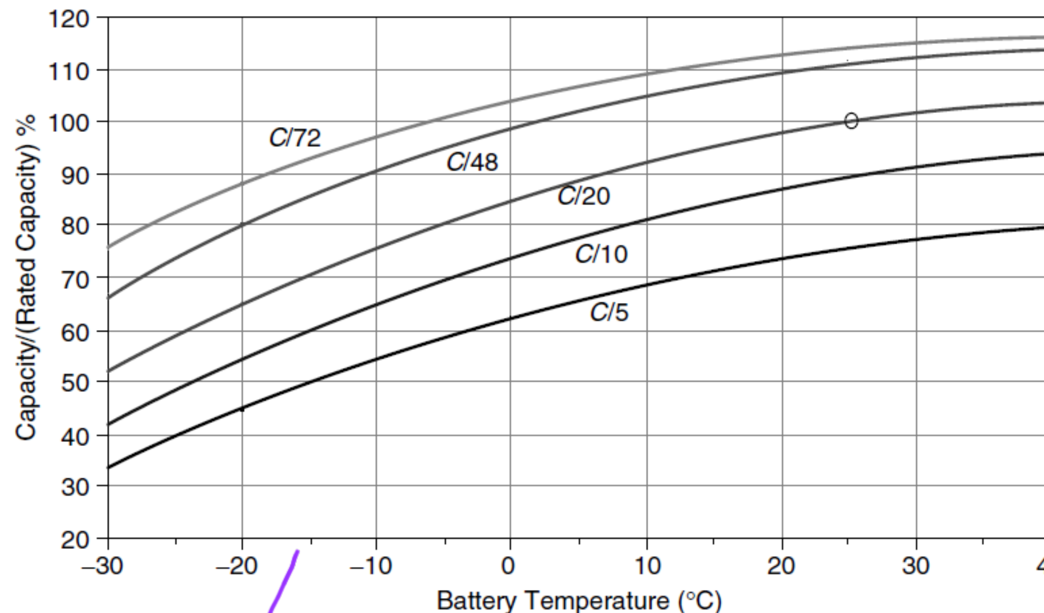


Fig. 9.42

- The combination of cold temperature effects on battery performance—decreased capacity, decreased output voltage, and increased vulnerability to freezing when discharged—mean that lead-acid batteries need to be well protected in cold climates.
- Also, the apparent improvement in battery capacity at high temperatures does not mean that heat is good for a battery.
- In fact, a rule-of-thumb estimate is that battery life is shortened by 50% for every 10◦C above the optimum 25◦C operating temperature.

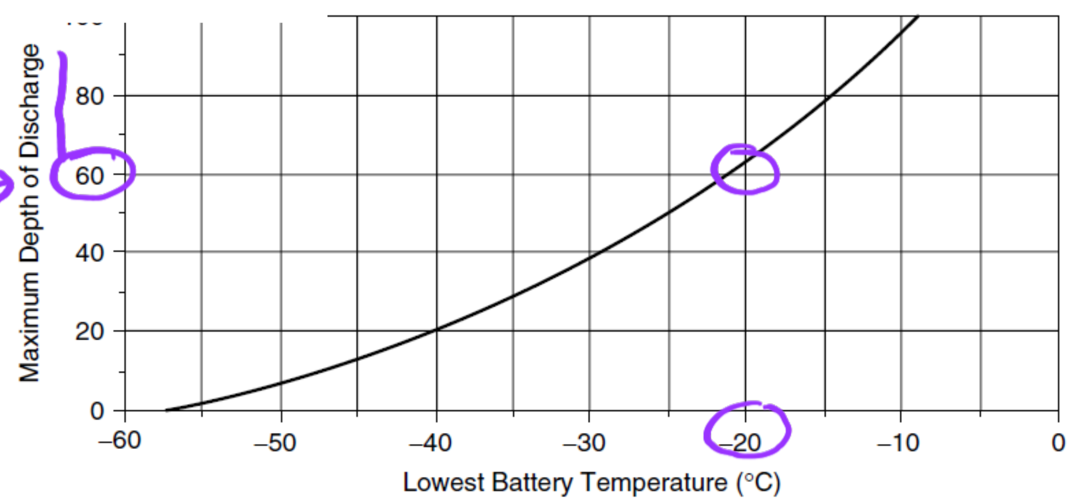


Lead-acid battery capacity depends on discharge rate and temperature. Ratio is based on a rated capacity at *C*/20 and 25◦C.

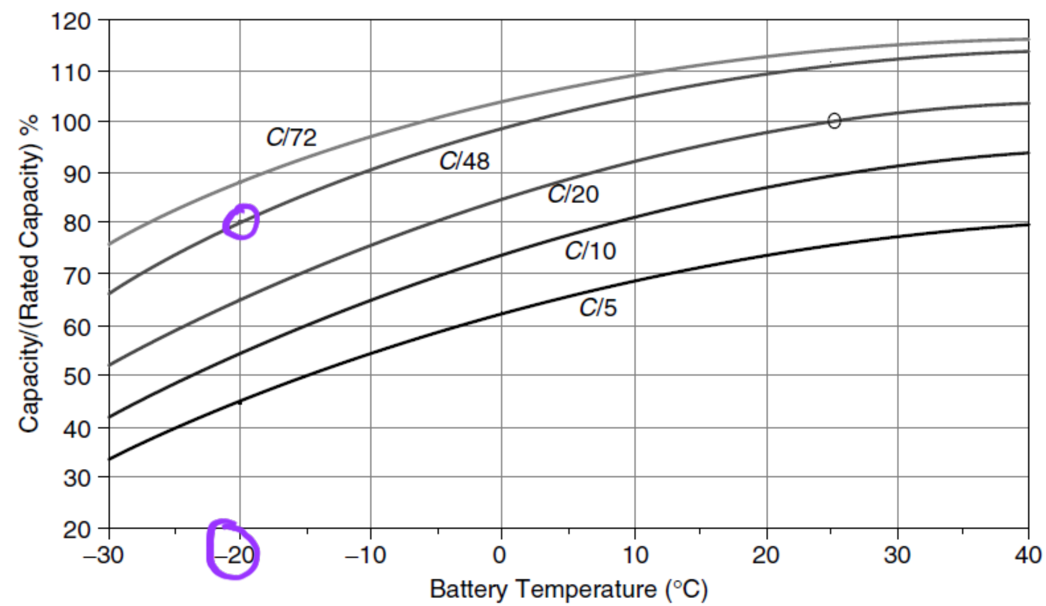
Example 9.16 Battery Storage Calculation in a Cold Climate

- Suppose that batteries located at a remote telecommunications site may drop to −20◦C. If they must provide 2 days of storage for a load that needs 500 Ah/day at 12 V, how many amp-hours of storage should be specified for the battery bank?
- ***Solution.*** From Fig., to avoid freezing, the maximum depth of discharge at −20◦C is about 60%. For 2 days of storage (autonomy), with a discharge of no more than 60%, the batteries need to store

$$\text{Battery storage} = \frac{500 \text{ Ah/day} \times 2 \text{ days}}{0.60} = 1667 \text{ Ah}$$



- Since the rated capacity of batteries is likely to be specified at an assumed temperature of 25◦C at a *C*/20 rate, we need to adjust the battery capacity to account for our different temperature and discharge period.
- From Fig. 9.42, the actual capacity of batteries at −20◦C discharged over a 48-h period is about 80% of their rated capacity. This means that we need to specify batteries with rated capacity

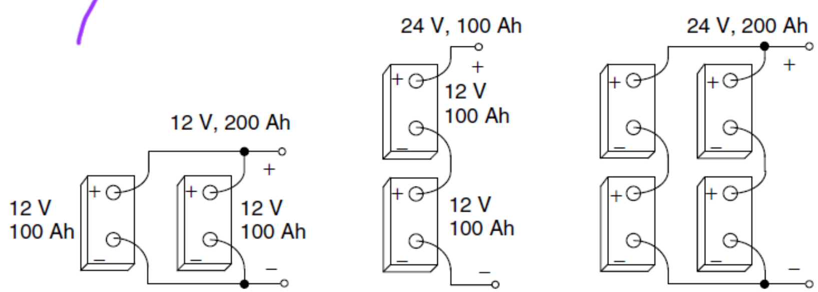


$$\text{Battery storage } (25^{\circ}\text{C, 10-hour rate}) = \frac{1667 \text{ Ah}}{0.8} = 2083 \text{ Ah}$$

TABLE 9.11 Suggested System Voltages Based on Limiting Current to 100 A

Maximum ac Power	System dc Voltage
<1200 W	12 V
1200–2400 W	24 V
2400–4800 W	48 V

- Most PV–battery systems are based on 6-V or 12-V batteries, which may be wired in series and parallel combinations to achieve the needed Ah capacity and voltage rating.
- For batteries wired in series, the voltages add, but since the same current flows through each battery, the amp-hour rating of the string is the same as it is for each battery.
- For batteries wired in parallel the voltage across each battery is the same, but since currents add, the amp-hour capacity is additive.



(a) Parallel, Amp-Hrs add (b) Series, Voltages add (c) Series/Parallel

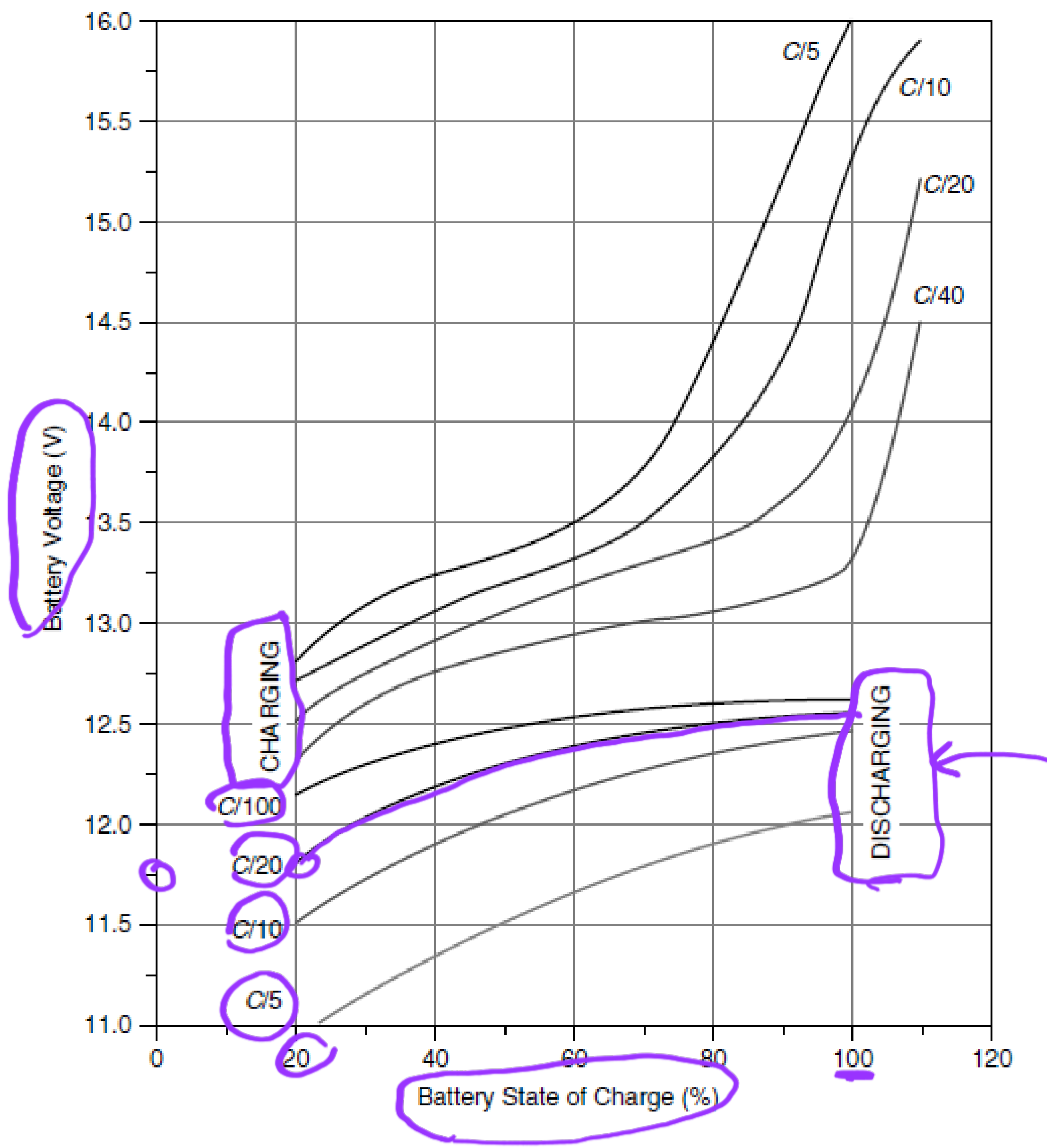
Series and parallel Batteries

- Since there is no difference in energy stored in the two-battery series and parallel example shown in Fig. 9.43, the question arises as to which is better.
- The key difference between the two is the amount of current that flows to deliver a given amount of power. Batteries in series have higher voltage and lower current, which means more manageable wire sizes without excessive voltage and power losses, along with smaller fuses and switches, and slightly easier connections between batteries.
- On the other hand, a storage system consisting of batteries in parallel is easy to expand, one battery at a time.
- In series, a whole new string of batteries must be added to increase storage.

SOC curve

state of charge

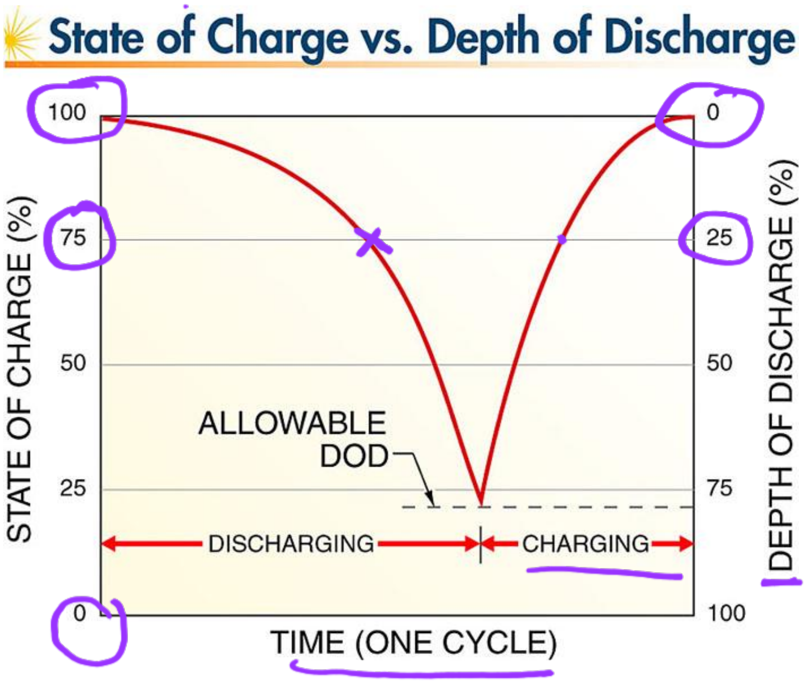
- Figure shows representative values of battery voltage for differing charging and discharging currents as a function of SOC.
- During charging, notice the sudden rise in cell voltage around the 14-V level as the battery nears full charge.
- This is when charging is most inefficient and when gassing occurs.



Gassing

- The release of generated hydrogen and oxygen gases removes water from the battery, which has to be replaced or the plates may be damaged.
- It also creates a potentially dangerous situation since hydrogen gas is so explosive.
- In addition, very small quantities of the poisonous gases arsine (AsH_3) and stibine (SbH_3) can be released when hydrogen comes in contact with the lead alloys arsenic and antimony.
- Proper ventilation is clearly an important consideration in the design of a safe battery storage system.

- The state of charge (SOC) and depth of discharge (DOD) of a battery always add up to equal 100%.
- SOC+DOD=100%



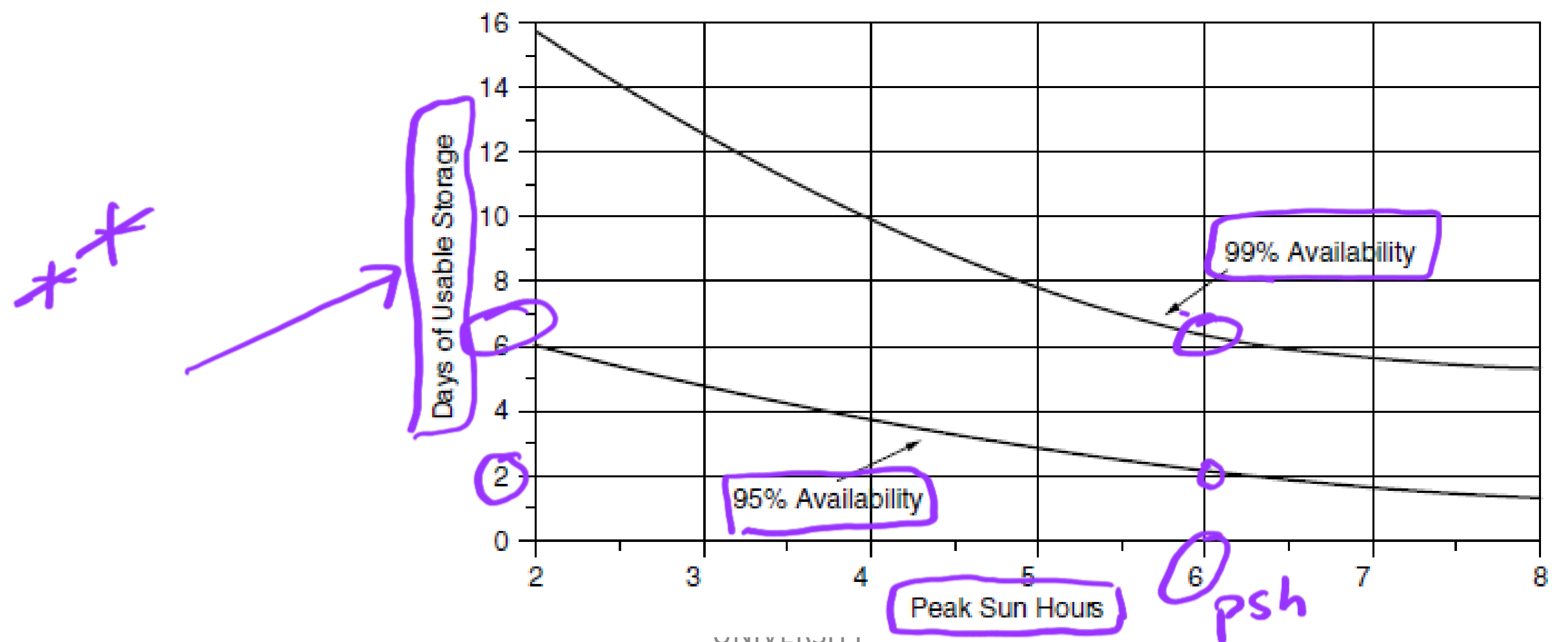
Battery Sizing

- If good weather could be counted on, battery sizing might mean simply providing enough storage to carry the load through the night and into the next day until the sun picks up the load once again.
- The usual case, of course, is one in which there are periods of time when little or no sunlight is available and the batteries might have to be relied on to carry the load for some number of days.
- During those periods, there may be some flexibility in the strategy to be taken.
- Some noncritical loads, for example, might be reduced or eliminated; and if a generator is part of the system, a trade-off between battery storage and generator run times will be part of the design

Availability

- Given the statistical nature of weather and the variability of responses to inclement conditions, there are no set rules about how best to size battery storage.
- The key trade-off will be **cost.**
- **Sizing a storage system to meet the demand 99% of the time can easily cost triple that of one that meets demand only 95% of the time.**
- As a starting point for estimating the number of days of storage to be provided, consider Fig. next slide,

- Days of battery storage needed for a stand-alone system with 95% and 99% system availability. Peak sun hours are for the worst month of the year and availability is on an annual basis.
- The graph gives an estimate for days of battery storage needed to supply a load as a function of the peak sun hours per day in the *design month*, which is the month with the worst combination of insolation and load. To account for a range of load criticality, two curves are given: one for loads that must be satisfied during 99% of the 8760 h in a year and one for less critical loads, for which a 95% system availability is satisfactory.



- The following can be used.

$$\text{Storage days (99\%)} \approx 24.0 - 4.73\,(\text{Peak sun hours}) + 0.3\,(\text{Peak sun hours})^2$$

$$\text{Storage days (95\%)} \approx 9.43 - 1.9\,(\text{Peak sun hours}) + 0.11\,(\text{Peak sun hours})^2$$

- Figure 9.46 refers to days of "usable storage," which means after accounting for impacts associated with maximum allowable battery discharge, Coulomb efficiency, battery temperature, and discharge rate.
- The relationship between usable storage and nominal, rated storage (at *C*/20, 25◦C) is given by:

$$\text{Nominal } (C/20, 25^{\circ}\text{C}) \text{ battery capacity} = \frac{\text{Usable battery capacity}}{(\text{MDOD})(\text{T, DR})}$$

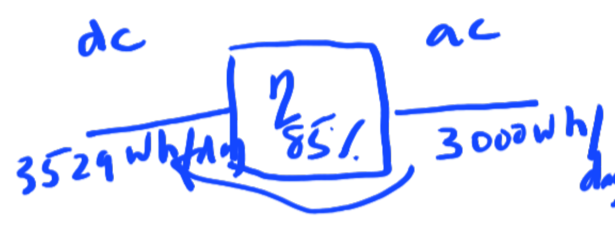
- where MDOD - maximum depth of discharge (default: 0.8 for lead-acid, deep-discharge batteries, 0.25 for auto SLI; subject to freeze constraints given in and T, DR stands for temperature and discharge-rate factor
- See following example

End of L18
17/5

Example

Battery Sizing for an Off-Grid Cabin.

- A cabin near Salt Lake City, Utah, has an ac demand of 3000 Wh/day in the winter months.
- A decision has been made to size the batteries such that a 95% system availability will be provided, and a back-up generator will be kept in reserve to cover the other 5%.
- The batteries will be kept in a ventilated shed whose temperature may reach as low as −10◦C.
- The system voltage is to be 24 V, and an inverter with overall efficiency of 85% will be used.



Example-solution

Battery Sizing for an Off-Grid Cabin

Solution. With an 85% efficient inverter, the dc load is

$$\text{DC load} = \frac{\text{AC load}}{\text{Inverter efficiency}} = \frac{3000\ \text{Wh/day}}{0.85} = 3529\ \text{Wh/day}$$

With a 24-V system voltage the batteries need to supply

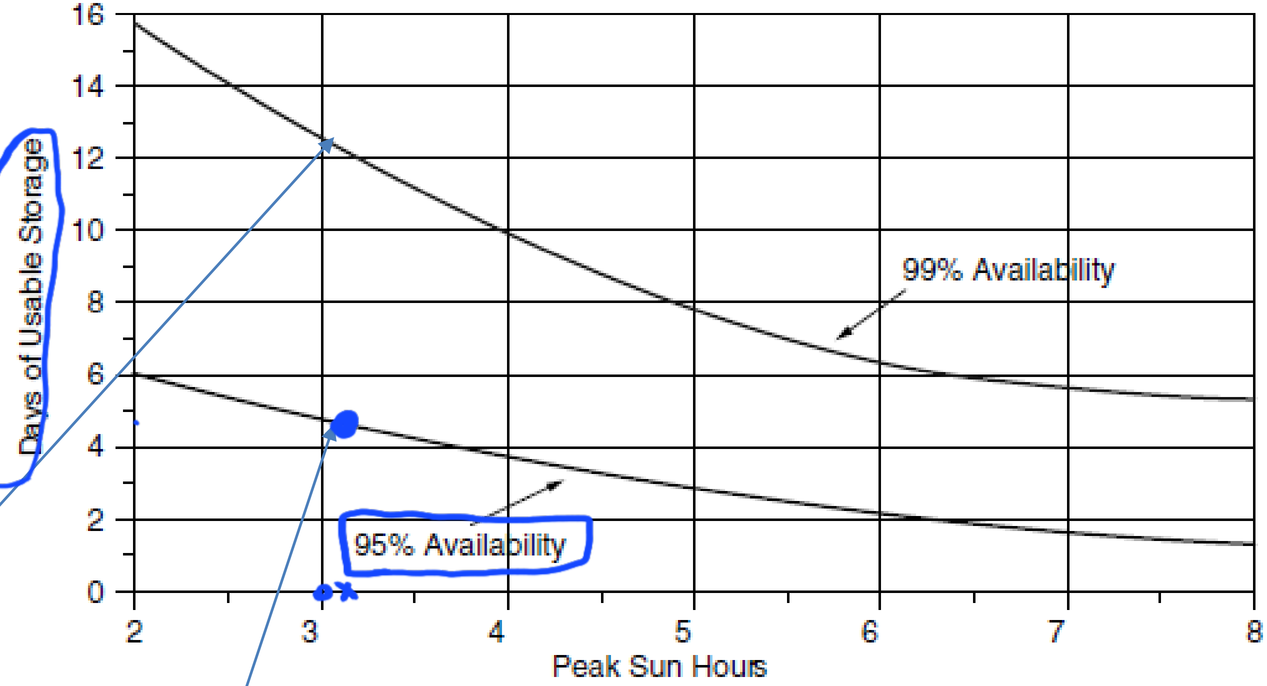
$$\text{Load} = \frac{3529\ \text{Wh/day}}{24\ V} = 147\ \text{Ah/day} \ @\ 24\ \text{V}$$

The following monthly insolation data are found for Salt Lake City:

Tilt	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Year
Lat − 15	2.9	4.0	5.0	5.9	6.6	7.2	7.3	7.0	6.3	5.0	3.3	2.5	5.2
Lat	3.2	4.3	5.2	5.8	6.2	6.6	6.7	6.7	6.4	5.4	3.7	2.9	5.3
Lat + 15	3.4	4.4	5.1	5.4	5.5	5.6	5.8	6.1	6.1	5.5	3.9	3.1	5.0

We use the lowest (worst case) peak sun hours which happens to be for the month of December that have the lowest insolation at latitude +15

- At 95% availability and 3.1 peak sun hours in December, it looks like we need about 4.6 days of storage.

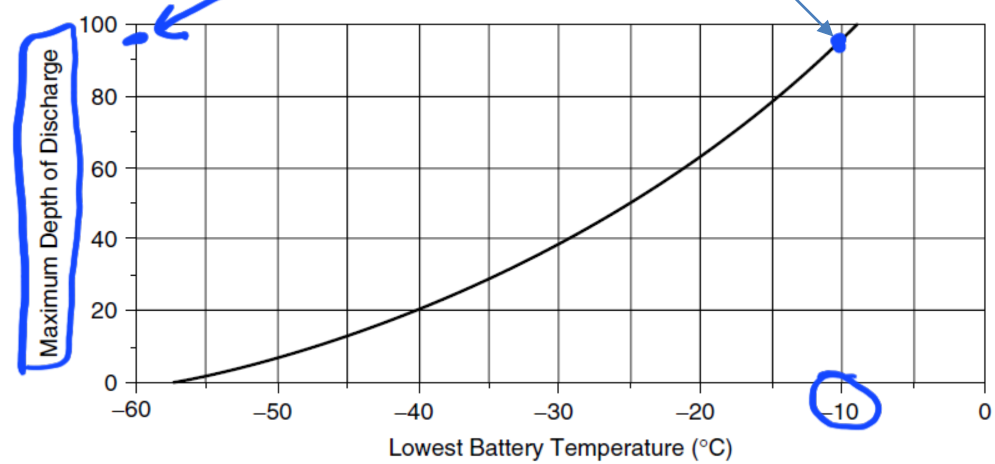


~ 12 days
For 99%
availability

$$\text{Usable storage} = 147\ \text{Ah/day} \times 4.6\ \text{day} = 676\ \text{Ah}$$

@ 24 V

- We'll pick deep discharge lead-acid batteries that can be routinely discharged by 80%. But, we need to check to see whether that depth of discharge will expose the batteries to a potential freeze problem.
- So we continue solution as previous example
- Applying the de-rating factors for temp (0.97) and (0.8) for max discharge rate



$$\text{Nominal } (C/20, 25^{\circ}\text{C}) \text{ battery capacity} = \frac{676 \text{ Ah}}{0.80 \times 0.97} = 871 \text{ Ah (at 24 V)}$$

- By looking at a list of available batteries of table , different possibilities can be explored

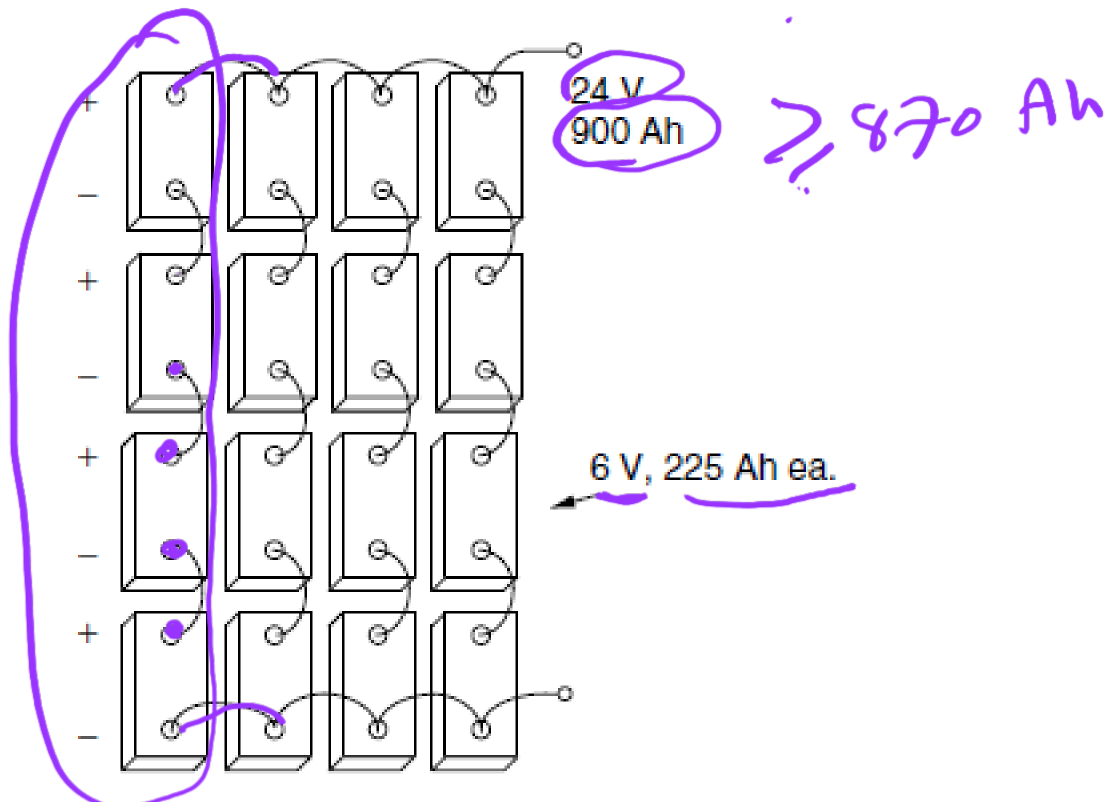
TABLE 9.15 Example Deep-Cycle Lead-Acid Battery Characteristics

BATTERY	Voltage	Weight (lbs)	Ah @ C/20	Ah @ C/100
Concorde PVX 5040T	2	57	495	580
Trojan T-105	6	62	225	250
Trojan L16	6	121	360	400
Concorde PVX 1080	12	70	105	124
Surette 12CS11PS	12	272	357	503

Batteries	Vbat	lb	AH@C/20	Ah@C/100	series (=24V/Vbat)	parallel (=871/Ah@C/20)	total No	tot weight
Concorde PVX 5040T	2	57	495	580	12	2	24	1368
Trojan T-105	6	62	225	250	4	4	16	992
Trojan 1.16	6	121	360	400	4	3	12	1452
Concorde 1080	12	70	105	124	2	9	18	1260
Surrete 12CS11PS	12	272	357	503	2	3	6	1632

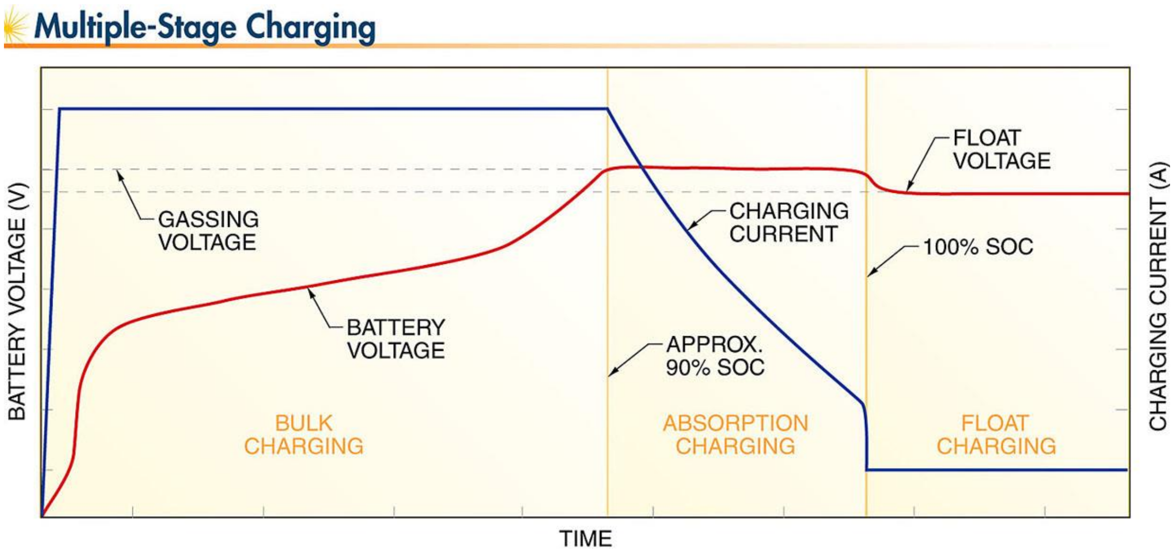
- Trojan T-105 provides the choice with less weight
- total number of batteries is 16 (4x4) to get 24V and 900Ah

4X4



The 24-V, 900-Ah battery bank for the cabin in Example

More On Battery Charging

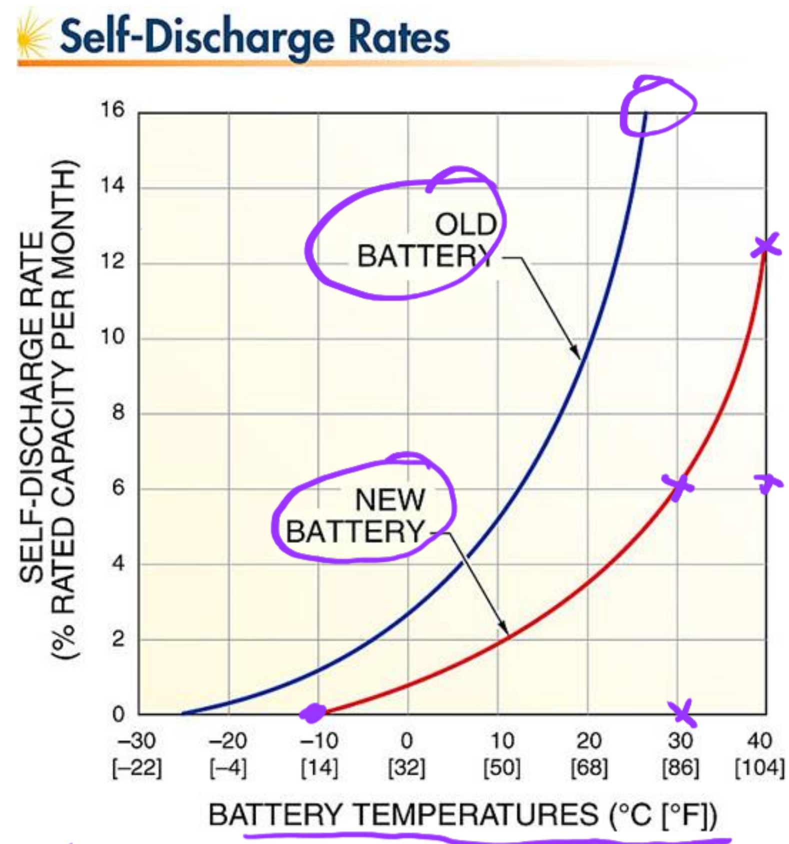


- **Gassing and charging losses can be minimized, by using a charge controller that has been designed to slow the charging rate as the battery approaches its fully charged condition.**

•*Self-discharge*

is the gradual reduction in the state of charge of a battery while at steady-state condition. Self-discharge is also referred to as standby or shelf loss.

- Self-discharge is a result of internal electrochemical mechanisms and losses.
- The rate of self-discharge differs among battery types and increases with battery age.
- Self-discharge rates are typically specified in percentage of rated capacity per month



Batteries exhibit high self-discharge rates at higher temperatures.

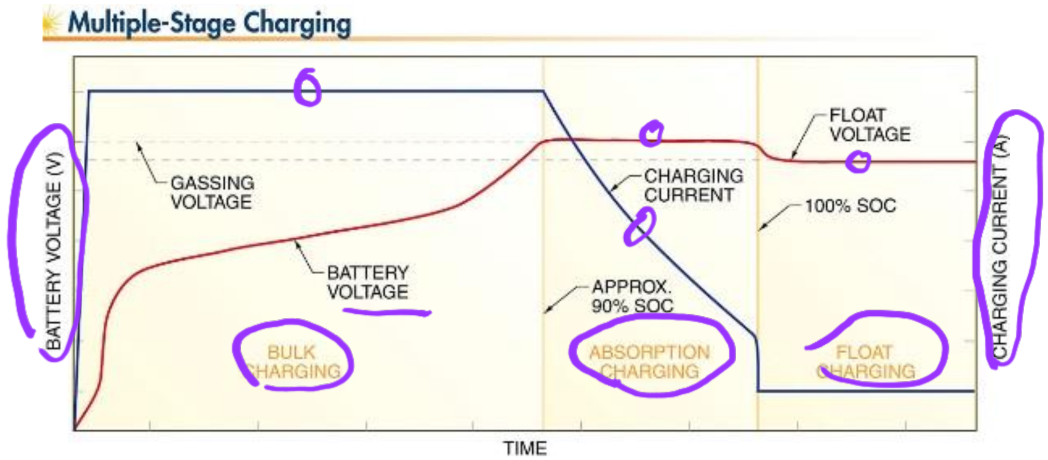
STEADY STATE

- *Steady-state* is an open-circuit condition where essentially no electrical or chemical changes are occurring.
- The *open-circuit voltage* is the voltage of a battery or cell when it is at steady-state.
- The open-circuit voltage of a fully charged lead-acid cell is about 2.1 V.

Voltage Levels

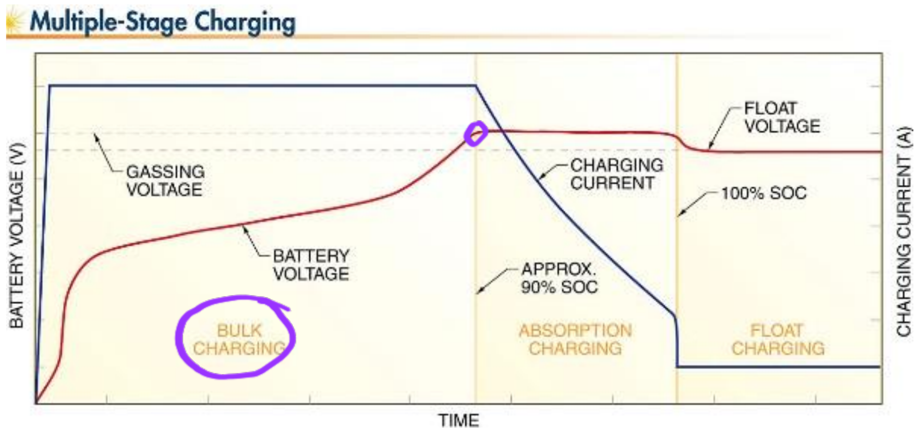
- The voltage of a battery system is not constant but ranges from a few volts above its nominal voltage to a few volts below.
- For example, a nominal 12 V lead-acid battery is between **12.6 V** and **13 V** at steady- state when fully charged.
- The battery voltage falls to a voltage between **10.8 V** and **11 V** during discharge, depending on the discharge current.
- The ***cutoff voltage*** is the minimum battery voltage specified by the manufacturer that establishes the battery capacity at a specific discharge rate.
- Below the cutoff voltage, there is no further usable capacity.

Charging



- Charge rate is quantified in the same way as discharge rate.
- For example, a charging rate of C/50 to a 100 Ah battery applies 2 A of current until the battery reaches a specific fully charged voltage.
- The *gassing voltage* is the voltage level at which battery gassing begins.
- Batteries can be charged in one stage or multiple stages.
- Three stages of battery charging are **bulk charging, absorption charging, and float charging.**
- **Equalizing charging** is an additional type of charging.

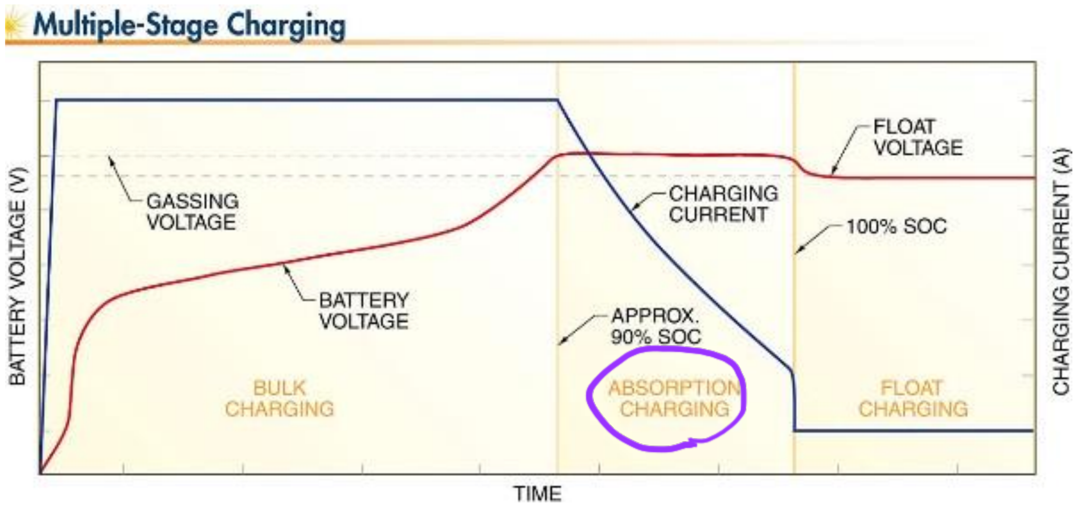
Bulk Charging (up to 90% SOC)



- *Bulk charging* is battery charging at a relatively high charge rate that charges the battery up to a regulation voltage, resulting in a state of charge of about 80% to 90%.
- This is also called normal charging or single stage charging.
- This mode is simple to implement, but does not fully charge the battery.
- Multiple-stage charging includes additional charging modes to reach a higher state of charge.

Absorption Charging

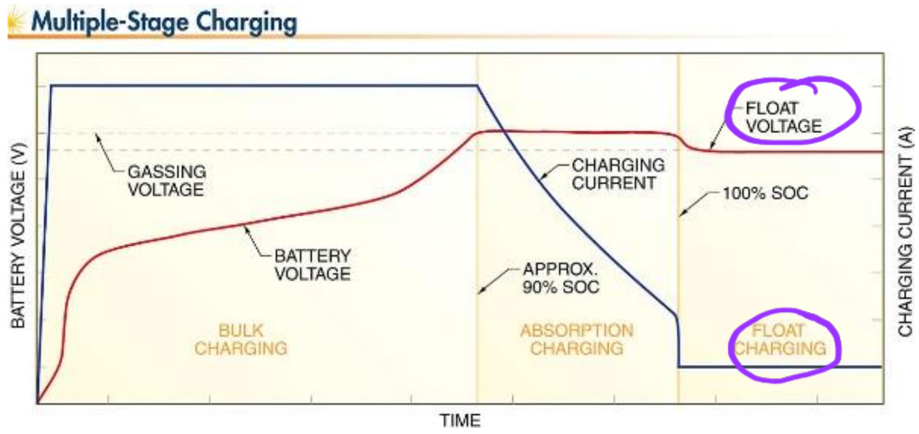
(maintain battery voltage at regulation- low charge current)



- **Once a battery is nearly fully charged, most of the active material in the battery has been converted to its original form, and current regulation is required to limit the amount of overcharge supplied to the battery.**
- ***Absorption charging*** **is battery charging following bulk charging that reduces the charge current to maintain the battery voltage at a regulation voltage for a certain period.**
- **The absorption charging period can be preset or adjustable, and is usually 1 hr to 3 hr. Absorption charging charges another 10% to 15% of battery capacity.**

Float Charging

(counteracting self-discharge)*



- When the battery reaches nearly 100% state of charge, the charging voltage is lowered slightly to the float voltage and the charging current is set to a very low rate.
- ***Float charging* is battery charging at a low charge rate that maintains full battery charge by counteracting self-discharge**.
- The float charge rate must not exceed the self-discharge rate or the battery will be overcharged. Float charging is also called trickle charging or finish charging. A charge controller remains in float charge mode until the array current is no longer high enough to maintain the battery at float voltage.

Equalizing Charging

(to maintain consistency among individual lead-acid cells)

- An equalizing, or refreshing, charge is used periodically to maintain consistency among individual lead-acid cells.
- ***Equalizing charging*** **is current-limited battery charging to a voltage higher than the bulk charging voltage, which brings each cell to a full state of charge.**
- Equalizing charging is a controlled overcharge to produce gassing ensuring that every cell is fully charged.
- Equalizing a battery helps to prevent electrolyte stratification, sulfation, and cell voltage inconsistencies that develop during normal battery operation, and maintains battery capacity at the highest possible levels.

Equalizing Charging

- For batteries that are deeply discharged on a daily basis, an equalizing charge is recommended every one or two weeks.
- For batteries less severely discharged, equalizing may only be required every one or two months.
- An equalizing charge is typically maintained until the cell voltages and specific gravities remain consistent for a few hours.
- Only flooded open-vent batteries need equalization. Sealed or valve-regulated batteries can be damaged by equalization.

Gassing and Overvoltage

- When a battery is nearly fully charged, essentially all of the active materials have been converted to their fully charged composition and the cell voltage rises sharply.
- Further charging at this point results in gassing.
- ***Gassing*** **is the decomposition of water into hydrogen and oxygen gases as the battery charges. Hydrogen forms at the negative plate and oxygen forms at the positive plate.**
- The gases bubble up through the electrolyte and may escape through cell vents, resulting in water loss from the electrolyte

Gassing and Overvoltage

- Some level of gassing is required to achieve full charge, but gassing must be carefully controlled to prevent excessive water loss.
- Water may need to be periodically added to the electrolyte to maintain the proper acid concentration, though this cannot be done for all types of batteries.
- Gassing is useful for gently agitating the electrolyte, which ensures that its concentration is uniform. However, excessive gassing can dislodge active materials from the grids, increase battery temperature, or expose the plates, which can permanently damage the battery.
- The gassing voltage is a function of battery chemistry, temperature, charge rate, voltage, and state of charge.

Gassing and Temperature

- As battery temperature decreases, the corresponding gassing voltage increases, and vice versa.
- At a battery temperature of 0°C (32°F) the gassing voltage of lead-acid cells increases to about 2.5 V.
- The effect of temperature on the gassing voltage is the reason why the charging process should be temperature compensated.
- This ensures that batteries are fully charged in cold weather and not overcharged during warm weather.

Overcharge

- ***Overcharge*** is the ratio of applied charge to the resulting increase in battery charge.
- For example, a 100 Ah battery may require 110Ah of charge to account for charge loss due to gassing.
- The overcharge in this case is 110%.
- Varying amounts of overcharge are required for different battery types and from different states of charge.
- Some batteries may require as much as 120% overcharge while many others require only about 110%.

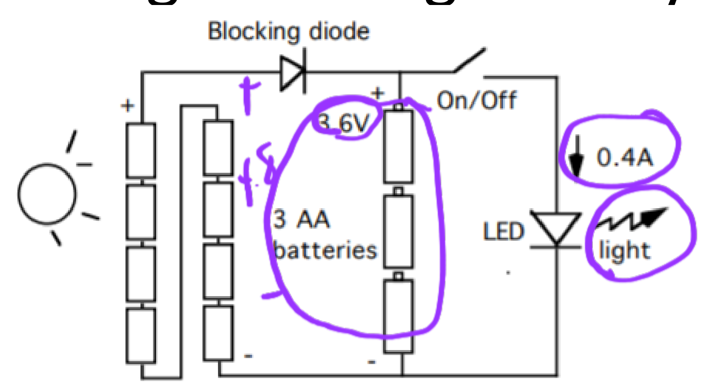
Overcurrent Protection

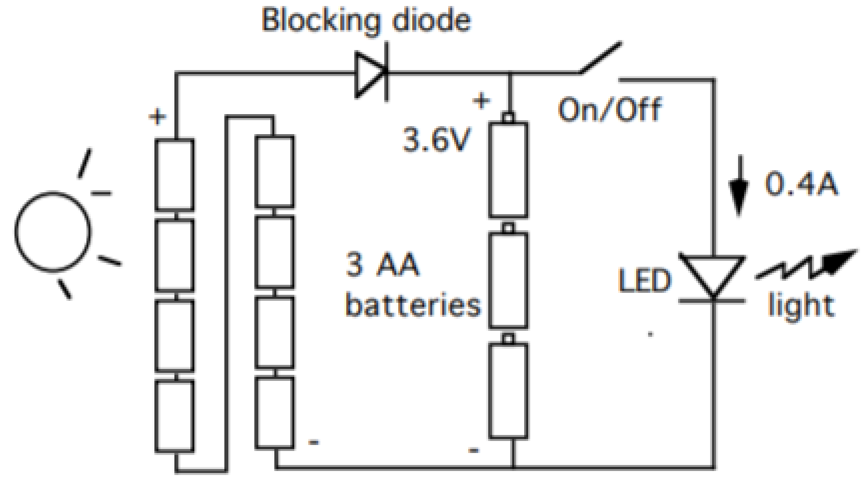
- Like any other electrical system, battery systems must have proper DC-rated overcurrent protection and disconnects to protect system conductors and to isolate the battery bank from the rest of the system for testing and maintenance.
- Batteries can deliver extremely high discharge currents *, so overcurrent protection* devices must have the appropriate interrupting rating
- Other Safety precautions related to ventilation and electrolyte spill must be taken


05/13
IMPORTANT - NONSERVICEABLE
DO NOT ATTEMPT TO OPEN VENTS.
Non-spillable battery, I.C.A.O., I.M.D.G., I.A.T.A., and D.O.T. air transport approved.
Ventilate well. Do NOT install in airtight container.
Charge/Absorption/Equalize between 13.8 – 14.6 volts @ 77°F (25°C).
Float/Standby between 13.4 – 13.6 volts @ 77°F (25°C).
Temperature corrected charging required.
DANGER/POISON
SHIELD EYES.
EXPLOSIVE GASES CAN CAUSE BLINDNESS OR INJURY.
NO •SPARKS •FLAMES •SMOKING
SULFURIC ACID CAN CAUSE BLINDNESS OR SEVERE BURNS.
FLUSH EYES IMMEDIATELY WITH WATER
GET MEDICAL HELP FAST
KEEP OUT OF THE REACH OF CHILDREN
DO NOT OPEN BATTERY!
Remove proper month and year tabs to show date sold.
BATTERY MUST BE RECYCLED.
MADE IN USA
12V
PART NO.
8G31
485 CCA
98 A.H.
@20Hr
C/20

Example

- Consider the design of a small PV-powered light-emitting-diode (LED) flashlight.
- The PV array consists of 8 series cells, each with rated current 0.3A @ 0.6V.
- Storage is provided by three series AA batteries that each store 2Ah at 1.2V when fully charged.
- The LED provides full brightness when it draws 0.4A @ 3.6V
- The batteries have a Coulomb efficiency of 95% and for maximum cycle life can be discharged by up to 80%. Assume the PVs have a 0.90 derating due to dirt and aging.
- a. How many hours of light could this design provide each evening if the batteries are fully charged during the day?





- b. How many kWh/m^2-day of insolation would be needed to provide the amount of light found in (a)?
- c. With 14%-efficient cells, what PV area would be required?

Solution

allowable DOD is 80%.

- SOLN (a) :

2 Ah x 0.80 = 1.6 Ah available.

LED needs 0.4 A so 1.6/0.4 = 4 h of light

SOLN (b) :

Ah battery = I_R x (h @ full sun) x PV derate x Coulomb

1.6 = 0.3 A x (kWh/m^2-day) x 0.90 x 0.95

kWh/m^2 -day = 1.6 /(0.3 x 0.90 x 0.95) = 6.24

SOLN (c) : Each 14%-efficient cell produces 0.3A x 0.6V = 0.18 W at STC

P_R (W) = 1,000 W/m^2 x A (m^2) x η

A = 0.18W/cell x 8 cell/(1000 x 0.14) = 0.01028 m2