Thank you for joining us for the presentation on battery energy storage systems. Many of you may have attended the presentation I did a couple of years ago. I wanted to update that presentation and provide some information on some of the changes that have affected codes since 2018.

We will be discussing the following:

- System operating requirements
- Technology differences
- Code compliance issues
- Safety features
- Performance differences

Battery Technology- *Applications*

Applications Considered Today: WHY?

Applications prevalent in new construction for:

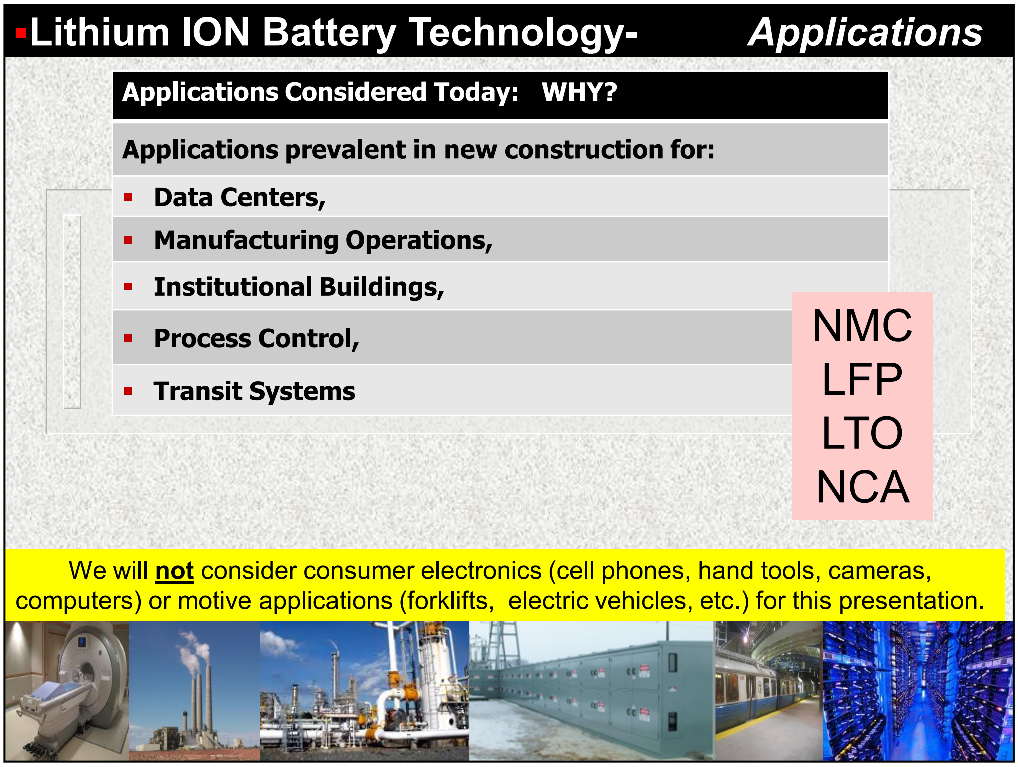
- **Data Centers,**
- **Manufacturing Operations,**
- **Institutional Buildings,**
- **Process Control,**
- **Transit Systems**

We will **not** consider consumer electronics (cell phones, hand tools, cameras, computers) or motive applications (forklifts, electric vehicles, etc.) for this presentation.

These are the applications we will discuss in detail today. Primarily because these are the types of systems prevalent in new construction for Data Centers, Manufacturing Operations, Institutional Buildings and Process Control. What these applications have in common:

1. They all use primarily taper current charging systems,
2. They are all emergency standby applications,
3. They all are primarily float charging applications,
4. These systems are rarely cycled to a significant depth of discharge.

If I am using unfamiliar terminology, don't hesitate to speak up.



These are the applications we will discuss in detail today. Primarily because these are the types of systems prevalent in new construction for Data Centers, Manufacturing Operations, Institutional Buildings and Process Control.

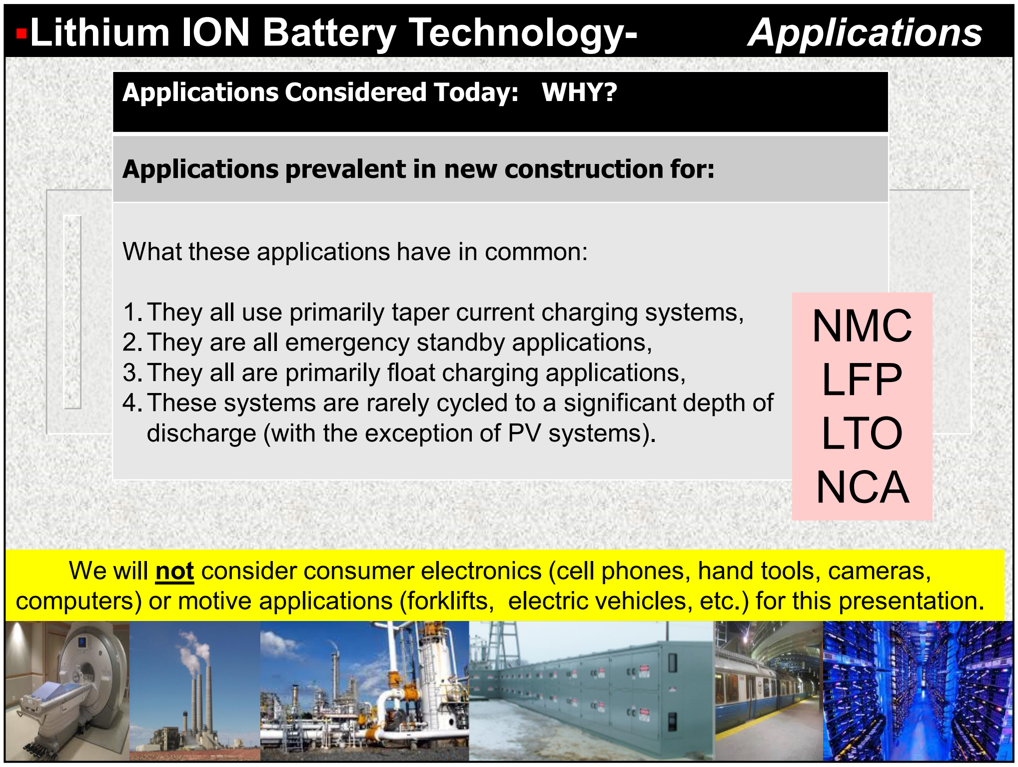
The batteries used in these applications have some commonalities in:

- How often they are cycled,
- How they are charged,
- Whether or not they are used for standby or for prime power applications.

The chemistries we will consider for the lithium ion family will be:

- NMC
- LFP
- LTO
- NCA

These are the acronyms for the electrode chemistries that are the most common for station power applications.



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Battery Technology- *Applications*

Applications Considered Today: WHY?

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These are the applications we will discuss in detail today with respect to lithium ion batteries. Primarily because these are the types of systems prevalent in new construction for Data Centers, Manufacturing Operations, Institutional Buildings and Process Control. What these applications have in common:

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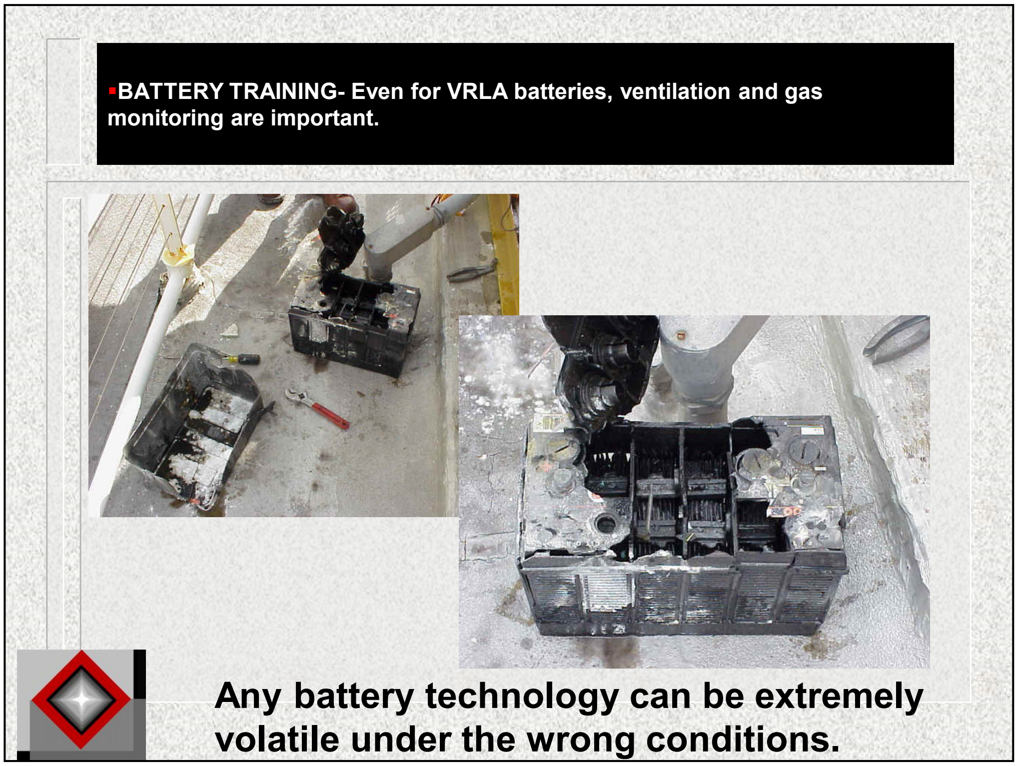
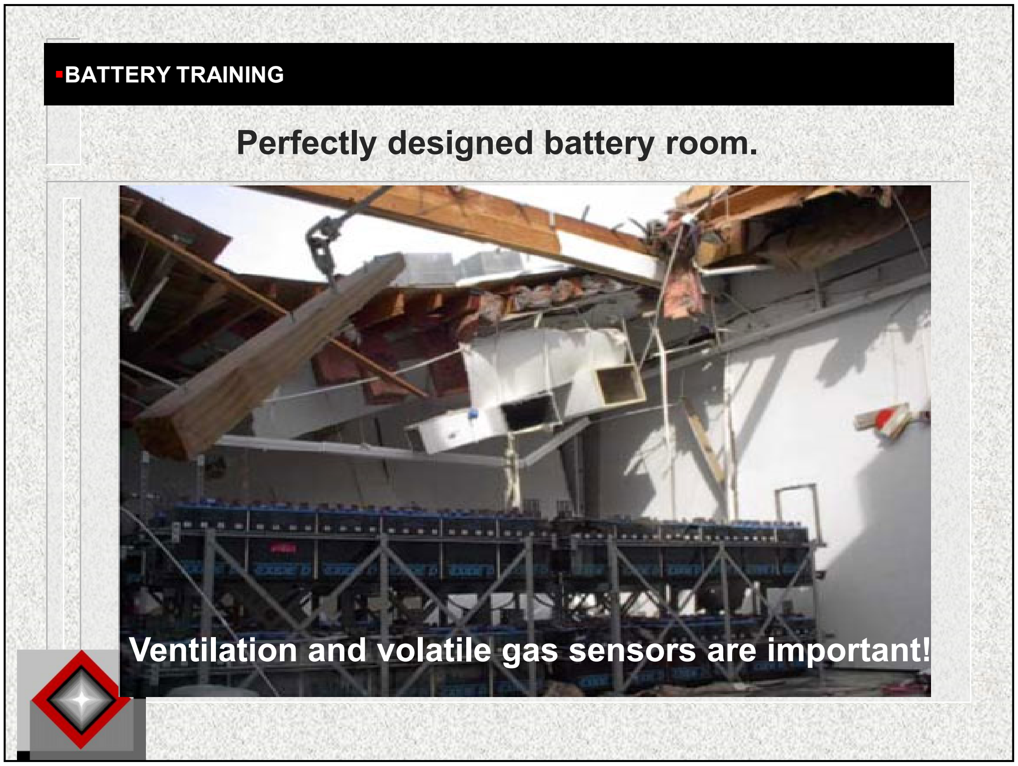


Any battery technology can be extremely volatile under the wrong conditions.

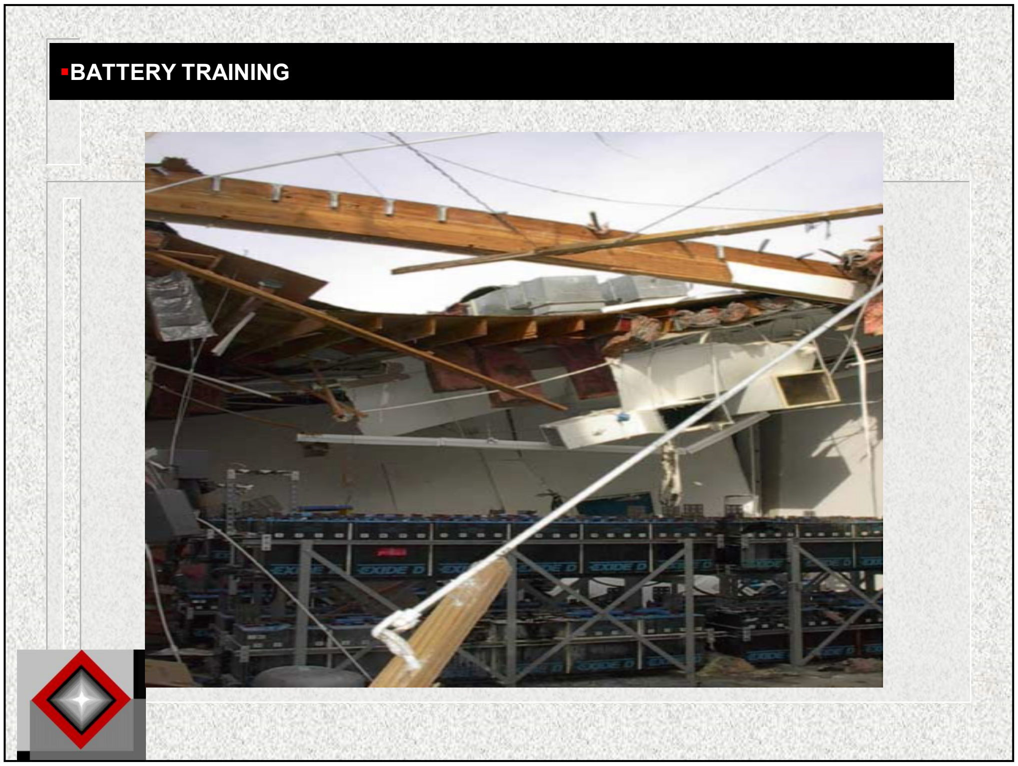
These batteries were removed from UPS systems that were installed in pristine environments. Rooms were temperature controlled. Batteries were maintained per manufacturer's instructions….so the end-user thought. Valve regulated batteries gained huge appeal for station power due to lack of requirement for watering the cells. But as we know too well….maintenance is equally as important with this battery type as it is with any other. In fact, it Is probably more important. Due to the low volume of electrolyte in this type of battery and the fact that most of these batteries use lead calcium alloy in the positive plates, they are highly susceptible to premature failures that are catastrophic in nature. They are much more sensitive to issues caused by elevated temperature, cold temperatures, improper charger, ripple current created by spent capacitors…..than flooded battery systems.



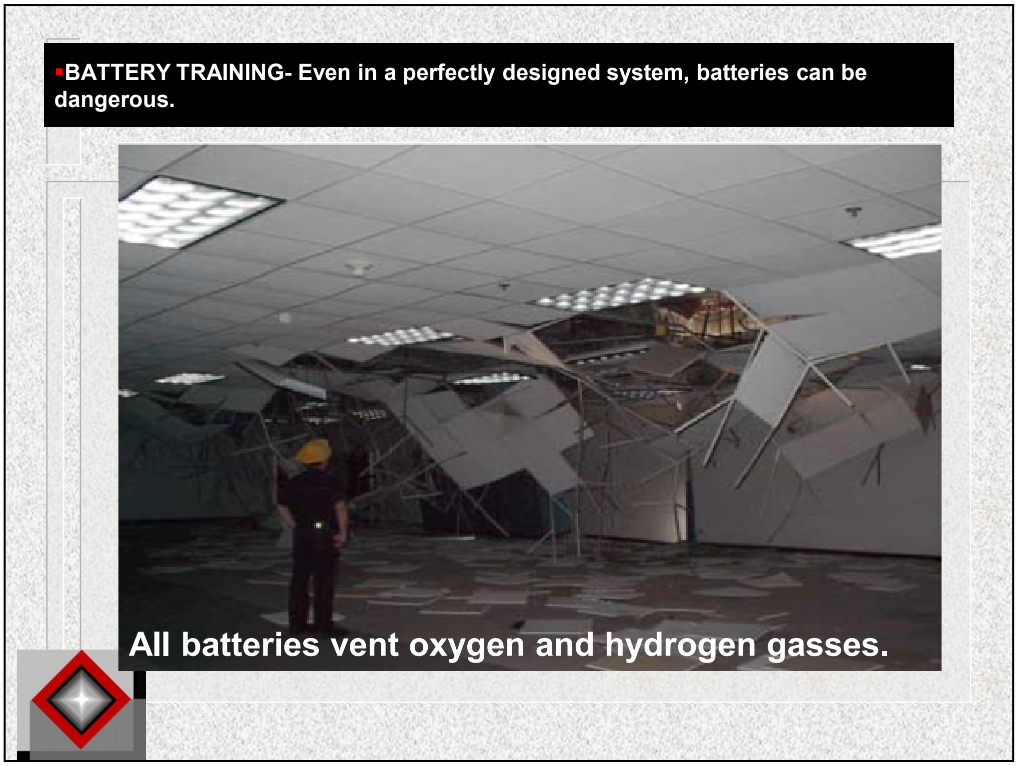
This was a perfectly designed battery room. On a hot summer day, the air conditioning system failed in this site. The air ducts had flow sensors, flow sensor monitoring, duct temperature monitoring, volatile gas monitoring which all worked as it was supposed to. The batteries went into a condition called thermal runaway. Unfortunately, the site superintendent did not respond to the alarms until the explosion from hydrogen gas ruptured the roof propelling the air conditioning units into the parking lot.

This photo shows the battery before the room was cleared out. It is hard to grasp the size of the batteries in this photo, but each cell in this rack weighs 800 pounds. This is a really large string of batteries. Keep in mind that this was an excellent design. Notice also that the batteries are still in tack and still on the racks. Hydrogen gas was produced in large amounts when the air conditioning failed in this room. The UPS charger kept pushing as much charging current to the batteries as the battery would take. As the room heated up, the battery electrolyte kept getting warmer. As the battery impedance dropped, the charger current kept elevating until the UPS ultimately stayed in current limit. This is a classical case of thermal runaway. Once a battery is fully charged, the battery will generate hydrogen gas during thermal runaway. If the ventilation is not active, the hydrogen gas gets contained at the highest part of the room (hydrogen is lighter than air). Despite multiple alarms on the building automation system, no one responded to the alarms until the rooftop units were laying on top of cars in the parking lot.

These batteries are known as "flooded" or "vented" batteries. Notice that the batteries are still in tact and on the racks. The batteries are not displaced by the hydrogen gas explosion. The gasses that are generated inside these batteries are allowed to vent to the atmosphere during normal and abnormal charging conditions. The oxygen and hydrogen gas that is generated is a result of the electrolysis of the water in the electrolyte during the charging process. As the oxygen and hydrogen are generated, they escape outside the battery where they will mix with the air in the room. If the ventilation in the room is not functioning and the gasses can not mix or dissipate, a situation can be created in which the gasses become contained or trapped. Because hydrogen is the smallest atom of all, it will float to the highest point in the room. If the gas ratios get unbalanced, the air in the room because highly volatile.



This is a different angle but of the same site. Again, even though the batteries appear to be unscathed, they are quite compromised. The damage that is created when a lead acid battery experiences thermal runaway is irreversible and will lead to catastrophic failures if this system were to be placed back into service.



This is from a different angle with the batteries removed.

Aftermath of a hydrogen gas explosion caused by thermal runaway. This photo shows the remains of a battery room in southern California. This was a perfectly designed battery room.

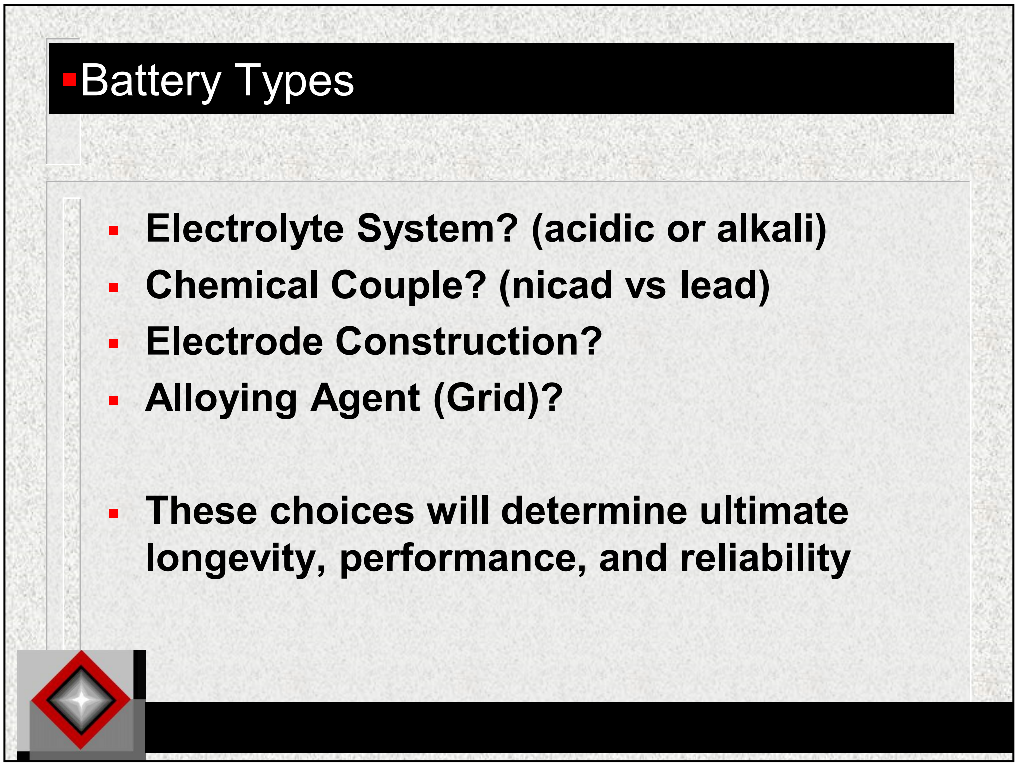
When I discuss lithium ion batteries with consulting engineers, it is very frequent that someone will bring up a horror story of a lithium ion battery fire. It is important to note that all of the batteries I am discussing today have potential to be harmful under the right circumstance… or better said, the wrong circumstances.

- Proper ventilation
- Pressure sensors in the ventilation
- Flow sensors in the ducting
- Multiple ambient and air flow sensors
- Proper spill containment.

It is also important to note that all of the lithium battery technologies I will discuss in this presentation are "lithium ion" and NOT lithium metal type batteries.

Lithium ion batteries must have careful control systems to prevent thermal runaway events and to ensure safe operation.

Slides from H2LL Database sponsored by the Department of Energy.

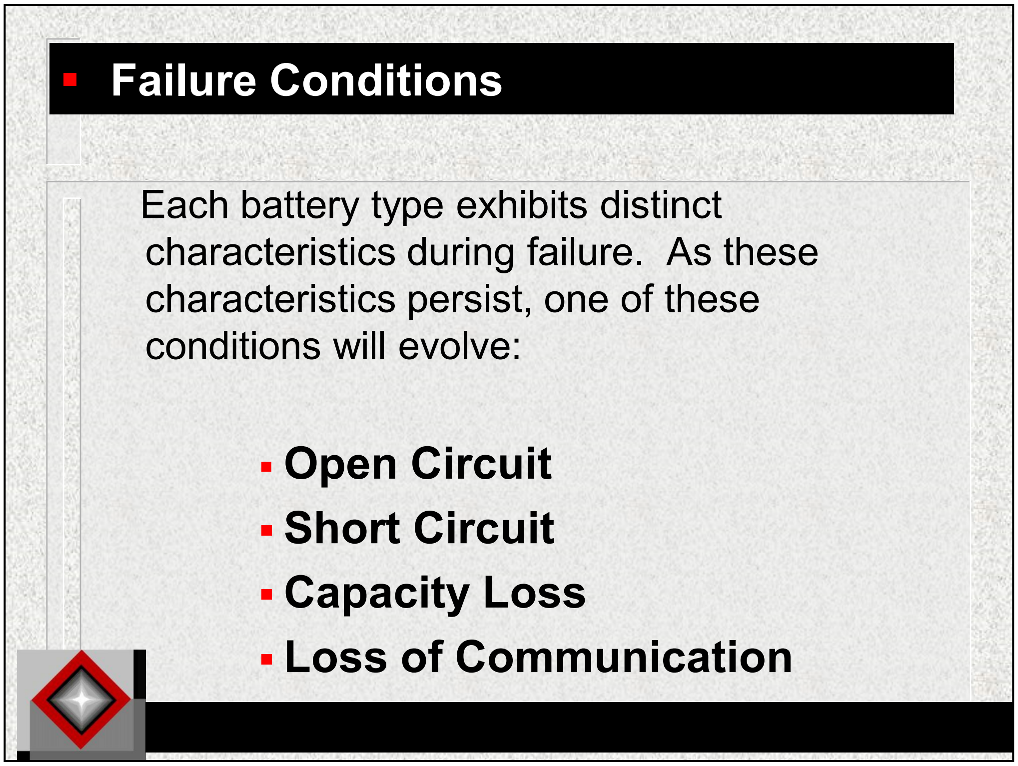


As a specifier, or as a user, you have a lot of choices when it comes to selecting a back-up battery system. All of these categories are distinguishing features of the different types of batteries that are available for stationary power applications. The choice you make, will determine the reliability, the performance, the maintainability and the ultimate service life of the battery system.

Chemical Couples

- For station control power, UPS, gen start and relay applications:
  - **Nickel Hydroxide/Cadmium Hydroxide (Nicad)**
  - **Lead/Lead Oxide (lead acid)**
  - **Lithium Titanate**
- Future:
  - Lithium/Carbon & Lithium /Metal Hydride

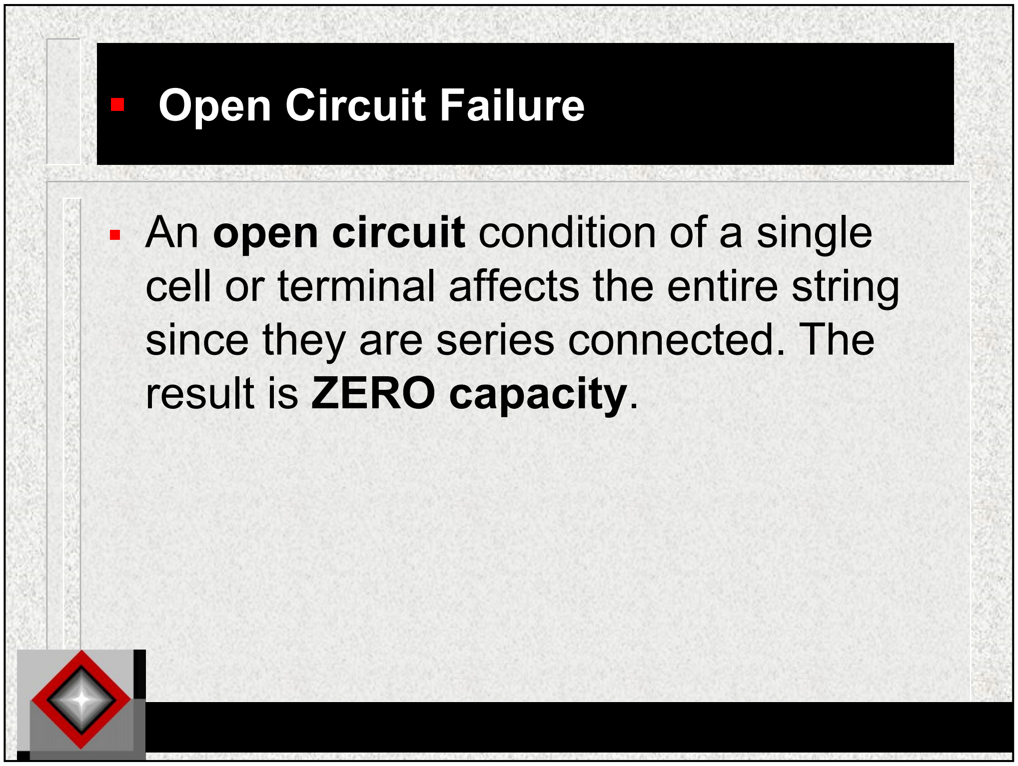
Currently, these are the chemical couples that are widely available for station power, generator start applications, and UPS applications.



Just as diseases can be distinguished by outward symptoms, batteries often display tell-tale characteristics when they are suffering or prematurely failing.

We will discuss how these different types of failure impact the customer and the ultimately reliability of systems.

The bottom one “Loss of Communications” was just recently added to this list for the sole purpose of defining one of the most prevalent types of failure of the lithium ion batteries.



For lead acid batteries and for nickel cadmium batteries, IEEE has designed criteria to help the user prepare for the “end-of-life” of either type of system. When the battery fails to perform to 80% of it’s nameplate capacity, the recommendation is to budget for the replacement.

If degradation of performance is somewhat predictable, and it has very low potential to be “service-affecting”, that would be the preferred method of experiencing the symptoms of an aging battery. The nickel cadmium chemistry is so stable, that is exactly how they typically fail. They tend to fail by a very gradual decline of discharge capacity over time.

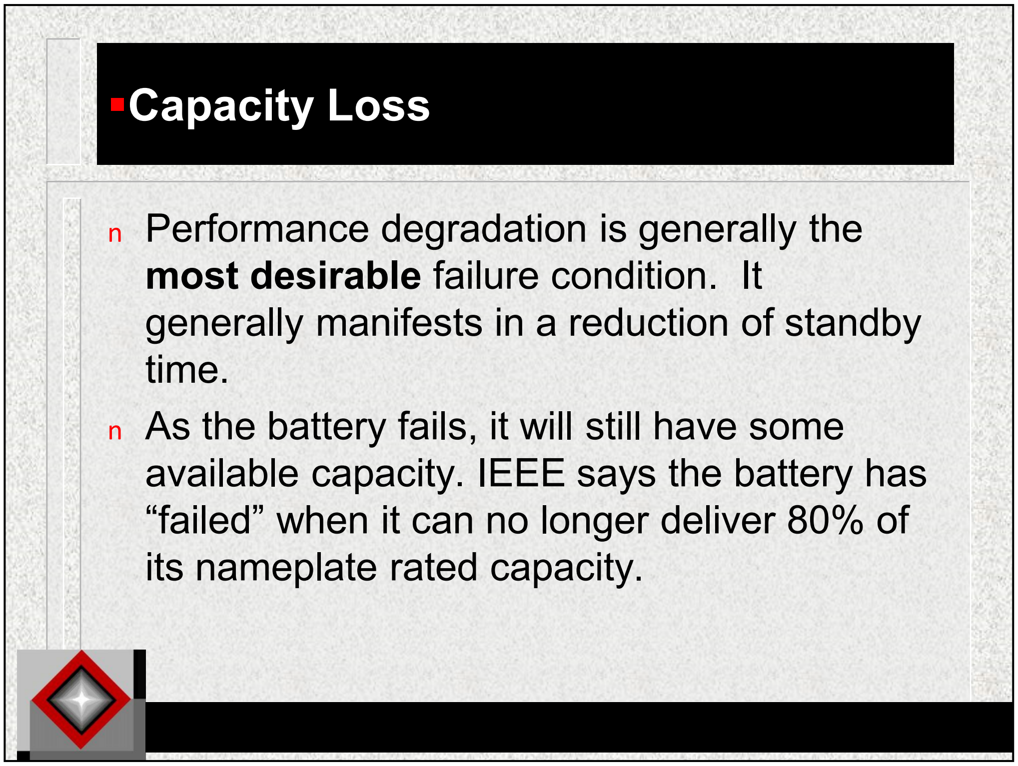
Short Circuit Failure

- Generally, single cells will fail (unless terminals are shorted). As a cell fails it acts as a shunt. Other cells will suffer the consequences of higher charging voltages and higher charging currents.
- Long term result is usually **catastrophic** (fire, meltdown, explosion).

In electrical distribution systems, a short circuit condition nearly always conjures up images of volatile thermal events. That is especially true of batteries for two reasons:

- The high amount of short circuit current available,
- The potential for a catastrophic meltdown, fire or explosion.

Additionally, a shorted condition in a single cell, often propagates thermal events to the other cells in the near proximity.



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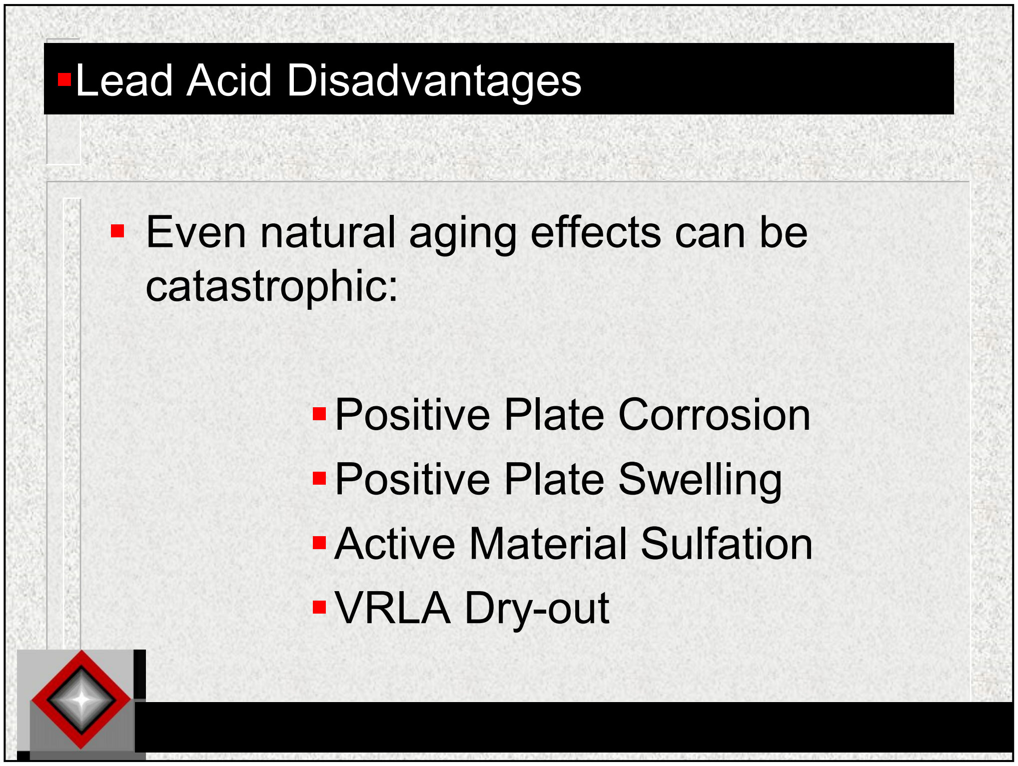
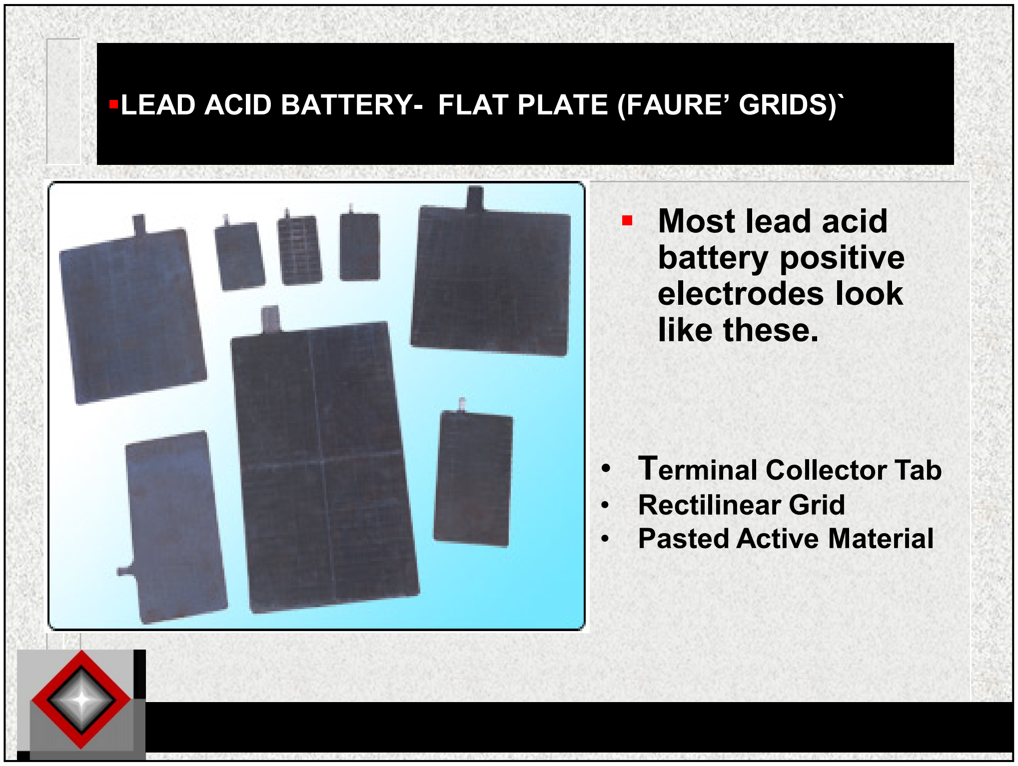


One of the biggest disadvantages of lead acid batteries is that the chemistry is not very stable and is naturally prone to open circuit failure conditions.

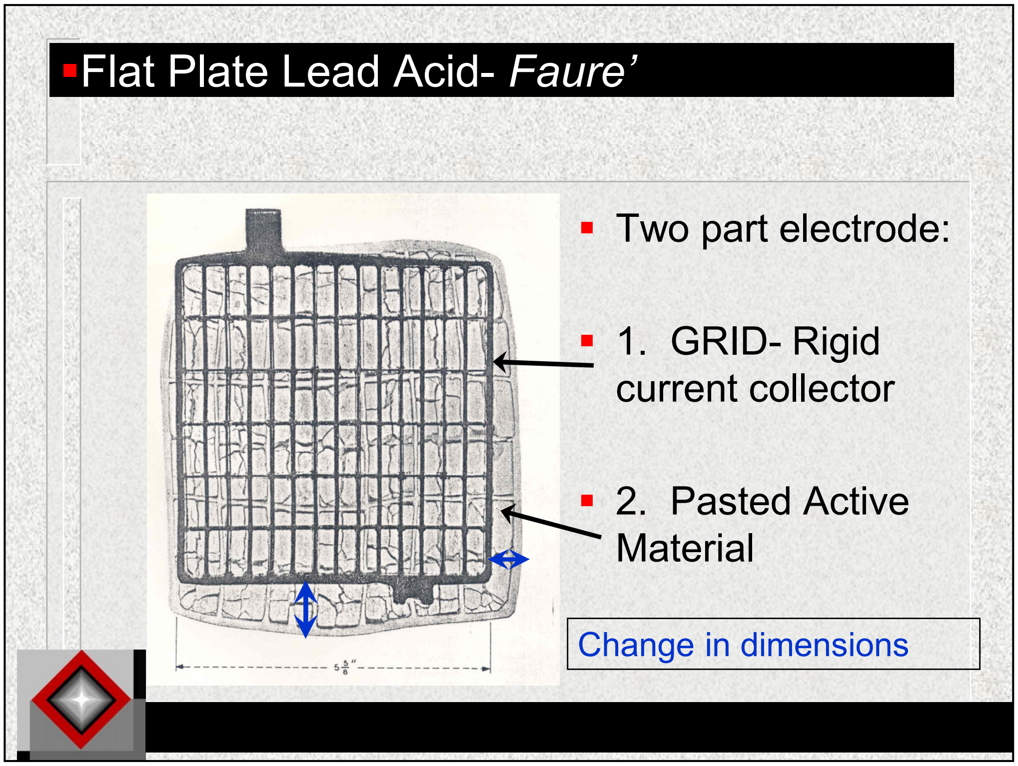
This propensity is caused by the following conditions which are likely to occur during normal and abnormal operation:

- **Positive Plate Corrosion**
- **Positive Plate Swelling**
- **Active Material Sulfation**
- **VRLA Dry-out**



The positive plate of a lead acid battery is easy to distinguish by it's gray color when the active material is pasted to the grid. The collector tab is the connection point to the battery positive terminal. The collector tabs are welded together to add more plate groups and to increase the power and capacity of a battery.

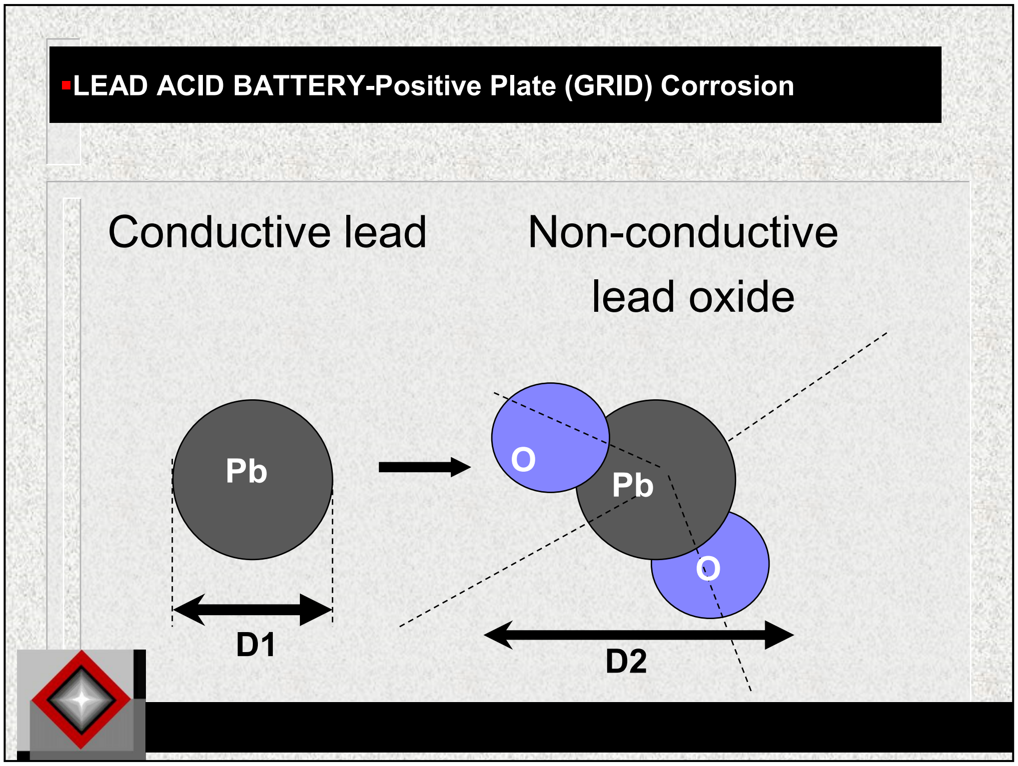
This slide shows how over time, the aging of the grid has caused acid to leak out of the battery and corrode the terminal posts, and create conductive paths of electrolyte on the case of the battery. In really severe cases, the sides of the battery can split, ground faults can occur, and even thermal melt-down or fires can occur. The white colored powdery crystals on the tops of the container seals is evident of leaking of the electrolyte and this indicates where the seals have been compromised.



This image is a brand new grid from a 200 amphr lead calcium battery, that was placed on top of the positive plate that was removed from the same model of but of a 20 year old battery. The top dark gray colored grid photographed on this slide is actually a new and unused grid that has not been exposed to sulfuric acid electrolyte yet. The lighter colored electrode below it is a grid that was removed from a battery that had been in service for @20 years on a float charge.

You can see the difference in the dimensions from new to end of life. The oxidation of the lead alloys in the grid actually cause the grid to swell by as much as 15% to 20% in all directions. The grid will physically grow in the path of least resistance which typically caused the battery to swell resulting in ruptured enclosures, or for the grid to swell so much it penetrates the separator between the plates and short circuits. Not only does this oxidized material physically grow, but it becomes less conductive.

The electrodes from most lead acid batteries is a 2-part system consisting of a rigid metallic grid or current collector, and the active material that is applied to the grid. The active material is where all of the active chemical processes for charge and discharge take place. Any chemical reaction with the grid is considered **"parasitic".**

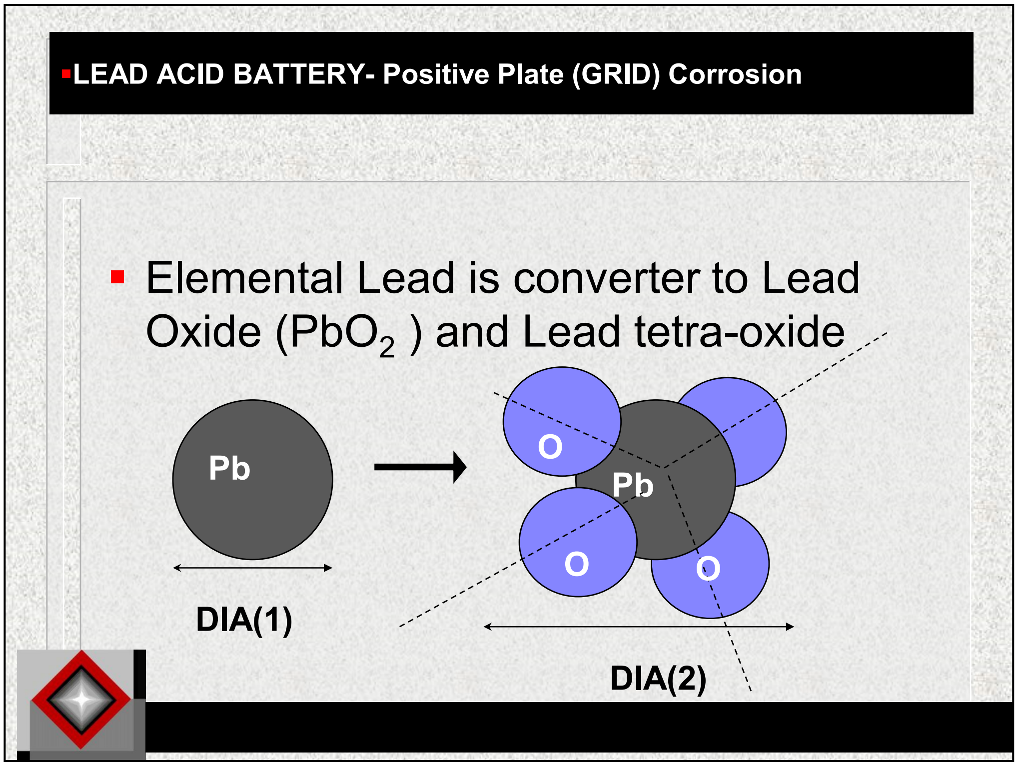


Since the current collector (grid) is mostly metallic lead on a lead acid battery, the normal aging of all lead acid batteries is the oxidation of the positive plate grid. This sulfuric acid causes the metallic lead to be converted to lead oxide.

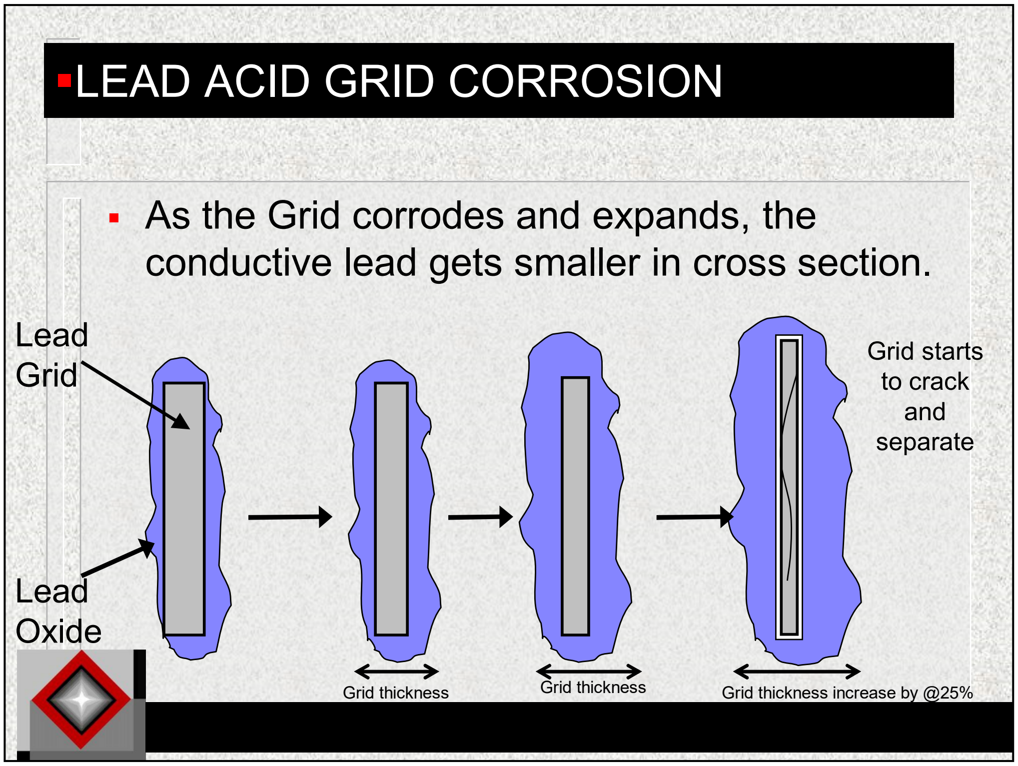
You can visualize that as oxygen molecules are added to a metallic lead molecule, the actual diameter of the molecule expands. If you do not have a way to manage this expansion, the molecules will cause expansion of the grid and it will enlarge in the "path of least resistance". This typically causes the grid to expand either in length or in thickness. Expansion in length will force the grids to push the terminal posts outward and will cause cracking in the terminal post seals, or in the case/cover. Expansion in the thickness, will cause the grids to either force their way through the separators, or will crack the battery case sidewall corners.

By increasing the thickness of the lead grid, you can make a battery last longer. However, once the acid is put into a battery, you cannot slow down or reverse this oxidation process. The following things cause this to accelerate and will result in premature failures:

1. Elevated ambient temperatures,
2. Elevated charge voltage and charging currents,
3. Elevated concentration of sulfuric acid in the electrolyte,
4. Heavy cycling of the battery,
5. Overcharging of the battery.

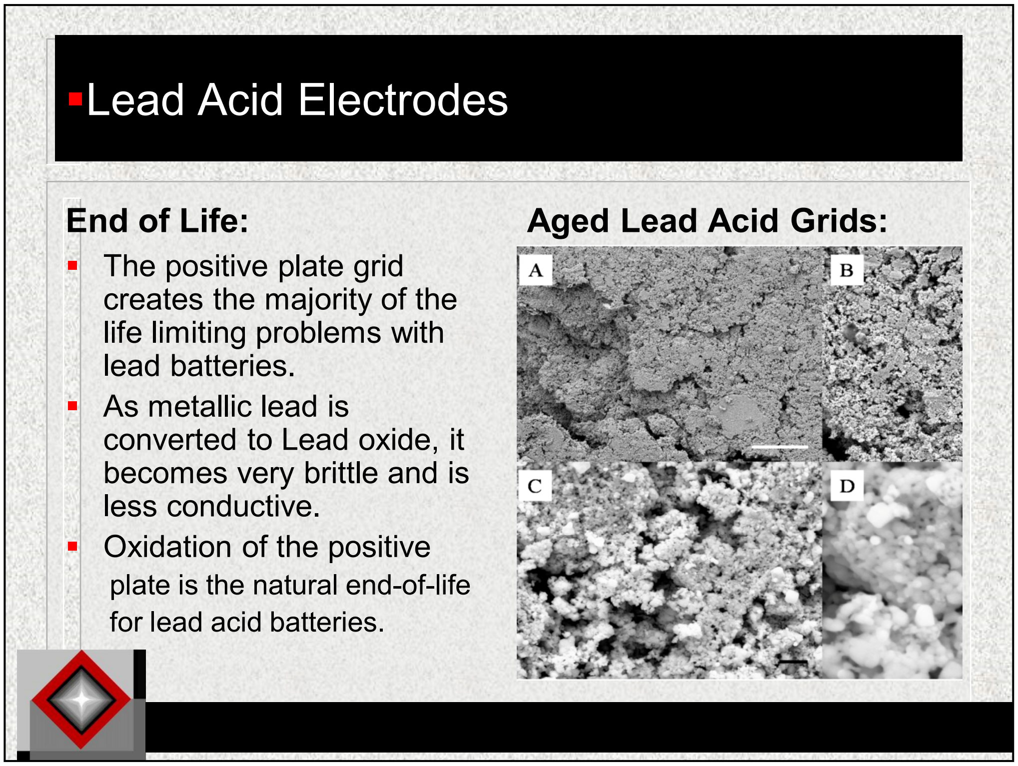


You can see what happens to the diameter of a lead molecule. When through the oxidizing process, first 2 oxygen molecules and ultimately 4 oxygen molecules are added to the atom of lead. The volume of the grid has to expand. This expansion is called “swelling” or corrosion of the positive plate grid. It is the mechanism that degrades the battery performance of lead acid batteries over time. As this grid “swells” the active material bonding interface breaksdown making it harder for the grid to collect the anion and ions to transport them to the battery terminal. It also causes the active materials to slough off of the grid losing contact surfaces. Both of these dynamics cause the battery impedance to increase. To add to the detriment, lead oxid is much less conductive than lead and is a very soft and brittle substance. Over time, these grids will literally fall apart.



As the conductive lead on the positive plate grid starts to convert to lead oxide, the grid starts to swell. As the grid swells, several things are occurring:

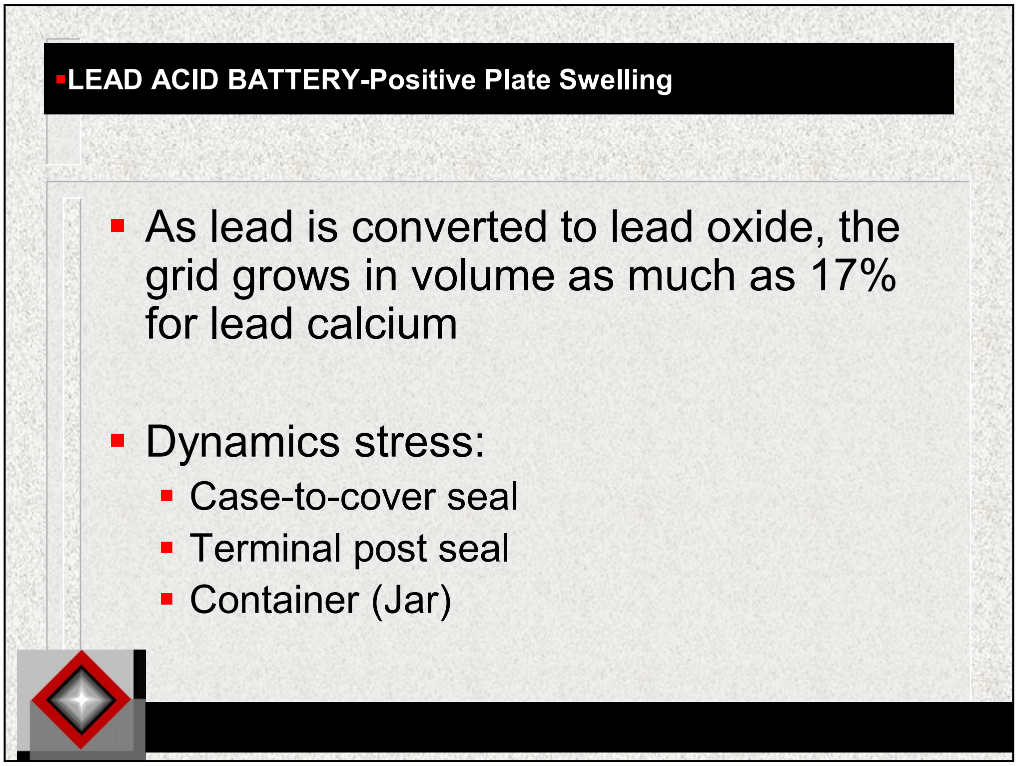
1. The lead metal is being oxidized and the lead oxide is less conductive than the metallic lead. As this occurs the conductance decreases, and the impedance increases.
2. The lead oxide is quite brittle. It mechanically begins to loose the ability to adhere to the active material substrate and becomes fragile. Overtime this forces the contact surface between the grid and the active materials to separate, further decreasing the conductivity and also creating the situation where the active material will slough off of the electrode and either lodge as lumps, or fall to the bottom of the battery.
3. As the volume of the grid increases, it can force itself through the separators and ultimately short circuit to the negative plate which will result in a potential melt-down of the battery, a fire, or an explosion. The volume for a lead calcium battery can increase by as much as 25% over a 20-year life span on charge. The higher the ambient temperature, the faster this occurs and the more severe the plate growth can be.
4. If the path of swelling is vertical, the plates will force the terminal posts to push through the case/cover of the battery and either crack the terminal seals or crack the casing. This setup the problem of acid wicking up the posts and potential pooling of electrolyte on the tops of batteries. If the electrolyte wicking is severe, it can cause short circuits as the conductive liquid drip down the sides of the battery and either makes contact with the metallic racks, or shorts the terminal posts.
5. As the conductive lead metal shrinks in dimensions, it also becomes more brittle and can actually develop fissures and cracks which will cause the battery voltage to “open-circuit” under load. This is commonly called **sudden death syndrome**.



Under an SEM high powered microscope, you can see the change in structure of the lead grid at 1 year (A), 5 years (B), 10 years (c), and 20 years (D) of operation.

Tubular plate battery construction was introduced to have a physical means of holding the active materials tightly to the grid…even while the grid is oxidizing.

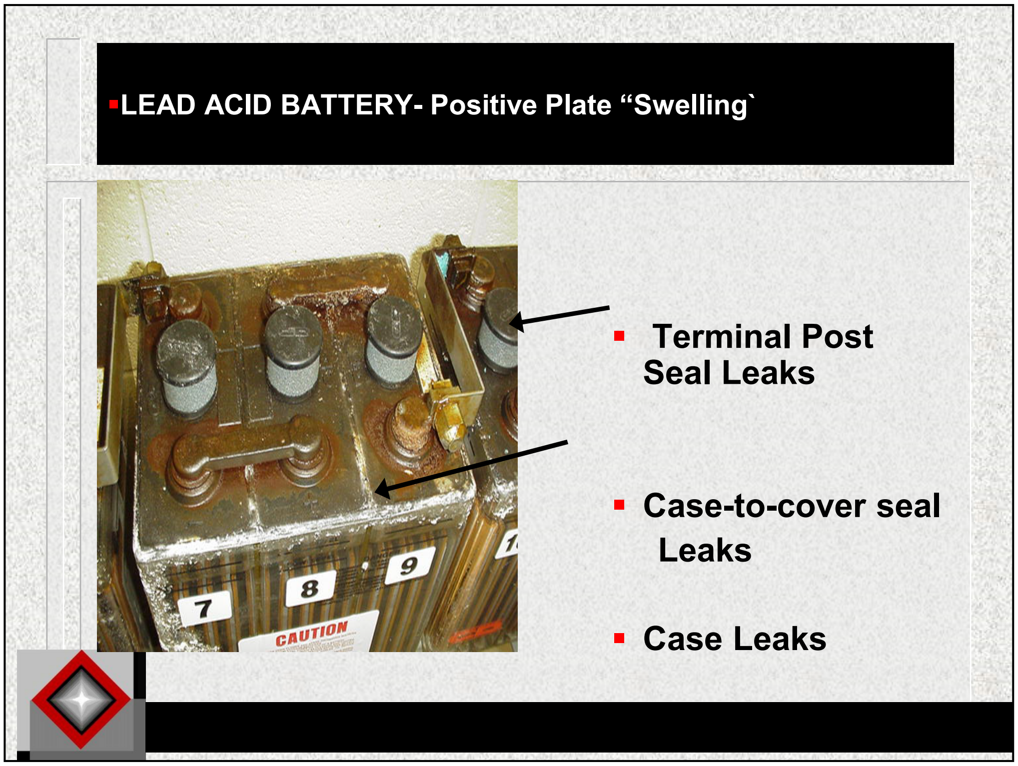
The positive electrode is still aging, but it is being physically held together by the pressure of these polymer sleeves.



The oxidation or corrosion of the positive plate will cause this grid to grow. It will grow in the path of least resistance which is often through the cover of the battery. This puts stress on the cover, the case-to-cover seal, and on the terminal post seals.

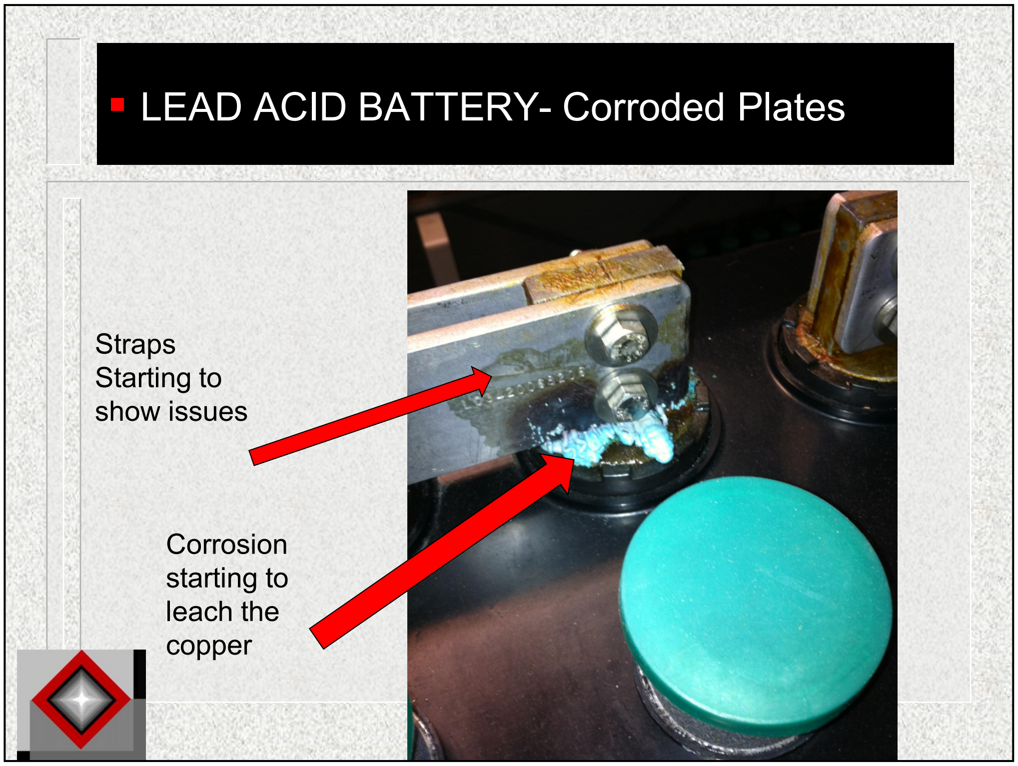
As lead is converted to lead oxide, the grid grows in volume as much as 17% for lead calcium. This causes a lot of stress on the battery cases as the internal workings of the battery tend to expand in the path of least resistance. This is typically through the top of the container, or through the side walls. Either of these create nuisances and a potential to spillage of electrolyte.

- Dynamics stress caused by positive plate corrosion:
    - Case-to-cover seal
    - Terminal post seal
    - Container (Jar



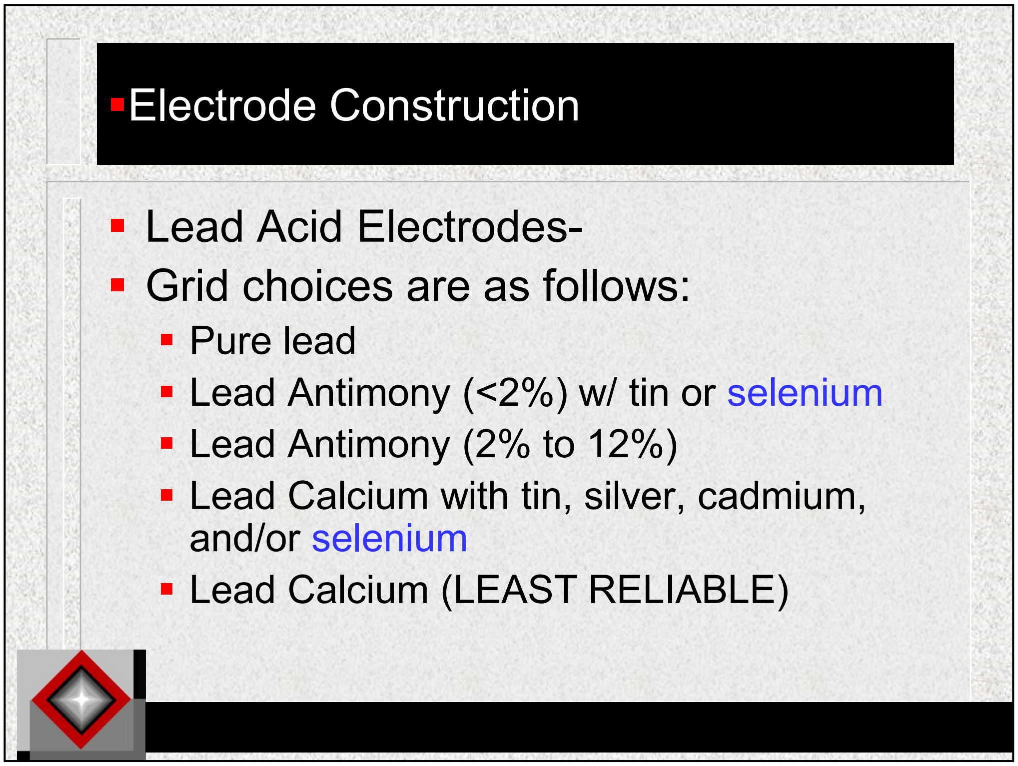
The white residue is indication that acid has wicked up through cracks that are developing on the cases and covers. If not replaced, this battery will eventually crack down the side walls and release sulfuric acid all over the rack and floor.

This slide shows how over time, the aging of the grid has caused acid to leak out of the battery and corrode the terminal posts, and create conductive paths of electrolyte on the case of the battery. In really severe cases, the sides of the battery can split, ground faults can occur, and even thermal melt-down or fires can occur. The white colored powdery crystals on the tops of the container seals is evident of leaking of the electrolyte and this indicates where the seals have been compromised.



Effect of Swollen positive Plates:

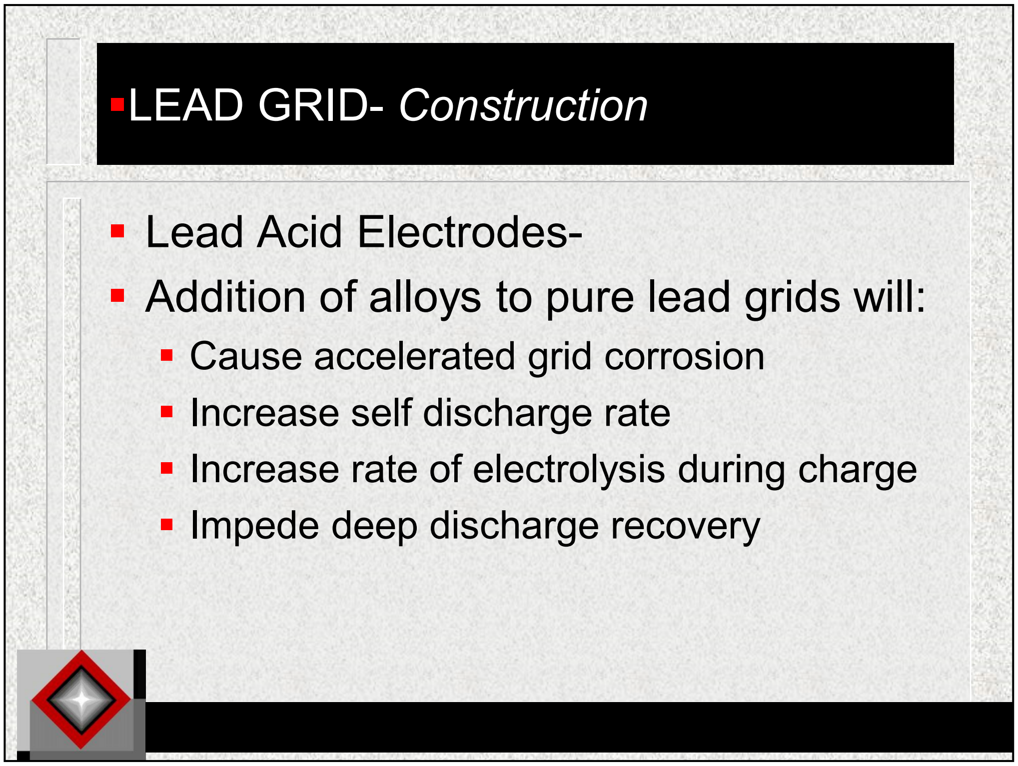
- This is a different string of batteries at an early stage of the wicking.
- Post seal has broken due to the positive plate swelling.
- Acid is corroding the lead plating on the battery strap (slight blackening of the strap where the acid has contacted the lead plating).
- Corrosion is forming a blueish green discoloration indicating that the copper metal from the strap or from the copper insert is now leaching out and being oxidized.
- Over time this will worsen and the impedance of the battery and the strap will increase.
- This terminal will also get hotter when current flows through it affecting both discharge capability and recharge of the battery.
- By the time you see this type of damage on the battery, it's performance will always be suspect and steps should be taken to minimize further damage.



This information provides a little bit more detail of the types of chemistries you can ask for by name when specifying or sourcing lead acid station batteries.   These are the most common types of lead acid battery grid “classes” which are distinguished by the alloying agent that is added to the metallic lead in the grids:

- Pure lead (none, or very little alloying)
- Lead Antimony (<2% by molecular weight) w/ trace amounts of tin or selenium
- Lead Antimony (2% to 12% by weight)
- Lead Calcium with tin, silver, cadmium, and/or selenium
- Lead Calcium (Poorest in dependability and reliability)

Of these technologies, lead selenium is the best value when considering ultimate performance <u>and price</u>. Selenium offers the best overall value without sacrificing reliability.



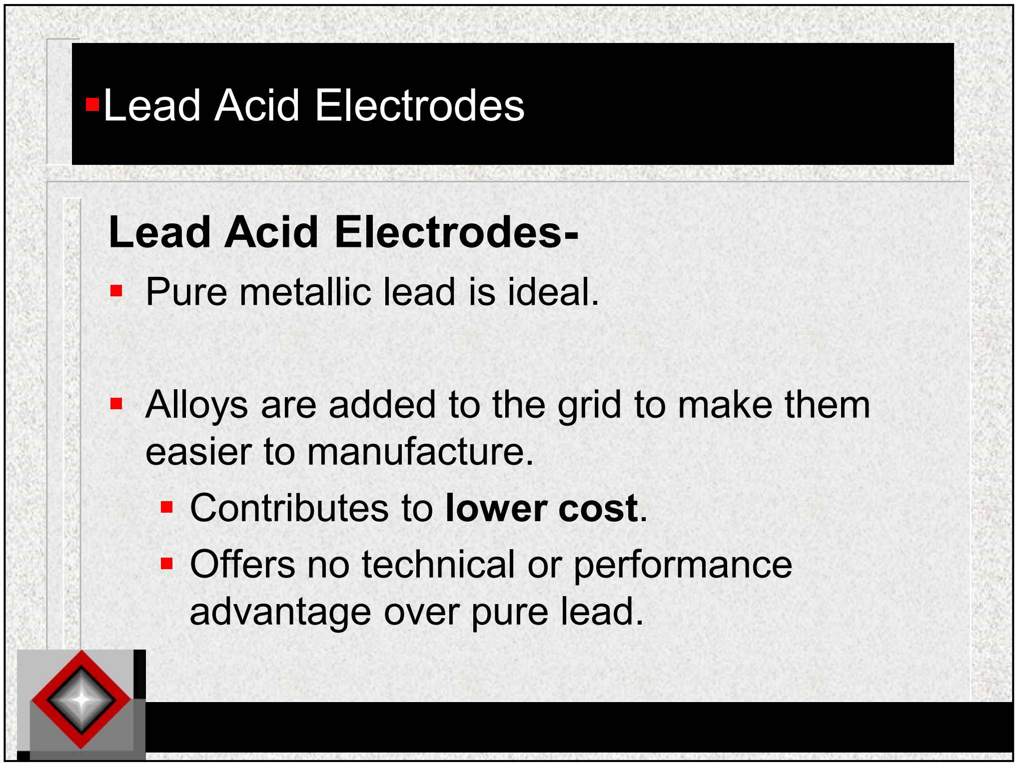
Adding alloys will lower the manufacturing cost of battery grids, but will have negative repercussions:

- Accelerated grid corrosion
- Increase self discharge rate (reduces storage time)
- Increase rate of electrolysis during charge (electrolyte evaporates faster causing increased watering intervals)
- Impede deep discharge recovery (can make it more difficult to recharge the battery after a deep discharge)

This slide is just to recap that the addition of any of the following alloys to a pure lead grid will only accelerate the undesirable aging conditions:

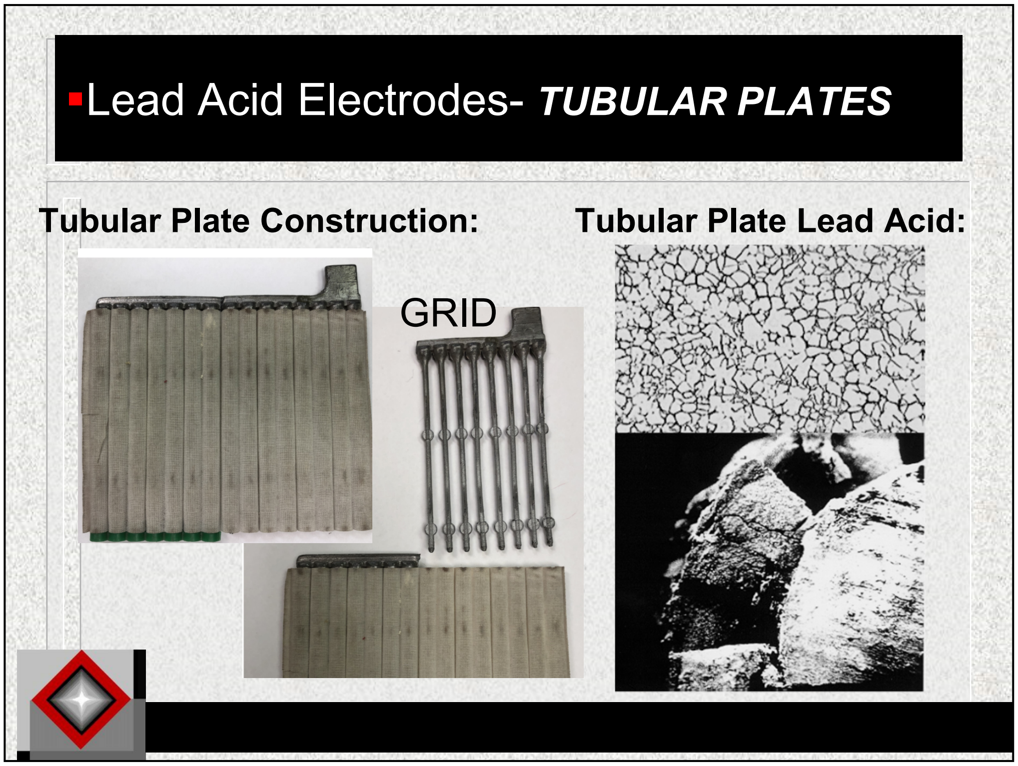
- Calcium
- Silver
- Antimony
- Tin
- Lithium Bisulfate
- Selenium

Some of these additives are better than others at minimizing some of the aging process. In particular, selenium and silver both give desirable attributes to lead acid battery performance while minimizing temperature limitations, deep discharge recovery issues, and cycle life.



Metallic lead is a very soft and ductile material. That makes it very difficult to use in a manufacturing process where dimensions and form need to be retained.

The use of any additive (tin, calcium, silver, magnesium…) to a pure lead grid, is purely for the purpose of making it easier to manufacture. This inherently lowers the cost.



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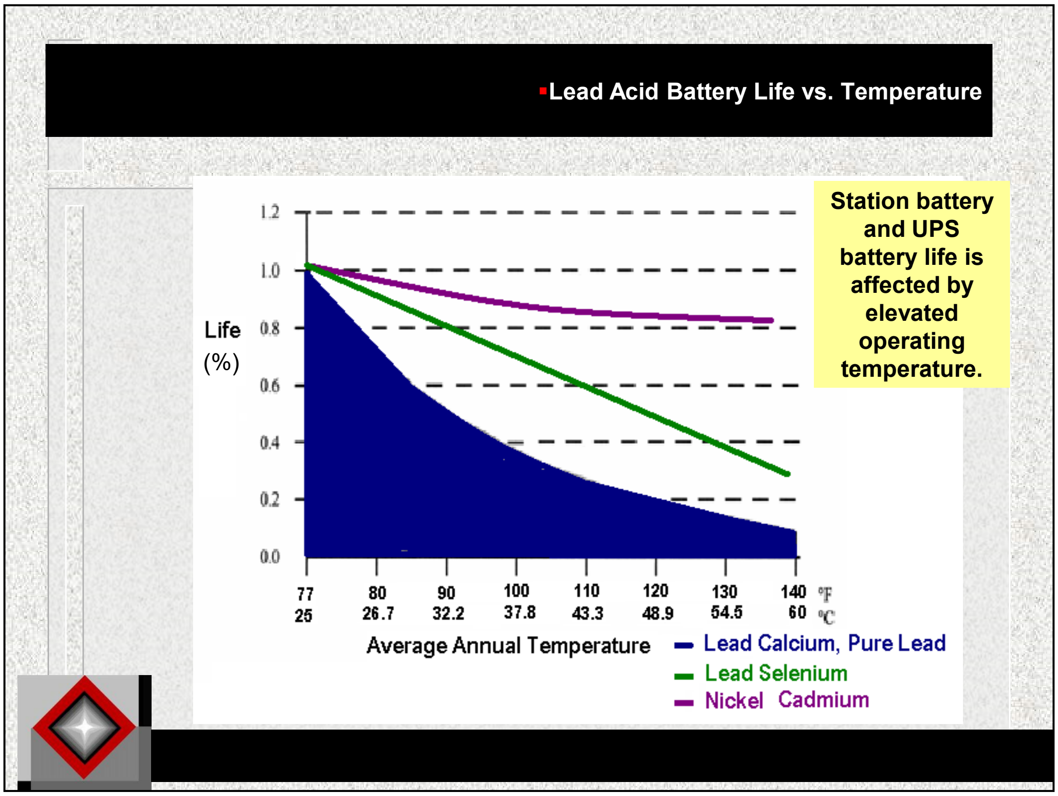
The positive electrode is still aging, but it is being physically held together by the pressure of these polymer sleeves.

The tubular positive plate batteries still have a conductive grid which uses a selenium alloy. However, the grid is shaped like splines of a long fork instead of like a rectangular grid. The top SEM photo shows the grain structure, ensuring low corrosion and avoiding grain boundary corrosion which leads to significant performance improvements over a lead calcium plate.

Tubular plate benefits:

- Excellent cycling characteristics
- Improved deep discharge recovery
- Low manufacturing cost
- Extended float life
- Reduces potential for grid corrsosion to @4% over a 25 year float life.

The bottom SEM photograph shows the core section of one of the splines after 15 years on charge. It has a small layer of lead oxide on the outside, but the core spline is still in tact and unperturbed. For lead acid type batteries, the selenium tubular plate type is the most dependable and can deliver greater than a 25 year float life at 72 degrees F.



Historically we have always specified nickel cadmium batteries for use in extremes of temperature. As you increase the ambient temperature of a battery, you will get a reduction of the anticipated float life. You can see at 120 degrees F, the lead calcium battery life is derated by 80%, the Lead selenium battery is derated by @50% and the nickel cadmium battery is only derated by about 18%.

Many battery monitoring systems use ambient temperature, as well as battery temperature, for state of health determination. Temperature measurements in conjunction with on-charge float current measurements can be a very valuable tool for understanding the condition of your battery.

This makes nickel cadmium a better choice for extremes of temperature. That is true for either hot or cold temperatures.

The ambient temperature accelerates the degradation of the lead grids which ultimately determine the natural end of life of a lead acid battery which is used in a float charging application. A really good rule of thumb for lead acid batteries is: “you half the life of the battery for every 15 degrees in Fahrenheit rise in temperature. So at 90 deg F ambient temperature will cause a 20 year design life battery to deliver @10 years of life….the catch is that the higher this ambient temperature, the higher the propensity to premature failure modes.

The nickel cadmium batteries are the top fuscia line and you can see that both elevated temperature performance and low temperature performance and much less degraded by high or low temperature.

Lead Acid Aging Mechanisms

Battery Type	Aging at Normal Temp	Condition
Wet lead antimony w/ selenium pasted plate	Pos. Grid Corrosion Sulfation	Open Circuit Capacity Loss
Wet lead antimony tubular plate	Pos. Grid Corrosion Sulfation Antimony migration	Open Circuit Capacity Loss Capacity Loss
VR lead calcium Pasted plate	Pos. Plate Corrosion Sulfation Dry-out	Open Circuit Capacity Loss Open Circuit

Not to belabor a point, but this slide shows what the typical aging mechanism would be for the different categories of lead acid batteries. It also shows how the condition would propagate over time.

The most important message I want to leave with you about lead acid batteries is the following.

Lead acid batteries are prone to open circuit failure (commonly described as **"sudden death"**). The most advanced monitoring systems in the world cannot predict the exact time that the battery will fail open. It is highly unpredictable.

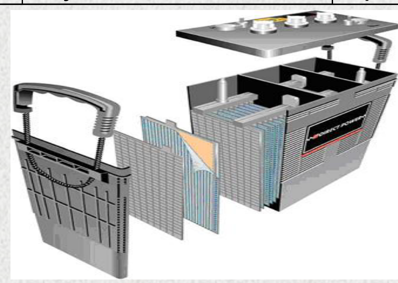
Lead Acid Aging Mechanisms

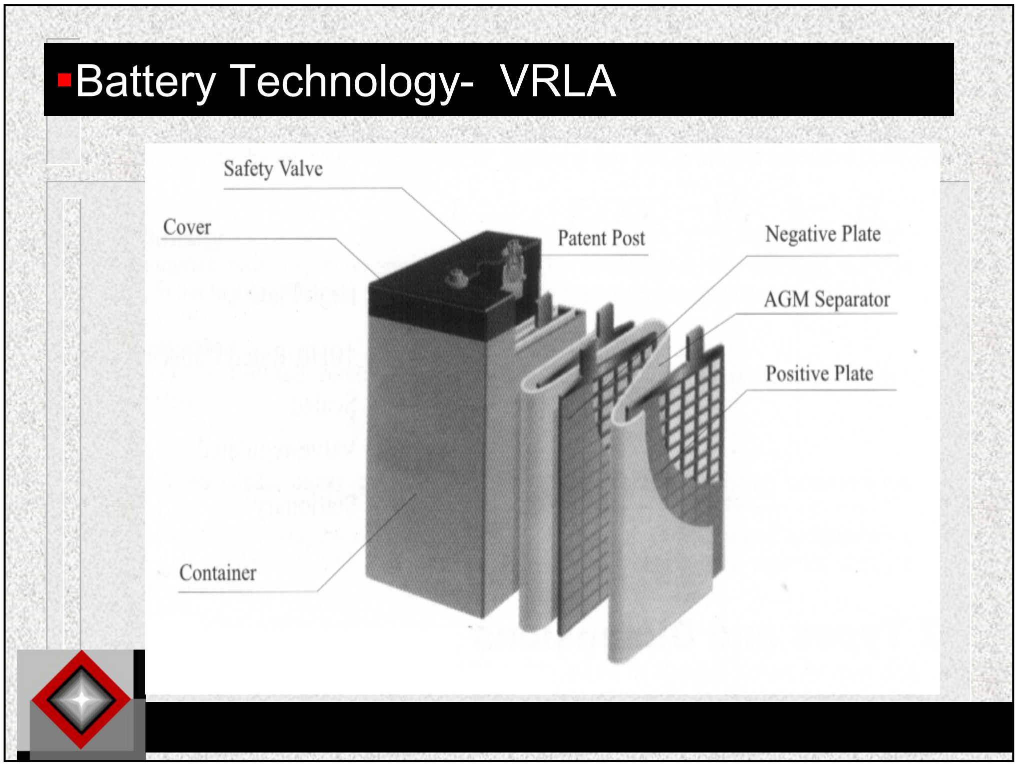
Battery Type	Aging at Normal Temp	Condition
Wet lead calcium pasted plate	Pos. Grid Corrosion Sulfation	Open Circuit Capacity Loss
Wet lead antimony pasted plate	Pos. Grid Corrosion Sulfation Antimony migration	Capacity Loss Open Circuit Capacity Loss
Wet Plante’	Pos. Plate Corrosion Sulfation	Open Circuit Capacity Loss

Grid corrosion by itself will limit the life of the battery. When compounded with other detriments like sulfation, you may also experience capacity loss.

Lead Acid Aging Mechanisms

Battery Type	Aging at Normal Temp	Condition
VR lead calcium Pasted plate	Pos. Plate Corrosion Sulfation Dry-out	Open Circuit Capacity Loss Open Circuit





Valve regulated lead acid VRLA batteries are actually more prone to premature failure than flooded lead acid batteries. You still have many of the basic internal components:

- Separators
- Positive electrode
- Negative electrode
- Sulfuric acid electrolyte
- Container
- Cover
- Terminal posts…..

The difference is that due to the following:
1. Electrolyte is minimized and immobilized which makes them susceptible for "dry-out" during heavy cycling or for improper charging conditions.
2. The electrolyte still undergoes electrolysis during charging. In the VRLA batteries, since the battery is internally pressurized, the oxygen and hydrogen ions that are formed will migrate together and recombine into the electrolyte. Unfortunately, this reaction is exothermic so now you have additional heat generated on the battery that is the equivalent of 7 degrees Fahrenheit. You are already cutting the battery life by ¼ if you cannot actively dissipate and cool the battery. For this reason, this technology is highly prone to thermal run-away in non-temperature controlled environments.

3. of system, these batteries have very poor cycle life which limits their deep discharge cycle capability to less than 50 cycles.

Valve Regulated Battery Options

- **Design Life Options:**
  - **5 Year**
  - **10 Year**
  - **15 Year**
  - **20 Year**
- **Alloy Options:**
  - **Pure lead**
  - **Silver, Tin**
  - **Calcium**

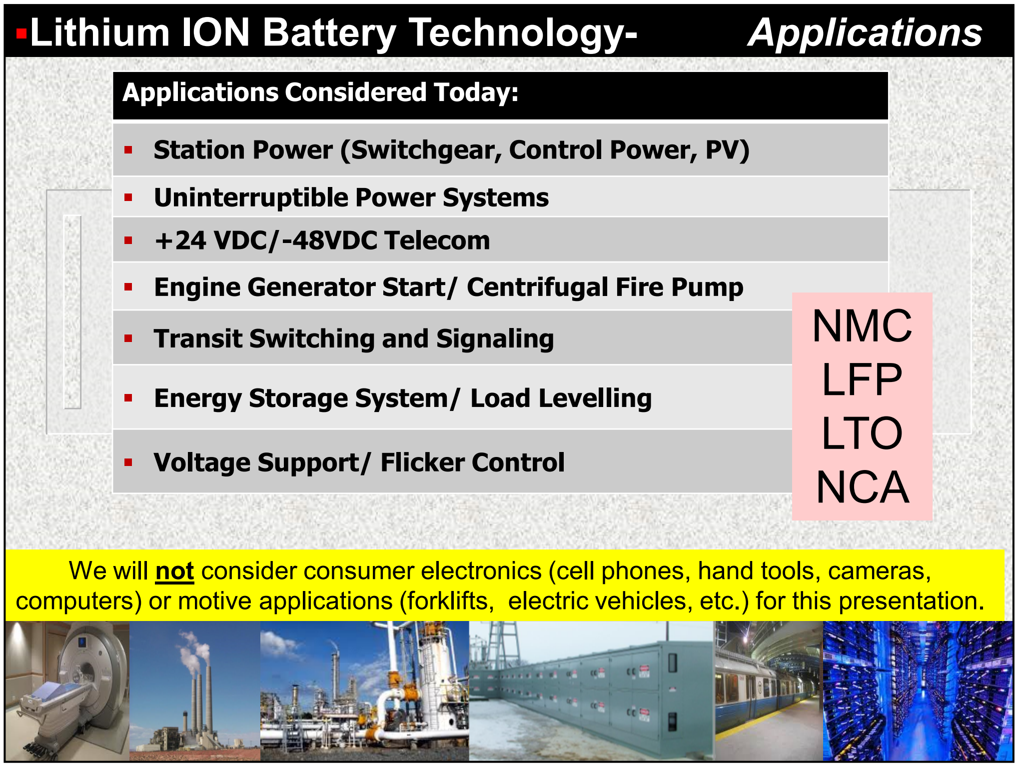
The valve regulated lead acid batteries come in many varieties and with many “engineered” design life options from 1-year to 20-years. The reality is that nobody polices battery performance data and warranties are not representative of performance. It is important for all users of lead acid batteries to understand that the manufacturer's warranty is a guarantee against manufacturing defects only and is **not** a performance guarantee.

Configurations:

The lead acid battery come in many configurations:

- Cabinetized
- Open Rail Racks
- Vertically Stacked Modular Systems

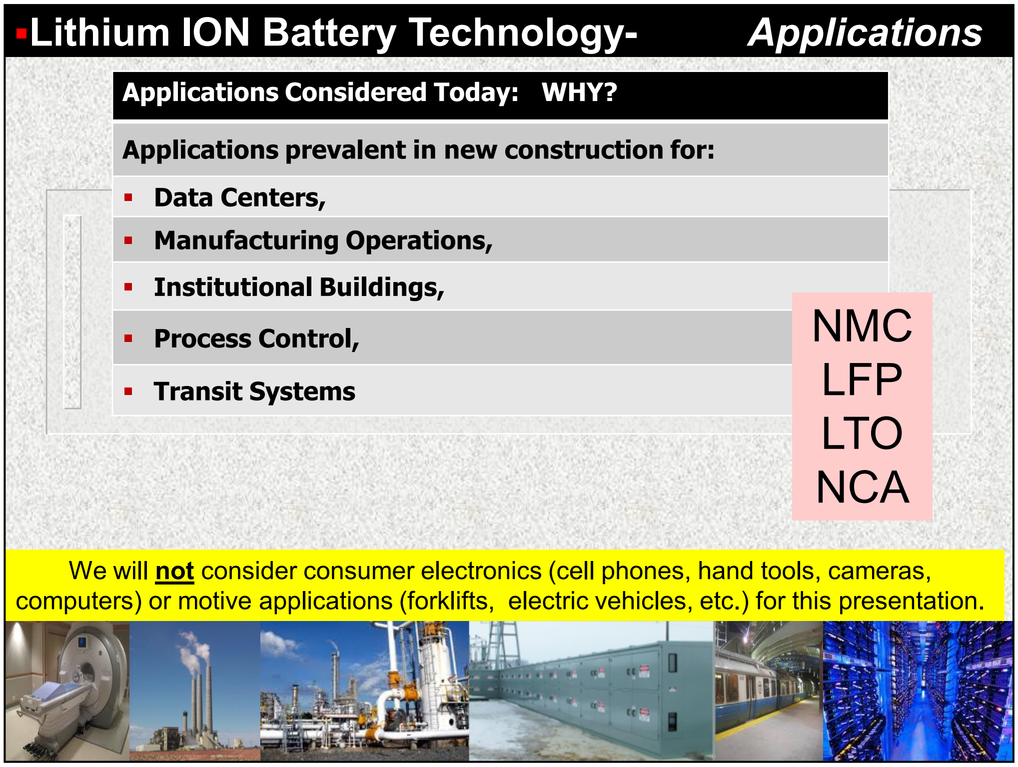
They are also offered with varying anticipated float life. Many batteries offered include a 20 year design life warranty. Still others may only be 3-year, 5-year 10-year or 15-year design life.



These are the applications we will discuss in detail today. Primarily because these are the types of systems prevalent in new construction for Data Centers, Manufacturing Operations, Institutional Buildings and Process Control. What these applications have in common:

1. They all use primarily taper current charging systems,
2. They are all emergency standby applications,
3. They all are primarily float charging applications,
4. These systems are rarely cycled to a significant depth of discharge.

If I am using unfamiliar terminology, don't hesitate to speak up.



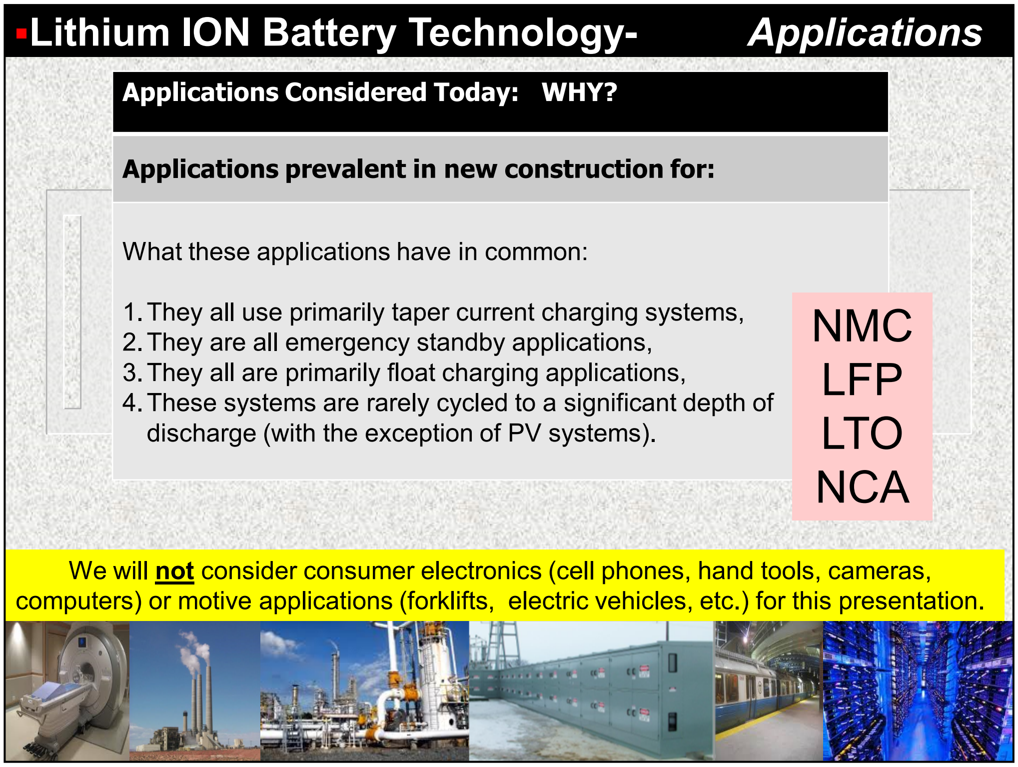
These are the applications we will discuss in detail today. Primarily because these are the types of systems prevalent in new construction for Data Centers, Manufacturing Operations, Institutional Buildings and Process Control.

The batteries used in these applications have some commonalities in:

How often they are cycled,

How they are charged,

Whether or not they are used for standby or for prime power applications.



These are the applications we will discuss in detail today. Primarily because these are the types of systems prevalent in new construction for Data Centers, Manufacturing Operations, Institutional Buildings and Process Control. What these applications have in common:

1. They all use primarily taper current charging systems,
2. They are all emergency standby applications,
3. They all are primarily float charging applications,
4. These systems are rarely cycled to a significant depth of discharge.

The chemistries we will consider for the lithium ion family will be:

- NMC
- LFP
- LTO
- NCA

These are the acronyms for the electrode chemistries that are the most common for station power applications.

Battery Failures

Modes of Failure	Lead Acid	Nickel Cadmium	Lithium
Natural Aging	Open Circuit (Sudden Death)	Gradual reduction of capacity	Gradual reduction of capacity (SEI interface growth Lithium Plating, Intercalation)
Premature Failure	Typically Open Circuit	Gradual loss of capacity	Loss of communication
Manufacturing Defects	Rare	Rare	Rare

Understanding the limitations of the different chemical systems available for station battery applications is important. ***How do batteries typically fail in a perfect operating condition?*** We call this the "Normal End of Life Failure Mode". Let's consider the (2) most common types of failure for each lead acid, nickel cadmium and lithium ion chemistries. Note that **manufacturing defects** are actually quite rare for all types of batteries produced in North America, Europe, India, and Asia.

Lead acid battery chemistry is very unstable. From the moment acid is introduced into the battery, the internal components of the battery are already degrading from the normal aging process. As the battery is charged and ages, the battery positive grids become oxidized and the battery will eventually fail to an open circuit condition. Unfortunately, this type of failure cannot be predicted under the best monitoring available. Additionally, most abnormal operating conditions will only accelerate this eventuality, unless a premature failure mode (such as thermal runaway or elevated temperature operation) caused a short circuit condition which can be highly catastrophic.

Nickel cadmium batteries offer the most stable chemistry for any operating condition. Not only are they more stable, but they are more dependable in extreme temperature. Nickel cadmium batteries have NO propensity to fail to an open circuit condition either in natural aging or premature failure. The normal failure for a nickel cadmium battery is a very predictable decline of capacity of time.

Lithium batteries behave a lot like nickel cadmium batteries for aging effects on performance, but lithium battery systems are equipped with considerable electronic monitoring systems for thermal detection and management, over/under voltage detection and management, over-current detection and management, that these may yet prove to be even more dependable than the nickel cadmium batteries.

Understanding how each battery type fails, helps us mitigate potential loss of service, but also helps us avoid catastrophic failures.

Most electrical engineers are very familiar with the typical aging of a lead acid battery.

Lead Acid Failures:

Corrosion of positive electrode grid (Natural)

Dryout for VRLA (Premature)

Short Circuit due to grid growth (Premature)

Active material shedding and breakdown due to heavy cycling (Premature)

Nickel Cadmium Failures:

Gradual degradation of electrodes (Natural)

Carbonation of the electrolyte (Natural)

Iron migration from the current collector (Natural)

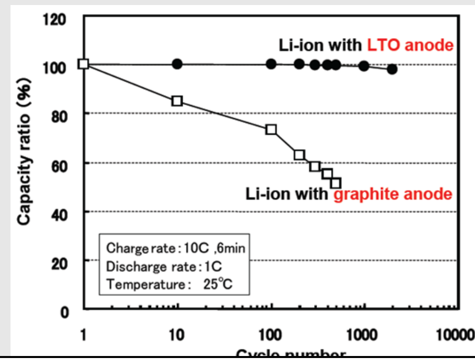
Pemature (Any acceleration of natural affects)

Lithium Ion Failures:

SEI interface growth (Natural)

Lithium Plating (Natural)
Intercalation (Natural)
Communication Loss (Premature)

Lithium ION Battery Technology- *End of Life*

Aging Mechanisms:	Resulting Symptom
Intercalation **(Natural)**	▪ Parasitic chemical reactions that prevent the lithium ions from populating the interstices of the active materials. Conductivity of the battery is gradually reduced as this occurs.
Repetitive Cycling **(Natural)**	▪ **Very gradual decline of BOL capacity.** 

Note that we are strictly talking about the actual battery “cell” in this slide. We will not bring the electronics for monitoring, control, communication, or protection into this discussion at this time.

According to the Lithium ion battery manufacturers, as the battery ages (in a UPS application), there are negligible amount of chemical/electrolytic failure modes. The cell does not degrade significantly even past 20,000 cycles (although it drops to 80% BOL at around 17,000 cycles). Cross-sectional microscopic electro-lithography (based observations) vouches for our claims.

SCiB LTO does have natural aging just extremely slowly (as compared to other li-ion chemistries as mentioned above).

Lithium ION Battery Technology- *End of Life*

Premature Aging Mechanisms:	Resulting Symptom
Internal Overheating	▪ Removal of the cell from the string. ▪ Venting of the cell
Cell Imbalance (Overcharge/overdischarge	▪ Imbalance of cell voltage levels can cause the cells to age at different rates and affect the internal cell temperature. Improper sizing can also cause similar symptoms.
Lithium Plating	▪ Results from too deep of a discharge with too fast of a recharge repetitively, ▪ When charged at too low of a temperature.
Dendrite/Lithium Deposition	▪ Internal short circuit of a cell
Active Material Instability	▪ **Overtemperature resulting in disconnection**

Note that we are strictly talking about the actual battery “cell” in this slide. We will not bring the electronics for monitoring, control, communication, or protection into this discussion at this time.

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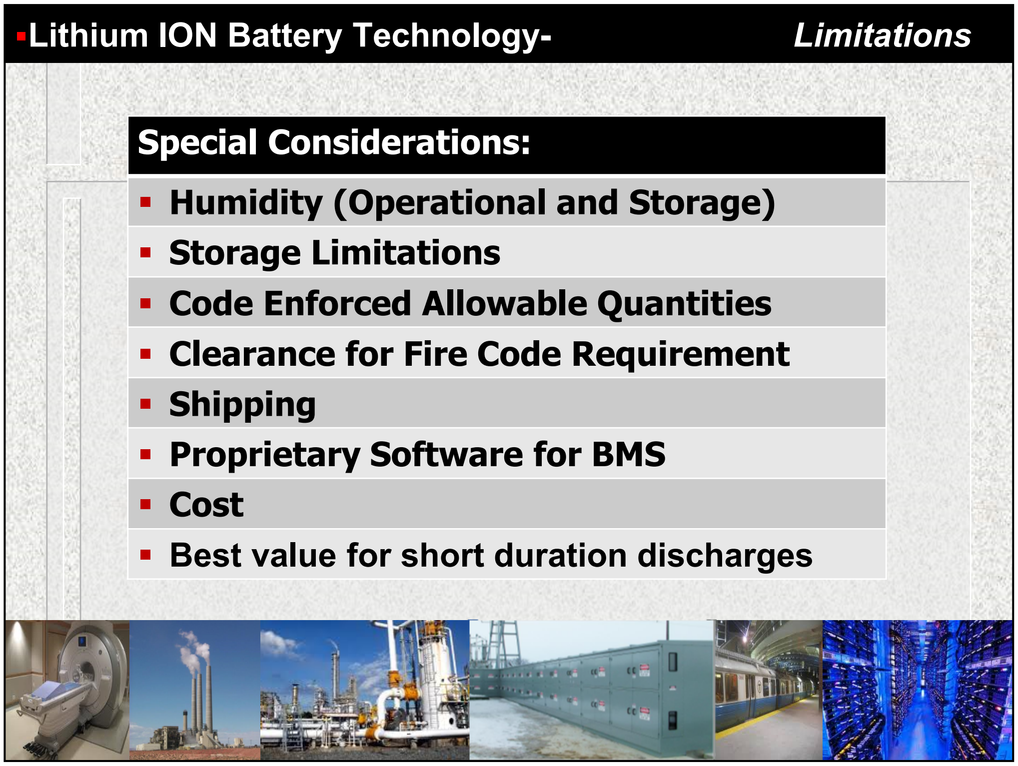
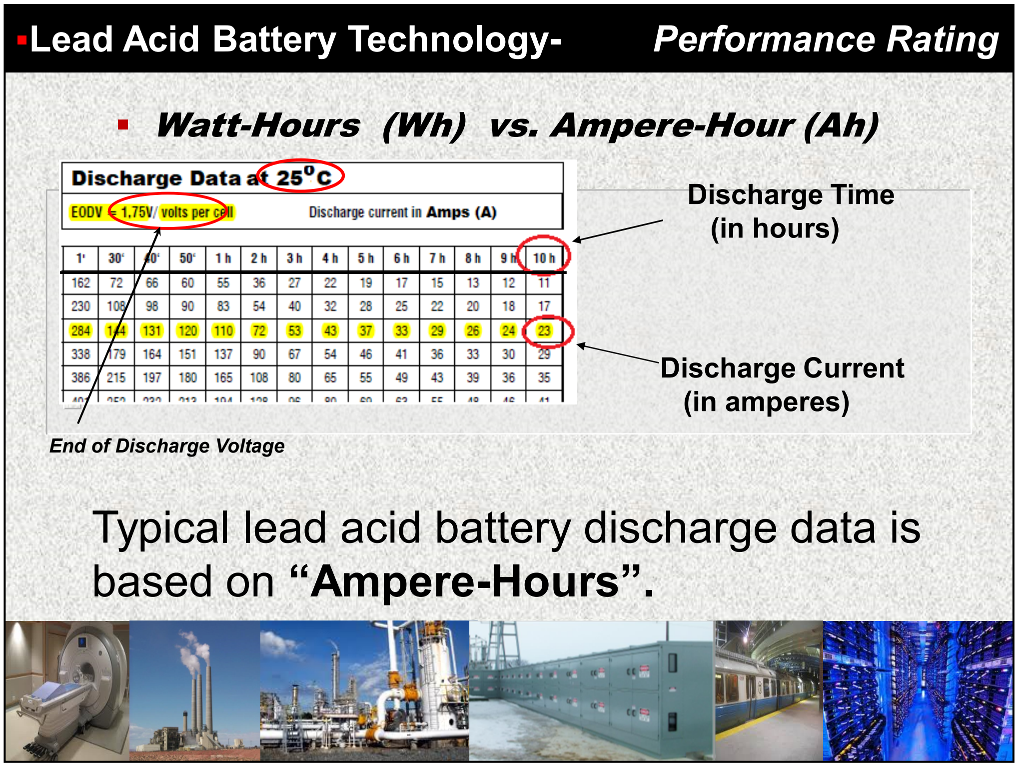


Prudent engineering requires an understanding of the limitations of the different battery technologies as well as the benefits.

When considering technologies for large stored energy systems, all of the topics on this slide could be considered limitations for which the designer must mitigate the long term and short term impact.

WHO is the fire code enforcement agency?

WHAT BUILDING CODE and **WHAT FIRE CODE** is being enforced?



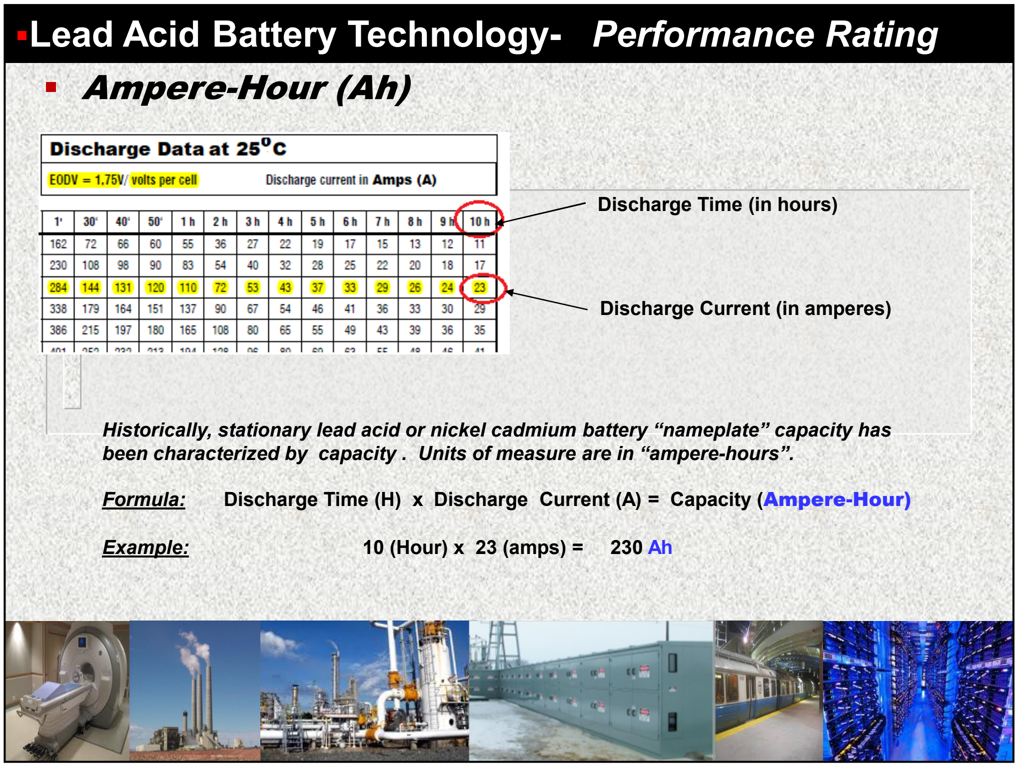
1'	30'	40'	50'	1 h	2 h	3 h	4 h	5 h	6 h	7 h	8 h	9 h	10 h
162	72	66	60	55	36	27	22	19	17	15	13	12	11
230	108	98	90	83	54	40	32	28	25	22	20	18	17
284	144	131	120	110	72	53	43	37	33	29	26	24	23
338	179	164	151	137	90	67	54	46	41	36	33	30	29
386	215	197	180	165	108	80	65	55	49	43	39	36	35

Watt-hours versus Ampere-hours:

That is a topic we have to set as a foundation for the rest of the presentation.

When selecting a traditional lead acid battery, the manufacturers publish discharge data for the particular battery or cells. This data becomes the baseline data used for sizing and it depends on 4 factors:

- **Discharge Time**
- **End of Discharge Voltage**
- **Temperature**
- **Discharge Current**



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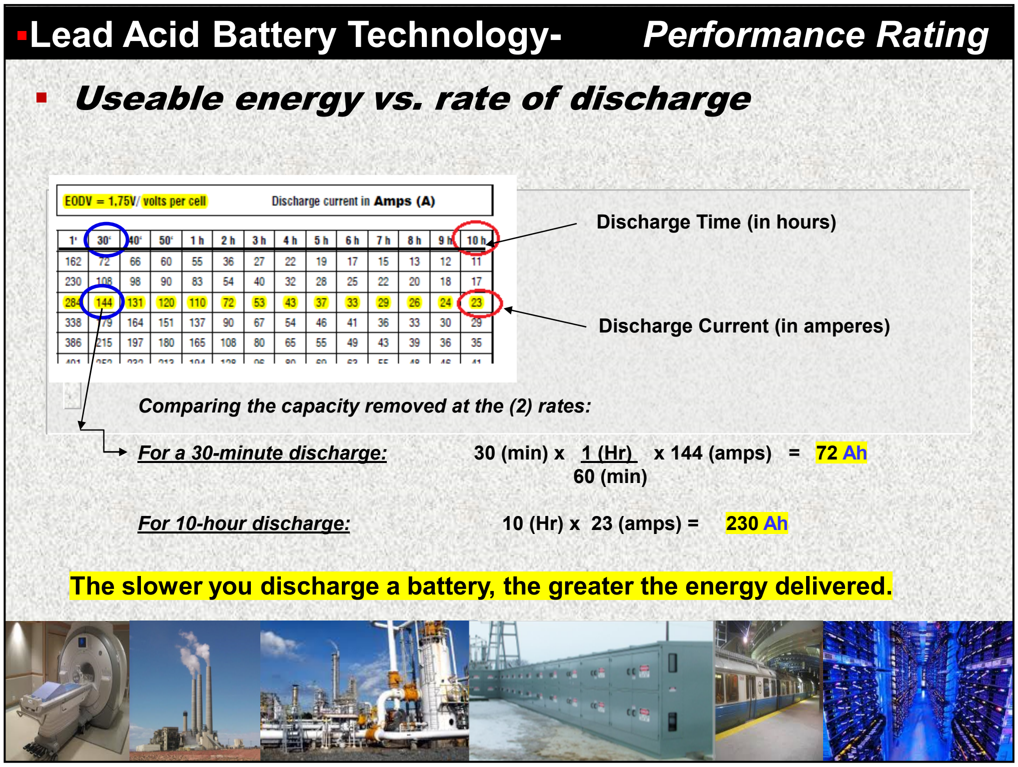
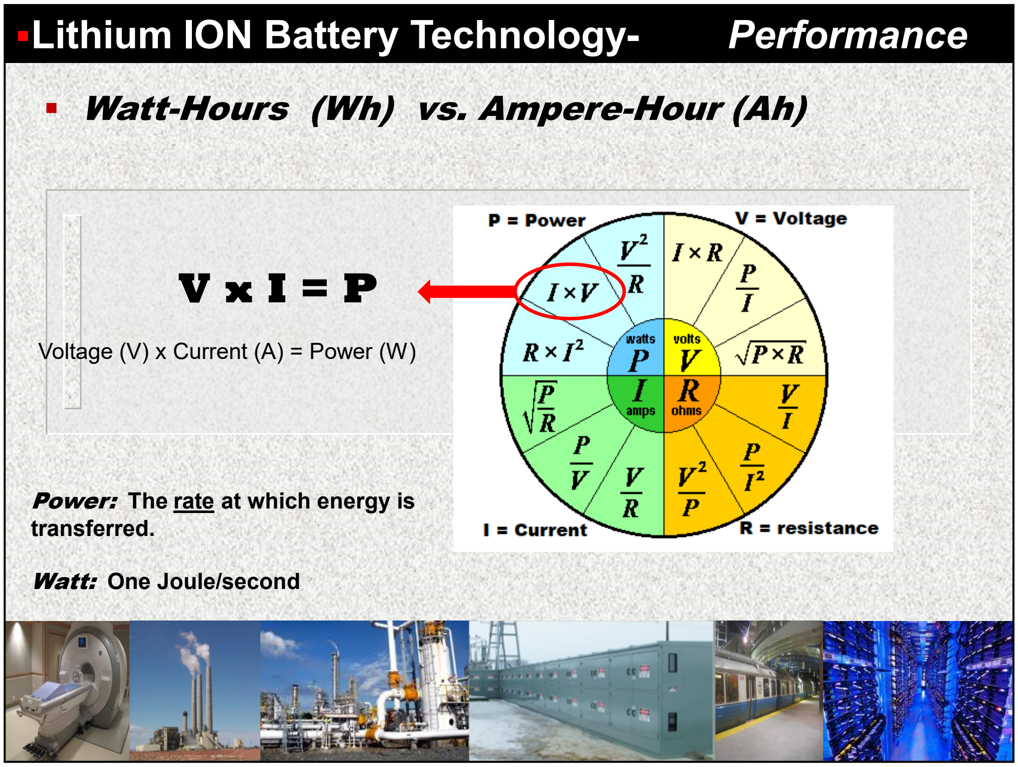
338	179	164	151	137	90	67	54	46	41	36	33	30	29
386	215	197	180	165	108	80	65	55	49	43	39	36	35

Traditionally, stationary lead acid and nickel cadmium battery manufacturers used "Capacity" based on the constant current discharge to a particular cut-off voltage (end-of-discharge-voltage) to describe battery capacity. The nickel cadmium battery manufacturers selected the 5-hr discharge rate, while the lead acid battery industry typically used the 10-hour discharge rate. This is shown on the slide, that you would take the discharge table for 1.75 volt per cell end voltage, and apply the amperage for the 10-hour rate, and this would give us the "nameplate" rating or relative capacity. This was purely a relative term since the useable energy or power extracted from a battery is not linear or constant.

The slower you discharge a battery, the more useable energy you can remove from the battery. Let's take this example on this slide. When I discharge the particular battery highlighted at the 10 hour rate, I can extract 23 amps continuously over the 10 hours before I reach an end voltage of 1.75 volts per cell. Keep in mind at this point I have not imposed any design margin, temperature derating or again factor.



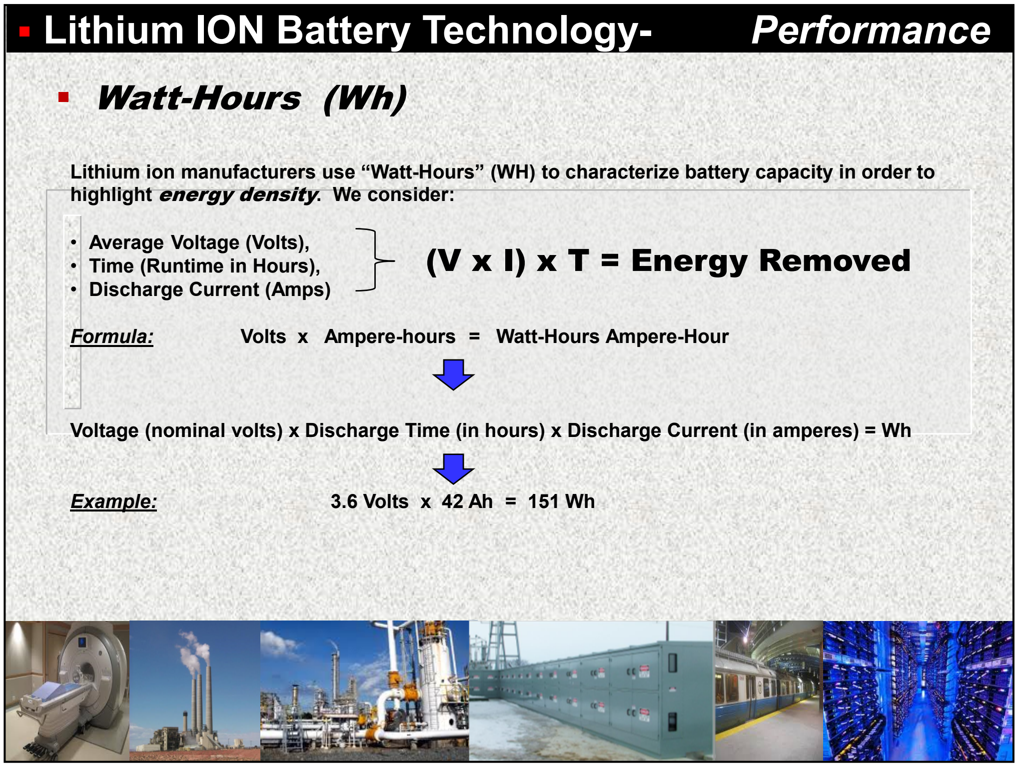
We will use the same table from the last slide and now let's compare the 30-minute discharge rate. From the table the blue circle highlights the 30-minute rate, and I can extract 144 amps from this battery continuously for a full 30-minutes before reaching the end voltage of 1.75 vpc. So let's compare the capacity removed at 30-minutes, vs. the capacity removed at 10-hours:



To understand how lithium ion batteries are rated, we first have to understand the difference between energy and power.

Further, to understand the ratings for lithium ion batteries in comparison to other stationary power battery types, we will borrow from the formulas on our “Power wheel”, namely Ohms Law as it applies to linear circuits. Though battery discharge curves are not actually linear, the relationship between voltage and current is a fairly well approximated using Ohm’s Law for a given period of time.

Reference: Power wheel image from: http://www.sengpielaudio.com/calculator-ohm.htm.



For lithium ion batteries, performance is often defined by:

- **Energy Density , and**
- **Power Density**

Energy Density is predominantly used to characterize the "capacity" rating for the lithium batteries, whether the application is for a stationary application, or for a UPS application.

This practice factors in the nominal discharge:

- **Voltage,**
- **Time,**
- **Current**.

IFC 2018 chapter 1206.2 and NFPA-1 chapter 52
MAXIMUM ALLOWABLE QUANTITIES (MAQ)

BATTERY TECHNOLOGY	Maximum Allowable Quantity	Group H Occupancy
Lead Acid **(All Types)**	**Unlimited**	**N/A**
Nickel Cadmium	**Unlimited**	**N/A**
Lithium, (All Types)	**600 kWh**	**Group H-2**
Sodium, **(All Types)**	**600 kWh**	**Group H-2**
Flow Batteries	**600 kWh**	**Group H-2**
Other Batteries	**200 kWh**	**Group H-2 ***

Exceeding these levels means the facility has to be reclassified as a "**High Hazard Occupancy".**

International Fire Code (IFC)- developed and updated by review of proposed changes submitted by code enforcement officials, industry representatives, design professionals and other interested parties.

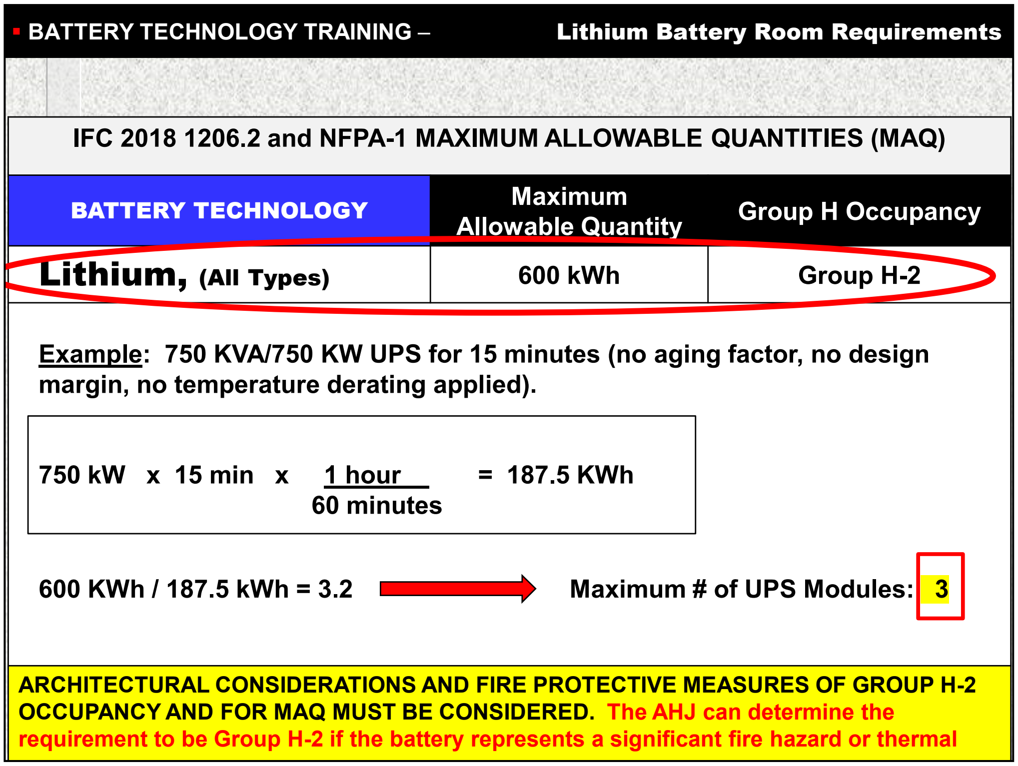
The biggest changes to the Fire Codes happened in 2018 and mostly to address the flammability and potential volatility of emerging battery technologies. This data was provided in IFC chapter 12 and NFPA-1 chapter 52. Group H-2 applies as "deflagration hazard or hazard from accelerated burning.

Risk Mitigation and Failure mode analysis and AHJ approval is required for installations over the Maximum Accepted Quantities

Storage batteries, prepackaged stationary storage battery systems and pre-engineered stationary storage battery systems are required to be segregated into stationary battery arrays (strings) not exceeding 50 KWh (180 Mega joules) each. Exceptions include:

- Lead acid and nickel cadmium storage battery arrays
- Listed pre-engineered stationary storage battery systems and prepackaged stationary storage battery systems shall not exceed 250 KWh (900 Mega joules) each
- The fire code official is authorized to approve listed pre-engineered and prepackaged battery arrays with larger capacities or smaller battery array spacing if large scale fire and fault condition testing conducted or witnessed and reported by an approved testing laboratory is provided showing that a fire involving one array will not propagate to an adjacent array, and be contained within the room for a duration equal to the fire resistance rating of the room separation specified in Table 509 of the International Building Code

Flow batteries use liquid electrolyte to store energy….vanadium-redox, zinc-bromine, iron-chromate



If 600 kWh is the Maximum Allowable Quantity allowed per IFC and NFPA, then we must be cognizant of how this impacts the battery room designs for the lithium ion batteries. Remember in the previous slide, there was no MAQ for either nickel cadmium batteries or for lead acid batteries.

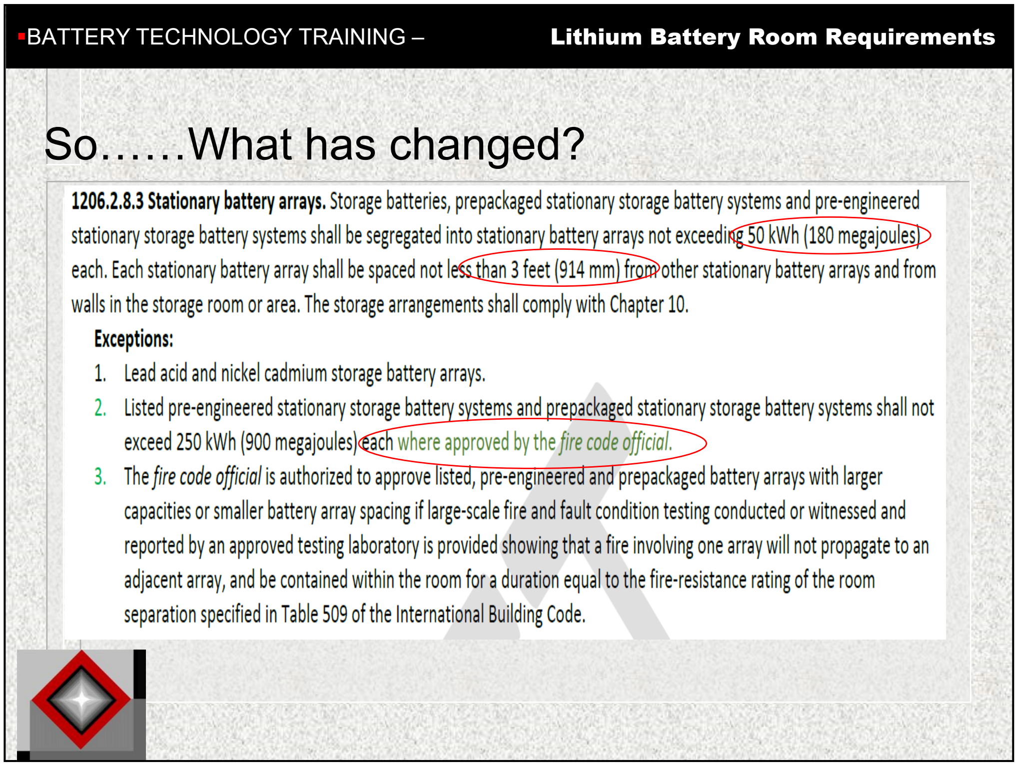
If we multiply the battery capacity for a very common size of a UPS (750 KWb), and we intend the run-time to be 15 minutes to the EODV, then the formula shown in the rectangle applies. We convert the 15 minutes to hours and multiply the discharge time by the KW rating.

IFC 2021 chapter 12 and NFPA-1 chapter 52 MAXIMUM ALLOWABLE QUANTITIES (MAQ) FOR A SINGLE STRING/ARRAY	
BATTERY TECHNOLOGY	**Maximum String Allowable Quantity**
Lead Acid **(All Types)**	**70 KWh**
Nickel Cadmium	**70 KWh**
Lithium, (All Types)	**20 KWh**
Sodium, **(All Types)**	**20 KWh**
Flow Batteries	**20 KWh**
Other Batteries	**10 KWh**

Exceeding these levels means the facility has to be reclassified as a "**High Hazard Occupancy".**

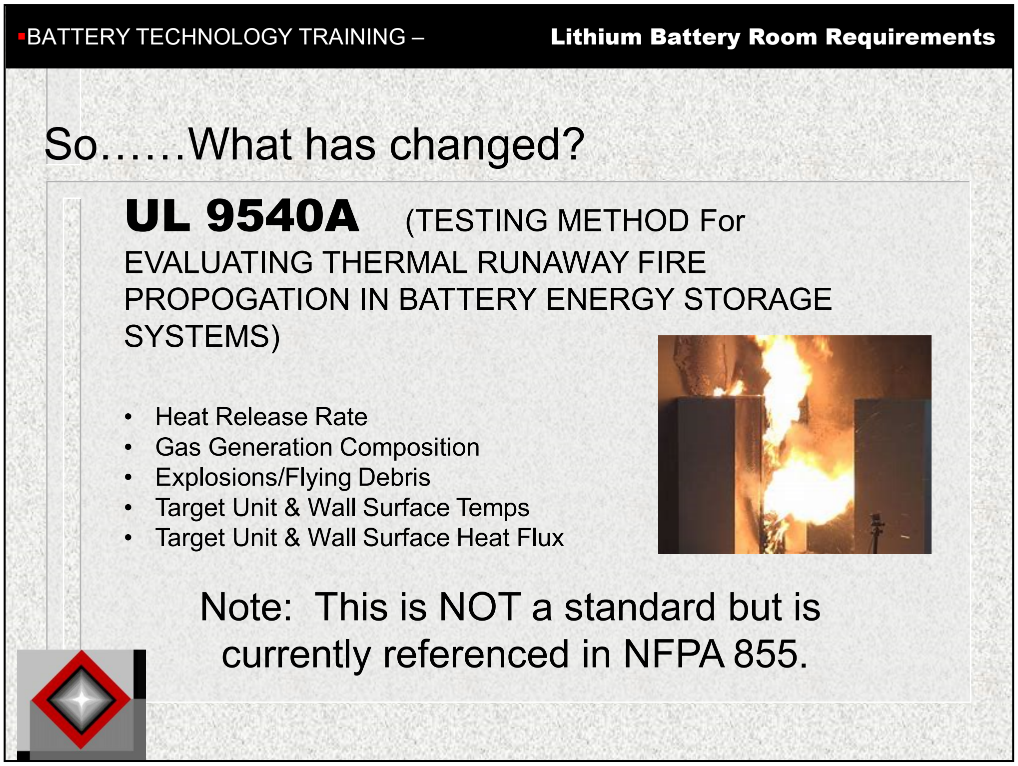
International Fire Code (IFC)- developed and updated by review of proposed changes submitted by code enforcement officials, industry representatives, design professionals and other interested parties.

The IFC and NFPA-1 codes additionally require a limit for the capacity allowed as a single string or array per the Table above. This data was provided in IFC chapter 12 and NFPA-1 chapter 52. It is my understanding that within the month of September 2019, NFPA 855 will also be adapting these quantities as the definition for an array.



Several things about the Chapter 12 requirements of the IFC are pretty important as they pertain to ANY battery system. The definition of an array was somewhat cryptic and by interpretation of the AHJ. But here we have clearly defined the following:

1. ARRAY- not to exceed 50kWhr
2. CLEARANCE- between arrays is 3 feet from walls and other battery arrays
3. APPROVAL- up to the fire code official.

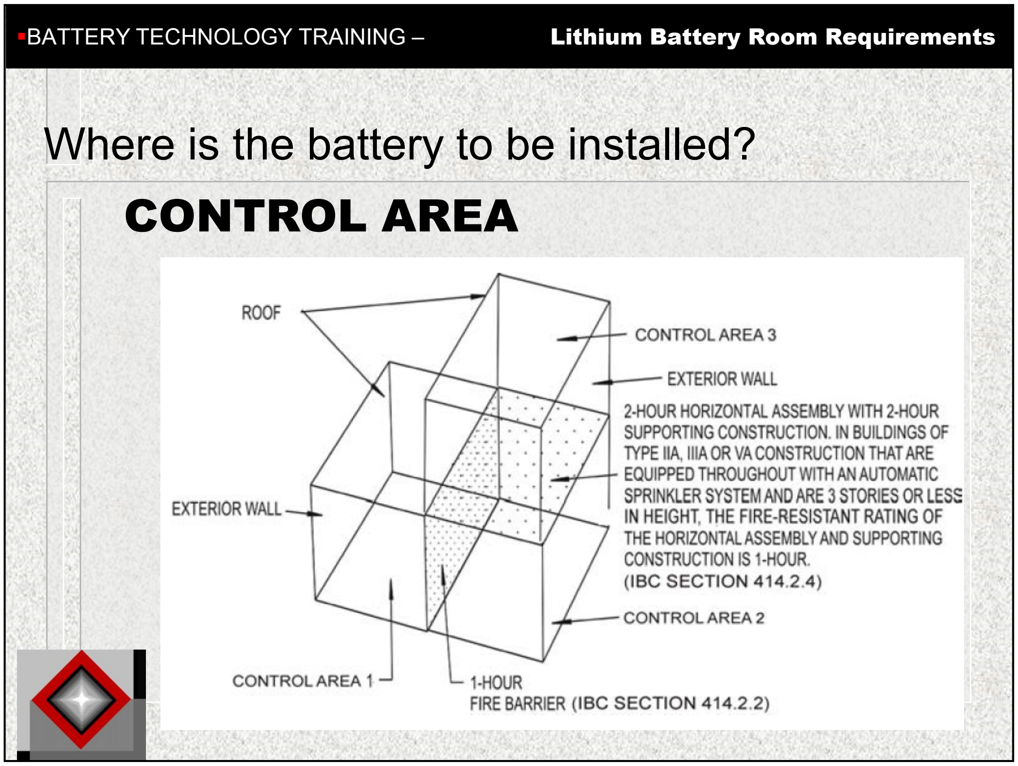


So how does the manufacturer gain the fie official's approval? By satisfactory completion of the UL9540A testing.

Safety Testing for stored energy systems changed April 24th, 2021. UL 9540A determined that a new safety testing procedure be introduced which created a minimum allowable capacity allowed as an "ARRAY" which required specific clearances in order to meet fire propagation testing and thermal runaway testing. The list shows the basis of this testing:

- Heat Release Rate
- Gas Generation Composition
- Explosions/Flying Debris
- Target Unit & Wall Surface Temps
- Target Unit & Wall Surface Heat Flux

This testing is performed at the cell level, module level, system level and array level.



The control area inside of a building or structure is defined as:

“A space bounded by exterior walls, fire walls, fire barriers, horizontal assemblies, roofs or a combination of these.”

The amount of hazardous materials **stored** and **used** in a control area must be equal to or less than the MAQ (IBC).

Again, it is imperative that you know the architectural requirements that will be imposed by the AHJ. IBC may differ from IFC who may also differ from NFPA. It is almost certain that each inspector or code enforcer will have different interpretation of the codes.

Lithium ION Battery Technology- *Performance*

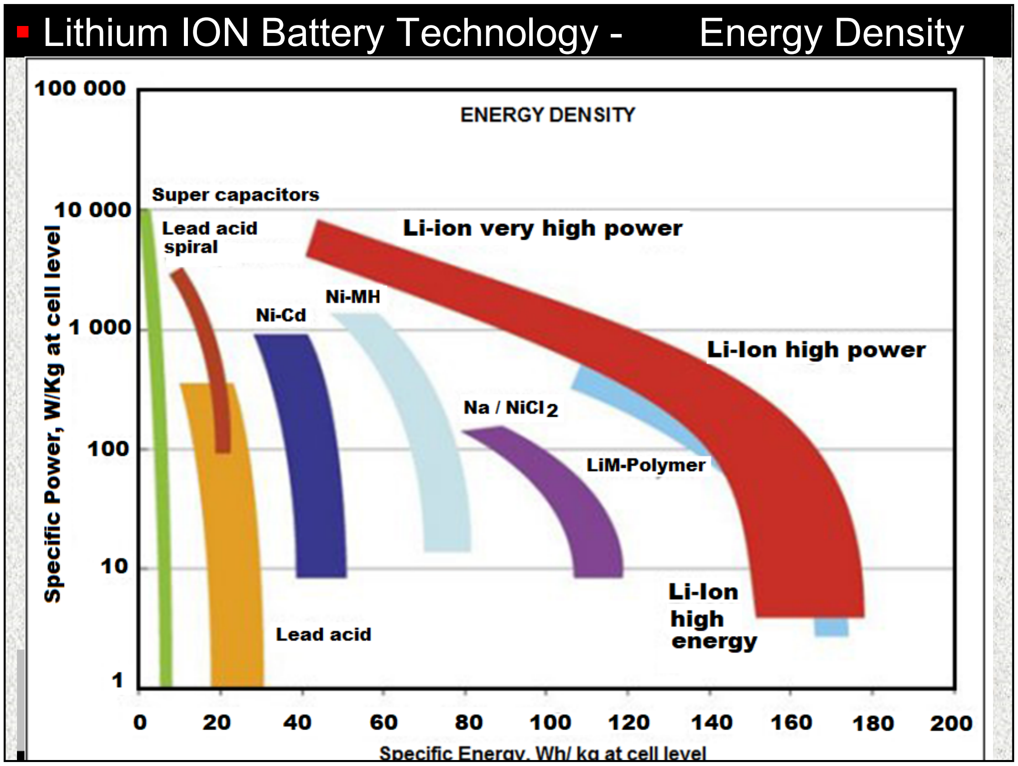
Performance Topics:

- **Capacity- Watt-Hours (Wh) vs. Ampere-Hour (Ah)**
- **High Energy Density**
- **Fast Recharge**
- **Flat Discharge Curve**
- **Predicted Float Life Curve (Shelf Life)**
- **Cycle Life Vs. Float Life**
- **Temperature Tolerance**
- **Reliability**
- **Safety**

Lithium ion batteries are receiving a lot of press. Largely for huge gains in power density, but also in catastrophic fire events. These are the “Performance” factors that we will discuss today regarding the emergency standby applications.

Ultimately, we want you to be prepared to address any and all safety concerns when dealing with any battery in your power distribution.

Much of the preset safety and code compliance considerations have been detailed fully in this presentation. Please refer to the references to some of the sources for much of this information which is sometimes listed in the notes section.



This slide is nice depiction that compares the lithium ion technologies to other stationary battery chemical couples for specific energy and specific power. By weight, the performance of lithium ion is highly preferred, especially in applications requiring minimal payload. It is not hard to see why the automotive and motive power manufacturers are interested in the evolution of lithium ion batteries.

The automotive industry will be the driver that drives down the cost of the lithium ion batteries.

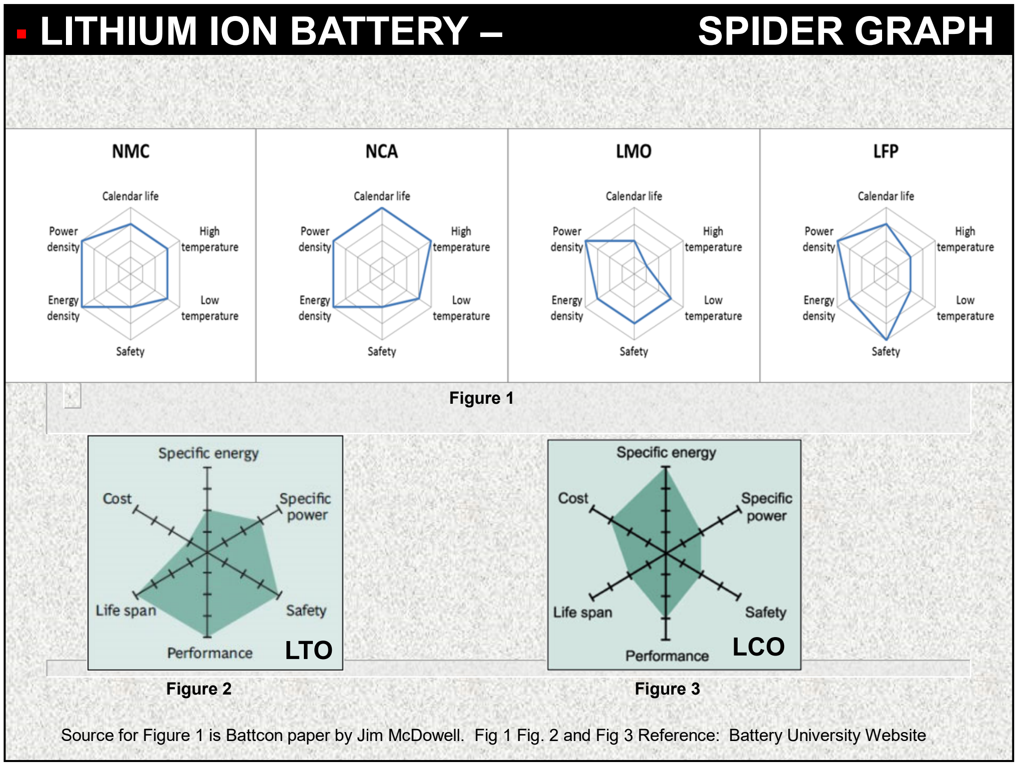
Lithium ION Battery Technology- *Performance*

PREVALENT LION Chemistries:

Station Battery Technology	Chemistry
LTO Lithium Titanate Oxide	$Li_4Ti_5O_{12}$ / $6LiCoO_2$
LFP Lithium Iron Phospate (LFP/LiFePO4)	LiFePO4 / LiC_5
SLFP Super Lithium Iron Phosphate (LFP / LiFePO4 +NCA	**LiFePO4 +** LiNiCoAlO2 / **LiC_5**
NCA Lithium Nickel Cobalt Aluminum Oxide	**LiNiCoAlO2** (9% Co)
NMC Lithium Nickel Manganese Cobalt Oxide	LiNiMnCoO2

These are the chemical systems that are typically being produced for the lithium ion station batteries.

Again, with the exception of photovoltaic systems, most of the station charging applications are what are known as “taper current” chargers. Each of these chemistries produce a unique terminal voltage, and also enjoy distinct operational performance features. The balance of this presentation is focused on the “Performance Factors” of these lithium ion technologies for emergency standby applications.

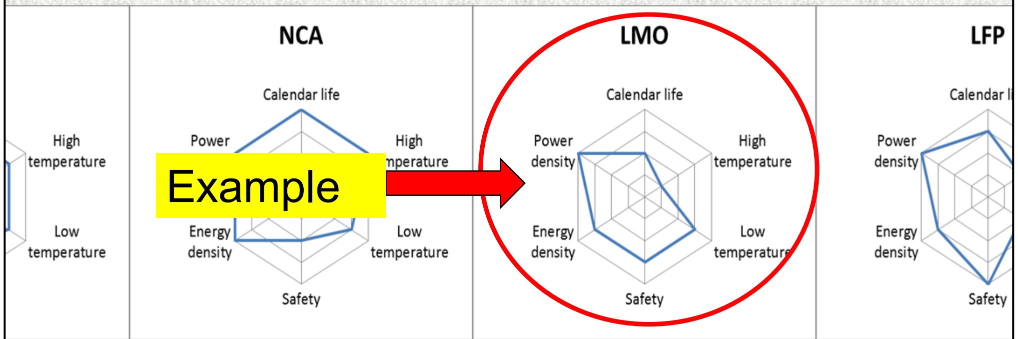


Everyone has seen these "Spider Web Graphs" that each manufacturer will produce to highlight the critical features of their products. It provides a nice self assessment and allows us to compare technologies side-by-side. As you move along the converging axis, the factor is higher as you move from the center of the graph. So if we use any one of these graphs as an example, let's look at LMO as an example.

- Calendar life at 20°C to 25°C
- Calendar life at high temperature
- Capacity availability at low temperature
- Safety of positive active material
- Energy density
- Power density

Top Figures: Source Battcon Paper authored by Jim McDowell. Figure 2 and Figure 3 source is Battery University Website.

LITHIUM ION BATTERY – SPIDER GRAPH



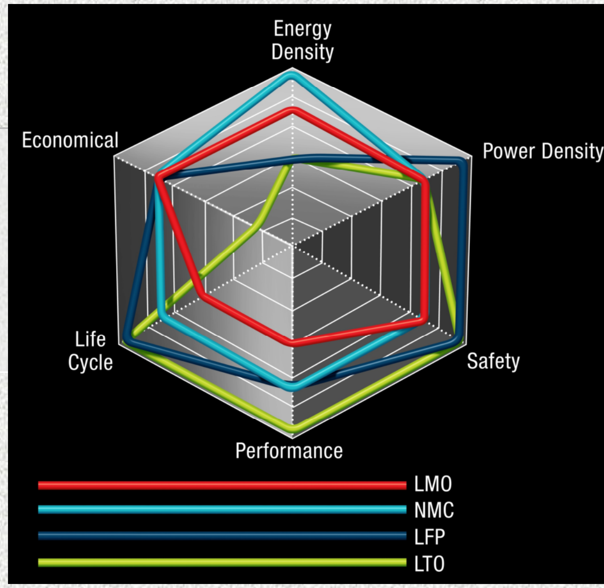
Feature:	
Power Density:	Very High (almost off the chart)
Life:	Not very good
Hi Temp Operation:	Poor
Energy Density:	Excellent
Safety:	Excellent

Reference: Battery University Website

Everyone has seen these “Spider Web Graphs” that each manufacturer will produce to highlight the critical features of their products. It provides a nice self assessment and allows us to compare technologies side-by-side. As you move along the converging axis, the factor is higher as you move from the center of the graph. So if we use any one of these graphs as an example, let’s look at LMO as an example. The table underneath the spider graph translates what the graphic is trying to portray in a glance:

LMO technology is characterized by extremely high power density, not so great high temperature operation, not so great longevity, but good safety and good energy density.

LITHIUM ION BATTERY – SPIDER GRAPH



Reference: Mitsubishi Electric Website

IEEE WG_1679-1) that is in the process of defining the criteria to be used for the comparison, selection and analysis of the electrical and safety performance criteria.

I borrowed this slide from the Mitsubishi Electric website. This is a nice depiction of the various chemistries with performance overlayed. Each of these items is somewhat subjective and IEEE has a working group (IEEE WG_1679-1) that is in the process of defining the criteria to be used for the comparison and analysis of the electrical and safety performance criteria.

Note that lithium ion battery sizing, installation, maintenance, and testing techniques are not covered in IEEE 1679.

Lithium Ion Battery- Electrode Configuration

Station Battery Technology	Chemistry	Electrode Construction
LTO Lithium Titanate Oxide	$Li_4Ti_5O_{12}$ / $6LiCoO_2$	Prismatic
LFP Lithium Iron Phospate (LFP/LiFePO4)	LiFePO4 / LiC_5	Cylindrical Jelly-roll
SLFP Super Lithium Iron Phosphate (LFP / LiFePO4 +NCA	LiFePO4 + LiNiCoAlO2 / LiC_5	Cylindrical Jelly-roll
NCA Lithium Nickel Cobalt Aluminum Oxide	LiNiCoAlO2 (9% Co)	Cylindrical Jelly-roll
NMC Lithium Nickel Manganese Cobalt Oxide	LiNiMnCoO2	Cylindrical Jelly-roll

Does cell construction matter for the end-user?

We won’t talk at all about the lithium cobalt oxide or LCO that is really high power density used for cell phones, cameras, and laptops.

In fact the three most prevalent chemistries we will discuss have to do with the LTO, LFP, NMC and NCA. All of these chemistries use lithium in an organic solvent typical of LiPF6.

There are some differences in performance that do appear to be related to the cell configuration as we will see on the next slides

Lithium Ion Battery- *Performance Comparison*

Electrode (Product No.)	Potential vs. Li/Li^+ (V)^A	Specific Capacity, (mAh/g)	Advantages	Disadvantages
Positive Electrodes				
$LiCoO_2$ (442704)	3.9	140	Performance	Cost and resource limitations of Co, low capacity
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (760994)	3.8	180–200	High capacity and voltage, excellent rate performance	Safety, cost and resource limitations of Ni and Co
$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (761001)	3.8	160–170	High voltage, moderate safety	Cost and resource limitations of Ni and Co
$LiMn_2O_4$ variants (725129)	4.1	100–120	Low cost and abundance of Mn, high voltage, moderate safety, excellent rate performance	Limited cycle life, low capacity
$LiFePO_4$ (759546)	3.45	170	Excellent safety, cycling, and rate capability, low cost and abundance of Fe, low toxicity	Low voltage and capacity (substituted variants), low energy density
Negative Electrodes				
Graphite (698830)	0.1	372	Long cycle life, abundant	Relatively low energy density; inefficiencies due to Solid Electrolyte Interface formation
$Li_4Ti_5O_{12}$ (765155)	1.5	175	"Zero strain" material, good cycling and efficiencies	High voltage, low capacity (low energy density)

A. Average

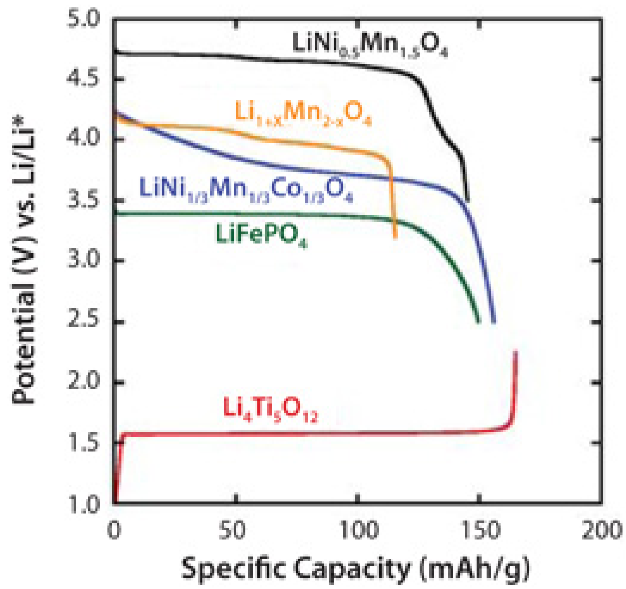
Does technology really matter for stationary battery performance?

Figure 2; Reference *"Recovery of Electrodic Powder from Spent Lithium Ion Batteries (LIBs)"*, authors: S.M. Shin, G.J. Jung, Woo-Jin Lee, C.Y. Kang, J. P. Wangg ARCHIVES OF METALLURGY AND MATERIALS Volume 60 2015 Issue 2 DOI: 10.1515/amm-2015-0086

Lithium dissolved in organic solvent is the electrolyte for most LION batteries.

Electrode stack photo courtesy of Leclanche' Energy Storage Solutions.

▪Lithium Ion Battery- ***Performance Comparison***



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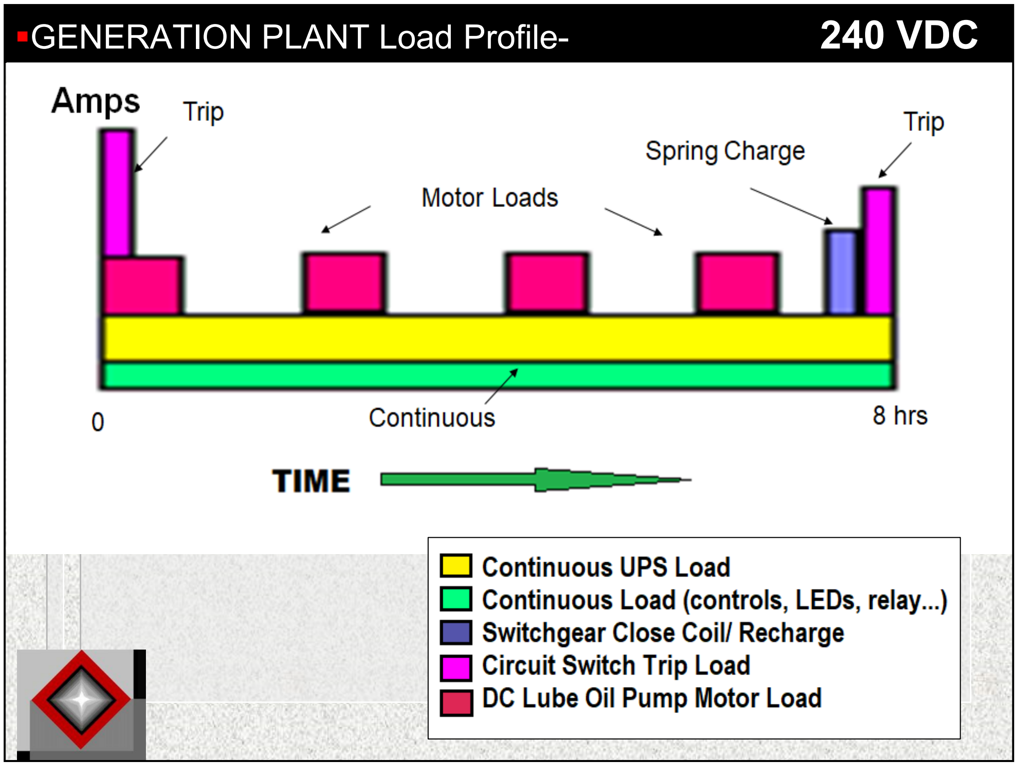
Lithium dissolved in organic solvent is the electrolyte for most LION batteries.

Electrode stack photo courtesy of Leclanche' Energy Storage Solutions.


GENERATION PLANT Load Profile-
240 VDC
Amps
Trip
Spring Charge
Trip
Motor Loads
0
Continuous
8 hrs
TIME
Continuous UPS Load
Continuous Load (controls, LEDs, relay...)
Switchgear Close Coil/ Recharge
Circuit Switch Trip Load
DC Lube Oil Pump Motor Load

▪Generation Plant Example- 240VDC (50KW 8 Hours)

Raw Material	Price per Pound (US$)
Titanate Oxide	$25.70
Cobalt Oxide	$14.52
Lithium Carbonate	$7.36
Nickel	$5.60
Lead (New)	$0.92
Lead (Scrap)	$0.75

 **?? = transparency**

Lithium batteries need exotic materials for improvement of operating characteristics. Before we compare the pricing of these different systems, I thought it might be helpful to put into perspective the heaviest weighted material pricing in the different batteries we are going to discuss today. Wallstreet Journal is reporting that the LME is reported to be rolling out an “exchange traded contract” for lithium in 2019.

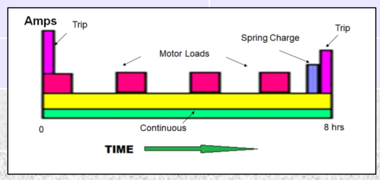
Reference: LME 2/17/2019 for lead and cobalt pricing. Lithium trending courtesy of Wallstreet Journal Nov. 27th, 2018, “Lithium Boom Raises Question: What is Its Price?” Lithium metals pricing based on article s1.q4cdn.com/337451660/files/doc_articles/2016/161214-Benchmark Minerals Intelligence and Fastmarkets-approved-for-distribution “Lithium-ion Supply Chain.pdf”.

Nickel pricing is dominated by the stainless steel industry of which China is currently the largest user. Cobalt Oxide pricing is dominated by the Chinese EV market. 46% of the world market for lithium goes to EV market. Today, Australia, Chile, Argentina, China, Zimbabwe are the world’s largest producers…the USA is the 8th largest producer.

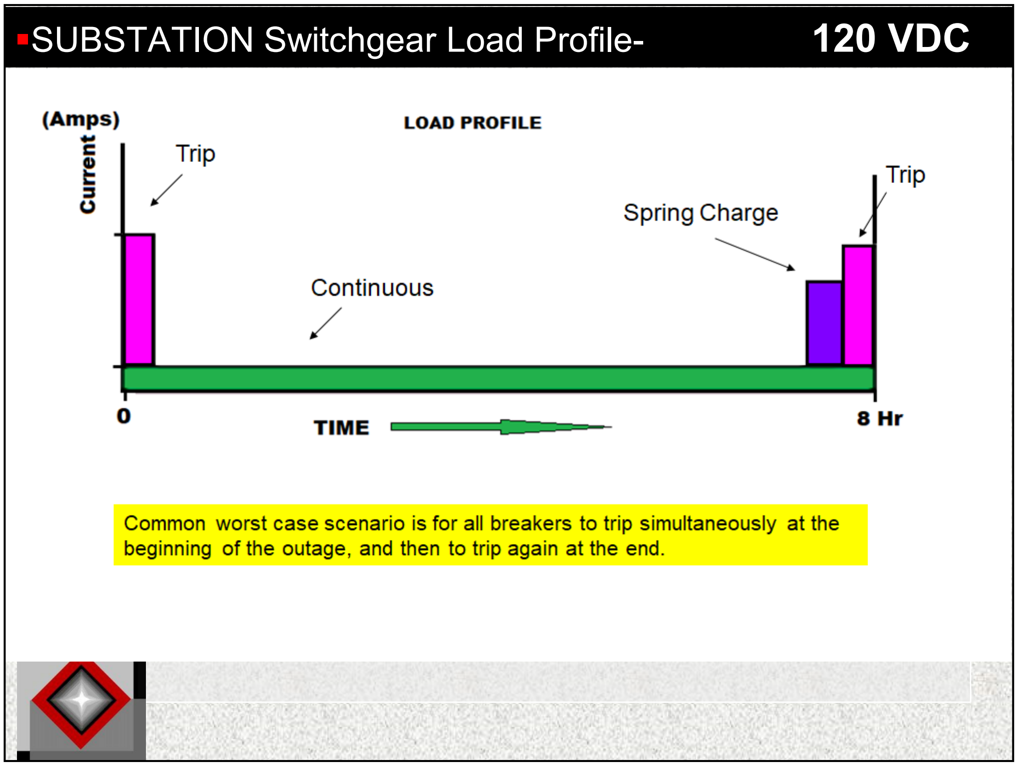
▪Generation Plant Example- 240VDC (50KW 8 Hours)

50KWB GENERATION PLANT
UPS APPLICATION

Battery Type	Cost	Battery Type	Cost
Flooded Pb Calcium Faure'	$165,600	VR Pb antimony Gel Faure'	$384,200
Flooded Pb antimony Faure'	$162,680	Flooded VR Nicad	$212,689
Flooded Plante'	$179,500	Flooded Nicad Pocket plate	$205,564
Flooded Pb Selenium	$135,360		
Flooded lead antimony tubular	$160,720	Flooded NicadPBE	$256,556
VRLA calcium	$184,024	Flooded Nicad Fiber	$233,073
Lithium LFP	$288,000		
Lithium Titanate	$252,000		



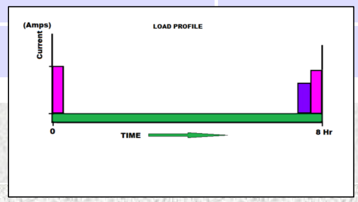
Pricing established here is based on batteries that are commonly quoted for this type of application. Note that no accessories are included in these figures, strictly batteries and standard non-seismic racking, except for the Lithium LFP and Lithium Titanate which are in cabinets.



The X-Axis represents time from 0 hours to 8 hours. The Y-Axis represents the current values for the battery discharge over time. This is a typical load profile for a station battery that provides back-up power for switchgear lineups. The bright fuscia color represents the load of having the circuit breakers trip at the beginning of an 8-hour period. The green shows the steady state load of all of the protective relaying, communication equipment, LEDs, and power metering loads. Then at the end of the 8 hour period, you would have burden created the recharge of the coils for the breakers (purple). Immediately followed by the tripping of all of the circuit breakers again (in the event that the fault has not cleared, you want the battery to be strong enough to trip the breakers again.

Substation Example- 120VDC

Battery Type	Cost	Battery Type	Cost
Flooded Pb Calcium Faure’	$7,844	VR Pb antimony Gel Faure’	$6,070
Flooded Pb antimony Faure’	$7,643	Flooded VR Nicad	$12,595
Flooded Plante’	$18,842	Flooded Nicad Pocket plate	$5,812
Flooded Pb Selenium	$6,700		
Flooded lead antimony tubular	$7,800	Flooded Nicad PBE	$7,985
VRLA Calcium 10- Yr	$2,784	Flooded Nicad Fiber	$6,378
Lithium Titanate	$14,000		
SLFP	$12,224		

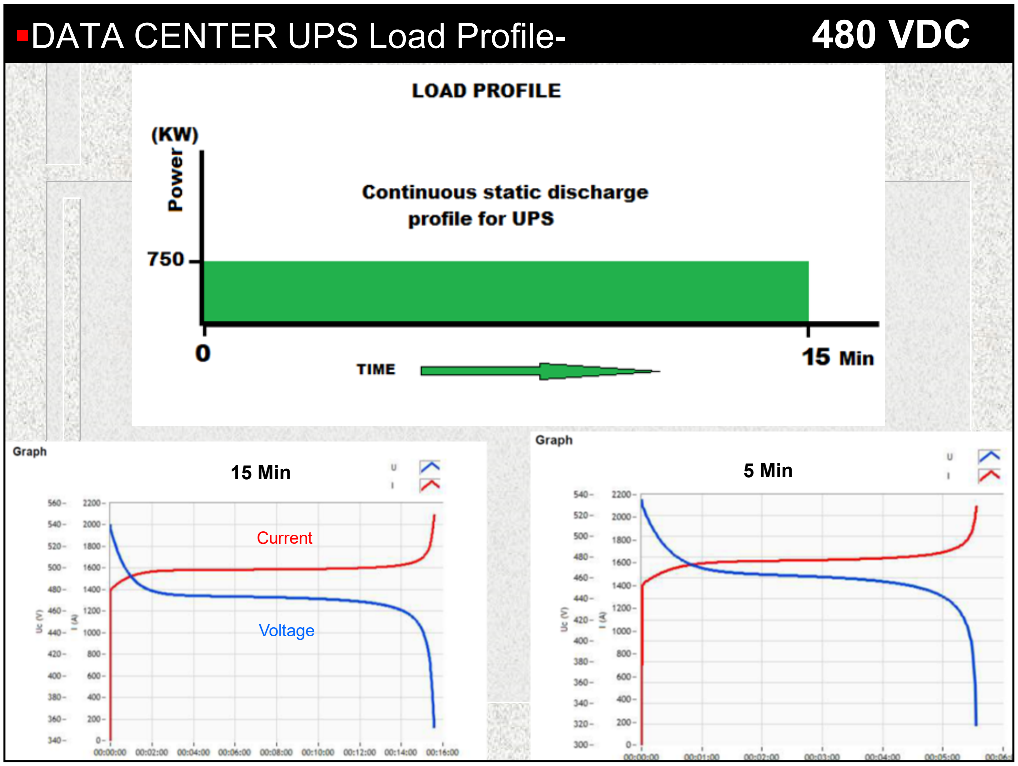


I caution people about using cost figures off of the internet when developing budgets for battery systems. You can see from this slide a huge variation in costs depending on the type of station battery used to meet this load profile.

This pricing is based on the following:

- No end of life aging factor
- No temperature derating
- No DC landing/Distribution
- No design margin
- No seismic adder for bracing.

You can see how the different technologies compare from a pricing standpoint. In this application, most people would think that the pricing for nickel cadmium or for lithium ion would be unfavorable, but they are the most dependable chemistry for this application and they are not as unaffordable as one might think. In fact, when considering the cost of a dc system failure, these two options might be better than insurance.

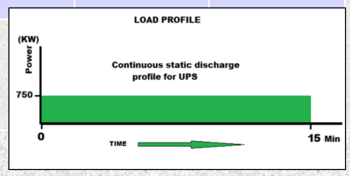


Typical Data Center UPS loads are constant power for the duration of the discharge as the load profile on this slide suggests. The (2) graphs below show the red line for current, and the blue line for voltage from time = 0 on the x-axis to time = 5 minutes, or 15 minutes. Note that there is no Coup de Fouet as the load starts.

We ran a couple of examples of lithium ion technologies to compare pricing footprint, floor loading and pricing. So we chose 5 minutes and 15 minutes for comparison sake.

Lithium Ion Battery- 480V 750kWB 15-Min UPS

UPS APPLICATION 480VDC 15 Minute Battery @ 750KWB							
Technology	**# of Strings**	**# of Cabinets**	**Length (In)**	**Width (In)**	**Height (In)**	**Total Weight (lbs)**	**Cost**
Flooded NICAD	1	2+2T Racks	1490	25	76	46,800	$390,000
VLA Calcium	1	3T Racks	510	35	78	59,916	$225,000
VLA Selenium	1	2+2T Racks	570	32	82	70,640	$258,000
VRLA (10-Yr)	6	6 cab	240	29.5	78.7	29,266	$98,266
Lithium NMC	20	20 cab	446	27.2	92.1	28,020	$205,000
Lithium LFP	12	12 cab	288	20.5	84	10,440	$214,800



Here is our cost comparison, but now throw **foot print** into our comparison.

NOTE the number of **parallel strings** to meet this application.

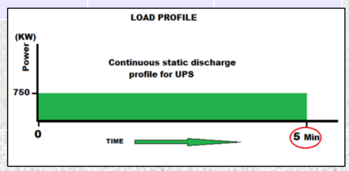
I wanted to use this slide to highlight one of the benefits of the lithium ion batteries. Note the reduction in footprint and the reduction in weight for this specific application.

This type of a load profile may well be the trigger for data centers to consider replacing single strings of nickel cadmium and flooded lead acid batteries with the cabinetized lithium batteries. The cabinetized lithium batteries are multiple strings (which reduces single points of failure) and they are also equipped with very advanced battery monitoring and battery management systems.

It is noteworthy that the flooded lead acid battery and the flooded nickel cadmium battery were both single strings of batteries for this load profile.

Lithium Ion Battery- 480V 750kWB 5-Min UPS

UPS APPLICATION 480VDC 5 Minute Battery @ 750KWB							
Technology	**# of Str**	**# of Cab**	**Length (In)**	**Width (In)**	**Height (In)**	**Total Weight (lbs)**	**Cost**
Flooded NICAD	1	2+2 Racks	1490	25.0	76.0	46,800	$241,000
VLA Calcium	1	3T Racks	816	32	78	42,528	$153,360
VLA Selenium	1	2+2 Racks	570	32	78	45,360	$178,320
VRLA (10-Yr)	4	4 cab	194	33.6	78.7	28,720	$66,250
Lithium LTO	16	8 cab	273	34.1	80.7	15,360	$311,900
Lithium LFP	6	6 cab	144	20.5	84.0	5,220	$107,400

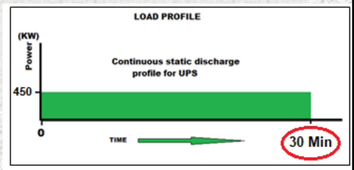


For this example, we have the same load, but now we only need 5 minutes of battery back-up.

Here is a similar UPS load profile for a 750KW UPS but this time the runtime is for only 5 minutes of battery discharge. It is a significant reduction in cost regardless of the chemistry, but you can see that the lithium ion actually becomes particularly favorable from a pricing and from a space allocation perspective.

Lithium Ion Battery- 480V 450kWB 30-Min UPS

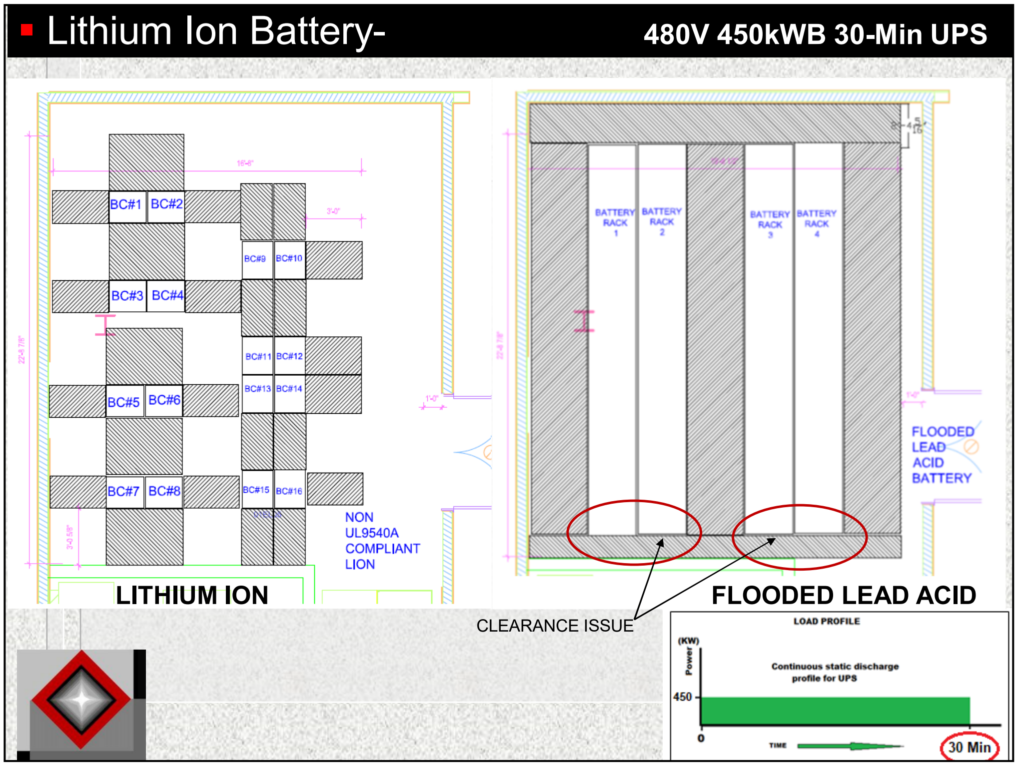
UPS APPLICATION 480VDC 30 Minute Battery @ 450 KWB							
Technology	# of Str	# of Cab	Length (In)	Width (In)	Height (In)	Total Weight (lbs)	Cost
VLA Selenium (Flooded)	1	4 ea 2-Tier Racks	996	35	84	67,440	$221,040
VRLA (10-Yr)	4	4 cab	194	33.6	78.7	28,720	$142,140
Lithium LTO	24	24 cab	818.4	34.1	80.7	47,820	$1,169,280
Lithium LFP (UL 9540A approved)	16	16 cab	384	20.5	84.0	6,368	$267,017
Lithium LFP (Non- UL 9540A approved)	12	12 cab	288	20.5	84.0	4,776	$236,945



The point of this exercise is to show that cost is not linear with runtime. You really need to get the **manufacturer's support** when budgeting a project.

REAL application: 450kWB for 30 minutes of runtime. Why? 2 systems for an A side and a B side keep me under the 250 kWhr target.

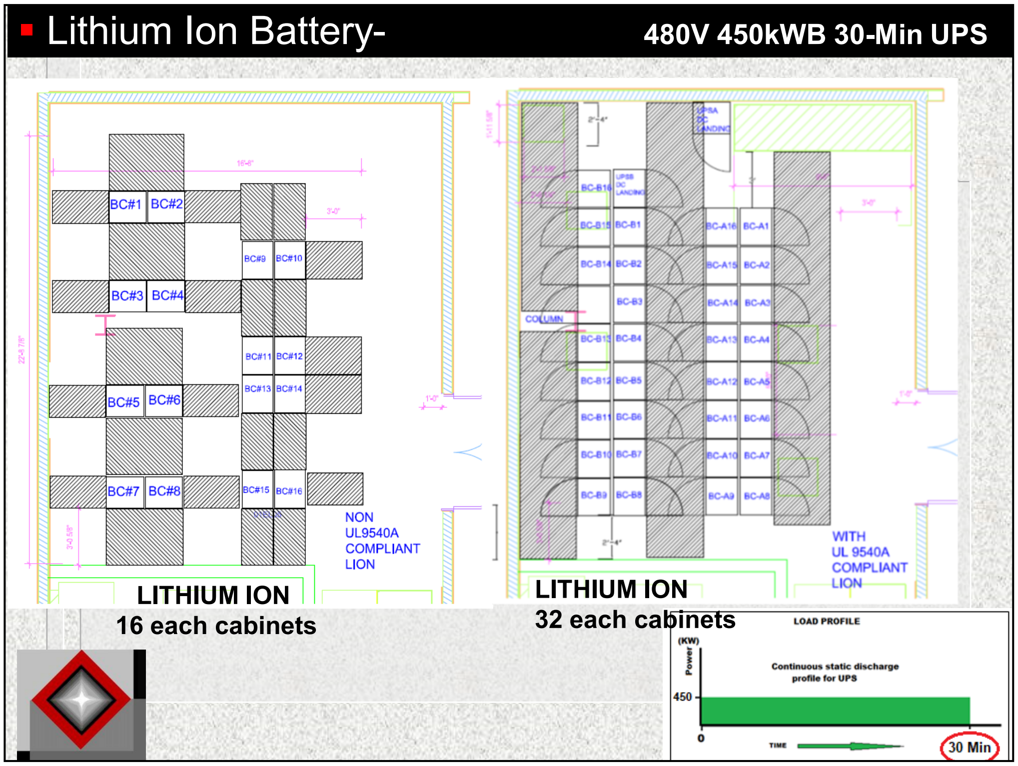
Here is a similar UPS load profile for a 780KW UPS but this time the runtime is for only 5 minutes of battery discharge. It is a significant reduction in cost regardless of the chemistry, but you can see that the lithium ion actually becomes particularly favorable from a pricing and from a space allocation perspective.



Here is a similar UPS load profile for a 750KW UPS but this time the runtime is for only 5 minutes of battery discharge. It is a significant reduction in cost regardless of the chemistry, but you can see that the lithium ion actually becomes particularly favorable from a pricing and from a space allocation perspective.

The diagram on the left shows you an actual Autocad layout for a Lithium Ion LFP system. I will remind you that per the table previous, for this particular UPS application, the table indicated that the Lithium ion battery would require 384" in length x 20.5 inches in depth for this 450 kWB 30 minute application. It also indicated that the flooded lead acid battery would require 996" in length x 25 inches in width for the same load profile. However, due to the 36" clearance requirements for UL 9540A, you can see, what was advertised as an advantage in energy density, is not actually realized in footprint.

In this case, the only advantage offered from a foot print standpoint is that it solved the egress aisle clearance issue at the lower end of the racks….code requires 28" for existing and 36" for new construction.



Both drawings on this slide are the exact same space. Here we have the same comparison with:

LFP Battery (Non-UL 9540A compliant testing)

LFP Battery (UL 9540A Compliant testing).

Here is a similar UPS load profile for a 750KW UPS but this time the runtime is for only 5 minutes of battery discharge. It is a significant reduction in cost regardless of the chemistry, but you can see that the lithium ion actually becomes particularly favorable from a pricing and from a space allocation perspective.

The difference is the required 36" clearances for the non UL 9540A product. With product that has favorable results from he UL 9540A fire safety testing, we can literally fit double the number of lithium ion cabinets than for the product which has not been tested. **CAUTION: It is up to the AHJ to accept either product.**

Lithium Ion Battery- *Electrode Configuration*

Cylindrical Cell

Fig 1

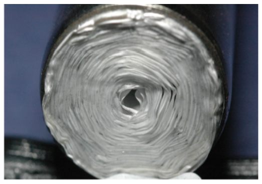


Fig 2

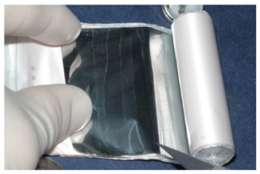


Fig 3

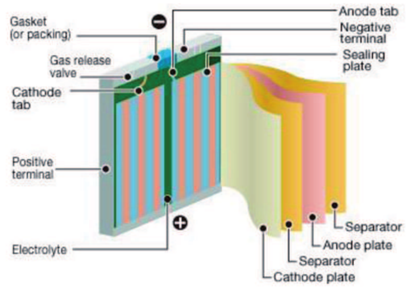


Fig 4

Benefits:

- Good heat dissipation
- Best for high temperature mgmt
- Flexible form factor
- **Lower cost**

Does cell construction matter for the end-user?

Figure 1 and 2; Reference *"Recovery of Electrodic Powder from Spent Lithium Ion Batteries (LIBs)"*, authors: S.M. Shin, G.J. Jung, Woo-Jin Lee, C.Y. Kang, J. P. Wangg ARCHIVES OF METALLURGY AND MATERIALS Volume 60 2015 Issue 2 DOI: 10.1515/amm-2015-0086
Figure 3, courtesy of Saft

Lithium dissolved in organic solvent is the electrolyte for most LION batteries. Additional reference for cylindrical cell photos: Table 1. from Measured flash points auto-ignition temperatures, and heats of combustion of some typical lithium-ion cell organic electrolyte components. Reference: **Lithium-Ion Batteries Hazard and Use Assessment *Final Report***

Prepared by: Celina Mikolajczak, PE, Michael Kahn, PhD, Kevin White, PhD, Richard Thomas Long, PE

Exponent Failure Analysis Associates, Inc.

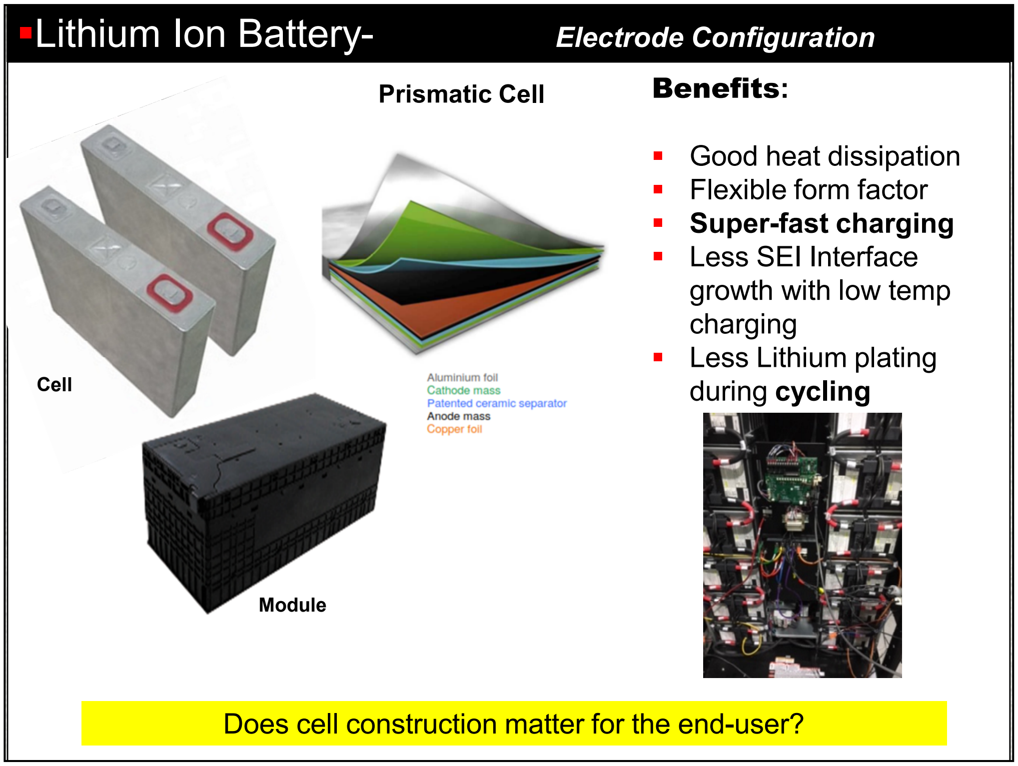
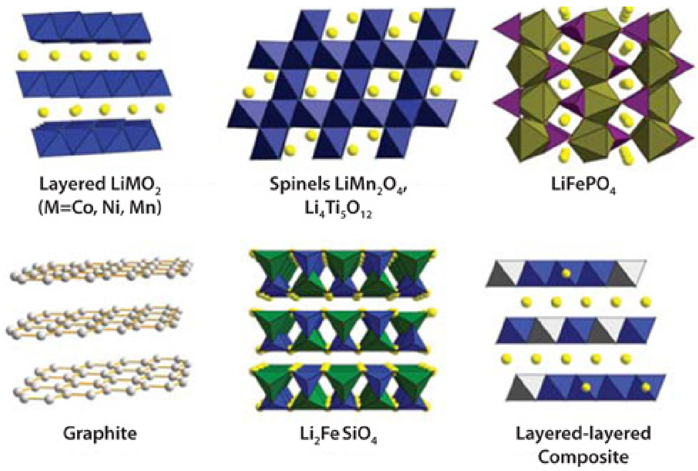


Figure 2; Reference *"Recovery of Electrodic Powder from Spent Lithium Ion Batteries (LIBs)"*, authors: S.M. Shin, G.J. Jung, Woo-Jin Lee, C.Y. Kang, J. P. Wangg ARCHIVES OF METALLURGY AND MATERIALS Volume 60 2015 Issue 2 DOI: 10.1515/amm-2015-0086

Lithium dissolved in organic solvent is the electrolyte for most LION batteries.

Electrode stack photo courtesy of Leclanche' Energy Storage Solutions.

Lithium Ion Battery- *Performance Comparison*



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Lithium dissolved in organic solvent is the electrolyte for most LION batteries.

Electrode stack photo courtesy of Leclanche' Energy Storage Solutions.

Lithium Battery Training- Electrolyte

FLASHPOINTS FOR VARIOUS LITHIUM ION ELECTROLYTES

Table 1. Measured flash points, auto-ignition temperatures, and heats of combustion of some typical lithium-ion cell organic electrolyte components

Electrolyte Component	CAS Registry Number	Molecular Formula	Melting Point[25]	Boiling Point[25]	Vapor pressure (torr)[26]	Flash Point[26]	Auto-Ignition Temperature[26]	Heat of Combustion[27]
Propylene Carbonate (PC)	108-32-7	$C_4H_6O_3$	-49°C -56°F	242°C 468°F	0.13 at 20°C	135°C 275°F	455°C 851°F	-20.1 kJ/ml -4.8 kcal/ml
Ethylene Carbonate (EC)	96-49-1	$C_3H_4O_3$	36°C 98°F	248°C 478°F	0.02 at 36°C	145°C 293°F	465°C 869°F	-17.2 kJ/ml -4.1 kcal/ml
Di-Methyl Carbonate (DMC)	616-38-6	$C_3H_6O_3$	2°C 36°F	91°C 195°F	18 at 21°C	18°C 64°F	458°C 856°F	-15.9 kJ/ml -3.8 kcal/ml
Diethyl Carbonate (DEC)	105-58-8	$C_5H_{10}O_3$	-43°C 45°F	126°C 259°F	10 at 24°C	25°C 77°F	445°C 833°F	-20.9 kJ/ml -5.0 kcal/ml
Ethyl methyl carbonate (EMC)	623-53-0	$C_4H_8O_3$	-14°C 6.8°F	107°C 225°F	27 at 25°C	25°C 77°F	440°C 824°F	None available

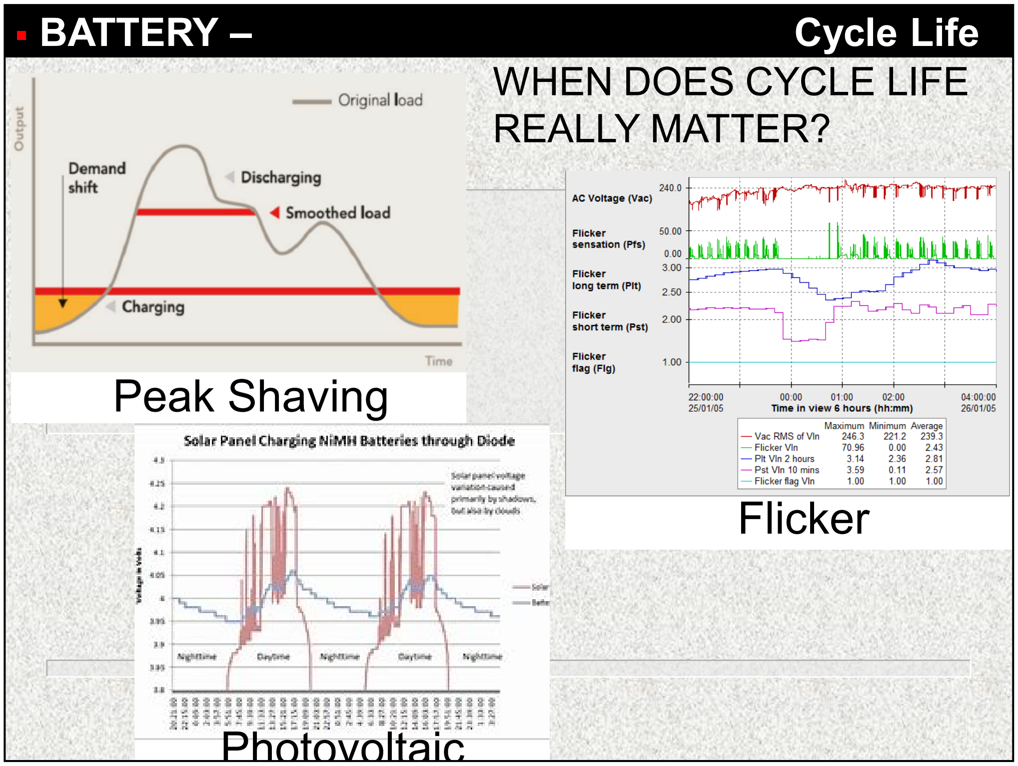
Organic solvents and dissolved lithium salts are the composition of the electrolytes used in LION batteries. I was curious about the flash points of the common electrolytes used by the standby power lithium products. That is when I came across the table above. The curious thing, is how low the flash point is for many of these organic solvents. …in particular the Ethyl carbonate, Di-Methyl carbonate and the Ethyl Methyl carbonate……**near or below typical room temperatures. Per Wikipedia: The flash point is the lowest temperature at which a particular organic compound gives of sufficient vapor to ignite in air**

Table 1. from Measured flash points auto-ignition temperatures, and heats of combustion of some typical lithium-ion cell organic electrolyte components. Reference: **Lithium-Ion Batteries Hazard and Use Assessment *Final Report***

Prepared by: Celina Mikolajczak, PE, Michael Kahn, PhD, Kevin White, PhD, Richard Thomas Long, PE

Exponent Failure Analysis Associates, Inc. July 2011 Source from 1100034.000 ADFO 0711 CM01

Everyone is busily hunting for a non-flammable electrolyte….it will take some time for a safer alternate to be validated.



<u>When does cycle life really matter?</u>

1. It matters if the battery installation is expected to cycle daily or even several times a day for:

    - **<u>Photovoltaic applications</u>**
    - **<u>Opportunity charging applications (stock pickers, EV, amusement park rides)</u>**
    - **<u>Peak-Shaving applications.</u>**

2. It matters for standby power applications with volatile utility line voltages.

All of these applications need batteries which can deliver the maximum number of cycles reliably.

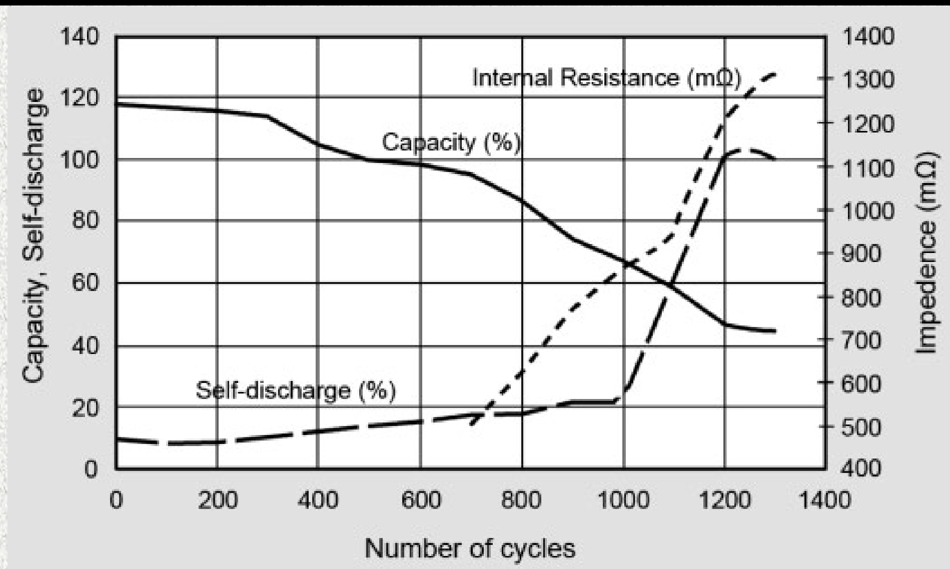
Lithium Ion Battery- ***Cycle Life*** **Comparison**

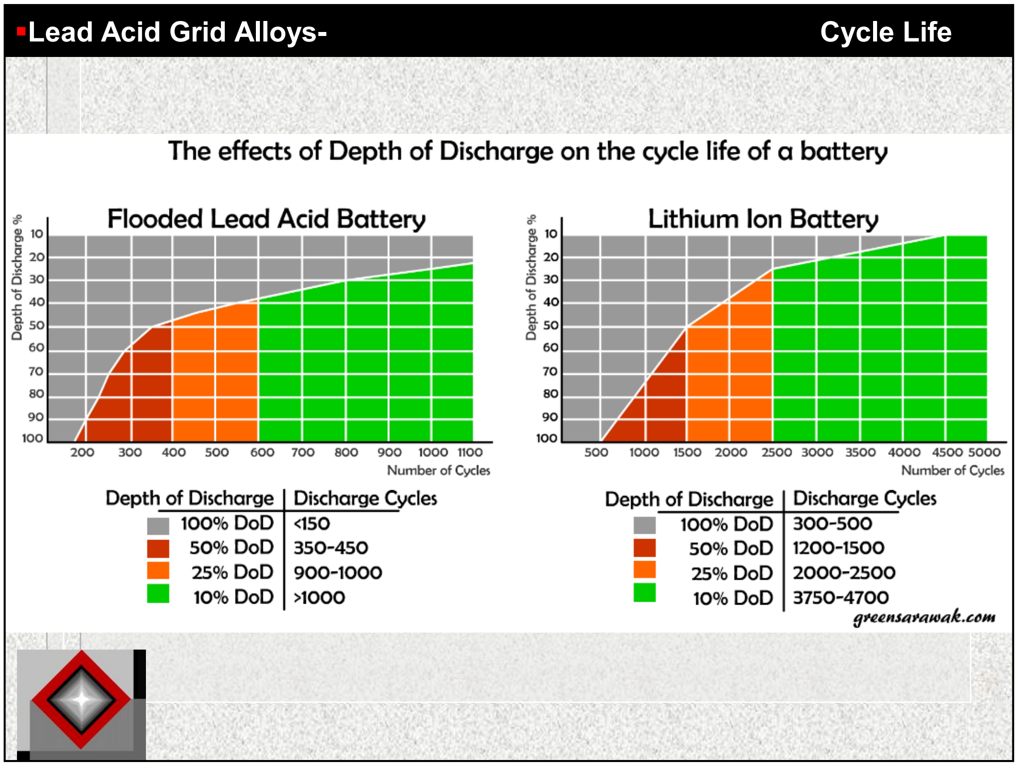
Stationary Battery Type:	Operating Voltage (per cell)	Specific Energy (Wh/Kg)	Operating Temperature	Cycle Life (to80% DOD)
Nickel Cadmium Pocket Plate	**1.2**	**40**	-40C to 50C (-40⁰F to 122⁰F)	>1500
Nickel Cadmium PBE	**1.2**	**60**	-20C to 50C (-4⁰F to 122⁰F)	>2000
VR Lead Acid (Pure lead grid)	**2.0**	**30-50**	-40C to 50C (-40⁰F to 122⁰F)	>500
VR Lead Acid (Ca)	**2.0**	**30-50**	30C to 50C* (-22⁰F to 122⁰F)	>300
Flooded Lead Acid (Ca)	**2.0**	**30-50**	0C to 49C (32⁰F to 120⁰F)	<100
Flooded Lead Selenium	**2.0**	**33 - 42**	-20C to 55C (-4⁰F to 131⁰F)	800 - 1000
LTIO (NMC cathode, LiTO anode)	**2.3**	**60 - 110**	0C to 40C (32⁰F to 104⁰F) (average over 24hr period 41-95⁰F)	>10000
Super Lithium Iron Phosphate (SLFP / LiFePO4 +NCA)	**3.7**	**90-120**	-40C to 50C (-40⁰F to 122⁰F)	7000
Lithium Iron Phoshpate (LFP/LiFePO4)	**3.2**	**90 - 110**	-20C to 60C (-4⁰F to 122⁰F)	>2000
Lithium Nickel Cobalt Al (NCA)	**3.6**	**2.1 kWhr**	-40C to 75C (-40⁰F to 167⁰F)	4300

We took the same chart from the previous slide, but reproduced it based on the stationary power applications. Again, the source used were averages from OEM manuals.

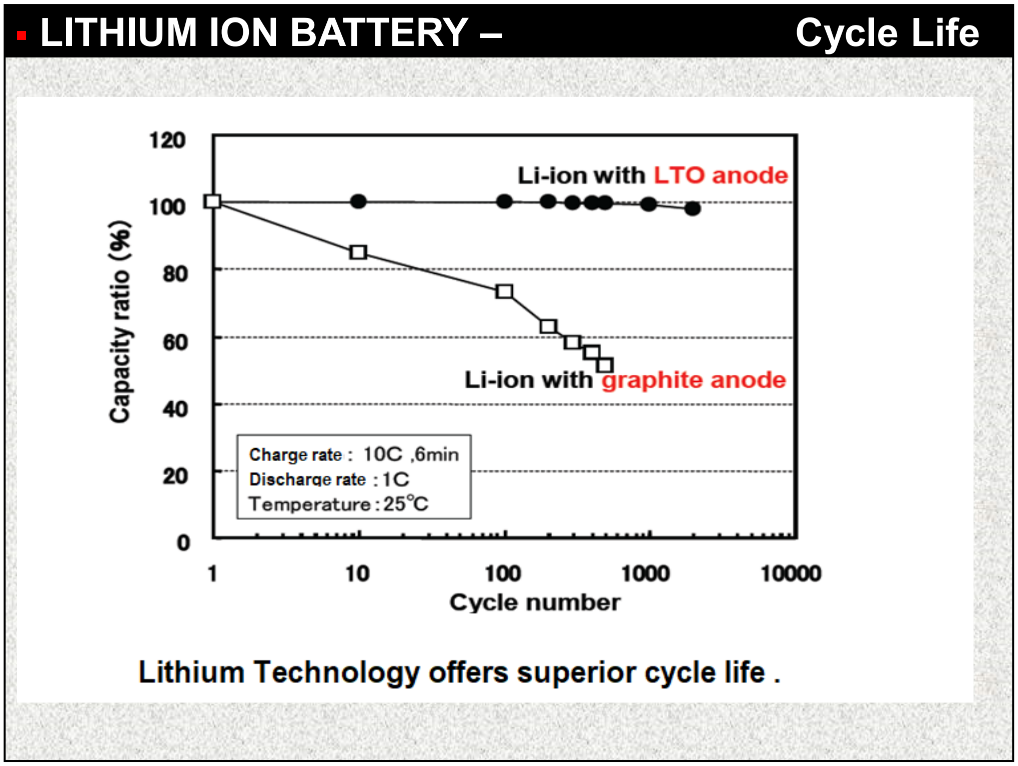
- VRLA Batteries must not be charged above 90 deg F, or below 32 deg F.

Cycle Life- Nickel Cadmium Pocket Plate



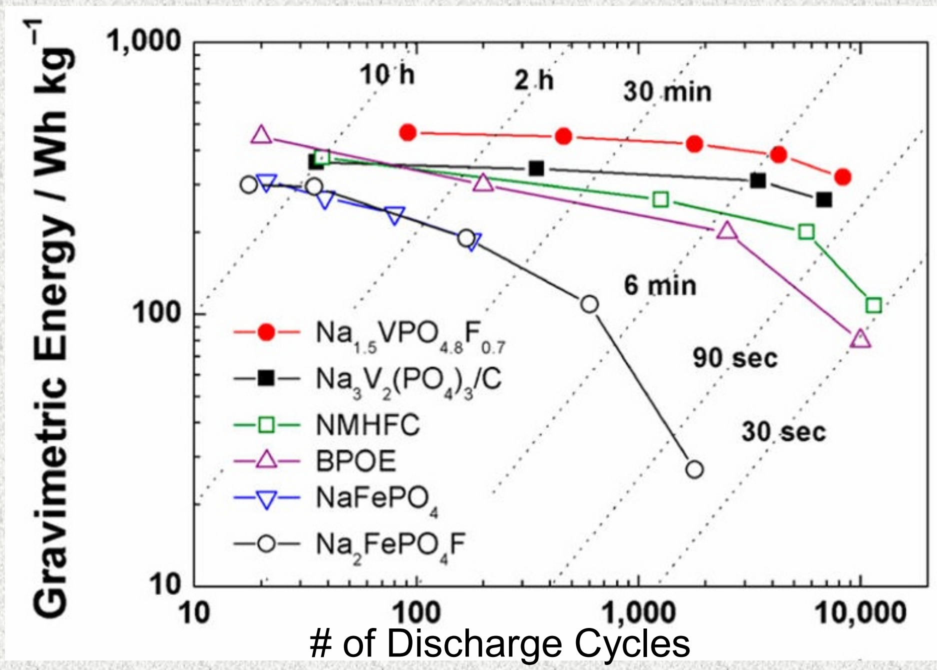


I searched for a good pictoral that shows the effect of depth of discharge versus cycle life for LPF lithium ion batteries used in a photovoltaic application (image courtesy of https://greensarawak.com/wp-content/uploads/2017/12/deapthofdischargeandcyclelife.jpg)



The top curve is the present day Lithium Titanate battery cycling profile. The bottom curve is for lithium titanate batteries with a graphite anode. You can see that adding a graphite anode depletes the cycling capability. Adding graphite also dramatically increases the potential for fire risks.

▪ SODIUM ION BATTERY – Cycle Life



Sodium ion batteries are very economical for some storage battery applications. However, it is important to note, that the number of cycles available from this battery is significantly reduced depending on the duration of the discharge period. This technology is the most advantageous for discharges less than 30 minutes in duration. Again, some sodium ion chemistries are better than others….not just from an energy density standpoint, but also in the available discharge cycles.

BATTERY TRAINING- ***Best Practice*** *Standards*

Sizing Guidelines	Lead Acid	Nickel Cadmium	Lithium Ion
IEEE Sizing (Standby, station power, and UPS)	**IEEE 485**	**IEEE 1115**	**None Available**
NFPA Sizing (Engine Starting Emergency Gensets Centrifugal Fire Pumps)	**NFPA99 NFPA110 NFPA20**	**NFPA99 NFPA110 NFPA20**	**NFPA99 NFPA110 NFPA20**
Maintenance & Test Guidelines	**IEEE 450 (flooded) IEEE 1188 (VRLA)**	**IEEE 1106**	**IEEE 2030.2.1 (NERC PRC-005-2) (BESS)**
Fire Protection	**NFPA 52.3.2.7-8 NFPA 850 Chapter 4**	**NFPA 52.3.2.7-8 NFPA 850 Chapter 4**	**NFPA 52.3.2.7-8 NFPA 850 Chapter 4**

Presently, if you need to have a lithium ion battery sized for your application, you have to reach out to the manufacturer or use a “configurator” provided by the manufacturer. Battery sizing for lithium technologies is considerably more complicated than sizing for nickel cadmium or lead acid batteries. This chart explains the reference standards which help us determine how each technology is:

- Maintained,
- Sized for Specific Applications,
- Protected for Fire Suppression.

BATTERY TRAINING- ***Best Practice*** Standards

Design Guidelines	BATTERY	CHARGER	INVERTER
Station Power	**NFPA1 Chapter 52** **IFC 608** **IEEE 450**	**IFC 1206.2.10.4** **UL 1564** **NEMA PE 5**	**IFC 1206.2.10.5** **UL 1741**
UPS	**NFPA 1 Chapter 52**	**NEMA PE 5**	**UL 1778** **AS 562040.1.1**
BESS	**NFPA 855** **UL 1774 (Repurpose)**	**IEEE 1106**	**IEEE 2030.2.1** **(NERC PRC-005-2)** **(BESS)**

Some new standards have evolved with the onset of lithium ion technologies and large chemical energy storage systems.

UL 1741 is a "product safety standard". UL1741 SA specifically addresses the following equipment used with "Distributed Energy Resources" such as grid intertie applications:

Inverters

Controllers

Converters,

and Interconnection system equipment.

IFC Section 608 *applies to stationary storage battery systems having an electrolyte capacity of more than 50 gal for flooded lead-acid, nickel-cadmium (Ni-Cd), and VRLA or more than 1,000 lb for Li-ion and lithium-metal-polymer used for facility standby power, emergency power, or UPS.*

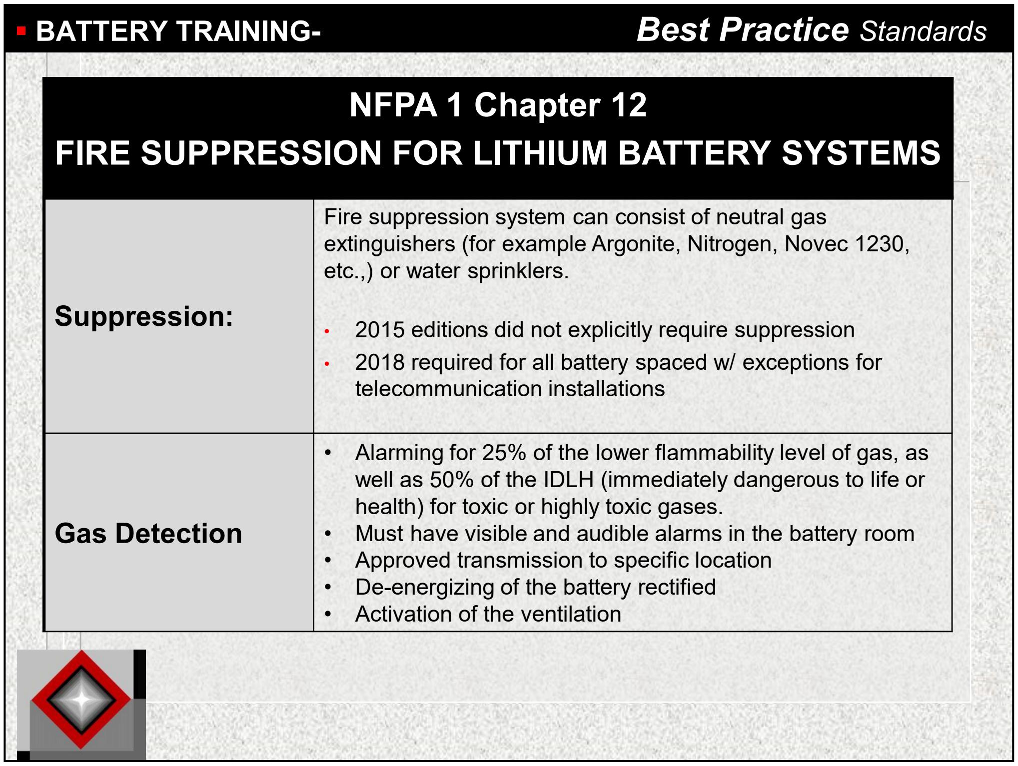
As defined by IFC 608.6.1, room ventilation:

Ventilation shall be provided in accordance with the International Mechanical Code and the following:

1.For flooded lead-acid, flooded Ni-Cd, and VRLA batteries, the ventilation system shall be designed to limit the maximum concentration of hydrogen to 1% of the total volume of the room.

2.Continuous ventilation shall be provided at a rate of not less than 1 cfm/sq ft of floor area of the room.

Exception: Li-ion and lithium-metal-polymer batteries shall not require additional ventilation beyond that *which would normally be required for human occupancy of the space in accordance with the International Mechanical Code.*


BATTERY TRAINING- ***Best Practice*** *Standards*

NFPA 1 Chapter 12
FIRE SUPPRESSION FOR LITHIUM BATTERY SYSTEMS

Suppression:	Fire suppression system can consist of neutral gas extinguishers (for example Argonite, Nitrogen, Novec 1230, etc.,) or water sprinklers. • 2015 editions did not explicitly require suppression • 2018 required for all battery spaced w/ exceptions for telecommunication installations
Gas Detection	• Alarming for 25% of the lower flammability level of gas, as well as 50% of the IDLH (immediately dangerous to life or health) for toxic or highly toxic gases. • Must have visible and audible alarms in the battery room • Approved transmission to specific location • De-energizing of the battery rectified • Activation of the ventilation

When designing battery rooms for lithium ion batteries, fire suppression system can consist of neutral gas extinguishers (for example Argonite, Nitrogen, Novec 1230, etc.,) or water sprinklers.

Suppression:

- 2015 editions did not explicitly required suppression
- 2018 required for all battery spaced w/ exceptions for telecommunication installations

Gas Detection

- Alarming for 25% of the lower flammability level of gas as well as 50% of the IDLH (immediately dangerous to life or health) for toxic or highly toxic gases.
- Must have visible and audible alarms in the battery room
- Approved transmission to specific location
- De-energizing of the battery rectified
- Activation of the ventilation

Lithium Ion Battery- ***Operating Temperatures*** **Comparison**

Stationary Battery Type:	Operating Voltage (per cell)	Specific Energy (Wh/Kg)	Operating Temperature	Cycle Life (to80% DOD)
Nickel Cadmium Pocket Plate	**1.2**	**40**	-40C to 50C (-40^{0}F to 122^{0}F)	>1500
Nickel Cadmium PBE	**1.2**	**60**	-20C to 50C (-4^{0}F to 122^{0}F)	>2000
VR Lead Acid (Pure lead grid)	**2.0**	**30-50**	-40C to 50C (-40^{0}F to 122^{0}F)	>500
VR Lead Acid (Ca)	**2.0**	**30-50**	30C to 50C* (-22^{0}F to 122^{0}F)	>300
Flooded Lead Acid (Ca)	**2.0**	**30-50**	0C to 49C (32^{0}F to 120^{0}F)	<100
Flooded Lead Selenium	**2.0**	**33 - 42**	-20C to 55C (-4^{0}F to 131^{0}F)	800 - 1000
LTO (NMC cathode, LiTO anode)	**2.3**	**60 - 110**	0C to 40C (32^{0}F to 104^{0}F) (average over 24hr period 41-95^{0}F)	>10000
SLFP+NCA	**3.7**	**90-120**	-40C to 50C (-40^{0}F to 122^{0}F)	7000
LFP Lithium Iron Phoshpate (LiFePO4)	**3.2**	**90 - 110**	-20C to 60C (-4^{0}F to 122^{0}F)	>2000
NCA (Lithium Nickel Cobalt Al Oxide) (LiNiCoAlO2	**3.6**	**200-260**	-40C to 75C (-40^{0}F to 167^{0}F)	4300

We took the same chart from the previous slide, but reproduced it based on the stationary power applications. Again, the source used were averages from OEM manuals.

- VRLA Batteries must not be charged above 90 deg F. or below 32 deg F.

Notes:

Special care should be taken when trying to research the technology best suited for your applications. Much of the data produced is based on laboratory findings, or on applications/products not specifically used for station power and/or UPS applications. Data from widely reputable sources can be very misleading. The data presented here comes straight from either the warranty statement or from the Safety Data Sheet for each of the most predominant manufacturers of station battery power.

Lithium Ion Battery- ***Specific Energy*** **Comparison**

Stationary Battery Type:	**Operating Voltage** (per cell)	**Specific Energy** (Wh/Kg)	**Operating Temperature**	**Cycle Life (to80% DOD)**
Nickel Cadmium Pocket Plate	**1.2**	**40**	-40C to 50C (-40⁰F to 122⁰F)	>1500
Nickel Cadmium PBE	**1.2**	**60**	-20C to 50C (-4⁰F to 122⁰F)	>2000
VR Lead Acid (Pure lead grid)	**2.0**	**30-50**	-40C to 50C (-40⁰F to 122⁰F)	>500
VR Lead Acid (Ca)	**2.0**	**30-50**	30C to 50C* (-22⁰F to 122⁰F)	>300
Flooded Lead Acid (Ca)	**2.0**	**30-50**	0C to 49C (32⁰F to 120⁰F)	<100
Flooded Lead Selenium	**2.0**	**33 - 42**	-20C to 55C (-4⁰F to 131⁰F)	800 - 1000
LTIO (NMC cathode, LiTO anode)	**2.3**	**60 - 110**	0C to 40C (32⁰F to 104⁰F) (average over 24hr period 41-95⁰F)	>10000
Super Lithium Iron Phosphate (LFP / LiFePO4 +NCA)	**3.7**	**90-120**	-40C to 50C (-40⁰F to 122⁰F)	7000
LFP Lithium Iron Phospate (LFP/LiFePO4)	**3.2**	**90 - 110**	-20C to 60C (-4⁰F to 122⁰F)	>2000
Lithium Nickel Cobalt Al (LiNiCoAlO2/NCA)	**3.6**	**200-260**	-40C to 75C (-40⁰F to 167⁰F)	4300

We took the same chart from the previous slide, but reproduced it based on the stationary power applications. Again, the source used were averages from OEM manuals.

Lithium Ion Battery- *Storage Comparison*

Stationary Battery Type:	Self Discharge Rate	Shelf Life	Storage Temperature
Nickel Cadmium Pocket Plate	1.2	5 Years	-40C to 50C (-40^{0}F to 122^{0}F)
Nickel Cadmium PBE	1.2	2 Years	-20C to 50C (-4^{0}F to 122^{0}F)
VR Lead Acid (Pure lead)	2.0	2 Years	-40C to 50C (-40^{0}F to 122^{0}F)
VR Lead Acid (Ca)*	2.0	6-Mo*	30C to 50C* (-22^{0}F to 122^{0}F)
Flooded Lead Acid (Ca)	2.0	1 Year	0C to 49C (32^{0}F to 120^{0}F)
Flooded Lead Selenium	2.0	1 Year	-20C to 55C (-4^{0}F to 131^{0}F)
LTIO (NMC cathode, LiTO anode)	2.3	15 Year	0C to 40C (32^{0}F to 104^{0}F) (average over 24hr period 41-95^{0}F)
LFP+NCA	3.7	12-15	-40C to 50C (-40^{0}F to 122^{0}F)
Lithium Iron Phoshpate (LFP/LiFePO4)	3.2	N/A	-20C to 60C (-4^{0}F to 122^{0}F)
Lithium Nickel Cobalt Al(NCA) (LiNiCoAlO2/NCA)	3.4	10 -20	-40C to 75C (-40^{0}F to 167^{0}F)

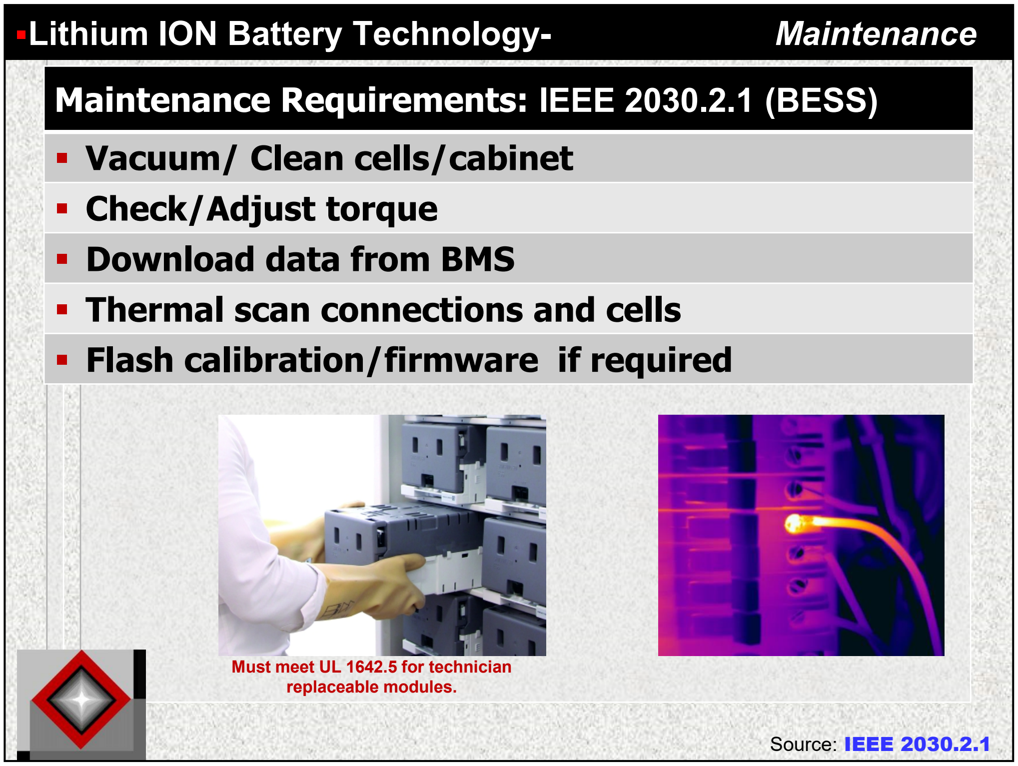


Photo courtesy of Vertiv Website and FlirT2000 training presentation.

Information regarding the required maintenance was derived from the IEEE 2030.2.1.

Note that UL 1642 is an exact copy of IEC 62133

LITHIUM BATTERY TRAINING- Best Practice Standards

2021 IFC CHAPTER	SUBJECT (CHANGES)
7	Fire and smoke protection features
8	Interior finish, decoration materials and furnishings
9	Fire protective and life safety systems
10	Means of egress
12	Energy Systems (1206.2 Stationary Storage Battery Systems)
33	Fire safety during construction and demolition

Chapter 12 Energy Systems. Chapter 12 was added to address the current energy systems found in the IFC. It introduces a wide range of systems that generate and store energy in, on and adjacent to buildings and facilities. The expansion of such energy systems is related to meeting today's energy, environmental and economic challenges. Ensuring appropriate criteria to address the safety of such systems in building and fire codes is an important part of protecting the public at large, building occupants and emergency responders. Previously, requirements for energy systems, such as standby power systems, PV systems and stationary battery systems, were scattered about

in various locations in **Chapter 6**, which addresses building services and systems. However, with the addition of fuel cells and capacitor energy storage systems to the IFC, a chapter dedicated to such related issues needed to be created. This chapter provides an **appropriate location for the addition**

of future energy systems

BATTERY ROOM DESIGN- IEEE and NFPA Guidelines

Battery Room Considerations:	Lithium Ion
Charger/s *	Single only
Spill containment	N/A
Spill Neutralization (5.0-7.0 PH)	N/A
PPE	Yes (Electrical)
Eyewash station (15 min flush Minimum)	N/A
Gas Detection & Alarm	YES
Ventilation	N/A
Safety Signage	Yes
Battery Disconnect	Yes
Battery cabling	Special
Access/Egress	Yes/ Location Dependent
Fire Suppression * 2018 NFPA 52.3.2.7-8	Yes
Fire Protective Clearances * 2018 NFPA 52.3.2.7-8	Yes

Suppression Required:

- 2015 editions did not explicitly require suppression
- 2018 NFPA 52.3.2.7-8 required for **all** battery spaced w/ exceptions for telecommunication installations

Gas Detection Required

- Alarming for 25% of the lower flammability level of gas as well as 50% of the IDLH (immediately dangerous to life or health) for toxic or highly toxic gases.
- Must have visible and audible alarms in the battery room
- Approved transmission to specific location
- De-energizing of the battery rectified
- Activation of the ventilation

BATTERY TECHNOLOGY – CODES AND REGULATIONS

IFC 608.1 (prior 2018)	Flooded Lead Acid	Flooded Nickel Cadmium	Valve Regulated Lead Acid	Lithium Ion	Lithium Metal Cells
Safety caps	Venting Caps (608.2.1)	Venting Caps (608.2.1)	Self sealing flame arresting caps (608.2.2)	N/A	N/A
Thermal Runaway Management	N/R	N/R	Required (608.3)	N/R	Required (608.3)
Spill Control	Required (608.5)	Required (608.5)	N/R	N/R	N/R
Neutralization	Required (608.5.1)	Required (608.5.1)	Required (608.5.2)	N/R	N/R
Ventilation	Required (608.6.1 and 6.08.6.2)	Required (608.6.1 and 6.08.6.2)	Required (608.6.1 and 6.08.6.2)	N/R	N/R
Signage	Required (608.7)	Required (608.7)	Required (608.7)	Required (608.7)	Required (608.7)
Seismic Protection	Required (608.8)	Required (608.8)	Required (608.8)	Required (608.8)	Required (608.8)
Smoke Detection	Required (608.9)	Required (608.9)	Required (608.9)	Required (608.9)	Required (608.9)

Reference:

BATTERY TECHNOLOGY – Lithium Battery Room Requirements

ADDITIONAL RESTRICTIONS FOR LION BATTERIES)

1. Must have means of disconnect from charging source on overtemp.
2. Must be installed below 75 feet from ground level.
3. Must be installed higher than 30 feet below ground. 506.4 and 506.5
4. **High Hazard Classification required for exceeding MAQ.**
5. Separation of 36” between **arrays** of batteries and/or other equipment that is not 1-hour fire rated. Array for battery is defined by NFPA855 as 20kWhrs of battery for lithium ion technologies.
6. Additional permitting requirements for operation as well as location within the interior of a building.
   Section 506.4, 506.5, 508.2.3, 508.3.2, 508.4.2

The biggest changes to the Fire Codes happened in 2018 and mostly to address the flammability and potential volatility of emerging battery technologies. This data was provided in IFC chapter 12 and NFPA-1 chapter 52.

There has been a lot of confusion about the NFPA’s definition of a “battery array”. In 2018 the NFPA855 defined that limit for a lithium battery to be 20kWhrs. It originally was proposed as 50KWhrs but due to recent events, the array capacity was reduced.

Photo courtesy of Times of India (Beaumonde Towers in Worli) June 13, 2018.

The Nickel Magnesium Cobalt coupling for lithium ion manufactured by LG was the battery that caught fire in this photo from ESS fire at a cement plant in Jecheon, S. Korea. / Courtesy of North Chungcheong Province Fire Service Headquarters

APS in Surprise, Arizona on April 19th, 2019 suffered a fire event that resulted in a complete safety stand-down from the ESS industry when a container of 240 cells caught fire and 4 firemen were killed and 5 others hospitalized with serious injury. APS has formed a team of engineers, fire reactors, and safety experts to experiment with utility, Fluence –battery manufacturer and others to remove and test the 378 modules and to know what actually happened. The 378 module consists of McMicken battery system. Again, this system used the NMC lithium ion technology manufactured by LG. (This photo was courtesy of the Arizona Tribune, June 25th, 2019 (June Seay).

Hazard

The use of Li-ion Batteries can create the potential for a fire protection hazard known as thermal runaway. If your fire protection design is for as a Class C fire, you may not be prepared for this catastrophic threat. Thermal runaway (a Class B Fire) is not the same as an electrical or Class C Fire. This fire hazard is a thermal heat transfer issue because there is a disconnection from the power source which permits more current thus the risk of fire is not eliminated. **Damaged batteries can reignite hours or days later due to thermal runaway. Fire suppression is just the beginning of mitigating a fire event.** As concentration levels for a Class B fires are different than that of the Class C fires, chemical suppression alone will not stop thermal runaway. Suppression will extinguish a Class C fire inside the ESS container or building and will stop an electrolyte fire from off-gassing of the batteries **but not** thermal runaway.

Risk

Risk should be evaluated based on the upcoming **NFPA 855 code**.

▪Lithium ION Battery Technology- *Safety*

How Safe are these LION systems:

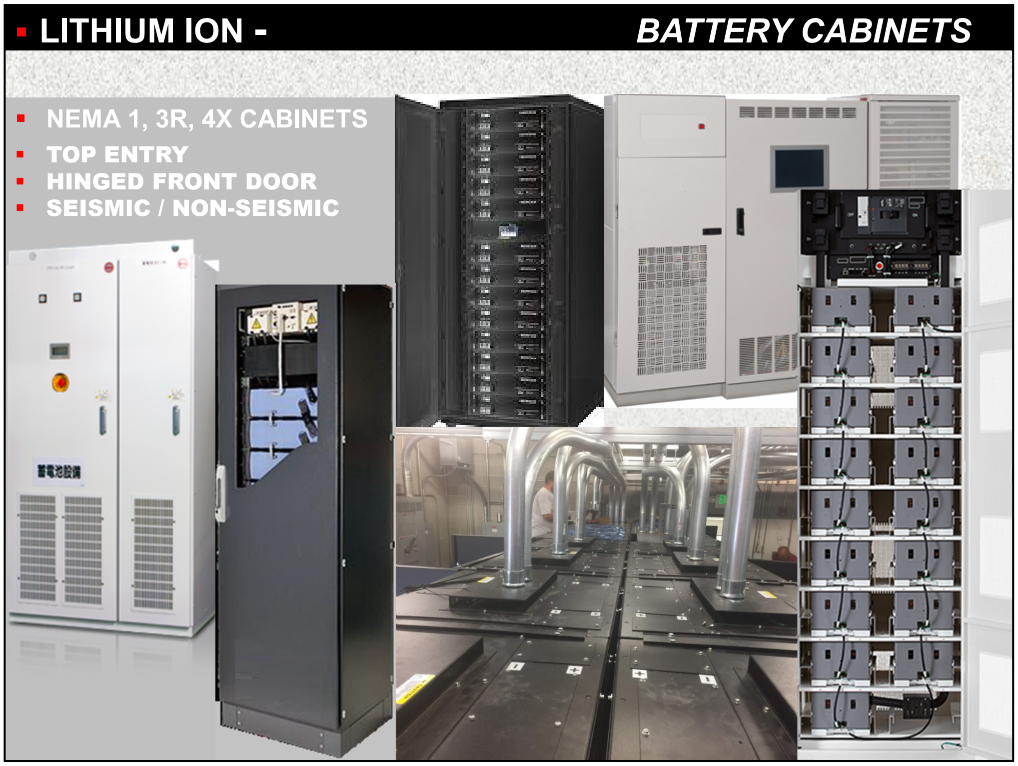
Monitoring makes the difference.	▪ **Each <u>cell</u> is monitored for:** Voltage, Temperature, Current.
	▪ **Each <u>string</u> is monitored for:** Reverse Polarity Protection, Impedance, Voltage, Temperature, Current.
Controls provide additional safety.	▪ **Hardened electronics/PLC**
	▪ **Thermal Runaway Control (55°C alarm/ 65°C disconnect)**
	▪ **<u>Cell</u> Balancing**
	▪ **CANBUS for Local and Remote Communication**
	▪ **Each <u>cell</u> and string has the ability to be removed from the DC bus without impacting operation of the others (cell-level disconnecting means)**

If communication is lost between modules, the string is disconnected from the system. This will not impact the system if it is configured as N+1…..It will affect the runtime of the system IF it is not N+1 or higher for redundancy.

The Lithium ion batteries are designed to be very stable for float charge and taper current charge applications with the thermal runaway temperature somewhere between 272 degrees F and 300 degrees F. In the case of a thermal event, most of the manufacturers has the ability to disconnect the battery charging from the module, or string, but still have a path through a diode and resistor that still allow the battery to discharge.

It is also important to note that all of the lithium battery technologies I will discuss in this presentation are "lithium ion" and NOT lithium metal type batteries.

Lithium ion batteries must have careful control systems to prevent thermal runaway events and to ensure safe operation.



Nearly all of the 48 VDC, 120 VDC, 240 VDC, 360 VDC and 480VDC systems we have seen are mounted in cabinet systems as seen on this slide. They are available with top cable entry, side cable entry, bottom cable entry.

▪Lithium ION Battery Technology- *Cabinetized Systems*

Cabinetized Systems:

Cabinetry	▪ Typically 90" (2286 mm) Height
	▪ Multi-string cabinet (offers redundancy) ▪ Single String cabinet (no redundancy) ▪ Disconnect per string ▪ Disconnect per cabinet ▪ Seismic rated per IFC 1206.2.4
	Components: ▪ Battery monitoring/alarm notification system ▪ Battery management system ▪ System communication module ▪ Battery modules ▪ Battery DC disconnect
	▪ NEMA1 (IP20), NEMA3R (IP54) or Higher
Electronics	▪ Hardened electronics
	▪ Redundant monitoring (Not typical. Most manufacturers operate without the communications interface.)

▪Lithium ION Battery Technology-	*Safety Concerns*
Predominant Safety Concerns:	**Remedy within the system:**
▪ **Over-temperature**	▪ Cell, module, and string level protection
▪ **Over-Voltage**	▪ String level DC Disconnect, but still able to charge
▪ **Over-Discharge**	▪ Module level disconnect from load at 2.5 vpc, but continues to charge
▪ **Thermal Runaway**	▪ **Alarm at 55^0 C, Charge termination at 70^0C**
▪ **Moisture Intrusion**	▪ Humidity and moisture control
▪ **Cell Rupture (physical)**	▪ Containment within the module
▪ **Fire Propagation / Containment**	▪ Fire Suppression. Notification, clearances, testing per UL9540A and **UL9540**, Noncombustible Cabinets IFC 608
▪ **Communication Failure**	▪ Redundant real time communication modules, if N+1
▪ **Remote Comm Failure**	▪ Does not affect the module and inter-string communications.
▪ **Battery Management System Failure**	▪ Autonomy, optional redundancy in BMS
▪ **Charge Control Failure**	▪ Disconnection at the string level, module level and system level

These are the items feared the most by the different OEMS. The temperature at which manufacturers disconnect varies from manufacturer to manufacturer, but most disconnect from the charging source between 65 and 70 ^{0}**C.**

Safety is mitigated with considerable controls and status monitoring. UL9450 is for safety standard for monitoring Battery Energy Storage Systems.

UL9450A is a method for evaluating and detecting thermal runaway. Do not buy a lithium ion system that does not carry both listings for UL9450 and UL9450A.

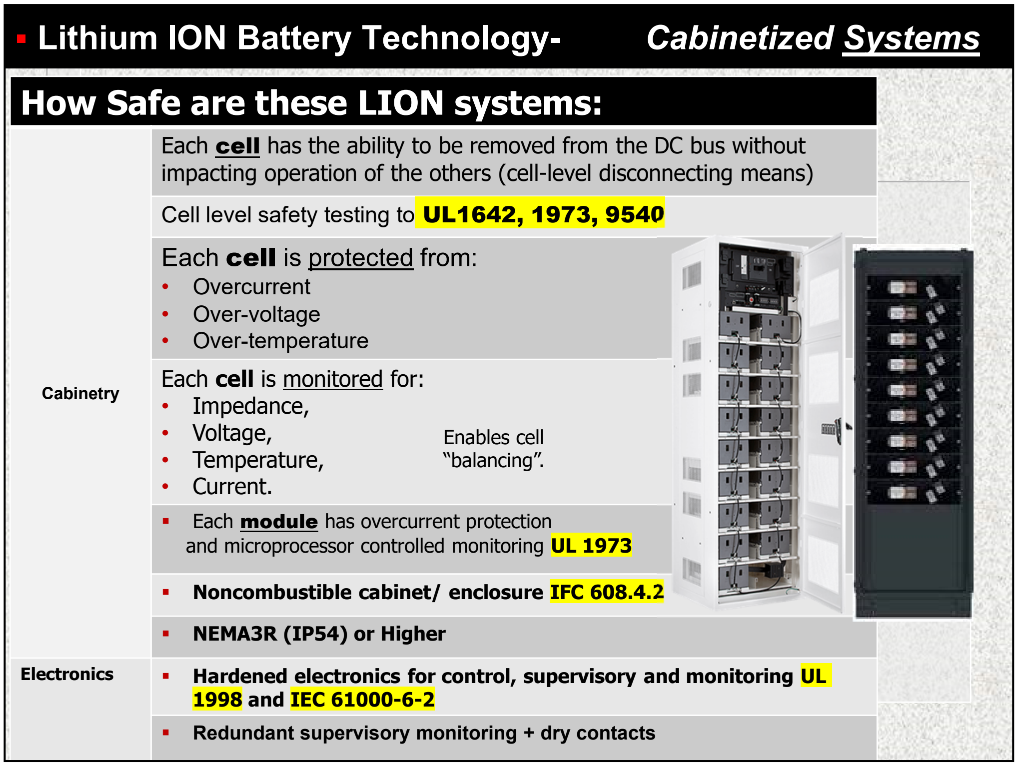
Lithium ION Battery Technology- BMS *SAFETY*

CERTIFICATION	Description
UL 9540; Article 706 of NFPA 70, (Also 9540A)	* Environmental Tests, Electrical Tests, Mechanical Tests, and 9540A for test methods for Thermal Runaway Fire Propagation.
UL 1973	Materials, Enclosures, Safety Analysis, Safety Controls, Bonding, Insulation, Spacings, Grounding…Fire Test
IEC 61508	Functional safety of electrical/electronic / Programmable electronic safety-related systems
IEC 62040-1	Uninterruptible Power Systems (UPS) Safety Requirements
IEC 62040-2	Uninterruptible Power Systems (UPS) Electromagnetic Compatibility Requirements
IEC 62040-3	Uninterruptible Power Systems (UPS) Environmental Aspects
IEEE P2686	Recommended Practice for Battery Management Systems in Energy Storage Applications
FCC 47 CFR Part 15 Subpart B Class A	FCC EMC Conformity (Unintentional Radiators)
FM DS 5-33	Recommendations for construction, location, fire protection, electrical system protection and design of LIB ESS

- References presentation by UL: https://share.ansi.org/Shared%20Documents/Standards%20Activities/International%20Standardization/Regional/Staff/LMM/US-Africa-CESP/CESP%20Kenya%202018/Presentations/UL%20Presentation.pdf

- One of the important aspects of UL 1973 is the Fire testing:

  Internal Fire Test Proposed Revisions • Revised name of test to “Single Cell Failure Tolerance” • Divide the test into two methods: • Lithium ion method • Other technology method (applies to solid state lithium metal, sodium beta, lead acid batteries) • Both methods are single cell failure to determine if there is propagation outside of the DUT enclosure • Addition of details on cell failure methods in new Appendix F • Test is essentially a failure of a single cell to determine if there is propagation. (Pass fail criteria: no explosion and no fire propagation outside of the enclosure.) The new UL9540A went into effect April of 2021.



Most of the manufacturers provide for several levels of protection:

- Cell Level
- Module Level
- String Level

- The UL 9540 certifications pertain for fire detection and suppression pre NFPA 550 and NFPA 551 , safety analysis and control systems, (ie. Remote controls cannot override local controls and systems must have a means to disconnect from remote control…)

- UL 1973 is the standard for stationary power for SAFETY BATTERIES including rail and substations.

Lithium ION Battery Technology- *Shipping*

Shipping Requirements:

- **Each cell / module must ship in its own carton (Shipped loose for field installation)**
- **Replacement Cells are carrier specific for shipping and handling**
- **UN classification (spent) ship as Class 9**
- **Requires 3-6 months for air cargo approval**
- **CDL Hazmat licensed driver required for transport**
- **Certified to UN/DOT 38.3**

Packing per 49 CFR 173.185:	Lithium Ion Battery	Lithium Metal Battery
Stand Alone	(P.I. 965) UN 3480 Class 9 group 2	(P.I. 968) UN 3090
Packed w/ Eqt but not installed in equipment	(P.I. 966) UN 3481	(P.I. 969) UN 3091
Contained in Equipment	(P.I. 967) UN 3481	(P.I. 970) UN 3091

Lithium Batteries must be certified to UN/DOT 38.3 requirements:

T1 – Altitude Simulation (Primary and Secondary Cells and Batteries)
T2 – Thermal Test (Primary and Secondary Cells and Batteries)
T3 – Vibration (Primary and Secondary Cells and Batteries)
T4 – Shock (Primary and Secondary Cells and Batteries)
T5 – External Short Circuit (Primary and Secondary Cells and Batteries)
T6 – Impact (Primary and Secondary Cells)
T7 – Overcharge (Secondary Batteries)
T8 – Forced Discharge (Primary and Secondary Cells)

Chemistry

CHEMISTRY: ***(LITHIUM IRON PHOSPATE)*** $LiFePO_4$

2-Part Reaction:

$$LiFePO_4 \longleftrightarrow FePO_4 \xleftarrow{} \text{Electrolyte} \xrightarrow{} Li + e- + C \longleftrightarrow LiC_5$$

Cathode (+ electrode)
Aluminum Current Collector

Ethylene Carbonate (EC)
/Dimethylcarbonate (DMC)

Anode (- electrode)
Copper Current Collector

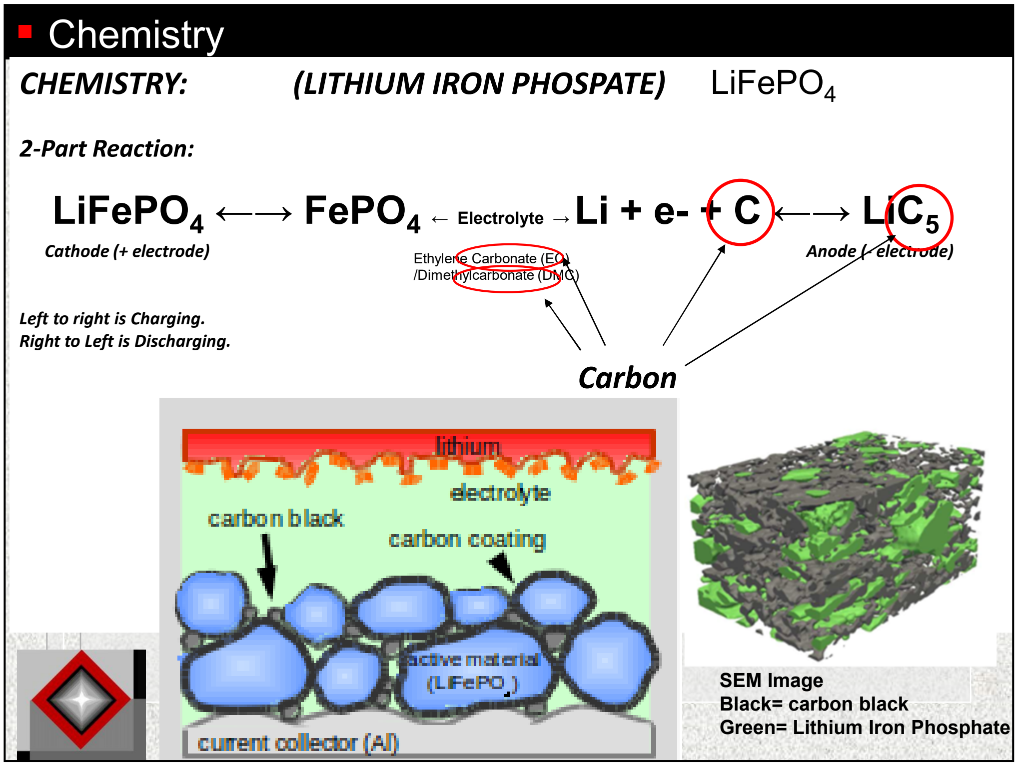
→ ***Left to right is Charging.***

← ***Right to Left is Discharging.***

Larger ***voltage per cell*** means fewer cells required for the same output power.

CELL VOLTAGE:

3.4 VDC per cell



This slide depicts the chemistry involved in creating voltage at the battery terminals for LiFePO4. This chemistry uses ethylene carbonate and dimethylcarbonate as the electrolyte. The electrolyte is essentially a salt.

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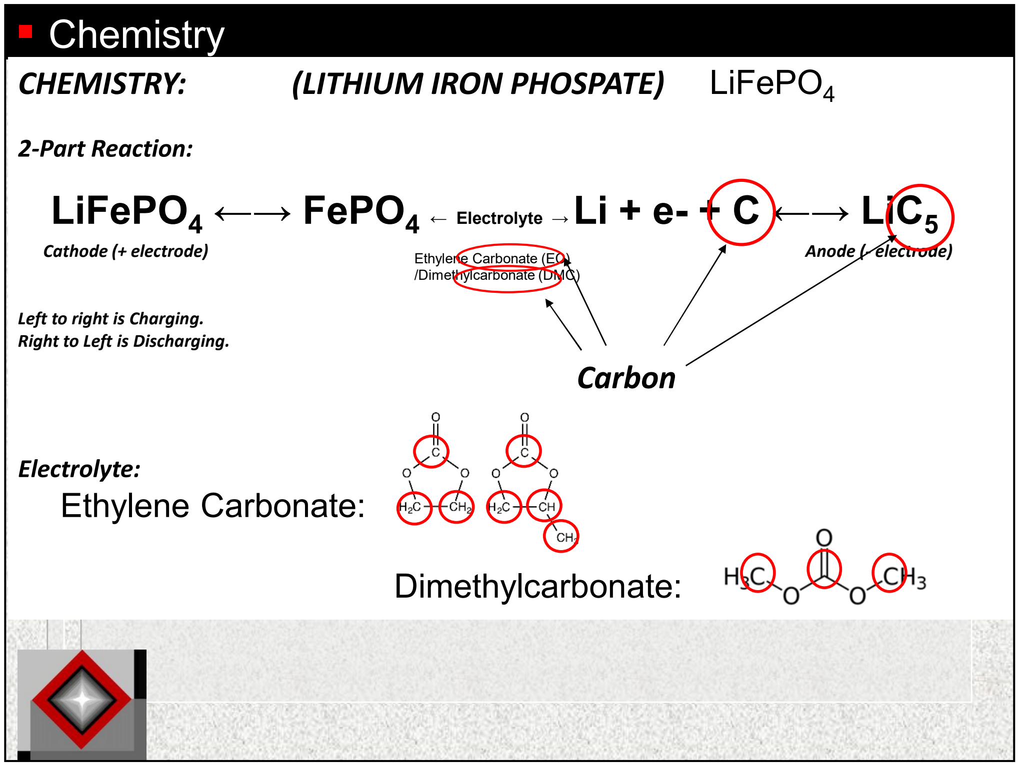
The image from Karisruhe Institute of Technology IAM 20-11-1022, shows: depiction of of different electrode materials, the electrodes microstructure is of enormous importance. In this case, the microstructure is reflected by the spatial distri-bution of the different phases (active electrode material, binder, pores) (fig. 2) of an electrode as well as further properties like the particle size distribution, active surface and others.
A microstructure, which is optimized for a specific material combination, is able to establish a balance between slow and fast reaction steps.
The aim of this work is the optimization of the microstructure, and the adaption to specific requirements regarding energy and power density.
Therefore, a microstructural model will be developed and simulated using the finite element method (FEM). Thereby the transport processes and reactions inside the three-dimensional electrode structures are described space- and time-resolved.



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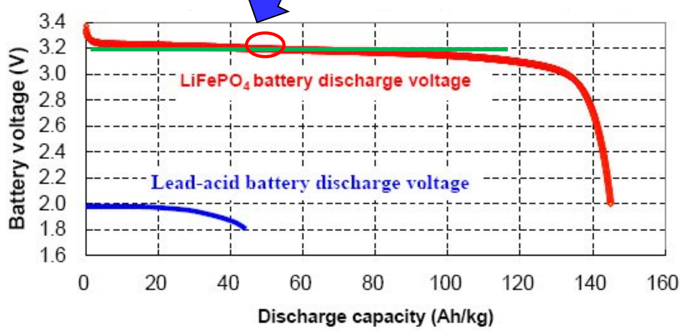
Chemistry

CHEMISTRY: (LITHIUM IRON PHOSPATE) $LiFePO_4$

Nominal Voltage:

The average voltage is where the flat part of the curve intersects the green line. This is the “nominal cell voltage” @ 3.2 vpc.

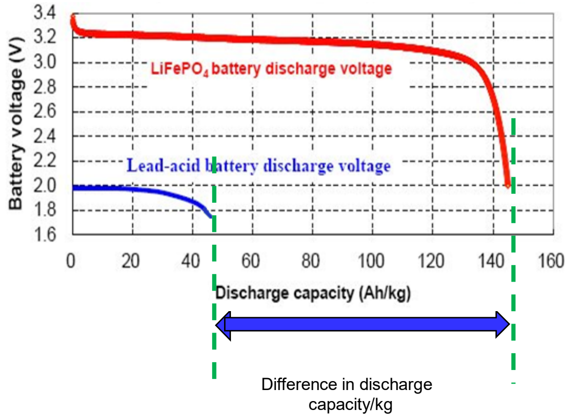


In establishing a “Nominal Voltage” the manufacturers will use the “Discharge curve of voltage on the Y-axis and Capacity /Kg on the X-axis. The tope curve shows how the LiFePO4 compares to a high-rated sealed lead acid battery. The lead acid battery curve is more round, while the LiFePO4 is very flat through the largest part of the discharge curve, and then drops off rapidly. If we draw a straight line through the flat part of this curve, the intersection point established the average or “mean” voltage on this curve. This intersection point is where the “Nominal” or nameplate rated voltage of the cell comes from.

Reference: Chart reproduced from

▪ Chemistry

CHEMISTRY: ***(LITHIUM IRON PHOSPATE)*** $LiFePO_4$



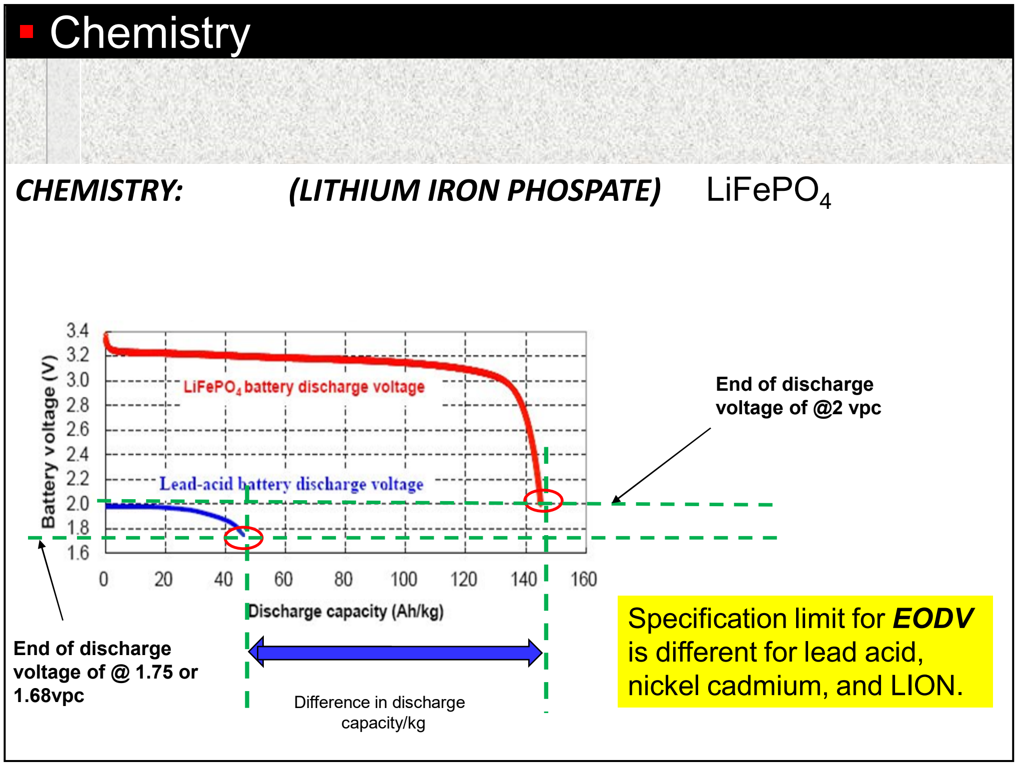
The capacity per kilogram is nearly 3.5 times that of lead acid high rate batteries.

For a short duration discharge, meaning a high rate discharge, the graph above illustrates the difference in capacity per kg for a traditional high rate UPS battery and a liFePO4 battery. The X-axis is labeled Ah/kg. The curves are actually voltage and shows that the voltage delivered by the battery is not constant. In fact, the battery voltage declines as the battery discharges. This decline in voltage not only affects power, but also energy density.

To get the same capacity during this discharge period, I would need 4 parallel strings of this particular lead acid batteries.

Question: Will that difference in number of strings be realized when I consider a real application? Yes. The impact is in floor loading.

Let's find out.



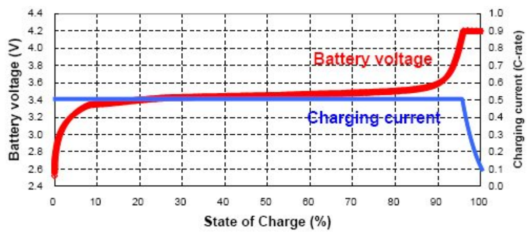
This is the exact same slide as before, except we are now focused on the EODV.

Notice the difference in EODV for each chemistry:

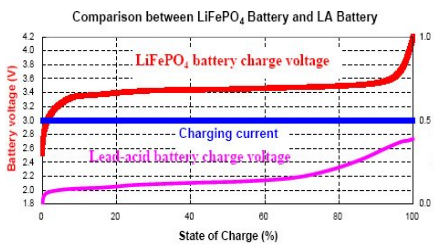
For lead acid, we use 1.75 vpc for long duration discharges, and 1.68 vpc for fast discharges. For lithium ion, most manufacturers will terminate discharge at 2.0 vpc. Th

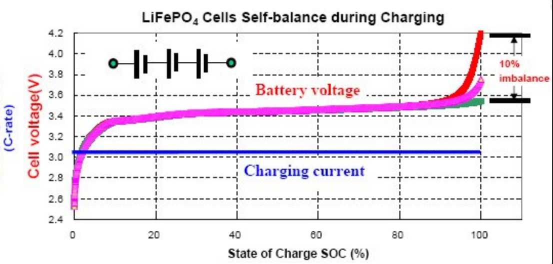
▪ Chemistry

CHEMISTRY: (LITHIUM IRON PHOSPATE) $LiFePO_4$



Overcharge tolerance is better on LiFePO4 than with LTO/LiCoO2





2. **Large overcharge tolerance and safer performance**

A LiCoO2 battery has a very narrow overcharge tolerance, about 0.1V over the 4.2V per cell charging voltage plateau, which also the upper limit of the charge voltage. Continuous charging over 4.3V would either damage the battery performance, such as cycle life, or result in fire or explosion.

A LiFePO4 battery has a much wider overcharge tolerance of about 0.7V from its charging voltage plateau of 3.5V per cell. When measured with a differential scanning calorimeter (DSC) the exothermic heat of the chemical reaction with electrolyte after overcharge is only 90 Joules/gram for LiFePO4 versus 1600 J/g for LiCoO2 . The greater the exothermic heat, the more vigorous the fire or explosion that can happen when the battery is abused.

A LiFePO4 battery can be safely overcharged to 4.2 volts per cell, but higher voltages will start to break down the organic electrolytes. Nevertheless, it is common to charge a 12 volt a 4-cell series pack with a lead acid battery charger. The maximum voltage of these chargers, whether AC powered, or using a car's alternator, is 14.4 volts. This works fine, but lead acid chargers will lower their voltage to 13.8 volts for the float charge, and so will usually terminate before the LiFe pack is at 100%. For this reason a special LiFe charger is required to reliably get to 100% capacity.

Due to the added safety factor, these packs are preferred for large capacity and high power applications. From the viewpoint of large overcharge tolerance and safety performance, a LiFePO4 battery is similar to a lead-acid battery.

■ Chemistry

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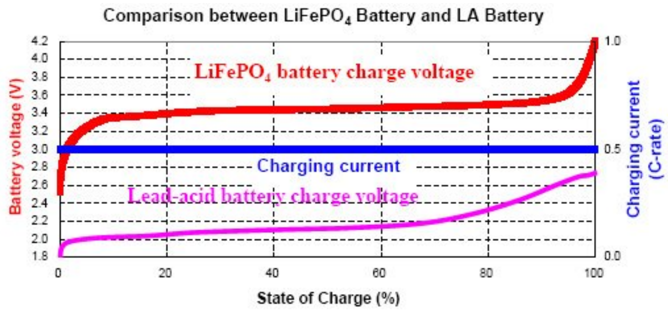

Charging Voltage per cell is different than the lead acid batteries as you can see from the chart. The charging voltage of most chargers and UPS modules is adjustable. Care must be taken to ensure that the charging voltage of the equipment is taken into consideration for battery sizing purposes.

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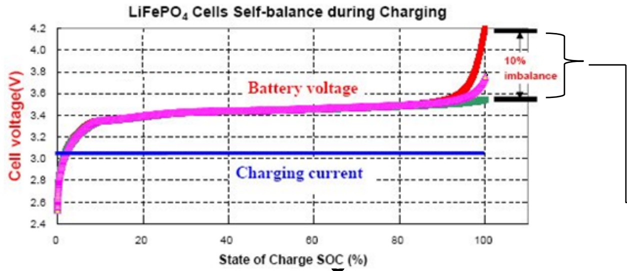

The profile above shows that at about 90% state of charge, the batteries will have some differences in the time at which they reach the 100% state of charge.

2. **Large overcharge tolerance and safer performance**
Once a battery has reached a full state of charge, charging current injected into the battery is considered “overcharge”.

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Chemistry- LTO

CHEMISTRY: ***(LITHIUM TITANATE OXIDE ANODE)*** $Li_4Ti_5O_{12}$

Chemical Formula:

$$\mathbf{Li_4Ti_5O_{12} + 6LiCoO_2 \longleftrightarrow Li_7Ti_5O_{12} + 6Li_{0.5}CoO_2}$$

$Li_4Ti_5O_{12}$	$6LiCoO_2$	$Li_7Ti_5O_{12}$	$6Li_{0.5}CoO_2$
(Anode)	(Cathode)	(Anode)	(Cathode)
Aluminum Current Collector			***Copper Current Collector***

Cell Potential: 2.1 VDC per cell
(patented)

Li = Lithium
Co = Cobalt
Ti = Titanium
O = Oxygen

→ ***Left to right is Charging.***
← ***Right to Left is Discharging.***

The “Ti” in this formula stands for Titanium. The “Co” in this slide stands for Cobalt. The “Li” stands for Lithium, and the “O” in this slide stands for Oxygen.

Electrolyte for this cell type consists of lithium ions dissolved in organic solvents.

You will not that there is no elemental carbon on this slide, so no carbon participates in the reaction for developing the voltage at the battery terminals. NOTE: Notice the absence of the elemental carbon in this reaction. There is no carbon participating in the reaction. Again, this is important when we start talking about fire safety later in this presentation.

Chemistry- *(LITHIUM TITANATE OXIDE ANODE)*

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(Anode) (Cathode)

Cell Potential: **2.1** VDC per cell

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O = Oxygen

Noteworthy: Absence of Carbon

The “Ti” in this formula stands for Titanium. The “Co” in this slide stands for Cobalt. The “Li” stands for Lithium, and the “O” in this slide stands for Oxygen.

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LITHIUM ION BATTERY – *SUMMARY*

- **BENEFITS:**

Excellent benefits over single strings of VLA or NICAD

Excellent repetitive **Cycling**

Excellent high & low temperature operation

Rapid Recharge capability

Built-in **Charging Regulation**

Very **compact** and light weight for short duration discharges

Very **predictable** and stable life and cycle life

12-15 year “**Maintenance Free”** operation

Built-in **Thermal Runaway Control**

Cell and string level **Battery Monitoring (**standard)

Superior **Shelf Life**

Not all lithium ion chemistries can be considered safe for all station power applications. If used properly, the end-user can enjoy the benefits described. These systems are heavily controlled and monitored.

Careful consideration should be applied to using only lithium couplings that minimize or eliminate the use of graphite in the anode and cathodes. That is the only way to ensure safe operation.

▪ LITHIUM ION BATTERY – *SUMMARY*

▪ BEST APPLICATIONS:





Single String VLA or NICAD Replacement

Engine Generator Start

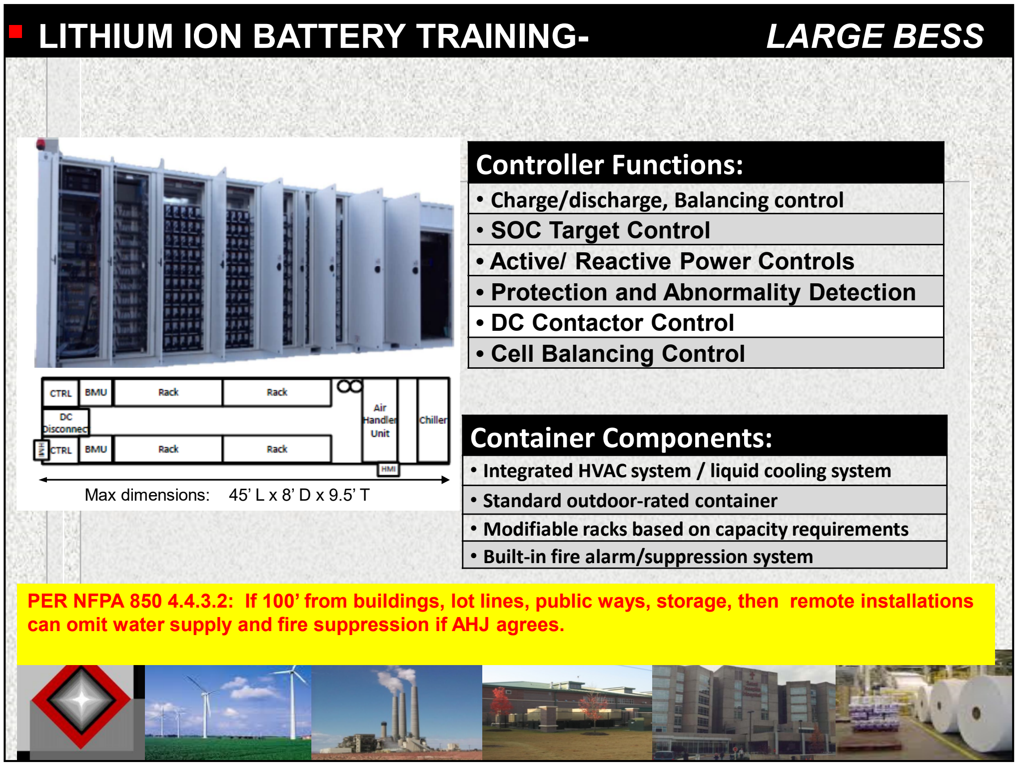
Switchgear/Process Control

Wind Turbine Energy Storage

Photovoltaic System Energy Storage

<5 Minute UPS Applications

Flicker and Voltage Control Applications



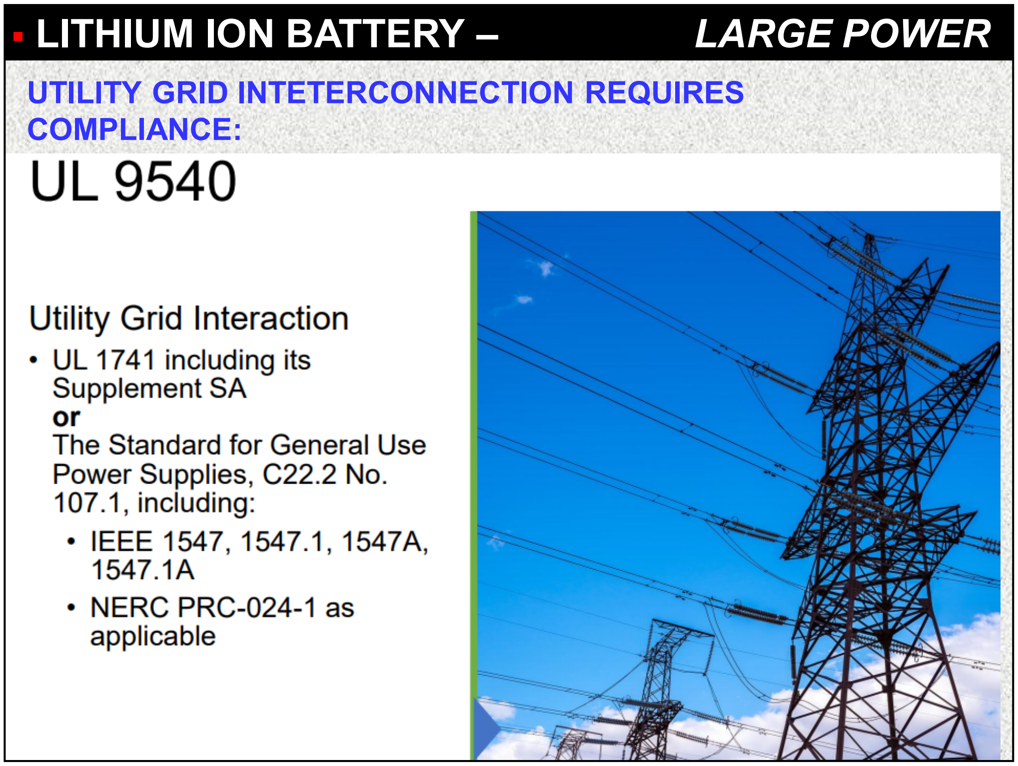
Paragraph 4.4.3.3 advises these outdoor system can’t be larger than 45’ x 8’ x 9.5 or they have to comply with indoor installation requirements.

LITHIUM ION BATTERY – *LARGE POWER*

- **LARGE POWER (BESS)**
  Super cycling and fast recharge
  No Building Code Compliance
  Excellent repetitive cycling
  Excellent high temperature operation
  Excellent low temperature operation
  Very compact and light weight
  Very predictable and stable life and cycle life
  12-15 year maintenance free operation
  Battery & cell monitoring is standard

Ideal:
PV
Wind
Regen
Standby
Transfer


This photo is courtesy of presentation Korba Battery Research and Development Association of Korea, Shin-Yongin S/S



Slide adapted from:
https://share.ansi.org/Shared%20Documents/Standards%20Activities/International%20Standardization/Regional/Staff/LMM/US-Africa-CESP/CESP%20Kenya%202018/Presentations/UL%20Presentation.pdf

This testing requires testing for electrical function and compatibility:

Electrical Tests: • Functional Safety/reliability evaluation of Electronics • Normal Operations (temperature and check of component operating parameters under maximum loading) • Dielectric Voltage Withstand • Impulse • Equipment Grounding and Bonding • Insulation Resistance.

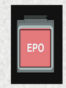
Environmental Tests: • Special Environment Installations • Outdoors installations subject to moisture exposure • Outdoor installation near marine environments • Installation in seismic environments

It also defines mechanical tests as follows:
Mechanical Tests: • Containment of Moving Parts • Over speed qualification • Faulted securement qualification • Blocked shaft qualification • Mechanical failure qualification • Leakage • Strength • Hydrostatic • Pneumatic

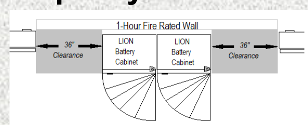
▪ LITHIUM ION BATTERY – *SUMMARY*

▪ LIMITATIONS:

- FM, NFPA and IEEE practices are lagging for Station Power.
- **Charging Compatibility** must be approved and/or certified by the manufacturer.
- External System DC breaker may be required for systems of 3+ cabinets for **EPO** capability with UPS.



- Manufacturers want **compatibility** for replacements.
- Maximum allowable quantities affects **Occupancy Classifications.**



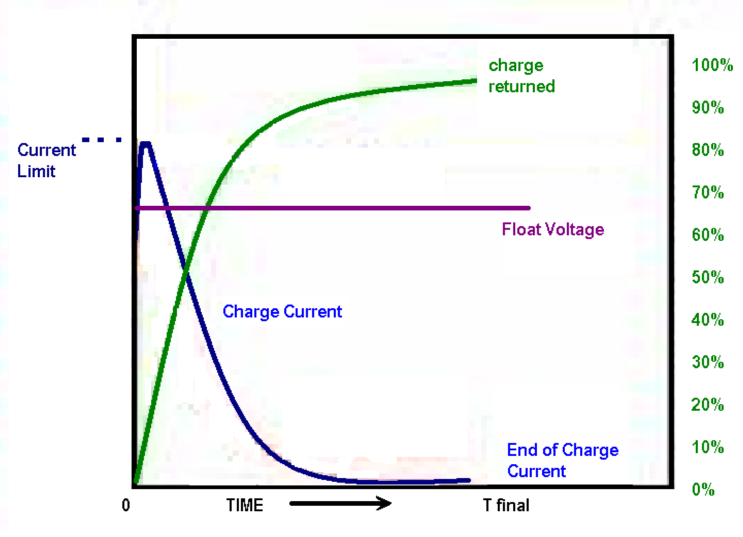
- **36" Clearance** requirement all around.
- **Fire Suppression** reqs keep changing.
- **Transport** must be by certified DOT driver.
- **Sizing programs** are not available to the public.
- **Higher purchase price.**

LITHIUM ION BATTERY – *SUMMARY*

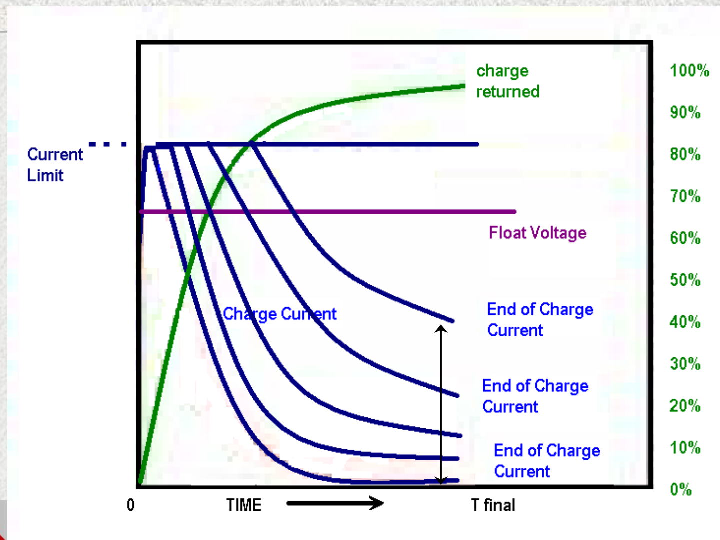
LIMITATIONS: *Continued*

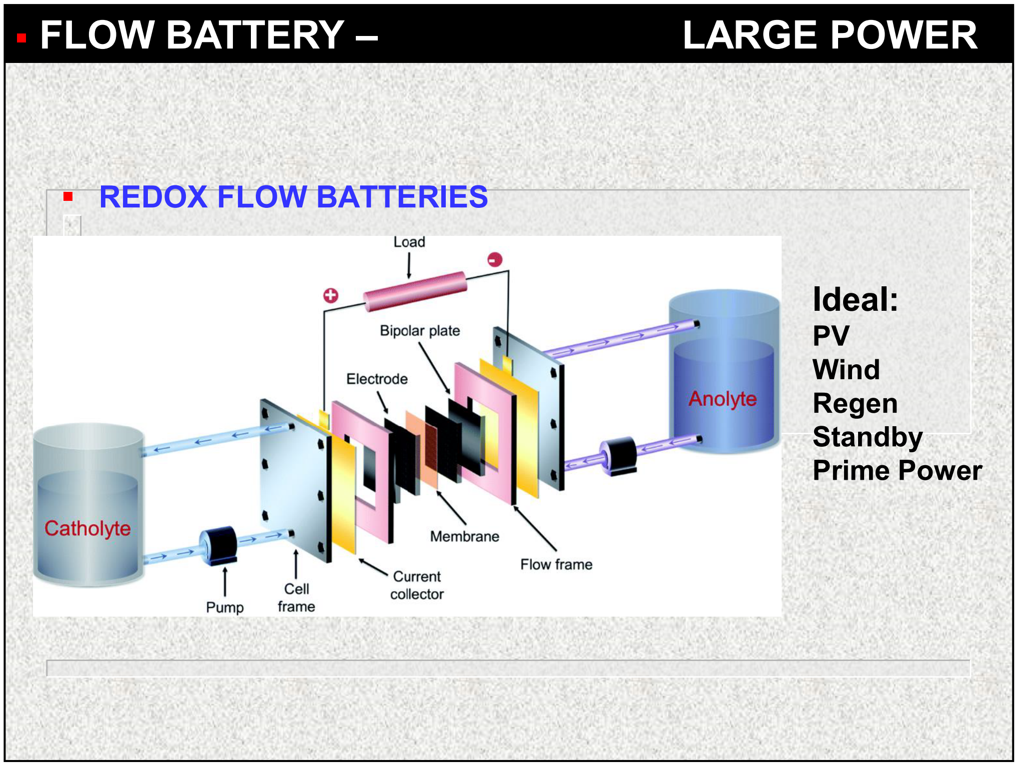
- **Electronics required for battery management and monitoring are not as hardened for temperature extremes as the battery modules.**
- **System capacity and physical size is restricted by the NFPA 850**
- **Many manufacturers ship the batteries loose which means certified installation team has to be dispatched.**

Battery Recharge Curve



Classical Thermal Runaway





Used for milliseconds of storage for typically sub-cycle voltage flicker events. This photo is courtesy of presentation Korba Battery Research and Development Association of Korea.

Flow batteries use liquid electrolyte to store energy….vanadium-redox, zinc-bromine, iron-chromate