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Key Considerations for Evaluating Lithium-ion Batteries for Stationary Applications

Lead-acid batteries have long been the default backup power choice for the uninterruptible power supplies (UPS) that ensure the availability of data centers, communications equipment, and industrial processes.

While they provide the power and reliability required for these applications, when supported with appropriate monitoring and maintenance practices, they have traditionally been regarded as the weak link in the critical power chain. They tend to be high maintenance, heavy and require frequent replacement.

Now, lithium-ion batteries have emerged as a viable alternative and a growing number of users are evaluating this technology for UPS applications in mission-critical environments. As a leading global provider of critical infrastructure systems, Vertiv has worked with a range of customers considering lithium-ion batteries to address key considerations they face when deciding whether to move forward with this technology.

A summary of this information is presented in the companion document, *Frequently Asked Questions About Using Lithium-ion Batteries in UPS Applications*.

Life Expectancy for a Lithium-ion Battery in a Stationary Application

One of the key attractions for moving to lithium-ion batteries is the battery life being multiples of what is possible with lead-acid batteries. Yet, with limited operating data in UPS applications available today, it's natural for potential users to question how long lithium-ion batteries will actually last.

To address this question, it's necessary to first understand how lithium-ion batteries degrade under normal circumstances. They have two largely independent modes of degradation: *calendar life* and *cycle life*.

Calendar life describes how the capacity will decline and how the resistance will increase over time. For calendar life, the operating temperature of the battery is the most important factor in determining how long it will last. Heat can accelerate degradation and cooler temperatures minimize degradation.

As for cycle life, the term itself is easily understood but projecting cycle life of a lithium-ion battery is not as simple as it would seem. This is because different characteristics of the cycle determine how damaging that cycle is to the battery.

A baseline test in the lithium-ion industry is to fully discharge the battery in one hour and then recharge it fully in one hour at room temperature (25°C / 77°F). For high-quality cell designs, this is an easy test that will result in thousands of cycles before the cell reaches 80% of its initial capacity. However, cycle life is typically quite sensitive to the charge and discharge rates and other factors. A summary of the key factors that influence cycle life is shown in Figure 1.

Cycle Parameter	Influence on Cycle Life	Description
Charge / Discharge Rate	Significant	Charging or discharging a battery at rates higher than it was designed for will shorten its cycle life considerably
Depth of Discharge	Moderate	Partially discharging a battery before recharging is less damaging than discharging it completely
Temperature	Moderate	While a warmer battery will have less resistance and lower self-heating rates, cooler operating temps are generally better for life. Many lithium-ion batteries are also sensitive to charging at cold temps (usually below freezing) but this is generally not a concern for data center applications
State of Charge (SOC) Window	Minor	When using a battery at partial depth of discharge, cycling it near completely full (100% SOC) or completely empty (0% SOC) is more damaging than specifying an operating window at partial states of charge

Figure 1. *Summary of key factors that influence lithium-ion battery cycle life.*

In data center applications, calendar life is typically the primary driver because battery cycling is infrequent. The exception to this would be when UPS batteries are being used to support site energy management or providing grid services to the local electricity distribution network. Those applications are outside the scope of this paper. In conventional use cases, the batteries are idle for most of their operating life.

To assess calendar life, cell manufacturers typically store batteries at different temperatures for long periods of time and periodically check their remaining capacity. Charting this data provides a relationship between time, temperature and remaining capacity. After enough data has been collected, it's possible to fit the data to a generally accepted equation for calendar life which has been proven over decades of lithium-ion battery field experience. An example of a lithium-ion battery calendar life chart is shown in Figure 2.

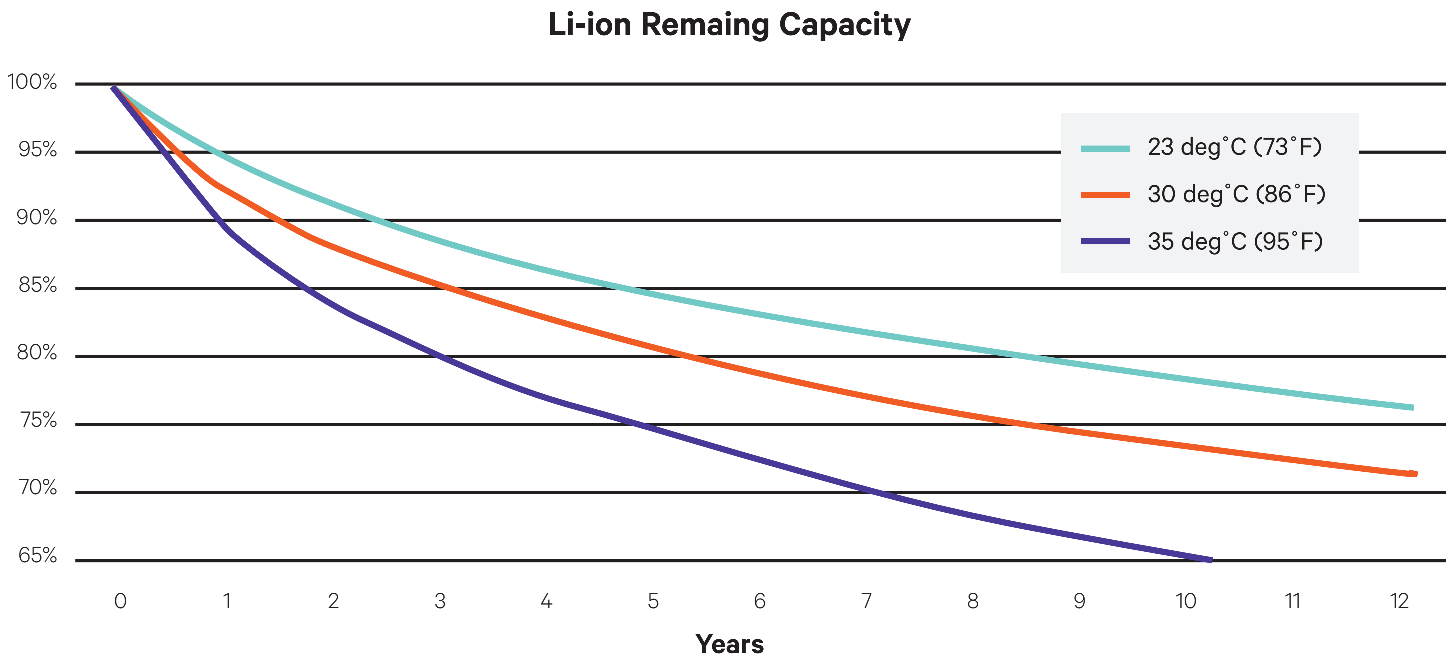

***Figure 2.** Lithium-ion battery calendar life chart.*

Figure 2 shows that 80% of initial capacity remains after about ten years at temperatures of 23°C (73°F) for the particular lithium-ion battery tested. Different lithium-ion batteries will have different rates of degradation. What is important is that 80% capacity is not a significant milestone in the life of a lithium-ion battery because the rate of annual degradation is slowing down around 80% and will continue to degrade predictably. The next section will cover how the remaining capacity and battery resistance influence the runtime in a specific application.

Projecting Future Runtimes for Lithium-ion Batteries

One of the most common questions potential users of lithium-ion batteries have concerns the impact of battery age on projected run times. This concern is reflected in a common question: *Is a lithium battery susceptible to surprise failures late in life similar to lead-acid batteries?*

To address this question, it's important to consider the previous discussion on lithium-ion battery degradation as well as the design of the electrodes in each cell of the battery system. A lithium-ion battery cell can be tailored to different performance objectives by the manufacturer and one key trade-off is between how fast you can charge or discharge the battery and how much energy it holds. The extreme ends of these trade-offs are summarized in Figure 3.

Performance Metric	Cell optimized for energy density	Cell optimized for power
Energy density	Today's lithium-ion technology can produce cell energy densities as high as 600 Wh/liter, which enables a very small footprint, but these batteries can't discharge their energy very quickly.	Cells optimized for power performance make compromises on energy density. In extreme cases, the energy density of these cells can be just half of the high energy alternatives.
Rate capability	A cell optimized for energy density may take an hour or more to fully discharge at its fastest sustainable rate.	Cells optimized for power can achieve full discharge in a few minutes without damaging the battery.
Electrical resistance	The internal resistance of these batteries is considerably lower than lead-acid batteries but high compared to a lithium-ion power battery. If they are charged or discharged at their maximum rate, more heat will be generated.	The electrode design parameters that lead to high power capability also yield very low cell resistance, so these batteries generate less heat, even during fast cycling.
Relative cost	These cells are less expensive to manufacture and are generally produced in higher volumes. Market reports touting lower battery prices in terms of $ / kWh are almost always referring to batteries of this type.	The electrodes in high power cells are more difficult to manufacture and have additional cost drivers in the design. High-power batteries are typically much more expensive for the same amount of capacity (measured in kWh).

Figure 3. *Trade-offs involved in optimizing lithium-ion cells for power and density.*

For a UPS application, the key design objective for the battery manufacturer is to provide the required runtime at the lowest possible cost. As a result, most UPS solutions in the market today tend to use cells that are more optimized for energy density and cost and don't usually employ cells that are inherently more capable of fast discharges. This also means that the chosen lithium-ion cells don't have the lowest possible internal resistance and tend to experience considerable temperature increases when they are discharged in less than 10 minutes.

When analyzing runtimes for a lithium-ion battery in a UPS application, it's important to understand the characteristics of the cells being used because the end of discharge could be caused by the battery reaching minimum voltage, the battery reaching maximum temperature or the battery running out of energy due to its capacity limitations. In many cases, the condition that causes the discharge to end is also different at different loads.

Projecting runtime ten years in the future adds yet another level of difficulty. Contrary to popular belief, remaining capacity in the battery as it ages may not be what limits your runtime, particularly at high loads. In addition to losing capacity, lithium-ion batteries also experience increases in their internal resistance over their life and this leads to larger voltage drops and more self-heating than when they were new. As a result, the battery manufacturer should know not only how capacity declines but also how resistance increases according to the battery's operating history and number of years in service.

Although runtime analysis for lithium-ion batteries can be complex to get right, users generally don't face the risk that the battery might suddenly give them half the runtime they were expecting or were promised by the specifications. According to IEEE recommended practice on VRLA batteries (1188), lead-acid batteries need to be replaced when they reach 80% of their original capacity. That's because the remaining capacity falls off very quickly after that point. That failure mode doesn't happen with lithium-ion technology which tends to fade gradually and predictably.

Lithium-ion Battery Safety

Lithium-ion batteries have a few known conditions that can lead them to ignite or release gases if the internal pressure gets too high. Knowing these risk conditions and controlling them is the purpose of the battery management system (BMS).

For any product with safety relevance, good system integration practice starts with understanding the probability and severity of each potential failure mode. In the case of lithium-ion batteries, the riskiest abuse conditions are generally overcharge, overheating and short-circuiting of the battery cells. Each of these conditions can cause the electrolyte in a lithium-ion battery to decompose into gases or, in extreme cases, to ignite.

While some battery manufacturers make claims about the safety of their batteries based on the chemistry used in the cathode or anode, lithium-ion battery failures almost always start in the electrolyte and virtually all cells that are commercially available today use a flammable electrolyte. This is not to say that the chemistry of the cathode and anode do not influence battery safety. Those material choices can drive significant differences in the intensity of a failure, but it would be wrong to suggest that any lithium-ion cell is immune to the risks of abusive operating conditions.

To characterize any cell design's response to abusive operating conditions, the lithium-ion industry has developed a series of tests to assess safety risks. The most well-known of these is the nail penetration test. The purpose of a nail test is not to assess the effects of physical damage to a cell. The nail is inserted through all the electrodes because this causes an immediate short circuit across the entire cell. The resulting energy discharge is extremely fast and leads to the nail becoming so hot that it will ignite the electrolyte in a poorly designed cell.

Other tests are used to study the effects of other failure modes and when all the cell-level abuse tests are complete, the system integrator can determine the operating limits that ensure safe operation of the system.

The primary purpose of the BMS is to implement controls that keep the battery within its safe operating range. This involves continuous measurement of cell voltages, system temperatures and battery current in addition to other parameters.

When the BMS senses that the battery is approaching one of its operating limits, a warning is communicated to the connected power device such as a UPS. If the UPS doesn't react appropriately to keep the battery within its permissible operating boundaries, the BMS can disconnect the battery from the load or charger to maintain safety. The functionality and effectiveness of the BMS itself are also verified by the testing necessary to achieve UL or CE certification of the battery system.

Since the BMS plays such an important role in the safety of a lithium-ion battery system, redundancy within the BMS itself is an important design consideration. For example, many BMS designs have a hardware circuit that will operate the battery disconnect if there's a software malfunction in the BMS's processor. Key sensor values are also often measured in multiple ways and compared to confirm that the measurements are reliable. Finally, the UL1973 requirements for using lithium-ion batteries in a UPS application requires a functional safety analysis of the BMS design. Functional safety analysis is a systematic means of ensuring a control system behaves as intended and the principles have been applied in the aviation industry for more than 20 years. While these safety assurance methods are relatively new to data center equipment, there's no doubt that certified BMS designs are built on a very solid foundation of reliability.

Some operating thresholds in the BMS also consider more than just safety. In UPS applications, the thermal limit of the battery is a good example. Generally speaking, the BMS in data center applications has a temperature limit which is well below the level necessary to ensure safety because life considerations are also involved in setting that threshold. Therefore, a case of the BMS disconnecting a battery does not necessarily mean that safety was in question.

While a well-engineered BMS provides a high degree of confidence regarding lithium-ion battery safety, the one significant risk that it can't control is the battery being in the presence of fire. It's impossible to guarantee that a lithium-ion battery cabinet will never be in a building that catches fire for reasons that have nothing to do with the battery. This reality has recently driven the considerable expansion of fire codes related to lithium-ion batteries.

The Impact of Fire Codes on Lithium-ion Battery Deployment

In some parts of the world, recent fire code changes have brought increased attention to battery safety. In particular, the National Fire Protection Association (NFPA) in the United States has been driving new regulations which are gradually being adopted in various jurisdictions. While these initiatives should be applauded for their intent to ensure safety and weed less robust solutions from the market, the initial versions are not without their issues.

The new NFPA fire standards seem to be based on the assumption that lithium-ion battery fires are inevitable and show little awareness of the means battery manufacturers have for making lithium-ion batteries more resilient to abusive operating conditions.

To gain perspective, consider the development of lithium-ion batteries in the automotive market which was an early adopter of the technology. More than a decade ago, the automotive industry defined a series of safety tests for lithium-ion batteries and established clear pass / fail criteria. At the time the tests were established, many battery designs struggled to pass but the existence of stable requirements ultimately drove every battery manufacturer to comply or leave the market.

Today, stationary battery applications benefit from the safety developments already driven by the auto industry. At the same time, it's necessary to acknowledge that there are still lithium-ion battery designs in the market that cannot pass the more rigorous safety tests.

The greatest challenge with the evolving fire standards for stationary batteries, particularly in the U.S., is that some of the tests require the battery manufacturer to apply whatever means are necessary to ignite a battery fire, regardless of how extreme those conditions might be. In most cases, a fire is very difficult to start without first disabling the BMS.

It would be reasonable to expect that cells with stronger abuse tolerance or systems with better BMS functionality would be rewarded for their better safety performance but the initially specified fire tests for stationary applications don't consider the probability of a fire actually starting in a real application. They only require that a fire be started by any means necessary and then to observe the degree to which the resulting fire spreads. If a manufacturer cannot demonstrate through a UL9540A large-scale fire test that their system design prevents a fire from spreading, each battery cabinet must be installed with three feet of clear space on all sides, which effectively negates the floorspace benefits of that particular lithium-ion product in relation to lead-acid batteries.

Although these fire code requirements are still maturing, it is technically feasible to develop systems with today's lithium-ion cells that will prevent a fire from propagating outside its battery cabinet and those solutions will be rewarded with footprint advantages compared to others that must accept three feet of clear spacing. Over time, the regulations can be expected to stabilize and the better-performing solutions will likely gain market share.

Lithium-ion Battery Monitoring

The BMS in a lithium-ion battery system is continuously monitoring numerous operating parameters to ensure safety. Since all this operating data is already stored in BMS memory, it is relatively simple for the BMS manufacturer to make the data available to external systems via a Modbus IP connection or some similar data acquisition protocol. This is a key advantage of lithium-ion batteries over lead-acid systems where any monitoring system needs to have its sensors installed.

When deciding what battery parameters to monitor externally, care should be taken not to record everything that the BMS makes available because valuable insights can be lost in excessive amounts of data.

Take battery cell voltages for example. In higher voltage battery systems, there are typically more than 100 cell groups for which the BMS has a voltage measurement, but the individual values are far less important than the consistency among all of those values. In some cases, the BMS will also provide the maximum and minimum cell voltages across the whole system and it's the difference between these two extremes that can provide a better indication of the battery's condition.

No current standards are governing what BMS data is available to an external monitoring system so it's impossible to define a monitoring strategy that will work in every case. Generally speaking, temperature data is meaningful, and data collected during a discharge or recharge event is much more valuable to assessing battery health than the operating data when the system is idle.

Additionally, some BMS models provide a state-of-health (SOH) variable which is the control system's overall assessment of where the battery is in its useful life. However, don't put too much trust in the SOH value without knowing how it's calculated because different BMS solutions in the market have substantial differences in the sophistication of the algorithm used to compute that value.

Finally, the best way to monitor a lithium-ion battery system in a data center also depends on how well integrated the BMS is with the UPS controller. There are operating advantages to the increased sharing of operating data between these two controllers and, in cases where a tighter integration has been achieved, it may be possible to monitor key battery data through the monitoring interface of the UPS.

Installation, Maintenance and Disposal

Some lithium-ion battery systems can be shipped mostly assembled while others require assembly on site. Purchasing a packaged system can save on installation costs and time.

The battery modules themselves should arrive factory tested but they may not all be at the same state of charge when they are delivered. The best practice is to give the BMS time to balance the voltage of all cells before commencing functional tests. Also, ensure the batteries are installed in a stable ambient temperature long enough to be thermally consistent as measured by the BMS before running a test discharge or charge cycle.

In general, maintenance frequency is lower for lithium-ion batteries compared to lead-acid batteries because the remote monitoring capabilities of the BMS enable condition-based maintenance and replacement. Degradation is also more predictable so the risk of a sudden drop in capacity is minimized.

Also, the terminals on a lithium-ion battery module are not subject to distortion as is the case with terminals on lead-acid batteries so retightening of the connections is not a persistent need. Your selected lithium-ion battery integrator should provide specific maintenance protocols based on the design of the system.

Lithium-ion batteries are recyclable and recycling costs are largely driven today by the disassembly process required to extract the cells from the overall construction. Recycling processes are steadily becoming more effective at extracting the valuable materials from a lithium-ion battery, improving the profit potential of recycling. This could drive costs down in the coming years.

While it's impossible to predict future costs, the lithium-ion recycling industry will be more mature by the time the current generation of lithium-ion batteries reach end of life and continues to benefit from the scale and experience of the automotive industry.

Making the Move to Lithium-Ion Batteries

Lithium-ion batteries have reached a stage of maturity where they can be considered as a viable replacement for lead-acid batteries in UPS applications. Despite the lack of operating data available, calendar life testing indicates that lithium-ion batteries can deliver a significantly longer life than lead-acid batteries without an increased risk of failure when capacities fall below 80%. In addition to ensuring safety, lithium-ion battery management systems can help maximize battery life and minimize downtime by enabling continuous monitoring that supports condition-based maintenance. An experienced integrator can help you evaluate the total cost of ownership for lithium-ion batteries compared to lead-acid batteries for a particular application.

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