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The Comparison of Valve Regulated Lead Acid and Lithium Titanate Batteries for UPS Applications

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Abstract: Uninterruptible Power Supplies (UPS) have evolved over the years to become increasingly more efficient in terms of their energy usage and footprint, but batteries, essential components of this back-up power system, have not been updated with the latest technology for several decades. This paper aims to highlight the differences in performance of valve-regulated lead acid (VRLA) and lithium titanate (LTO) batteries with respect to their discharging rate, cycle and shelf life, safety, and specific energy in an UPS application with the goal of demystifying the battery selection process between these two options so that customers can make informed choices.

Introduction: Lead acid batteries have dominated the UPS application landscape for several decades and are the archaic default for most applications. However, given the advancements in lithium-ion battery development, specifically with LTO cells, it is worth considering what these cells could offer to the end users and how they could revolutionize the market. For the purposes of specificity, this paper shall focus on VRLA and LTO offering for a short duration (less than 15 minutes) UPS application and compare data from an unspecified VRLA manufacturer and Toshiba's SCiB LTO battery. All data, figures, and numbers cited in this paper have been measured empirically.

Background: To be able to accurately compare these two different chemistries, it is necessary to understand how they are called into service, how they are manufactured, how the requirements on them are applied, and why they have come to be as they are. Since VRLA batteries predate lithium batteries by more than a century, most of the requirements in the industry have been set up according to the specifications and short-comings specific to the VRLA battery. The background of the LTO battery shall be considered first, followed by VRLA's background and finally a quick overview of the UPS market as it stands today.

There have been several LTO manufacturers who have tried to innovate and establish themselves in the market. Most manufacturers have faced difficulties in developing LTO cells due to the hefty capital investment, the high degree of technical know-how, and the meticulous monitoring and control of the delicate manufacturing process. LTO manufacturing is especially tricky when trying to manufacture in a pouch cell format given the outgassing issues arising out of stringent purity requirements of the anode material and the electrolyte. Hence, few manufacturers remain in this niche and as a result this chemistry sees limited exposure to UPS applications. Yet, LTO chemistry has proven itself to be a leader in fast charge and discharge applications such as start-stop in passenger vehicles and frequency regulation for utilities. Extrapolating off of this performance, LTO seems to be the ideal lithium-ion candidate for short duration applications.

Since their inception in 1859 at the hands of French physicist Gaston Planté, lead acid batteries have found their way into myriad applications and have changed form several times since. Today, they can be widely broken down into two categories: VRLA and flooded or sealed lead acid (SLA) batteries. A relatively recent development has been the absorbent glass mat (AGM) lead acid batteries and these can fall into either of the above mentioned categories depending on their construction. AGM batteries typically involve less maintenance and are more expensive. However, lead acid batteries are reaching saturation in terms of potential advancements and improvements. There are established manufacturers who have been in place for decades and advancements are limited to increasing surface area of lead plates or the absorbency of glass mats.

In fact, lead acid batteries have been the immutable standard for so long that people have forgotten the reason behind why 10 minutes is considered the standard back-up requirement or why it is prudent to have an n+1 redundancy built into the design. The archaic 10 minute back-up time requirement was derived as a rule of thumb by those who understood VRLA degradation, in that 8 minutes beginning of life capacity would translate to 4 minutes at the end of life for the battery. This degradation in capacity coupled with the Coup de Fouet effect, renders VRLA batteries unable to provide the required kW needed to support the load if the initial battery runtime was below 10 minutes. As a refresher, Coup de Fouet is the observable drop in battery voltage when the batteries are called into service. This phenomenon ranges from a few milliseconds to a few seconds depending on the battery chemistry, the state of health, the state of charge and the sizing of the load in comparison to the battery. Typically, as the battery ages, this effect becomes more prominent and severe. In terms of UPS applications, if the generators are unable to come online in 2 minutes, then it is doubtful that they would come online at all in time to avoid dropping the load. Hence, the 10 minute back-up time VRLA requirement shields an actual 2 minute back-up time requirement that VRLA cannot meet. On the other hand, LTO chemistry need not be as grossly oversized and does not suffer from Coup de Fouet to the same extent. However, customers continue to conflate this issue with runtimes and to worry about outage scenarios where a longer back-up runtime would be beneficial. Such fears are unfounded as the 2003 publication from Berkeley National Laboratories shows that over 67% of total cost impact by power interruptions is caused by momentary interruptions, those lasting less than 5 minutes, which are more frequent than sustained interruptions, those longer than 5 minutes. In fact, when looking at total incidences of power quality and downtime, the data is skewed more in favor of short outages, power sags or fluctuations from the utility lasting shorter than 10 seconds; 96% of all incidences affecting commercial and industrial applications are short outages. Hence, battery back-up should ideally provide only a few seconds worth of power; enough to provide the generator and back-up generator two chances to come online. This adds up to be between 45 seconds and 90 seconds, depending upon the availability of a redundant generator, and can be easily provided by a two minute battery. Thus, an ideal setup with an UPS and generator only needs the batteries to provide 2 minutes of back-up runtime, thereby minimizing the battery requirement and the footprint utilized.

Similarly, strings of lead acid batteries continue to fail when called into service, especially as they age and the load is higher than normal, so an n+1 redundancy is, in fact, a necessity. Lithium batteries do not suffer from the same issue and can be called into service in a matter of 10 milliseconds, namely in grid connected ancillary services and auxiliary power applications. VRLA cells suffer from several short-comings such as Coup de Fouet effect, memory effect, and an accelerated degradation of capacity (as compared to lithium based chemistries), making it essential to oversize the batteries to meet the requirements of the application. As a side note, memory effect is the physical effect whereby batteries are able to “remember” suppressed capacities owing to ambient conditions and then fail to recover capacity when those conditions return to normal. However, lead acid batteries are inexpensive and hence find use in applications where other chemistries may not be financially feasible.

As seen from the above exposition, the two chemistries in consideration are vastly different and as a result have differing properties. We will look at a few important properties and see how this has an impact on the application in the next section.

Chemistry Comparison: Lithium-ion batteries are more energy dense, lighter, and discharge faster than VRLA, and LTO is no different. However, lithium chemistries differ in how safe they are, how long they can last, and the temperature ranges in which they can operate. LTO is leagues ahead of its lithium-ion peers in these arenas and is more power dense compared to other lithium chemistries, but that is a discussion for a different paper. Please see the following chart for an overview of the properties and costs of VRLA and LTO batteries:

Chemistry	VRLA	LTO
Cost Comparison	X	2.5X
Cell Voltage	2.4V	2.3V
Specific Energy	40Wh/kg	90Wh/kg
Charge rate	0.5C	7C*
Discharge Rate	1C	7C*
Cycle Life	200	15000
Operating Temp.	10° to 30°C	-30° to 55 °C

Table 1: Chemical Properties of LTO and VRLA cells

As seen on the previous page, VRLA costs less compared to LTO. To be precise, LTO is 2.5 times the cost of VRLA. There may be some variance in price which arises out of different configurations, run-times, and heat dissipation requirements; however, that is the only area where VRLA fares better than LTO. LTO energy density is 90Wh/kg compared to VRLA's 40Wh/kg, which means that LTO is more than twice as energy dense as VRLA. This distinction holds true on a volumetric basis as well and is the reason behind the smaller footprint and lighter cabinets. For example, a LTO battery cabinet supporting a load of 2MW for a 2 minute runtime will weigh less than 14,000 lbs., while a VRLA battery cabinet supporting a 2MW load with 5 minute runtime will weigh 55,000 lbs. This comparison may seem skewed to some given that LTO is being measured at a 2 minute runtime, while VRLA is being measured at a 5 minute run-time. The reason for this is because VRLA cannot support a 2 minute runtime over a 6 year period without being grossly oversized. However, even if LTO were required to provide a 5 minute runtime, it would weigh less than 28,000 lbs., making close to half the weight of the comparable VRLA battery cabinet. This reduction in weight is often the savings in terms of floor loading and the ability to have battery rooms vertically distributed in urban landscapes. Another notable difference is the C-rate between the two; we find VRLA at or below 1C while we find LTO at 7C. C-rate, is the inverse proportion of nominal battery capacity and the time taken to charge (or discharge) that capacity. Hence, we can see that LTO is capable of discharging the battery at a rate 7 times that of the VRLA discharge time. For UPS applications, this means that you can reduce the installed capacity of battery needed for a shorter run time. For example, a 5 minute run-time would require a 12C rate or a 6C rate cabinet paralleled with another 6C rate cabinet, which would translate to a 6:1 ratio for LTO in terms of kW:kWh; whereas, VRLA would only be able to perform at best at a 1:1 ratio. This means, that VRLA would need to be oversized 6 times for a 5 minute run-time as compared to LTO. Once we factor in the price differential between the two chemistries, we can see how LTO would be at par or better than VRLA cost for smaller run-times. Similarly, cycle life for LTO is orders of magnitude more than that of VRLA. This means that all the burdens of having to replace the batteries every 5 to 7 years would cease to be a concern for facility

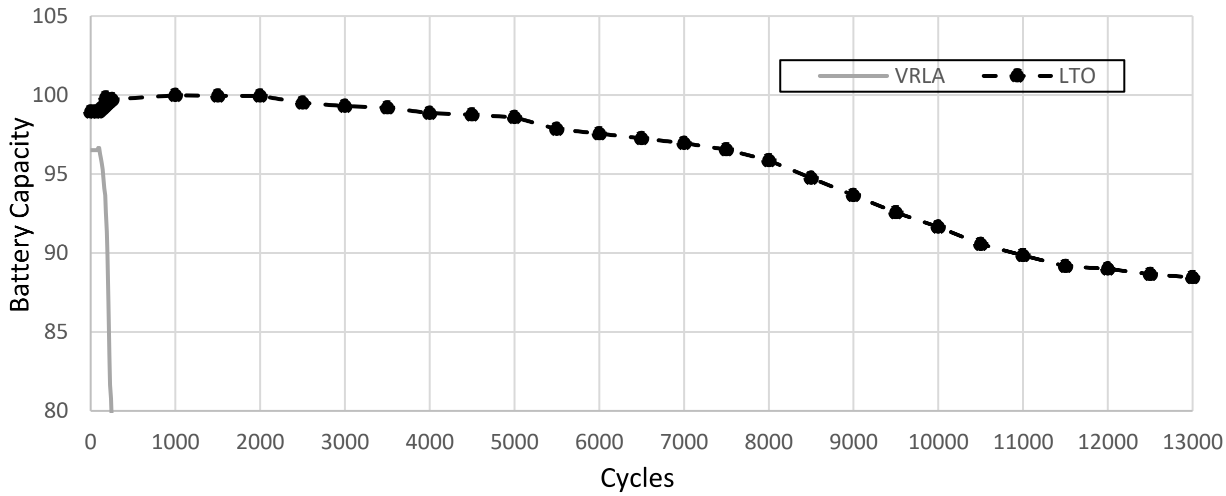

Figure 1: Life Cycle Comparison of LTO and VRLA**

managers. Additionally, LTO batteries can be left untouched for 1.5 years from date of shipment before any attention is required, while VRLA batteries will be fully discharged within a matter of months. Lastly, in terms of ambient temperature, VRLA batteries have a 20° range, but when the ambient temperate deviates more than 5°C from 25 °C, the life of the battery is significantly impacted. Although, this was not measured in lab, it was found from sources that such deviations can cut the VRLA life in half. LTO cells saw negligible cycle life degradation in the allowable range. Hence, we can see that LTO fares much better than a VRLA by requiring a smaller footprint, reducing the kWh capacity required to support the same load and run-time, and having a significantly longer cycle and shelf life.

Other Considerations: Although, most of the user and application requirements are covered in the sections above, there is another salient feature of LTO that VRLA cannot match: safety. There is significant concern about the safety of lithium-ion chemistries after a string of incidents involving flaming phones, laptops, and vehicles. However, LTO is the safest lithium chemistry that has been commercialized as it does not have carbon as the anode material, which is the culprit behind thermal runaway based fires. Instead, LTO is utilized as the anode material and a different lithium compound as the cathode material, eliminating carbon from the reaction. This eliminates any carbon from the anode to cathode reaction, thereby insulating LTO from overcharge and deep discharge thermal runaway conditions to which other lithium chemistries are prone. This safety blanket is further fortified by battery management system (BMS) that is internal to lithium ion batteries, which have fail-safes and protective functionality at each level of the hierarchy. This has the added advantage of remotely monitoring the state of the LTO batteries. Most lithium chemistries experience some sort of thermal event between the temperatures of 150° to 300° C, while LTO displays no outgassing or fumes in that interval. On the other hand, VRLA is prone to thermal runaway even at room temperature and requires constant up-keep. Having LTO replace VRLA would not only make sites requiring containment and special battery rooms safer for the employees working there, but also make the task of maintaining the battery easier.

Conclusion: There are several applications where VRLA may still be a viable option, particularly when the payback period is shorter and when capital expense are prioritized over operational expenses. However, it is evident that LTO chemistry has several advantages as compared to traditional VRLA chemistry; specifically, C rates, cycle and shelf life, safety, and specific energy. With all these benefits to the customer, LTO becomes the clear winner over VRLA for short run-time UPS applications.

* 7C is the measured rate for a 24 cell module in a UPS application. The continous C rate for the 2.3V 23Ah LTO cell was measured at 8C, while the peak C rate was found to be 24.5C.

** Full depth of discharge and recharge cycles were used to measure cycle life. VRLA capacity fell below 80% beginning of life capacity after 240 cycles. From earlier observations, it is known that LTO cells did not drop below 80% beginning of life capacity until after 17,000 full cycles.

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Figures and tables:

Table 1: Chemical Properties of LTO and VRLA cells

Figure 1: Life Cycle Comparison of LTO and VRLA