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Low Temperature Operation of Lithium Start Batteries

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ABSTRACT

The department of defense currently uses a number of models of vehicle start batteries with the "6T" form factor. These batteries are typically found in almost every vehicle in the DOD fleet and other systems that require 28VDC power. The use of power and energy on the battlefield is significantly changing and the Warfighter now requires a "start" battery that is used for more than just starting, lighting and ignition (SLI) for the vehicle. Lithium ion battery technologies are showing great promise in addressing these challenges by providing higher power capability for extended silent watch, battery monitoring and extended cycle life. One concern, however, is their ability to operate at low temperatures.

One of the most challenging aspects of battery use in military applications is their operation at extreme high and low temperatures. These wide temperature swings can potentially have a dramatic effect on cycle life and performance. One significant concern, especially for lithium ion technology, is the ability to provide sufficient cold cranking amps (CCA) and maintain their overall performance, including vehicle starting. Other important considerations at low temperature are the operation and accuracy of the battery monitoring system, whose electronics could potentially be sensitive in these operating conditions.

There are a number of ways to effectively mitigate cold weather operational risk, which include the use of advanced battery materials (anode/cathode material or electrolyte) or integration of heating systems within the battery. This paper will discuss the challenges for lithium ion batteries at low temperatures as well as present, with data, some effective means of overcoming this obstacle while not significantly impacting cost. To demonstrate the performance of lithium ion at low temperatures, data from cold chamber testing using the A123 Lithium Ion start battery will be presented.

INTRODUCTION

As electronics become increasingly important on the battlefield, vehicle batteries that were designed for engine start and providing minimal lighting during engine off are now being used to provide increasing loads when the vehicle engine and generator are off. Communications, jammers, sensors and other critical components all need to be kept running throughout a mission. In many cases this includes the need to power these loads for extended periods of engine off for silent watch scenarios.

Lithium Nanophosphate batteries provide a solution to many of the issues this raises. While lead acid batteries are typically rated for a capacity at a C/20 rate and the capacity decreases as the rate the energy is used increases (a result of Peukert's law), Lithium Nanophosphate is significantly less impacted by this effect and can continue to provide closer to rated capacity even at higher C rates.

Battery management systems are often included as part of advanced battery chemistries such as Lithium Ion. These battery management systems provide the warfighter with accurate information about the battery state of charge so that batteries can be used with confidence that there is enough power remaining for an engine crank at the end of silent watch.

Lithium Nanophosphate also provides a longer cycle life than lead acid batteries, meaning that each battery can be used for more silent watch and/or engine cranking when using this chemistry. This longer battery life provides a life cycle cost advantage and reduces required maintenance.

One drawback to Lithium Ion chemistries is a higher sensitivity to temperature extremes than lead acid batteries. Exposure to high temperatures can result in a reduction of battery life, partially offsetting the longer cycle life advantages of the chemistry. At extreme cold temperatures lithium ion chemistries often see a reduction in power availability, reducing the cold cranking amperage available for an engine start. Heaters can be added to offset this performance reduction but then several integration concerns need to be considered.

LITHIUM ION AND TEMPERATURE

Often times as we read specifications for "widgets" we look to see how well they perform. Often times these "widgets'" outstanding performance has a number of caveats, one being, "at room temperature". To really understand how well that "widget" works in your given application, its operation must be understood not only at room temperature, but also at the realistic temperature.

Figure 1 shows a depiction of some common temperature windows for various targeted systems. It is important to note that other than NASA and the drilling industry, the Military temperature band is one of the widest. This often creates problems for batteries of all types. Some technologies are better at one end of the spectrum, or the other, but operation through the entire window must be considered from a total system approach. For instance, if you know your technology works well at high temperatures, but not so well at low temperatures, you have a couple of options. First option would be to use a different technology. Second option would be to include "external" features to your technology to accommodate the deficiency at the extreme temperature range.

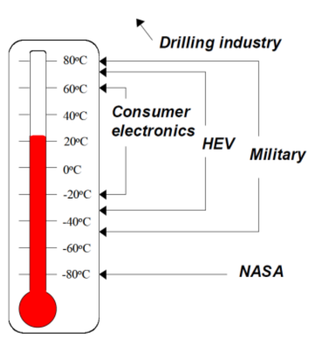

Figure 1. Typical Battery Operating Ranges [2].

High Temperature Impact on Lithium Nanophosphate

Lithium Nanophosphate typically works very well (electrical performance) at higher temperatures, up to a point. Figure X shows typical performance data for A123's AHR18700 F1 high power cell. This cell sees a drastic increase in specific power as temperature increases. However, these increases in electrical performance often come with trading battery cycle life, which needs to be factored into your design. Often it is not just the ambient operating temperature that needs to be considered, but the self heating of the battery in its environment (IE: in a battery package) plus the ambient temperature of the environment that dictates the negative effects.

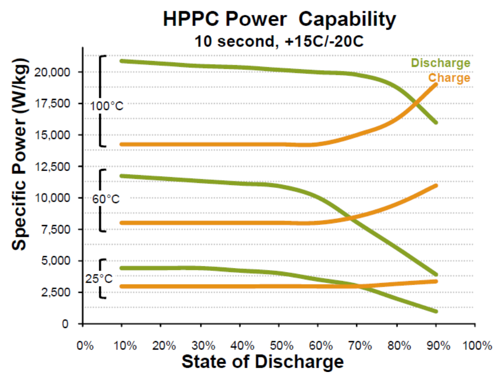

Figure 2. A123 18700 F1 cell Power Capability vs. Temperature.

As high temperatures reduce battery life it is important to realistically specify the environment batteries will be used in. This should take the form of specifying the maximum temperature the battery will see and providing a histogram of time to be spent at each temperature range.

While many climates see temperatures as high as 50 degrees Celsius, this temperature is usually experienced for only a few hours a year. This short time spent at high temperature means the impact on battery life will be reduced. As an example the yearly temperature histogram for the Baghdad airport is below. Only a very small portion of the year is spent at temperature above 40 degrees Celsius.

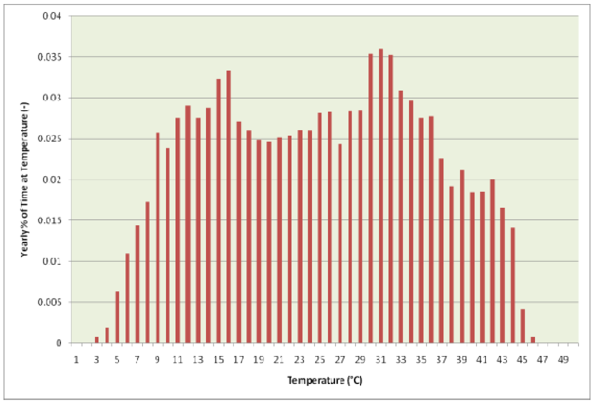

Figure 3. Typical temperature histogram used for evaluating battery performance.

It is very important that a battery can survive and operate in maximum expected temperatures, but the time spent at these extreme high temperatures is small enough that impact on battery life is minimized.

High Temperature Mitigation Strategies

There are a number of ways to mitigate the negative effects of high temperature on lithium ion batteries. The most obvious is to apply some sort of cooling method to ensure the battery stays within the operating temperature. Although this sounds like a complicated solution, integrating this from a systems approach has a number of impacts. Inclusion of fans potentially decreases the overall reliability of the system and integrating a cooling loop could have impacts on the size, weight and complexity of the total solution. These things need to be considered if this approach is utilized.

Another method that is very less invasive is to "just live with it". Lithium Ion batteries (particularly Nanophosphate) have outstanding cycle life, and although the cycle life will be decreased in high temperature, it still may be better than the solution it is replacing. This method, however, is only effective if the proper analysis is performed.

Finally, by taking a system approach another mitigation method that can be considered. For instance, the battery can be incorporated into a conditioned crew compartment (where it is cooler) instead of in the engine compartment if high temperature is a concern. This, too, may take some analysis, and may have some system level impacts, but good systems engineering will allow for this solution to be effective.

Low Temperature Impact on Lithium Nanophosphate

Figure 4 shows the impact on cycle life of the AHR18700 F1 cell (shown in the previous section) in regards to cell temperature. It clearly shows that at lower temperatures (in this case the lowest temperature provided is Room Temperature), the cycle life is much better. However, at low temperatures, most lithium ion electrolyte materials become very viscus and demonstrate low lithium ion transport properties [2]. In other words, at low temperatures, the power capability of some lithium ion batteries are not as good as some other chemistries.

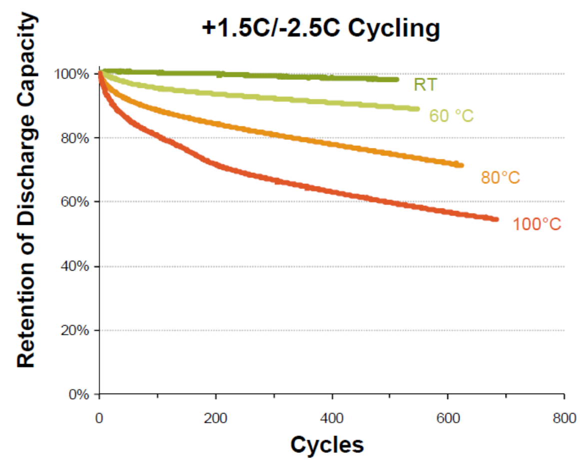

Figure 4. Impact of temperature on cell life, AHR18700 cell

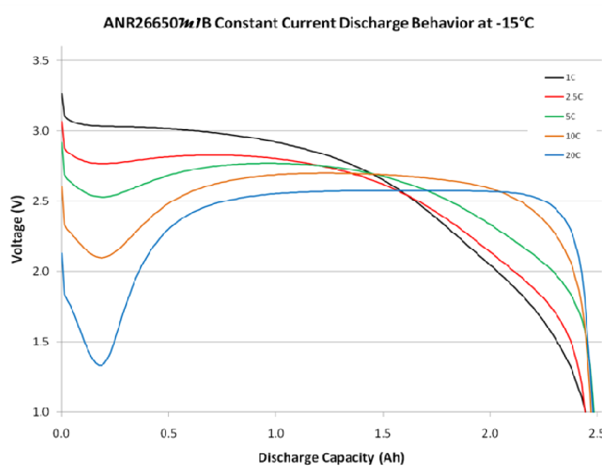

Figure 5. Low Temperature performance of ANR26650 Cells.

In the case of lithium start batteries for vehicles, at room temperature (and often elevated temperatures) there is a potential for significant increase in cycle life and power density, but trading that for performance at extreme low temperatures. This basically says that an increase in cycle life has the potential of reducing the life cycle cost of the battery (and eliminate early battery failure that requires significant logistics to replace), with potential shortcoming in cold cranking Amperage. Figure 5 is representative of the performance impact for cold cranking potential of Lithium start batteries (in this case A123 26650 cells at -15C). Under these conditions (and below -15) the system integrator must determine if this can meet their application need or if other mitigation strategies are warranted.

Low Temperature Mitigation Strategies

There are a number of ways to mitigate the negative effects on Lithium start batteries at low temperature. One method that will continually gain attention is the research and development of the batteries themselves. This would include low temperature electrolytes, suitable active materials and optimum design of electrode morphology [3]. Often implementing some of these advanced solutions presents some drawbacks that could potentially include reduce life and stability at elevated temperatures, or significantly impact manufacturing cost.

One common method for mitigating the negative effects of lithium ion batteries at low temperatures is the use of external heaters. In this case, a ceramic or thin film heater is integrated into the battery body design and utilizes the energy the battery is able to provide at this temperature (often along with self heating) to warm the battery for a designated warm-up period. Often times the warming period depends on the battery chemistry and design and must be coordinated through some sort of system supervisory controller in order to ensure the battery is not unnecessarily depleted. This can often be a very impactful mitigation method without significant impact on manufacturing cost.

A third method commonly used to mitigate negative effects at low temperature is combining multiple energy storage technologies to take advantage of their properties and realize an effective total solution. One common method that is often presented by researchers is the use of capacitors or ultra-capacitors with lithium ion batteries [4]. In this case, ultra-capacitors exhibit outstanding power performance (even at low temperatures), but lack significant energy (compared to the battery). Using the ultra-capacitor in conjunction with the battery allows the capacitor to bear the power load during starting and does not significantly impact the solution (other than added cost and complexity) during other operating conditions.

One thing that must be considered when using all mitigation methods is ensuring the electronics package (if the battery uses one) can endure the low-temperature. If the battery includes a battery management system (for balancing, safety and battery status), this system often needs to be functional at the low temperature to communicate with the battery to determine battery status prior to starting. Careful component selection and sound mechanical design will ensure the system integrator is successful in extreme cold environments.

The electronics and the connections inside the battery also present a resistance within the battery that reduces power at all temperatures. System design to minimize the losses within the pack will help maximize the cranking amperage that can be delivered.

A123 Nanophosphate EXT

A123 Systems recently introduced Nanophosphate EXT, a new lithium ion battery technology designed to maintain long cycle life at extreme high temperature and deliver high power at extreme low temperatures.

EXT is based on A123's proprietary Nanophosphate lithium iron phosphate chemistry, which offers high power, long cycle life, greater usable energy and increased safety as compared to competing battery technologies. Nanophosphate EXT extends these capabilities over a wider temperature range.

Specifically, Nanophosphate EXT is designed to deliver 20 to 30 percent higher power than standard Nanophosphate with two to three times longer cycle life than typical lithium competitors. A comparison of Nanophosphate EXT with standard A123 Nanophosphate is presented in figure 6.

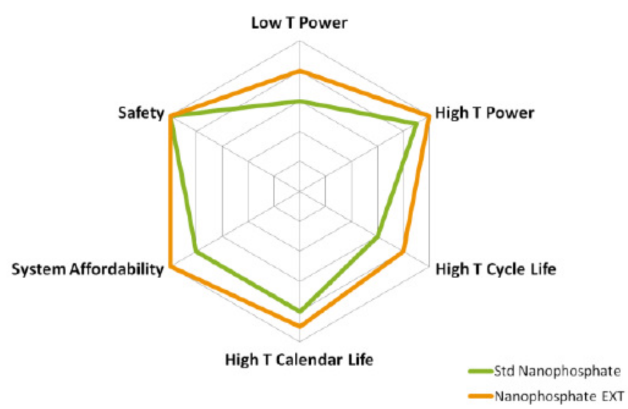

Figure 6. Nanophosphate EXT advantages

Figure 7 shows the results of 1C-1C 100% depth of discharge cycling testing conducted at 45 degrees Celsius. These results are being independently verified by Ohio State University's Center for Automotive Research (OSU-CAR) as shown in the figure.

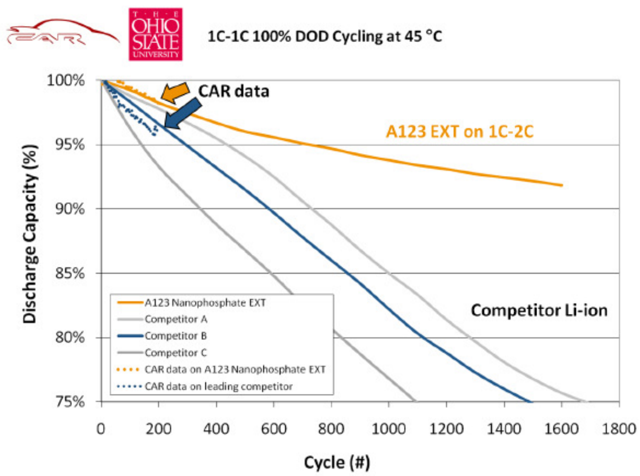

Figure 7. Nanophosphate EXT cycle life testing

In order to compare Nanophosphate EXT performance with existing lead acid absorbed glass mat (AGM) battery performance, 30 second cold crank tests were conducted on batteries after they were left overnight in a cold chamber at both -18 degrees C and -30 degrees C. Two different AGM batteries, one rated for a 70Ah capacity and one rated for an 80Ah capacity were compared against Nanophosphate EXT (shown as E73 in the results) rated for a 60Ah capacity. It should be noted that the EXT test was conducted on a module only, so some small losses would be introduced by battery electronics. Also note that the EXT module is of a lower capacity than the lead acid batteries it is being compared to.

Results are summarized in figures 8 and 9. The battery cycler used for this testing has a maximum rating of 1000A, so some results are clipped where they would have exceeded this limit. As noted, cranks were conducted until battery voltage was pulled down to 7.0V minimum.

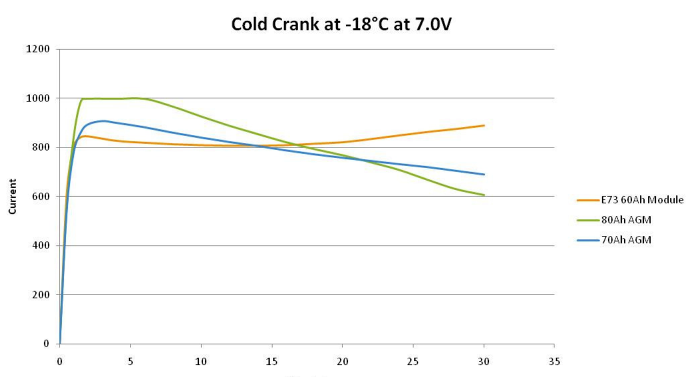

Figure 8. -18 deg C cranking capability

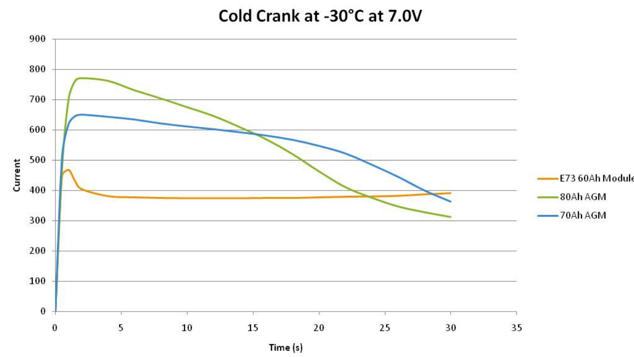

Figure 9. -30 deg C cranking capability

Another characteristic shown by these cranking tests is the ability of Nanophosphate EXT to hold or improve its delivered amperage throughout a crank event. While the AGM batteries decrease their amperage delivered throughout the 30 second crank event, EXT actually increases its current delivery as the crank event heats the cells.

Conclusion

Although we all wish that our applications were tested and used at room temperature, the reality of the matter is that we often have to operate at temperature extremes. The advantages and shortcomings of our technologies at these extremes needs to be fully understood so that not only can the systems integrator perform a trade study on the total solution, but so the user can feel confident that their system will work in the rugged conditions we often call reality.

This paper talked about the temperature effects of lithium ion batteries, particularly at low temperature. Lithium Ion batteries show a compelling case for life cycle cost and outstanding power and energy density with a trade-off for electrical performance at low temperature. There are a number of mitigation strategies that are often considered for every situation which include cooling systems and optimal battery placement for high temperatures and integrated heaters or advanced chemistries for low temperatures. The bottom line, however, is for the system integrator to perform a system level analysis and trade study to ensure they understand the strengths and weaknesses of each solution and use them to realize the best total system solution to support the Warfighter.

Cranking results were presented showing one possible approach to improving cold cranking capability through chemistry. A full system solution will likely combine this type of improvement with the other approaches presented.

Acknowledgement

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