PERFORMANCE OF PHOSPHATE LITHIUM-ION BATTERIES IN MOTIVE APPLICATIONS

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ABSTRACT

Do lithium-ion batteries have the performance to replace lead-acid batteries in electric vehicles, medical scooters, and other motive applications? Until recently, the motive industry has had to rely on lead-acid traction batteries for the energy storage solutions of electric vehicles, while still enduring lead-acid's shortcomings of low energy, poor cycle life, heavy weight and constant maintenance. This paper will illustrate the benefits of using phosphate lithium-ion as an alternative motive power source to lead-acid. Benefits of phosphate lithium-ion include longer run-time, lower total cost of ownership, maintenance-free, lighter-weight and safer characteristics than lead-acid batteries.

The session will also highlight a lithium-ion chemistry that replaces the traditional cobalt oxide cathode material with phosphate based cathode materials. This mass produced chemistry provides high energy density and safe operation essential to large format batteries. The paper will show that the well rounded characteristics of phosphate lithium-ion batteries can be used in many different markets including stationary float and motive cycling applications. In order to make phosphate lithium-ion batteries more affordable, the batteries should be attractive to a wide range of markets. Success in the mobility/motive markets will allow cost reductions in stationary battery markets and vice versa. For example, the same battery used for stationary float applications is used in the electric vehicle under test with high cycling requirements.

INTRODUCTION

A battery's performance is the most important factor of an electric vehicle (EV) or electric wheelchair's usefulness for a user.[1] Motive applications such as electric vehicles, electrical wheelchairs, medical scooters, and electric bicycles all benefit from a light-weight, high energy, and compact power source. These 3 aspects combine to extend driving range, which is the ultimate determination of an electric vehicle's performance and usability. Proven in the consumer electronics industry, lithium-ion batteries have advantages of small size, light weight and high energy and would be the ideal replacement for the commonly used lead-acid batteries. However, used in larger systems such as 360V, 35.8KWhr electric vehicle battery packs or even in smaller 24V, 624Whr electric wheelchair batteries, the need for an inherently safe lithium-ion solution is needed. The lithium-ion battery system must be able to perform in a safe manner while meeting all the charge/discharge requirements without concerns of thermal runaway or special charge regimes.

A phosphate lithium-ion battery has been shown to be much more thermally stable under abuse conditions.[2] The intrinsic safe characteristic of phosphates allows the creation of large battery systems, leveraging the strengths of traditional lithium-ion without compromising on safety. The need for an inherently safe chemistry is needed when batteries are subjected to harsh conditions or when they are placed in sensitive areas such as near a person (i.e. in an electric vehicle). Abuse conditions can always occur and can subject a battery to a condition in which various electronic safety circuits may not be able to prevent a thermal runaway.

DESCRIPTION OF BATTERY SYSTEM TESTED

The tested power pack consists of twenty-eight off the shelf phosphate lithium-ion batteries in series. The same batteries are also used in stationary float applications like solar telecom backup. Each phosphate lithium-ion battery is a BCI Group 24 sized battery with 12.8V nominal and 100Ah rating. Nominal system voltage rating is 358.4V with a total energy of 35.8KWhr. Battery weight of the power system is 823 lbs (375 kg). All phosphate lithium-ion batteries were installed in a battery tray designed originally for lead acid batteries for use in the electric vehicle as pictured in Figure 1. By using a phosphate lithium-ion battery with the same form factor and size as a standard lead-acid battery, it allowed a seamless and easy transition for the battery replacement. Having the same form factor and size, but with more energy and less weight, is a critical part of allowing phosphate lithium-ion technology to fully replace lead acid batteries.

Figure 1. Battery Tray for Electric Vehicle with 28 (Group 24) Phosphate Lithium-ion Batteries in Series

Figure 2. Electric Vehicle with 90KW AC Motor Controller and 6.6KW Integrated Charger[2]

STANDARD DRIVING CYCLE DESCRIPTIONS

Highway Fuel Economy Driving Schedule (HFEDS) Test Description

Standardized driving cycles are used to test the fuel economy and emissions of a vehicle. The driving cycle consists of a known pattern of velocity versus time data that is appropriate for the conditions being simulated. Highway patterns like the Highway Fuel Economy Driving Schedule (HFEDS) consists of varying speeds with zero stops as shown in Figure 3. Average velocity is 77.6 kph (48.2 mph) with a maximum acceleration of 1.5m/sec^2.

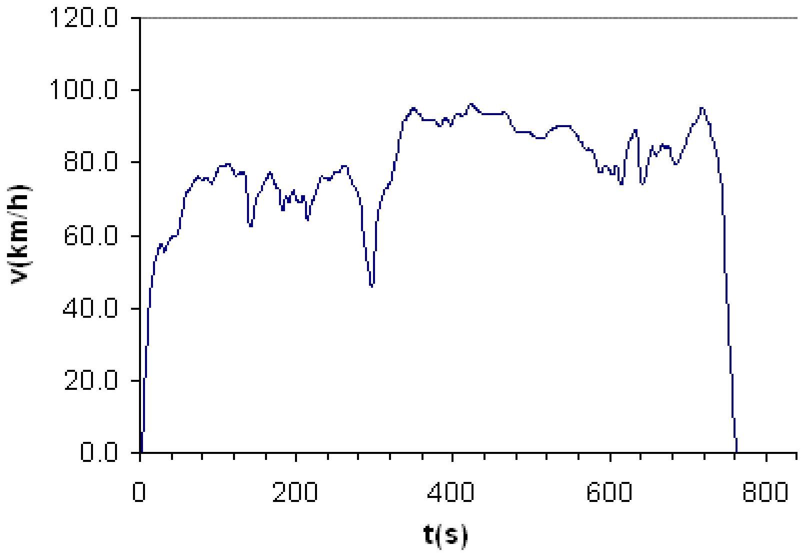

Figure 3. HFEDS Velocity versus Time

Urban Dynamometer Driving Schedule (UDDS) Test Description

An urban or city simulation consists of many stops and starts to pattern driving in heavier city traffic situations as shown in Figure 4. The Urban Dynamometer Driving Schedule (UDDS) has an average velocity of 31.4 kph (19.5 mph) with a maximum acceleration of 1.5 m/sec^2.

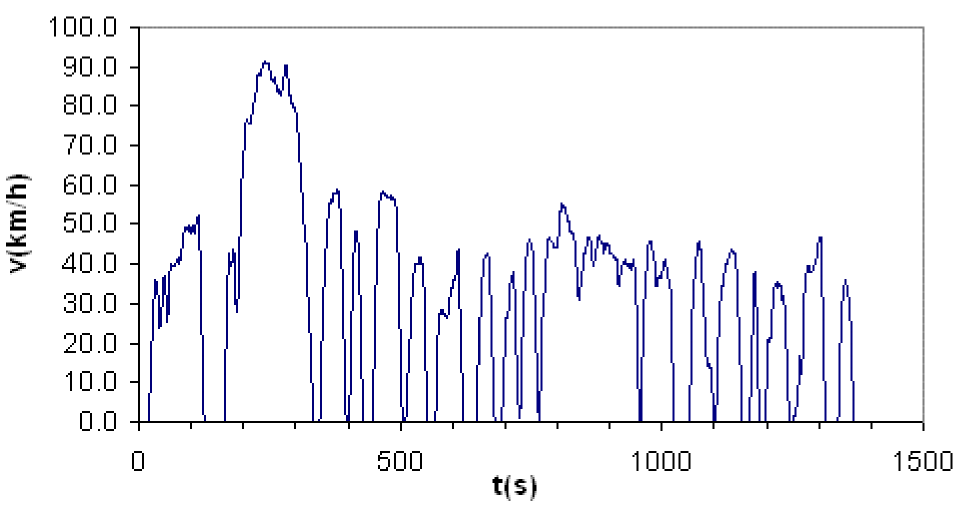

Figure 4. UDDS Velocity versus Time

HIGHWAY FUEL ECONOMY DRIVING SCHEDULE (HFEDS) TEST RESULTS[3]

After proper dynamometer calibration, the electric vehicle was driven on the dynamometer according to the specified pattern for the HFEDS test. This yielded the voltage curve profile in Figure 5. Voltage remained very flat throughout the test affording good efficiency to the motor and motor controller. Current demands fluctuated greatly under the varying loads with peaks of over 100A. Under the constant high speed mode of HFEDS, the temperature rise of the battery pack was only 6degC over ambient temperature. Under the high current demands, the phosphate lithium-ion battery pack delivered a full 97Ah. When combined into a system of 28 modules in series with high current demands, the phosphate lithium-ion battery was still able to maintain 97% of its capacity rating. Pack voltage ranged from 386V to 318V, which equates to an average of roughly 13.78V to 11.35V per module.

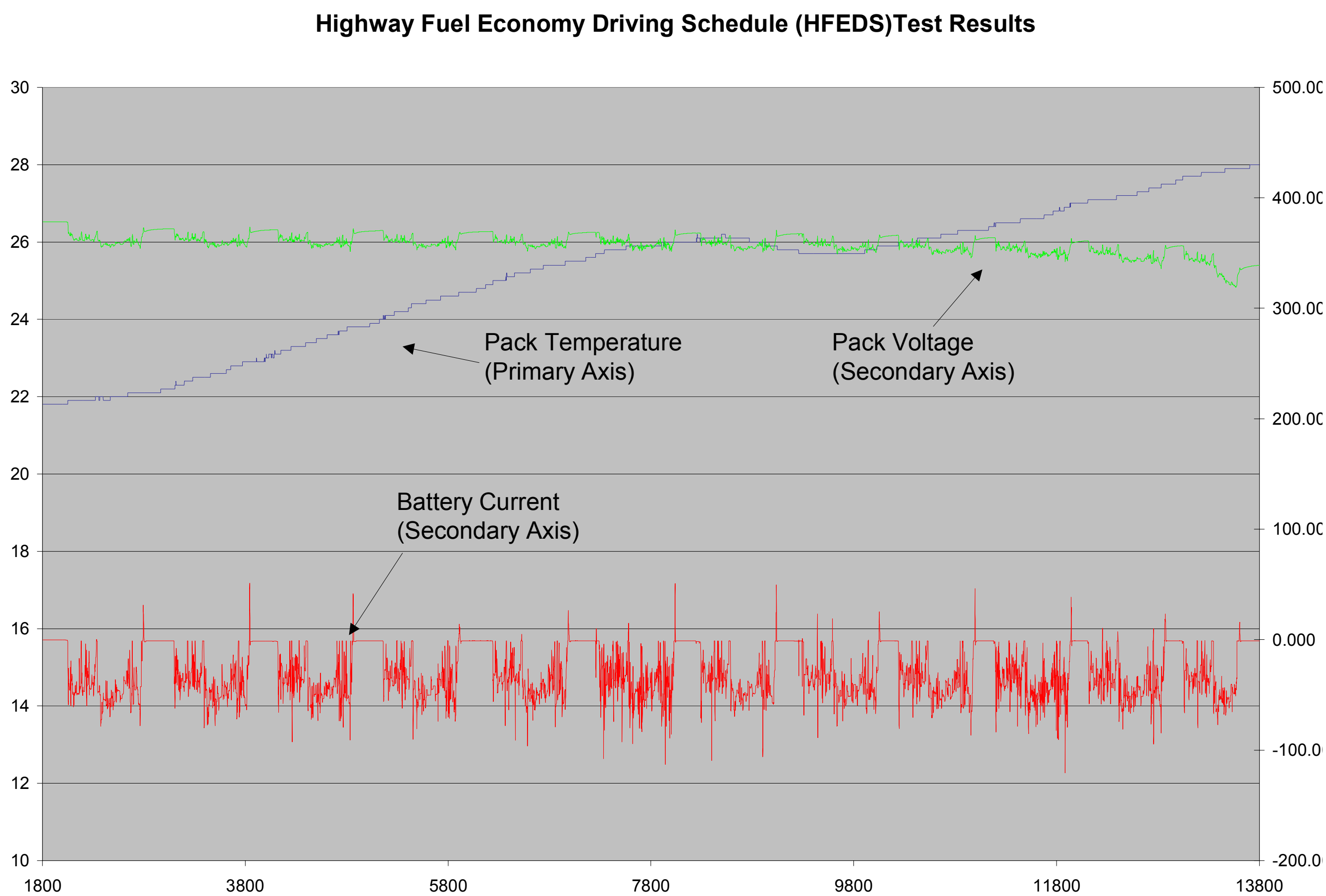

Figure 5. HFEDS Test Results

The electric vehicle was able to achieve 116 miles on a full charge for the HFEDS test which is well beyond the typical 60 miles driven daily by owners.

URBAN DYNAMOMETER DRIVING SCHEDULE (UDDS) TEST RESULTS[3]

The battery voltage remained very flat as before even under higher stresses of multiple stops and starts. The consistent voltage allows the electric motor to operate cooler and more efficiently. Current demands varied even more than before with even more peaks above 100A. The temperature rise above ambient remained at about 6degC. Under the higher stress of varying loads, the battery pack was still able to provide 97% of its rated capacity. Pack voltage ranged from 386V to 320V, which equates to an average of roughly 13.78V to 11.4V per module.

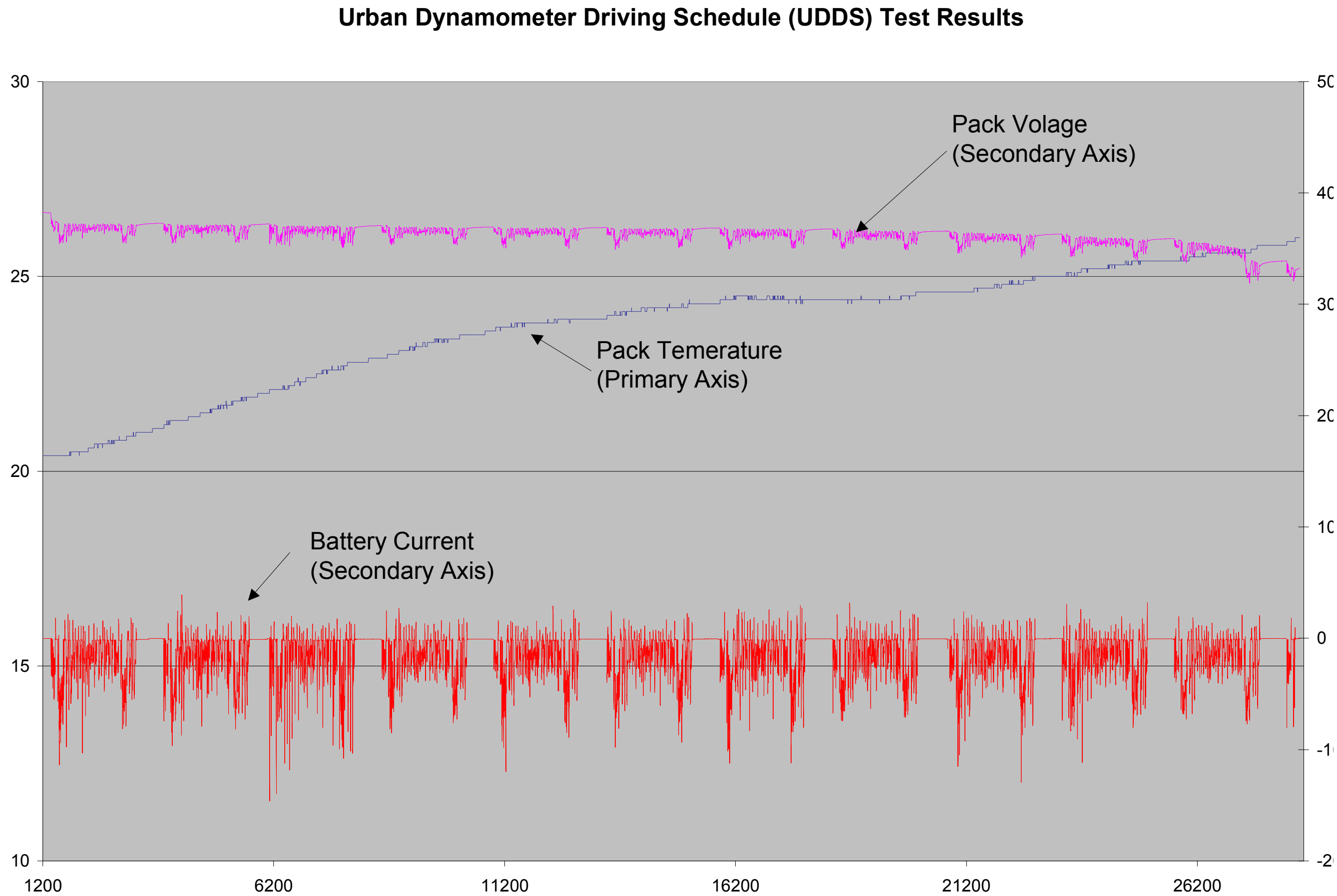

Figure 6. UDDS Test Results

For the UDDS test, the electric vehicle was able to achieve 121 miles on the dynamometer. Most daily driving is no more than 60 miles in distance. The 121 miles achieved provides a large enough buffer to allow safe daily driving without fears of needing a place to "plug-in".

Additional testing yielded a range of 160 miles at a continuous 35mph speed. 0-60mph acceleration tests resulted in a respectable time of 9.43 seconds. A 30% higher capacity battery is also due to be tested and will be presented in future papers.

CHARGE RATE PERFORMANCE

Different battery chemistries have different characteristic columbic charge efficiency and maximum safe charge rates. Nickel metal hydride batteries currently used in hybrid electric vehicles have a columbic efficiency of approximately 66% (if you put 100 amp hours into the battery you get out 66 amp hours). Similarly, lead acid batteries have a typical 75% charge efficiency.

Inefficiency during charge generates heat, which accelerates cell aging. Phosphate lithium-ion has a charge efficiency of greater than 95% and consequently can tolerate much higher rates of charge. Charge rate characterization for phosphate cells are shown in Figure 7. The 2C charge rate corresponds to a 30 minute charge time.

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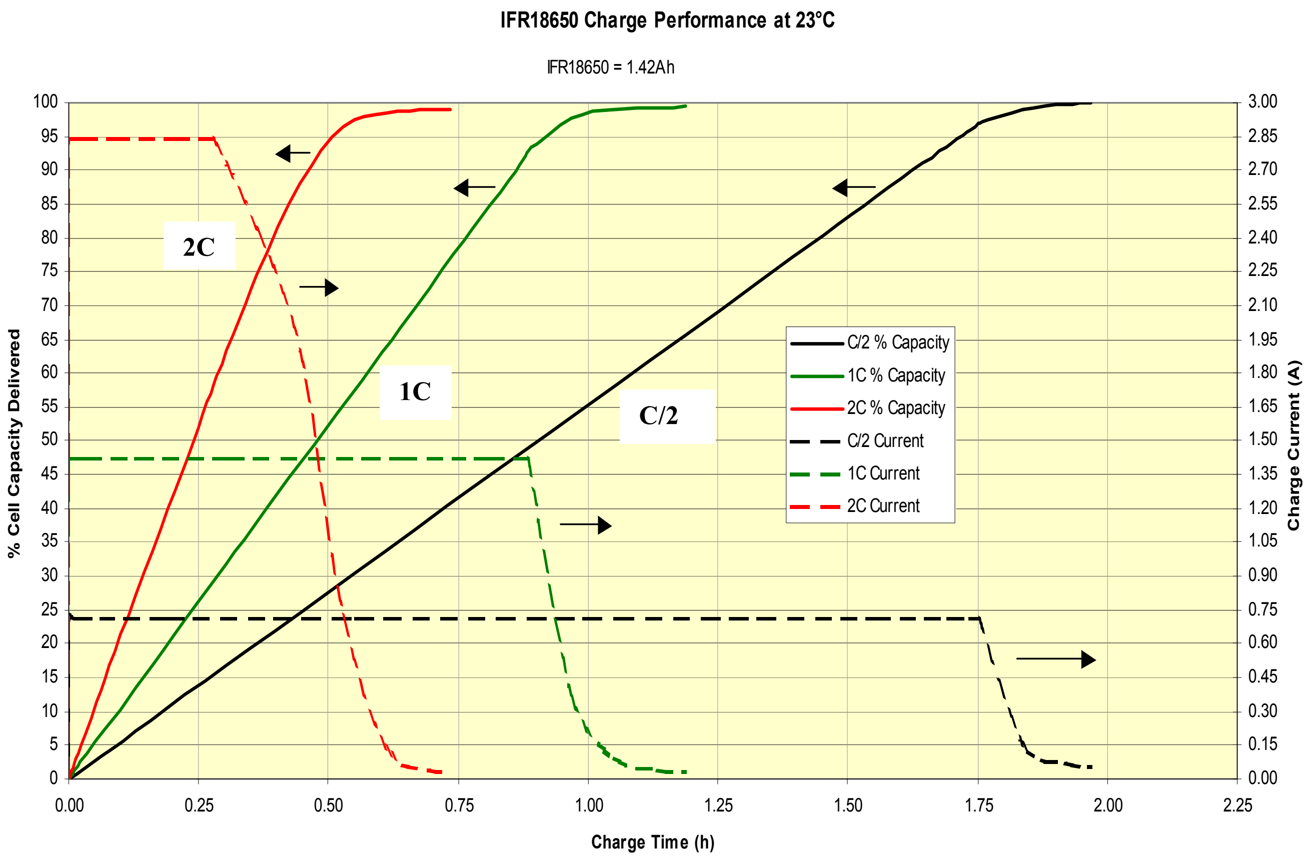

Figure 7. Cell Level Charge Rate Performs at 99% Efficiency

Being able to quickly recharge a battery allows an individual to greatly increase the usefulness of their EV or wheelchair. The user no longer must endure long down-times waiting for their battery to recharge. Overnight charges are also no longer mandatory. Long trips followed by a much shorter charge time is now possible with phosphate lithium-ion batteries in EV and electric wheelchairs.

With a properly sized charger, phosphate lithium-ion batteries in EVs can be recharged to 90% or more of capacity in one hour. A one hour charge (90% capacity) equates to adding 100+ mile range to this particular electric vehicle. The flexibility of an EV is now dramatically increased. The user of an electric vehicle can now take a long 100 mile trip to a store or relative's house, plug the car in for only an hour to go shopping or have dinner, and then be able to drive another 100 miles home.

High charge efficiency and charge rates are also helpful on vehicles with regenerative systems. Phosphate lithium-ion batteries can utilize more of the regeneration, thereby improving the range of an electric vehicle even further.

SHELF LIFE AND EXTREME TEMPERATURE STORAGE COMPARISON

Phosphate lithium-ion batteries have demonstrated the ability to maintain excellent cycling ability even when abused. To mimic the storage of an EV or wheelchair stored in a "hot garage", a phosphate lithium-ion cell is placed at 85°C for an entire week. Figure 8 shows that phosphate lithium-ion cells are able to maintain its capacity on subsequent cycles. On the other hand, a common high capacity rated cobalt lithium-ion cell is unable to maintain anywhere close to its original capacity. The cobalt lithium-ion cell may start out at a higher capacity, but it quickly loses its capacity after several cycles. However, the phosphate lithium-ion cell is able to continue cycling well and maintaining its capacity.

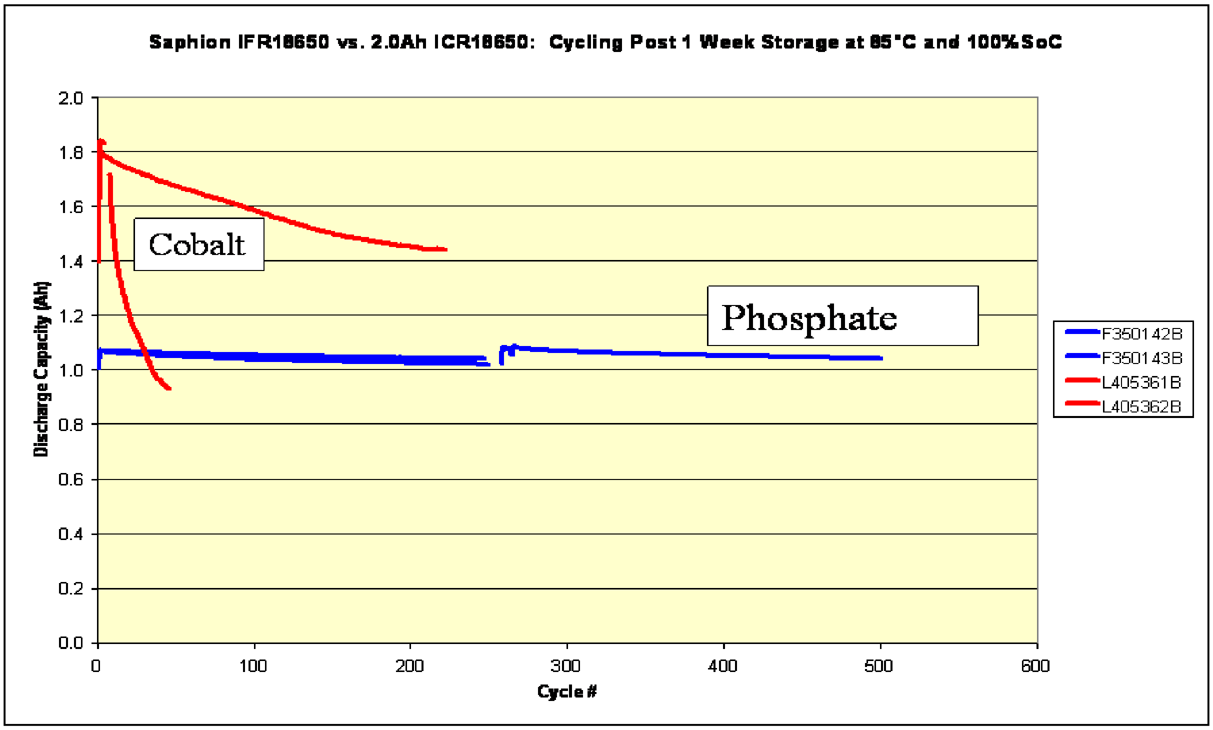

Figure 8. Cycling After One Week Storage at 85°C and 100% SoC

EVs and wheelchairs are often left unused during the winter or when the user is on vacation. Often times, a user does not go through the hassle of trickle charging a battery during winter storage, causing a battery to die prematurely. Figure 9 shows a cell being left at 0V for a week. The cell is then fully charged and then cycled. The phosphate lithium-ion cell shows it's robust character by continuing to cycle well. On the other hand, the cobalt lithium-ion cell shows a dramatic drop in capacity after a several cycles. The cobalt cells may have started at a higher capacity than the phosphate cells, but after several cycles in this harsh environment, the cobalt cells now have lower capacity than the phosphate cells.

The robust character of phosphate lithium-ion allows greater flexibility to the EV or wheelchair user. The batteries do not require the attentive care as before which makes EV and wheelchairs more viable to a larger group of people. Having a robust technology which requires less maintenance from the user will allow a faster adoption of the new technology.

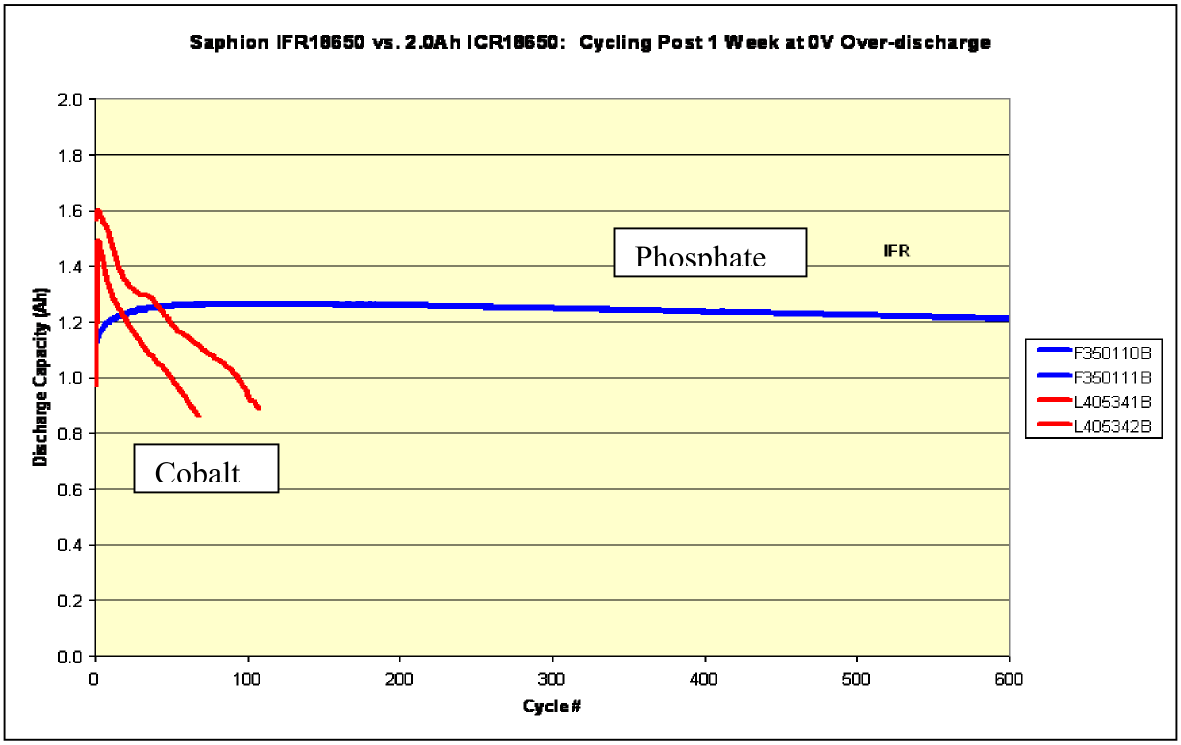

Figure 9. Cycling After 1 Week at 0V Over-discharge

CYCLE LIFE PERFORMANCE

Phosphate lithium-ion batteries have superior cycling ability over lead acid batteries at all depths of discharge. At high demanding, 100% depths of discharge, phosphate lithium-ion has 5 times the cycling ability as other traction lead acid batteries. Current test data on a cell level shows an expected 2000 cycles to 80% of original capacity. The linear predictable decay rate should allow the battery to extend its life to below 60% of original capacity. The superior cycling allows electric vehicles to be used daily, greatly extending their usefulness. The battery can now match or exceed the life expectancy of the electric vehicle itself.

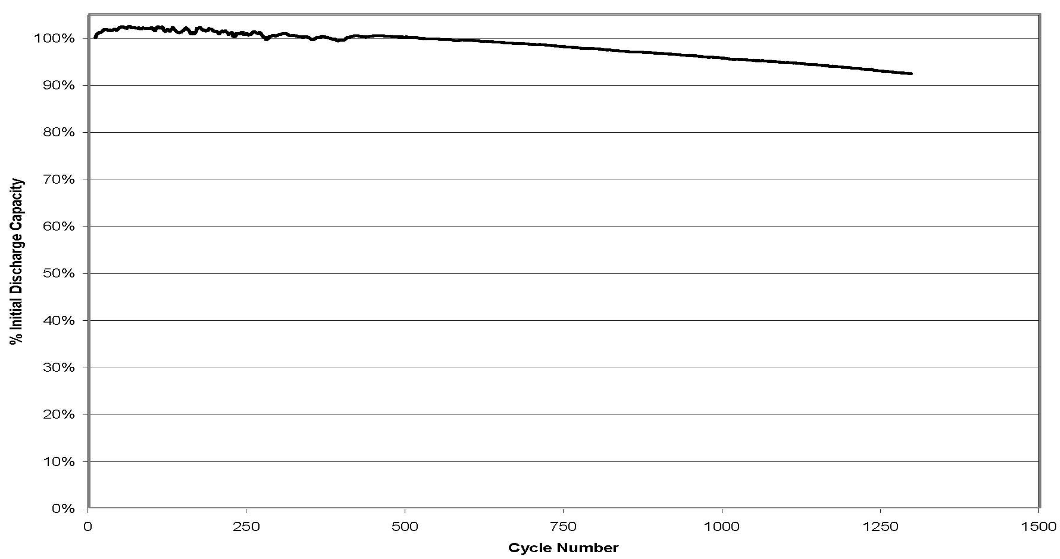

Figure 10. Excellent Cycling at 100% Depth of Discharge

OTHER FEATURES AND BENEFITS OF PHOSPHATE LITHIUM-ION USE IN ELECTRIC VEHICLES

The following summarizes additional features and benefits to using a phosphate lithium-ion battery in motive applications such as electric vehicles, electric wheelchairs, medical scooters and electric bicycles.

- Phosphate technology – inherently safe, rechargeable, lithium-ion chemistry with no thermal runaway; remains thermally stable on electrical abuse and physical abuse; critical in case of inevitable accidents
- Virtually zero maintenance over the service life of the battery – saves from high maintenance cost and wasted time
- Lightweight, high energy (2 times energy at same size and 3 times energy at same weight as lead acid) – reduces vehicle weight and size; reduces wear on vehicle's suspension, tires, brakes
- No battery memory effect – no loss of capacity at partial depths of discharge/charge; can re-charge at any time
- Low Peukert's Effect (low capacity loss as discharge rates increase) – more usable energy at high discharge rates
- Sleep mode (low self-discharge) – no seasonal conditioning needed for long term storage
- No sudden death syndrome – linear and predictable battery fade is reliable down to 50% of original capacity
- No explosive hydrogen gassing – eliminates hydrogen gassing concerns in enclosed passenger cabins
- No corrosion on power terminals – reduces costs and down time by eliminating periodic cleaning
- No free electrolyte – no electrolyte re-filling and acid concerns; enhances safety
- Flat discharge curve over time – maintains higher voltage/power even towards end of charge; vehicle continues to run fast even towards end of capacity
- Environmentally friendly phosphate based chemistry – below EPA's Toxicity Characteristic Leaching Procedure (TCLP); no recycling needed; please follow local laws/regulations for disposal

SUMMARY

A battery's performance is the most important factor of an electric vehicle or wheelchair's usefulness for a user. A consumer should not have to worry about special battery practices and care for their electric vehicle. Phosphate lithium-ion batteries solve many of the disadvantages of lead-acid technologies and have been shown to greatly extend driving range. Significantly expanding the range of a medical scooter or electric wheelchair will have a direct improvement on a person's quality of life. The person can now focus on their enjoyment rather than whether their vehicle can have enough range to carry them through the day. In standardized driving cycles, the electric vehicle using the phosphate lithium-ion battery was able to get an industry best of 116 miles highway and 121 miles city and receive CARB EV certification.

Vehicles with the CARB EV emission rating essentially have no exhaust emissions, allowing owners to qualify for full zero emission vehicle credits. California owners are eligible for one-time rebates of up to $5,000 from their local air quality management districts, enjoy free parking in some of the most heavily trafficked areas of the state, drive in carpool lanes with a lone occupant, and are exempt from some excise and luxury taxes. In addition, owners may also qualify for a one-time federal tax credit of 10% of the purchase price up to $4,000.

Two primary aspects have prevented lithium-ion batteries from being used in electric vehicles: price and safety. Phosphates solve the safety issues as discussed before. Price is being solved by achieving the 100+ mile range, which qualifies the car for the maximum rebates and offsets a significant part of the battery costs. Using similar batteries in stationary float applications will introduce volume efficiencies, which in turns reduces the costs of motive batteries. Phosphate lithium-ion technology is now an enabling technology for electric vehicles as the major hurdles are being lowered significantly.

REFERENCES

1 Gage, Thomas, "*Lead-Acid Batteries: Key to Electric Vehicle Commercialization,*" pp.1, The Fifteenth Annual Battery Conference, 2000.

2 Saidi, Yazid, "The Safety Advantages of Valence's Saphion Technology," pp. 9, Valence Technology White Paper.

3 Electric Vehicle provided by Daniel Riegert of Phoenix Motorcars, Ojai, California.

4 Dynamometer testing by Phoenix Motorcars and California State University of Los Angeles.