XM1124 High Power Battery Pack Utilizing Nanophosphate® Cells

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Abstract – The US Army has an interest to investigate new, possibly safer Nanophosphate® Lithium-ion batteries and assess the performance capability in an operational vehicle environment. Lessons learned can be leveraged to improve technology maturity and be applied to future work on hybrid electric vehicle systems. One such battery considered is a Lithium Iron Phosphate (LiFePh04) battery that is made by A123 Systems, Inc.

A123 Systems, Inc. has developed several large format battery configurations built around its Nanophosphate® cell chemistry. Battery packs with voltages of 350 VDC (nominal), and 100kW pulse power capability have been fabricated and tested. The inherent safety and weight advantages of the A123 Nanophosphate® batteries spark a genuine research effort to evaluate the cells for a wide variety of ground transportation applications such as city buses, and fleet delivery vehicles. Military applications include integration into hybrid electric vehicles, silent watch, and unmanned ground vehicles.

This paper will discuss and summarize the testing of an A123 LiFePh04 battery pack that has been in integrated into the XM1124 hybrid electric HMMWV at DRS Test and Energy Management in Huntsville, Alabama. Prior to integration into the XM1124, the battery pack was subjected to a number of bench tests that included constant charge and discharge tests, cycle testing, pulsed power testing and a power profile that simulated the charge and discharge cycles of an XM1124 HE HMMWV navigating the Hartford Loop at Aberdeen proving grounds. Upon integration on the vehicle, the pack was tested in a number of challenging environments to include acceleration testing, brief and extended road testing and hill testing that culminated in an aggressive climb to the state park on the top of Monte Sano mountain in Huntsville, Alabama. Analysis and testing showed the validity for potential consideration of this technology in future military and commercial applications.

1.0 Introduction

Environmental impact of the use of fossil fuels and the rising costs of these fuels coupled with the knowledge that world oil supplies are dwindling down has prompted the world to consider changes in its energy infrastructure. The U.S. Army has also been deeply interested in improving the efficiency of its vehicles. Strategically it makes sense to shy away from oil as over 60% of the oil used by the United States is imported from politically unstable regions of the world and where the U.S. is viewed as unwelcome. Several approaches are being investigated to reduce the reliance of the Army on oil. One approach has been the conversion of its fleet of vehicles to hybrid electric mode to considerably ease the oil consumption. Among the battery technologies available, Nickel metal hydride and Lithium ion systems are at the forefront. While currently available hybrid vehicles for general public have been using Ni-MH system as a battery of choice, leading hybrid electric vehicle manufacturers like TOYOTA and HONDA have been considering switching over to Lithium ion batteries. These batteries have higher operating voltage and higher specific energy and power. For this reason, it is well known that the Army is also adapting Lithium Ion (Li Ion) battery technology for use in hybrid-electric vehicle power and mobility. TARDEC has been charged with developing and advancing Li Ion technologies as well as with identifying, addressing, and solving problems inherent in these batteries. While performance characterization of this technology is proceeding, the phenomenon of Lithium ion battery thermal runaway phenomenon has been raised as a potential issue. The widely reported incidences of lithium ion battery powered lap tops bursting into flames have reinforced the need to find a system that is safe and performs well. TARDEC is taking the lead role in understanding this phenomenon and trying to suggest possible solutions before mass adaptation of this technology in the Army reaches a point of no-return.

Among Lithium ion battery chemistries, the lithium iron phosphate chemistry has been heralded as a safe system while still providing excellent performance. The principal disadvantage of this system is the lowering of operating voltage of the cell. As a result the specific energy and energy density (Wh/kg and Wh/L) are lower than the cells based on lithium cobalt oxide cathodes. One of the three major auto companies in the U.S. has already decided to consider this technology for their 'Plug –in Hybrid' vehicles. A123 systems in Boston, MA has been pioneering this battery technology. This paper will present results of the investigations using the LiFePh04 batters that were tested as a collaborative effort between A123, TARDEC and DRS Test and Energy Management.

1.1 Army targets for this technology

There are two areas where the Army would like to incorporate this lithium ion battery technology and take advantage of its performance superiority and safety:

1. Powering hybrid electric vehicles for propulsion require batteries to have high specific energy, high energy density and a flat discharge voltage. In addition, the battery system has to have the ability to absorb very high pulse currents produced by the regenerative braking system. High charge rates, high discharge rates, good low and high temperature performance, high reliability and safety are good attributes required for use of this system for HEV propulsion applications.

2. Silent Watch/silent power stipulates the absence of thermal, electrical, mechanical or sonic signals from the vehicle as well as the equipment it carries. This application demands battery packs to provide energy from 35 kWh to 75kWh, depending upon the vehicle type. The typical, minimum duration for which this energy is needed is 2 hours with a desirable duration of 8 hours. The power drain from the battery to sustain all the applications depends upon the vehicle type and the type of operation it is engaged in.

2.0 Nanophosphate® cell technology

The A123Systems Nanophosphate® 26650 is a 3.3 V, 2.2 Ah (nominal) cell. An 11 mΩ internal resistance (1.0 s DC pulse) is typical. The mass is approximately 72 g. This cell is rated for 70 A continuous discharge and 120 A discharge under a 10 s pulse. These cells were compared with commercial nickel cobalt aluminate (NCA) cell rated at 2.6Ah at 3.8V and an internal resistance of 13 mΩ.

In addition to the cathode material, there are two key differences between the cells. The NCA cell is packaged in a stainless steel can, whereas the NP cells are packaged in aluminum cans. The NCA cells also include a protective layer on the anode, which contributes to higher impedances, most notably at low temperatures (< 0 °C). Since the steel can contributes a large parasitic mass, performance is compared on a volumetric basis rather than gravimetric basis. This is reasonable for vehicle applications in which the space claim for the battery is typically more stringent than the weight claim. Table 1 provides the typical characteristics of each cell.

Table 1. Comparison of ANR26650M1 Cell and an NCA 26650 Cell

Cell	Format	Cathode	Energy, Whrs	Capacity, Ahrs
A123 M1	26650	Nanophosphate®	7.3	2.2
NCA	26650	$LiNiCoO_2$:Al	9.4	2.6

Both the Nanophosphate® and NCA handled a silent watch cycling program without difficulty. At 60°C, the starting impedance, as measured by a 5 amp-1 second pulse, was 7.24 milli-ohms for the 26650NP cell versus 13.0 milli-ohms for the NCA cell. Capacity retention as a function of cycle number is shown in Figure 1. For the first 100 cycles, the NCA cell shows higher capacity retention than does the NP cell, but after that, the rate of capacity loss for the NP cell is considerably less than that of the metal oxide cell. Note in Figure 1 that the CID (current interrupt device) on the metal oxide cell opened, rendering the cell inoperable. CID's are pressure actuated and indicate that the internal pressure on the metal oxide cell had reached a level high enough to trigger the CID. The end of life for the NCA cell was 180 cycles, at which point the retained capacity was 79.6%. The M1 cell reached 79.6% retained capacity at 380 cycles.

Full discharge is generally considered to be 2.0 volts for A123's Nanophosphate® cells. At an average open circuit voltage (it has a flat discharge curve) of 3.3 volts, NP cells have a much higher overpotential range on both charge and discharge than does metal oxide chemistry. This increase in overpotential range translates to higher discharge currents, hence high peak power, and higher charging currents which lead to a very high regenerative power capability when compared to NCA cells.

Under emergency conditions, one might anticipate that power levels exceeding the "safe" levels are required. Because the Nanophosphate® cells can be safely operated up to 4.2 volts, and, under high current drain, down to as low as 1.65 volts, we can extend the voltage limits to increase the power levels. Of course, by doing this repeatedly, one is likely to lose battery capacity and/or see an increase in the impedance.

The peak power results show that NP can perform over a wider SOC range. For a silent watch/HEV application, this means that HEV capabilities can be retained from pre-watch high SOC to post-watch low SOC. An additional concern is the wear and tear accumulating on the battery over repeated deep discharge cycling. Whereas most end-of-life testing emphasizes capacity degradation, increasing impedance may be a greater concern if it prevents the battery from meeting peak power loads.

The results for our Silent Watch/HEV protocol validate this concern. Initially, the NCA cells started with better capacity retention and slower impedance growth, but there is a cross-over in performance at < 100 cycles. Beyond that, the robust NP chemistry prevailed and the NP cells offered roughly double the cycle life. Furthermore, there were no CID or other failures of NP cells.

3.0 Integration of Nanophospate Cell Technology in XM1124 Hybrid Electric (HE) HMMWV

3.1 General overview of XM1123 Series Hybrid Vehicle

The objective of this research effort was to integrate an A123 HD-100 battery pack into a battery box of an XM1124 HE HMMWV. The initial battery design is as shown in Figure 2 . The pack was built as an early demonstration unit and designed to provide 100kW output power, 65kW input power, 350V nominal (250V-420V operating range) 13.8Ah nominal capacity, 4.8kWh energy storage and 400A 10s max pulse. A 3-D design of the battery tray is also shown in Figure 2. This pack was delivered to DRS TEM on January 3, 2008. Upon delivery, the box was inspected and final changes/additions to the battery test plan were developed and approved by A123 and TARDEC on January 23, 2008.

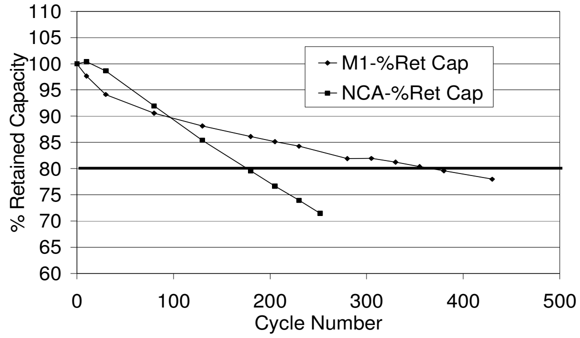

Figure 1. Retained Capacity vs. Cycle Number for an ANR26650M1 Cell and NCA Cell. NCA cell CID failed at cycle 252.

The initial effort was to perform bench testing on the pack to determine if it could safely be integrated into the XM1124. This testing culminated in simulating the power profile of the vehicle navigating the Harford loop at Aberdeen proving grounds. In March, 2008 bench testing of the A123 HD-100 pack was completed and the pack was cleared for integration to the XM1124 Hybrid Electric vehicle. Some time was spent modifying the vehicle to accept that pack and in May 2008 the pack was integrated with new hardware and software.

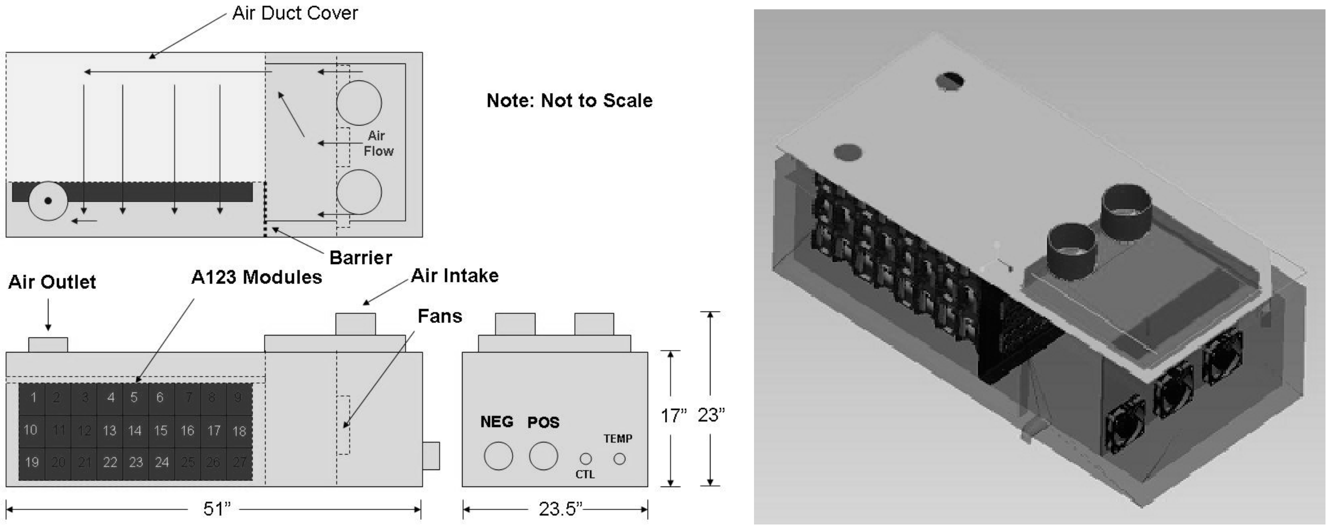

Figure 2. DRS XM1124 battery tray.

Upon integration of the pack, the vehicle was tested to ensure the overall system was functional, stable, and safe. The test plan was then executed to test the effectiveness of the pack when used in the Hybrid Electric XM1124. A number of ideas for additional tests were conceived during testing and extended testing was performed in addition to those tests that were originally included in the vehicle road test plan. Normal testing (as outlined in the vehicle test plan) included functional testing, acceleration testing, normal road test validation and hill climb testing.

Extended testing included a 2-hour normal drive test to include a number of terrains such as flat highway and a hill climb up Monte Sano Mountain in Huntsville, Alabama. All-electric testing was also performed to determine for how long and how far the vehicle can operate in all electric mode.

3.2 XM1124 Vehicle Integration

There were a number of modifications that were required to be made to the XM1124 to allow integration of the A123 HD-100 pack. These included normal modifications that would have to be made when integrating any new pack to the vehicle in addition to modifications that were identified during bench testing. These modifications included the introduction of new hardware and modification of software in the existing vehicle.

There have been a number of different types of batteries integrated into the XM1124 since the program's inception. Each time a new pack is developed, it is important to ensure safe and efficient operation. This typically includes ensuring the pack is connected through a known impedance to vehicle (chassis) ground. This ensures the battery Voltage does not "run away" to a point where touch voltages could cause injury. Other modifications made to the vehicle included the incorporation of a Thermo-scan module to monitor the temperature of various cells into pack to ensure the vehicle is protected in an over-temperature situation. The ICBM master battery manager and Battery Control Unit (BCU) software was also modified to ensure the pack was maintained as efficiently as possible. This includes modifying the software to reflect the specific parameters of the pack and ensure the series hybrid vehicle maintains the pack within a state of charge window that is acceptable to the user (for drivability) and the pack (for safety).

4.0 XM1124 Nanophosphate® Battery Pack Testing

4.1 Vehicle Testing

Since this technology had not been included into the vehicle prior to this research effort, it was important to perform a number of bench tests on the vehicle to identify any issues that may arise when integrated into the vehicle. Bench testing consisted of a number of reference performance tests (to monitor battery state of health through testing) as well as a number of standard tests such as constant discharge, constant charge. More rigorous tests were performed on the pack such as cycle testing and pulsed power testing. Finally, a power profile from an XM1124 navigating the Harford Loop at Aberdeen proving grounds was levied on the pack to determine how the pack would react (mostly concerned with self-heating) in a simulated vehicle environment.

Aberdeen testing was performed by connecting the battery pack to an ABC-150 DC power processing system. This system has the ability to be programmed with various power scripts that can simulate vehicle operation by charging and discharging the pack at various rates. Data taken from an actual XM1124 navigating the Hartford Loop at the Aberdeen Proving Grounds was used as a basis for testing the ability of the battery pack to deliver and accept power. The test was run multiple times with all critical data (including temperature) being recorded. The overwhelming goal of this test is to ensure the pack could operate under the strenuous charge/discharge conditions of the profile while maintaining an acceptable temperature in a "real world" environment. This test was the final planned test prior to integration into the actual XM1124 vehicle.

Figure 3 shows the commanded power profile that was run using the ABC-150 compared with the actual power that was delivered/recovered during testing. During the first portion of the test, the power was maintained at a constant value to prevent overcharging due to a maximum limitation of the pack of 90%SOC. The value of acceptable charge that was obtained from the pack's BMS dictated the actual power that was used to charge the battery pack and limited it in this region.

4.2 Extended Bench Testing

One factor that was considered an advantage of this pack was its ability to equalize pack voltages quickly because of its modular design. Prior technologies that have been tested in this application showed very long wait periods as the internal cells equalized. Although this test was not specifically called out in the test plan, it was performed based on observations during testing that this pack equalized its voltages quickly.
The procedure for quantifying the pack equalization is as follows:

1. Fully charge the pack and let the cells equalize.
2. Completely discharge the pack at 50A constant discharge.
3. Charge the pack to 100% SOC, but do not allow the cells to equalize.
4. Start a timer.
5. Stop the timer when the minimum and maximum cell voltages are within 10mV.

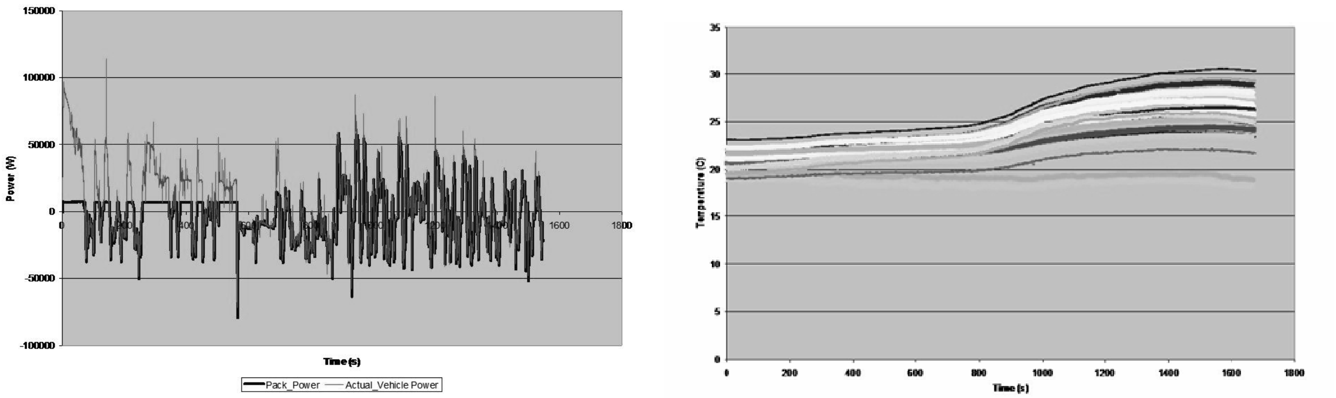

Figure 3. Aberdeen test power and temperature response.

Upon completion of step 3 of this test, the maximum cell voltage was reported as 3.752V and the minimum cell voltage was reported as 3.592V. The pack was then allowed to perform its equalization routine. The routine was completed in approximately 33 minutes. The maximum final cell voltage was reported as 3.429V and the minimum cell voltage was reported as 3.419V (within 10mV of each other). This is considerably quicker than previous cell technologies that had been previously integrated into the pack.

4.3 Vehicle testing

In late May, 2008 the A123 Nanophosphate® battery tray was installed in the XM1124. This started the initial vehicle testing phase of the battery pack in an actual vehicle environment. Initial vehicle testing included a Functional test, Acceleration test, Road test and a Hill climb test. The objective of each test was different and the results of each test are presented in this section.

4.3.1 Acceleration Test

Once the vehicle pack was proven to be operating properly (through a static functional system test), the acceleration test was executed. The acceleration test had the user mark off a 100 yard distance point in a flat, concrete area. The XM1124, with integrated A123 Nanophosphate® pack, would safely move to the start line and stop. The user would then command 100% power delivery (accelerator pedal to maximum) for the entire 100 yard course (without the APU running, i.e. all-electric mode) and command 0% power upon crossing the finish line.

The purpose of this test was to perform it at various states of charge to determine how this particular vehicle's acceleration performance changed as the state of charge of the pack changed. The above test was performed twice at 75% SOC, at 60%SOC, 50% SOC and 40% SOC. Table 2 shows approximately how long it took the vehicle to execute the 100 yard course and the highest speed attained as reported by the vehicle's maintenance unit. Figure 4 shows the speed profiles for each test during the test and while the vehicle coasted to a stop.

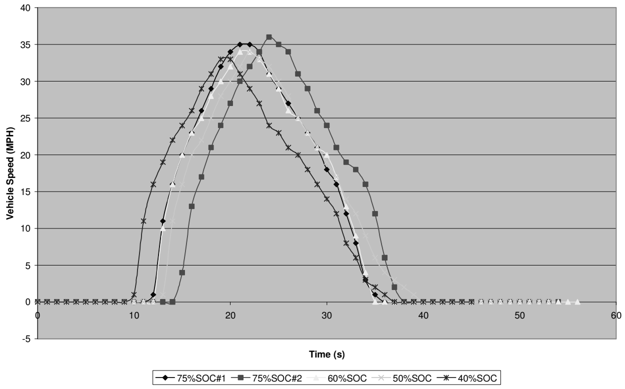

Figure 4. Vehicle speed profile at various SOC during acceleration tests.

Table 2. Vehicle performance at various states of charge for the acceleration test.

State of Charge (SOC)	Time to execute 100 Yds.	Highest Speed Attained
75%	9 seconds	35 MPH
75%	9 seconds	36 MPH
60%	10 seconds	34 MPH
50%	10 seconds	34 MPH
40%	10 seconds	33 MPH

It can be seen from Figure 4 that for a fast, 100 Yard acceleration, the performance did not degrade significantly as the initial state of charge decreased. This was validated by the driver's perception during the test. This test shows that as the SOC varies, the vehicle does not appear to be "sluggish" to the driver. Throughout testing the voltage did not exceed the recommended values during acceleration at various states of charge.

4.3.2 Road Test, Short Hill Climb Test

Upon completion of acceleration testing, the vehicle was taken on a road test. The route spanned 11.2 miles over a generally flat hardball surface without any stopping of the vehicle. The test was run once and took approximately 14 minutes for the vehicle to execute the route. The vehicle's driver reported that they were able to maintain the flow of traffic and there were no thermal or performance issues to report.

4.3.3 Extended Testing

Three tests were performed as part of the extended testing. The first was an extended road test to see how well the batteries performed during long operations. The test took approximately 2 hours of constant driving over various terrains from flat hardball, to the culmination of testing where its was required to climb a small mountain. The second test that was performed was the climbing of the same small mountain using a paved back road. Finally, the vehicle was subjected to testing in all-electric mode. The all-electric mode is the most stressful test on the batteries because the pack is not receiving any power burden help from the motor/generator. During this test, the entire amount of power supplied to the drive train of the vehicle is from the battery pack.

During the extended road test, the vehicle was constantly driven for approximately 2 hours. The purpose of this test is to observe if the batteries would self-heat to an unacceptable level when the vehicle is operated over a long period of time over various terrains. The test also was performed to validate that the vehicle was robust over long periods of time up to 2 hours. The first part of this test had the vehicle navigate in the city in hybrid mode. Figure 5 shows the power profile of the extended test. The left plot shows the power (commanded and actual) of the "city" mode portion of the test, while the right plot shows the climb up Monte Sano Mountain.

During the test, the temperature continuously rose during the city mode and "flattened" off as the vehicle reached the base of the mountain and navigated the mountain road. It was noticed that during this test, the ambient air temperature rose during the early periods of the test and flattened out towards the end of testing. The inlet air temperature is measured by a thermocouple mounted inside of the battery tray. Some self heating from the batteries at that point was being reflected into the ambient air temperature rise. This suggests that the thermal properties of the cooling system should be revisited and analyzed in detail.

Overall the vehicle performed very well during this test. The operator noted that the vehicle maintained the flow of traffic and was very responsive as it climbed the paved road up Monte Sano Mountain. The pack responded well in all-electric mode as it traversed down the mountain. No errors were reported by the vehicle system and no problems were encountered during the test.

4.3.4 Vehicle Mountain Climb

The author of this document personally wanted to experience how the vehicle felt as it traversed up the back mountain road of Monte Sano as fast as possible. The author drove the vehicle extremely hard (accelerated quickly and frequently as opposed to slow acceleration) to try to incur as much stress on the battery pack as possible. Figure 6 shows the power profile of the vehicle moving to the mountain, moving up the mountain, moving down the mountain and moving back to the DRS-TEM facility. During this test, the vehicle operated with the APU (Generator) functioning during the entire test (in hybrid mode for the entire test).

The vehicle was surprisingly responsive over the entire test. The vehicle seemed to accelerate with traffic from standstill (i.e. at stoplights) and very comfortably operated with other cars on the road. There was no problem "keeping up" with traffic. During the mountain phase of testing, the vehicle was again very responsive and had plenty of acceleration at various grades while climbing the mountain. The vehicle handled very well and the temperature and all battery pack parameters stayed within rated values during the entire test

4.3.5 All-Electric Testing

The most stressful test that can be performed on the battery pack is all-electric testing for extended periods of time. In all-electric mode, the power that is sent to the front and rear wheel motors is obtained directly from the battery pack and NOT from the motor and generator mounted to the internal combustion engine. The worst case scenario that the vehicle will encounter is to commanded full traction power for extended periods of time without the aid of the generator.

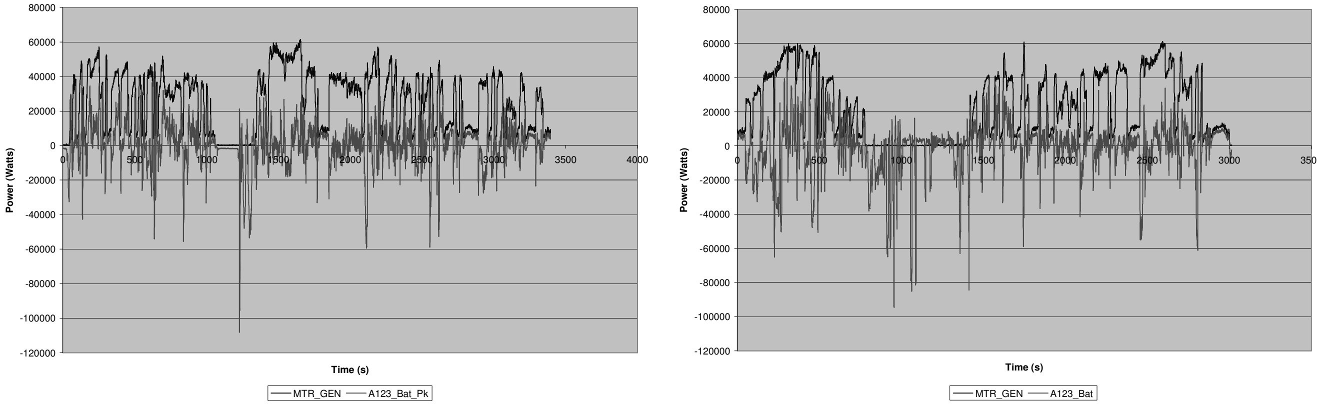

Figure 5. City and mountain testing portions of extended road testing.

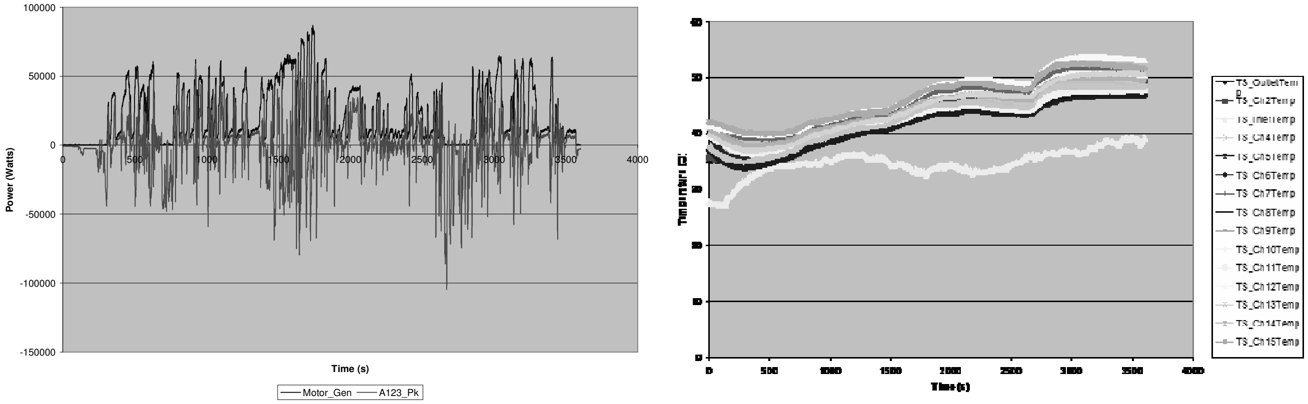

Figure 6. Power Profile and Temperature response during driving up Monte Sano Mountain.

Two separate tests were performed during the all-electric phase of testing. The first was to put the vehicle in all-electric mode and travel at a constant 30MPH until the battery pack showed one of its critical parameters to be out of normal operating conditions. This simulates a soldier having to “silently” move out of an area without the engine being on. This is also similar to how a number of the tests were terminated during bench testing. Upon completion of the 30MPH test, the vehicle performed the same test at a constant 50MPH.

Table 3 shows the distance traveled and time the vehicle was able to operate in all-electric mode. It is interesting to note that the 30MPH test concluded because the vehicle’s state of charge was low. The 50MPH test was terminated because the temperature of at least one of the battery pack modules was approaching an over temperature limit.

Table 3. Summary of All-electric testing.

Test	Distance Traveled	Time before test termination
30MPH	5.70 Miles	12.283 Minutes
50MPH	5.30 Miles	7.52 Minutes

The vehicle handled very well during the 30MPH testing and 50 MPH testing. The battery pack can be run at 30MPH for an extended period (over 12 minutes and 5.7 miles) without problem. The pack was run until the SOC was too low to continue. The 50MPH test, however, was terminated because the module temperatures were too high. The protection algorithms in the vehicle software will not allow the user to operate the vehicle if the temperature exceeds 63 degrees C. Over-temperature of the cells can create a potentially unsafe condition. It is clear that if the vehicle is to be stressed like it was stressed during the 50MPH test, the cooling system for the battery tray needs further analysis and improvement. Fortunately, the addition of another HD-100 pack will greatly improve this condition (each pack will now only have to provide ½ the current resulting in ¼ of the power being dissipated), but a better thermal management strategy should be considered.

5.0 Conclusion

Overall the A123 HD-100 pack that was retrofit to occupy the XM1124 battery tray performed well during bench testing and vehicle testing. The 13.8Ah, 100kw/10sec rating of the pack is fairly low compared to other packs previously integrated into the XM1124 (the 40 Ah, 100kW lead acid packs and the 60Ah, 300 kW Lithium Ion Phosphate packs). The intent of this phase of the project, however, was to determine the feasibility of its integration into the XM1124 and if the technology seemed promising. Further work is being considered to increase the amount of energy stored to increase performance and robustness of the system.

The final conclusion after testing is that the Nanophosphate® technology should be considered in future hybrid electric vehicle designs. The cells equalize very quickly, the cells are available and have reasonable cost. The cells also perform very well. The data presented in this paper showed that although the pack had significantly lower energy density, it performed extremely well and maintained safe operating parameters throughout testing. The only limitation was when the vehicle was operated in all-electric mode at high-vehicle speeds. This shortfall can be easily overcome by increasing the energy density of the pack.

Future work will include the design, development and testing of a similar pack with a higher energy density. Also, lesson learned from this effort can help designers develop a more effective cooling scheme to remove heat from the battery box during all operating conditions. This research can also be considered as a basis of design for silent watch packs for various vehicles and as a battery pack for commercial hybrid vehicles.