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TESTING OF NANOPHOSPHATE™ PRISMATIC BATTERY CELLS IN THE XM1124 HYBRID ELECTRIC HMMWV

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ABSTRACT

The XM1124 HE HMMWV has the potential for providing this capability on the battlefield. The XM1124 is a TARDEC funded program that converts a standard HMMWV into a series, HE HMMWV. Over the past 5 years, this vehicle has been in the hands of the warfighter and has undergone a significant amount of testing and a number of upgrades. In a joint effort between TARDEC, DRS, and A123 Systems, the vehicle is being upgraded using A123 Nanophosphate™ prismatic cells to provide additional energy storage. This technology shows the potential for providing the energy and power needed for a ruggedized Military Application, while providing a safe, efficient means of energy storage and transfer that can be used in this extremely challenging environment.

INTRODUCTION

As the need for power and energy on the battlefield grows, systems that support the transfer and storage of energy will be critical. Commercial hybrid and plug in electric vehicles are gaining momentum in the commercial market, so the need for this technology to support the Military's power and energy strategy on the battlefield is starting to become apparent at a rapid rate. Not only do hybrid and plug in electric vehicles reduce the dependence on fossil fuels on the battlefield due to their increased fuel economy, but they could potentially be a key asset in the support of providing power to the Warfighter.

In 2008, A123 and DRS Test and Energy Management, under funding from TARDEC, built a hybrid electric vehicle battery pack for the XM1124 made out of A123's ANR26650 cylindrical cells. The pack was first bench tested and then integrated into the XM1124, where it underwent a battery of performance testing to include a 100 yard dash and long term drive testing. The battery performed very well during this testing.

In 2010, A123 and DRS Test and Energy Management worked jointly, again with TARDEC, to upgrade the pack using the A123 AMP20M1HD-A prismatic cell. This cell is extremely energy dense, highly manufacturable and is one of the common cells used by A123 for its commercial hybrid solutions. This upgraded pack would allow TARDEC and the Army to realize a high energy solution that can be easily manufactured for future hybrid vehicles.

This paper will describe the history, design and integration process for a Lithium Ion prismatic battery pack into the XM1124 Hybrid Electric HMMWV. Prior to the pack build, a number of design decisions and simulation scenarios were performed to predict the performance prior to integration of the pack. This would include normal testing procedures such as capacity check and constant charge/discharge. In addition, a power profile (acquired from previous pack testing) of the vehicle navigating the Hartford loop at Aberdeen Proving Grounds was run in simulation to evaluate a "real world" scenario to understand pack performance. The pack will be built and real world data will be available in July/August 2011.

ABOUT THE XM1124

The XM1124 is a series hybrid electric HMMWV that utilizes two electric traction machines on each axle for propulsion and a single motor/generator system that is used to charge the battery pack. The vehicle replaces the conventional HMMWV drive train with a hybrid drive train that maximizes performance and, at a minimum, retains the standard capabilities of the HMMWV

Because of the improved hybrid drive train, the XM1124 is able to provide a number of significant advantages for the Warfighter who is fighting on today's battlefield. The hybrid design allows for an exportable power capability through an Auxiliary Power Distribution System (APDS). This allows the Warfighter to export power for common battlefield uses where a tactically quiet generator would be required. It also allows for extended silent watch capability and a quiet mobility "stealth" mode where the vehicle is operated using the battery and traction motors, with the internal combustion engine being completely silent.

Table 1 shows the significant advantages the XM1124 HMMWV can provide the Warfighter on the battlefield compared to conventional vehicles currently being used. Figures 1 and 2 show depictions of the XM1124 HE HMMWV.

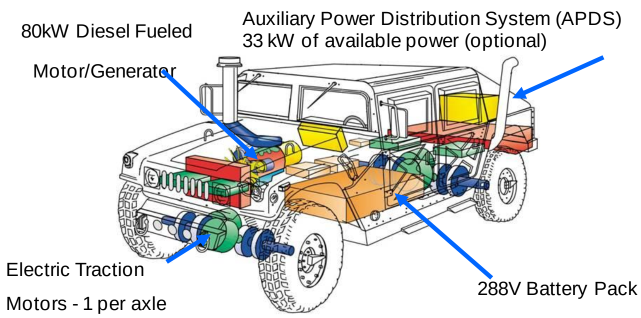


Figure 1. Graphical depiction of the XM1124 HE HMMWV

Table 1. XM1124 battlefield advantages.

Mobility	Power and Energy
Equivalent mobility performance	**Reduced logistics footprint with ripple effects across theatre**
Reduced fuel consumption	**Support battery recharging**
Delivers utility grade power	**Provides uninterruptable power**
Provides Silent Watch/Mobility	**Reduces the dependence of generators operating on the battlefield**
Power on the Move capability	**Provides power when and where it is needed on battlefield**
Reduces logistics footprint	

Currently, the XM1124 HE HMMWV is used by TARDEC and DRS as a test platform for strategic, innovative technologies that can be displayed on today's battlefield. This could potentially include advanced batteries, advanced Hybrid control systems (and hardware), advanced machines and controls, fuel economy and how mobile power can be integrated into today's battlefield.

Figure 2. XM1124 HE HMMWV on display.

ABOUT A123 SYSTEMS NANOPHOSPHATE™ TECHNOLOGY

Lithium-ion systems, with their outstanding cycle life, specific energy, and energy density, offer a unique weight and volume solution to military and aerospace applications. The cells and chemistries developed by A12Systems offer significantly improved sustained power levels and device safety over other commercially available systems.

At the heart of A123 Systems' cell chemistry is a patented Nanophosphate™ material, the electro-active ceramic material that serves as the cathode in A123 Systems' advanced-chemistry cell design. The Nanophosphate™ chemistry offers many attractive features over conventional lithium-ion cathode materials, all based around variants of lithiated cobalt oxide (LCO); the Nanophosphate™ chemistry currently offers the best combination of power, safety and life.

Aside from its high power capability, the Nanophosphate™ chemistry is a highly stable system and can run to greater than 6500 cycles; however, one of the most attractive features of the chemistry is its enhanced safety. Unlike LCO, the Nanophosphate™ chemistry is thermally stable and is not susceptible to the dramatic failure modes infamously associated with LCO-based batteries: violent releases of gas and flame. Also unlike LCO, it is also environmentally friendly. Nanophosphate™ does not contain any toxic heavy metals, easing disposal and recycling requirements. Using this chemistry, A123 Systems has developed several cell configurations to meet the needs of a wide variety of applications.

A123 Nanophosphate™ AMP20M1HD-A Cell

Designed for plug-in hybrid and electric vehicle applications, the AMP20 prismatic cell is built to deliver high energy and power density combined. The AMP20 cell demonstrates industry-leading abuse tolerance coupled with excellent life performance under the most rigorous duty cycles. The AMP20 delivers high useable energy over a wide state of charge (SOC) range to minimize pack oversizing and offer very low cost per watt-hour.

One other significant advantage of the A123 NanoPhosphate™ AMP20M1HD-A Cell is its ability to be integrated into a standard module. Because of its shape, it allows for "stacking" into standard modules that exhibit a significant amount of surface area that facilitates the removal of parasitic heat. Modules of various types (can vary voltage and capacity by varying the number of cells) can be build on the same manufacturing hardware and allow the module to serve as "building blocks" for complete systems. Figure 3 shows a typical module "building block" and a standard vehicle "core pack" that is comprised of multiple modules and targeted towards hybrid applications.

Figure 3. A123 Prismatic module and Core pack

XM1124 LEGACY BATTERY PACK

The legacy A123 XM1124 battery pack integrates an A123 ANR26650, HD-100 battery pack into the existing battery box of an XM1124 HE HMMWV. The cylindrical base battery design is as shown in Figure 4. The pack was built as a 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. 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.

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.

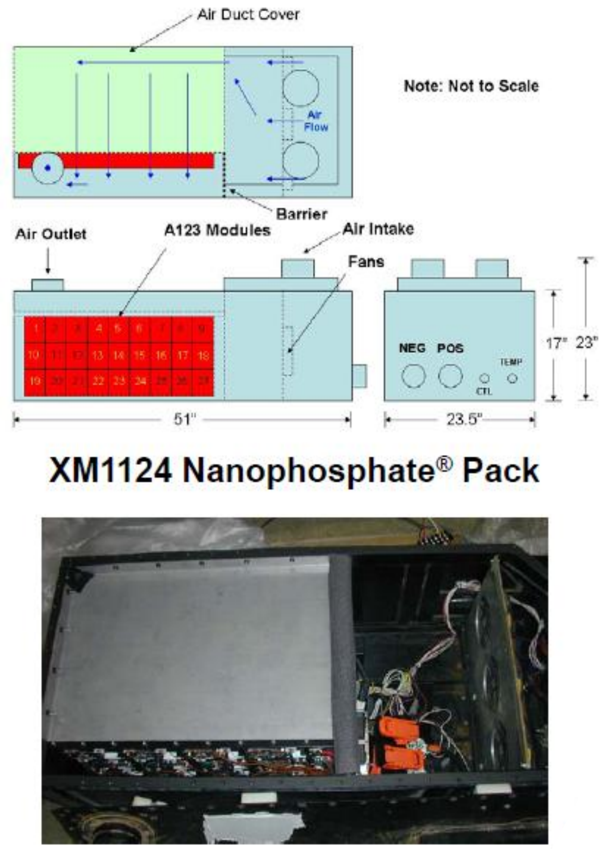


Figure 4. XM1124 First generation hybrid pack.

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 generated 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.

Overall the A123 Legacy XM1124 pack 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, but seemed to perform very well throughout testing.

The final conclusion upon completion of testing is that the Nanophosphate™ technology should be considered in future hybrid electric vehicle designs. The cells equalize very quickly, the technology is available and has reasonable cost. The data showed that although the pack had significantly lower energy density, it performed extremely well and maintained safe operating parameters throughout testing. The only limitation for this particular pack 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 and was the basis for the upgraded design discussed later in this paper.

XM1124 UPGRADED PRISMATIC PACK

In 2010, the initial design for an upgraded battery tray was funded by TARDEC. The goal of the pack was to provide more energy in the same space in a low-cost and manufacturable pack that meets the vehicle's requirements. The new pack would include multiple prismatic modules

The existing battery tray in the XM1124 is custom made and is designed to fit snugly into the belly of the XM1124. Because of this, it was important to integrate all system components (energy storage, contactors, control electronics, etc.) into this existing space. Because of its minimal impact on volume and the significant advantages it will provide for the future roadmap of the XM1124, a cold plate was included into the design to facilitate heat transfer. Additionally, it was imperative that not only the mechanical interface, but the electrical interface (connectors, etc.) be maintained so that integration into the vehicle would not require a major upgrade to the vehicle. Figure 5 shows a graphical depiction of the prismatic pack for the XM1124.

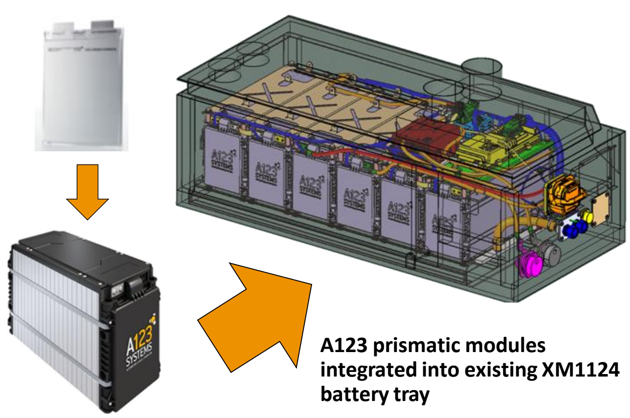


Figure 5. A123 XM1124 Prismatic Pack.

Predicted Performance

Upon completion of the design, the predicted performance (based on the cell and module configurations) was determined. Two different scenarios were identified. The first was a "sealed" pack that uses only convection cooling. This method will use the vehicle as the heat sink as the only method of cooling. Depending upon how rigorous the duty cycle is, this pack will take advantage of the reduced environmental exposure that is often a problem with these types of packs. Table 2 shows the predicted performance of the pack without active cooling.

Table 2. A123 XM1124 prismatic pack predicted performance with no liquid cooling.

	No Liquid Cooling			
	CHARGE		*DISCHARGE*	
Duration	*CONT*	*10-sec*	*CONT*	*10-sec*
Test Pack Power (kW)	-22	-67	21	61
Pack Vmax	389	389	389	389
Pack Vnom	350	350	350	350
Pack Vmin	270	270	270	270
Min Pack Energy (kW-Hr)	19.8			
Test Current (A)	-60	-180	60	180
Test Temperature (DegC)	25	25	25	25
Test SOC (%)	50	50	50	50

Although the vehicle is not currently outfitted with an active cooling system, the team decided to integrate a cold plate into the design to take advantage of the cooling interface of the prismatic modules. This cooling plate would allow heat transfer between the module and cooling interface, allowing higher power capabilities. Because today's commercial hybrid vehicles often include a separate electronics cooling loop, it is important to investigate the performance impact the vehicle could potentially sustain if it were included. Table 3 shows the predicted performance of the pack that includes active cooling.

Table 3. A123 XM1124 prismatic pack predicted performance with liquid cooling.

	With Liquid Cooling			
	CHARGE		*DISCHARGE*	
Duration	*CONT*	*10-sec*	*CONT*	*10-sec*
Test Pack Power (kW)	-22	-113	61	184
Pack Vmax	389	389	389	389
Pack Vnom	350	350	350	350
Pack Vmin	270	270	270	270
Min Pack Energy (kW-Hr)	19.8			
Test Current (A)	-60	-300	180	600
Test Temperature (DegC)	25	25	25	25
Test SOC (%)	50	50	50	50

SIMULATION/TEST RESULTS

The testing of the upgraded XM1124 pack will include simulated testing (performed before the pack is built and during the engineering design process), bench testing and vehicle testing. It is important to include the simulation testing as part of the process so that any potential shortcomings of the pack can be identified during the design process, not after. Incorporating major design changes after the design often increases time and expense.

Simulation Results

The A123 modules that are used in this design are made in Livonia, MI and are subjected to the same quality tests that most of the commercial automotive modules are tested against. This allows for high confidence for not only prototyping, but also for production. That allows the engineering team to use analytical data that is clearly understood and is predictable.

There are a number of performance parameters that are considered when performing a simulation on a pack. First, the pack must be able to supply the power that is required while maintaining the safe operating characteristics for voltage and current. This will ensure that the hardware (to include cabling, busbars, sensors, etc.) will be operating in it's safe operating area. The second major consideration is pack temperature. Not only is this a safety consideration, but consistent, high temperatures have the potential of reducing the cycle life of the pack. Because a significant amount of testing was performed on the first pack, the parameters recorded during the testing of the first pack (Voltage, Current, Demanded Power, Temperature, etc.) can be used to compare packs. Some profiles, such as power demand of the vehicle, can be used in simulation as a test profile to predict performance of this pack.

Figure 6 shows the results of the pack being subjected to a power profile (charge and discharge) as the XM1124 navigates the Hartford Loop at Aberdeen Proving Grounds. The pack is not actively cooled and the profile subjects the pack to demanding ("real world") charge and discharge cycles while the "vehicle" navigates the whole loop (in excess of 25 minutes). The results showed that with no active cooling, the pack met all performance requirements and only resulted in a 4 degrees C temperature rise inside the pack.

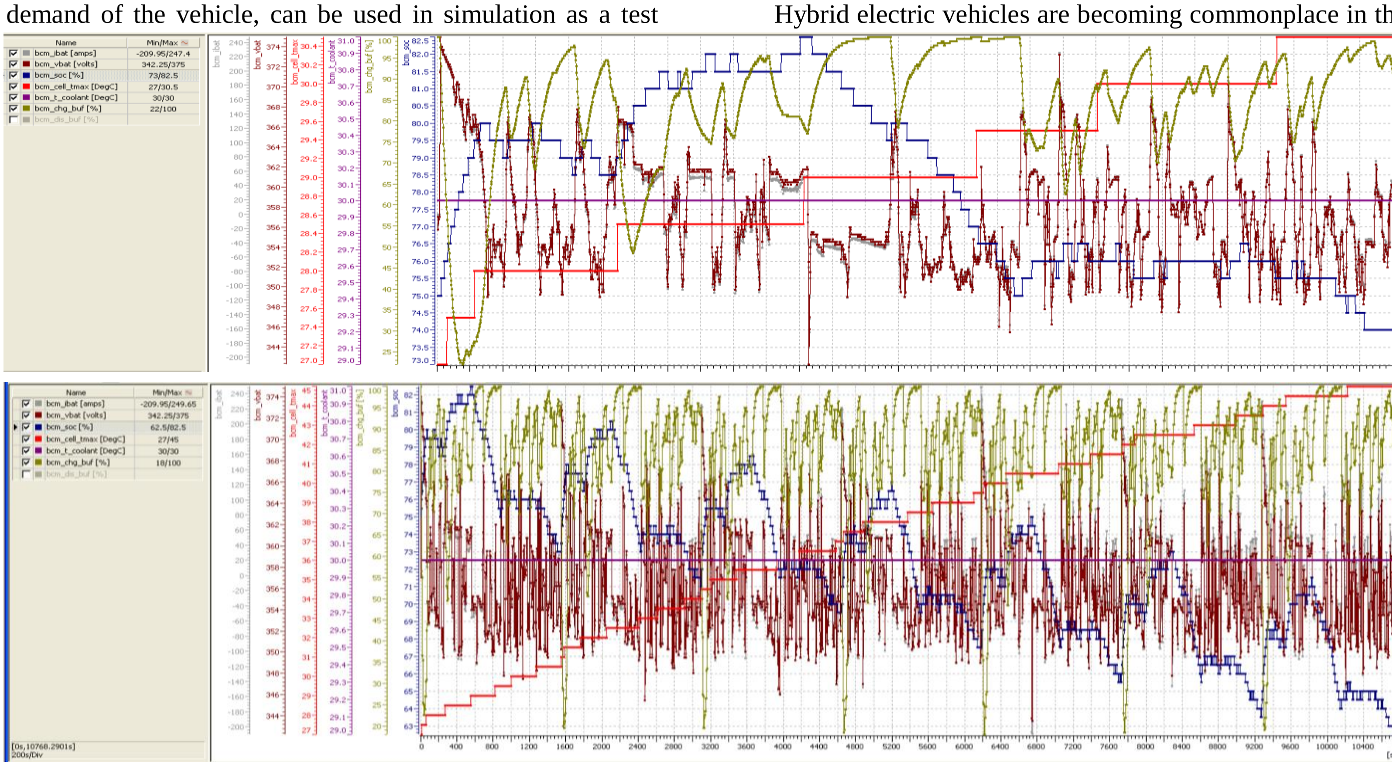
Figure 7 shows the same Aberdeen cycle that was simulated in Figure 6, but run for 3 hours. This would simulate the vehicle being driven around the loop approximately 7 times. This is similar to the "extended drive" test that was performed on the vehicle. The main concern during this test would be to determine if the vehicle could still maintain the performance metrics after significant periods of time. The results showed that the convection cooled pack still maintained all of these performance parameters with a temperature rise of less than 18 degrees over the entire 3 hours. The temperature stayed significantly under the Safe operating temperature of the pack and demonstrated its ability to perform. This test gave the team confidence, that when tested in the vehicle, it will perform well.

Pack Testing Results

At the time of publication for this paper, the pack had not completed its build and no test data is available. The team anticipates the pack build to be complete in early July 2011 with test data available in July/August 2011.

CONCLUSION

Hybrid electric vehicles are becoming commonplace in the



Figures 6 and 7. A123 XM1124 Pack using Hartford Loop Simulation Profile.

commercial automotive market. Due to their potential of reducing the dependence of fossil fuels and their ability to strengthen and support the grid, make them extremely important to the future. The XM1124 Hybrid Electric HMMWV is showing the potential of contributing to the long term power and energy strategy of the Army. As new technologies become available (advanced batteries, vehicle control algorithms, etc.) and as the DOD focuses on reducing the consumption of fuel in theatre, the HE HMMWV can support the future needs of DOD.

This paper described an advanced battery pack that is to be integrated into the HE HMMWV. It shows an extremely power and energy dense solution for the HE HMMWV with potential applications in other Hybrid DOD systems (renewable energy systems and advanced vehicles) as well as a multitude of commercial applications.

ACKNOWLEDGEMENTS

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