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LITHIUM-ION 6T BATTERY TECHNOLOGY- FIELD TESTING IN COMMERCIAL TRUCKS

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ABSTRACT

The overall goal of the program was to demonstrate use of Li-ion 6T –type batteries for commercial and military applications with a stable supplier base and verified business case. In the first phase of this program we demonstrated that Lithium-Ion 6T batteries can be successfully used in commercial vehicles as starter batteries. The results include the field testing of three battery suppliers in Class 8 truck tractors in a two different climate regions. For a future phase of the testing more challenging battery applications The Lithium-Ion 6T batteries would be used to power vehicle loads in addition to starting the engine. The applications we have identified include: 1) hotel load-idle reduction, 2) ePTO-Engine Start/Stop, 3) Hydraulic-Electric Lift-Gate.

INTRODUCTION

The use of Lead-Acid batteries as energy storage devices has widespread use in the commercial and military vehicle sector. Their low cost and reliable operation under different environmental conditions make them an attractive choice in a variety of applications. However, advanced battery chemistries and materials, specifically Lithium-Ion based materials, have increased power and energy densities, are much lighter in weight and have longer lifecycles. They can replace Lead-Acid batteries in a variety of vehicle applications.

These are important advantages with practical implications which have led the military to pursue development and testing of 24V Lithium-Ion batteries in the common NATO 6T form factor. One of the main barriers of advanced Lithium-Ion batteries is their high cost. If the use of these Lithium-Ion batteries can be expanded to the commercial sector, this would drive prices down and address the cost issue. For this reason, there is interest in expanding the market for Lithium-Ion NATO 6T form-factor military batteries by developing dual use of batteries that would meet the needs of both military and commercial sector.

The goal of this project was to develop 12V 6T form factor Lithium-Ion battery packs and evaluate their performance in commercial trucks. To the best of our knowledge, this is the first time that Lithium-Ion 6T batteries have field tested in commercial trucks.

BATTERY AND VEHICLE SELECTION

Battery Selection

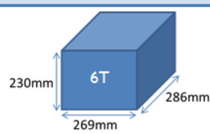
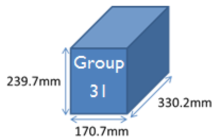
The project involved three different battery suppliers; Navitas, SAFT, and EaglePicher. Each of the three battery suppliers built six 12V 6T batteries for testing on commercial vehicles. The suppliers built their individual 6T batteries to the specifications outlined in Military Specification MIL-PRF-32143B [1], summarized in Table 1 below.

Table 1: NATO 6T Battery Specifications

Battery Metric	Value
Minimum Reserve Capacity (Minutes)	230 min
Minimum Ampere Hours (20-hour Rate)	120 Ah
Nominal System Voltage	12V
Capacity	120Ah @ 1C
Discharge rate and time 7.2V **@ -18°C** **@ -40°C**	1100A for 30 sec pulse 400A for 30 sec
Retention of charge @ 40°C Reserve capacity after 90 days	200 minutes
Operating Temperature Range	-20°C to 60°C
Storage Temperature Range	-46°C to 71°C

For this first field testing we chose to test the batteries in a starter application, being it is the most common application in a wide variety of commercial trucks. The commercial vehicle sector targeted in this project uses a standard Lead-Acid battery known as Group 31 in nearly all of its vehicles, regardless of make or model. This standard is primarily size-based and therefore dictates the physical dimensions and on-board placement of the vehicle battery compartment. Since the 6T batteries were replacing Group 31 units on the test vehicles, it was imperative that we fully understand the sizing considerations of this industry standard. The dimension specification of 6T and Group 31 are listed in Table 2 below.

Table 2: NATO 6T and Group 31 specified dimensions

	NATO 6T	Group 31
		
		
Max Length (mm)	286	330.2
Max Width (mm)	269	170.7
Max Height (mm)	230	239.7
Terminal Post	Straight Threaded	Tapered Threaded/Unthreaded

The three suppliers (identified as A, B, and C) use different cell chemistries and battery management systems (BMS) which control the operating procedures for each individual battery pack such as pack charging and cell heater activation. Supplier A employed cylindrical, Lithium-Iron Phosphate cells connected in a 13-parallel, 4-series configuration for a total of 52 cells per pack. Supplier B also employed Lithium-Iron Phosphate-based prismatic cells wired in a 4-series, 6-parallel configuration for a total of 24 cells per pack. Supplier C used Nickel Cobalt Aluminum Lithium-Ion cells wired in a 7-parallel, 3-series configuration for a total of 21 cells per pack. This chemistry was selected for its high power capability, long lifetime and excellent low temperature performance.

Test Vehicles and Regions

CALSTART identified a commercial fleet to conduct the field testing. This fleet is one of the market leaders in providing for-hire freight services. With more than 20,000 motorized vehicles in its ground fleet and approximately 355 service centers across North America, this fleet was an ideal partner for the project. Each battery supplier integrated the batteries into trucks operating within two regions of operations. Table 3 lists the characteristic of the vehicle.

Table 3: Vehicle Characteristics

Vehicle Characteristics	Description
Chassis Manufacturer / Model / Model Year	Kenworth / T800B / 2006 & 2007
Engine Manufacturer / Model	Cummins / ISX 450 L6, 14.9L
Power Rating	450 hp
Torque Rating	1,650 lbs.-ft. @1,200 rpm
Drive Line	4x2
Transmission	Eaton-Fuller 10 speed FR15210B
GVWR	34,700 lbs
Alternator	PACCAR D27-6001-0130P
Voltage / Current	12V / 130A
Batteries	Interstate 31-LHD
Capacity	99 Ah
Cold Cranking	4 x 750 CCA (3000 CCA)
Dimensions	Group 31 (L = 12 ¾ in., W = 7 ¾ in., H = 8.5 in.)
Cycle Life (J-2185 Cycles)	~200
Weight	59 lbs.
Price	~$100 and Includes disposal/recycling costs
Battery Compartment Location	38 in. x 34 in. / Below cab
Battery Replacement Interval	Checked & cleaned 36,000mi Changed if failing / ave 3 to 5
Vehicle Electronics	Minimum voltage required 12.3V
Cable Size Gauge	Dynacraft Flex HD: 4/0, 2/0, 1/0

The selected fleet uses the same Class 8 day-cab truck tractor specification nationwide, though it purchases a variety of different makes and models. For their starter systems the trucks use four 12V Lead-Acid Group 31 batteries. The amperage rating for the industry-standard Group 31 battery is quite variable, ranging anywhere from 700 to 1000 Cold Cranking Amps (CCA). The partner fleet standard uses four Group 31 batteries, for a minimum starter system capability of 3000 CCA. This system was replaced with three 6T batteries per vehicle to provide the same minimum starter system capability.

San Bernardino, California service center was selected as the hot and mountainous location and the Henderson, Colorado service center as the cold and mountainous location. The purpose of the two test regions was to ensure a performance evaluation across a wide range of environmental and operating conditions.

Test Plan

The original Lead-Acid starter batteries were replaced by the 12V 6T Lithium-Ion batteries. Three trucks were tested in the cold region and three in the hot region for a period of 6 months each. The trucks were also equipped with data logger systems to track the vehicle and battery performance parameters during the testing. The data was collected via CAN bus / J1939 using Isaac Instruments DRU900 data loggers and GPS receiver at frequency of 1Hz. Table 3 and 4 list the vehicle and battery parameters tracked.

Table 3: Vehicle parameters

Parameter	Units
Time	Seconds
GPS Altitude	m
GPS Speed	km/h
Accelerator Pedal Position	%
Drivers Demand Engine Percent Torque	%
Actual Engine Percent Torque	%
Engine Speed	RPM
Engine Demand Percent Torque	%
Transmission Current Gear	-
Engine Coolant Temp	°C
Parking Brake Switch	-
Wheel Based Vehicle Speed	km/h
Engine Fuel Rate	l/h
Ambient Air Temperature	°C
GPS Latitude	-
GPS Longitude	-

Table 4: Battery parameters

Parameters	Units
Current	A
Voltage	V
State of Charge	%
Temperature	°C
Error Messages	-
Alternator Current	A

Wireless transfer was used to access and download the data from each truck.

RESULTS

Battery Installation

The installation process involved replacing original 4 Lead-acid batteries with 3 6T Lithium-Ion 12V batteries.

Figure 1: Existing Group 31 Lead-Acid batteries

Figure 2: 6T batteries in the existing compartment

In order to fit the batteries properly and safely, custom designed hold-down trays needed to be included during the installation of the 6T batteries. This shows that the replacement is not exactly a drop-in process.

This was the most significant addition during the installation. The CAN line routing, data logger installation, and power and communications connections

Performance Results

Table 5 below summarizes the data collected on the six trucks operating in California and Colorado.

Table 5: Summary of field testing

Recorded Days	**328 days**
Engine Time	2,195 hours
Cranking Events	8,699 times
Distance Travelled	88,476 miles
Fuel Consumed	14,248 gallons
Average Fuel Economy	6.2 MPG
Average Driving Speed	39.0 MPH
Min. Ambient Temperature	-26.8°C on February 5th, 2014 in Colorado
Max. Ambient Temperature	+45.6°C on September 9th, 2013 in California

All six trucks operated for a total of 328 days, representing 2,195 hours of engine operation. The Lithium-Ion 6T batteries successfully started the trucks 8,699 times, an average of 26 times per day in operation. The six trucks covered more than 88,400 miles over Arizona, California, Colorado, Kansas, Nevada, New Mexico and Utah and at an average driving speed of about 39 MPH.

Throughout the nine months of data collection, the six trucks operated under a wide variety of weather and climate conditions. For instance, the maximum recorded ambient temperature during truck operation was 45.6°C on September 9th, 2013 in California and the minimum recorded ambient temperature during truck operation was -26.8°C on February 5th, 2014 in Colorado.

The batteries started the commercial Class 8 truck tractors successfully in all cases. Table 6-11 show the operations data in the hot and cold regions during the field testing. The number of starting events per truck was 15-30 per day.

Table 6: Summary of vehicle operation data for Supplier A truck in California (hot region).

Recorded Days	Cranking Events	Distance	Fuel Econ. MPG	Min T, °C	Max T, °C
98	2559	18,607	6.9	-16.3	+45.6
	Ave 26/day				

Table 7: Summary of vehicle operation data for Supplier B truck in California (hot region).

Recorded Days	Cranking Events	Distance	Fuel Econ. MPG	Min T, °C	Max T, °C
9	196	2530	6.9	-10.9	+37.1
	Ave 22/day				

Table 8: Summary of vehicle operation data for Supplier C truck in California (hot region).

Recorded Days	Cranking Events	Distance	Fuel Econ. MPG	Min T, °C	Max T, °C
86	2619	44,167	5.7	-21.8	+39.8
	Ave 30/day				

Table 9: Summary of vehicle operation data for Supplier A truck in Colorado (cold region).

Recorded Days	**Cranking Events**	**Distance**	**Fuel Econ. MPG**	**Min T, °C**	**Max T, °C**
22	359	8643	6.4	-26.0	+16.0
	Ave 16/day				

Table 10: Summary of vehicle operation data for Supplier B truck in Colorado (cold region).

Recorded Days	**Cranking Events**	**Distance**	**Fuel Econ. MPG**	**Min T, °C**	**Max T, °C**
74	1993	9914	7.5	-26.8	+28.5
	Ave 27/day				

Table 11: Summary of vehicle operation data for Supplier C truck in Colorado (cold region).

Recorded Days	**Cranking Events**	**Distance**	**Fuel Econ. MPG**	**Min T, °C**	**Max T, °C**
39	973	4615	6.3	-13.5	+25.7
	Ave 25/day				

A direct comparison between battery suppliers is difficult because each supplier installed Lithium-Ion 6T batteries on trucks that were slightly different (mileage, model year, etc.) and each was operated in different routes (pick-up and delivery and/or line-haul) and under different weather. However, we observed several differences and similarities between the suppliers.

Variation in State of charge (SOC) among battery suppliers was the most significant difference. Supplier C had small SOC variation, Supplier B moderate, and Supplier A high. Figure 3 below shows state of charge variations for Supplier A.

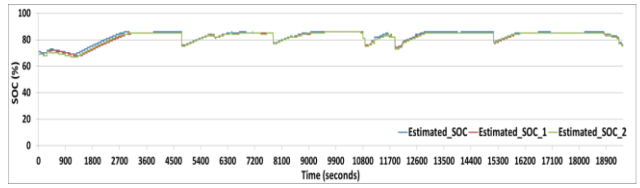


Figure 3: State of Charge on January 7, 2014 for Supplier A truck in California

Cell temperatures were very different between the 3 battery suppliers. All battery suppliers installed internal cell heaters were deactivated for the batteries provided by Supplier B. Figure ES-6 below shows the cell heaters warming up the cells of Supplier A batteries in about 10 minutes from below 0°C to about 10°C.

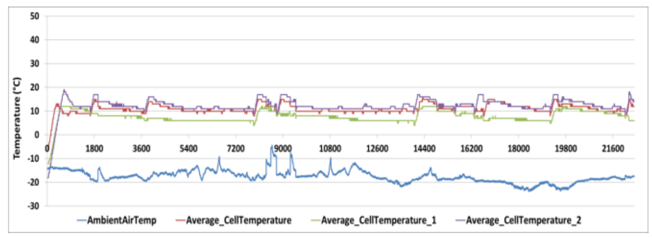


Figure 4: Ambient & battery temperatures on December 5, 2013 for Supplier A truck in CO

A decrease in state of charge was observed for each battery supplier when the vehicle was not in use (over the weekend for instance). Figure 5 below shows that the batteries state of charge for Supplier C batteries dropped roughly 60% while the vehicle was not in use for over 5 days f. The decrease in state of charge was a result of the battery electronics consuming energy when the batteries are in sleep mode.

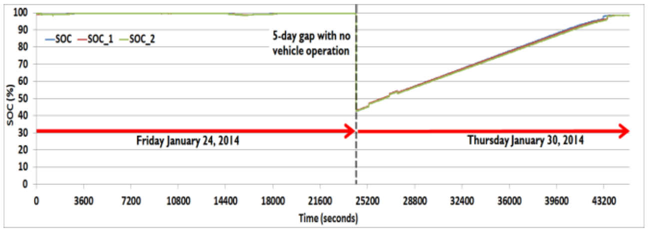


Figure 5: State of Charge on January 24th and 30th, 2014 for Supplier C truck in California

Voltage and capacity testing after the field service from one battery supplier indicate the batteries could be expected to last at least 4-5 years in the warm temperature climate. Results showed that colder temperatures negatively impact battery life due to cell heater power consumption.

Vehicle and Battery Issues

As previously mentioned, the Lithium-Ion batteries performed well in the starter application. Some issues that were encountered involved data communication issues between the battery management system and the Isaac data loggers which meant that certain parameters were not collected.

Some vehicles were forced out of service due to a faulty EGR value in one case and a leaky head gasket in another. While in the shop for repair, the batteries were over-discharged due to repeated cranking. This then caused a failure of the battery. In the other event the batteries were not connected properly and a lose cable caused a short circuit that forced the batteries into a safe mode. None of the issues of pulling the vehicle out of service were caused by malfunctioning of the batteries themselves.

Conclusions and Future Work

Lithium-Ion 6T batteries from each supplier were successfully integrated on six commercial Class 8 day cab truck tractors in California and Colorado. The performance evaluation provided valuable information to validate that Lithium-Ion 6T batteries can be used as substitutes for conventional Lead-Acid starter batteries and generated preliminary performance statistics of the batteries provided by three battery suppliers.

We found that the NATO 6T format can fit into existing commercial trucks with modifications to the battery box.

We demonstrated that batteries from all suppliers worked well as engine starter batteries for commercial Class 8 day cab truck tractors. The Lithium-Ion 6T batteries successfully started the test trucks 8,699 times, an average of 26 times per day in operation. They also operated without any major issues in ambient temperatures ranging from -26.8°C and +45.6°C.

We found that commercial fleets are interested in batteries that are more reliable and last longer than current Lead-Acid Group 31 batteries. While Lithium-Ion 6T batteries work well as engine starter batteries for commercial Class 8 day cab truck tractors, we determined that, unless customers are willing to pay a premium for battery reliability, engine starter batteries may not be the best application because of high costs and limited return on investment.

As a next step and an immediate follow-up to this project we believe commercialization pathways should be explored that target trucks using considerable fuel to power accessories and/or idle for long periods of time. In particular, current Lead-Acid starter batteries could be replaced with Lithium-Ion 6T batteries on a Class 8 day cab truck tractor with high vehicle accessory usage or on a Class 8 sleeper cab truck tractor. The Lithium-Ion 6T batteries would be used to power vehicle loads in addition to starting the engine. The applications we have identified include: 1) hotel load-idle reduction, 2) ePTO-Engine Start/Stop, 3) Hydraulic-Electric Lift-Gate.

REFERENCES

[1] Military Specification MIL-PRF-32143B, Available at: www.everyspec.com/MIL-PRF/MIL-PRF-030000-79999/download.php?spec=MIL-PRF-32143B.037624.PDF

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