Anti-Idling Battery for Truck Applications

Final Scientific / Technical Report for Assistance Agreement DE-EE0001038

December 30, 2011

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1.0 Introduction / Executive Summary

In accordance to the Assistance Agreement DE-EE0001036, the objective of this project was to develop an advanced high voltage lithium-ion battery for use in an all-electric HVAC system for Class-7-8 heavy duty trucks. This system will help heavy duty truck drivers meet the tough new anti-idling laws being implemented by over 23 states.

Quallion will be partnering with a major OEM supplier of HVAC systems to develop this system. The major OEM supplier will provide Quallion the necessary interface requirements and HVAC hardware to ensure successful testing of the all-electric system. At the end of the program, Quallion will deliver test data on three (3) batteries as well as test data for the prototype HVAC system.

This contract began in December 2009 and this is the final summary report for the project which concluded in December 2011.

2.0 Financial Info, Objectives & Accomplishments

At the end of December 2010, Quallion has accumulated $1,903,000 out of a contract award of $1,903,000 awarded. Quallion provided a 50% cost share to that point, but then funded the program to completion with internal resources.

The objectives of the program are shown below.

- Battery Development
    - Objective 1: Define battery and electronics specifications in preparation for building the prototype module. (Completed – summary included in report)
    - Objective 2: Establish a functional prototype battery and characterize three batteries in-house. (Completed – photos and data included in report)
- HVAC Development
    - Objective 1: Collaborate with manufacturers to define HVAC components, layout, and electronics in preparation for establishing the prototype system. (Completed – photos and data included in report)
    - Objective 2: Acquire components for three functional prototypes for use by Quallion. (Completed – photos and data included in report)

The major milestones and status for this program are listed below

- Battery design and process development: April 2010 – June 2010 (Complete)
- HVAC system assembly: June 2010 (Complete)

- Testing: September to October 2010 (Complete for three batteries)
- Final report: December 2011 (This document)
- Prototype Battery data to DOE March 2011 (Complete – included in report)

3.0 Summary of Work Performed

In December 2009, Quallion held a kick-off meeting with the DOE and discussed our plan forward, the system design with the HVAC OEM, program funding and major tasks. In addition a preliminary concept drawing for the Quallion high voltage battery was developed and sent to the HVAC OEM.

Since the initial kick-off meeting, Quallion has acquired a Class 8 truck for testing, completed a battery design and assembly process, developed an electrical system design, developed and programmed a test plan, and established where the battery is to be placed on the system. Further, we acquired the first prototype HVAC components, integrated them with the first prototype battery and installed the components on the truck. Quallion and the HVAC supplier also performed testing of the prototype system as installed on the truck and of all three batteries. Details regarding these developments are in the sections that follow:

3.1 All-electric HVAC System Level Design

An anti-idling battery would operate in a complex system involving an engine, a battery, and a charging mechanism. During main engine shutoff the anti-idling battery would power the HVAC system by pushing current through a compressor; in this case, a specially developed compressor that uses electrical energy instead of mechanical energy. These distinct parts of the process will operate on different voltages: the alternator of the main engine battery operates on 12V, the anti-idling battery will operate on a different voltage (dependent on specifications) and the compressor of the HVAC system will operate on 288V. Those differences in voltage will mandate the use of DC-DC converters at one or more steps in the process. The HVAC system that uses a battery for power would have the components listed in **Table 1** and **Figure 1**.

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Battery HVAC System Components
Alternator
DC-DC Convertors (2 types)
Condenser
Blower
Circuit Breaker
Noise Filter
Battery Charger
Charge/Discharge
Inverter
Compressor
HVAC Electric Management
Battery Cooling System

Table 1: Electric HVAC Component Parts

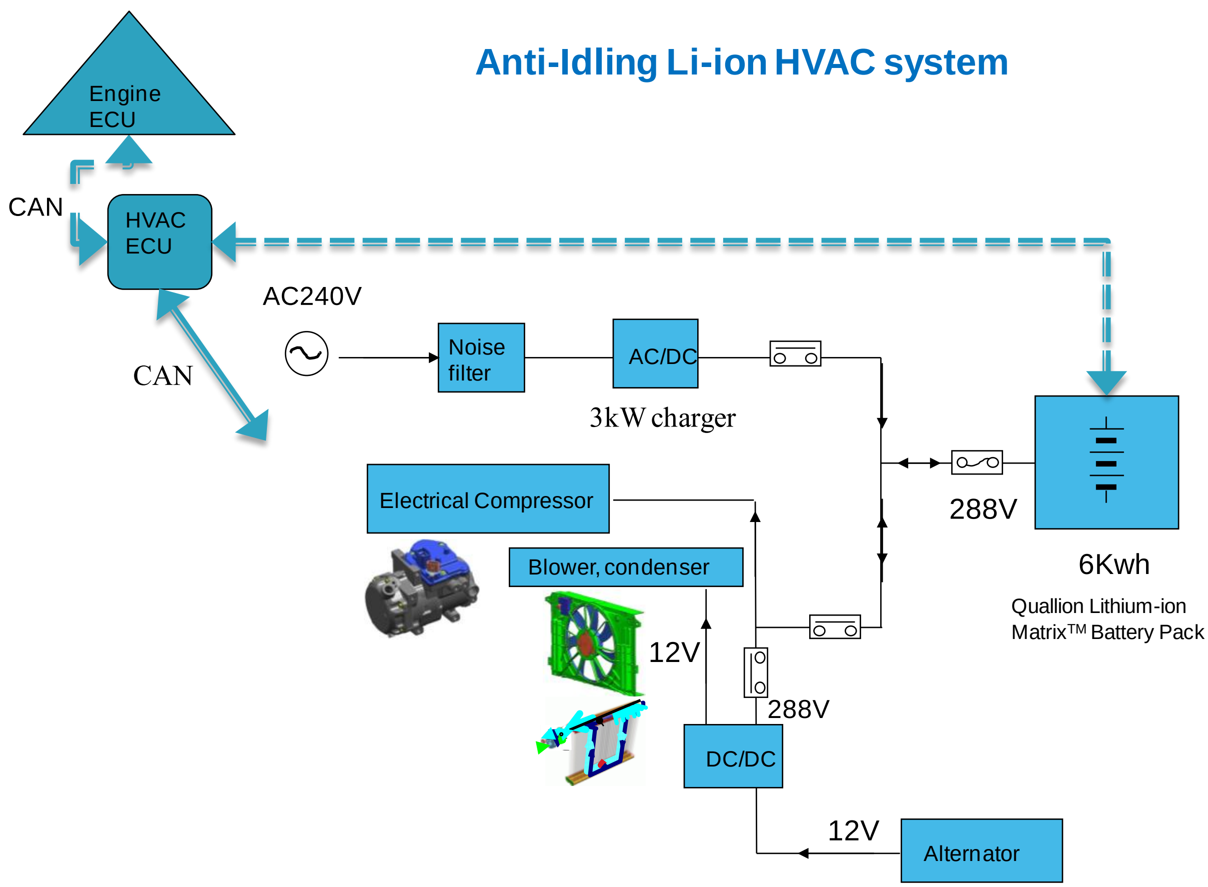


Figure 1. System Overview

Quallion has completed our negotiation with the HVAC OEM supplier and has procured the HVAC system design. **Figure 2** shows the preliminary system fit check design of the HVAC component with battery would fit into a sleeper cab. In addition, the OEM supplier has provided a sample HVAC duty cycle for Quallion to design our battery system. **Figure 3** shows this expected duty cycle.

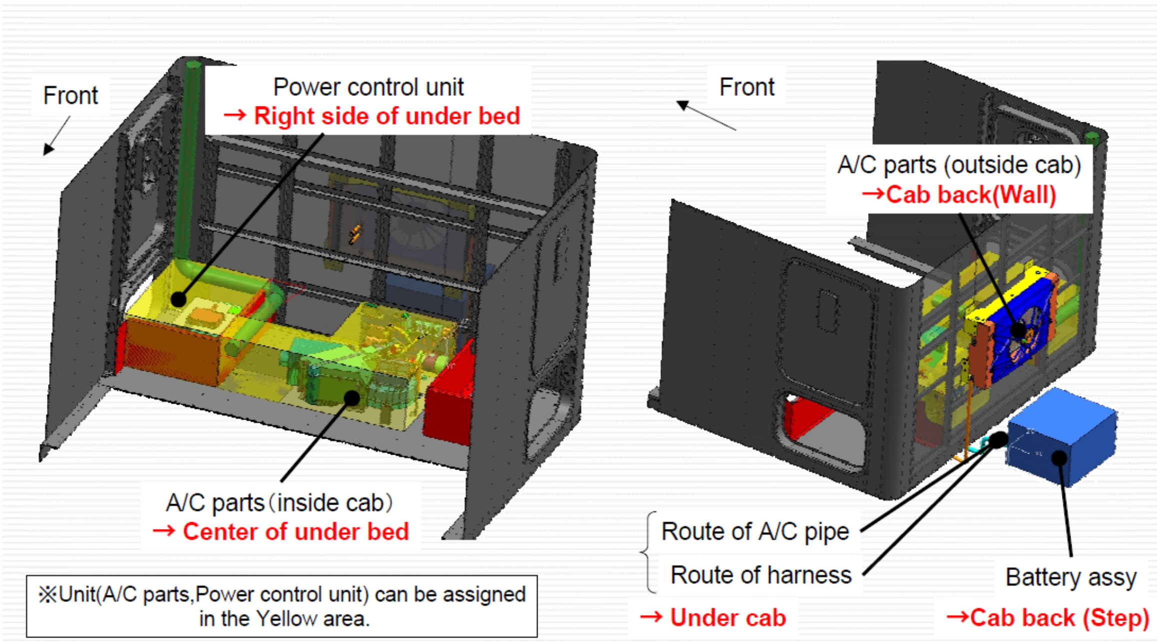


Figure 2. Installation Idea of Battery HVAC System.

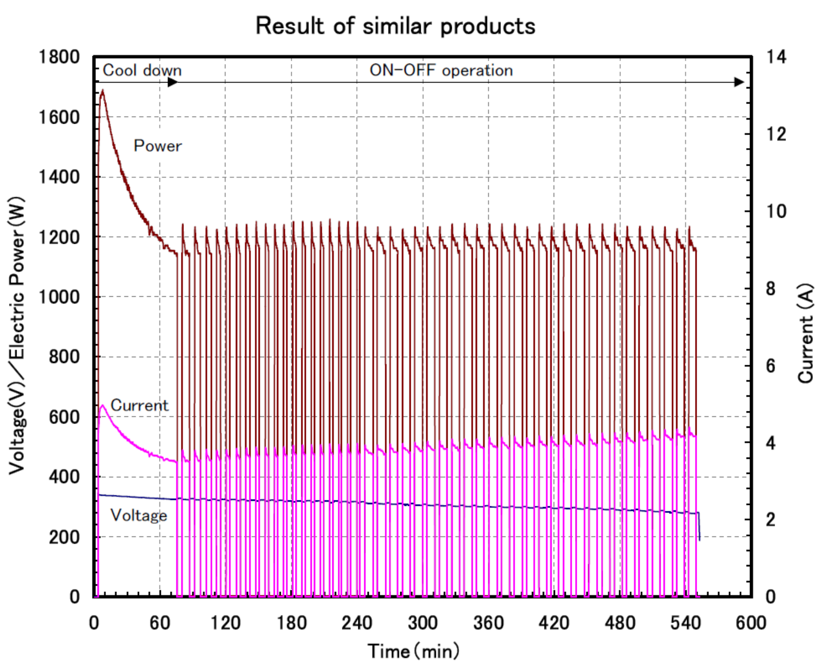


Figure 3. Expected Power Profile

3.2 Quallion All Electric HVAC System Design

(Proprietary Data Redacted)

Figure 4. Quallion System Design

Quallion's all electric HVAC system design uses a 6kWh battery to power an HVAC system. The battery can be charged via two methods:

1. Truck Engine
2. Plug-in (to electric circuit); the Quallion system is unique as it has the capability to be plugged in.

The system battery charges in 3 hours via an AC-DC inverter with either method of charging. The ability to charge in two modes makes the system more efficient and allows for extended use anti-idling even when the truck is not driven for an extended period.

The battery system discharge also has two modes:

1. A 12V discharge that allows for the powering of HVAC components such as the condenser, blower and/or evaporator. And,
2. A 288V discharge that powers an electric compressor that powers the Air Conditioning compressor.

The high voltage discharge option is a critical design element as it improves system efficiency. If a low-rate discharge were to power an electric compressor for an air conditioner, much of the battery energy would be dissipated in the process. The high-voltage design thereby allows for a smaller battery system overall that is capable of supporting an HVAC system for a class 9 truck. The system designed is theoretically capable of cooling a truck cab for at least 9 hours.

3.3 Current Battery Specification

Quallion has finalized the design for the lithium-battery envelope for this HVAC system. The system uses a commercial cell with a standard rating of 3.3 – 4.1 V. The basic module specification is detailed in **Table 2** below. Dimensions and characteristics for the entire battery system are detailed in **Table 3** below. Internal space claims have been allocated to allow for high voltage battery electronics as well as interface boards for SPI communication. As a safety mechanism, the system is equipped with a 500V 30A fuse. The charge-discharge parameters of the system are detailed in **Table 4**.

Module Specifications	
Voltage	**Typical 296V**
Voltage Range	**264-328V**
Usable Capacity (at 1C)	**15.8 Ah**
Energy	**4.7kWh**
Maximum Charge Voltage	**328V**
Discharge end Voltage	**264V**
Maximum charge current	**14A**
Maximum discharge current	**20 A (continuous current)**

Table 2: Quallion Base Module Specification

System Specifications	
System Dimensions	**33.5” x 25.3” x 32.5”**
Weight	**240lbs**
Volume	**15.94 ft^3**
Operating temperature	**-20 to 50°C**
Storage Temperature	**-20 to 50°C**
Installation Site	**On the chassis of the truck (outdoor)**
Waterproof	**IP67**
Vibration	**Withstand typical road vibration (class 8 Truck)**

Table 3: System Specifications

Charging	
Upper limit of charging voltage	**330V**
Charging Ampere	**3A**
Charging Characteristics	**CC/CV**
Discharge end voltage	**328V**
Charging rate	**0.186C**
Discharging	
Normal Discharge	**4-6A/DC, 15 A/DC max.**
Cut off voltage	**DC264V**

Table 4: System Charge - Discharge Parameters

3.4 Battery Design

3.4.1 Mechanical

The system mechanical design has been finalized with a drawing shown in **Figure 5.** The system designed is capable of handling expected truck vibrations via the use of a mounting bracket that will be used to attach it to the truck cab. A Bill of Materials (BOM) has been compiled to catalog and manage system parts. Parts have been assigned numbers and procured as needed to meet project needs.

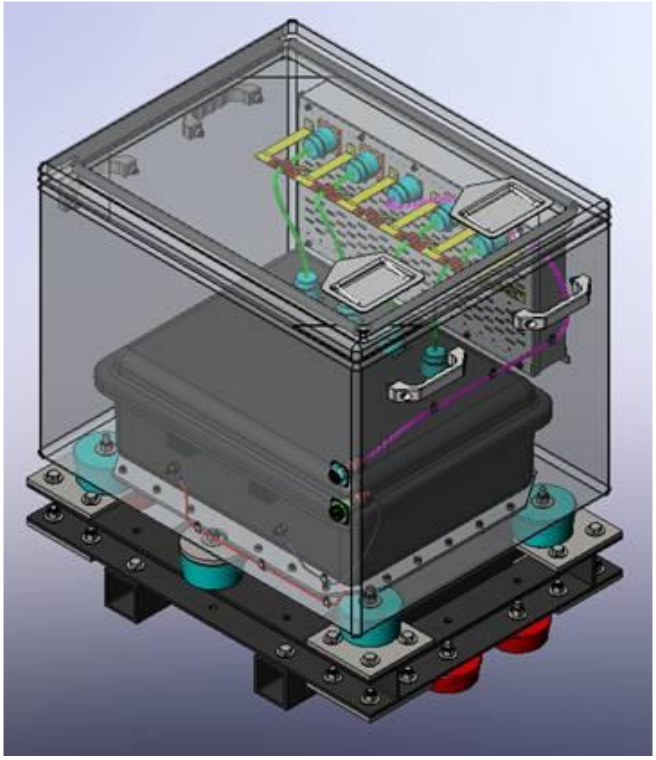


Figure 5. Mechanical Design

3.4.2 Quallion Design Element: S-BMU

As shown in **Figure 4**, the Quallion all electric HVAC system includes an S-BMU (Slave Battery Management Unit) located next to the battery a well as the M-BMU (Master Battery Management Unit) which has a direct connection to the HVAC ECU (HVAC Electrical Control Unit) and computer monitors.

The S-BMU is created as an intermediary system by which the analog data from the battery is coalesced and converted to a digital feed which is then sent the M-BMU (2 connections). The M-BMU is the main processor controlling the battery and is the mechanism by which the battery system interfaces with the HVAC ECU and monitoring devices. The HVAC ECU is what then further interfaces with the entire truck system ECU. If it were not for the S-BMU, the M-BMU would have many connectors from the battery (80 – 100) relaying analog data. The M-BMU would have to parse the data to be able to use it further. The number of connections as well as the added load to the M-BMU would complicate the BMU design. By separating battery raw data through the S-BMU the communications process within the system can be streamlined.

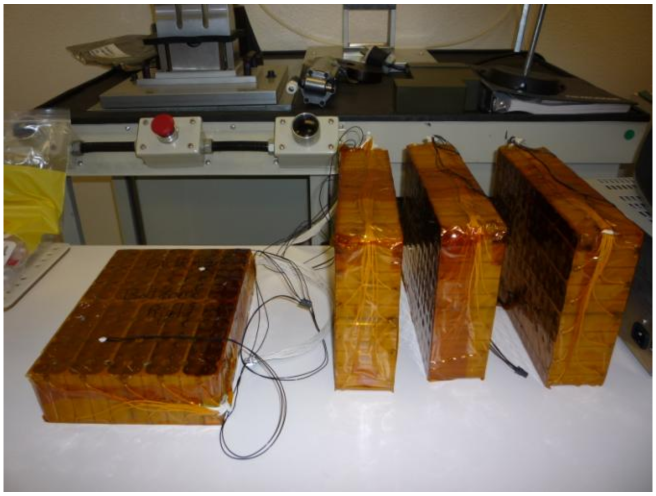
Figure 6. Testing Electronics Boards

3.5 Battery Manufacturing Status

3.5.1 Assembly Process

Quallion has completed assembly of the first prototype battery that is now mounted on the truck cab. The general assembly process is as follows with the images in **Figure 7** highlighting assembly steps:

- Sub-modules of 20 S x 7 P modules were fabricated.
- Four sub-modules were assembled and stacked into a complete core cell pack of 80 S x 7 P configuration.
- The stacked assembly was installed into a plastic casing and integrated with sensor wiring, data connectors, safety fusing, and power wiring.
- The core pack assembly was installed into the metal truck box.
- The HVAC OEM electronics was installed into the metal truck box, and the electronics were integrated to the data connectors of the core pack assembly.
- The metal truck box was installed onto the truck.



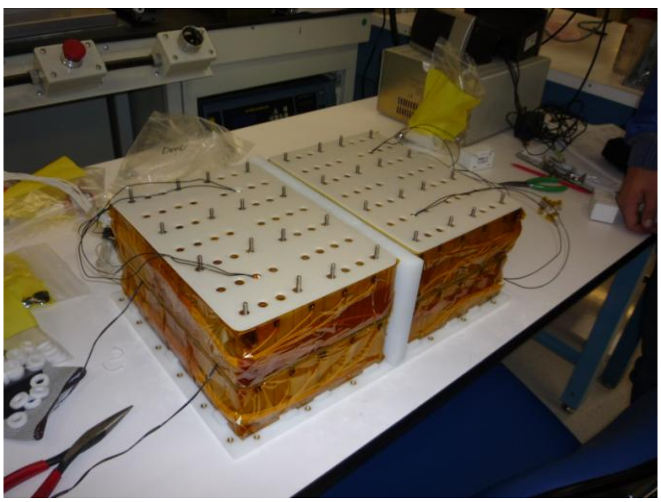


Figure 7. Battery Assembly Process

Figure 8. Battery and Evaporator Mounted on Truck

3.6 Battery Test Plan

Quallion has created software in order to test the battery system developed as part of the DOE anti-Idling project. The test protocol has been designed to measure a multitude of things including charge time, discharge time, and voltage (over time) of the battery. Additionally, the testing plan includes tests which will validate system operation parameters including the ability to cool for ≥9 hours, the extent to which a truck cab is cooled (measure relative to outside temperature), temperature distribution within the cabin, as well as system charging time. These extensive tests will thoroughly quantify system abilities.

3.7 Vehicle Integration and Location

Conventional class 8 trucks place the battery in the orientation shown in **Figure 9** but the newly designed battery pack from Quallion will be placed in the orientation in **Figure 10** eliminating the need for engine cooling. Quallion has designed the communication between the battery system and the truck HVAC system to operate on the SPI protocol per the HAVC OEM specifications.

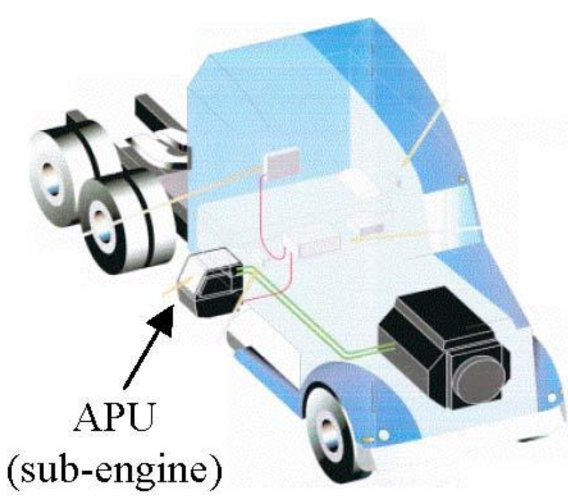


Figure 9. Conventional Battery Orientation

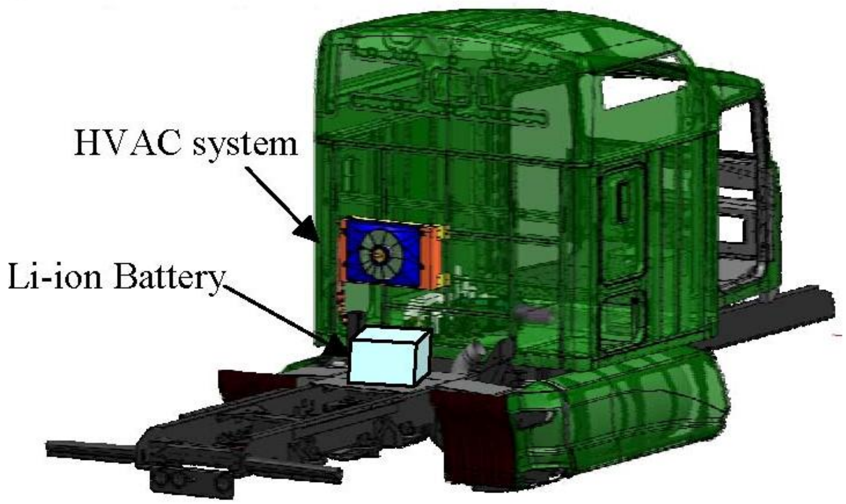


Figure 10. New Battery Orientation

3.8 Battery Powered HVAC System Test Results

Test Objectives:

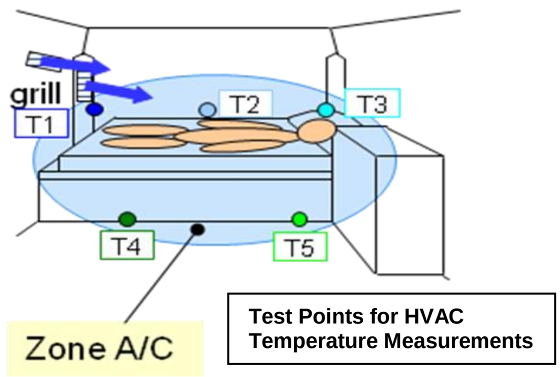
Battery

- Obtain battery charge, discharge and thermal characteristics
- Confirm battery charge time
- Verify ability to charge battery using truck alternator or wall current

HVAC Components

- Verify cooling performance
- Confirm occupant comfort level

Figure 11. Test Setup



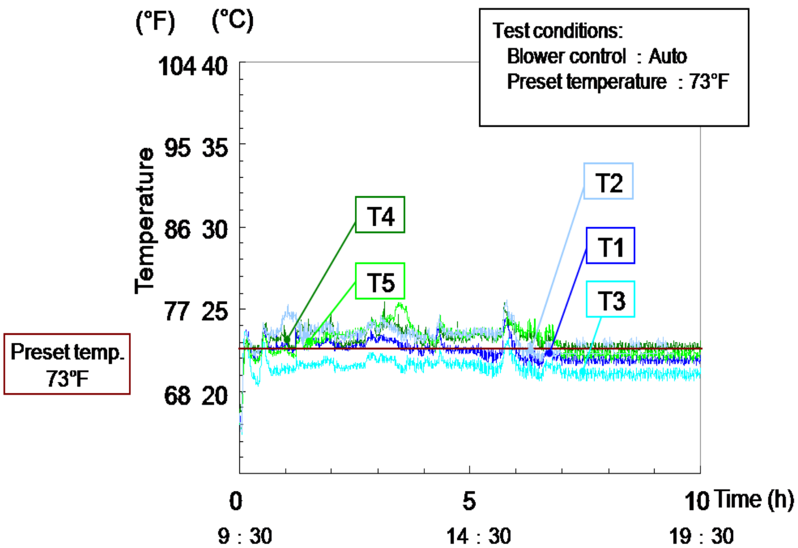


Figure 12. Cabin Temp. vs. Time

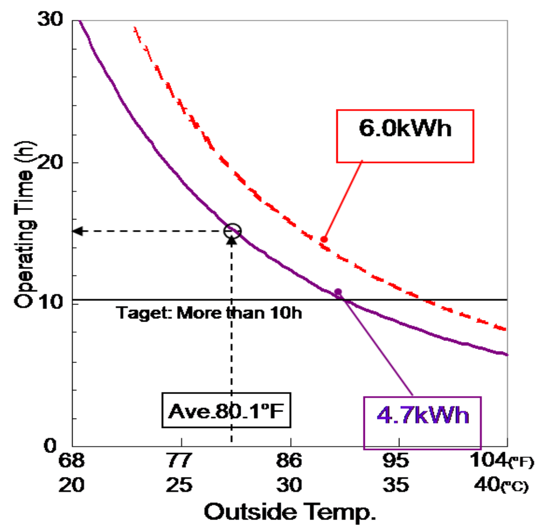


Figure 13 Op. Time for Given Battery Power

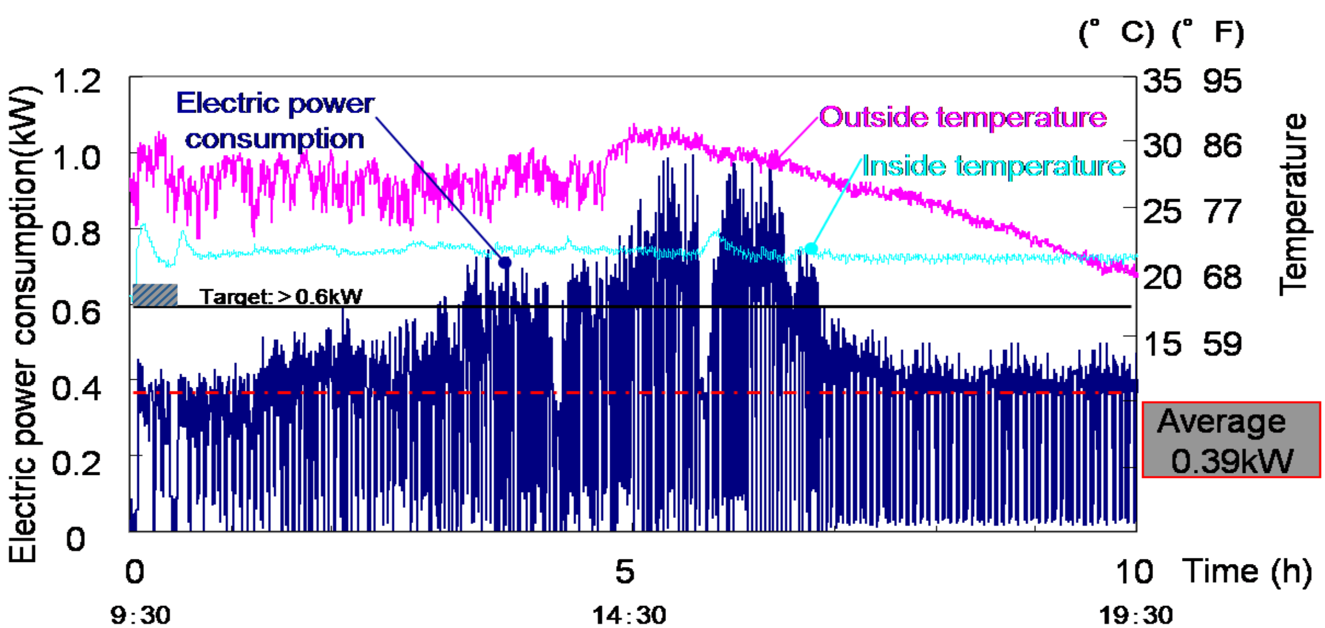
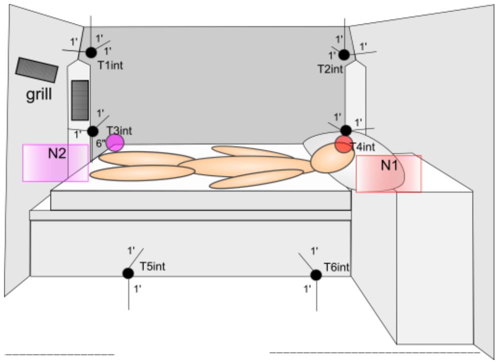


Figure 14 Power Consumption and Inside / Outside Temperatures vs. Time



		Li-ion HVAC	Original rear A/C
Panel side (N1)		56.2dBA	65.7dBA
Air outlet side (N2)		59.6dBA	68.1dBA
Engine Operation State		Off	Idle
A/C	Blower	Hi	Hi
A/C	Compressor	3000rpm	Idle

Figure 15 Operational Noise Measurements Set Up and Results vs. OEM A/C System

3.9 Assembly of Two Additional Prototype Batteries

In the October through December period Quallion assembled two additional batteries:

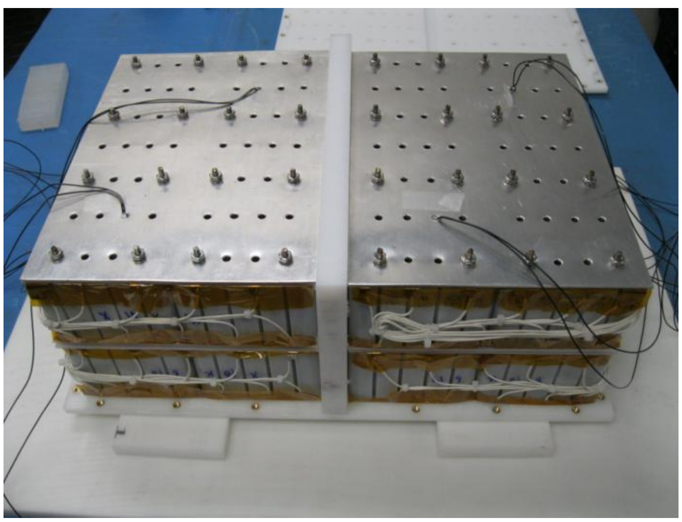


Figure 16 Assembly of Two Additional Battery Packs

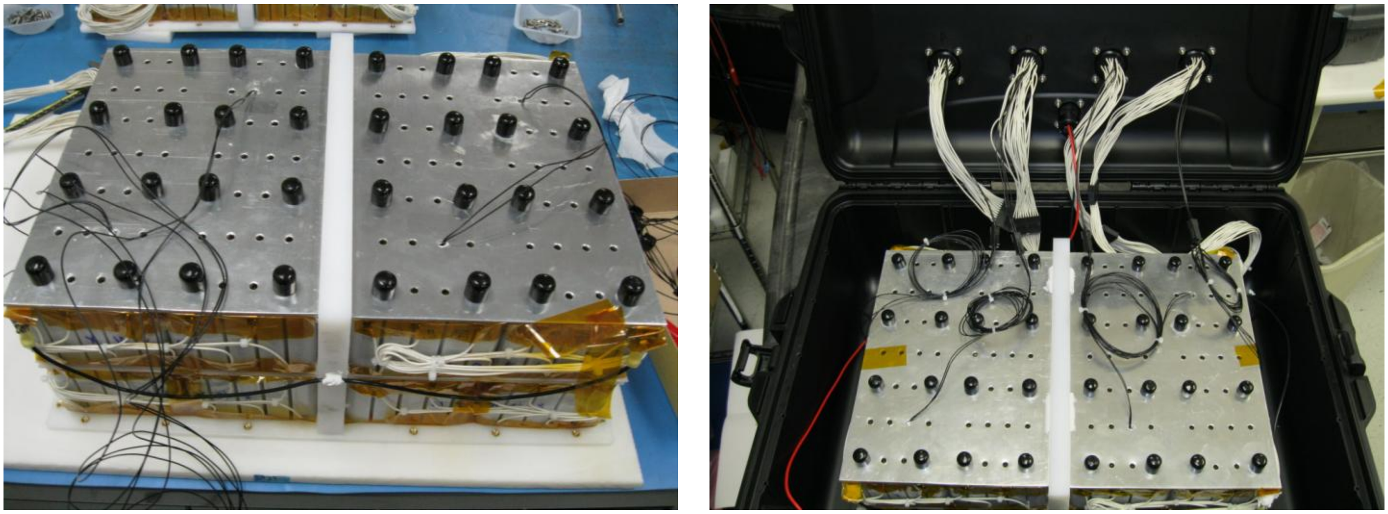


Figure 17 Installation of Battery Packs In The Case

After assembly, the batteries were integrated with the slave battery management unit and connected to the test equipment.

Figure 18 Completed Batteries Integrated with Slave BMU and Test Equipment

3.10 Test results of the final two batteries

3.10.1 Test result of battery without the slave BMU

The two batteries without the slave BMU were evaluated under the following conditions.

Charge: Constant Current (CC) 3A, 328V, then Constant Voltage (CV) until 0.186A cutoff at R.T.
Discharge: Discharge Constant Current (CC) 5A to 264V at R.T.

Figure 19 shows the voltage and current profile during the charging. Table 4 summarizes the charging time for module 1 and 2. Both modules took about 7 hours to complete the charge. After charging, the batteries were discharged at 5A to 264A shown in Figure 20. Table 5 summarizes the discharging time and capacity.

Both module 1 and module 2 delivered around 15.90 Ah and total discharge time was 3.1 hours. Both modules exhibit similar characteristics.

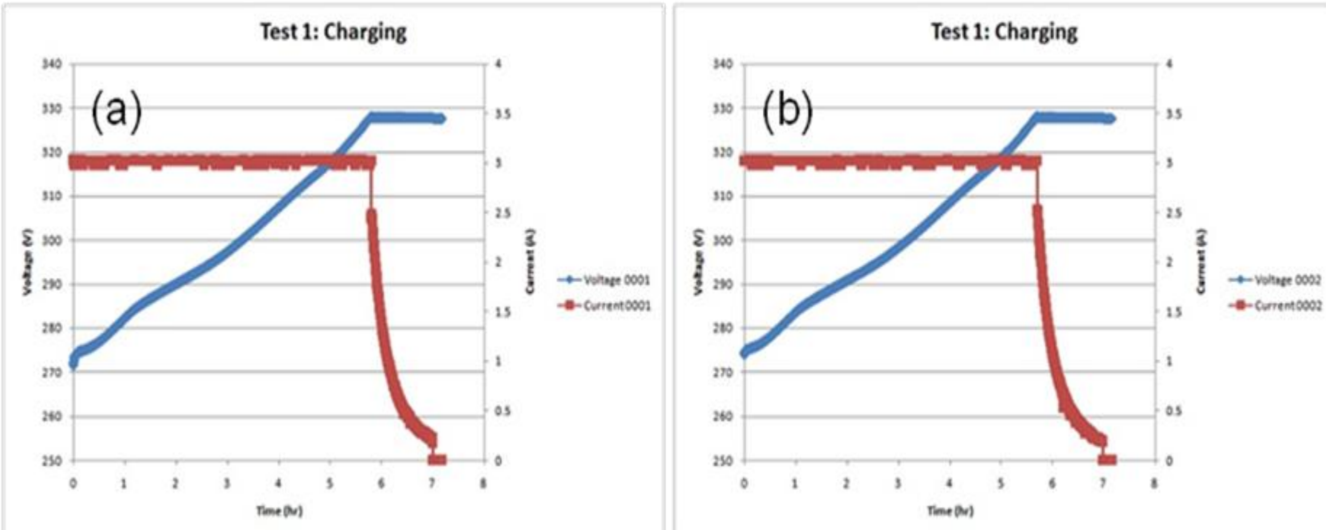


Figure 19 Voltage and current profiles of (a) module 1 and (b) module 2.

Table 4 Charge time and capacity for module 1 and module 2

Module	Module 1	Module 2
Charge time (h)	7.17	7.15

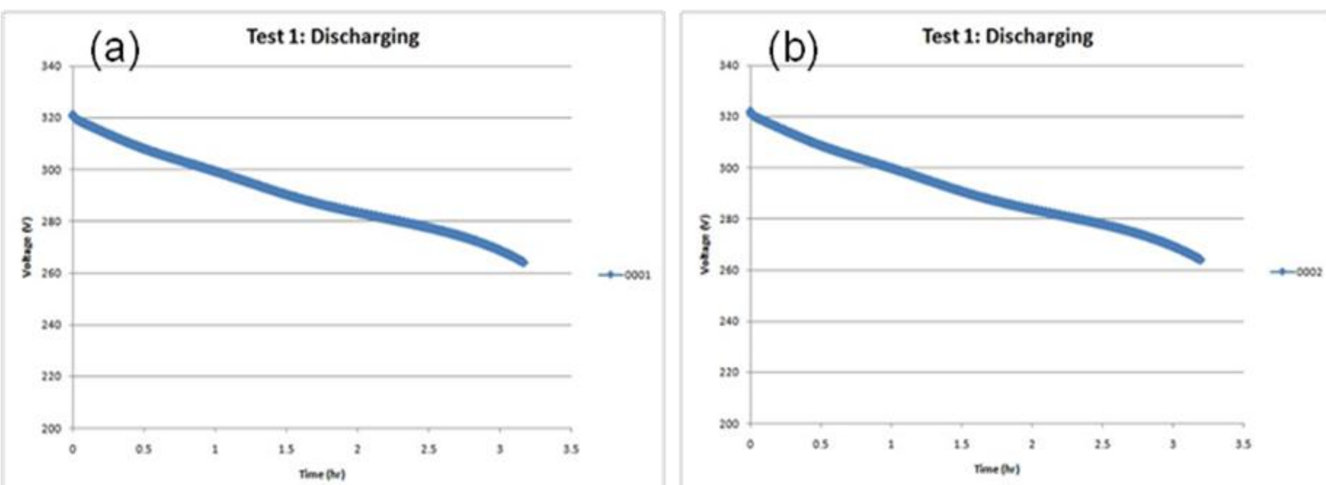


Figure 20 Discharge profiles of (a) module 1 and (b) module 2

Table 5 Discharge time and capacity for module 1 and module 2

Module	Module 1	Module 2
Discharge time (h)	3.16	3.19
Discharge capacity (Ah)	15.80	15.95

3.10.2 Test results of battery with the slave BMU

After module level testing, the modules were connected to the slave BMU shown in Figure 21. The voltages of the modules with the slave BMU were monitored over the 3 hours to check for any leakage current or shorting. Figure 22 exhibits the voltage change for both packs. Both packs show the voltage drop less than 0.05V and does not indicate a short or large leak current by the slave BMU.

Figure 21 the module connected to the slave BMU

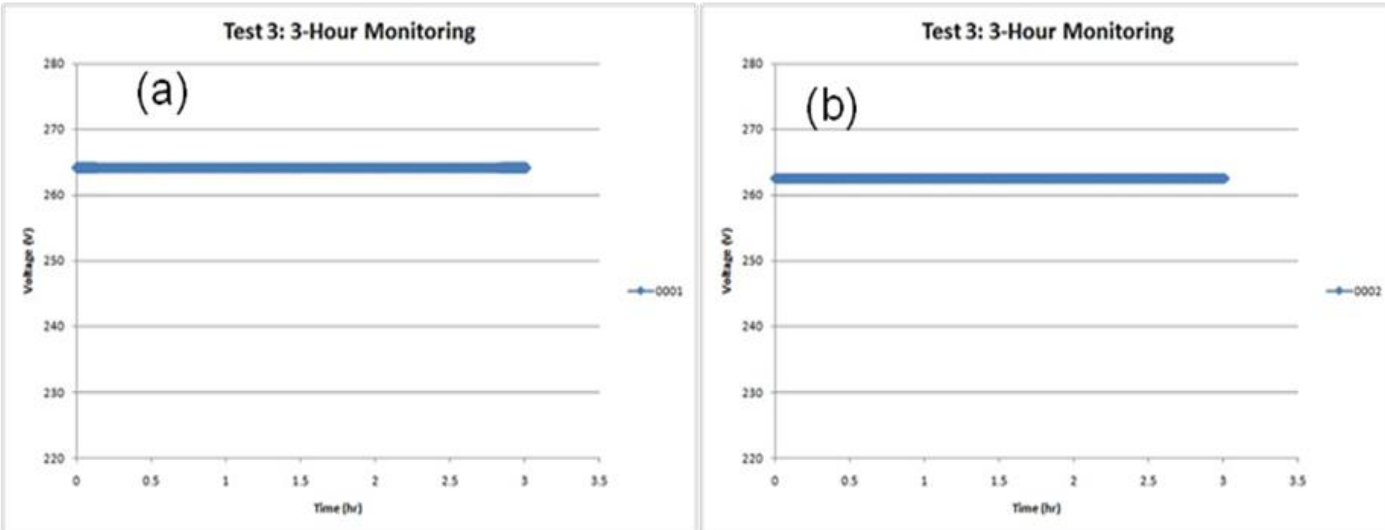


Figure 22 Voltage change over 3 hours for (a) module 1 and (b) module 2

3.10.3 Summary

Overall, the newly assembled battery packs meet the discharge capacity specification of 15.8 Ah shown in Table 2. Both battery packs display similar charging and discharging characterization. Based on the testing conducted, the battery modules are complete and satisfy all requirements.

4.0 Future Work

While this report documents the completion of the DOE supported project, Quallion plans to continue our experiments with battery powered anti-idling systems while we market the technology to OEM and retrofit manufacturers. The next step is to evaluate a larger capacity battery for longer duration operation at higher ambient temperatures.