CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

Clean Transportation Program

FINAL PROJECT REPORT

Expansion of Battery Management System Integration Facilities for Lithium-Ion Battery Modules

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Prepared by: Quallion LLC

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Acknowledgement also goes to Land Systems Corporation for teaming with us and providing their RailScout electric vehicle as the test platform onto which the Quallion Battery Management System Electronics and Battery Module System were integrated and deployed for field data collection.

Quallion, LLC also wishes to acknowledge Clean Fuel Connection, Incorporated for providing support in generating the emissions reductions projections and environmental impact included in this report.

PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance, and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-11-604 to provide funding opportunities under the Clean and Transportation Program for projects to support the development and deployment of alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. In response to PON-11-604, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards June 20, 2012. and the agreement was executed as ARV-12-010 on February 26, 2013.

ABSTRACT

Quallion, LLC upgraded existing on-site facilities to implement a Battery Management Systems Electronics laboratory to enhance its capability to test and integrate Battery Management System's with battery modules to address an increasing demand for alternatives to hydrocarbon fueled vehicles. State of the art test equipment was procured, installed, and validated for use in the Battery Management System Electronics laboratory.

The design, manufacture and test of Battery Management System electronics was also undertaken as was the build of battery modules to demonstrate the functionality of the upgraded Battery Management System Electronics lab in integrating Battery Management System and battery modules for use in electric vehicle platforms. Quallion's Battery Management System and Battery Modules were integrated into the RailScout electric vehicle (EV) provided by Land Systems Corporation. The RailScout is an unmanned, battery powered railroad track inspection vehicle developed as an alternative to the gasoline and diesel fueled rail track inspection vehicles currently in use. The unmanned RailScout is expected to provide higher efficiency and safer inspection capabilities as comparted to the operator manned inspection vehicles currently in use.

The project is expected to reduce toxic and criteria pollutant emissions continually since replaced track inspection vehicles would use battery power instead of gasoline or diesel. The greenhouse gas emission reduction is estimated to be four metric tons per year, at projected RailScout implementation for a typical year. Finally, the project increases awareness of EV's as alternatives to non-traditional vehicles that use hydrocarbon fuels.

Keywords: Quallion, LLC, BMS Electronics and Battery Modules, EV integration, petroleum displacement, greenhouse gas, emission reduction

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EXECUTIVE SUMMARY

This project enhances Quallion's capacity to design, produce, and test advanced lithium ion Battery Management System electronics and to incorporate these electronics into modules and batteries in California to meet the growing demand for electric vehicle applications. This project leverages Quallion's extensive intellectual property and technical know-how related to lithium-ion Battery Management System with appropriately scaled facilities that expand the company's production capacity for larger vehicle systems. This project also aligns the company's capacity to develop and integrate Battery Management System electronics to make complete battery systems with its previously outgrowing capacity to produce lithium-ion cells and modules.

The Expansion of Manufacturing Capacity for High Volume Integration of Battery Management System Electronics into Electric Vehicle Batteries project budget was $2,230,595 from the Energy Commission with a Quallion match share of $2,235,863 for a total budget of $4,466,458. This project facilitated the development of an advanced Battery Management System electronics laboratory consisting of state-of-the-art equipment specifically designed for advanced Battery Management System and battery module integration and testing. This capability was used to design, build, and test Battery Management System electronics and battery module systems for use on potential electric vehicle platform candidates.

Quallion partnered with Land Systems Corporation who provided the prototype RailScout electric vehicle (EV) platform onto which a Quallion Battery Management System and Battery Module system was installed for field evaluation. The objective of the field evaluation was to verify the production readiness of the newly established Quallion advanced lithium-ion Battery Management System electronics and Battery Module system design, production, and test capability which this project helped establish.

The RailScout EV has seen field evaluation at a railway test site in Fillmore, California and in New Orleans, Louisiana, on the Huey P. Long Bridge over the Mississippi River. The RailScout monitored (via remote control) the condition of the four-mile span of tracks of this historical bridge. Runs of the eight-mile round trip were conducted periodically during the deployment period at up to the eleven miles per hour maximum speed. Sensors on board the RailScout monitored the condition of the tracks. From the data collected, the Battery Management System and battery system performance at different speeds and settings were evaluated. The field evaluation demonstrated the viability of the RailScout EV as a clean fuel replacement option to the hydrocarbon fueled track inspection vehicles currently in use. Additionally, the field evaluation has provided insight into the Battery Management System and battery system real world operation, helping to identify potential new applications and opportunities to refine design and operational parameters for future optimization consideration.

CHAPTER 1:
Purpose and Approach

Lithium-ion batteries are crucial components to electric vehicles, and they require battery management systems (BMS) electronics to operate safely and meet the performance needs and pricing targets of electric vehicles. The BMS monitors various parameters of battery operation and controls the functions of the battery to ensure safety and optimal performance. This project demonstrated the capabilities of a Quallion designed and built BMS to meet the needs of a high voltage (>300V) battery system for electric vehicle (EV) applications. BMS for high voltage EV applications require precise control of charge and discharge, and to monitor battery parameters and communicate and record data.

The effectiveness of advanced BMS electronics contributes to improved safety of electric vehicles, helping to alleviate legitimate concerns of potential EV customers. Such advances in lithium ion BMS technology can help enable widespread deployment of electric vehicles and reduce pollution and greenhouse gas (GHG) emission targets in California.

The Expansion of Manufacturing Capacity for High Volume Integration of Battery Management System Electronics into Electric Vehicle Batteries project enhances Quallion' s significant technical experience with advanced BMS design and production by addressing the company's limited facilities and equipment to scale up production capacity to incorporate these advances into its batteries to meet the needs of the growing electrified transportation market.

The resulting facilities and equipment enhancements facilitated the design, fabrication and testing of an advanced BMS which was integrated into a prototype EV which was deployed for a field demonstration period of two months. During this demonstration period, data was collected and analyzed to help quantify the long-term performance of the BMS as well as the potential environmental and economic benefits of an EV replacement to its hydrocarbon fueled vehicle counterpart currently in use.
The ARV-12-010 grant Scope of Work essay topics are displayed below in blue italics as they are addressed in the body of the report.

1.1 Project Goals

This project enhances Quallion's capacity to design, produce, and test advanced lithium-ion Battery Management System electronics and to incorporate these electronics into modules and batteries in California to meet the growing demand for electric vehicle applications. This project leverages Quallion's extensive intellectual property and technical know-how related to lithium ion BMS with appropriately scaled facilities that expand the company's production capacity for larger vehicle systems. This project also aligns the company's capacity to develop and integrate BMS electronics to make complete battery systems with its previously outgrowing capacity to produce lithium-ion cells and modules

1.2 Project Objectives

Through the execution of this project, Quallion succeeded in achieving the key objectives of this project including:

- Establishing the feasibility of a high voltage, high throughput electronics facility.
- Supporting Quallion's new automated cell and module manufacturing lines with enhanced electronics facility.

- Determining trade-offs among cost, capacity, performance, and reliability of equipment used for electronics design, testing, production, and integration into battery packs.
- Quantifying the environmental benefits of incorporating advanced BMS electronics in green technology applications, namely electric vehicle applications.

1.3 Activities Performed

The Expansion of Manufacturing Capacity for High Volume Integration of Battery Management System Electronics into Electric Vehicle Batteries project consisted of facilities construction and upgrade effort to install and bring on-line a BMS Electronics laboratory. It included the procurement, installation, and validation of associated BMS test equipment to facilitate the design, fabrication and test of BMS Electronics hardware which was subsequently integrated into an electric vehicle prototype for deployment and field data collection. The effort followed a systematic development methodology to ensure results consistent with expectations.

1.3.1 Electronics Laboratory Facilities Design and Construction

Establish the Feasibility of a High Voltage, High Throughput Electronics Facility

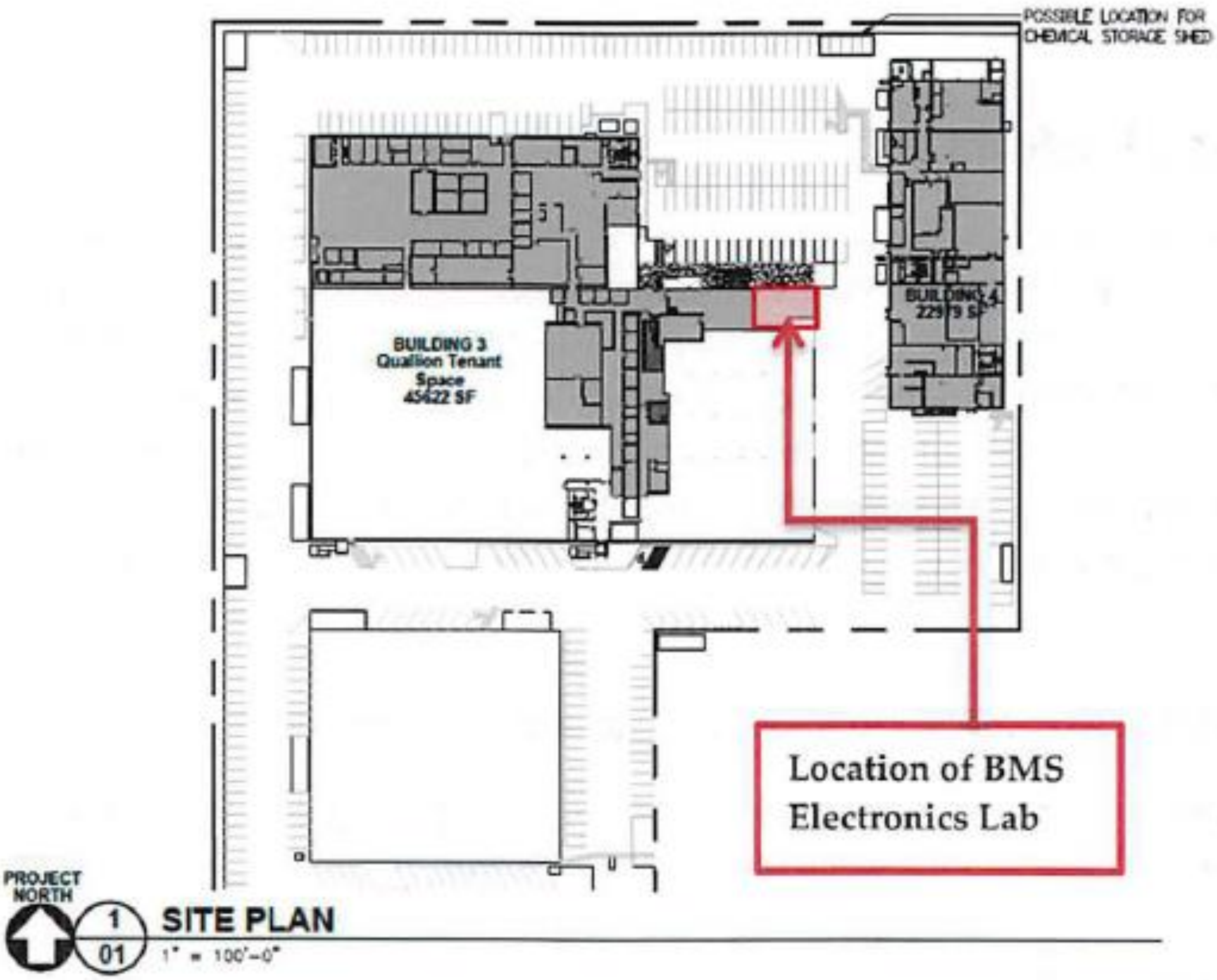
Prior to undertaking this project, Quallion' s facilities had been primarily focused on the needs of low voltage batteries for medical, military and aerospace applications, such as batteries for implantable devices, satellite batteries and unmanned aerial vehicle batteries. The available facilities would not accommodate the increased workload Quallion anticipates from electric vehicle projects and the large high voltage equipment needed to support these projects.

A key output of this project was the expansion of Quallion's capabilities to design, produce and test advanced lithium-ion BMS electronics and to incorporate these electronics into modules and batteries to meet the growing demands of electric vehicle applications. This project sought to match Quallion's extensive intellectual property and technical know-how related to lithium ion BMS electronics with appropriately scaled facilities that will expand the company's production capacity for larger vehicle systems.

The resulting electronics lab will combine and integrate cells and modules with Quallion designed BMS electronics. The designated high voltage, high throughput BMS/battery integration and test capability electronics lab is to be the final assembly station where BMS electronics and battery modules are integrated into complete battery packs.

Quallion identified underutilized space in its existing facility, shown in Figure 1, which is suitable to house the expanded electronics lab. The area was cleared of existing storage items and renovated for conversion to the BMS Electronics lab area. While the facilities upgrade required no demolition or major construction, it did require extensive electrical rewiring work which was performed by licensed contractors and followed all applicable codes and standards. Quallion secured the necessary Los Angeles County permits for the electrical work performed.

Figure 1: Location of BMS Electronics Lab in Quallion's Facility



Source: Quallion, LLC

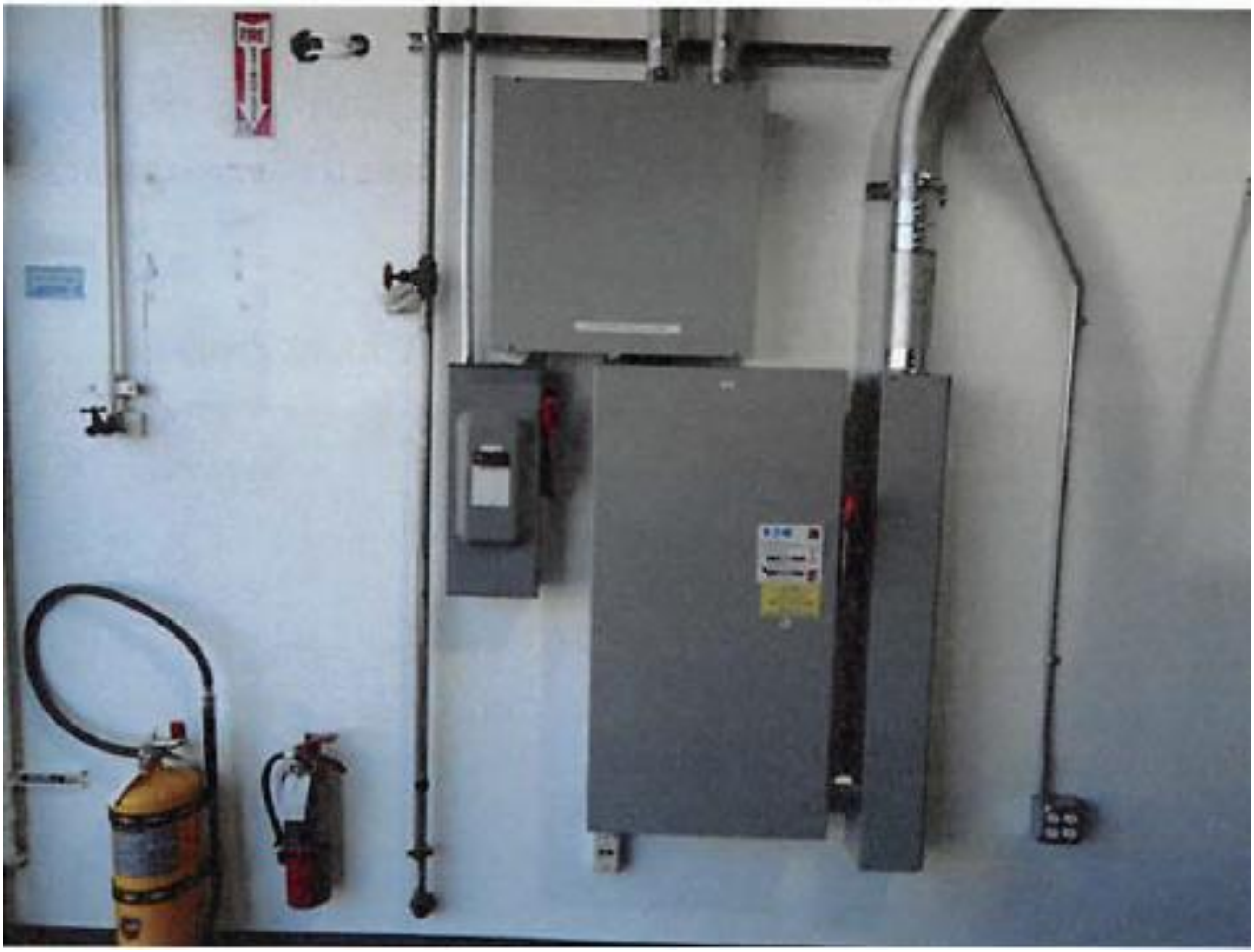
The electrical lab upgrades include: 400-amp feed and 400-amp switch with fuses for the major pieces of equipment, 20-amp 120V quads on separate circuits, 30-amp 208V single phase, overhead lab lighting, and a 100 amp three phase four wire load center. Multiple ceiling 20-amp 120V cord drops were also provided to enable flexible access to electrical connection for portable laboratory test equipment (i.e., meters, computer, and thermal camera) which are mounted on wheeled carts for mobility and easy equipment access. Figure 2 shows the BMS electronics lab site undergoing the electrical work needed to support the BMS test equipment power requirements. Given the high-power nature of the specialized BMS test equipment, particular care was taken to install electrical safety shutoffs at the electrical panels with easy access as shown in Figure 3.

Additional upgrades to the BMS electronics lab area included anti-skid flooring and the installation of a partitioning wall to segregate the lab area form the adjacent storage warehouse.

Figure 2: BMS Electronics Lab Electrical Work in Progress

Source: Quallion, LLC

Figure 3: BMS Electronics Lab Completed Electrical Work



Source: Quallion, LLC

1.3.2 Electronic Laboratory Equipment Procurement, Installation and Validation

Plan and order electronic design, production, and test equipment specific to BMS technology, plan a facility layout that accommodates the efficient workflow, and expedites assembly processes.

1.3.2.1 Equipment Procurement

Quallion identified specific equipment and vendors capable of meeting Quallion's unique needs for the BMS electronics lab. A review of the performance, cost and capacity of commercially available equipment identified sources of key pieces of equipment needed to enhance current electronics capabilities. Commercially available equipment includes thermal imaging camera, humidity and thermal controlled test chamber which allows for evaluating battery and BMS function in a variety of real-world simulated conditions, and data acquisition recorders and probes to facilitate the gathering and processing of large volumes of test data. Several pieces of specialized equipment are also needed to support Quallion' s specific needs, such as high voltage and high current battery testers. The equipment identified is summarized below.

- Av900 computer controlled two-channel direct current power processing system

- Nhr9200 battery test system - low voltage, high current cycler
- Test equity 1007c series thermal chamber
- Flir a325sc thermal camera
- Test battery consisting of panasonic ncr 18650b cells
- National instruments data acquisition (DAQ) computer system -with labview test software

The description of each key piece of test equipment and its capabilities follows.

The A V900 is a heavy-duty cycler solution for testing high voltage batteries for electric and hybrid electric vehicles. The A V900 can test batteries up to 900V Direct Current and handle up to 250kW of power. The cycler has charging and discharging capabilities. The A V900 can be controlled remotely using RS-232 serial port and programmed via Lab VIEW.

The NHR9200 is a flexible cycler solution for testing low voltage batteries up to 40V Direct Current. The cycler can test batteries up to 1800A and handle up to 36kW of power. The cycler has charging, discharging and battery emulating capabilities. The NHR9200 has an interactive front panel for configuring tests. The NHR9200 can be controlled remotely using Ethernet and programmed via Lab VIEW.

The TE1007C Thermal Chamber is essential for performing high or low temperature battery testing. It has a temperature range between-73°C to 175°C and accuracy better than 2.66°C. This environmental chamber can be used for temperature cycling or limit tests so is very practical. The TE1007C can be controlled remotely using a General-Purpose Interface Bus and programmed via Lab VIEW.

The National Instruments (NI) data acquisition computer is the central nervous system for controlling and programming equipment through Lab VIEW. This DAQ computer acquires battery measurements and communicates controls to test equipment. There are 18 slots for different cards such as RS-232, RS-485, Controller Area Network (CAN) communications and voltage, temperature, and current data acquisition devices. These enhancements to the DAQ computer enable a fully capable and functional test program to be performed in a centralized fashion.

The specific electrical power requirements, basic dimensions, and weights for key pieces of equipment are shown in Table 1. These equipment requirements were used to guide the layout design and installation of the equipment as well as establish the electrical modifications that the BMS Electronics lab area would need.

Table 1: BMS Electronics Laboratory Key Equipment Installation Specifications

Equipment Tag	Equipment Function	Width	Depth	Height	Weight (pounds)	Voltage	Amps	Phase
AV-900 HV	Battery Cycling	73"	37"	76.5"	4500	480	335	Three
NHR-9200 LV	Battery Test	56"	31"	72"	1200	480	51	Three
NI PXI System	PC and DAQ	18.5"	18.5"	7"	100	120	10	Single
A325	Thermal Camera	5"	3"	3"	5	120	5	Single
Test Equity 1007C	Thermal Chamber	33"	54.25"	67.75"	850	230	25	Single

Source: Quallion, LLC

1.3.2.2 Equipment Installation

Quallion worked with the test equipment suppliers to ensure appropriate installation of the new equipment, their connection with the building systems and to provide operational training prior to their use. Figure 4 shows the AV 900 HV Direct Current power processing system as it is being prepared for installation. Figure 5 shows the AV 900 as installed in the BMS Electronics Lab. The other key pieces of equipment, the NHR-9200 Battery Test System, the Test Equity 1007C Thermal Chamber, and the National Instruments DAQ Computer System are shown if Figure 6 and Figure 7 as installed in the BMS Electronics Lab.

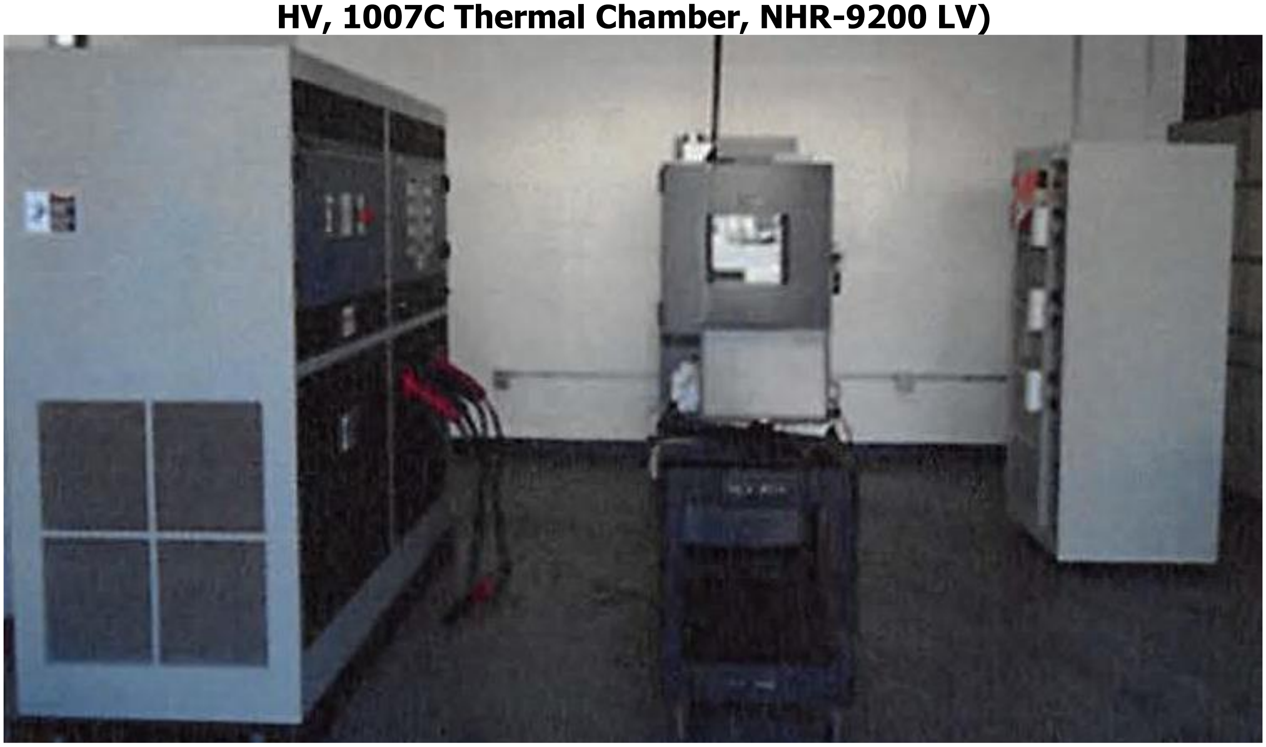
Figure 4: AV 900 HV Lab Equipment Being Prepared for Installation

Source: Quallion, LLC

Figure 5: AV 900 HV Lab Equipment Installation Complete

Source: Quallion, LLC

Figure 6: BMS Lab Equipment Installation Complete (From Left to Right: AV 900 HV, 1007C Thermal Chamber, NHR-9200 LV)



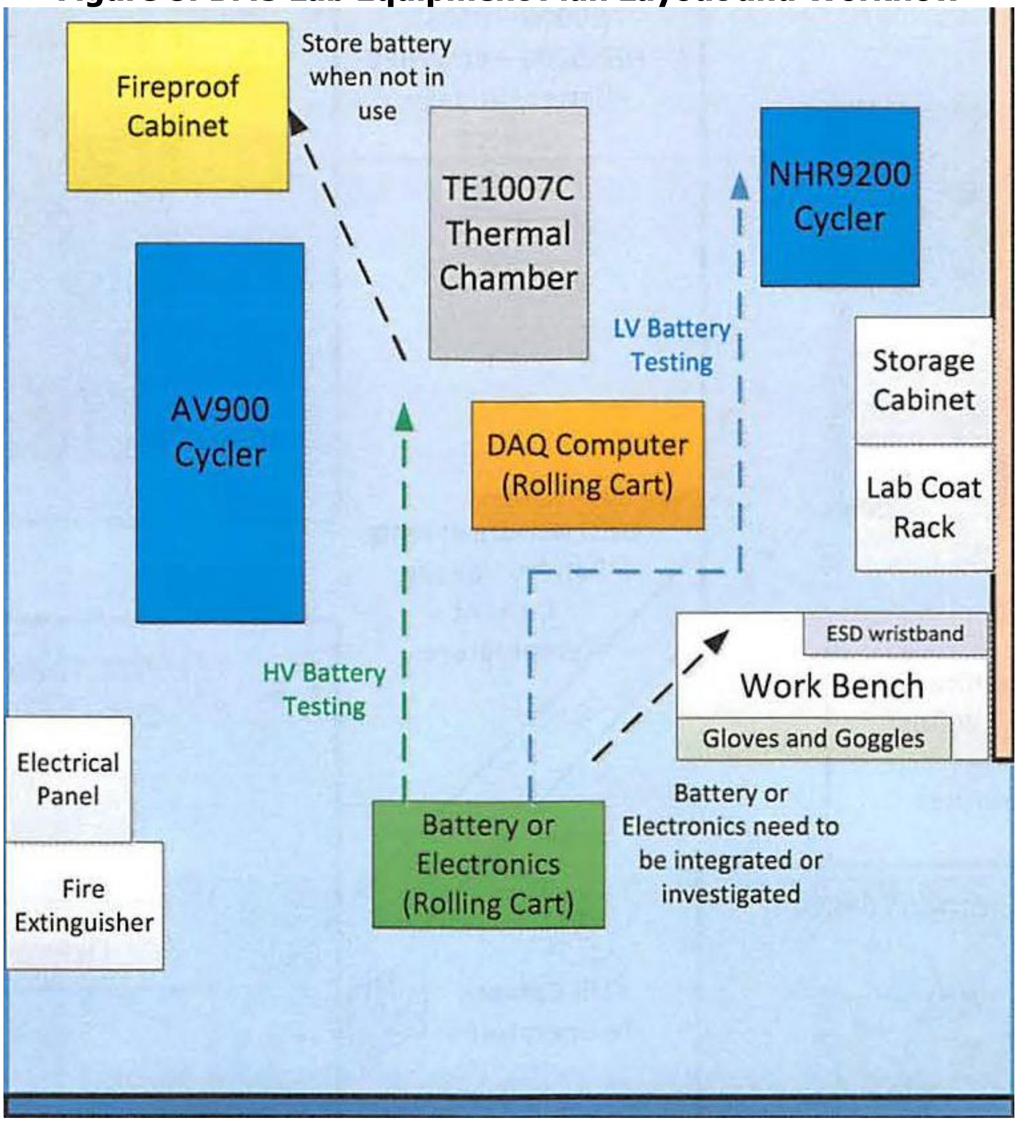
Source: Quallion, LLC

Figure 7: Another View of BMS Lab Equipment Installation Completed (Note PC and DAQ on cart)

Source: Quallion, LLC

The BMS Electronics Lab equipment layout was designed to provide efficient workflow and to facilitate good access to the test equipment by BMS electronics and battery units undergoing test and integration. The test units are mounted on rolling carts and can be maneuvered to the appropriate test station as shown in Figure 8. The equipment installation layout integrates the new equipment to create a series of workstations for all aspects of BMS electronic and battery modules integration and testing. The flow of work product within the BMS Electronics Lab is facilitated by the open floor plan and the use of mobile carts to maneuver BMS electronics and battery modules for appropriate proximity to the designated test equipment for conducting integration, test or troubleshooting. Key to safe equipment operation is the open and clear access to the emergency shut-off switches on the electrical power panels. Additionally, fireproof cabinets are available for safe storage of battery modules when not in use.

Figure 8: BMS Lab Equipment Plan Layout and Workflow

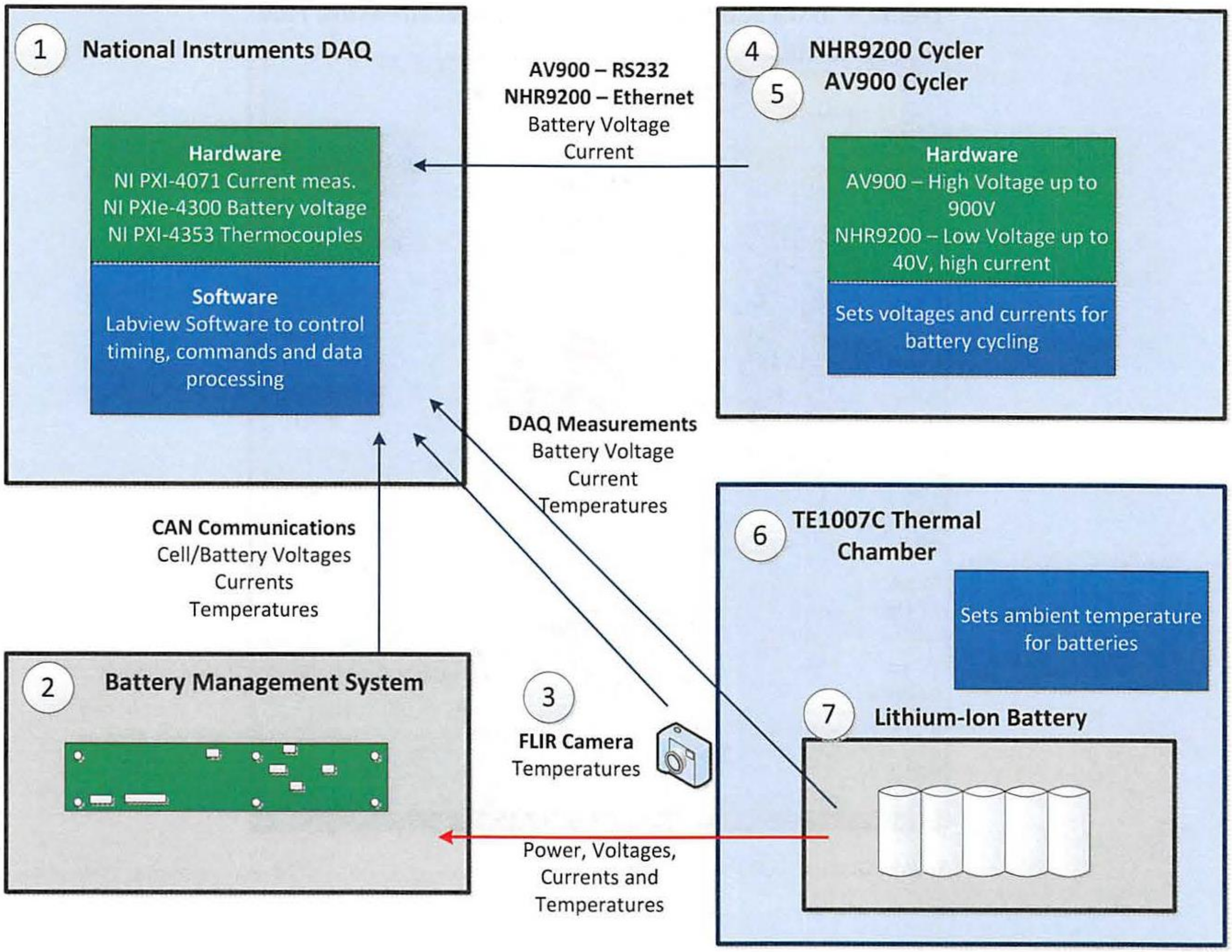


Source: Quallion, LLC

1.3.2.3 Equipment Validation

Quallion conducted equipment validation to ensure that the equipment for testing BMS and lithium-ion batteries would perform to specifications. Seven major components for testing lithium-ion batteries and electronics were identified as illustrated in Figure 9. The primary instrument is the National Instruments DAQ computer. This computer controls and communicates with all other pieces of equipment using Lab VIEW software. The BMS electronics communicates data collected from the battery to the computer via Control Area Network (CAN) communications. The NHR9200 is a low voltage cycler that operates up to 40V and the AV900 is a high voltage cycler that operates up to 900V. The Lab VIEW software executes test programs on these cyders to charge and discharge the battery under test.

Figure 9: BMS Electronics Major Test Equipment for Validation



Source: Quallion, LLC

Temperature is a critical parameter during the use and testing of a lithium-ion battery and BMS electronics. By using thermocouples and a FLIR thermal imaging camera, Quallion can monitor temperatures gradients accurately. Quallion performed calibrated resistor load tests to confirm that observed temperatures were accurate. Quallion also uses a thermal environmental chamber to provide a temperature-controlled environment for baseline testing of batteries and electronics.

The ability to measure battery voltages and currents accurately is essential for battery management systems. Quallion uses two different types of FLUKE current clamps to measure the battery current. These measurements are converted and logged for future reference by the DAQ computer during testing.

Checklists are used to ensure a controlled and systematic validation process. Expected response for each unit under test is established as a guideline for assessing the validation acceptability of the test results obtained for the unit under test

During validation testing, the performance specifications of each piece of equipment as established by the manufacturer were compared with the test results obtained to confirm validation and the equipment's readiness for use.

The successful completion of equipment validation testing confirms Quallion ability to successfully integrate and test lithium-ion batteries and BMS electronics consistently and at the desired throughput. The BMS Electronics laboratory provides Quallion with the capabilities to test BMS electronics and BMS electronics integrated with modules and batteries to verify that they meet applicable performance and quality standards. Also, Quallion's certification which include ISO 9001:2000, AS9100B (validation of Quality Management System to Aerospace standards) and ISO 13485:2003 (validation of Quality Management System to Medical Standards) enables a BMS and battery test and integration approach that is consistent with industry standard practices to ensure quality and reproducibility in automated manufacturing environments.

1.3.3 Battery Management System Design, Fabrication and Testing

Use completed facility to design and produce BMS Electronics integrated with battery modules for testing purposes.

1.3.3.1 BMS Electronics Design

The primary objectives for the BMS Electronics design were to provide safety monitoring of a high voltage battery pack and to communicate and record captured data. Quallion's approach was to upgrade an existing incomplete design that monitored 18 virtual cells per board to 24 virtual cells per board. This would reduce the number of boards needed but would require a higher voltage tolerance.

There were several changes to upgrade the existing Control Board and Interface Board. Quallion had to replace several of the components on the Control Board to accept higher voltages. The Control Board also combined cell balancing and current sensing which had been on separate boards. The Interface Board was enhanced by adding new functionality such as contactor controls, ground fault detection and hall-effect current sensing.

The approach Quallion took regarding the Control Board firmware was to update the existing firmware to be compatible with the updated board and RailScout electric vehicle. Quallion modified the safety limits to reflect a different cell chemistry and stack-up. Quallion changed the number of messages being sent by the electronics to accelerate the message rate and minimize data for recording.

Quallion's approach with the Single Board Computer was to reuse as much of the existing software as possible. The Single Board Computer board is a commercial-off-the-shelf item that is readily available. Quallion decided to use the Single Board Computer because it had a built-in controller area network (CAN) bus with easy access to memory for recording data. Quallion's plan was to record data using the single board computer.

The BMS Electronics design is composed of three boards shown in Figure 10: a Control Board, an Interface Board, and a Single Board Computer. The Control Board performs the monitoring and safety control for the battery. There are four of these boards used in the final battery system, with each assigned monitoring duty over six modules (for a system total of 24 modules).

Figure 10: Control Board (top), Interface Board (bottom left) and Single Board Computer (bottom right)

Source: Quallion, LLC

The Interface board is the intermediary between the Control Board, Single Board Computer and external systems. The Interface Board filters voltages and is the Controller Area Network bus junction. The Single Board Computer receives and records the messages from the Control Board. This data is saved locally and sent to USB memory at the completion of test for future reference.

1.3.3.2 BMS Electronics Fabrication

To support the BMS Electronics test program, the quantity of boards fabricated and their intended designation for either engineering testing or final integrated battery use are summarized in Table 2. Engineering designated boards were used to support setting up test stations and deriving performance metrics. The boards designated for integrated battery use underwent more rigorous testing to verify functionality and safety performance as they were to be used for integration into the battery assembly destined for the RailScout EV.

Table 2: Board Quantities Fabricated for Engineering Testing and Integrated Battery Use Boards for Engineering for Integrated Manufactured Us

	Boards Manufactured	For Engineering Use	For Integrated Battery Use
Control Board	12	6	4 + 2 spares
Interface Board	4	2	1 + 1 spares
Single Board Computer (SBC)	4	2	1 + 1 spares

Source: Quallion, LLC

Additionally, six battery modules (designated for laboratory testing) were fabricated to support BMS electronics and battery integration and testing. Fabrication of the battery modules was performed in-house while fabrication of the BMS electronics boards was outsourced to local suppliers. Quallion's purchasing organizations flowed down all appropriate procurement clauses on the Purchase Orders to ensure full traceability and conformance certification. All hardware received from suppliers underwent incoming inspection and where applicable, acceptance testing as well, prior to it being issued to the production floor. Similarly, all fabricated battery modules followed fully documented fabrication processes and underwent the appropriate level of inspection and testing to ensure they met all performance and physical requirements prior to use. Testing of the battery modules included individual cell testing for safety and electrical characteristics, and final testing of the assembled modules to ensure they met the battery specifications set by Quallion engineering and Land Systems.

The Battery Management System Printed Circuit Board was manufactured to IPC-6011 and 6012 standards and also to meet the requirements of IPC-A-600, Class2, Level C. The PCB is approximately 15.4 inches long and 2.7 inches wide. The PCB is four layers thick consisting of 1.0 ounce and 2.0-ounce copper layers.

1.3.3.3 BMS Electronics Testing

Provide performance data and results for the batteries and BMS tested.

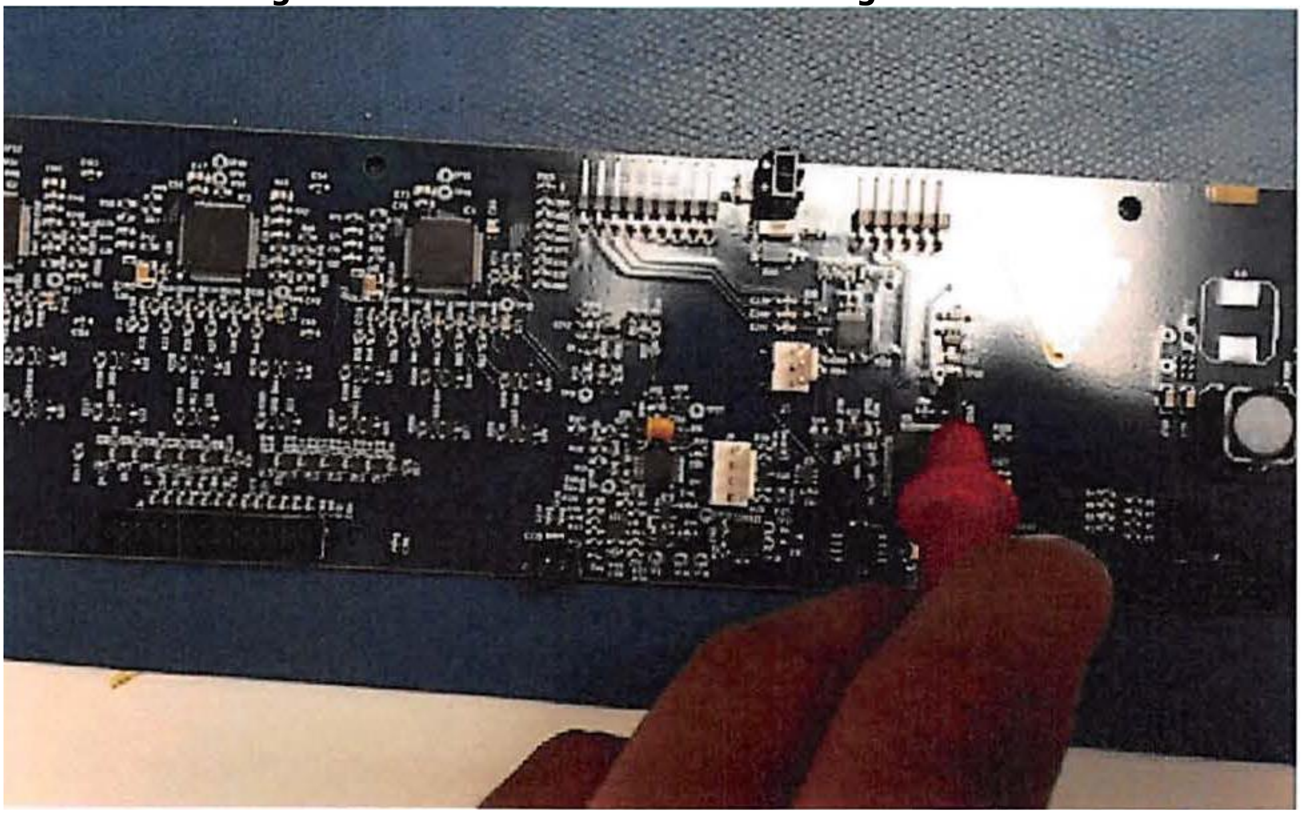
The test methodology used to validate the environmental, safety and performance parameters of BMS Electronics subsystems and the integrated battery system involved testing at various levels of assembly. First, individual BMS boards were tested, followed by testing at the integrated boards level, then testing at the BMS electronics and Battery Module level, and finally with the BMS Electronics and Battery Modules integrated into the Land Systems RailScout Electric Vehicle (EV). Key metrics for electronics such as voltages, currents, temperatures, and power were captured and compared to other standard Quallion BMS' s to derive test limits. All lower-level testing was conducted in the newly completed BMS Electronics Lab, with testing of the BMS Electronics and battery system integrated into the RailScout conducted at the Land Systems facility in San Pedro and in the field on tracks at test sites in the cities of Fillmore, California and New Orleans, Louisiana.

1.3.3.3.1 BMS Electronics Board and Unit Level Testing

BMS board level testing was divided into three sections: shorts and isolation testing, power-on functional testing and integrated boards testing. The shorts and isolation test verified proper board manufacturing, shipping, and handling by checking for any shorts and improper isolations while the board was powered down. Figure 11 shows a shorts and isolation probing test being conducted. By probing test points on the board using a multimeter, Quallion verified that as designed, certain points were shorted to ground, and others separated from ground.

Table 3 summarizes the Shorts and Isolations Probing Test requirements for the Control Board.

Figure 11: Shorts and Isolation Probing Test Points



Source: Quallion, LLC

Table 3: Shorts and Isolations Probing Test

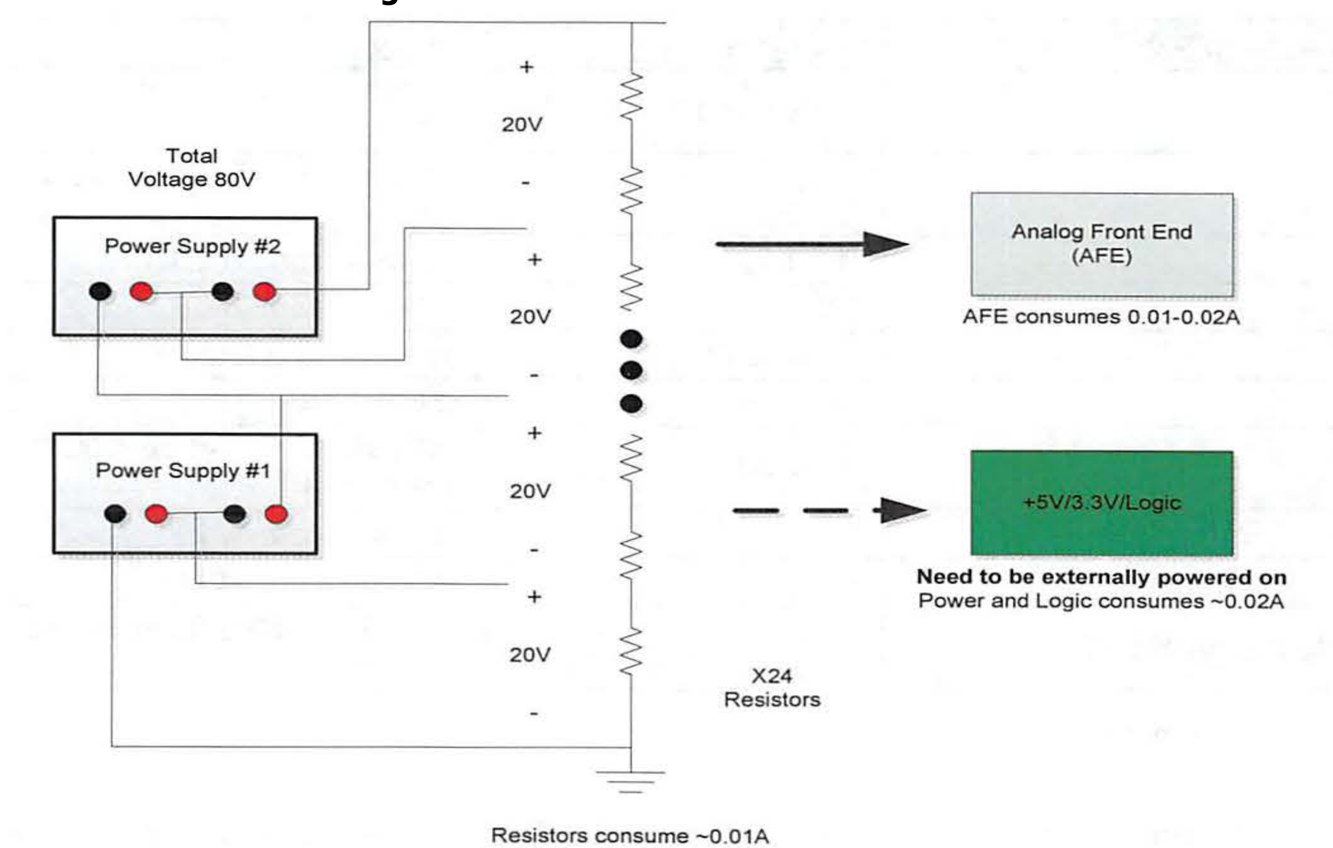
Control Board (Top Side)	Location	Verify
GND	TP18 and TP29	TP18 and TP29 should be less than or equal to 0.2 ohms
GND1	TO15	TP15 and TP27 should be less than or equal to 0.2 ohms
GND2	TP10	Greater than 100 kilohms from TP15
GND3	TP22	Greater than 100 kilohms from TP15
GND4	Pin 1 of 13	Open Loop from TP18
GND5	TPS	Greater than 100 kilohms from TP15

Control Board (Top Side)	Location	Verify
Analog Ground	Both Sides of R107	Both sides should be less than or equal to 0.2 ohms from TP18
VDD	TP28	Greater than 100 kilohms from TP29
+5V	TP17	Greater than 100 kilohms from TP18
1 Plated Hole (lower right)	-	Open Loop from TP18 and Pin 1 of 13

Source: Quallion, LLC

The next test was the power-on functional test. Here, test cables, power supplies and firmware were used to verify that the boards were functioning correctly. The power consumption of the boards was computed at this step. At power on, the Control Boards drew between 0.02 to 0.03 amps of current from the power supplies. When the +5V/3.3V and logic were switched on, the current changed to 0.04 to 0.05 amps. Figure 12 shows the Control Electronics Power On schematic. To turn on the logic, Quallion programmed the firmware on the Control Boards. No issues were found with programming the Control Boards.

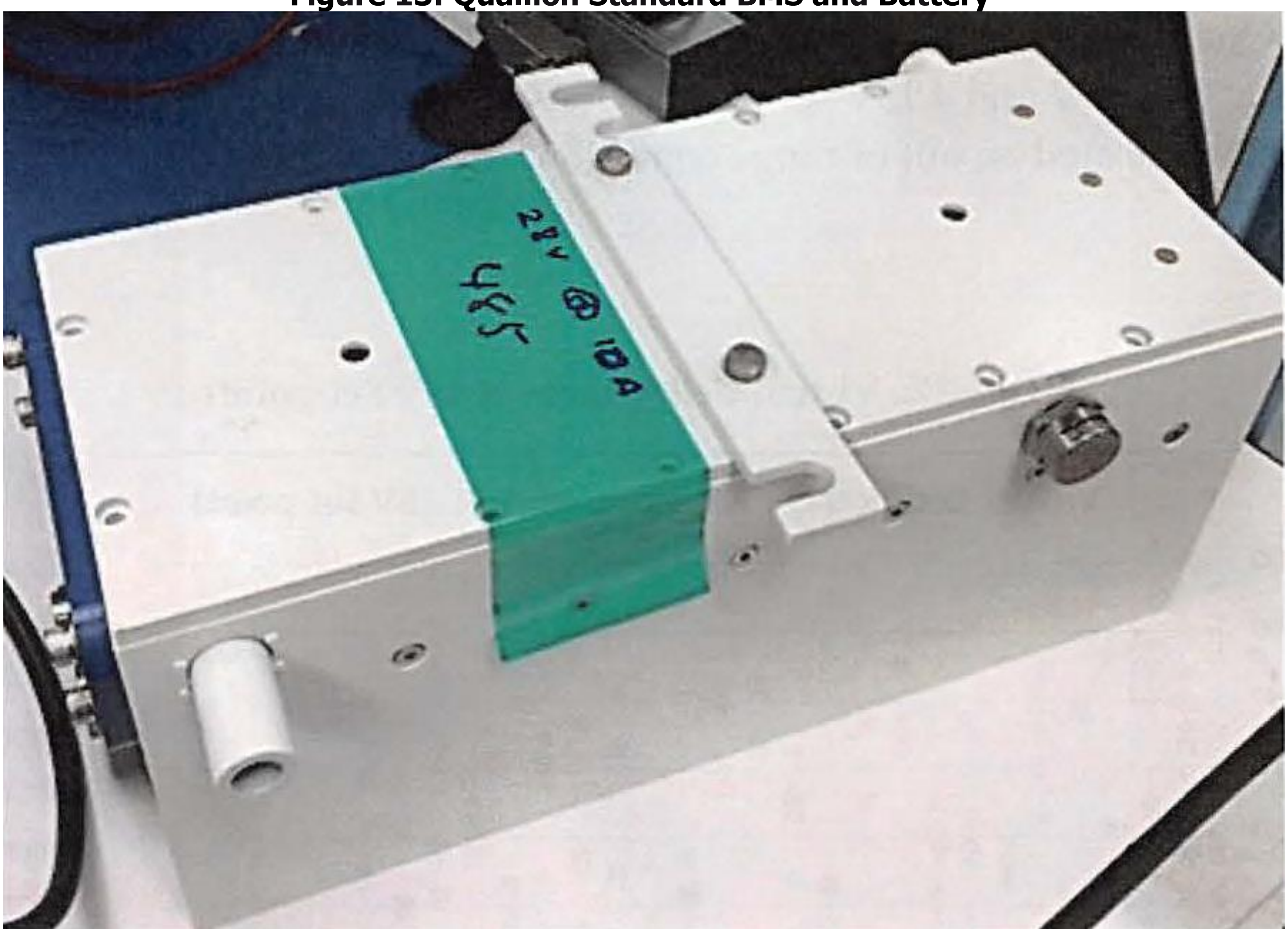
Figure 12: Control Electronics Power On



Source: Quallion, LLC

The third board level testing was the integrated boards test. This test connected the BMS's Gateway and Control Electronics boards together to verify that voltages, currents, and temperatures were being accurately measured and recorded. Connecting the boards enabled performing safety limit balancing time-on and thermal cycling testing. By connecting the boards, Quallion also verified the cable performance and communications. During this testing, Quallion determined accuracy limits for voltage, current and temperature by comparing with standard Quallion BMS's. Figure 13 shows the standard Quallion battery and BMS (integrated into a single enclosure) that was used for comparison purposes. One key difference between the two BMS's is that the standard BMS measure seven to eight virtual cells, while the high voltage BMS measures 24 virtual cells. This results in different test methods and accuracies. However, Quallion was able to ascertain the accuracy that would be expected. As elements of the data of interest already existed with the standard BMS, Quallion reused as much of the available data as possible. Most of the test data was obtained from tests performed on five standard units.

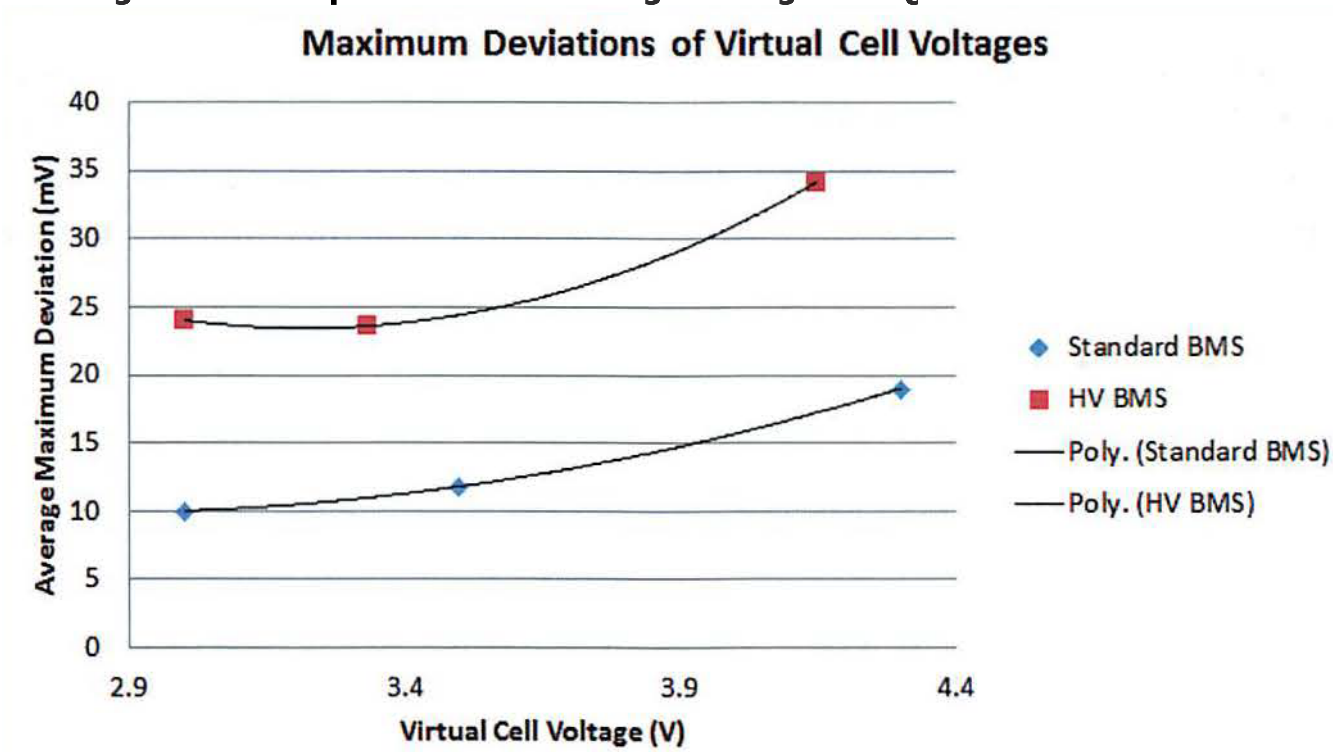
Figure 13: Quallion Standard BMS and Battery



Source: Quallion, LLC

Figure 14 compares the virtual cell voltages of the high voltage BMS and standard BMS. The figure indicates that the maximum deviation of virtual voltage measurements from the set point varied between 10 and 35mV.

Figure 14: Comparison Between High Voltage and Quallion Standard BMS

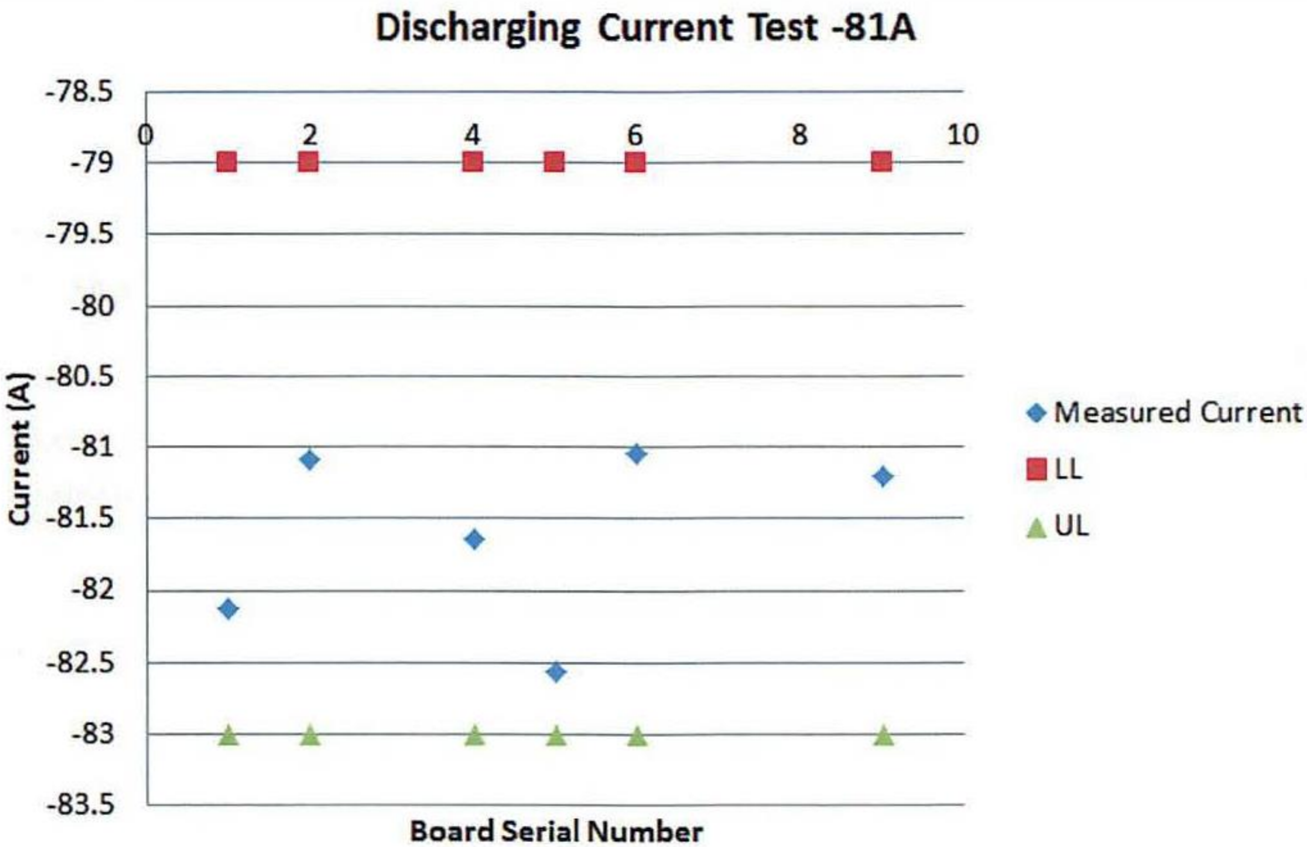


Source: Quallion, LLC

From analysis, Quallion determined that an appropriate limit would be 38. Sm V. Quallion conducted tests at 3V, 3.5V and 4.15V set points.

Quallion compared charge and discharge current tolerances between the high voltage and standard BMS's. Quallion emulated a 49-amp charge and -81-amp discharge with the high voltage BMS using resistor voltage dividers. Quallion determined that a 2.0-amp tolerance was acceptable based on analysis. All boards measured current within this limit as shown in Figure 15.

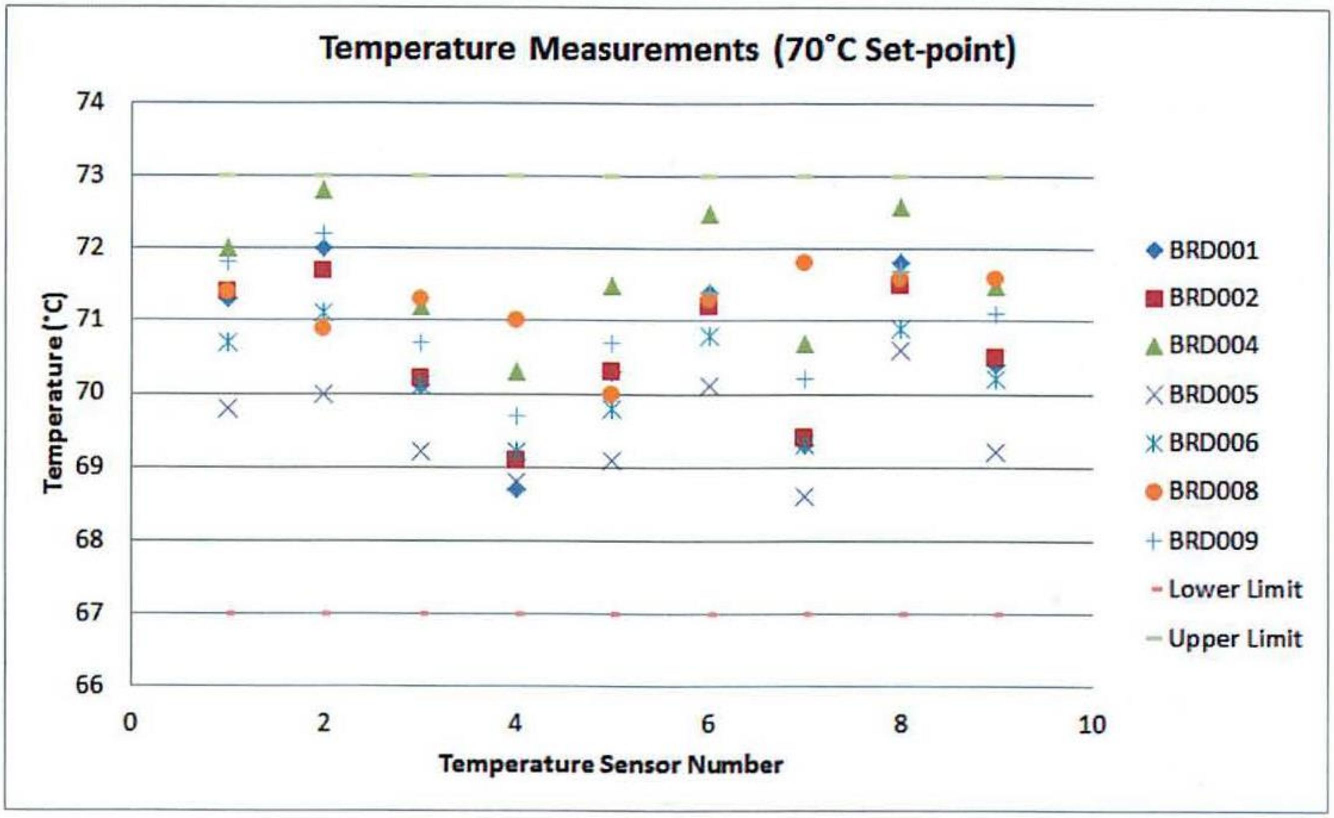
Figure 15: Current Measurements at -81A Set-point



Source: Quallion, LLC

Quallion compared temperature accuracies between the high voltage and standard BMS' s and based on analysis, determined that 3°C tolerance would be acceptable. Both BMS reported temperatures less than 3°C from the set-points -5°C, 23°C and 70°C as shown in Figure 16.

Figure 16: Temperature Measurements at 70 °C Set-point



Source: Quallion, LLC

In addition to testing the board accuracies, Quallion performed safety limit, balancing, time-on and thermal cycling tests. Each board underwent safety limit testing as specified in Table 4 to verify that the BMS safety limits functioned correctly. The balancing test insured that the balancing resistors on the board would turn on when cells needed to be balanced. The time-on test confirmed that the boards would have no problem powering on and transmitting data to the single board computer over a minimum period of six hours. The thermal cycling test was performed after the boards had been conformal coated to ensure their survivability at the temperature extremes.

Table 4: High Voltage BMS Safety Limits

Safety Limit Descriptions	Limits	Persistence Time (seconds)
High Cell Voltage	4.25 V	10
Secondary High Cell Voltage	4.35 V	3
Low Cell Voltage	2.9 V	10
Secondary Low Cell Voltage	2.2 V	3
High Charging Current	65A	20
Secondary High Charging Current	75A	<1

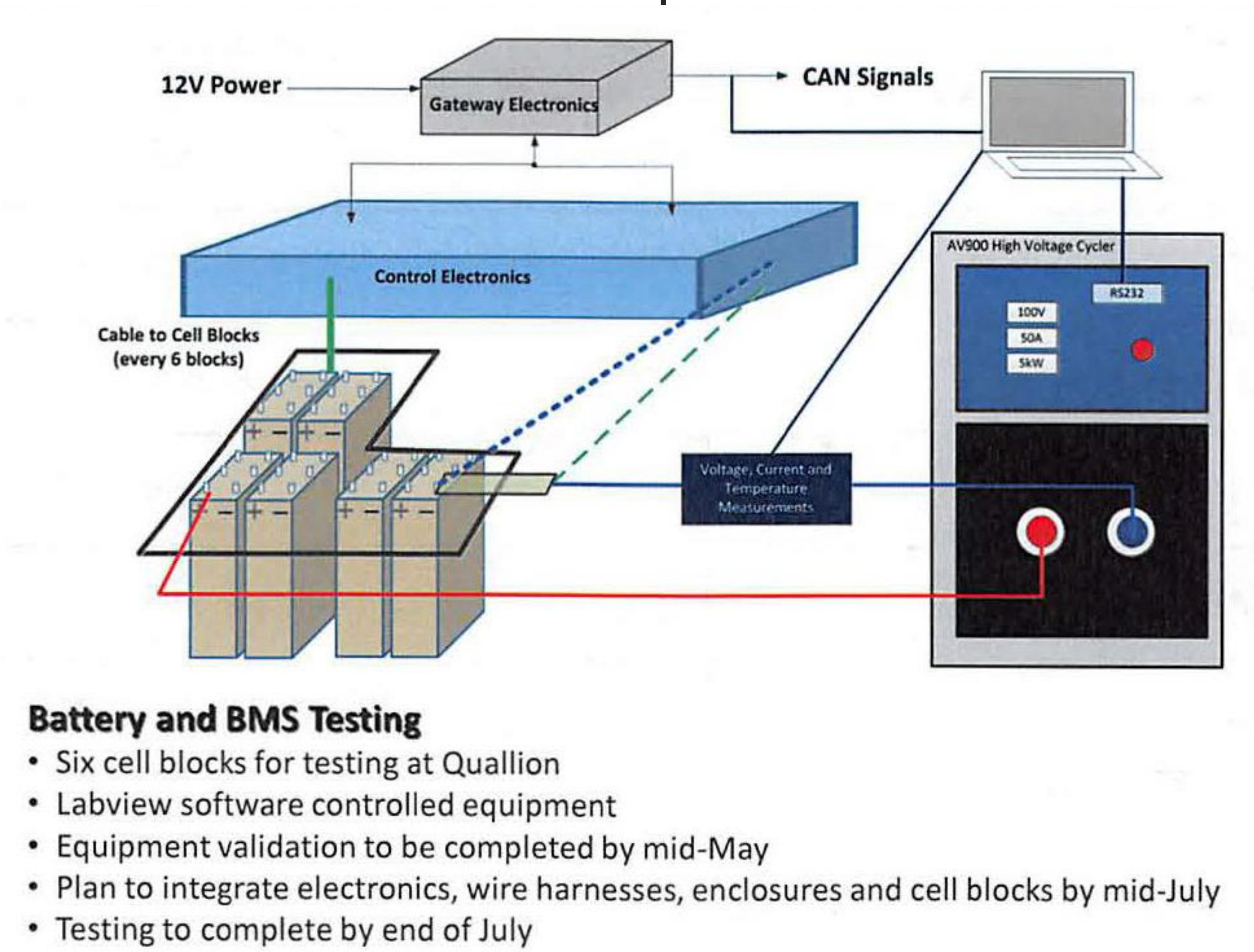
Safety Limit Descriptions	Limits	Persistence Time (seconds)
High Discharging Current	-150A	20
Secondary High Discharging Current	-440A	<1
High Temperature	75°C	5
Low Temperature	0°C	5

Source: Quallion, LLC

1.3.3.3.2 Integrated BMS Electronics and Battery Module Level Testing

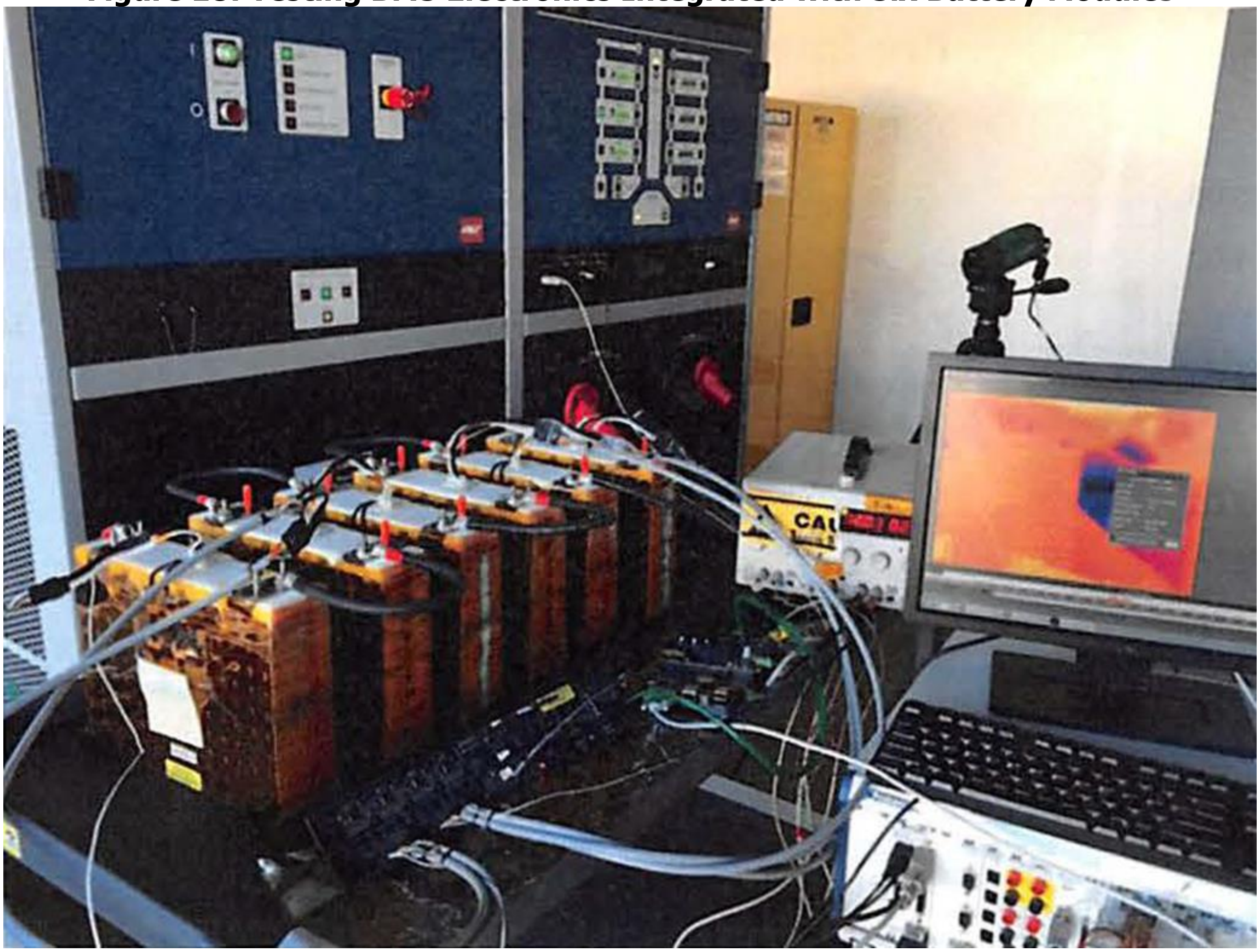
Once the BMS lower-level board performance parameters had been validated, the BMS electronics was integrated with the engineering battery modules. The objectives of this testing were to verify the system performance of the integrated BMS and Battery system using the newly developed BMS Electronics Lab capabilities. For this test, the BMS was connected directly to six battery modules and the AV900 high voltage cycler, DAQ computer and current clamps. Figure 17 illustrates how the integrated BMS electronics and Battery system test was instrumented. Figure 18 shows the actual test setup with the BMS Electronics boards connected to the six battery modules which are in turn connected to the A V900 HV Cycler. Note the FLIR thermal imaging camera on the tripod in the background transmitting the thermal images captured from the battery modules to the PC. The six modules were interconnected to each other using power cables to form a six-module battery with a shunt resistor connected to the most negative end. Sense cables were wired to the BMS Control Board and the Single Board Computer and Interface Board and were then powered on. Once it was verified that the BMS electronics were communicating and producing data, battery charging, and discharging was performed using the A V900 Cycler. With the DAQ computer and Lab VIEW Battery Data Acquisition and Test Software, Quallion successfully ran AV900 charge and discharge cycles on the battery. During the execution of a discharge or charge test program, the A V900 was remotely set to the programmed parameters and automatically ran the test profile. During the module-electronics testing, the ability to capture data through the USB memory stick was verified.

Figure 17: Integrated BMS Electronics and Battery Modules Test Instrumentation Setup



Source: Quallion, LLC

Figure 18: Testing BMS Electronics Integrated with Six Battery Modules



Source: Quallion, LLC

Each board underwent 10-amp charge and -10-amp discharge of the six-modules for approximately one minute. Table 5 indicates that all, but one board was within 0.2 amp of the expected value. Board 002 was clearly out of tolerance and was designated as not to be used for integration because of the higher-than-normal cell voltage reading during the board level testing. Board 005 had the closest match to 10 amps and was selected to be the Control Board for measuring the current for the vehicle battery. The Board 002 anomaly causing the noted variation is attributed to an isolated issue unique to this board.

Table 5: Current Measurements During Integration Testing

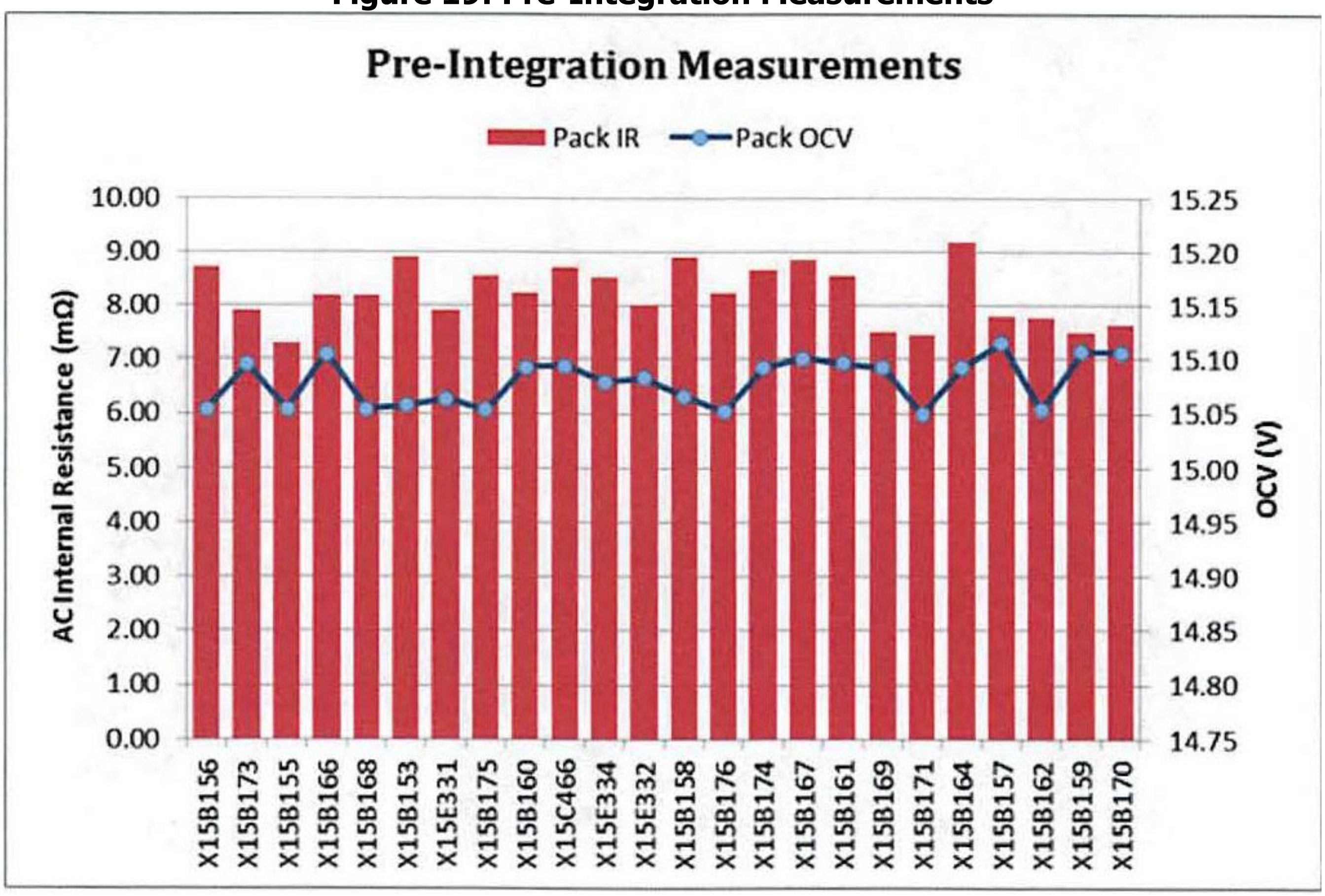
	BRD001	BRD002	BRD004	BRD005	BRD006	BRD009
10A Discharge (A)	-9.88	-11.68	-9.8	-9.96	-9.84	-9.84
10A Charge (A)	10.12	11.92	10.06	10.04	9.92	10.04
Maximum Delta (A)	0.12	1.92	0.2	0.04	0.16	0.16

Source: Quallion, LLC

1.3.4 BMS and RailScout Electric Vehicle Integration and Testing

Having validated all the lower level BMS electronics operations, integration of the BMS electronics with the 24 battery modules of the RailScout EV followed. Prior to integrating the 24 modules into the EV battery, Quallion performed a series of measurements to verify the state of the modules before integration. Figure 19 shows the pre-integration measurement results.

Figure 19: Pre-Integration Measurements



Source: Quallion, LLC

Figure 20 shows this testing being conducted on the twenty-four battery modules at the Land Systems facility in San Pedro, California. Detailed battery measurements are listed in Appendix A. These pre-integration measurements were used to prevent virtual cell imbalances between modules once integrated, which could lead to decreased battery performance in the long term.

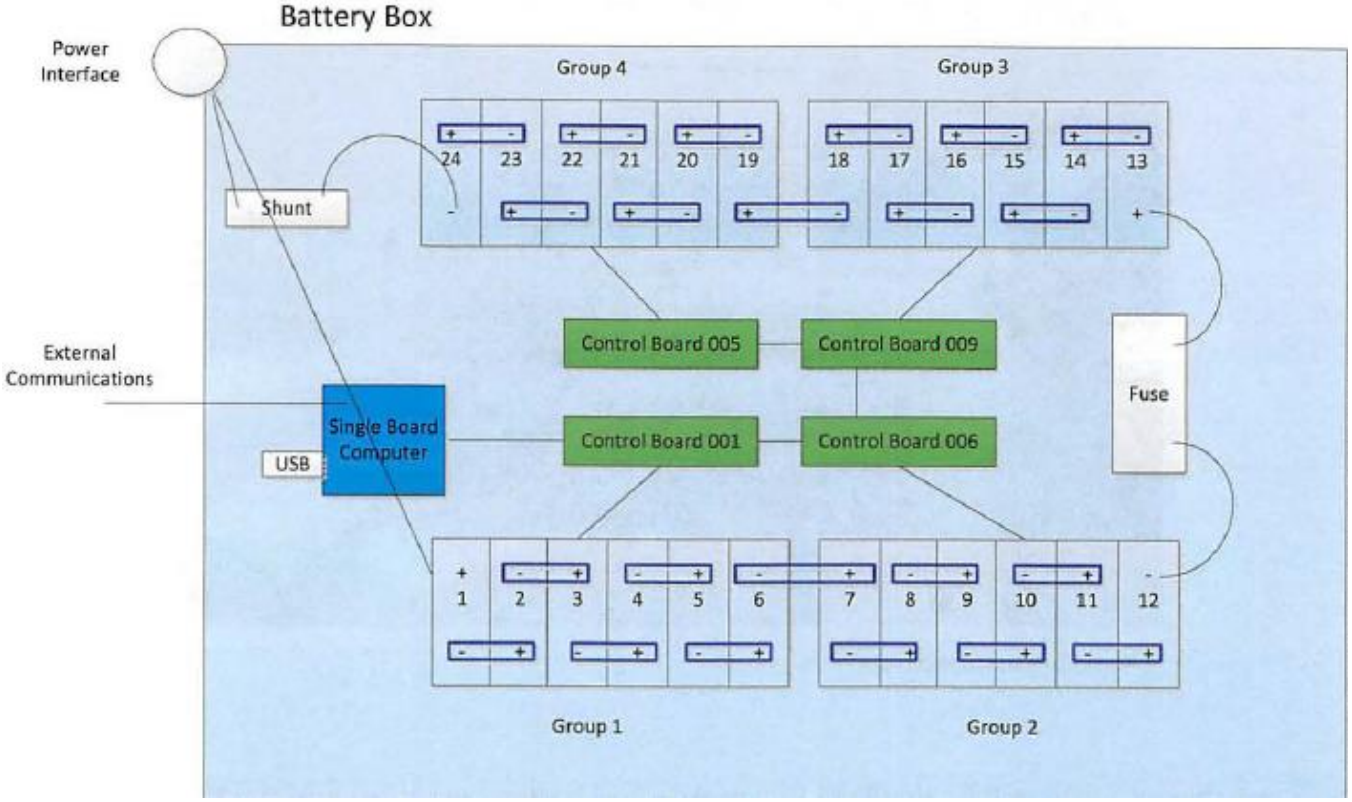
Module state verification was performed using a breakout connector box that allowed Quallion to capture readings directly from the individual sense lines for each of the virtual cells.

Figure 20: Battery Module Testing Prior to Installation into RailScout EV

Source: Quallion, LLC

As a precursor to integrating the BMS Electronics and battery modules into the RailScout, the electronics were installed in the vehicle battery box and connected to the modules as illustrated in Figure 21. Note the designated module group numbers and corresponding board serial numbers. Each Control electronics board controls six modules or one group. There are four groups, each group consisting of six battery modules for a total of 24 battery modules. After connecting the modules to the BMS electronics, the electronics were powered on to verify BMS measurements. Measurements were taken from Controller Area Network bus readings through the Single Board Computer.

Figure 21: Layout for Modules and BMS Integration in Battery Box



Source: Quallion, LLC

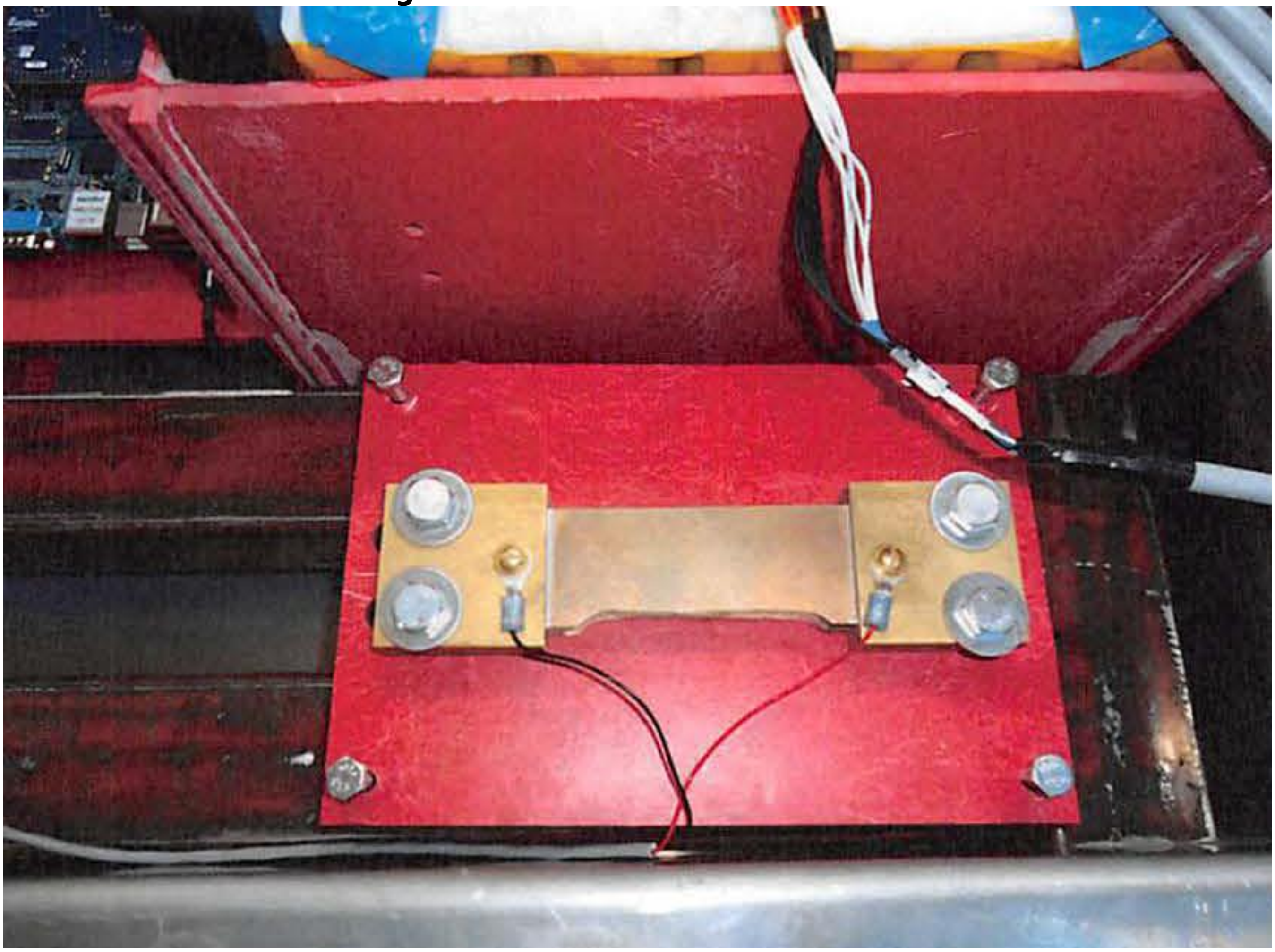
The integration of the battery modules occurred in several steps. Step 1: mount the BMS, Gateway and Single Board Computer to the baseplate. Step 2: install the components to handle the high current/voltage demands. Step 3: set up the module for placement and install in the vehicle. Step 4: interconnect the battery modules and electronics. The BMS and Gateway and the Single board computer are the monitoring, data acquisition and communication systems of the battery. The function of the BMS is to monitor voltage, current, and temperature and, control the safety mechanisms of the battery system. The Gateway is used to access the data from the BMS. The Single Board Computer handles the communication to the outside world. The electronics are mounted to be electrically isolated from the system and mechanically supported for the mission profile of the vehicle. Quallion took care to ensure that the electronics were mounted in the RailScout system to be electrically isolated and mechanically supported. This was accomplished by mounting the PCBs on standoffs that were fastened to a fiberglass base plate as shown in Figure 22. Once the electronics were secured on the base plate, they were mounted into the battery compartment of the RailScout.

Figure 22: Fiberglass Base Plate with BMS Electronics Mounted in Place

Source: Quallion, LLC

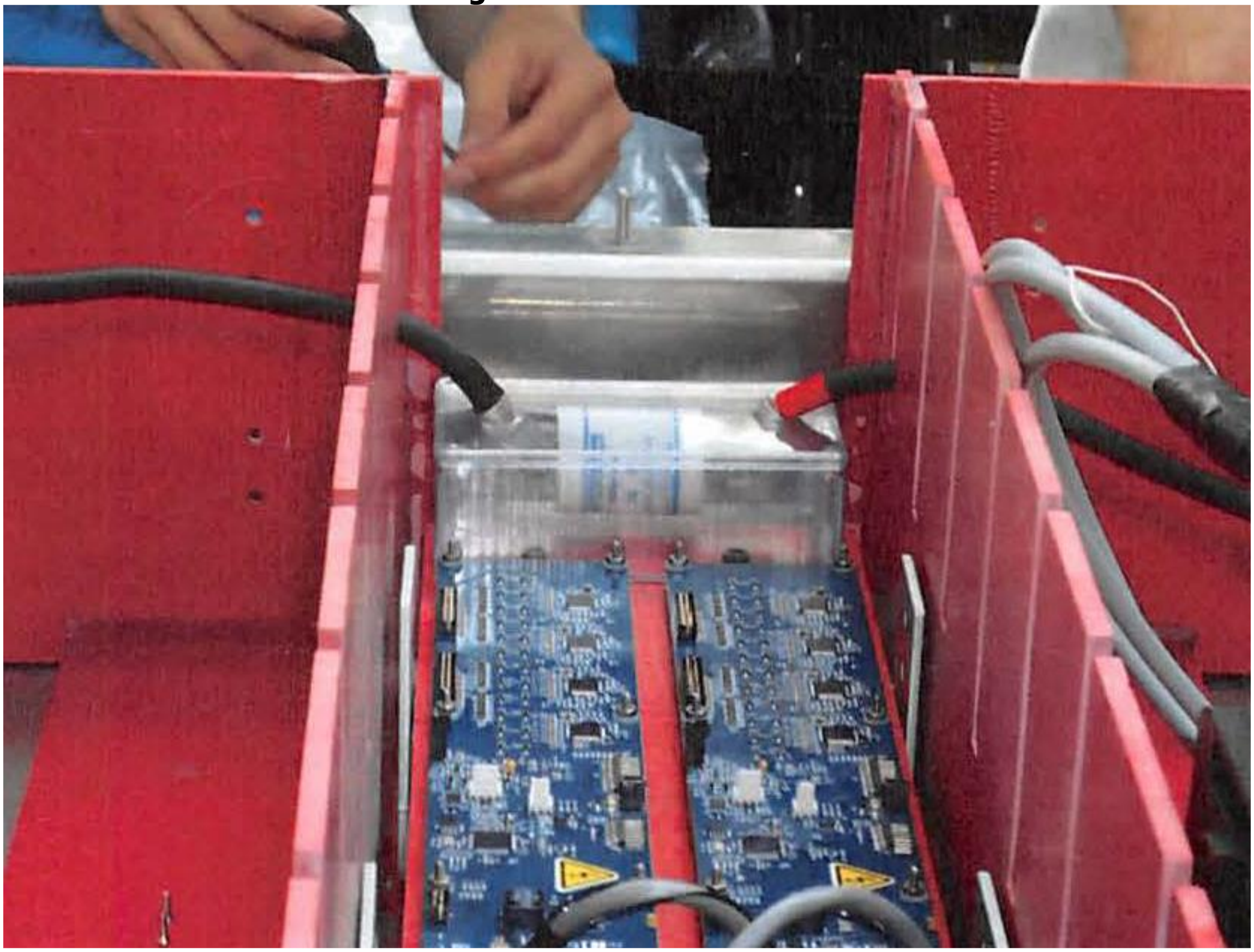
In designing a high current high voltage battery system there are several components that require special consideration. The Shunt resistor (Figure 23) is an electronic device that allows measurement of current values that are too high for the electronics in the battery system. The shunt resistor was mounted near the motor and isolated on a fiberglass base plate. The other component is the fuse. The fuse must be properly sized and isolated from accidental contact with electrically conductive materials. The fuse in the RailScout is rated for 250 amps 500v. The fuse was electrically isolated in a plastic enclosure and mounted to the BMS base plate as shown in Figure 24.

Figure 23: RailScout Shunt Resistor



Source: Quallion, LLC

Figure 24: RailScout Fuse



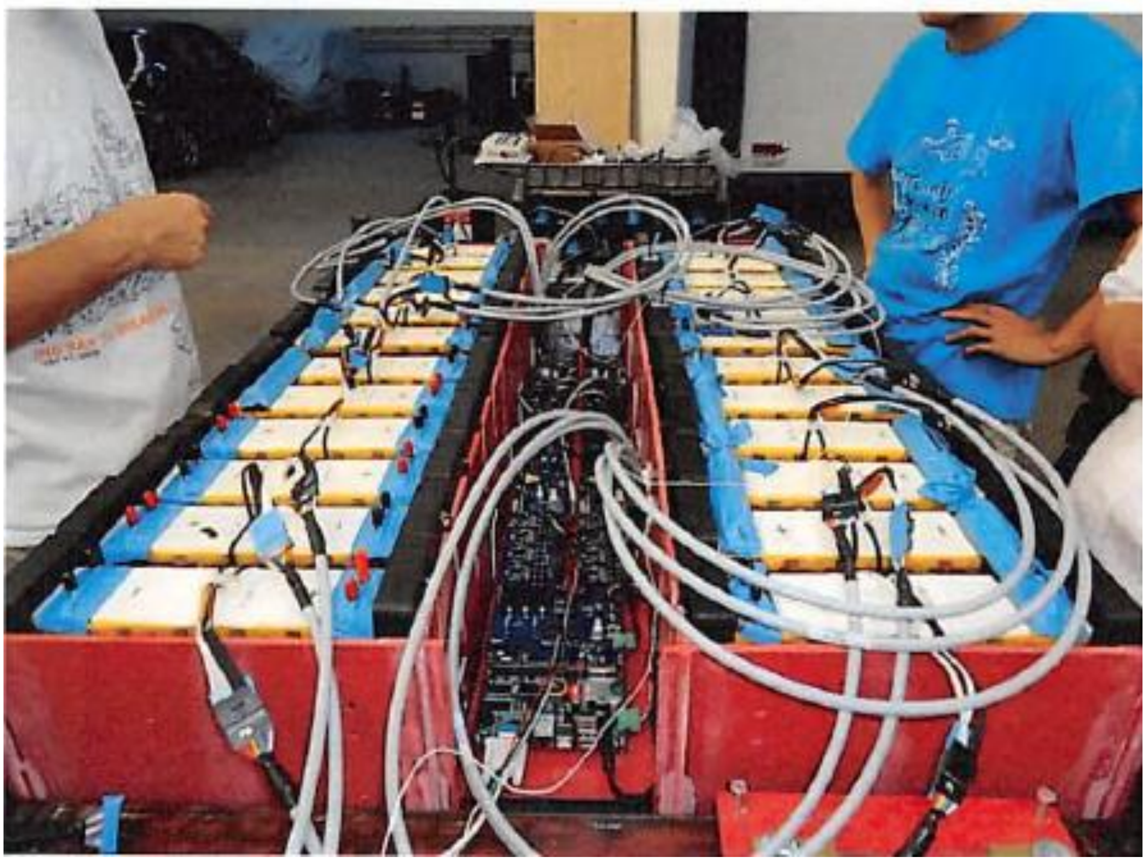
Source: Quallion, LLC

Installation of the battery modules was accomplished in several steps. First, the modules were tested for Over Current Voltage and Internal Resistance to verify their readiness for integration. Once this was established, Quallion proceeded to install the Rubber Bumpers on the ends of each battery module for mechanical isolation and to facilitate securing each module into the battery box. Quallion then placed the modules in the battery compartment in groups of six. After one group of six was populated, the modules were interconnected to each other, and then the BMS was connected to the six modules. The BMS was tested for functionality. This operation was repeated four times. Once all four groups of six battery modules were functional, each of the four groups was interconnected to complete the battery assembly. The final battery assembly as installed and interconnected is shown in Figures 25 and 26.

Figure 25: Final Battery Assembly

Source: Quallion, LLC

Figure 26: Assembled Battery Modules and Electronics in RailScout EV Battery Box



Source: Quallion, LLC

Once the battery was assembled, Quallion performed battery level tests. Quallion used a high voltage cycler to perform several test sequences as summarized in Table 6. The test set-up is shown in Figure 27. These tests were conducted to evaluate how the battery would perform at certain charge and discharge rates.

Table 6: Battery Test Sequence

Sequence 1	Perform discharge at -20A for -5 minute, charge at 20A for -5 minutes and charge at 60A for -5 minutes
Sequence 2	Set to discharge of-70A for -1 minute, then ramp up to -180A and stay for 5 seconds. Ramp down to -80.7 A for -10 minutes
Sequence 3	Perform charge at 20A for -10 minutes, charge at 40A for -20 minutes

Source: Quallion, LLC

Figure 27: Display of High Voltage Charger Showing Battery at 337.6 Volts being discharged at-80.7Amps

Source: Quallion LLC

From the collected data, Quallion determined that the BMS was accurately recording the current, voltage and temperature measurements. The BMS current measurements differed by less than one amp to what was set on the high voltage cycler. The voltage drops after a discharge and the rise after a charge were within expected ranges. The battery temperature, as measured by the thermistors, gradually increased, but did not exceed 41°C.

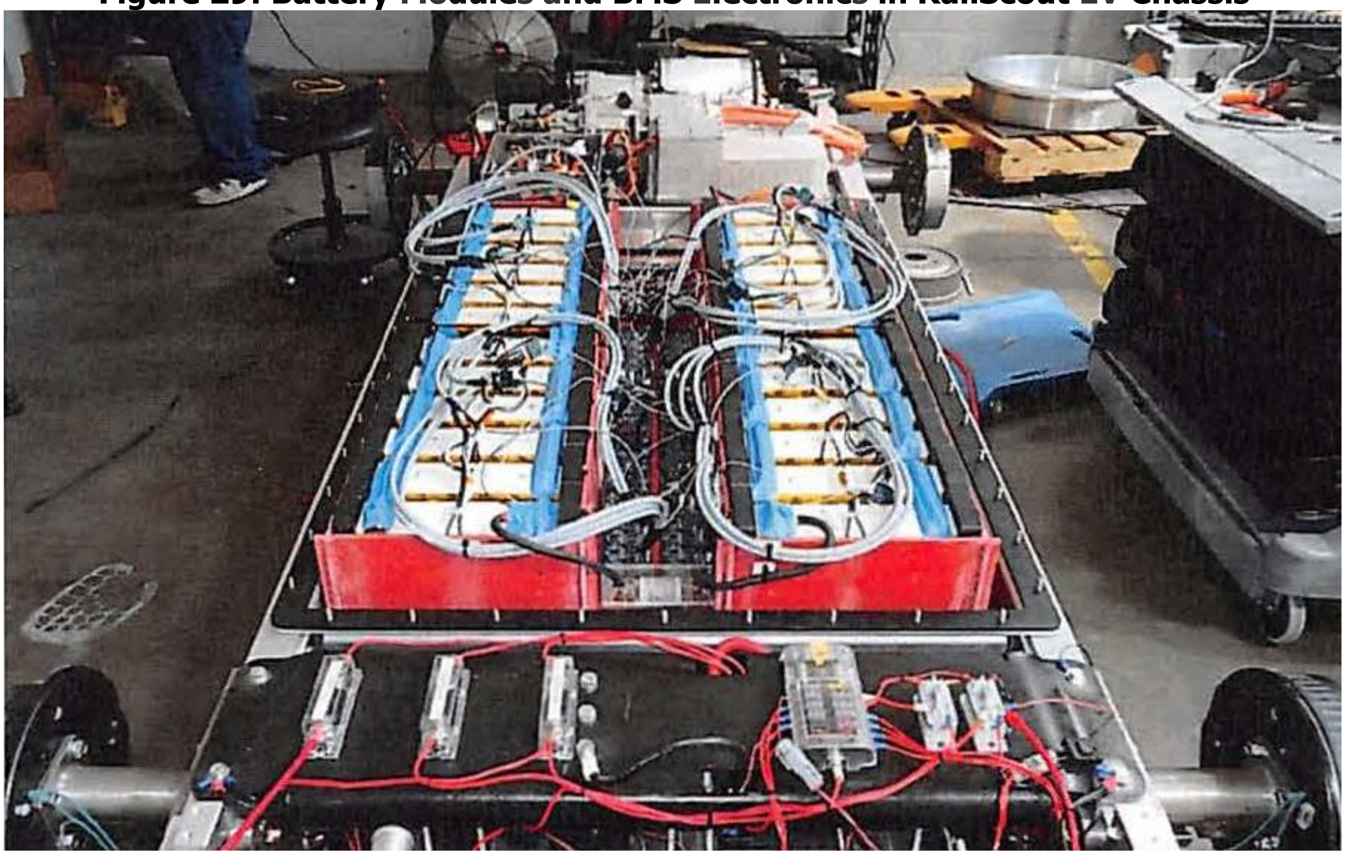
During Sequence 2 test of Table 6 (above), Quallion used the FLIR camera to monitor external battery temperature. When the discharge current increased to -180 amps, the camera detected a peak temperature of 97.3°C as shown in the captured thermal image in Figure 28. Note that this test was not a normal discharge and even though Quallion advises against routinely running this level of current, Land Systems wanted to assess design margin. Quallion has previously seen similar high temperatures at high levels of currents with the engineering module. Should the electronics detect discharge current greater than -150 amps for 20 seconds, Quallion designed in safety measures will stop the discharge. Quallion does not anticipate that the system will experience *this* high level of current during actual vehicle operation. The FLIR image allowed the localization of the temperature hot spots with the ex ternal bus bar to module bus bar interface appearing to be the hottest. Quallion has identified this as a design improvement opportunity for future implementation to lower the resistance and thus reduce the potential for high temperatures in this region of the battery module.

Figure 28: Thermal Image of Battery Being Discharged at 180 Amps

Source: Quallion LLC

With battery testing complete and observed results as expected, Quallion installed the modules into the battery box inside the RailScout vehicle as shown in Figure 29. Quallion performed testing with the battery and vehicle motor to verify that the battery was integrated properly. The motor was energized to spin and stop the wheels with the vehicle suspended. Quallion collected data showing the battery being discharged and temperature increasing. Quallion captured battery current, speed and odometer readings and verified that these measurements were consistent with expectations. The RailScout was now ready for field testing as described in Section 2.1.

Figure 29: Battery Modules and BMS Electronics in RailScout EV Chassis



Source: Quallion, LLC

1.3.5 Next Generation BMS Application Opportunities and Development Status

Many ground vehicle batteries used in military, industrial, and commercial applications are lead acid batteries. Currently these batteries have a low energy density. However, with increasing power requirements and the emerging push to lightening the loads on vehicles, a high capacity, more reliable, lighter-weight battery is needed.

The available lithium-ion (Li-ion) technologies are cost prohibitive when considered for these applications due to a lack of standard components. To make lithium-ion rechargeable batteries more cost effective, Quallion is developing modular component designs to expand the BMS applicability to a broader range of platforms for various applications including hybrid electric vehicles and advanced Start-Stop vehicles.

Quallion's next generation High Voltage BMS is specifically designed to take a more flexible modular approach employing multiple smaller circuit boards The BMS is hierarchical in design, with layers of hardware functional elements working in concert to assure safety and performance goals are met, while minimizing standby current draw and avoiding oversized components which increase cost. Details of the next generation BMS design approach follows.

Each 12 cells in series module within the high voltage system will have a cell interface board that performs the following functions:

- Cell monitoring for overcharge
- Monitoring module temperature sensors
- Cell balancing
- State of Charge monitoring based on cell open circuit voltage
- Safety circuits to protect from overcharge
- Temperature sensors and current sensors to provide battery health and operational data and to support load and temperature dependent State of Charge Algorithms

The high voltage battery system will also have a stack controller board that performs the following functions:

- Communicate with each of the constituent modules
- Dedicated Controller Area Network busses are assigned to each Battery Module
- Safety self-protection
- Battery Bus Switching/Isolation Contactor Control
- Communicate batter status to vehicle control panel
- Communicate with charge controller to provide optimal charging program

The BMS design, analysis, and testing activities are key aspects of the next generation BMS development program. The prototype cell interface board is currently in development. This design is centered on the LTC6804 Multicell Battery Monitor Unit (BMU) from Linear Technology. To aid in the development process, Quallion purchased Linear Technology's demonstration board and performed initial product evaluation. The following screen shots shows Linear Technology's graphical user interface measuring various cell voltages.

The data suggests that the accuracy of Quallion's measurements will be more than adequate to support the unique requirements of automotive systems. This BMU can measure all cell voltages within 300 microseconds. This fast speed allows the overall system to respond quickly and protect the cells from damaging over voltage or under voltage conditions thereby increasing the cell's useful life. Development of the next generation BMS prototype is planned to continue through the period of performance of this contract as Quallion evaluates options for additional future funding, either from internal sources or from follow-on contracts, to bring the next generation BMS to full fruition.

Through this continued development effort, Quallion expects to enhance the effectiveness of advanced BMS electronics to contribute to improved safety of electric vehicles, helping to alleviate legitimate concerns of potential EV customers.

1.3.6 Problems Encountered and Resolved

During the BMS and battery assembly development and integration, Quallion encountered and resolved several electronics related issues. The following outlines the problems encountered:

1. Various harness connectors lacked a locking feature which could impact the interconnect robustness.
2. Measurement of six-module voltage (sub-stack voltage) had larger than expected variance.
3. In-line debug mode caused Control Board to become un-programable

During the integration of the battery and electronics, it became apparent that several of the harness connectors which lacked a locking feature needed to be addressed to ensure system robustness. Because the BMS electronics and battery would be operating in a vibration inducing environment, Quallion needed to ensure that the cables and connectors were firmly fixed and secured. To resolve this, Quallion applied room temperature vulcanization (RTV) silicone to the male and female connectors to effectively fix and secure the interconnection. In the next revision of the board, Quallion intends to upgrade all connectors to have the appropriate mechanical locking feature.

Another problem Quallion discovered with the electronics was that the six-module voltage (sub-stack voltage) measurement had a larger than expected variance. The reason for the larger variance was attributed to the tolerance on Quallion' s voltage dividing resistors which was deemed too large. For this current design iteration, Quallion used the sum of virtual cell voltages to represent the overall pack voltage. Quallion plans to address this voltage variance in a future revision by using tighter voltage dividing resistor tolerances.

Quallion also experienced several boards that suddenly became un-programmable when the exited debug mode was entered and exited. To overcome this limitation, Quallion troubleshot the board by writing simple test functions in the firmware. Eventually, the need to debug the board was eliminated and it was made clear to not enter debug mode when programming boards.

CHAPTER 2:
Project Results

Chapter 2 discusses the deployment sites for the RailScout, and the results of the data obtained during the deployment period. The data collection effort involved coordination with the Land Systems team that was on site during the deployment period.

2.1 RailScout EV Deployment and Operational Data Collected

2.1.1 Vehicle Field Deployment, Site Description and Test Objectives

Field testing was performed on tracks at two test sites, one owned by Fillmore & Western Railways, located in Fillmore, California, in September 2015, the other on the Huey P. Long Bridge over the Mississippi River in New Orleans, Louisiana beginning in October 2015. The intent was to exercise the RailScout in real-world conditions to verify vehicle remote operation, communications, and control. From the data collected, the battery and BMS performance would be evaluated at different speeds and settings. By monitoring the battery state data, it would be helpful in refining parameters for future system optimization. Figure 30 shows the RailScout being prepared for testing at the Fillmore site.

Figure 30: Powering on the RailScout at the Fillmore Test Site

Source: Quallion, LLC

The Fillmore testing was intended to provide a preliminary vehicle operational evaluation and overall system communication and control check-out. The longer-term field test on the Huey P. Long Bridge in New Orleans would be used to better characterize vehicle field performance as it executed its intended rail inspection function. For this longer-term testing, the RailScout would run (via remote control) across the four-mile span of tracks of this historical bridge once a day, three to five times a week. During each run, numerous sensors on board the RailScout would automatically monitor the condition of the tracks.

The goal of this field demonstration was to perform an eight-mile round trip run at up to its 11 miles per hour maximum speed over a period and collect vehicle data to characterize and assess the performance of the various vehicle systems including power, communication, and control.

From the data collected of battery state at different speeds and settings, Quallion expects to be better able to refine parameters for future optimization for this BMS application as well as other potential EV platform applications.

Figure 31 shows the RailScout on site at the public belt railroad yard adjacent to the Huey P. Long Bridge in New Orleans, Louisiana.

Figure 31: RailScout on Site in New Orleans, Louisiana.

Source: Land Systems Corporation

Figure 32 and Figure 33 show two views of the Huey P. Long Bridge and the tracks monitored by the RailScout during its field deployment.

Figure 32: View of Huey P. Long Bridge Test Site in New Orleans, Louisiana.

Source: Land Systems Corporation

Figure 33: Another View of Huey P. Long Bridge Test Site Showing Four Mile Bridge Span

Source: Land Systems Corporation

2.1.2 Vehicle Field Data Collection and Analysis

The purpose of this project is to collect and analyze data a minimum of two months and show the benefits that these batteries and BMS yield as a result if implementing them into electric vehicles.

2.1.2.1 Fillmore Test Site

For the initial field testing, the RailScout was transported to the Fillmore test site via trailer as shown in Figure 34. Upon lowering the vehicle onto the tracks, the first step was to verify that the vehicle was powering up properly. With the push of a button, the BMS and vehicle electronics was activated. Then, via remote control, the RailScout vehicle was commanded to move forwards and backwards on the tracks.

Figure 34: Preparing to Lower the RailScout onto Fillmore Railroad Tracks

Source: Quallion, LLC

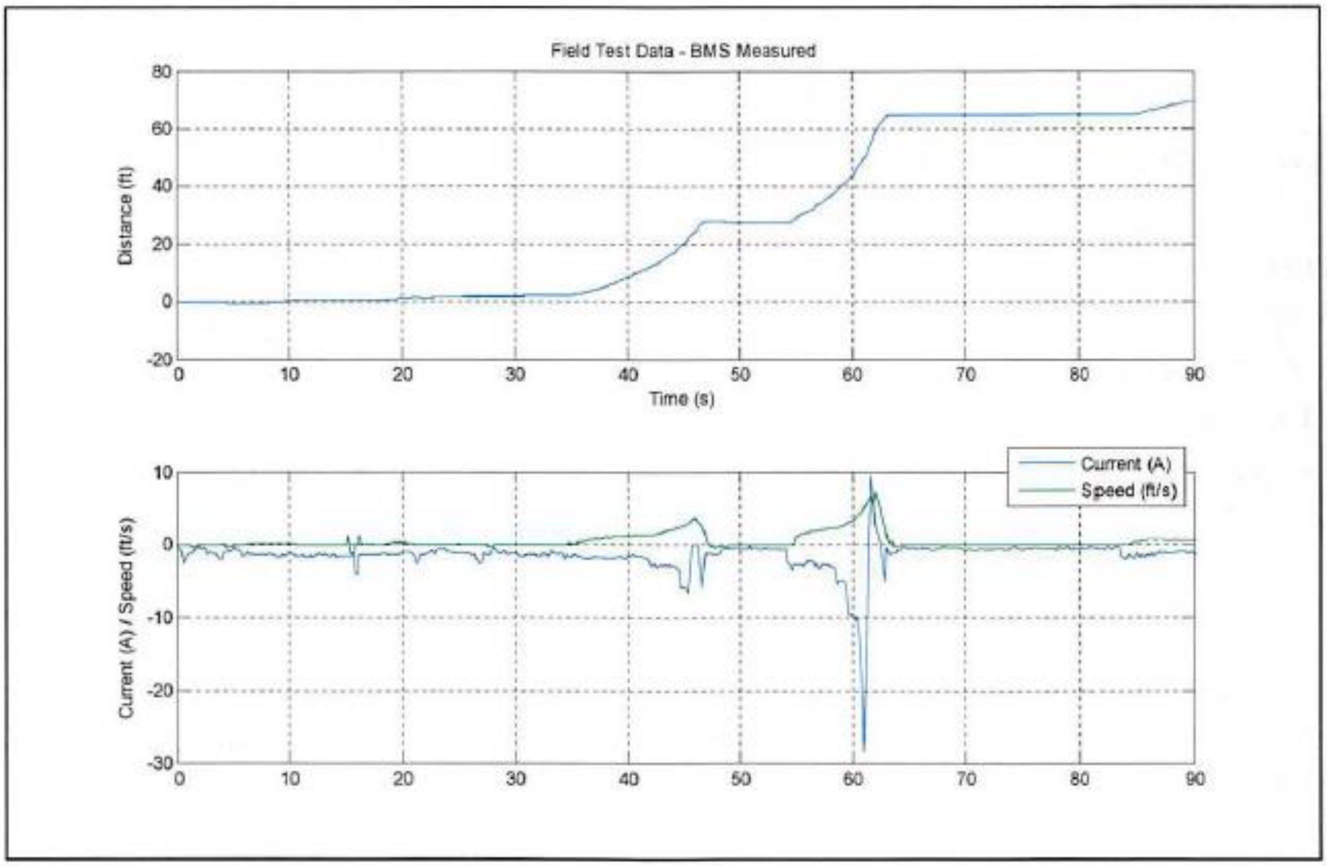
After confirming all RailScout systems operational, the Quallion and Land Systems team performed several higher speed fully automated runs as shown in Figure 35.

Figure 35: RailScout in Full Automated Operation

Source Quallion, LLC

After completing the field testing, the USB memory stick was extracted from the Single Board Computer to analyze the captured data. During one of Rail Scout's excursions, it traveled approximately 64.5 feet for two short runs. For this test, the RailScout reached a speed of approximately seven feet per second, less than its maximum speed, and discharged to approximately 28 amps as depicted in the data plots shown in Figure 36.

Figure 36: BMS Distance, Speed, and Current Measurement



Source: Quallion, LLC

During the field testing, the battery voltage decreased, and temperature increased slightly over time. This was expected because the short track length and only approximately a dozen lengthy runs were conducted. The virtual cell voltages ranged from 3.8 to 3.85 volts and the measured temperatures ranged from 33 to 36°C.

After implementing several software upgrades such as data formatting and making final adjustments to the electric vehicle, the RailScout was packed for transport to its long-term test site in New Orleans, Louisiana.

2.1.2.2 New Orleans Test Site

Once on site in New Orleans, the RailScout underwent a detailed operational checkout. Several intermittent issues involving systems communications required control software modifications and harnessing modifications which Land Systems implemented. After system operational verification, the RailScout was then deemed ready for testing.

RailScout has been running along 1000 ft. of track at the New Orleans Public Belt Railroad Yard Track #2. The vehicle was used for six days from October 1, 2015 to October 28, 2015. On average, 10 runs were made each day. Each run consisted of accelerating to approximately 17.75 km/h, sustaining speed and decelerating towards end of range. These runs were performed at 80-85°F ambient temperature and the unit was stored indoors at 72°F overnight. Table 7 summarizes the performance of the vehicle during this time.

Table 7: RailScout Vehicle Performance

Electric Vehicle Performance	Value
Days of Use	6.00
Average Runs per Day	10.00
Max Speed	17.75 kilometers/hour
Range Per Run	0.33 kilometers
Total Range	19.80 kilometers
Estimated Total Time In Motion (hours)	1.12 hours

Source: Land Systems Corporation

Table 8 shows battery performance as the vehicle accelerated to speed. The typical average current that was observed during accelerating to speed was 21.05 amps. At roughly 2.5 seconds, it is estimated that the total energy from the battery equaled 0.88 Amp-hour.

Table 8: RailScout Acceleration Performance Parameters

Acceleration	
Typical Average Pack Current Accelerating to Speed	21.05 A
Time to Speed (s)	2.50 sec
Typical Consumption Accelerating to Speed in 2.5 seconds	0.015 Ah
Total Number of Acceleration	60.00
Total Energy Accelerating to Speed (Ah)	0.88 Ah

Source: Land Systems Corporation

Similarly, Table 9 covers battery performance as the vehicle cruised at speed. The typical average current that was observed during cruising speed was 4.44 amps. At roughly 90 seconds, Quallion estimates that the total energy from the battery equaled 6.66 Amp-hour.

Table 9: RailScout Cruising Speed Performance Parameters

Cruising	
Typical Total Pack Current at Speed (Continuous)	4.44 A
Estimated Non-Traction Pack Current (Accessories, etc., for Test Duration)	1.00 A
Estimated Traction Pack Current	3.44 A
Time at Speed	90.00 sec
Typical Consumption at Speed	0.11 Ah
Total Number of Cruises 60.00	60.00
Total Energy at Cruising Speed	6.66 Ah

Source: Land Systems Corporation

During this period, the RailScout vehicle consumed approximately 7.54 Amp-hours energy from the Quallion battery pack. With a battery capacity of approximately 105 to 115 Amp-hours, the energy consumed represents less than 7.5 percent of total capacity. The battery pack has not had to be recharged since the first charge after arriving in New Orleans. Thus far, Quallion's partner Land Systems has commented "at this early stage, the Quallion pack provided performance within expectations."

2.2 Greenhouse Gas Emission and Toxic Air Pollutant Reduction Projections

It is well-established that electrification of the transportation sector will provide critical reductions in greenhouse gas and criteria and toxic air pollutant emissions. These reductions are important for the CEC and its sister state agency, the California Air Resources Board (CARB), to meet several important air quality and climate change initiatives[1] that include the Low Carbon Fuel Standard, the California Governor's Executive Order B-30-15, the Energy Commission's ARFVTP and the California Global Warming Solutions Act of 2006 (Assembly Bill 32).

As part of this project to upgrade existing on-site facilities to implement a BMS Electronics laboratory, the subject BMS was integrated into the RailScout. As noted earlier, the RailScout is an unmanned, battery powered railroad track inspection vehicle developed as an alternative to the gasoline and diesel-fueled rail track inspection vehicles currently in use. While existing rail inspection vehicles can vary in size from light-duty to heavy-duty vehicle platforms, most existing inspection vehicles is based on light-duty and medium-duty pick-up truck platforms.

The following discussion that follows provides an estimate of the petroleum fuel, criteria, and toxic pollutant and greenhouse gas emissions reduced with the RailScout prototype during a two-month field deployment. A projection of the potential long-term benefits of the zero emission RailScout at full market penetration (projected to be 600 units by 2025, nationwide) is also provided.

[1] Climate Change | California Air Resources Board https://ww2.arb.ca.gov/our-work/topics/climate-change

2.2.1 Discussion of Baseline Emissions

Regulatory agencies in California consider battery-electric vehicles, such as the RailScout, to have no tailpipe emissions, i.e., they are zero-emission vehicles. Thus, to estimate emission reduction benefits, it is only necessary to characterize the emissions of the vehicles that are being replaced by the zero-emission technology; these vehicles are referred to as the "baseline" vehicles. Knowing the emissions of the baseline vehicle means the emission reductions resulting from eliminating the baseline vehicle emissions are also known. Essentially, for a vehicle that is replaced with an electric vehicle, the emission reductions are equivalent to the baseline emissions.

For this project, the baseline gasoline and diesel vehicles are characterized utilizing CARB's Emissions Factor 2014 inventory model, or EMFAC2014[2] CARB provides a straight-forward web-based user interface to obtain model results based on user-selected inputs. In the tables that follow, there are four baseline vehicle configurations used to characterize the emissions benefits of this project and its technology development efforts:

- Gasoline-fueled LDT2, representing gasoline-fueled light-duty trucks with a gross vehicle weight rating (GVWR) of between 3,751 and 5,750 pounds.
- Diesel-fueled LDT2, representing diesel-fueled light-duty trucks with a GVWR between 3,751 and 5,750 pounds.
- Gasoline-fueled MDV, representing gasoline-fueled medium-duty vehicles with a GVWR of between 5,751 and 8,500 pounds.
- Diesel-fueled MDV, representing diesel-fueled medium-duty vehicles with a GVWR of between 5,751 and 8,500 pounds.

Both vehicle classes include gasoline- and diesel- fueled internal combustion engine configurations. Results are provided in this analysis for all four baseline configurations (each vehicle class operating on gasoline or diesel), since these options are the most common type of rail inspection vehicles in operation today.

Gallons per mile and grams of emissions per mile factors presented in Table 12 were developed based on the output of EMFAC2014 for the year 2015 average statewide fleet inventory. EMFAC2104 output includes a breakdown by vehicle class of the daily vehicle miles travelled tons of emission per day and the daily fuel consumption by vehicle class. Simple arithmetic operation of the EMFAC output allows development of the factors used to estimate project benefits that are summarized in Table 10. For example, EMFAC reports the total tons per day of a pollutant and the total miles per day travelled by all vehicles in the specified weight category. Tons per day divided by miles per day and converted by unit analysis results in grams per mile. Table 10 presents the calculated emission factors (grams per mile) and fuel consumption factors (gallons per mile) for each of the four baseline configurations for the fleet average emissions in the year 2015.

Four baseline configurations are considered in order to show the range of potential benefits that might be realized with wider scale implementation of the zero-emission technology. To

[2] EMFAC https://arb.ca.gov/emfac/

calculate the benefits of replacing one of the four types of baseline vehicles with zero-emission technology, simply multiply the number of miles by the factors in the table.

Table 10: Baseline Factors Based on California Fleet Average for 2015 Derived Using CARB's EMFAC2014 Model

Vehicle Class	Light Duty Truck (3,751 to 5,750 lb. GVWR) (gram/mile)		Medium Duty Vehicle (5,751 to 8,500 lb. GVWR) (gram/mile)	
Fuel Type	**Gasoline**	**Diesel**	**Gasoline**	**Diesel**
Reactive Organic Gases (ROG)	0.27	0.0254	0.36	0.0226
Carbon Monoxide	2.32	0.1792	3.44	0.2549
Oxides of Nitrogen (NOx)	0.28	0.1091	0.44	0.1036
Carbon Dioxide	461.15	392.70	600.55	517.26
Particulate Matter 1 O micron (PM_{10})	0.0024	0.0115	0.0026	0.0126
Particulate Matter 2.5 micron ($PM_{2.5}$)	0.0022	0.0110	0.0024	0.0120
SulFLIR Oxides (SOx)	0.0046	0.0037	0.0061	0.0049
Fuel Consumption (gallons per mile)	0.0546	0.0390	0.0712	0.0513

Source: Clean Fuel Connection, Inc. staff denvat1on of fuel consumption and em1ss1on factors using EMFAC2014
NOTE: PM2.s is a subset of PM1o, these are not additive.

2.2.2 Project Emission Reductions: Actual Field Demonstration Results

The factors summarized in Table 10 are applied to project activity data (i.e., number of miles during a period) to estimate the actual emissions and fuel consumption reduction for the project demonstration, as well as the projected technology benefits discussed previously. Table 11 provides the estimated actual reductions achieved during a two-month demonstration period, based on the following parameters:

- The RailScout operates one eight-mile round trip each operating day.
- During the first two weeks of the demonstration, the RailScout operated three days per week, or 24 miles per week. During the last six weeks of the demonstration, the RailScout operated five days per week, or 40 miles per week. Thus, the total two-month operational activity totaled 288 miles.

It is important to understand that Table 11 provides an estimate of the demonstration project reductions for four different baseline scenarios. For example, if one assumes the baseline truck being replaced by the RailScout is a light-duty gasoline truck, then an estimate of the reduction benefits is shown in the first data column. Similarly, if it is assumed that the baseline truck being replaced by the RailScout is a medium-duty diesel vehicle, then the estimated reduction benefits are shown in the last data column. Note that Table 11 includes carbon dioxide, which is a greenhouse gas (GHG). A more thorough analysis of potential GHG reductions provided in Section 2.2.4, Carbon Intensity and GHG Cost-Effectiveness.

Table 11: Emission and Fuel Consumption Reduction Estimates for the Field Demonstration (288 miles) for Four Different Baseline Vehicle-Type Scenarios

Vehicle Class	Light Duty Truck (pounds)		Medium Duty Vehicle (pounds)	
Fuel Type	**Gasoline**	**Diesel**	**Gasoline**	**Diesel**
Reactive Organic Gases (ROG)	0.17	0.02	0.23	0.01
Carbon Monoxide	1.47	0.11	2.18	0.16
Oxides of Nitrogen (NOx)	0.18	0.07	0.28	0.07
Carbon Dioxide	292.79	249.33	281.3	328.42
Particulate Matter 1 O micron (PM10)	0.002	0.0072	0.0016	0.0080
Particulate Matter 2.5 micron (PM2.5)	0.001	0.0070	0.0015	0.0076
SulFLIR Oxides (SOx)	0.003	0.002	0.004	0.003
Fuel Use Reduction (total gallons reduced)	0.02	0.02	0.05	0.03

Source: Clean Fuel Connection, Inc.

NOTE: PM2.s is a subset of PM,o, these are not additive.

Below are two examples to assist data interpretation for Table 11 (above):

- If the RailScout replaced a gasoline-fueled light-du ty truck for the 288-mile, two-month deployment period, then 0.18 pounds of NOx and 0.002 pounds of PMlO were reduced, respectively.
- If the RailScout replaced a diesel-fueled medium-duty truck for the 288-mile, two-month deployment period, then 0.07 pounds of NOx and 0.008 pounds of PMlO were reduced, respectively.

Actual estimated deployment reductions achieved by the prototype unit were minor, since they were evaluated over just 288 miles of operation. Thus, to assess the potential project benefits more effectively, it is necessary to consider larger scale implementation of the technology. Section 2.2.3 estimates projected benefits assuming wider-scale implementation.

2.2.3 Projected Emission Reductions

This section provides benefits projections for two scenarios. The first is a projection of the commercialized RailScout and the second looks beyond the RailScout to the large-scale manufacture (and therefore sales) of Quallion's BMS system, the primary subject of this project.

2.2.3.1 Projected Emission Reductions for the Commercialized RailScout

According to the Federal Rail Administration, there are approximately 220,000 miles[3] of railroad track throughout the U.S. For this analysis, it is assumed that this entire track is inspected, on

[3] Federal Railroad Administration: Railroad Security System," presentation by William J. Fagan. https://rsac.fra.dot.gov/, Accessed November 3, 2015.

average, three times per month, or 36 times per year, for a total of 7.92 million " track inspection" miles per year.

Table 12 summarizes the benefits of conducting all railroad track inspections with a zero-emission vehicle such as the RailScout. Basically, Table 12 presents the results of multiplying the factors in table 12 by 7.92 million miles.

Table 12: Estimated Annual Emissions and Fuel Consumption Reduction Benefits of Inspection of All U.S Railroad Track with Zero Emission RailScout Vehicle

Vehicle Class	**Light Duty Truck (3,751 to 5,750 lb. GVWR) (tons/year)**		**Medium Duty Vehicle (5,751 to 8,500 lb. GVWR) (tons/year)**	
Fuel Type	**Gasoline**	**Diesel**	**Gasoline**	**Diesel**
Reactive Organic Gases (ROG)	2.37	0.22	3.13	0.20
Carbon Monoxide	20.26	1.56	30.04	2.23
Oxides of Nitrogen (NOx)	2.43	0.95	3.83	0.90
Carbon Dioxide	4,026	3,428	5,243	4,516
Particulate Matter 1 O micron (PM10)	0.0021	0.01	0.023	0.11
Particulate Matter 2.5 micron (PM2.5)	0.0019	0.096	0.021	0.105
SulFLIR Oxides (SOx)	0.004	0.03	0.05	0.04
Fuel Reduction (gallons per year)	432,347	308,548	563,777	406,417

Source: Clean Fuel Connection, Inc.

NOTE: PM2.5 is a subset of PM10, these are not additive.

The Table 12 (above) results are a function of the baseline technology that the RailScout would replace. Examples of how these results can be interpreted include:

- If the zero-emission rail inspection equipment, such as the RailScout, replace light-duty diesel trucks (which are assumed in this case to conduct all the rail track inspections), then 0.95 tons of NOx and over 308,500 gallons of diesel fuel consumption would be reduced in one year, respectively.
- If the zero-emission rail inspection equipment, such as the RailScout, replace medium duty gasoline vehicles (which are assumed in this case to conduct all the rail track inspections), then 3.83 tons of NOx and over 563,770 gallons of diesel fuel consumption would be reduced in one year, respectively.

Land Systems Corporation projects that upon exiting the prototype demonstration phase, they will place 60 units in service each year over the following ten years, for a total fleet implementation in the U.S. of 600 units by about 2025. This fleet implementation would provide more than adequate capacity to meet the needs in the above projection.

2.2.3.2 Projected Emission Reductions of Battery-Electric Vehicles

Since the primary objective of this project was to upgrade existing on-site facilities to implement a BMS Electronics laboratory, with the goal to manufacture the BMS in California to support a wider variety of zero-emission transportation platforms, the project team also considered a more generic approach to evaluate project benefits. This approach assumes the State of California is successful in meeting its Low Carbon Fuel Standard (LCFS) regulation. This regulation requires[4] that the State of California achieve a ten percent reduction in carbon intensity (CI) of transportation fuels by the year 2020. There are a variety of methods that California will meet this goal to reduce CI by ten percent, including battery-electric technology. Since BMS technology is needed for all battery-electric vehicles, Quallion's BMS laboratory and manufacturing facility will support successful implementation of zero-emission vehicles as a contributing strategy to meet the LCFS.

To illustrate the significant potential benefits of zero-emission vehicles, a benefits analysis that assumes ten percent replacement of gasoline and diesel vehicles in the light-duty truck and medium-duty vehicle categories is summarized in Table 13. The same baseline factors derived from EMF AC that are provided in Table 10 are used for this analysis. Essentially, ten percent of the vehicle miles travelled in the two weight classes (and for each of the fuels), is assumed to be replaced with zero-emission propulsion technology, providing a substantial reduction in emissions and fuel consumption.

Table 13: Benefits of Replacing 10 Percent of Existing Light-Duty and Medium-Duty Vehicles with Zero-Emission Vehicles

Vehicle Class	**Light Duty Truck (3,751 to 5,750 lb. GVWR) (tons/year)**		**Medium Duty Vehicle (5,751 to 8,500 lb. GVWR) (tons/year)**	
Fuel Type	**Gasoline**	**Diesel**	**Gasoline**	**Diesel**
Reactive Organic Gases (ROG)	1,892	0.22	1,792	1.13
Carbon Monoxide	16,185	1.55	17,192	12.78
Oxides of Nitrogen (NOx)	1,943	0.95	2,193	5.19
Carbon Dioxide	3,126,982	3,408	3,000,325	25,930
Particulate Matter 1 O micron (PM10)	16.78	0.100	12.93	0.63
Particulate Matter 2.5 micron (PM2.5)	15.46	0.095	11.92	0.60
SulFLIR Oxides (SOx)	32.39	0.033	30.25	0.25

[4] Low Carbon Fuel Standard California Air Resources Board https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard

Vehicle Class	Light Duty Truck (3,751 to 5,750 lb. GVWR) (tons/year)		Medium Duty Vehicle (5,751 to 8,500 lb. GVWR) (tons/year)	
Fuel Type	**Gasoline**	**Diesel**	**Gasoline**	**Diesel**
Fuel Reduction (gallons per year)	345,477,867	306,684	322,632,486	2,333,665

Source: Clean Fuel Connection, Inc.

NOTE: PM2.5 is a subset of PM10, these are not additive.

As summarized above, replacement of just ten percent of gasoline or diesel fueled vehicles in these vehicle weight classes used in *this* analysis provides significant *air* emission and petroleum fuel consumption reductions. Remember that the columns in these tables are not additive. The analysis does not assume the replacement of a mix of vehicle class/fuel. Each column represents the reductions that result from rep lacing ten percent of current vehicles in the specified weigh t class and fuel type with zero-emission technology. The analysis is provided to illustrate the importance of zero-emission technology development and implementation.

2.2.4 Discussion of Carbon Intensity and GHG Cost-Effectiveness

Under its Low Carbon Fuel Standard, the California Air Resources Board defines[5] "carbon intensity" as a measure of the overall GHG contribution from all aspects of bringing a fuel to market (i.e., production, refining, transportation, etc.). The unit of carbon intensity (CI) is grams of carbon dioxide equivalent per mega-joule (gC0 2e/MJ), but each fuel has its own basis (i.e., for gasoline the CI is 99.78 gC02e/MJ of gasoline, whereas diesel has a CI of 102.01 gC02e/MJ of diesel - these two values are not comparable because the fuel basis is different. In order to estimate the GHG benefits of electrification compared to gasoline and diesel, the energy density (ED) and energy economy ratio (EER) of all three fuels are applied in accordance with the published methodology provided by CARB for its various grant funding programs[6] This methodology allows the CI from different fuels to be compared.

This assessment of GHG emission reductions and associated cost-effectiveness was simplified to consider only light-duty gasoline-fueled trucks as the single baseline vehicle configuration. Using the equations and factors provided by CARB in the referenced methodology, CHG emission reduction benefits are estimated as follows:

- For the field demonstration (i.e., 288 miles of operation), 15.72 gallons of gasoline were estimated to have been replaced with electricity to power the prototype vehicle. Using CARB's methodology previously referenced, the CHG reduction for this case is 0.13 metric tons of C02e in one year.

[5] Staff Report: Initial Statement of Reasons for Proposed Rulemaking for the Proposed Re-Adoption of the Low Carbon Fuel Standard, California Air Resources Board, December 2014 https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2018/lcfs18/isor.pdf
[6] Appendix D: Methodology for Determining Emission Reductions and Cost-Effectiveness, accessed 10/30/15. https://ww2.arb.ca.gov/sites/default/files/auction-proceeds/carb_lct_zedtipp_qm_final_2020.pdf

- When commercialized, the RailScout is projected to operate 120 miles per day, five days per week, 52 weeks per year, for total annual miles equal to 31,200. Per the CARB methodology, the CHG reduction for this case is almost 14 metric tons of C02e in one year for a single zero-emission RailScout that replaces a gasoline truck.
- If ten percent of all vehicle miles travelled are replaced with electric vehicle technologies, including the Quallion BMS, over 2.8 million metric tons of C02e would be eliminated in one year.

Cost-effectiveness is defined by the previously referenced CARB methodology as the annualized incremental cost of a technology, divided by the annual emission reductions in units of tons per year. Incremental cost is the extra cost of the advanced technology that is over and above the cost of the baseline (i.e., conventional) technology. For CHG cost-effectiveness, metric tons are used as the emissions reduction unit of measure. Currently, a discount factor of two percent is used to determine the annualized cost. Assessing cost-effectiveness is difficult for this project, since the project's primary objective was to expand manufacturing of BMS technology in California and there is no clear "incremental vehicle cost" to use for the cost-effectiveness evaluation. Instead, the cost-effectiveness is estimated based on the RailScout prototype vehicle and its projected cost and operational data:

- The incremental cost for the RailScout is estimated at $75,000. Assuming a ten-year project life and 31,200 miles of operation per year (120 miles, per day, five days per week, and 52 weeks per year), the project cost-effectiveness is $595 per metric ton of C02e.
- As an example, to place this in some context, the 2010 Los Angeles County Metropolitan Transportation Authority report entitled "Greenhouse Gas Emissions Cost Effectiveness Study"[7] considers $300 to $900 per ton to have moderate cost-effectiveness; projects at greater than $1,000 per ton are considered to have a high cost-effectiveness.

Note that this cost-effectiveness does not take into account the fuel cost savings that will be achieved by powering the RailScout with less expensive electric power.

2.3 Ancillary Project Benefits

The potential economic benefit of this project to the State of California comes from two sources. The first is the direct benefit from the commercialization of the RailScout battery-powered rail inspection equipment. The genesis of the RailScout concept was a request from the High-Speed Rail Authority in Spain for a clean, low-cost rail inspection option. In Spain, the tracks for the High-Speed train must be inspected every day before rail service begins. Since the Rail Authority does not own any rail inspection equipment, it must rent a locomotive to inspect the tracks every day. This is an expensive solution that results in additional vehicle emissions. The Spanish Rail Authority was interested in the development of a lower cost and less polluting option. The RailScout could be used for the daily track inspection, saving money and reducing emissions.

[7] Cost-Effective Approaches to Reduce Greenhouse Gas Emissions through Public Transportation in Los Angeles, California - Frank Gallivan, Jeff Ang-Olson, Cris B. Liban, Alvin Kusumoto, 2011
https://journals.sagepub.com/doi/10.3141/2217-03

The RailScout is also designed to fulfill the need for cost-effective track inspection in the U.S. According to the Federal Rail Administrations[8], there are over 220,000 miles of train track in the U.S. These tracks fall into Track Classes one to nine based on the speed of the trains and whether they run passenger or freight service.

Rail safety has come under increased scrutiny because of a number of high-profile derailments around the country. Most of these involve the transportation of oil. The Federal Rail Administration has recently issued new safety guidelines. These proposed regulations should only increase the demand for clean inspection vehicles such as the RailScout. Federal regulations require routine track inspections every two weeks or more frequently.[9]The inspection procedure for Class one to five tracks is described below.

Each inspection shall be made on foot or by riding over the track in a vehicle at a speed that allows the person making the inspection to visually inspect the track structure for compliance with this part .... If a vehicle is used for visual inspection, the speed of the vehicle may not be more than 5 miles per hour when passing over track crossings and turnouts, otherwise, the inspection vehicle speed shall be at the sole discretion of the inspector, based on track conditions and inspection requirements. When riding over the track in a vehicle, the inspection will be subject to the following conditions - (1) One inspector in a vehicle may inspect up to two tracks at one time provided that the inspector's visibility remains unobstructed by any cause and that the second track is not centered more than 30 feet from the track upon which the inspector is riding; (2) Two inspectors in one vehicle may inspect up to four tracks at a time provided that the inspector's visibility remains unobstructed by any cause and that each track being inspected is centered within 39 feet from the track upon which the inspectors are riding.

Section 213.365 of 49 CFR contains similar language for track classes six to nine. For classes six to nine automated inspection via special rail cars is also required. Figure 37 lists the required frequency of inspection by Class of Track and type of rail service.

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[8] Federal Railroad Administration: Railroad Security System," presentation by William J. Fagan. http://rsac.fra.dot.gov/document.php?type=meeting&date=20030520&name=FRASecurityProgram1.pdf. Accessed November 3, 2015.

[9] The requirements are part of the federal Track Safety Standards (TSS). Subpart F (49 CFR § 213.233) of the TSS addresses the requirements for track classes 1-5, while Subpart G (49 CFR § 213.365) addresses track classes 6-9, which typically would support passenger operations.

Figure 37: Required Frequency of Inspection

		Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9
Maximum Operating Speed (mph)	***Passenger***	15	30	60	80	90	110	125	150	200
	Freight	10	25	40	60	80				
Track Inspection Requirements										
Visual Inspections (Track)		2 weekly (passenger)	2 weekly	2 weekly	2 weekly	2 weekly	2 per week	2 per week	3 per week	3 per week
Visual Inspections (Switch/Crossing)		1 per month	1 per month	1 per month	1 per month	1 per month	1 per week	1 per week	1 per week	1 per week
Functional Inspections (Switches held by mechanism and single rod exercised in all positions)				1 per 3 months	1 per 3 months	1 per 3 months				
AUTOMATED Load Measuring Wheels (IWS)							During System Qualification	During System Qualification	During System Qualification, Annually	During System Qualification, Annually
AUTOMATED Accelerometers - Truck Frame							During System Qualification	1 per month	1 per day	1 per day
AUTOMATED Accelerometers - Carbody							1 per 3 months	1 per month	1 per day	1 per day
AUTOMATED Geometry Car								1 per 60 days	1 per 30 days	1 per 30 days
AUTOMATED Pilot or Inspection Train									If no operation in 8-hr period, next train restricted to 100 mph.	If no operation in 8-hr period, next train restricted to 100 mph.
AUTOMATED Gage Restraint Measurement System									1 per year	1 per year
AUTOMATED Rail Flaw				w/PSGR 1 per 40 mgt or 1 per year whichever shorter NO PSGR 1 per 30 mgt or 1 per year, whichever longer	1 per 40 mgt or 1 per year, whichever shorter	1 per 40 mgt or 1 per year, whichever shorter	2 per year	2 per year	2 per year	2 per year

Source: U.S. Department of Transportation, Federal Railroad Administration, Track Inspection Time Study July 2011.

California already has some 8,600 miles of rail that require safety inspection. Assuming biweekly inspections for most of these miles, that is over 223,000 miles of track inspected annually. With the growth of subways, light rail, and commuter rail in Northern and Southern California, the demand for inspection vehicles will only grow. In addition, the High-Speed Rail project that will travel from north to south will add another several hundred miles of tracks that will carry trains travelling over 100 miles per hour. Battery-powered inspection will FLIRther enhance the environmental benefit of the high-speed rail program.

The Federal Rail Administration's "Track Inspection Time Study" July 2011 studied a sample of track inspections and found that the largest number were done by vehicles with some on-foot inspections. The vehicles averaged 65 track miles of inspection per day.

Rail inspections are provided by a variety of vehicles that fall into the light-duty truck and medium-du ty truck categories. On-road light and medium duty vehicles such as Ford 350 trucks (Figure 38) or Chevy Silverado (Figure 39) are up-fitted with special equipment that allow the truck to drive on the rails and check the width of the gauge. These up-fitted vehicles are called High Rail Vehicles and are the ones that the RailScout would replace.

Figure 38: High Rail Vehicle Example 1

Source: Loram

Figure 39: High Rail Vehicle Example 2

Source: ENSCO

Both Land Systems Corporation and Quallion are in Southern California. The RailScout development and the BMS system have already created at least a dozen jobs and production of RailScout vehicles in California for domestic and international use would easily double that number with new jobs in equipment manufacture and assembly and BMS manufacture and assembly.

The second economic benefit of this project is the broader application of the BMS to other high voltage applications. Battery-powered electric drive motors are already being used in light duty on-road vehicles, in light duty forklifts and airport ground support equipment and for power take-off and mileage enhancement in hybrid work trucks. We have only begun to address the potential for battery technology in other medium and heavy horsepower applications such forklifts, marine vessels, port operations, refrigerated trucks and commercial buses. Each of these large-scale applications will require a battery management system to optimize performance for each type of operation.

Quallion' s next generation battery management systems are targeted to be used in various applications including hybrid electrical vehicles, advanced Start-Stop vehicles and underground mining vehicles.

In the underground mining industry energy supply is one of the biggest challenges as mines all over the world try to cut costs and increase efficiency. The spiraling price of diesel to fuel underground equipment is the biggest "villain", closely followed by the soaring cost of energy to power large scale ventilation systems which commonly represent as much as 30% of a mine's total running costs. Underground miners are dependent on a constant supply of clean air to breathe and carry out their duties underground without risking their health. This means that the toxic emissions from diesel powered equipment must be constantly evacuated by ventilation systems which require significant amounts of energy, irrespective of the size and complexity of the mine structure.

By replacing diesel powered equipment with electric powered equivalents, mines can realize huge potential savings at the same time as they improve the environment, not to mention the spin-off effect of increased job satisfaction and reduced personnel turnover.

Quallion is using the modular high voltage battery management system approach to design lithium-ion batteries for these vehicles. By providing more energy and the ability to charge on board the vehicle (due to fast charging capability), the mining operation can increase its productivity. Once the mining industry has accepted the use of lithium-ion batteries in underground operations, new opportunities to design battery or hybrid drive versions for vehicles that traditionally rely on diesel engines emerge, such as loaders, bolters, and feeder breakers.

In addition to the economic and safety benefits of this project, there are additional health and quality of life benefits. Diesel emissions have already proven to be a carcinogen and a major cause of air pollution. The health impacts of air pollution in terms of lost workdays, respiratory illnesses and even normal developmental growth are well documented.

The impacted areas also parallel rail lines and highways. By replacing gasoline or diesel high rail inspection vehicles, the RailScout will reduce the number of toxic emissions in these already heavily impacted communities adjacent to the rail lines.

CHAPTER 3: Conclusions and Recommendations

3.1 Achievement of Goals and Objectives

Through the implementation of a Battery Management Systems electronics laboratory equipped with state-of-the-art test hardware, Quallion has enhanced its capacity to design, produce, and test advanced lithium ion BMS electronics and to incorporate these electronics into modules and batteries for electric vehicle applications. This enhanced capacity to develop and integrate BMS electronics and complete battery systems is now better aligned with the company's capacity to produce lithium-ion cells and modules.

These developments improve Quallion' s ability to respond to new and larger business opportunities that are arising given the increasing demand for electric power vehicles in response to reduce pollution and GHG emission targets in California and nationwide.

3.2 Results Obtained

The successful design, construction, and equipment validation of the BMS Electronics laboratory and its implementation to design, develop and integrate a BMS and battery system into the RailScout EV demonstrated the excellent work of the project team. As discussed earlier, the project met original project goals and key results are summarized below:

- ABMS Electronics laboratory was implemented, and state of the art test equipment was procured, installed, and validated.
- The design, fabrication, tests, and integration of a BMS and Battery System into the RailScout EV was successfully completed.
- The RailScout was deployed for field demonstration at railroad sites in Fillmore California and New Orleans, Louisiana.
- The emissions reductions resulting from a two-month field demonstration period were established and the results used to determine the pollutant emission reduction estimations per year, and at a projected RailScout commercial implementation for a typical year which also yielded the potential GHG Cost-Effectiveness of the project.
- Quallion has enhanced its capacity to design, produce, and test advanced BMS electronics and to incorporate these electronics into modules and batteries in California to meet the growing demand for electric vehicles.

3.3 Future BMS Design Enhancements Opportunities

The BMS and battery system enhancements that Quallion believes merit consideration for future implementation are summarized below:

- To enhance the BMS and battery system operational reliability particularly in severe environments, modifications for improved thermal transfer in the battery pack (i.e., redesign of bus bar/nickel tab components configuration) to increase heat dissipation during high-current discharges.
- FLIRther refinement of the BMS design to reduce the number of interconnects to reduce cost and improve reliability.

- Continuation of the development and prototype build and testing of the next generation modular BMS. This in response to anticipated new BMS application opportunities including hybrid electrical vehicles, advanced Start-Stop vehicles and underground mining vehicles.

Quallion believes that through continuous improvement efforts and the implementation of the latest technology into our BMS design, significant improvements in the energy efficiency, cost effectiveness and reliability can be achieved. This would enable our BMS to be an attractive option for EV customers for integration into a wider range of electric vehicles.

3.4 Conclusions and Recommendations

Quallion is pleased with the results of this project. The success of this project could not have been achieved without Quallion' s and Land System's committed project teams and railway customer cooperation. The process of establishing a state-of-the art BMS Electronics laboratory to support the development of a BMS and Battery Module system for a non-traditional EV application such as the RailScout posed unique challenges, key of which were the successful development and integration of a BMS and battery system into a specialized vehicle that was being developed concurrently in a short period of time.

Quallion recommends that future upgrade and follow-on projects include sufficient planning time to coordinate with local railway customers to expand and facilitate access to railroad track test sites. This will improve test and demonstration logistics and broaden the exposure and public awareness of this exciting EV application.

Quallion appreciates the Energy Commission's support, especially the agreement manager, Darren Nguyen, whose guidance facilitated the successful execution of this project on-time and within budget.

GLOSSARY

ALTERNATING CURRENT (AC)—Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.

BATTERY ELECTRIC VEHICLE (BEV)—Also known as an "All-electric" vehicle (AEV), BEVs utilize energy that is stored in rechargeable battery packs. BEVs sustain their power through the batteries and therefore must be plugged into an external electricity source in order to recharge.

BATTERY MANAGEMENT SYSTEM (BMS)—Systems encompassing not only the monitoring and protection of the battery but also methods for keeping it ready to deliver full power when called upon and methods for prolonging its life. This includes everything from controlling the charging regime to planned maintenance.

CALIFORNIA AIR RESOURCES BOARD (CARB)— The state's lead air quality agency consisting of an 11-member board appointed by the Governor, and just over thousand employees. CARB is responsible for attainment and maintenance of the state and federal air quality standards, California climate change programs, and is fully responsible for motor vehicle pollution control. It oversees county and regional air pollution management programs.

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies.

CONTROLLER AREA NETWORK (CAN)—A serial network technology that was originally designed for the automotive industry, especially for European cars, but has also become a popular bus in industrial automation as well as other applications. The CAN bus is primarily used in embedded systems, and as its name implies, is a network technology that provides fast communication among microcontrollers up to real-time requirements.

CARBON INTENSITY (CI)—The amount of carbon by weight emitted per unit of energy consumed. A common measure of carbon intensity is weight of carbon per British thermal unit (Btu) of energy. When there is only one fossil fuel under consideration, the carbon intensity and the emissions coefficient are identical. When there are several fuels, carbon intensity is based on their combined emissions coefficients weighted by their energy consumption levels.

COMPRESSED NATURAL GAS (CNG)—Natural gas that has been compressed under high pressure, typically between 2,000 and 3,600 pounds per square inch, held in a container. The gas expands when released for use as a fuel.

DATA ACQUISITION (DAQ)—Data acquisition (commonly abbreviated as DAQ or DAS) is the process of sampling signals that measure real-world physical phenomena and converting them into a digital form that can be manipulated by a computer and software.

ELECTRIC VEHICLE (EV)—A broad category that includes all vehicles that are fully powered by electricity or an electric motor

GREENHOUSE GAS (GHG)—Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_x), halogenated fluorocarbons (HCFCs), ozone (O_3), per fluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

GROSS VEHICLE WEIGHT RATING (GVWR)—The maximum weight of the vehicle as specified by the manufacturer. Includes total vehicle weight plus fluids, passengers, and cargo.[10]

NATIONAL INSTRUMENTS CORPORATION (NI)—NI, formerly National Instruments Corporation, is an American multinational company with international operation. Headquartered in Austin, Texas, it is a producer of automated test equipment and virtual instrumentation software. Common applications include data acquisition, instrument control and machine vision.

[10] U.S. Department of Energy (https://afdc.energy.gov/data/10380)

APPENDIX A:
Pre-Integration Measurements of the Railscout Battery Modules

Figure A-1: Pre-Integration Measurements of the RailScout Battery Modules

Group	Pack Lot No	Group Voltage	Pack		Pin 1 to 2		Pin 2 to 3		Pin 3 to 4		Pin 4 to 5		Thermistor #1 (kΩ)	Thermistor #2 (kΩ)
			OCV	IR	OCV	IR	OCV	IR	OCV	IR	OCV	IR		
4	X15B156	90.5	15.0540	8.727	3.7651	171.740	3.7636	188.640	3.7631	196.940	3.7633	185.650	8.95	8.95
	X15B173		15.0950	7.916	3.7747	181.410	3.7744	184.550	3.7738	180.580	3.7741	183.840	9.02	9.02
	X15B155		15.0540	7.297	3.7764	171.500	3.7640	172.110	3.7688	168.530	3.7636	171.460	8.98	8.96
	X15B166		15.1050	8.168	3.7764	172.440	3.7773	167.600	3.7772	166.800	3.7768	175.040	9.00	8.98
	X15B168		15.0540	8.172	3.7640	190.130	3.7639	173.050	3.7641	189.660	3.7646	189.540	9.00	8.95
	X15B153		15.0570	8.905	3.7650	174.740	3.7635	175.200	3.7656	176.330	3.7659	174.930	8.91	8.94
3	X15E331	90.6	15.0630	7.923	3.7660	181.770	3.7660	177.030	3.7661	196.220	3.7672	186.130	8.90	8.90
	X15B175		15.0530	8.562	3.7640	168.910	3.7648	170.640	3.7639	172.040	3.7631	169.520	8.93	8.97
	X15B160		15.0930	8.223	3.7744	183.530	3.7738	176.520	3.7742	175.660	3.7739	185.840	8.92	8.89
	X15C466		15.0940	8.705	3.7753	171.020	3.7739	172.350	3.7744	173.460	3.7736	183.040	8.83	8.82
	X15E334		15.0790	8.521	3.7698	173.720	3.7700	175.100	3.7707	173.870	3.7714	183.700	10.22	10.19
	X15E332		15.0830	8.026	3.7712	179.920	3.7711	173.270	3.7714	172.450	3.7722	178.630	10.18	10.22
2	X15B158	90.6	15.0660	8.901	3.7673	170.430	3.7659	171.420	3.7666	171.630	3.7680	175.930	8.25	8.27
	X15B176		15.0520	8.245	3.7630	176.220	3.7640	177.010	3.7635	174.150	3.7638	175.290	8.46	8.48
	X15B174		15.0920	8.664	3.7740	177.610	3.7738	177.200	3.7732	172.180	3.7739	183.170	8.50	8.52
	X15B167		15.1010	8.849	3.7764	170.330	3.7762	167.830	3.7754	172.410	3.7754	177.910	8.53	8.51
	X15B161		15.0960	8.562	3.7752	172.000	3.7738	173.390	3.7742	177.000	3.7756	181.530	8.48	8.49
	X15B169		15.0920	7.499	3.7737	185.030	3.7737	182.290	3.7736	178.500	3.7735	176.560	8.49	8.43
1	X15B171	90.6	15.0490	7.459	3.7628	170.800	3.7627	183.230	3.7625	185.650	3.7635	177.980	8.40	8.39
	X15B164		15.0920	9.175	3.7735	175.180	3.7732	169.680	3.7742	170.860	3.7738	172.950	8.39	8.42
	X15B157		15.1150	7.799	3.7795	175.620	3.7786	174.640	3.7794	175.370	3.7803	176.940	8.37	8.41
	X15B162		15.0530	7.775	3.7639	177.960	3.7637	171.740	3.7638	178.060	3.7647	183.080	8.37	8.3[illegible]
	X15B159		15.1070	7.504	3.7777	172.120	3.7771	176.670	3.7779	182.150	3.7776	182.000	8.38	8.44
	X15B170		15.1060	7.644	3.7783	179.850	3.7770	174.450	3.7764	173.630	3.7773	176.440	8.29	8.31
	Minimum	90.50	15.0490	7.297	3.7628	168.910	3.7627	167.600	3.7625	166.800	3.7631	169.520	8.25	8.27
	Average	90.58	15.0794	8.218	3.7712	175.999	3.7703	175.234	3.7706	177.255	3.7707	179.463	8.78	8.78
	Maximum	90.60	15.1150	9.175	3.7795	190.130	3.7786	188.640	3.7794	196.940	3.7803	189.540	10.22	10.22
	Std Deviation	0.05	0.0221	0.538	0.0056	5.486	0.0056	5.180	0.0054	7.863	0.0055	5.179	0.51	0.51

Source: Quallion, LLC