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LLNL-TR-648213

Novel Battery Management System with Distributed Wireless and Fiber Optic Sensors for Early Detection and Suppression of Thermal Runaway in Large Battery Packs, FY13 Q4 Report, ARPA-E Program: Advanced Management Protection of Energy Storage Devices (AMPED), Award 12/CJ000/05/01/0

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January 6, 2014

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

ARPA-E AMPED Program – LLNL Wireless BMS Project – FY1 Q4 Report LLNL Tracking Number IM-764593

ARPA-E Program: Advanced Management Protection of Energy Storage Devices (AMPED)

Funding Opportunity Announcement: DE-FOA-0000675

Control Number: 0675-1577

Award Identification: 12/CJ000/05/01/0 (DE-AR0000281)

Date of Report: 10/07/2013

Reporting Period: 07/01/2012 to 10/01/2013

Prime Recipient: Lawrence Livermore National Laboratory

Project Title: Novel Battery Management System with Distributed Wireless and Fiber Optic Sensors for Early Detection and Suppression of Thermal Runaway in Large Battery Packs

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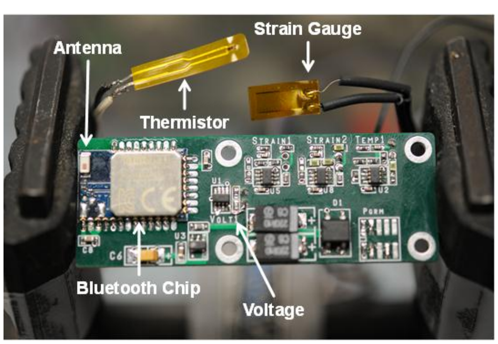
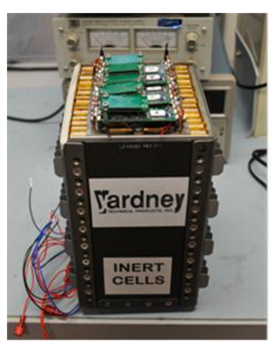
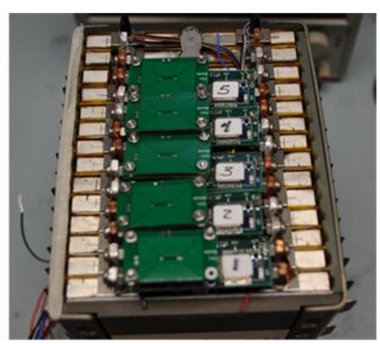
Section I. Executive summary (less than one page): Utilize this section to address the general state of the project and highlight points of success and/or concern. Examples might include: exceeding major milestones, attracted follow-on investment, schedule slippage, met a milestone early or late, etc.

Technology has been developed that enables monitoring of individual cells in high-capacity lithium-ion battery packs, with a distributed array of wireless Bluetooth 4.0 tags and sensors, and without proliferation of extensive wiring harnesses. Given the safety challenges facing lithium-ion batteries in electric vehicle, civilian aviation and defense applications, these wireless sensors may be particularly important to these emerging markets. These wireless sensors will enhance the performance, reliability and safety of such energy storage systems. Specific accomplishments to date include, but are not limited to: (1) the development of wireless tags using Bluetooth 4.0 standard to monitor a large array of sensors in battery pack; (2) sensor suites enabling the simultaneous monitoring of cell voltage, cell current, cell temperature, and package strain, indicative of swelling and increased internal pressure, (3) small receivers compatible with USB ports on portable computers; (4) software drivers and logging software; (5) a 7S2P battery simulator, enabling the safe development of wireless BMS hardware in the laboratory; (6) demonstrated data transmission out of metal enclosures, including battery box, with small variable aperture opening; (7) test data demonstrating the accurate and reliable operation of sensors, with transmission of terminal voltage, cell temperature and package strain at distances up to 110 feet; (8) quantification of the data transmission error as a function of distance, in both indoor and outdoor operation; (9) electromagnetic interference testing during operation with live, high-capacity battery management system at Yardney Technical Products; (10) demonstrated operation with live high-capacity lithium-ion battery pack during charge-discharge cycling; (11) development of special polymer-gel lithium-ion batteries with embedded temperature sensors, capable of measuring the core temperature of individual of the cells during charge-discharge cycling at various temperatures, thereby enabling earlier warning of thermal runaway than possible with external sensors. Ultimately, the team plans to extend this work to include: (12) flexible wireless controllers, also using Bluetooth 4.0 standard, essential for balancing large-scale battery packs. LLNL received $925K for this project, and has $191K remaining after accomplishing these objectives.







Section II. Bulleted list of summarizing milestones due: Briefly report on milestones scheduled to be completed during the reporting period or that are past due. Milestones that are 100% complete ahead of schedule may also be reported. Please indicate their task number affiliation and whether the milestone is complete, incomplete, or still in progress. Include a sub-bullet to briefly describe the status including any relevant key data or references to figures, tables, and charts (generally no more than 2-3 lines each).

- Fabrication and Testing Prototype Tags & Sensors (Milestone 1.4.7 – 6/24/2013)
- Demonstration on Representative Module (Milestone 1.3.6 – 6/24/2013)
- Demonstrate Tag with Internal Temperature Sensor (Milestone 1.4.4 – 6/24/2013)
- Fabrication of Components for 20-Ah Cells Completed (Milestone 1.1.1 – 6/24/2013)
- Assembly of 20-Ah Simulation Cells (Milestone 1.1.1 – 6/24/2013)
- Testing at YTP in Rhode Island – Execution of Test Protocol at Yardney
    - Receive & Unpack LLNL Equipment
    - Backup Files for Laptop – LABVIEW IX
    - 100W Audio Amplifier
    - Stanford Signal Generator
    - Zero to 40 Volt Power Supply at 5 Amps
    - Miscellaneous Equipment
    - Hand Carry Sensor Boards (Two Strain Gauges, Two Thermistors, Battery Voltage)
    - Photograph Prior to Shipment
    - Photograph Test Setup at YTP
- Bench Test of LLNL Equipment – Bench Top A
    - Verify Operability of Sensors & Tags
    - Software Connection to Boards
    - Ready to Test with Demonstration Battery Pack
    - Photograph & Video
    - Bench Test YTP Simulator – Bench Top B
    - Setup YTP Thermistor Reader
    - Verify Operation of YTP Thermistors
    - Verify Operation of YTP Heaters on Outside of Cells
    - Verify Pressurization of YTP Cells
    - Glue LLNL Strain Gauge to YTP Cells
    - Photograph & Video
- Bench Test with YTP BMS System – Bench Top C
    - Verify Operability of YTP BMS System
    - Verify Receipt of External Voltage
    - Conduct BMS/RFID Interference Test
    - Prove RFID System Operates with BMS
    - Prove BMS Operates with RFID System
- Co-Locate LLNL Equipment with YTP Simulator
    - Photograph & Video
- Place Tags Inside Simulator Housing
    - Verify Operability of Single Tag
    - Begin Test Protocol
    - Repeat with Multiple Tags

- Specific Tests to Conducted
  - Transmit Voltage Data from Tag to Laptop
  - Transmit Temperature Data from Tag to Laptop
  - Transmit Strain Gauge Data from Tag to Laptop
  - Simultaneously Transmit Signals from All Sensors
- Specific Simulator Data Collected & Plotted
  - Establish Sampling Frequency for 1-Hour Test
  - Sampling Once Per Second (3600 Points in Hour)
  - Voltage Calibration for 1 Hour
  - External Ramped/Triangular Wave Voltage vs. Time
  - Temperature Calibration for 1 Hour
  - Temperature vs. Time During Heating
  - Temperature vs. Time During Cooling
  - Pressure Calibration for 1 Hour
  - Strain vs. Time During Pressurization
  - Strain vs. Time During Depressurization
  - Export All Data in Excel Format
  - Generate Sensor vs. Time Charts for Each
- EMI & Pack Testing by LLNL and Yardney
  - EMI Testing of Wireless System with BMS system (Milestone 2.1.3 – 6/24/2013)
  - Five (5) Cells Wirelessly Monitored in 120-V Pack & Preliminarily Compared to Wired System (Progress Towards Milestone 3.4 – 6/24/2013)
- Construction of Twenty (20) Additional Boards for Two-to-Three (2-3) Wireless BMS System to Enable Simultaneous Development at LNLL and Industrial Partners
  - Upgrading Printed Circuit Board Designs
  - Ordering of Approximately 20 Miniature Printed Circuit Boards and Receipt of Initial Shipments for Fabrication of Two Additional Sets of Wireless Lithium Ion Cell Sensors and Antennas (Progress Towards Milestone 3.4.0 – Approximately 8/15/2013)
  - Ordering of Sufficient Electronic Components, Including Resistors, Capacitors, Sockets, and Integrated Circuits to Populate Approximately 20 Miniature Printed Circuit Boards and Receipt of Initial Shipments for Fabrication of Two Additional Sets of Wireless Lithium Ion Sensors and Antennas (Progress Towards Milestone 3.4.0 – Approximately 8/15/2013)
  - Commenced Fabrication of Two Additional Sets of Wireless Lithium Ion Cell Sensors and Antennas (Progress Towards Milestone 3.4.0 – Approximately 8/15/2013)
- Modified Tasks, Milestones & Deliverables Based Upon LLNL-YTP Testing with Submission to ARPA-e Sponsor for Review and Comment
  - These modified tasks, milestones and deliverables, including a revised T2M plan, are given in Section IV of this report.

Section III. Supporting data and additional information (length varies): please provide supporting data to substantiate any claims against milestones, including appropriate figures, tables, etc.

Wireless Tags & Sensor Suites to Enable Wireless BMS Systems

Technology has been developed that enables monitoring of individual cells in high-capacity lithium-ion battery packs, with a distributed array of wireless Bluetooth 4.0 tags and sensors, and without proliferation of extensive wiring harnesses. In addition to enabling the monitoring of lithium-ion batteries, this technology will also enable better monitoring and control of virtually all primary and secondary batteries, electrolytic capacitors, fuel cells, engines, hybrids, converters, photovoltaic cells, thermoelectric generators, gas and steam turbines, sterling engines, electrical generators and motors, fuel tanks and sub-stations.

Given the safety challenges facing lithium-ion batteries in electric vehicle, civilian aviation and defense applications, these wireless sensors may be particularly important to these emerging markets. These wireless sensors will enhance the performance, reliability and safety of such energy storage systems. Specific accomplishments to date include, but are not limited to: (1) the development of wireless tags using Bluetooth 4.0 standard to monitor a large array of sensors in battery pack; (2) sensor suites enabling the simultaneous monitoring of cell voltage, cell current, cell temperature, and package strain, indicative of swelling and increased internal pressure, (3) small receivers compatible with USB ports on portable computers; (4) software drivers and logging software; (5) a 7S2P battery simulator, enabling the safe development of wireless BMS hardware in the laboratory; (6) demonstrated data transmission out of metal enclosures, including battery box, with small variable aperture opening; (7) test data demonstrating the accurate and reliable operation of sensors, with transmission of terminal voltage, cell temperature and package strain at distances up to 110 feet; (8) quantification of the data transmission error as a function of distance, in both indoor and outdoor operation; (9) electromagnetic interference testing during operation with live, high-capacity battery management system at Yardney Technical Products; (10) demonstrated operation with live high-capacity lithium-ion battery pack during charge-discharge cycling; (11) development of special polymer-gel lithium-ion batteries with embedded temperature sensors, capable of measuring the core temperature of individual of the cells during charge-discharge cycling at various temperatures, thereby enabling earlier warning of thermal runaway than possible with external sensors. Ultimately, the team plans to extend this work to include: (12) flexible wireless controllers, also using Bluetooth 4.0 standard, essential for balancing large-scale battery packs.

Large lithium-ion battery packs for space exploration require extensive wiring harness, as shown in Figure 1. More sensors are needed for enhanced safety in such systems, without the proliferation of wires. Elimination of such wiring harnesses promise to increase reliability, decrease weight, and increase mass-specific power and energy. The proposed wireless sensor and controller methodology is illustrated with Figure 2, and provides a means of eliminating the massive wiring harnesses, and are capable of increasing safety, reliability, specific power, and specific energy. Special lithium-ion battery simulators have been developed, as shown in Figure 3, to enable the safe development of wireless BMS components. The design of the BMS (battery management system) is continuing with the emphasis being its functioning with the wireless sensor system. Figure 4 shows an actual wireless Tag, with an optional antenna coil for passive operation. Figure 5 shows the Yardney Technical Products 7S2P battery simulator assembled with prototypical wireless tags and sensors installed for initial testing and capable of simultaneously monitoring several voltages, current, strain and temperature. The three cells with the polypropylene fittings (left of top image) enable pressurization of those cells for testing the strain gauges.

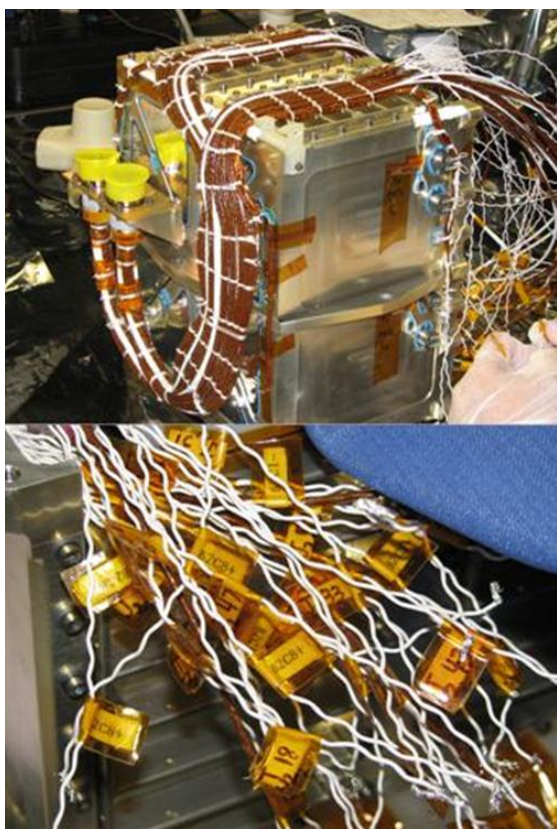


Figure 1 –2.5 kWh Li-Ion battery pack for NASA's Mars Science Laboratory requires extensive wiring harness; more sensors are needed in such systems without the proliferation of wiring harnesses. Elimination of the wiring harness promise to increase reliability, decrease weight, and increase mass-specific power and energy.

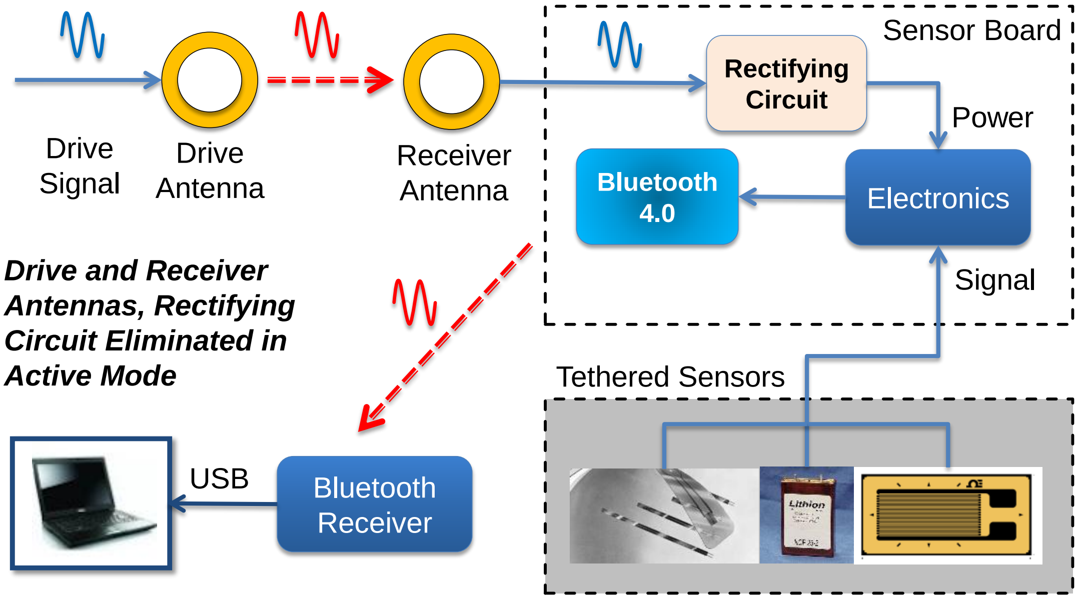


Figure 2 – The proposed wireless sensors and controllers provide a means of eliminating the massive wiring harnesses, and are capable of increasing safety, reliability, specific power, and specific energy.

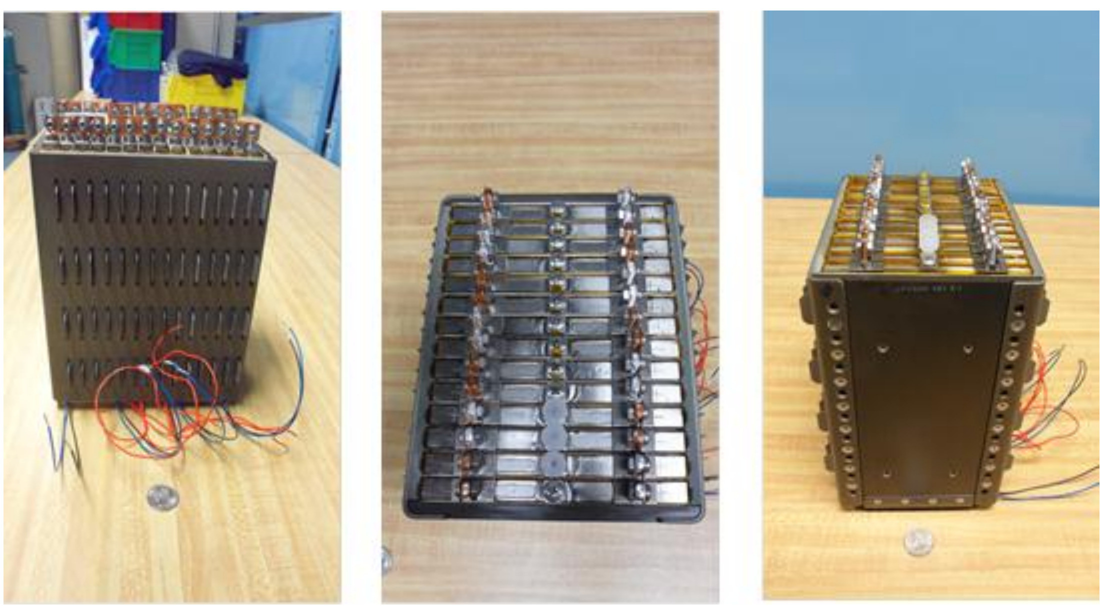


Figure 3 – These photographs shows the Yardney Technical Products 7S2P battery simulator assembled and ready for the initial testing of the Lawrence Livermore National Laboratory wireless tags and sensors.

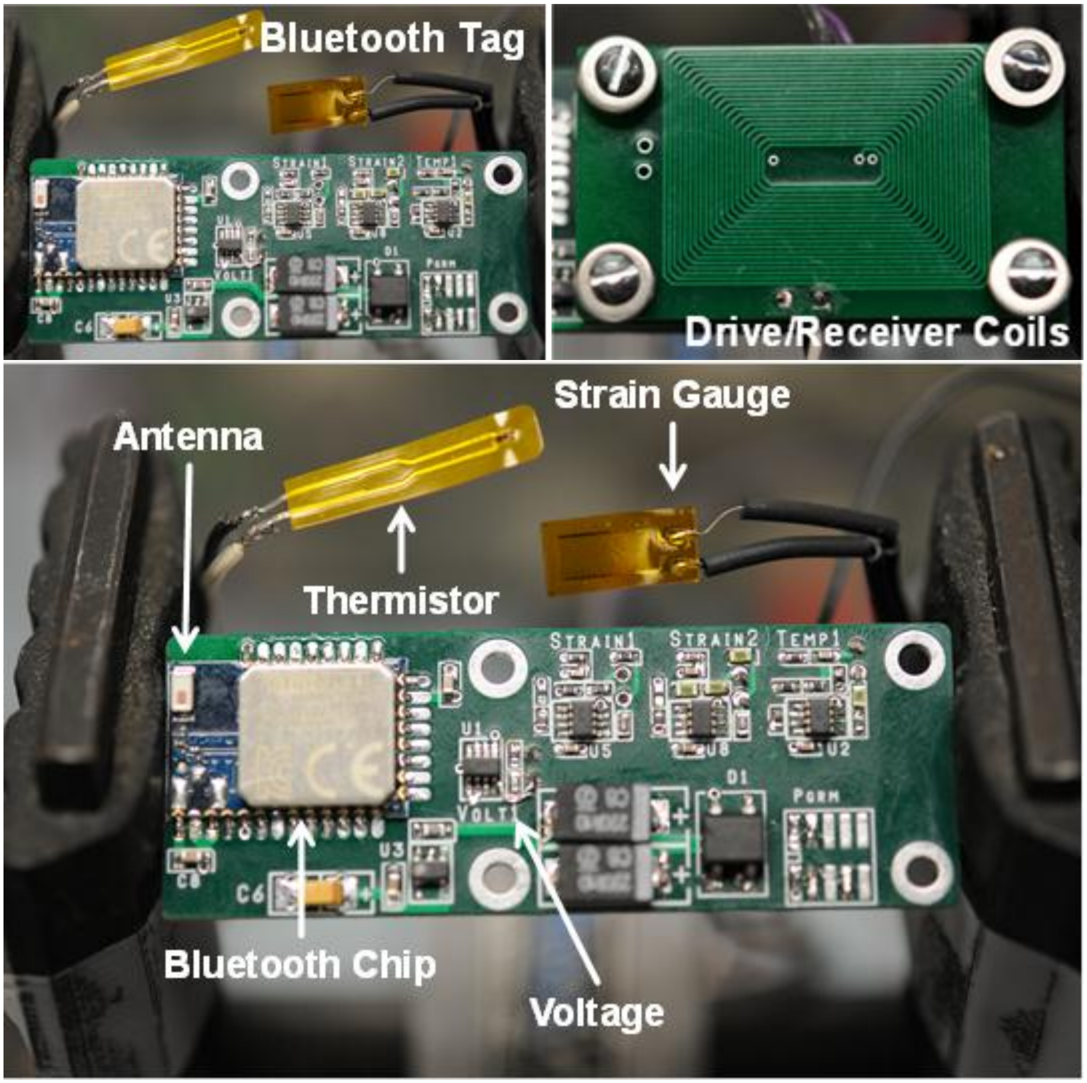


Figure 4 – Prototypical passive wireless sensor capable of simultaneously monitoring several voltages, current, strain and temperature, ideally suited for monitoring energy conversion and storage devices, including but not limited to photovoltaics, thermoelectric generators, primary and secondary electrochemical batteries, capacitors, flywheels, and various types of generators.

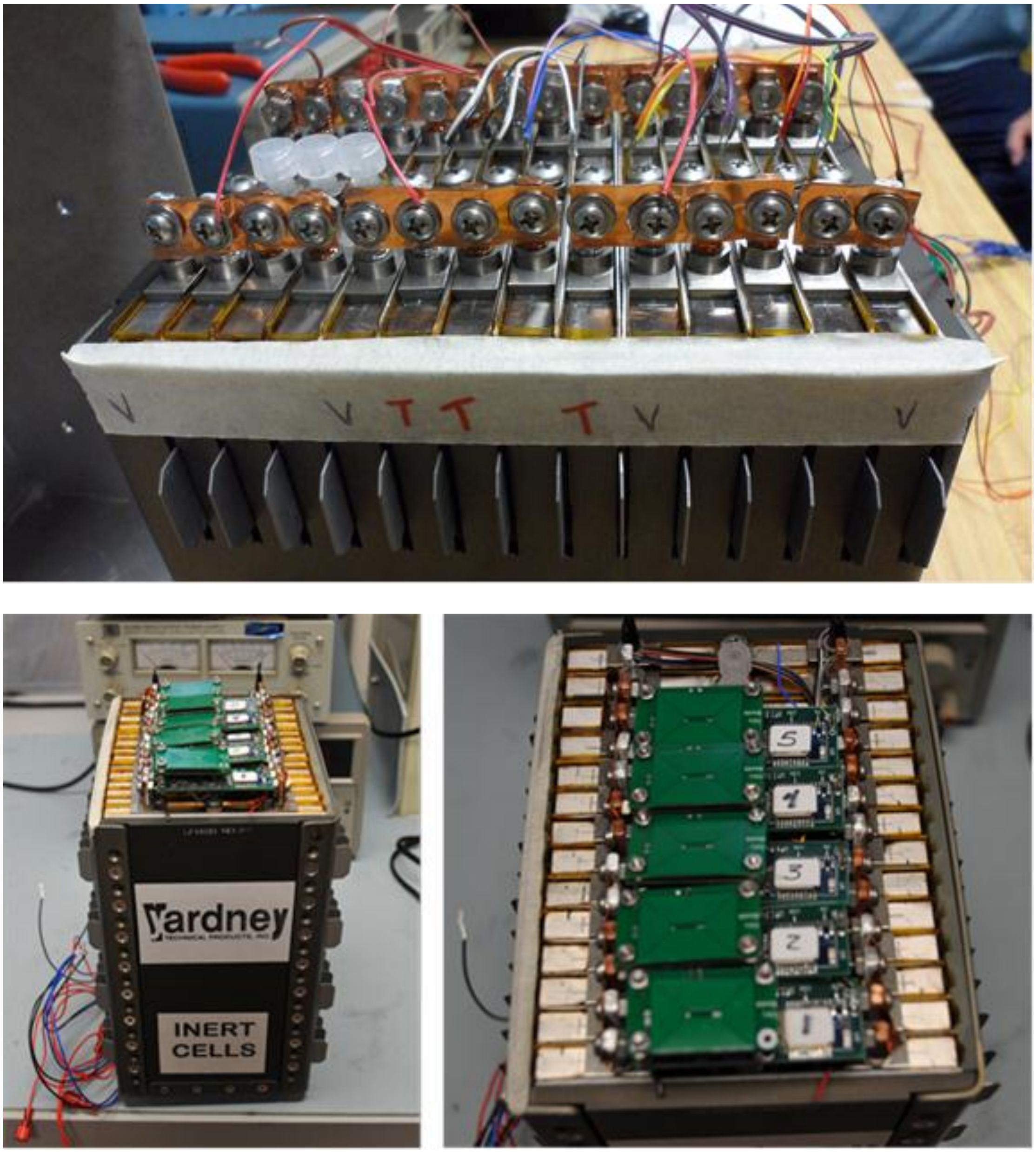


Figure 5 – These photographs shows the Yardney Technical Products 7S2P battery simulator assembled with prototypical wireless tags and sensors installed for initial testing and capable of simultaneously monitoring several voltages, current, strain and temperature. The three cells with the polypropylene fittings (left of top image) enable pressurization of those cells for testing the strain gauges.

Initially, wireless voltage sensors were used to follow the terminal voltage of several simulated lithium-ion cells in the battery simulator, with applied voltage steps comparable to those expected during actual charge-discharge cycling. These measurements were successfully made in both active and passive modes, as shown in Figures 6 and 7, respectively. In the active mode, power to operate the board is obtained from the posts of the lithium-ion cell being monitored (or an auxiliary battery), while in the passive mode the power is obtained from the drive coil (antenna) shown in Figure 4.

Similarly, wireless temperature sensors are capable of following the temperatures of individual lithium-ion cells in high-capacity battery pack during charge-discharge cycling, with representative data shown in Figure 8. The same capability can be used for monitoring localized temperatures from a large array of distributed thermistors. Wireless strain gauges are capable of following the swelling of individual lithium-ion cells in battery pack, as shown in Figure 9. The same capability can be used for monitoring localized strain in individual cells, from a large array of distributed strain gauges, as indicators of internal pressure in the cells.

Following tests with the wireless sensors and the battery simulator, the wireless sensors were used to monitor a live lithium-ion battery pack curing charge-discharge cycling. This battery pack is shown in Figure 10 and was assembled with live lithium-ion cells, intentionally selected with different histories so that differences in performance could be observed with the wireless sensors during cycling. The wireless voltage sensors, being operated in a passive mode, proved to be capable of accurately following the terminal voltages of individual lithium-ion cells in the live battery pack during charge-discharge cycling, as shown in Figure 11.

As part of the Technology-to-Market (T2M) Plan, several potential early adopters, including commercial manufacturers of EVs, HEVs, civilian aircraft, and defense systems, all reliant on high-capacity high-performance lithium ion batteries have been contacted to begin exploring actual market entry opportunities. One commitment exists for a demonstration within defense, with significant interest shown by one manufacturer of civilian aircraft.

Prototypical passive wireless sensors, like the one shown in Figure 4, are capable of simultaneously monitoring several voltages, current, strain and temperature, ideally suited for monitoring energy conversion and storage devices, including but not limited to photovoltaic cells, thermoelectric generators, primary and secondary electrochemical batteries, capacitors, flywheels, and various types of generators.

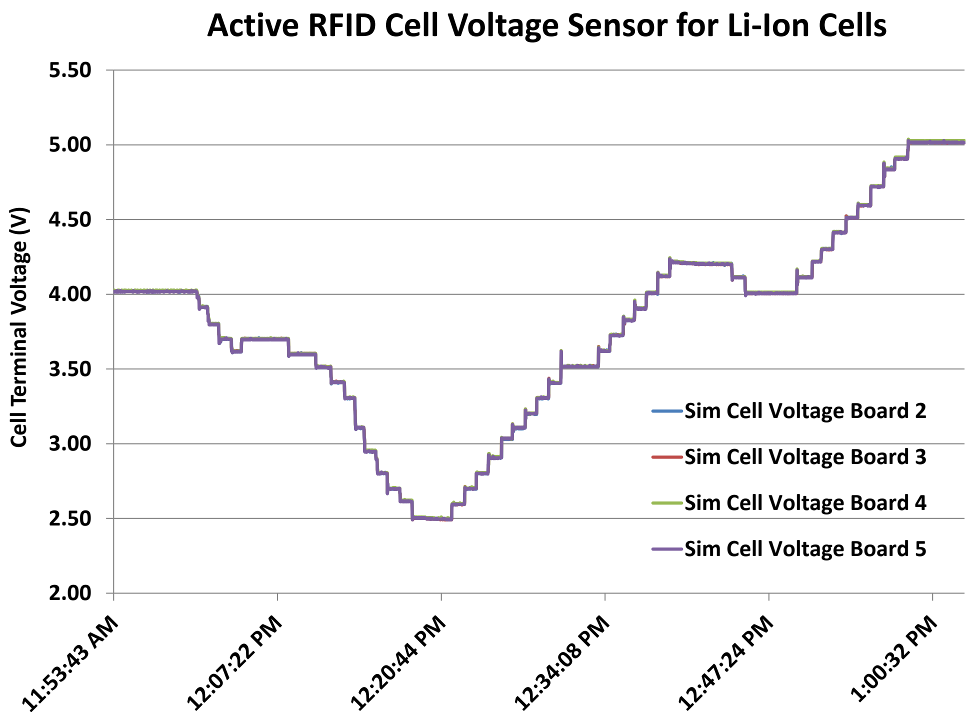


Figure 6 – Active wireless voltage sensors were used to follow the terminal voltage of several simulated lithium-ion cells in the battery simulator, with applied voltage steps comparable to those expected during actual charge-discharge cycling.

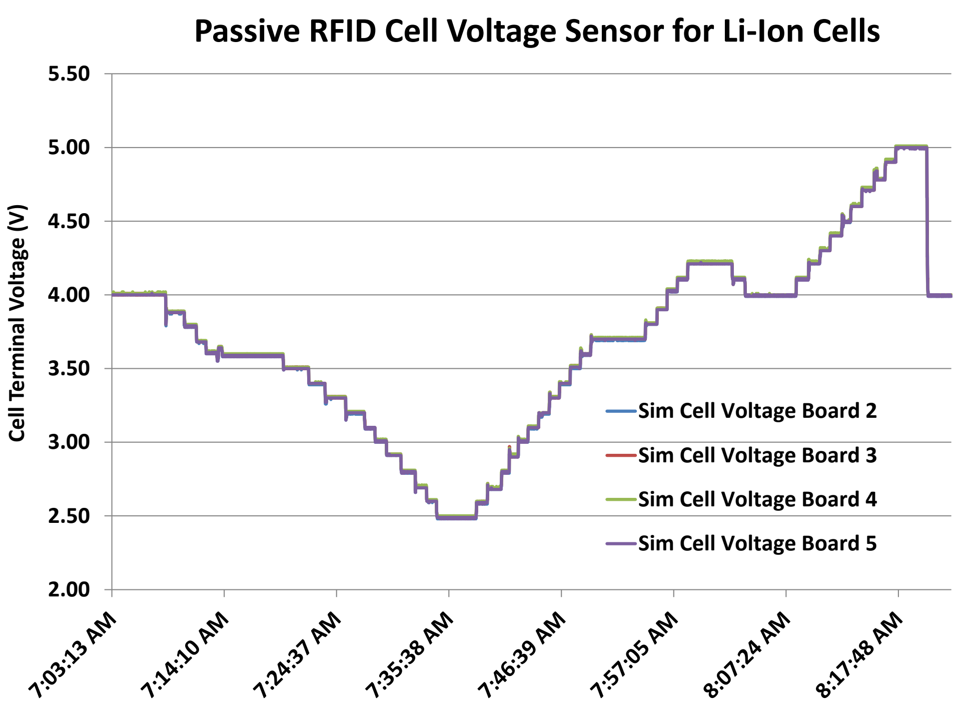


Figure 7 – Passive wireless voltage sensors were used to follow the terminal voltage of several simulated lithium-ion cells in the battery simulator, with applied voltage steps comparable to those expected during actual charge-discharge cycling.

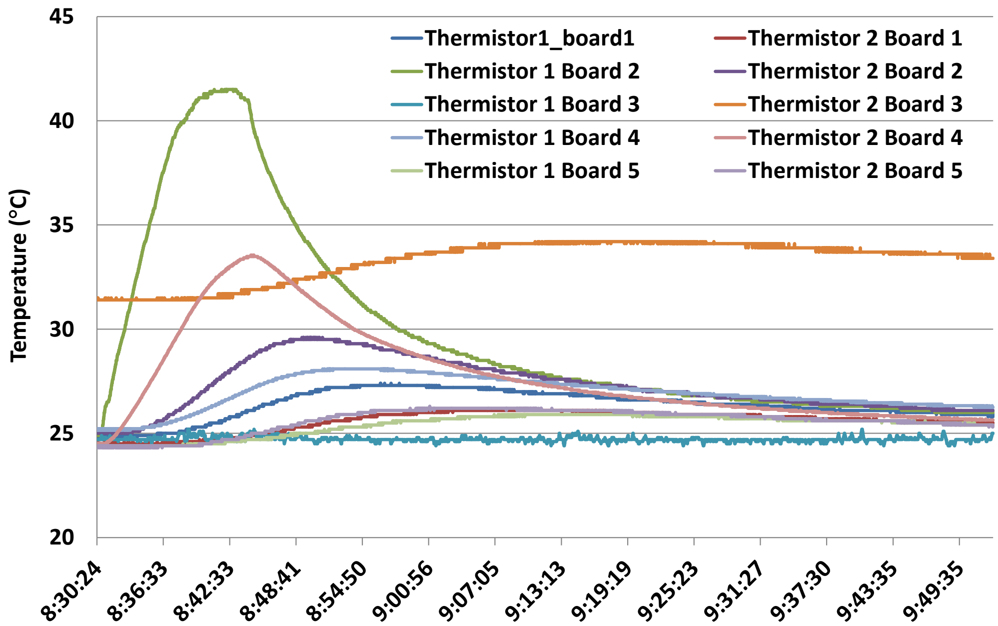


Figure 8 – Passive RFID temperature sensors following the temperatures of individual lithium-ion cells in battery pack during charge-discharge cycling. The same capability can be used for monitoring localized temperatures from a large number distributed thermistors.

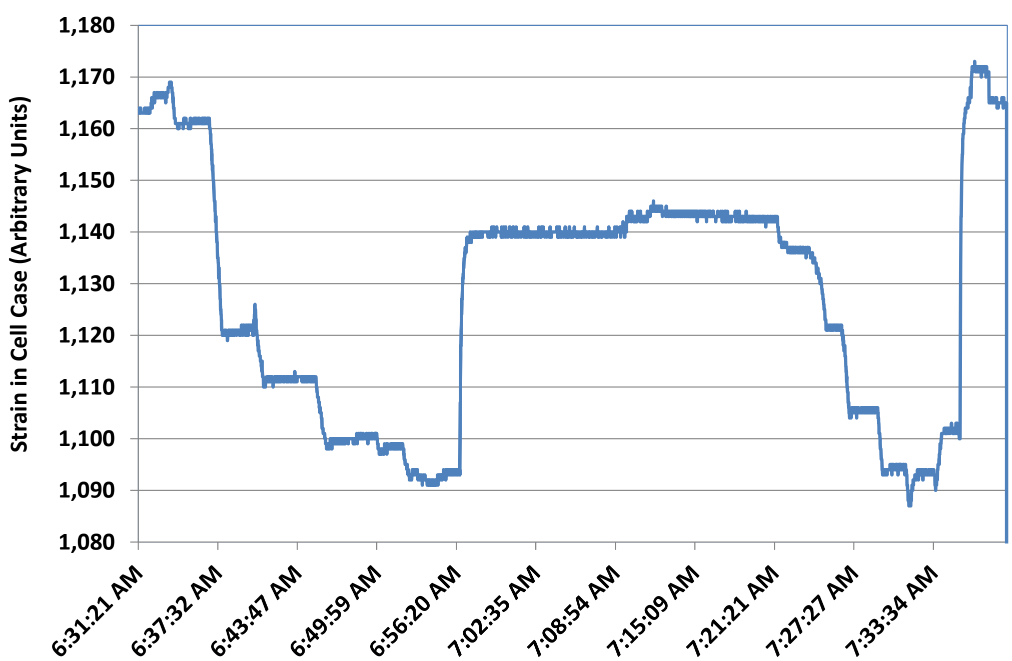


Figure 9 – Passive RFID strain gauges following the swelling of individual lithium-ion cells in battery pack. The same capability can be used for monitoring localized strain, as an indicator of cracking, from a large number distributed strain gauges.

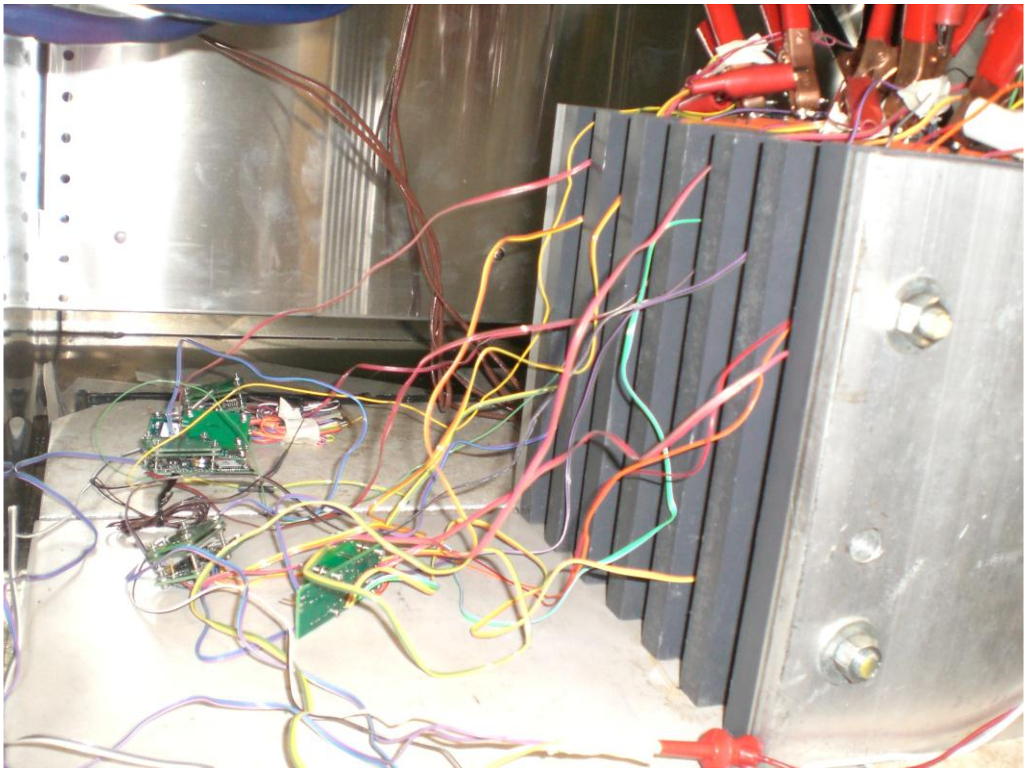


Figure 10 – Passive RFID voltage sensors following terminal voltage of individual lithium-ion cells in battery pack during charge-discharge cycling.

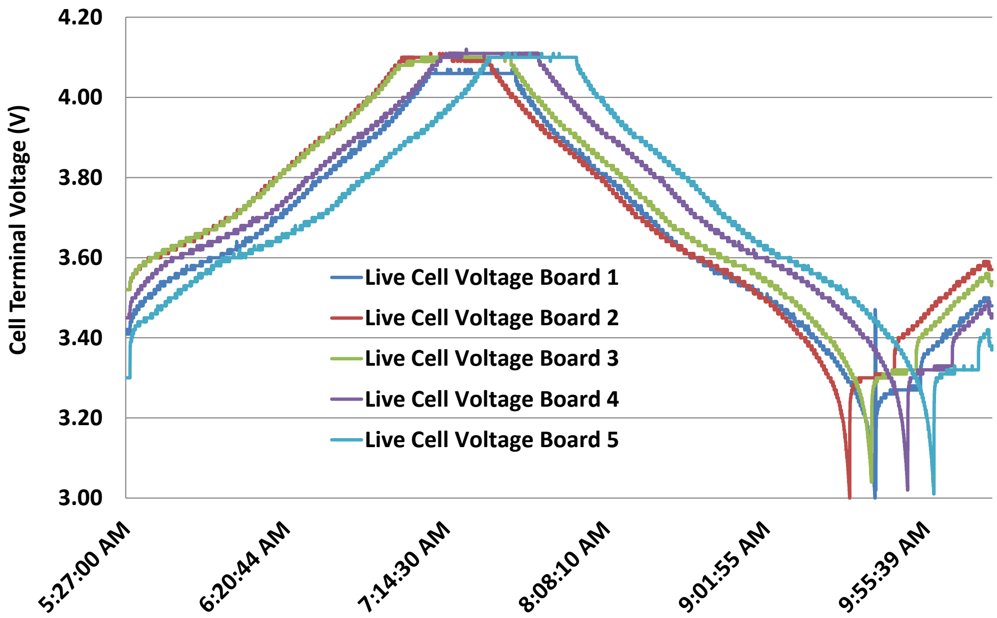


Figure 11 – Passive RFID voltage sensors following terminal voltage of individual lithium-ion cells in battery pack during charge-discharge cycling.

Yardney Technical Products has now coated, blanked, inspected, and prepared the electrodes for the lithium-ion cells for this program. Both anodes and cathodes were prepared, as shown in Figure 12. The electrodes are now ready for stacking and subsequent placing in the thin cell case. This type of cell case is the same type used in the cell cases to construct the battery simulator. These cells will be interchangeable with the simulation cells in the battery simulator. The design of the BMS (battery management system) is continuing with the emphasis being its functioning with the wireless sensor system. The marketing effort continues to explore additional end users. A company that manufactures energy systems for tractor trailers in interested in the wireless sensor technology. As the wireless sensor technology advances more options are available for additional number of sensors and additional types of sensors. Sensor location was investigated with additional locations and additional types. Electrical current sensors would be advantageous for battery monitoring.

Figure 12 – A photograph showing the anodes and cathodes (Left) ready for assembly into lithium-ion cells cases (Right)

Figure 13 shows the testing designed to quantify the data transmission error as a function of the distance of separation between the battery simulator with the wireless tags and sensor suites, and the Bluetooth 4.0 reader plugged into the USB port of the portable computer used for data acquisition.

Table 1 shows the quantification of data transmission error from the wireless tags and sensors inside laboratory building at LLNL. As expected, the data transmission error increases with the distance of separation. Even so, there was excellent performance, even at the maximum indoor distance of 30 feet. Figure 14 is a graphical representation of the data shown in Table 1, and is a quantification of data transmission error from the wireless tags and sensors inside laboratory building at LLNL.

Table 2 shows the quantification of data transmission error from the wireless tags and sensors outside laboratory building at LLNL. As expected, the data transmission error increases with the distance of separation. Even so, there was excellent performance, even at the maximum indoor distance of 110 feet. Figure 15 is a graphical representation of the data shown in Table 2, and is a quantification of data transmission error from the wireless tags and sensors outside laboratory building at LLNL. The peaks and valleys in error as a function of distance may be due to the scattering and reflection of signal from the complex outdoor environment.

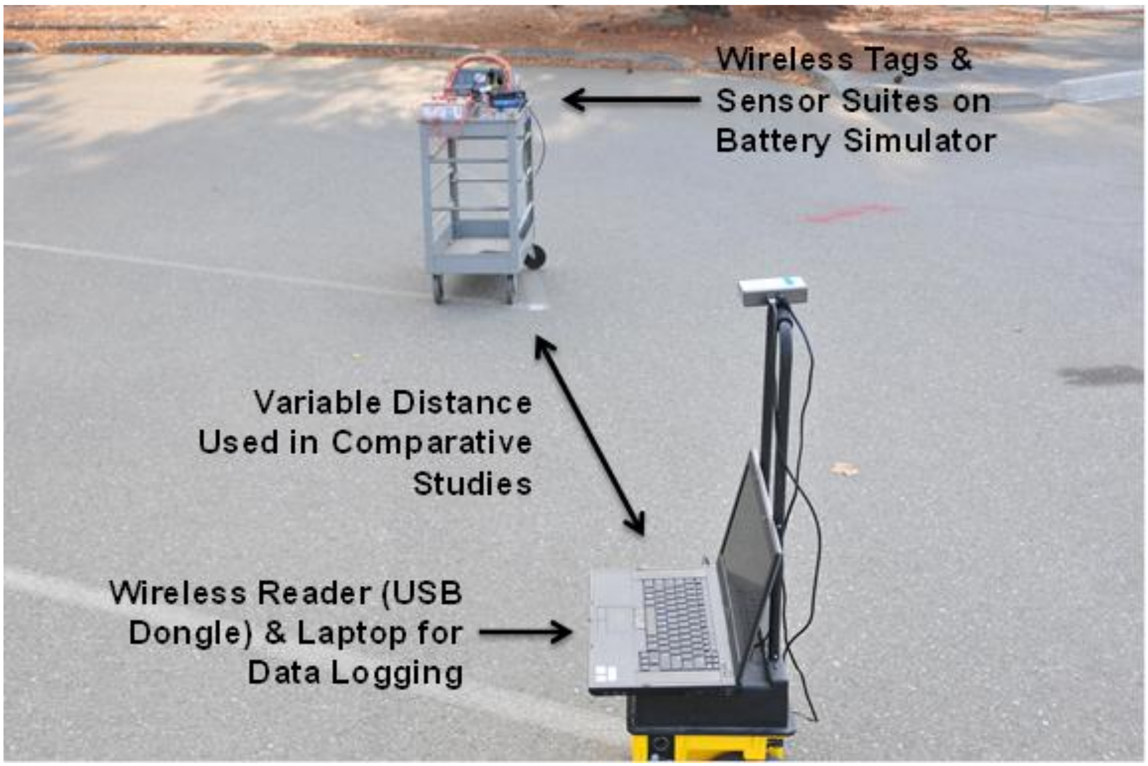


Figure 13 – This image shows the testing designed to quantify the data transmission error as a function of the distance of separation between the battery simulator with the wireless tags and sensor suites, and the Bluetooth 4.0 reader plugged into the USB port of the portable computer used for data acquisition.

Table 1 – This table shows the quantification of data transmission error from the wireless tags and sensors inside laboratory building at LLNL. As expected, the data transmission error increases with the distance of separation. Even so, there was excellent performance, even at the maximum indoor distance of 30 feet.

Distance	Acknowledgements	% CrC Errors	% Retransmissions	RSSI Board 1	RSSI Board 2	RSSI Board 3	RSSI Board 4	RSSI Board 5	RSSI Board 6	RSSI Board 7	RSSI Board 8
				dBm	dBm	dBm	dBm	dBm	dBm	dBm	dBm
1	100259	0.0548	0.623	-56.7	-58.1	-50.6	-61	-56.5	-57.7	-61.7	-62.7
		55	626								
5	100342	0.035	0.579	-65	-62.5	-64.6	-62.7	-66.9	-65.13	67.3	64.5
		36	581								
10	100371	0.0607	0.6326	-62.7	-65.4	-66.37	-67.4	-73	-69.9	-73	-66.8
		61	635								
20	100056	0.1898	1.404	-70.7	-73.2	-73.2	-71.2	-70.2	-71.5	-73.6	-70.2
		190	1405								
30	100043	0.732	6.18	-79	-75.2	-79.4	-83	-78.6	-82.6	-76.5	-79.8
		724	6187								

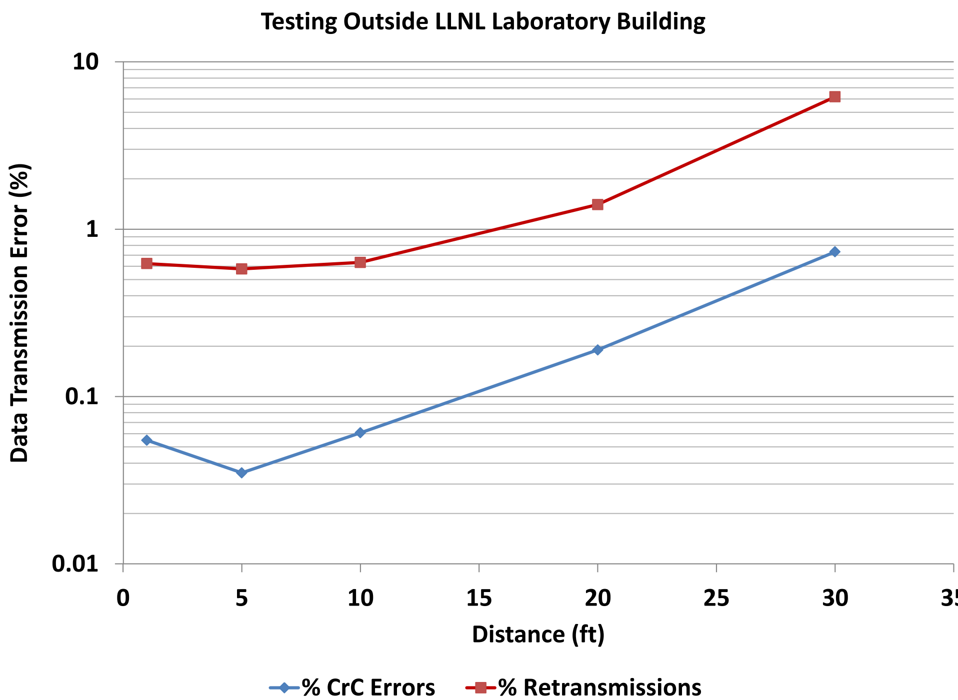


Figure 14 – This figure is a graphical representation of the data shown in Table 1, and is a quantification of data transmission error from the wireless tags and sensors inside laboratory building at LLNL. As expected, the data transmission error increases with the distance of separation. Even so, there was excellent performance, even at the maximum indoor distance of 30 feet.

Table 2 – This table shows the quantification of data transmission error from the wireless tags and sensors outside laboratory building at LLNL. As expected, the data transmission error increases with the distance of separation. Even so, there was excellent performance, even at the maximum indoor distance of 110 feet.

Distance	Acknolagements	% CrC Errors	% Retransmissions	RSSI Board 1	RSSI Board 2	RSSI Board 3	RSSI Board 4	RSSI Board 5	RSSI Board 6	RSSI Board 7	RSSI Board 8
				dBm	dBm	dBm	dBm	dBm	dBm	dBm	dBm
10	100096	0.0489	0.495	-64.3	-69.1	-66.1	-69.6	-63.5	-70.6	-70.3	-66.6
		49	493								
20	100113	0.0559	0.561	-74.1	-68	-68.3	-67.2	-66.3	-68.9	-69.5	-68
		56	562								
30	100059	0.0459	0.64	-68.2	-70.8	-66.3	-74.5	-74.2	-70.6	-66.1	-68
		46	641								
40	100079	0.351	3.46	-76.8	-76.4	-74.9	-76.7	-75.6	-76.9	-76.8	-80.9
		352	3464								
50	100050	0.396	3.849	-79.5	-80.1	-75.9	-82.1	-80.7	-76.6	-76.1	-77.4
		397	3851								
60	100080	0.2088	1.83	-74.7	-73.1	-73.4	-73.8	-74	-81.1	-78	-77
		209	1833								
70	100076	0.038	0.418	-74.7	-80	-73	-76.1	-74.5	-75	-73.4	-78.7
		39	419								
80	100050	0.108	1.667	-73.8	-79.7	-75.5	-80.2	-73.6	-73.5	-75	-76.8
		109	1666								
90	100129	0.201	2.445	-74.7	-77.8	-81.2	-79.6	-76.7	-76	-75.6	-77.2
		202	2452								
100	100085	1.29	14.6	-83.9	-85.8	-80	-80.9	-84.7	-80.3	-80.7	-84.8
		1294	14618								
110	100011	0.2158	2.68	-82	-75.8	-79.3	-79.8	-76.5	-76	-78.9	-77.5
		216	2682								

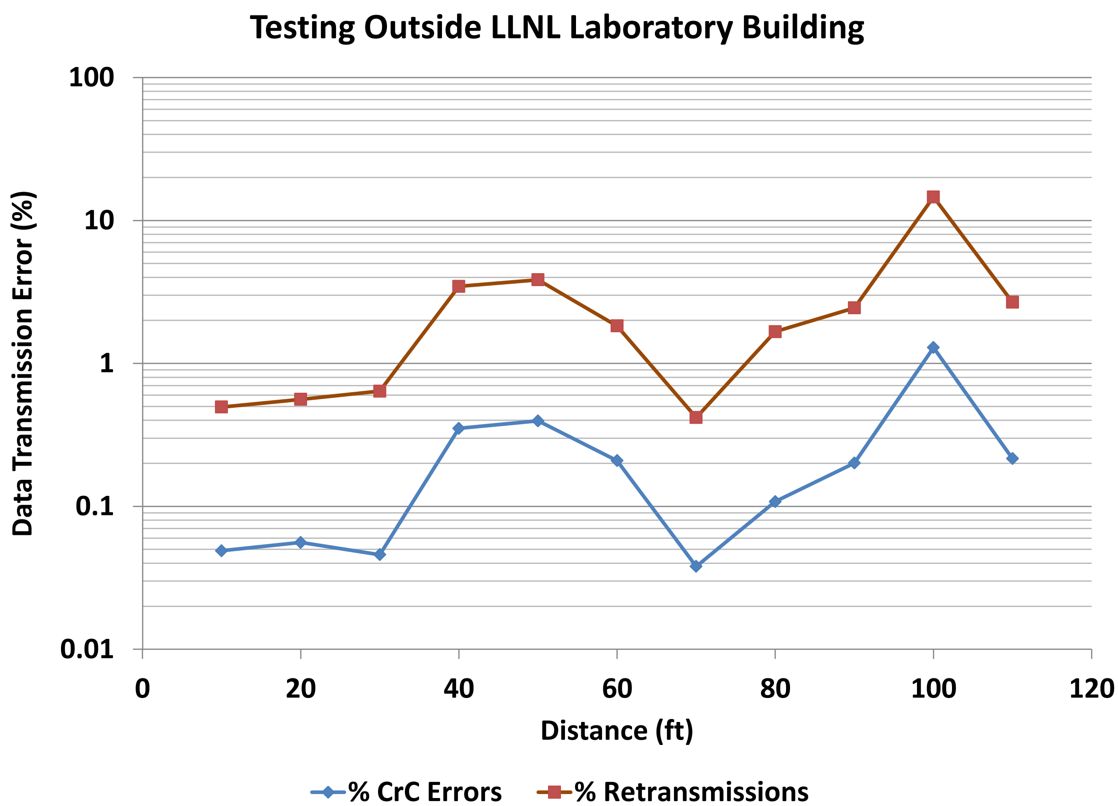


Figure 15 – This figure is a graphical representation of the data shown in Table 2, and is a quantification of data transmission error from the wireless tags and sensors outside laboratory building at LLNL. The peaks and valleys in error as a function of distance may be due to the scattering and reflection of signal from the complex outdoor environment. As expected, the data transmission error increases with the distance of separation. Even so, there was excellent performance, even at the maximum indoor distance of 110 feet.

The Electromagnetic Interference (EMI) test of the LLNL wireless tags and sensor suites with live YTP BMS system is shown in Figure 16. Both the wireless tags and sensors worked flawlessly, with little or no significant interference. This test indicates that the incorporation of the wireless tags and sensors into such high-power BMS systems with relays and other actuators should not be problematic.

The metallic environment tests at YTP and LLNL are shown in Figure 17. Tests have been conducted with the wireless tags and suites of sensors inside metallic closures that mimic battery boxes and containment vessels These enclosures were operated with variable aperture (openings) to alloy signal transmission from the tags to reach the reader. Figure 18 shows the successful transmission of temperature data from five wireless tags with temperature sensors in the aluminum battery pack enclosure shown in Figure 17 (left). The aperture in this case was very small (fraction of an inch), the sensors were powered with the drive coil and an external power amplifier, and the data quality was excellent. The temperature of these sensors increased slowly due to Ohmic heating of the air and structure inside the battery box by the battery simulator.

As the project progresses, the team would like to install a full complement of LLNL-YTP wireless tags and sensors on the Colorado State University (CSU) plug-in hybrid-electric vehicle (PHEV) known as EcoCAR 2, shown in Figure 19. This will enable Professor Bandhauer and his mechanical engineering students to further quantify tag performance in complex environments representative of state-of-the art PHEVs. Advantages of involving CSU include the opportunity to use these new wireless sensors and the more fully instrumented PHEV to educate next-generation energy engineers.

Special polymer-gel lithium-ion cells with temperature sensors embedded in the core have been designed and fabricated by PolyStor Energy Corporation (PSEC) of Livermore, California. These special cells with embedded temperature sensors have now been tested comprehensively at the United States Naval Postgraduate School, proving the viability of sensing the actual core temperature of lithium ion cells during operation. Figure 20 shows the special facilities constructed at NPS to enable support of the ARPA-E wireless BMS project, specifically the cycling and test-to-failure of the polymer-gel lithium-ion cells with embedded temperature sensors, and wireless signal transmission. Figure 21 shows data collected from the polymer-gel lithium-ion cell with both imbedded (internal) and external temperature sensors. In this case, the cell is being discharged at a rate of approximately C/10 and controlled external temperature of approximately 0°C. The internal temperature probe responds to the combined influence of Ohmic heating and external temperature cycling, as expected.

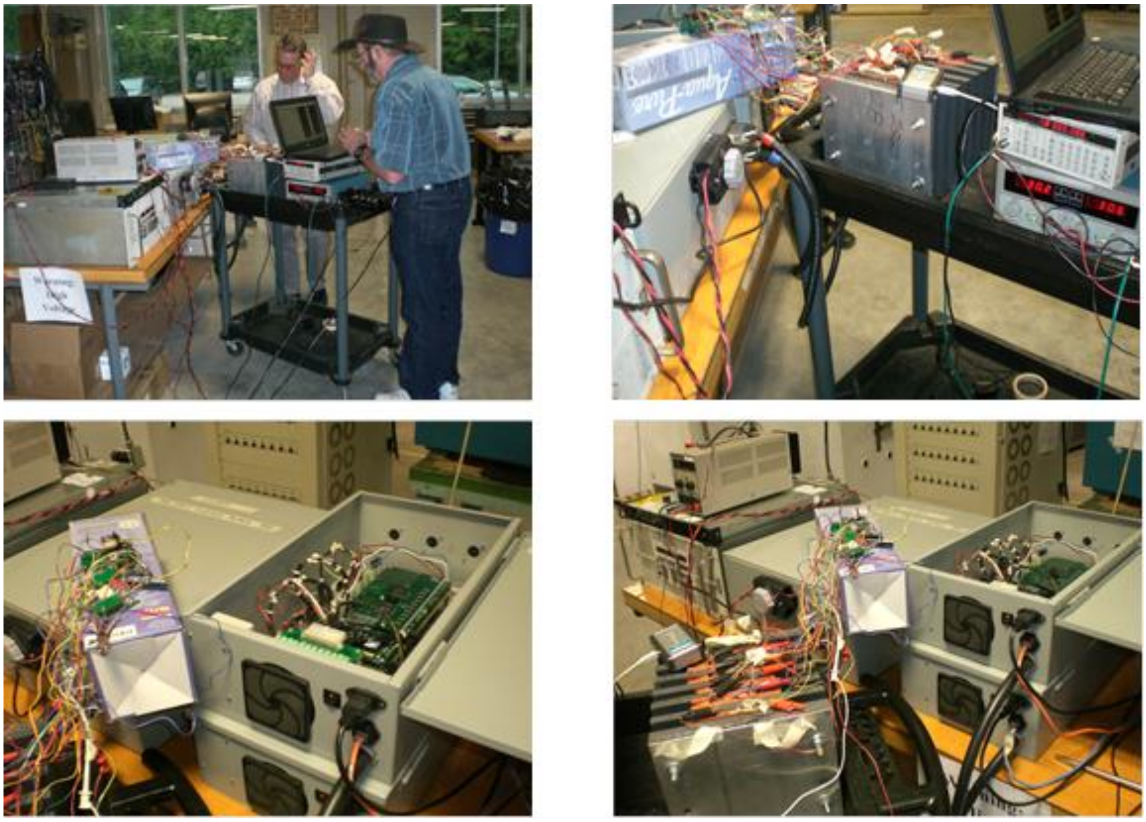


Figure 16 – Interference test at Yardney Technical Products. Photograph showing the Electromagnetic Interference (EMI) test of the LLNL wireless tags and sensor suites with live YTP BMS system. Both the wireless tags and sensors worked flawlessly, with little or no significant interference. This test indicates that the incorporation of the wireless tags and sensors into such high-power BMS systems with relays and other actuators should not be problematic.

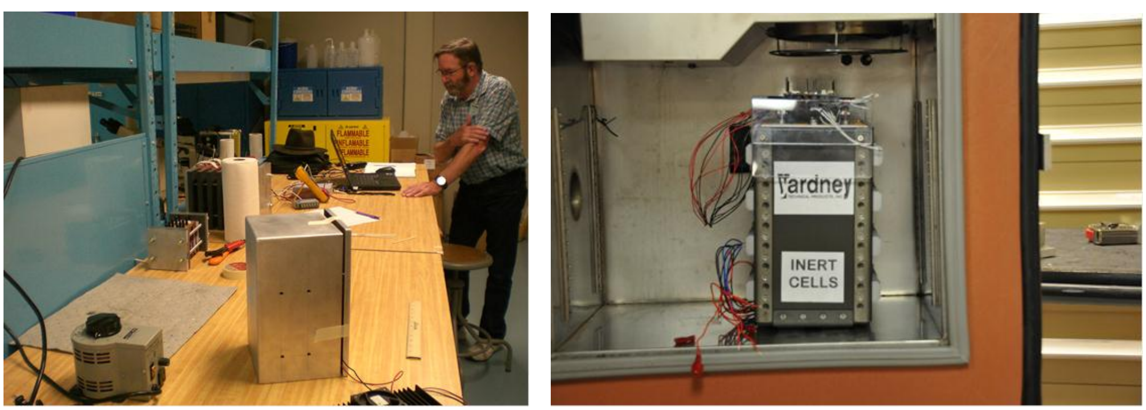


Figure 17 – Metallic environment test at Yardney Technical Products and Lawrence Livermore National Laboratory. Tests have been conducted with the wireless tags and suites of sensors inside metallic closures that mimic battery boxes and containment vessels These enclosures were operated with variable aperture (openings) to alloy signal transmission from the tags to reach the reader.

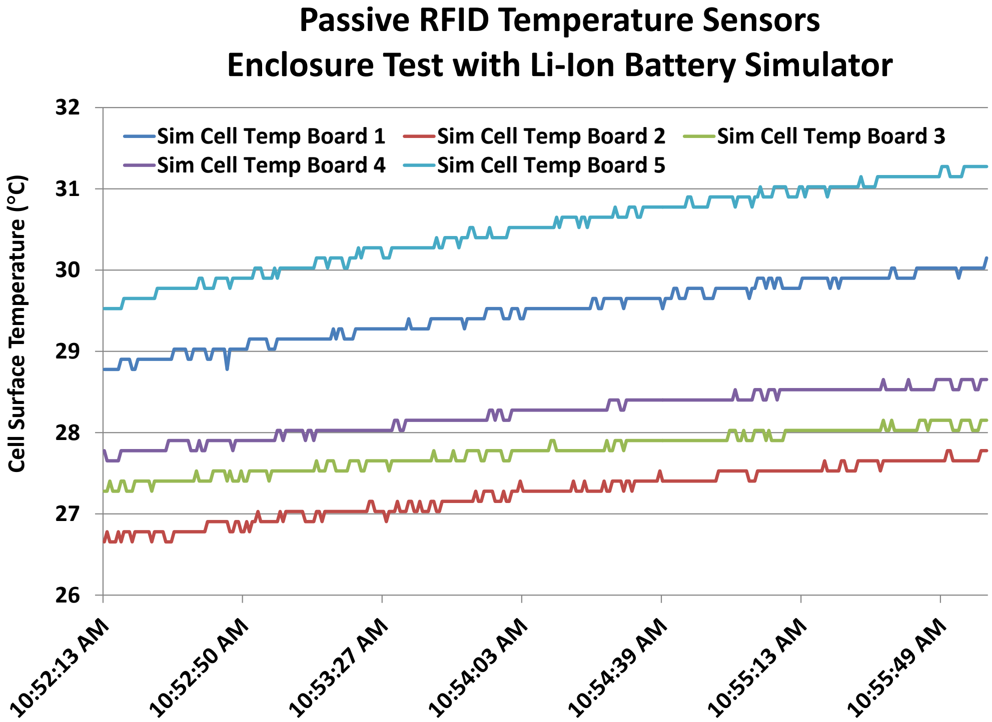


Figure 18 – This data shows the successful transmission of temperature data from five wireless tags with temperature sensors in the aluminum battery pack enclosure shown in Figure 17 (left). The aperture in this case was very small (fraction of an inch), the sensors were powered with the drive coil and an external power amplifier, and the data quality was excellent. The temperature of these sensors increased slowly due to Ohmic heating of the air and structure inside the battery box by the battery simulator.

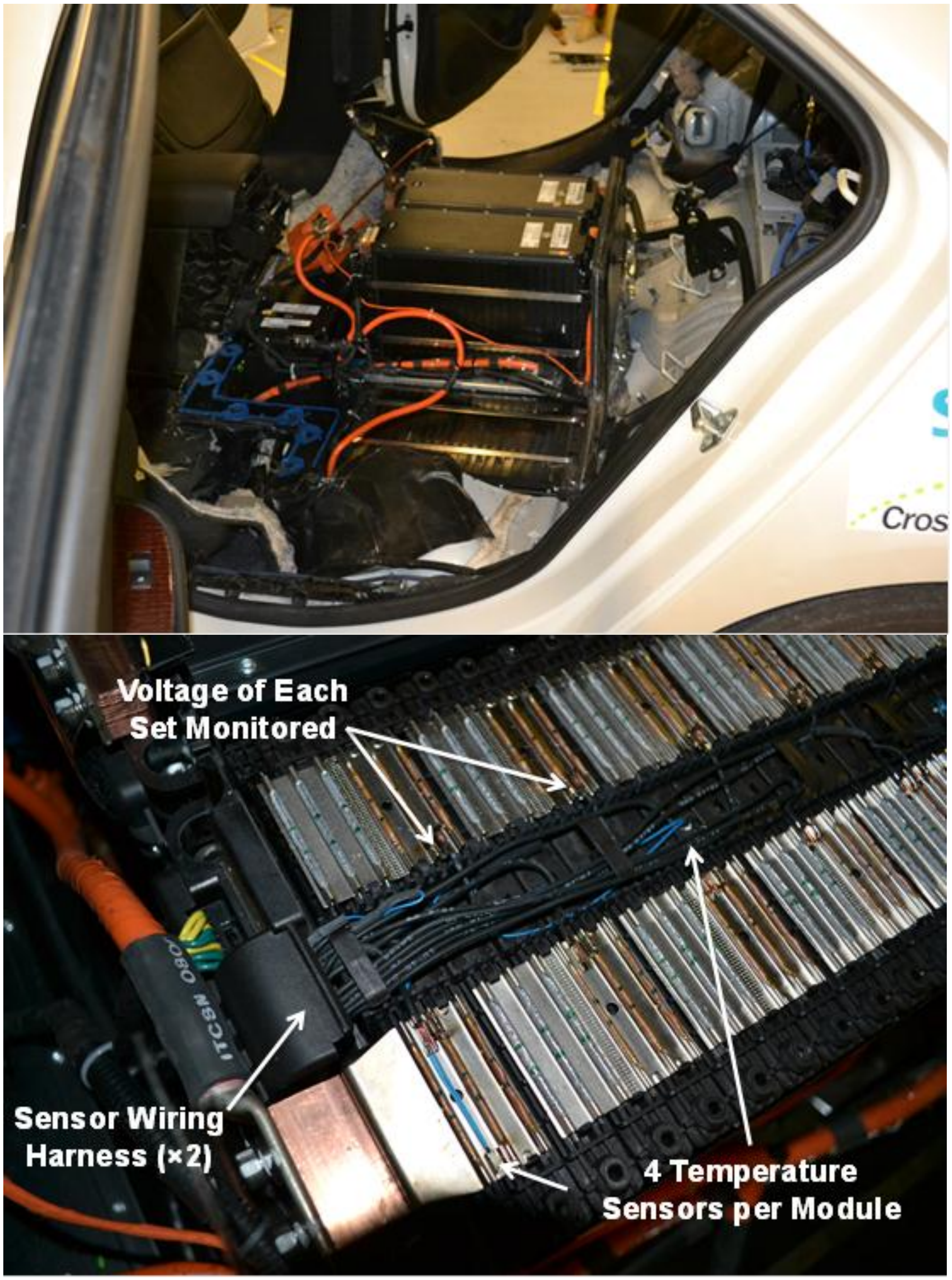
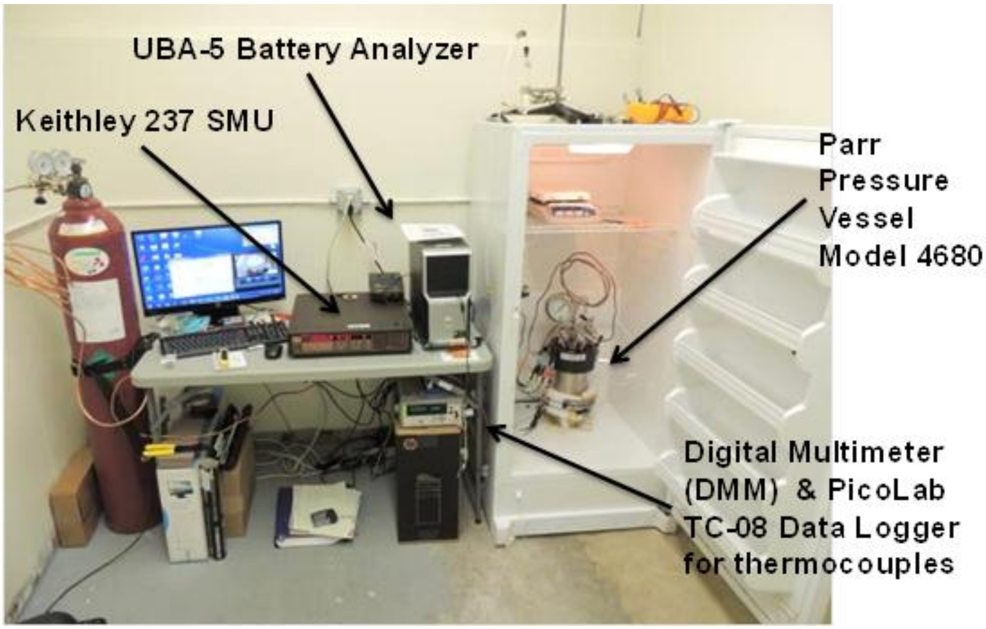
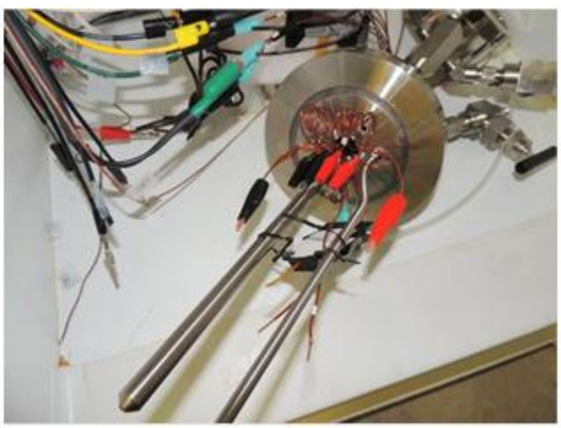
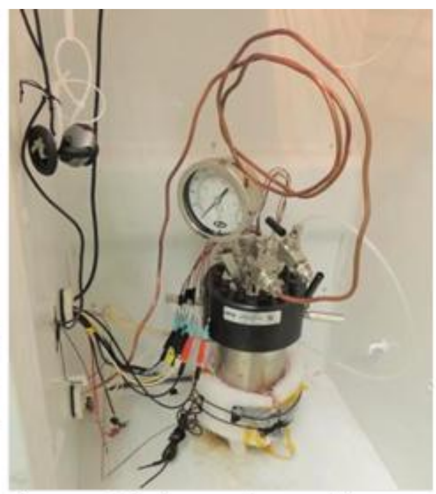


Figure 19 – As the project progresses, the team would like to install a full complement of LLNL-YTP wireless tags and sensors on the Colorado State University (CSU) plug-in hybrid-electric vehicle (PHEV) known as EcoCAR 2. This will enable Professor Bandhauer and his mechanical engineering students to further quantify tag performance in complex environments representative of state-of-the art PHEVs. Advantages of involving CSU include the opportunity to use these new wireless sensors and the more fully instrumented PHEV to educate next-generation energy engineers.



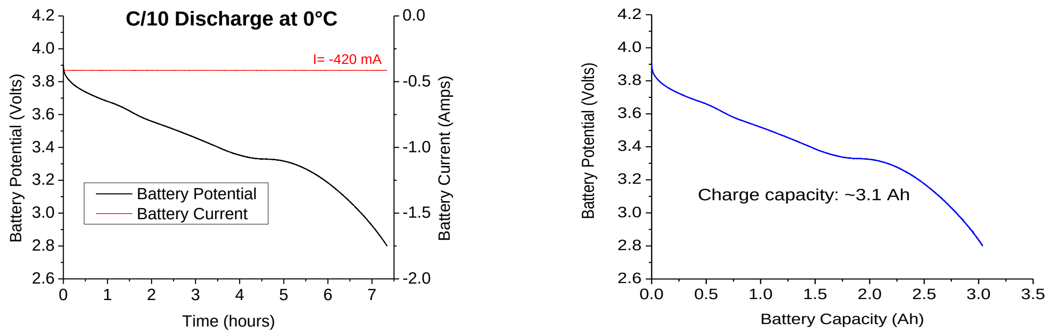


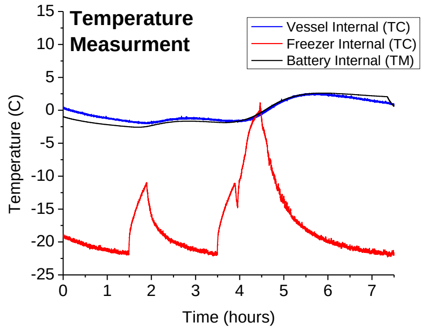
Autoclave interior connections with thermistor holding bracket. The holding bracket was replaced with direct connection to pouch cell and thermistors



Argon-filled autoclave with copper tubing and electronic connections

Figure 20 – Special polymer-gel lithium-ion cells with temperature sensors embedded in the core have been designed and fabricated by PolyStor Energy Corporation (PSEC) of Livermore, California. These special cells with embedded temperature sensors have now been tested comprehensively at the United States Naval Postgraduate School, proving the viability of sensing the actual core temperature of lithium ion cells during operation. This photograph shows the special facilities constructed at NPS to enable support of the ARPA-E wireless BMS project, specifically the cycling and test-to-failure of the polymer-gel lithium-ion cells with embedded temperature sensors, and wireless signal transmission.





- **Second battery discharge (C/10) at ~0°C.**
- **Discharge capacity: 3.1 Ah (~97% of 3.2 Ah charge).**
- **Accurate temperature reading by the internal thermistor during cell operation.**

Figure 21 – This figure shows data collected from the polymer-gel lithium-ion cell with both imbedded (internal) and external temperature sensors. In this case, the cell is being discharged at a rate of approximately C/10 and controlled external temperature of approximately 0°C. The internal temperature probe responds to the combined influence of Ohmic heating and external temperature cycling, as expected.

Section IV. Major risks to future milestones: please use this section to briefly discuss any actual or anticipated problems, risks, or issues, along with the actions planned or taken to resolve them.

Summary of Risks to Future Milestones:

- Impact of Federal Government Shutdown on Schedule & Budget
- Need to Reformulate Original Tasks & Milestones Consistent with Accomplishments
- Possible Insufficient Funds to Complete Technical Development of Wireless System
- Need to Revise the Technology-to-Market Plan
- Possible Insufficient Funds to Fully Execute Revised Technology-to-Market Plan
- Any Failure of Patent Applications and Inability to Protect Intellectual Property
- Any Inability to Attract and Maintain Interest of Early Adopters in Technology
- Any Inability to Negotiate License Between LLNL and Early Adopter
- Prudent Succession Plan for Long-Range Project Execution & Transition to Market

Need to Reformulate Original Tasks & Milestones Consistent with Accomplishments

- Milestone 1 (Revised): Develop individual wireless sensors & tags capable of being operated in either passive or active mode (6/24/2013).
- Milestone 2 (Revised): Demonstrate one-to-five wireless tags with voltage, temperature & strain sensor, in both active and passive mode, with battery simulator and live battery pack (6/24/2013); 1st integration into YTP product (6/15/2014); destructively test actual YTP product with distributed array of wireless sensors integrated (6/15/2015).
- Milestone 3 (Revised): Demonstrate passive and active wireless sensors & tags (6/24/2013); conduct comparative studies of passive vs. active approaches (12/15/2013); create first international Standard for wireless BMS (3/15/2014); 1st revision of standard (3/15/2015).
- Milestone 4 (Revised): Technology-to-Market (T2M) Plan – Quantify Cost Possible Reduction Based Upon ASIC and FPGA Production of Wireless Tags & Sensors (3/15/2014).
- Milestone 5 (Revised): Distributed Array of Wireless Controllers for Wireless BMS System: develop low-drain switch to control of current flow to each cell based upon sensed voltage, that can be controlled wirelessly by BMS, and can be used as distributed array in pack; develop low-drain operational amplifier circuits to charge each individual cell in pack with potential control; each operational amplifier will be capable of being wirelessly controlled by BMS, and can be used as distributed array in pack.
- Detailed descriptions of these revised tasks and milestones are described in the following pages.

Milestone 1: Develop Wireless Tags & Sensors Capable of Active or Passive Operation

- 1.1.1 – Design of 20-Ah simulation cells and battery pack simulator incorporating Li-ion liquid-prismatic simulation cells (6/24/2013).
- 1.1.2 – Fabrication of components and assembly of 20-Ah Li-ion liquid-prismatic simulation cells (6/24/2013).
- 1.1.3 – Assembly of 7S2P battery pack simulator with 20-Ah Li-ion liquid-prismatic simulation cells (6/24/2013).
- 1.2.1 – Design wireless tags and sensor boards capable of either active or passive operation based upon Bluetooth 4.0 (6/24/2013).
- 1.2.2 – Select and procure 1st lot of printed circuit boards, components to populate boards, wireless reader, and voltate, temperature & strain sensors (6/24/2013).
- 1.2.3 – Fabricate 1st lot of prototypical active and passive wireless tags with voltage, temperature & strain sensors (6/24/2013).
- 1.3.1 – Quantify power consumption of wireless tags and sensors through experimental measurement (6/24/2013).
- 1.3.2 – Test wireless tags and at least one sensor in both active and passive mode, with receiving and transmitting antennas (6/24/2013).
- 1.3.3 – Demonstrate performance of voltage, temperature and strain sensors with both active and passive wireless tags (6/24/2013).
- 1.3.4 – Document performance of wireless tags and sensors, in both active and passive mode in LLNL technical report (in progress)
- 1.3.5 – To enable initial integration into product by YTP procure: 2nd lot of printed circuit boards & components to populate boards; readers; and voltage, temperature & strain sensors (10/15/2013).
- 1.3.6 – To enable initial integration into product, fabricate 2nd lot of prototypical active and passive wireless tags, with voltage, temperature & strain sensors (10/15/2013).
- 1.4.1 – Document software enabling USB reader to communicate with arrays of LLNL's Bluetooth 4.0 wireless tags (12/15/2013).
- 1.4.2 – Integration of USB reader with BMS for 1st YTP product, demonstrating BMS & USB reader communication (12/15/2013).
- 1.4.3 – Refine communication software between BMS for 1st YTP product and USB reader (3/15/2014).
- 1.4.4 – Successful demonstration of operational BMS for 1st YTP product with wireless communication to distributed array of PCB-type wireless tags with full sensor suite (4/15/2014).
- 1.4.5 – Integration of prototypical PCB-type wireless tags with full sensor suite into 1st YTP product (6/15/2014).

- 1.4.6 – Successful demonstration of 1st YTP product with truly wireless BMS, based upon PCB-type technology (9/15/2014).
- 1.5.1 – Plan for integration of internal temperature sensors integration with individual polymer-gel lithium-ion cells (4/15/2013).
- 1.5.2 – Fabrication of at least two polymer-gel lithium-ion cells with internal and external temperature sensors at PSEC (4/15/2013).
- 1.5.3 – Testing of at least two polymer-gel Li-ion cells with internal and external temperature sensors in NPS autoclaves (6/24/2013).
- 1.6.1 – Plan for integration of internal reference electrode integration with individual polymer-gel lithium-ion cells (10/15/2013).
- 1.6.2 – Fabrication of at least two polymer-gel lithium-ion cells with internal reference electrode at PSEC (11/15/2013).
- 1.6.3 – Testing of at least two polymer-gel Li-ion cells with internal reference electrodes in NPS autoclaves (12/15/2013).
- 1.6.4 – Fabricate & test cells with internal temperature sensors and reference electrodes (3/15/2014).

Milestone 2: Testing of Wireless Tags & Sensors with Battery Simulator & Live Pack

- 2.1.0 – Demonstrate at least one (1) wireless tag with voltage, temperature & strain sensors, in both active and passive mode, with battery simulator (6/24/2013).
- 2.1.1 – Bench testing of LLNL of at least one (1) wireless tag with voltage, temperature & strain sensors at YTP, in both active and passive mode, with verification of operability by YTP (6/24/2013).
- 2.1.2 – Demonstrate transmission of individual voltage, temperature and strain data from wireless tag to USB reader and laptop at sampling rate of 1 Hertz for duration of 1 hour (6/24/2013).
- 2.1.3 – Demonstrate simultaneous transmission of voltage, temperature and strain data from tag to USB reader and laptop at sampling rate of 1 Hertz for duration of 1 hour (6/24/2013).
- . 2.1.4 – Bench testing of YTP battery simulator at YTP with verification of operability of simulation cell heaters and pressurization system, and thermistors by LLNL (6/24/2013).
- 2.1.5 – Initial electromagnetic interference (EMI) testing of at least one (1) wireless tag with voltage, temperature and strain sensors, in both active and passive mode, in close proximity to energized battery management system (BMS), demonstrating interference-free operation of wireless tag, reader and BMS (6/24/2013).
- 2.2.0 – Demonstrate at least five (5) wireless tags with voltage, temperature & strain sensors, in both active and passive mode, with battery simulator (6/24/2013).

- 2.2.1 – Bench testing of at least five (5) wireless tags with voltage, temperature & strain sensors at YTP, in both active and passive mode, with verification of operability by YTP (6/24/2013).
- 2.2.2 – Demonstrate transmission of individual voltage, temperature and strain data from wireless tag to USB reader and laptop at sampling rate of 1 Hertz for duration of 1 hour (6/24/2013).
- 2.2.3 – Demonstrate simultaneous transmission of voltage, temperature and strain data from tag to USB reader and laptop at sampling rate of 1 Hertz for duration of 1 hour (6/24/2013).
- 2.2.4 – Bench testing of YTP battery simulator with at least five (5) LLNL wireless tags with distributed array of voltage, temperature & strain sensors at YTP (6/24/2013).
- 2.2.5 – Initial electromagnetic interference (EMI) testing of at least five (5) wireless tags with voltage, temperature and strain sensors, in both active and passive mode, in close proximity to energized battery management system (BMS), demonstrating interference-free operation of wireless tag, reader and BMS (6/24/2013).

Milestone 3: Conduct Comparative Studies & Establish Standard for Wireless BMS

- 3.1.0 – Comparative analysis of active and passive wireless tags, with voltage, temperature & strain sensors, with quantification of their relative performance (6/15/2014)
- 3.1.1 – Establish standardized physical and electromagnetic test environments (STEs) representative of those expected for prototypical battery packs. STEs may include: 7S2P battery-pack simulator in air without enclosure; 7S2P battery-pack simulator in air with metal enclosure and variable aperture; actual lithium-ion battery-pack in air without enclosure and during cycling; actual lithium-ion battery-pack in air without enclosure and during cycling with metal enclosure and variable aperture; YTP 120-V lithium-ion battery pack or suitable alternative, with and without energized BMS system (6/24/2013)
- 3.1.2 – Quantify signal integrity (SI): measure bit error rate (BER) as a function of time and range for wireless tags with full suite of sensors, in both passive and active mode, in each standardized test environment (STE), with the results presented in the form of BER graphs. Communication rates will be varied from 1 Hz to up to 10 Hz, with the signal dropout rate measured at each operating frequency (10/15/2013).
- 3.1.3 – Quantify electromagnetic interference (EMI): determine the performance of wireless tags with full suite of sensors, in both passive and active mode, in each STE (11/15/2014).

- 3.1.4 – Quantify range of wireless tags: measure bit dropout rate as a function of distance for wireless tags with full suite of sensors, in both passive and active mode, in each STE(12/15/2013).
- 3.1.5 – Quantify power consumption: measure power consumption for single wireless tag with full suite of sensors, in both passive and active mode, as a function of STE and range; calculate the drain from lithium-ion battery pack for active mode (1/15/2014).
- 3.1.6 – Quantify economy of scale: perform engineering economic analysis to determine specific costs associated with transitioning "one-of-a-kind" active and passive printed circuit board (PCB) prototypes to mass-produced "N-of-a-kind" PCB tags (3/15/2014).
- 3.1.7 – Quantify form factor and flexibility: perform detailed engineering analysis based on design of printed circuit boards, antennas, ancillary hardware, and packaging, determining the characteristic external dimensions for active and passive PCB-type prototypes; determine suitability for various commercially available lithium-ion battery packs (6/15/2014),
- 3.1.8 – Demonstrate compliance of wireless tags and sensors, integrated into battery pack simulator and live battery pack with energized BMS to automotive and aerospace standards; specifically demonstrate compliance to CISRP 25 (automotive applications) and Mil-STD-461 (aerospace and military applications) (9/15/2014).
- 3.1.9 – Collaboratively test YTP battery pack, with active and passive tags, and with voltage, temperature and strain sensors at NTS or comparable sub-contractor (9/15/2015).

Milestone 4: Technology-to-Market (T2M) Plan & Cost Reduction Strategies for ASIC

- 4.1.1 – Initial protection of wireless BMS technology by LLNL with: formal records of invention (01/30/2012), provisional patents (submitted), and patent applications (01/30/2012).
- 4.1.2 – IP agreements to be finalized by all non-governmental team members; government team members are not required to sign; initial version completed and submitted to ARPA-e (02/13/2013)
- 4.1.3 – Technology to Market (T2M) Plan submitted to ARPA-e for approval; revision of T2M plan; acceptance of T2M plan (done)
- 4.1.4 – Identify possible early adopters for various applications that are key to market entry, including defense, aerospace, automotive, test equipment, UPS, and grid storage (6/24/2013).
- 4.1.5 – Investigate viability of wireless tags and full sensor suite for grid storage; document findings in formal report (12/15/2013).

- 4.2.0 – Contact possible early adopters in applications that are key to market entry, including defense, aerospace, automotive, grid, UPS, and test equipment (in progress).
- 4.2.1 – Contact early adopters in aerospace and national defense, beginning with Yardney Technical Products and Lawrence Livermore National Laboratory. Evaluate potential opportunities with YTP products, including 120-V, 400-V, and other systems (10/15/2013).
- 4.2.2 – Contact early adopters in civilian aviation, beginning with Boeing Corporation (10/15/2013).
- 4.2.3 – Contact early adopters for EV, HEV & SLI applications, beginning with Tesla and Ford Motor Companies (12/15/2013).
- 4.2.4 – Contact early adopters for grid, UPS, and test equipment applications, beginning with Maccor & General Electric (3/15/2013).
- 4.3.0 – Identify commercial suppliers of ASIC and lay foundation for credible cost estimates for N-of-a-kind active and passive wireless tags, with voltage, temperature & strain sensors (done).
- 4.3.1 – Contact IDM ASIC suppliers: IDM supplier's ASIC product is based in large part on proprietary technology such as design tools, IP, packaging, and usually although not necessarily the process technology. Work with these suppliers to prepare credible estimates for ASIC approach to the fabrication wireless tags and sensors. Quantify any possible cost savings over PCB approach (3/15/2014).
- 4.3.2 – Contact fabless ASIC suppliers: Fabless ASIC suppliers rely almost exclusively on outside suppliers for their technology. Work with these suppliers to prepare credible estimates for ASIC approach to the fabrication wireless tags and sensors. Quantify any possible cost savings over PCB approach (3/15/2014).
- 4.3.3 – Quantify cost for wireless tags and sensors, mass-produced as application-specific integrated circuits (ASICs), and compare to costs for printed circuit board (PCB) prototypes
    - ASICs are integrated circuits (ICs) designed for specific applications:
        - Microprocessors (CPU, etc.)
        - Memory devices (ROM, RAM, EEPROM, Flash, etc.)
        - ASICs have now grown from 5 thousand to over 100 million gates
        - ASICs designed with Hardware Description Languages (Verilog)
        - Complete by (3/15/2014)

- Today's Cost for Printed Circuit Board Technology
    - *Electronic Components = $300*
    - *Printed Circuit Boards = $60*
    - *Sensors = $2*
    - *Labor to Populate Board = 8 hours x $100/hour*
    - *Prototype Total = $1162 (Early Adopters)*
    - *Prototype Real Estate ~ 20 cm^2*
- Preliminary Cost Projection for Mass-Produced ASIC
    - ASIC = $2
    - Sensors = $2
    - ASIC Total = $4 (Automotive)
    - ASIC Real Estate ~ 0.4 cm^2

Milestone 4: Technology-to-Market (T2M) Plan & Cost Reduction Strategies for FPGA

- 4.4.0 – Identify commercial suppliers of FPGA technology, and lay foundation for credible cost estimates for N-of-a-kind active and passive wireless tags, with voltage, temperature, and strain sensors
- 4.4.1 – Contact FPGA suppliers: Contact FPGA suppliers and arrange meetings to discuss production scale-up. Work with these suppliers to prepare credible estimates for ASIC approach to the fabrication wireless tags and sensors. Quantify any possible cost savings over PCB approach.
- 4.4.2 – Contact fabless FPGA suppliers: FPGA suppliers rely almost exclusively on outside suppliers for their technology. Work with these suppliers to prepare credible estimates for FPGA approach to the fabrication wireless tags and sensors. Quantify any possible cost savings over PCB approach.
- 4.4.3 – Quantify cost for wireless tags and sensors, mass-produced as Field-Programmable Gate Arrays (FPGAs) , and compare to costs for printed circuit board (PCB) prototypes
    - FPGA is a more flexible technology for building prototypes from standard parts; programmable logic blocks and programmable interconnects allow the same FPGA to be used in many different applications
    - The non-recurring engineering (NRE) cost of an ASIC can run into the millions of dollars

  - Today's Cost for Printed Circuit Board Technology
    - Electronic Components = $300
    - Printed Circuit Boards = $60
    - Sensors = $2
    - Labor to Populate Board = 8 hours x $100/hour
    - Prototype Total = $1162 (Early Adopters)
    - Prototype Real Estate ~ 20 cm^2
  - Preliminary Cost Projection for Mass-Produced FPGA
    - FPGA > $2
    - Sensors = $2
    - FPGA Total > $4 (Automotive)
    - FPGA Real Estate > 0.4 cm^2
- 4.5.0 – Detailed cost analysis for producing prototypical PCB-type Bluetooth 4.0 wireless tags with full suite of sensors, with necessary USB readers and BMS integration.
- 4.5.1 – Detailed cost analysis for producing prototypical ASIC-type Bluetooth 4.0 wireless tags with full suite of sensors, with necessary USB readers and BMS integration.
- 4.5.1 – Detailed cost analysis for producing prototypical FMGP-type Bluetooth 4.0 wireless tags with full suite of sensors, with necessary USB readers and BMS integration.
- 4.5.3 – Use exemplar analysis to calculate N-of-a-kind cost for producing Bluetooth 4.0 wireless tags with full suite of sensors, with necessary USB readers and BMS integration, comparing PCB, ASIC and FMGP production technologies.

Milestone 5: Distributed Array of Wireless Controllers for Wireless BMS System

- 5.1.0 – Develop wireless control technology, thereby enabling high-fidelity balancing of individual cells with only bus cable (6/15/2015).
- 5.1.1 – Develop low-drain switch to control of current flow to each cell based upon sensed voltage, that can be controlled wirelessly by BMS, and can be used as distributed array in pack (6/15/2015).
- 5.1.2 – Develop low-drain operational amplifier circuits to charge each individual cell in pack with potential control; each operational amplifier will be capable of being wirelessly controlled by BMS, and can be used as distributed array in pack (6/15/2015).

Today's Wireless Sensors

- Cell Potential
  - Terminal
  - Internal Reference Electrode
- Cell Temperature
  - External
  - Internal Temperature Sensor
- Cell Strain
  - Infer Internal Pressure
- Emission Sensors
  - Acoustic
  - Optical

Tomorrow's Wireless Control

- Enable High-Fidelity Balancing of Individual Cells
- Distributed Wireless Low-Drain Switches for Control of Current Flow to Each Cell Based Upon Sensed Voltage
- Distributed Wireless Low-Drain Operational Amplifier Circuits to Charge Each Cell with Potential Control

Any Failure to Protect Intellectual Property or Have Patent Applications Granted

- ROI, Provisional Patents, and Patent Application Filings:
  - IL-12597 entitled Battery Management System with Distributed Wireless Sensors (parent invention);
  - IL-12593 Battery Management Systems with Distributed Wireless Sensors and Thermal Integrated Fire Suppression;
  - IL-12749 Li-Ion Battery Thermal Runaway Suppression System Using Microchannel Coolers and Refrigerant Injections.
  - Team is awaiting USPTO office actions.
  - Others including newer disruptive technologies are in process.

- NDA Execution – Mutual non-disclosure agreements have been executed between LLNL and all team members.

- IP agreements finalized by non-governmental team members and submitted to ARPA-e on February 13, 2013 (members are federal government employees covered by the "Federal Trade Secrecy Act").

Any Inability to Attract and Maintain Interest of Early Adopters in Technology

- Early Adopters in Aerospace & National Defense (Opportunities Identified)
  - Yardney Technical Products
  - Lawrence Livermore National Laboratory
- Automotive Applications (Three Contacts Made)
- Advanced Applications in Civilian Aviation (Three Contacts Made)
- UPS, Grid & Test Equipment Applications (One Contact Made)

Need to Execute Exclusive License with Battery Manufacturer

- Clearly Articulate Objectives – Rapid and Successful Establishment of U.S. Manufacturer as the First Supplier in the World with Wireless BMS Sensor Capability for Enhanced Safety
- Identify Knowledgeable Patent Attorney & Protect Intellectual Property – Eddie Scott, Intellectual Property Law, Lawrence Livermore National Laboratory
- Identify Appropriate Laboratory Authority for Licensing Negotiations – Richard Rankin, Director, Industrial Partnership Office, Lawrence Livermore National Laboratory
- Execute Fairness of Opportunity Announcement (FOA) – Standard CBD Announcement Prior to Licensing Negotiations
- Identify Industrial Authority 1 – Frank Puglia, Director of Research & Development, Program Manager, Yardney Technical Products
- Identify Industrial Authority 2 – Any Others Stepping Forward Following FOA
- Negotiate Exclusive License/Licenses for Defense Applications – Timely Meeting to Negotiate and Facilitate Transfer of Technology from LLNL to Industrial Entity/Entities to Enable Further Defense System Development & Marketing to Department of Defense
- Negotiate Field-of-Use Exclusive License/Licenses for Commercial Applications – Timely Meeting to Negotiate and Facilitate Transfer of Technology from LLNL to Industrial Entity/Entities to Enable Further Commercial Product Development & Marketing in Private Sector

Prudent Succession Plan for Long-Range Project Execution & Transition to Market

Dr. Todd Bandhauer, the initial Principal Investigator, left Lawrence Livermore National Laboratory in June 2013 to join the Mechanical Engineering Department at Colorado State University as an Assistant Professor. In his new role at Colorado State University, he is involved with the CSU PHEV (EcoCAR 2) Team. In the future, this PHEV may serve as a beneficial test platform for the emerging wireless BMS technology from ARPA-E.

Responsibility of the project was then passed to Dr. Joseph Farmer, Co-Investigator and Co-Inventor (first named) of the wireless BMS technology which serves as the basis for the project. He has been PI on several large programs at LLNL requiring electrochemical engineering expertise, including the: Special Isotope Separations (SIS) Program; Fissile Materials Disposition Program (FMDP) and others. He has managed programs sponsored by NIST ATP, DOE OBES, DOE OCRWM, DARPA DSO, USAF, USN, RPSEA, LDRD, NIF, Exxon Mobil, as well as numerous private sponsors. He is the LLNL subject matter expert in Li-ion technology, and served on both the B787 and ASDS RCA Teams. He was the Research Director for PolyStor, where he led NIST ATP project for the development commercial ultra-safe high-performance Li-ion cell technology, which involved ANL, LBNL, 3M, and others. He is Adjunct Professor in Mechanical and Aerospace Engineering at the Naval Postgraduate School. His contact information is:

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LLNL Collaborators / Non-LLNL Team Members:

Frank Puglia – Yardney Technical Products PI, Academic Credentials in Electrochemistry & Electrochemical Engineering, World-Class Expert in Lithium Ion Technology, Director of Research, Responsible for Successful Mars Rover Energy Storage Systems, Responsible for Other Large Battery Pack Designs of National Importance; Responsible for Program Execution at Yardney Technical Products.

Arthur Dobley, Ph.D. – Yardney Technical Products Co-PI, Academic Credentials in Electrochemistry & Electrochemical Engineering, World-Class Expert in Lithium-Ion and Lithium-Air Technologies, Responsible for Large Battery Systems of National Importance; Responsible for Successful Design & Deployment of Battery Simulator Described Here; Responsible for Successful Testing of LLNL Wireless Tags at LLNL,

Greg Moore, Ph.D. – Yardney Technical Products Co-PI, Academic Credentials in Electrochemistry & Electrochemical Engineering, World-Class Expert in Lithium-Ion and Lithium-Air Technologies, Responsible for Large Battery Systems of National Importance.

Sebastian Osswald, Ph.D., M.B.A, - Assistant Professor, Physics Department & Mechanical and Aerospace Engineering Department, Naval Postgraduate School, Monterey, California, Academic Credentials in Physics, Materials Science, Electrochemistry, and Business, Currently Teaches Core Courses in NPS Energy Curriculum at NPS; Responsible for Testing Lithium Ion Cells with Embedded Sensors.

Kevin Wolf – Senior Mechanical Engineer & Program Manager for the United States Navy, Port Hueneme; World-Class Expert in the Development and Deployment of Sophisticated Lithium-Ion Battery Packs with Specialized BMS Systems for Various Naval Applications; Responsible for Navy's Deep Ocean Simulation Facility for Several Years.

James Kaschmitter, M.S. – Electrical Engineer, Stanford University; World-Class Expert in State-of-the-Art Lithium-Ion Battery Technology, Aerogel Super-Capacitor Technology, and Micro Fuel Cells with Integrated Reformers; Founding CEO of PolyStor Energy Corporation with First Large-Scale Commercialization of High-Performance Polymer-Gel Li-Ion Cells in United States; Founding Several Companies in Silicon and Livermore Valleys; Successful Development and Deployment of Several Commercial Products; Led Power Systems Group for Strategic Defense Initiative at Livermore during Reagan/Bush Era.

Steve Eaves – Electrical Engineer, Expert in BMS Systems for Energy Storage Devices for National Defense Applications

LLNL Line Management Responsible for Project:

Until very recently, Dr. Edward Moses was the Principal Associate Director (PAD) for the National Ignition Facility & Photon Sciences (NIF&PS) Directorate at Lawrence Livermore National Laboratory (LLNL). The project was located in this directorate since the Principal Investigator(s) resided in this directorate, and much of the expertise to support the project also resided in this directorate, or works in this directorate as part of the LLNL matrix. Following record yields recently achieved at the National Ignition Facility (NIF), Dr. Moses was recently promoted into a special position working directly with Board of Governors for Lawrence Livermore National Security LLC, the M&O Contractor charged with operation of LLNL by DOE NNSA.

Replacing Dr. Moses as the NIF&PS PAD is the Dr. Jeff Wisoff, formerly the Deputy PAD. Dr. Wisoff is a veteran of NASA's Astronaut Program, and conducted four space walks during his role with NASA. Dr. Wisoff is an internationally-known expert in optical systems, aeronautical physics and engineering, and various directed energy systems that employs high-performance energy storage technologies. He also served as a faculty member at Rice University, and is eminently qualified to manage the personnel involved in this project to ensure that technology is successfully developed. Dr. Wisoff is well equipped to manage the further development, utilization and deployment of this new LLNL-YTP technology for the benefit of the Nation.

Section V. Budget Summary (generally less than 1 page): identify if the project was on budget, overspent, or under spent for the period, why, and how this will affect your future management of the project and expenses.

LLNL received $925K for this project, and has $191K remaining after accomplishing these objectives. See Table 3 (following page) for details.

Specific accomplishments to date include, but are not limited to: (1) the development of wireless tags using Bluetooth 4.0 standard to monitor a large array of sensors in battery pack; (2) sensor suites enabling the simultaneous monitoring of cell voltage, cell current, cell temperature, and package strain, indicative of swelling and increased internal pressure, (3) small receivers compatible with USB ports on portable computers; (4) software drivers and logging software; (5) a 7S2P battery simulator, enabling the safe development of wireless BMS hardware in the laboratory; (6) demonstrated data transmission out of metal enclosures, including battery box, with small variable aperture opening; (7) test data demonstrating the accurate and reliable operation of sensors, with transmission of terminal voltage, cell temperature and package strain at distances up to 110 feet; (8) quantification of the data transmission error as a function of distance, in both indoor and outdoor operation; (9) electromagnetic interference testing during operation with live, high-capacity battery management system at Yardney Technical Products; (10) demonstrated operation with live high-capacity lithium-ion battery pack during charge-discharge cycling; (11) development of special polymer-gel lithium-ion batteries with embedded temperature sensors, capable of measuring the core temperature of individual of the cells during charge-discharge cycling at various temperatures, thereby enabling earlier warning of thermal runaway than possible with external sensors. Ultimately, the team plans to extend this work to include: (12) flexible wireless controllers, also using Bluetooth 4.0 standard, essential for balancing large-scale battery packs.

Table 3 – Expenses through September 2013

CATEGORY	Total Project Cost	Quarterly Expenditures	Cumulative Expenditures to Date	Remaining Balance
a. Personnel	208,298	28,101	173,781	34,517
b. Fringe Benefits	127,062	15,188	103,133	23,929
c. Travel	15,362	3,471	3,711	11,651
d. Equipment	100,404	-	84,700	15,704
e. Supplies	10,000	2,038	13,502	(3,502)
f. Contractual				-
Sub-recipient	0	0	0	-
Vendor	0	0	0	-
FFRDC	0	0	0	-
Total Contractual	0	0	0	-
g. Construction	0	0	0	-
h. Other Direct Costs	50,768	485	34,659	16,109
Total Direct Costs	511,894	49,283	413,486	98,409
i. Indirect Charges	413,106	61,098	320,831	92,275
Total Project Cost	**925,000**	110,381	734,316	**190,684**

Acknowledgements

The author thanks ARPA-E for the support necessary to prepare this document. Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344.