High Energy Batteries for Hybrid Buses

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Final Technical Report

EnerDel, Inc.

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1. **Executive Summary**

EnerDel batteries have already been employed successfully for electric vehicle (EV) applications. Compared to EV applications, hybrid electric vehicle (HEV) bus applications may be less stressful, but are still quite demanding, especially compared to battery applications for consumer products. This program evaluated EnerDel cell and pack system technologies with three different chemistries using real world HEV-Bus drive cycles recorded in three markets covering cold, hot, and mild climates.

Cells were designed, developed, and fabricated using each of the following three chemistries:
- Lithium nickel manganese cobalt oxide (NMC) – hard carbon (HC)
- Lithium manganese oxide (LMO) – HC
- LMO – lithium titanium oxide (LTO) cells

For each cell chemistry, battery pack systems integrated with an EnerDel battery management system (BMS) were successfully constructed with the following features:
- real time current monitoring
- cell and pack voltage monitoring
- cell and pack temperature monitoring
- pack state of charge (SOC) reporting
- cell balancing
- over voltage protection

These features are all necessary functions for real-world HEV-Bus applications.

Drive cycle test data was collected for each of the three cell chemistries using real world drive profiles under hot, mild, and cold climate conditions representing cities like Houston, Seattle, and Minneapolis, respectively. We successfully tested the battery packs using real-world HEV-Bus drive profiles under these various climate conditions. The NMC-HC and LMO-HC based packs successfully completed the drive cycles, while the LMO-LTO based pack did not finish the preliminary testing for the drive cycles. It was concluded that the LMO-HC chemistry is optimal for the hot or mild climates, while the NMC-HC chemistry is optimal for the cold climate.

In summary, the objectives were successfully accomplished at the conclusion of the project. This program provided technical data to DOE and the public for assessing EnerDel technology, and helps DOE to evaluate the merits of underlying technology. The successful completion of this program demonstrated the capability of EnerDel battery packs to satisfactorily supply all power and energy requirements of a real-world HEV-Bus drive profile. This program supports green solutions to metropolitan public transportation problems by demonstrating the effectiveness of EnerDel lithium ion batteries for HEV-Bus applications.

2. Introduction

As progressive nations implement more rigid environmental requirements for exhaust emissions, the applications for HEVs will increase. The reduced fuel consumption reduces the emission of greenhouse gasses, both where the vehicles are employed, and also overall due to the higher efficiency and better environmental controls imposed on power plants compared to individual vehicles. The development of clean vehicles will increase as stricter regulations are enforced on gasoline and diesel powered cars. Although EVs may be more advantageous for protection of the environment and energy efficiency, the technology is still under development. Present HEV technology has advanced farther, and is the natural progression away from vehicles relying solely on ICEs (internal combustion engines). A typical HEV power system is comprised of an ICE, batteries, power generation, and management systems. In the future, these systems could also incorporate the use of alternative energy generation such as fuel cells instead of an ICE. An HEV is capable of recovering regenerative energy which is captured during the vehicle braking cycle to be used again to assist in acceleration. HEV technology is therefore quite attractive for use in applications where vehicles make many stops and starts, such as buses and delivery trucks. Additionally, power can be generated during low demand periods by the ICE. The HEV system is capable of conserving considerable energy and significantly reducing emissions compared to an exclusively ICE powered vehicle. The purpose of this initiative is to develop, produce, and evaluate a superior battery technology for mass transit HEV applications, specifically hybrid transit busses.

Presently, most hybrid buses employ NiMH (nickel metal hydride) battery technology. NiMH batteries are larger, less efficient, and have a lower cycle life than their lithium ion counterparts. New lithium ion based battery technologies developed by EnerDel, Inc. provide a safe, reliable, and cost effective solution for hybrid buses. Attractive features of EnerDel lithium-ion batteries include high energy density, no memory effects, and slow loss of charge when not in use. Even after many cycles, EnerDel's lithium ion battery can provide the necessary energy required for demanding HEV applications. EnerDel lithium ion batteries will last substantially longer, have higher energy density, provide larger usable portions of the charge and discharge curve, and require less volume than NiMH batteries.

In order to bring EnerDel's advanced HEV lithium ion battery products to market, the technology must be developed, evaluated, tested, validated, and mass manufactured. Some EnerDel technology is ready for production today, while others will require further battery development. EnerDel partnered with a major bus vendor on this initiative to implement a lithium ion replacement for their existing NiMH battery system currently used on urban hybrid bus fleets.

This EnerDel HEV-Bus program evaluated the effectiveness of EnerDel's lithium ion battery technology for heavy duty HEV bus applications.

3. Comparison of the goals and objectives of the project with the accomplishments

The overall project objective for the EnerDel HEV-Bus program was to evaluate lithium-ion cell and battery pack technologies for heavy duty HEV bus applications based on actual vehicle requirements in average and extreme climates.

The individual goals for this project were:

- To design, develop, and fabricate prismatic lithium ion cells based on three different cell chemistries, namely NMC-HC, LMO-HC, and LMO-LTO
- To design and construct pack systems using these three chemistries of EnerDel lithium-ion cells, which are suitable for HEV-Bus applications
- To collect drive cycle test data for three cell chemistries using real world drive profile under hot, cold, and mild climate conditions
- To evaluate the effectiveness of three EnerDel battery chemistries based on success of completing the real-world drive cycle profile, heating of the battery packs, and aging of battery packs

At the completion of the project, the individual goals of this project were successfully accomplished. The accomplishments are listed below:

- Successfully developed and fabricated prismatic lithium ion cells based on three cell chemistries (NMC-HC, LMO-HC, and LMO-LTO)
- Successfully designed and constructed battery pack systems integrated with an EnerDel BMS using three EnerDel lithium ion cells featuring real time current, cell/pack voltage and temperature monitoring, pack SOC reporting, cell-balancing, and over voltage protection, which are necessary functions for real-world HEV-Bus applications
- Successfully tested battery packs based on three cell chemistries using a real-world HEV-Bus drive profile under hot, cold, and mild climate; the NMC-HC and LMO-HC based packs successfully completed the drive cycle, while the LMO-LTO based pack didn't finish the drive cycle
- Successfully evaluated battery packs based on three cell chemistries using a real-world drive profile under hot, cold, and mild climate conditions; it was concluded that the LMO-HC chemistry is optimal for the hot and mild climates, while the NMC-HC chemistry is optimal for the cold climate

In summary, the objectives were successfully accomplished at the conclusion of the project. The HEV-Bus program provided technical data to DOE and the public for assessing EnerDel technology and it also helps DOE to evaluate the merits of underlying technology. The successful completion of this program demonstrated the capability of EnerDel battery packs to adequately supply all power and energy requirements of a real-world HEV-Bus drive profile. This program supports green solutions to metropolitan public transportation problems by demonstrating the effectiveness of EnerDel lithium ion batteries for HEV-Bus applications.

4. Project summary

The project included three phases:

- Phase I: Requirements analysis and system design
  - During Phase I, we discussed requirements of HEV-Bus with a vehicle vendor (we were asked to not disclose vendor information) who has an ongoing HEV-Bus testing program. Vendor agreed to supply real world HEV-Bus drive cycle profile recorded under normal public transit operation conditions. The drive cycle profile covers an 8-hour day-time operation period. Analysis of the real world drive cycle profile yielded requirements for EnerDel battery pack system design. Gap analysis was performed to arrive at suitable pack configuration and function to meet system requirements for HEV-Bus pack design.
- Phase II: Cell fabrication and pack construction
  - During Phase II, material research and fabrication processes were developed for prismatic battery cells based on LMO - HC and LMO - LTO chemistries. NMC – HC cell chemistry was already developed at EnerDel for use in EVs. Pack systems complete with BMS were constructed. The BMS for packs employing the LMO – LTO chemistry was modified to include Coulomb counting to accommodate the flat charge and discharge profiles.
- Phase III: Pack testing
  - During Phase III, a total of nine battery packs were tested, including three chemistries (NMC-HC, LMO-HC, and LMO-LTO) with three packs each, for testing in three different climate conditions (hot, cold, and mild).

5. Project overview

5.1 EnerDel company background

EnerDel designs, develops, and manufactures large formation lithium ion batteries for use in vehicle, grid storage, and military applications. Founded in 2006, with comprehensive facilities to design, manufacture, and test lithium ion batteries, EnerDel is located in Indianapolis, Indiana. EnerDel employees include research and development and production teams to design and produce lithium ion cells and then assemble the cells into packs employing integrated battery management systems. EnerDel's prismatic cell design allows cell modules to be configured into different pack configurations. EnerDel also employs different cell chemistries to meet the customer's energy and power requirements.

EnerDel has produced lithium-ion battery packs for multiple EV applications for both production and development programs. These applications include the Think City EV, Volvo Electric C30, Japan Postal, and the Mazda 2 under the Tsukuba Green Crossover Project. Since EnerDel has already demonstrated its capability in producing EV battery packs in multiple applications, it should be possible to produce batteries for HEV applications. HEV cells differ from EV cells mainly in their design, with a smaller size and also the ability to handle larger current draws (C-rate capability). Otherwise, the development and manufacture of HEV cells is nearly identical to that of EV cells.

5.2 Requirements and scope of EnerDel HEV Bus program

5.2.1 Project Objective

The planned objective for EnerDel HEV-Bus program was to evaluate lithium-ion cell and battery pack technologies for heavy duty Hybrid Electric Vehicle (HEV) bus applications based on actual vehicle requirements in average and extreme climates.

5.2.2 Project Scope

The "High Energy Batteries for Hybrid Buses" project was intended to provide actual battery performance data targeted for use in three diverse North American markets. The planned target markets were Houston, Texas; Phoenix, Arizona; and Minneapolis/St. Paul, Minnesota. These three distinct transit markets provide a broad range of driving and climate conditions. The Minnesota market provided data for an extremely cold climate market. The Houston area provided testing data for a high temperature market. Finally, the Seattle market provided data for a mild climate, but with the added demand of high annual rates of precipitation. Seattle also has some tunnel requirements for a "Battery Only" or "Hush" mode. All of these factors were considered while developing the test systems and the conditions at which these systems were tested.

5.2.3 Project Tasks

The program was divided into three distinct phases. The phases can be summarized as:

- vehicle/battery requirements,
- design/build of the scaled test system components, and
- scaled system assembly and testing.

EnerDel Hybrid Electric Vehicle (HEV) Bus program evaluated the effectiveness of EnerDel's lithium ion battery technology for heavy duty HEV bus applications. Attractive features of lithium-ion batteries include high energy density, no memory effects, and slow loss of charge when not in use.

6. HEV-Bus system design

6.1 Drive cycle analysis

We forged a partnership agreement with a major Hybrid-Bus OEM to allow use of actual drive cycle data for the selected US markets. Drive cycle data consists of current draw as a function of time. The selected OEM Hybrid-Bus manufacturer has asked that they not be identified in public reports. This company is actively seeking a supplier partner for several product lines including buses. The drive cycle requirements were chosen from those available that most closely match the market criteria described in the initial proposal. Some specific demands such as "tunnel-mode" (also called "hush" mode or "hotel" mode) requirements were jointly reviewed to ensure that they will meet the demand of the OEM's actual product.

In addition to the drive cycles developed from the data provided for by our partner (Figure 1), a "tunnel" mode has been added at the beginning of each hour. The "tunnel" mode simulates the condition when the diesel engine is not supplying power to the battery pack, while the battery pack is powering the operation of all electronics, lighting, and so on. The "tunnel" mode represents a constant current draw from the battery pack for several minutes. In the one hour baseline results shown, a two-minute, 80A current draw is used.

Due to the limited number of drive steps programmable in the Bitrode tester, the number of data points specified in the HEV-Bus drive cycle data cannot be duplicated exactly. Therefore, we have grouped consecutive similar current drives and replaced them with an average constant level for the same duration, while preserving current transition points and current peaks. There was good agreement between the drive cycle data and the drive test being constructed, with current transition and current peaks preserved (compare Figures 1 and 2).

Pack functional testing covers the general software, electronic and mechanical functionalities. Those functionalities include communication through the controller area network (CAN) network to the personal computer (PC), reporting of battery pack electrical status (for example, current, voltage, and temperature), and proper switching of the mechanical contacts at pack terminals. All functional tests on the packs were completed satisfactorily.

Temperature conditions were chosen to represent three different climates as shown in the table below. The packs were placed in an environmental chamber at the desired temperature, allowed to equilibrate, and tested.

Climate	Representative City	Temperature, °C (°F)
Hot	Houston	28.5 (83.3)
Cold	Minneapolis	-6.5 (20.3)
Mild	Seattle	11.2 (52.2)

6.2 Gap analysis for all three chemistries

A gap analysis was performed for all three chemistries and it compares the desired attributes against the design or actual attributes. The beginning of life (BOL) requirements are based on the nickel metal hydride batteries that will be replaced. Below are the results for each proposed chemistry.

HEV-Bus Chemistry 1 (NMC – HC) Module Gap Analysis

HEV-Bus Chemistry 1 (NMC-HC)	***Requirement***	**Design A**	
	BOL	**BOL**	**Notes**
Cell Chemistry - Cathode	*Mixed Oxide (NMC)*	Mixed Oxide (NMC)	
Cell Chemistry - Anode	*Hard Carbon*	Hard Carbon	
Configuration - parallel cells	*n/a*	2	
Configuration - series cells	*n/a*	24	
Power requirements:			
Peak Pulse Discharge, kW (10 sec, 100% SOC)	*n/a*	22.2	100% SOC
Continuous Power, kW	*n/a*	4.32	70% SOC
Maximum Current, A (10 second)	*220*	320	10C rate
Maximum Current, A (continuous)	*50*	250	8C rate
Rated Capacity, Ah	*14*	32	
Rated Energy, kWh	*1.20*	2.76	
Maximum Voltage, V	*98*	100.8	100% SOC
Nominal Voltage, V	*85*	86.4	70% SOC
Minimum Voltage, V	*55*	60	

Chemistry 1, which uses NMC cathodes and HC anodes, meets the BOL requirements.

HEV-Bus Chemistry 2 (LMO – HC) Module Gap Analysis

HEV-Bus Chemistry 2 (LMO-HC)	***Requirement BOL***	**Design A BOL**	**Notes**
Cell Chemistry - Cathode	*LMO*	LMO	
Cell Chemistry - Anode	*Hard Carbon*	Hard Carbon	
Configuration - parallel cells	*n/a*	2	
Configuration - series cells	*n/a*	24	
Power requirements:			
Peak Pulse Discharge, kW (10 sec, 100% SOC)	*n/a*	22.2	100% SOC
Continuous Power, kW	*n/a*	4.32	70% SOC
Maximum Current, A (10 second)	*220*	320	20C rate
Maximum Current, A (continuous)	*50*	250	16C rate
Rated Capacity, Ah	*10*	16	
Rated Energy, kWh	*1.20*	1.38	
Maximum Voltage, V	*98*	100.8	100% SOC
Nominal Voltage, V	*85*	86.4	70% SOC
Minimum Voltage, V	*55*	60	

Chemistry 2, which uses LMO cathodes and HC anodes, also meets the BOL requirements.

HEV-Bus Chemistry 3 (LMO – LTO) Gap Module Analysis

HEV-Bus Chemistry 3 (LMO - LTO)	***Requirement BOL***	**Design A BOL**	**Notes**
Cell Chemistry - Cathode	*LMO*	LMO	
Cell Chemistry - Anode	*LTO*	LTO	
Configuration - parallel cells	*n/a*	2	
Configuration - series cells	*n/a*	24	
Power requirements:			
Peak Pulse Discharge, kW (10 sec, 100% SOC)	*n/a*	15.3	100% SOC
Continuous Power, kW	*n/a*	3	70% SOC
Maximum Current, A (10 second)	*220*	400	20C rate
Maximum Current, A (continuous)	*50*	250	12.5C rate
Rated Capacity, Ah	*14*	20	
Rated Energy, kWh	*1.20*	1.2	
Maximum Voltage, V	*98*	69.6	100% SOC
Nominal Voltage, V	*85*	60.0	70% SOC
Minimum Voltage, V	*55*	38.4	

Chemistry 3, which uses LMO cathodes and LTO anodes, meets the rated energy and current requirements, but the module voltage is lower than desired. This is due to the higher potential of the LTO anodes compared to HC anodes, which reduces the cell voltage compared to cells employing hard carbon anodes. However, since the rated energy and current requirements are met, the module meets those criteria and should be able to perform as desired.

6.3 System design and features

The modules consist of 48 cells each, in a 2 parallel, 24 series configuration.

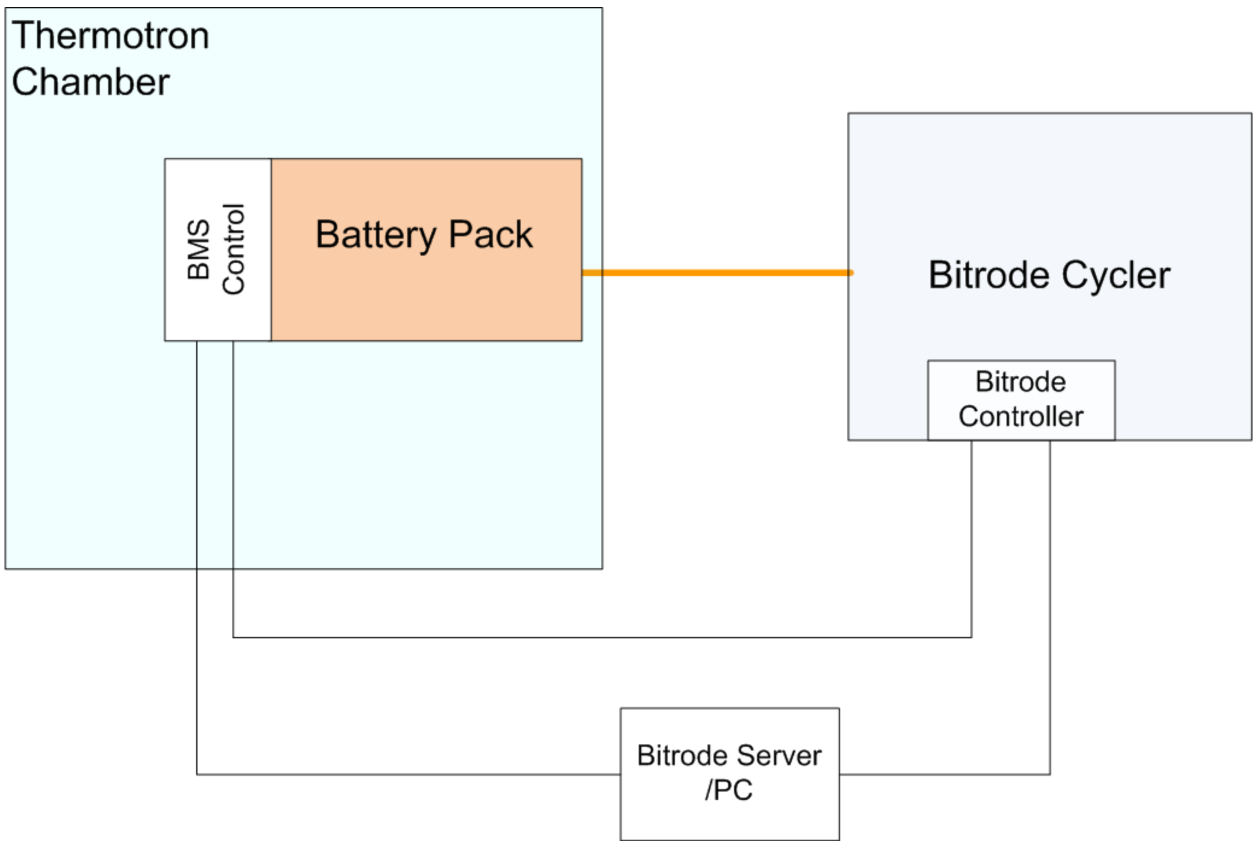
For each cell chemistry, battery pack systems integrated with an EnerDel battery management system (BMS) were successfully constructed with the following features:

- real time current monitoring
- cell and pack voltage monitoring
- cell and pack temperature monitoring
- pack state of charge (SOC) reporting
- cell balancing
- over voltage protection

These features are all necessary functions for real-world HEV-Bus applications.

The BMS uses the charge – discharge profile of the cell to determine the state of charge (SOC) in the case of the Chemistry 1 (NMC – HC) and Chemistry 2 (LMO – HC) cells. For the case of the Chemistry 3 (LMO – LTO) cells, the charge and discharge profile is too flat to allow the SOC to be determined accurately using this method, so the BMS had to be modified to perform Coulomb counting. Using Coulomb counting, the SOC is calculated based on the amount of electricity that is supplied to charge the cell or that is used to perform work that discharges the cell.

The test setup is as follows:



6.4 Test procedure: baseline/full drive cycle

The drive cycle evaluation was performed using Bitrode 450-FTF Pack Cyclers, which provide up to 450A charge and discharge current; ambient temperature was controlled by Thermotron SE2000 chambers. The pack cyclers and temperature chambers adequately meet drive cycle profile requirements, and dependably and efficiently perform battery pack cycling under controlled ambient temperature.

Modules were run through several pretest current-time profiles to ascertain that satisfactory and safe full drive profile cycling could be performed.

- 40 A charge – discharge cycling
- Simple one hour charge – discharge cycles with ramped current excursions to 200A
- Four hour baseline test, consisting of the first four hours of the drive profile

- Eight hour baseline test, consisting of the first eight hours of the drive profile
- Sixteen hour baseline test, consisting of one sixteen hour drive profile

After these tests were satisfactorily completed, the full drive profile cycling was run for 3 to 4 weeks. The drive profile was run for 16 hours, followed by an 8 hour rest. Module voltage, current, and temperature were recorded.

7. Testing with Chemistry 1 (NMC-HC)

7.1 Battery chemistry/cell characters and parameter limits

4-hour baseline and 16-hour drive cycle tests for Chemistry 1 battery modules were successfully completed. 27 rounds of regular test cycle consisting of 16-hour-drive profile and an 8-hour rest for Chemistry 1 under three different climate settings were successfully completed.

7.2 Test results

One-hour baseline runs were completed for each of the three representative climates. The data is shown in Figures 3 to 5.

Photos of the battery packs are included in Figures 6 to 9.

Regular test cycles consisting of a 16 hour drive profile and an 8 hour rest were successfully conducted for 20 days as seen in Figures 10, 11, and 12. Due to thermal chamber malfunction, the Minneapolis pack missed 10 days of low temperature cycling. Battery pack performances have met the requirements of the drive cycle profile satisfactorily under three difference climate conditions, namely cold (Minneapolis), mild (Seattle), and hot (Houston).

The “tunnel” mode, being added to the original drive cycle, results a net energy draw from the battery. As it was described in previous report, the “tunnel” mode simulates the condition that the battery pack powers the lighting, electronics and other accessories in addition to powering the motor, without the engine supplying any power. It amounts to a 5 minute, 20A current draw every 2 hours in addition to the original drive cycle profile. To compensate for this net energy draw, a charge step is added at the beginning of the drive cycle. The original drive cycle and the “tunnel” mode profile are shown in Figure 13.

Given the net energy draw presented in the drive cycle, pack voltages decrease as battery packs go through the 16-hour drive cycle. Through the same drive cycle, pack temperatures rise in high activity intervals, whereas temperatures drop during less active periods through the drive cycle. Detailed battery performance charts are shown in Figures 14 through 19 in successive time intervals. Note: the red circled portions in figures are magnified in following charts.

A random fifteen-minute segment of the current drive cycle was chosen for comparison with the same segment in testing data for all three climates. The segment stars at the 3800th second of the drive cycle ends at the 4800th second as seen in Figures 20 through 23. Those charts show close a match of the required drive cycle and the performance of the battery packs.

7.3 Discussion

The Chemistry 1 NMC – HC modules successfully completed 20 days of drive profile cycling in all three climates. The module temperatures reflected the ambient temperature, with the hot climate temperatures being the highest, the mild climate temperatures in the middle, and the low climate temperatures being the lowest. The module temperatures were all in a satisfactory range.

8. Testing with Chemistry 2 (LMO - HC)

8.1 Battery chemistry/cell characters and parameter limits

Three battery packs of chemistry 2 were subjected to HEV-Bus drive cycle tests (16-hour drive cycle and 8-hour rest) in 3 climate conditions for 20 cycles. Baseline tests (4-hour and 8-hour) were completed before HEV-Bus drive cycle tests. The BMS had to be modified to accommodate the Chemistry 2 cells due to the different voltage versus SOC profile compared to Chemistry 1.

8.2 Test results

Initial 4-hour and 8-hour baseline tests showed the capacities of Chemistry 2 packs were below the design target. It was discovered that the upper limit of cell charge voltage was only set for Chemistry 1, and should be raised to accommodate Chemistry 2 cells. By raising upper limit of charge voltage from 4.1V to 4.2V, pack capacity is brought within ±5% of design capacity target for Chemistry 2.

By the nature of the material, the packs made with Chemistry 2 are 50% lower in capacity compared to Chemistry 1 in theory. The lower capacity of Chemistry 2 requires a mid-cycle recharge to be added in the original drive cycle in order to complete the 16-hour drive cycle.

During the first week of the regular drive cycle test, all 3 packs were running the 16-hour drive cycle with an additional mid-cycle recharge under different climate conditions (hot, cold, and mild). Test results showed that the packs running under Houston (hot) and Seattle (mild) climates contained enough energy to complete the entire drive cycle without the additional recharge. However, the pack running under Minneapolis (cold) climate still needed mid-cycle recharge to complete the entire drive cycle. In subsequent tests, packs under Houston and Seattle climates ran full drive cycle without the mid-cycle recharge, the pack under Minneapolis climate ran with the added mid-cycle recharge.

Besides the results shown for Chemistry 2 battery packs performing under 3 different climates (see Figures 24 through 26), comparisons of voltage and temperature performances among packs under all 3 climates are presented (see Figure 27 to Figure 33); Chemistry 1 results are shown as a reference. Voltage comparisons show that for both Chemistry 1 and Chemistry 2, pack voltages drop faster under cold climate than in hot climate given the same drive cycle. Temperature comparisons show that for both Chemistry 1 and Chemistry 2, battery pack temperature rises are non-linear, with pack temperatures rising almost twice as much under cold climate conditions than under hot climate conditions. Temperature performance results show that Chemistry 2 observed lower temperature rise than that of Chemistry 1. This indicates under same drive condition, Chemistry 2 packs would require less cooling, which is an important advantage in battery system design.

8.3 Discussion

With the successful performance of 2 weeks of actual drive cycle, EnerDel battery packs built with Chemistry 2 are suitable candidates for hybrid bus applications with added advantage of lower temperature rise compared to Chemistry 1.

9. Testing with Chemistry 3 (LMO-LTO)

9.1 Battery chemistry/cell characters and parameter limits

Six (6) 24 cell modules were assembled with Chemistry 3 (LMO-LTO) cells. Control and monitoring algorithm updating was done to reliably control the high power systems. This was necessary due to the Chemistry 3 voltage profile being very flat compared to the previous two chemistries as can be seen in the capacity discharge curves shown in Figures 34, 35, and 36. The relatively flat discharge profile for the LMO-LTO system is a result of the flat charge and discharge profiles of each individual material. Since LMO and LTO materials individually exhibit flat charge and discharge profiles, their combination in a full cell also has a flat profile. This lack of slope makes it more difficult to dynamically determine the SOC accurately. Proper control and monitoring of Chemistry 3 systems required a more sophisticated approach, consisting of a modified algorithm that included Coulomb counting. Coulomb counting is a more complex method for SOC monitoring than simply monitoring the voltage. In summary, the rewriting of control and SOC algorithms for Chemistry 3 was necessary due to the relatively flat discharge curve.

9.2 Test results

The BMS software was modified to accommodate the drastically different voltage versus capacity profile of Chemistry 3. The improved algorithm can adequately address the slower rate of voltage change during the charge/discharge process compared to the two previous chemistries. Functional tests were successful to demonstrate smooth integration of cell operation and pack system functions. Baseline tests encountered issues of high pack internal resistance, as a result of high internal resistance of small number of individual cells. As the battery pack underwent increasing steps of charge/discharge currents, several cells were observed to have voltages that quickly breached the upper and lower limits, while showing sharp temperature rises. All symptoms pointed to a small number of cells with high internal resistance in the pack. Due to the limited number of cells fabricated for the pack test, not enough cells were available to replace high resistance cells. Due to safety reasons, drive cycle tests were not attempted given the results of baseline tests.

The number of cells that displayed high resistance was less than 5% of the total cells produced. Due to small quantity of Chemistry 3 cells produced for the HEV-Bus program, all of those cells were manually processed and fabricated. (In contrast, EnerDel mass production cells are manufactured on an automated line.) The tolerance of process control was compromised as human variations were introduced in the process. Several sources that had significant human input in cell fabrication were identified as principle contributors to the large internal resistance.

The larger than expected internal resistance was thought to be caused by the following factors:

- Poor adhesion of the negative material to the current collector foil; breaking and peeling off of the negative material from the foil were found after disassembling the tested cells
- Electrolyte quantity being applied to cells were under estimated due to expansion of dry cell after pressing (electrode “springback” was larger than expected)
- A significantly lower voltage was applied during cell formation process, and as a result the de-gassing process was not complete
- The SEI layer was not well formed due to lack of gassing during the formation process, so gassing during pack operation (that should have occurred during formation) severely increased internal resistance
- The selection of electrolyte was optimized to minimize gassing, however, the result was an electrolyte with lower conductivity. This decreased the rate capability of the cells.

In summary, all five factors could have contributed to the high resistance of a small number of cells. The small quantity production and special material handling required manual production of the Chemistry 3 cells. Thus significant variation in cell characteristics resulted, with a number of cells having high internal resistance. Those issues were recognized and improvements have been since implemented. Newly modified material combination and fabrication process have resulted in lower cell internal resistance, higher cycle retention, lower self-discharge cells, and high cell capacities.

9.3 Discussion

Some of the Chemistry 3 (LMO – LTO) cells exhibited high internal resistance and did not pass baseline testing, so drive profile cycling could not be performed. Root cause analysis revealed and five possible factors as possible causes for the high internal resistance of some of the cells. Changes have since been made to the design of Chemistry 3 type cells, so that the high internal resistance issue has since been mitigated.

10. Conclusions

10.1 Comparison of test results for three chemistries

Drive cycle test data was collected for each of the three cell chemistries using real world drive profiles under hot, cold, and mild climate conditions representing cities like Houston, Seattle, and Minneapolis, respectively. We successfully tested the battery packs using real-world HEV-Bus drive profiles obtained from a bus vendor under these various climate conditions. The Chemistry 1 NMC-HC and Chemistry 2 LMO-HC based packs successfully completed the drive cycles, while the Chemistry 3 LMO-LTO based pack did not finish the preliminary testing for the drive cycles. It was concluded that the Chemistry 2 LMO-HC chemistry is optimal for the hot or mild climates, while the Chemistry 1NMC-HC chemistry is optimal for the cold climate.

10.2 Discussion

The Chemistry 1 NMC – HC battery was determined to be optimal for the cold climate because it successfully completed the 16 hour drive cycle with no mid-cycle recharging required. The Chemistry 2 LMO – HC battery was determined to be optimal for the hot and mild climates because of the lower operating temperature of the pack. The Chemistry 3 LMO – LTO batteries were not successful due to the manual build, with a resulting high internal resistance for some of the cells. Measures based on the lessons learned from this project have since been taken to produce Chemistry 3 LMO – LTO batteries that are successful in large vehicle applications.

It has been demonstrated that EnerDel lithium ion batteries cell and pack system technologies successfully completed real world HEV-Bus drive cycles recorded in three markets covering cold, hot, and mild climates.

11. Glossary of terms

Ah	ampere-hour (cell capacity unit)
BMS	battery management system
BOL	beginning of life
CAN	controller area network
C rate	current rate
EV	electric vehicle
HC	hard carbon, an anode material
HEV	hybrid electric vehicle
ICE	internal combustion engine
LMO	lithium manganese oxide, a cathode material
LTO	lithium titanate, an anode material
NMC	lithium nickel manganese cobalt oxide, a cathode material
NiMH	nickel metal hydride
PC	personal computer
SOC	state of charge
V	volt
W	watt (cell power unit, 1 watt = (1 A)*(1 V))
Wh	watt-hour (cell energy unit, 1 Wh = (1Ah)*(1V))

12. Figures

Figure 1. Original drive cycle data from Vendor (sample)

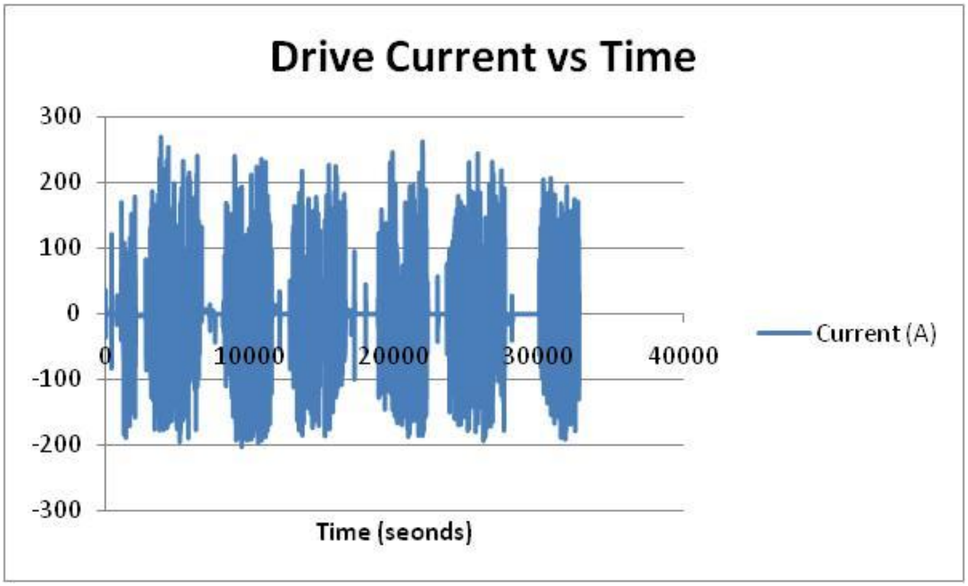


Figure 2. Test drive cycle data employed (sample)

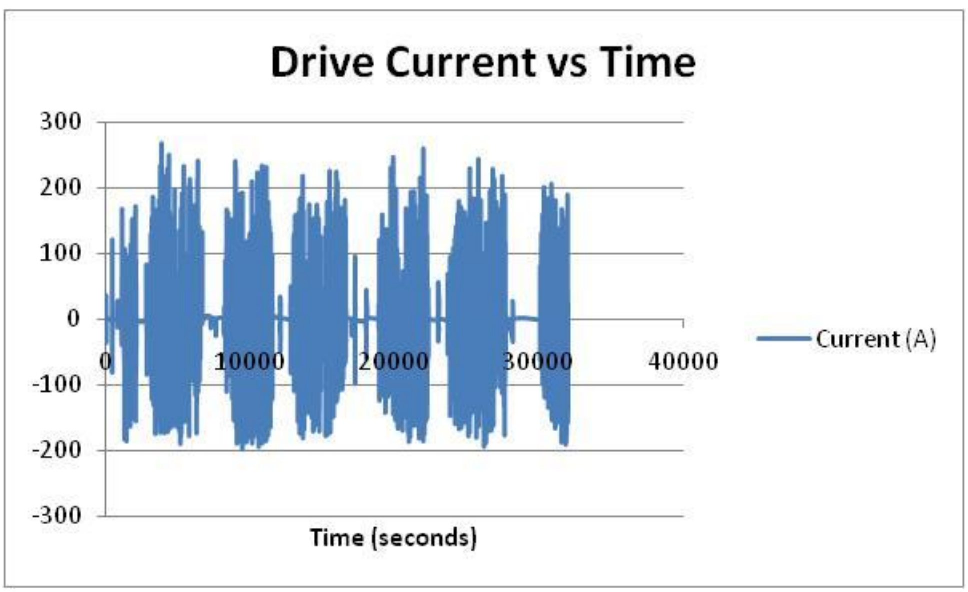


Figure 3. Chemistry 1 drive cycle for one-hour run in Minneapolis (-6.5°C)

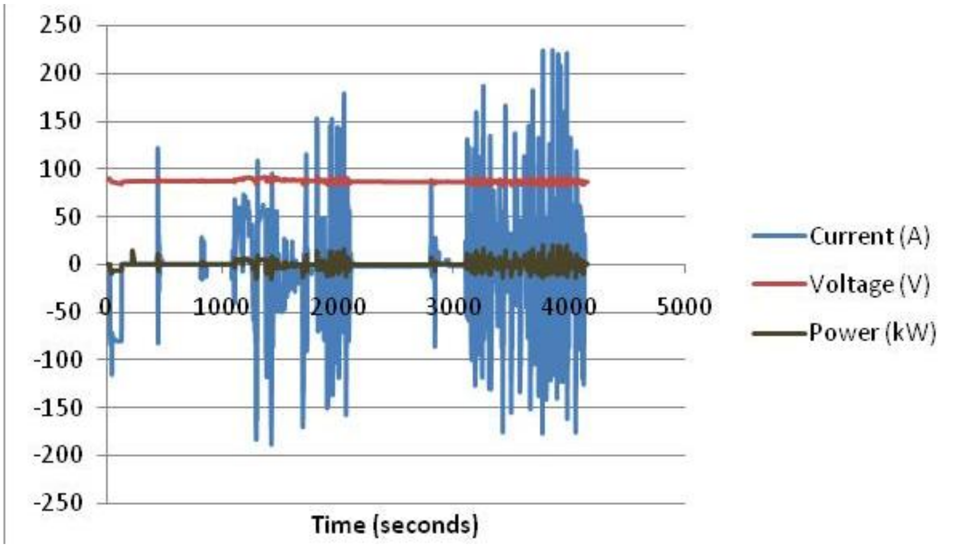


Figure 4. Chemistry 1 drive cycle for one-hour run in Seattle (11.2°C)

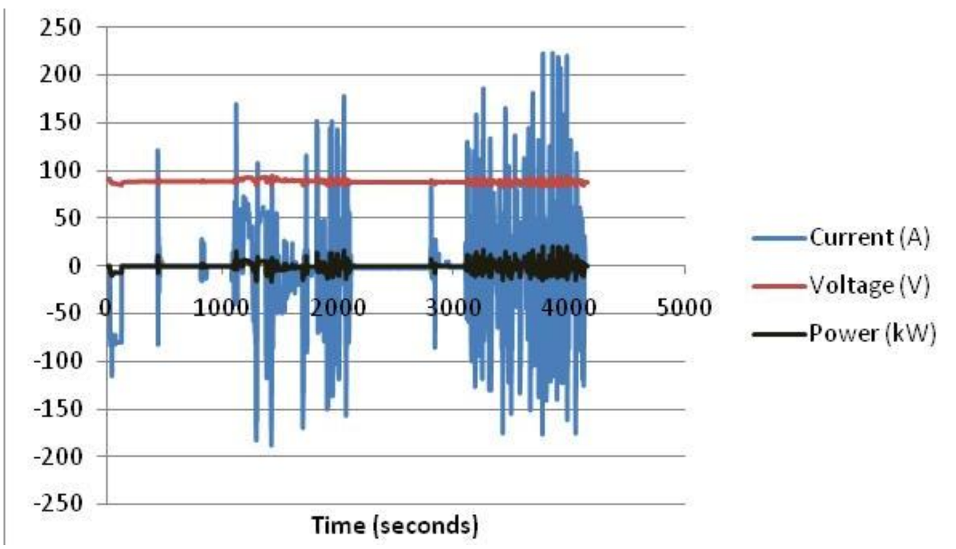


Figure 5. Chemistry 1 drive cycle for one-hour run in Houston (28.5°C)

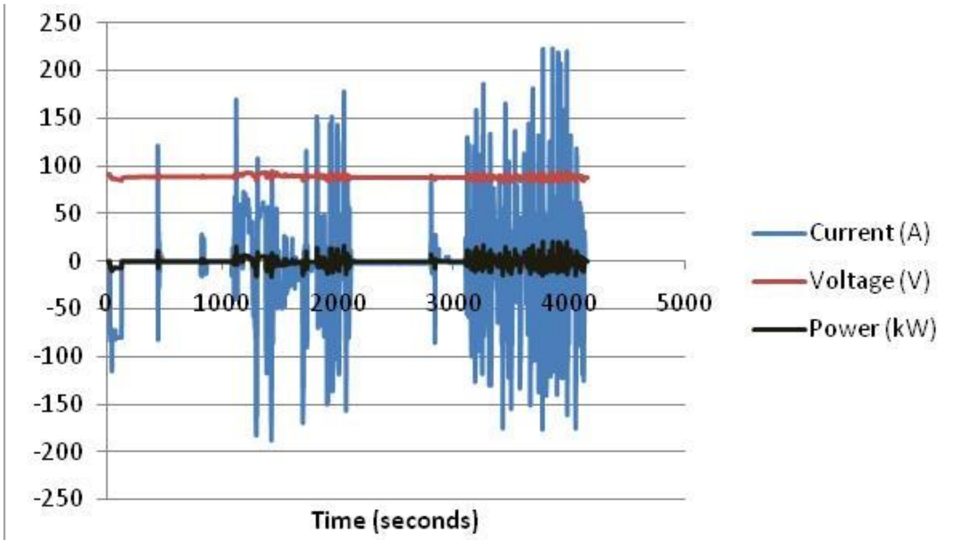


Figure 6. Assembled pack (front view)

Figure 7. Assembled pack (side view)

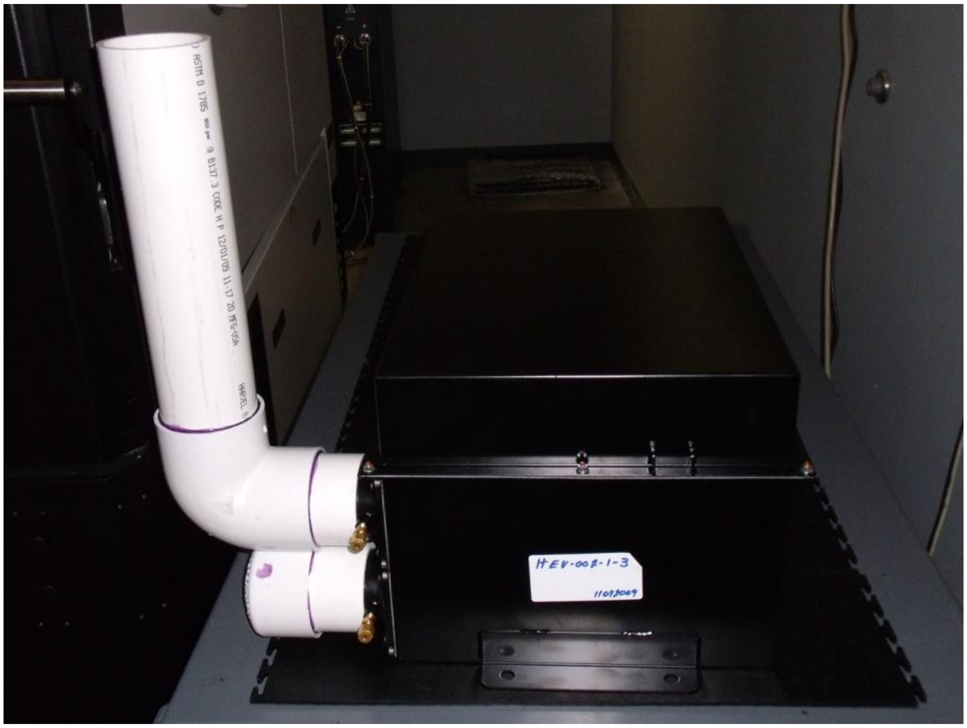


Figure 8. Assembled pack in environmental chamber (inside view).

Figure 9. Assembled pack in environmental chamber (outside view).

Figure 10. Chemistry 1 battery performance under Houston climate (for detail see Figure 14)

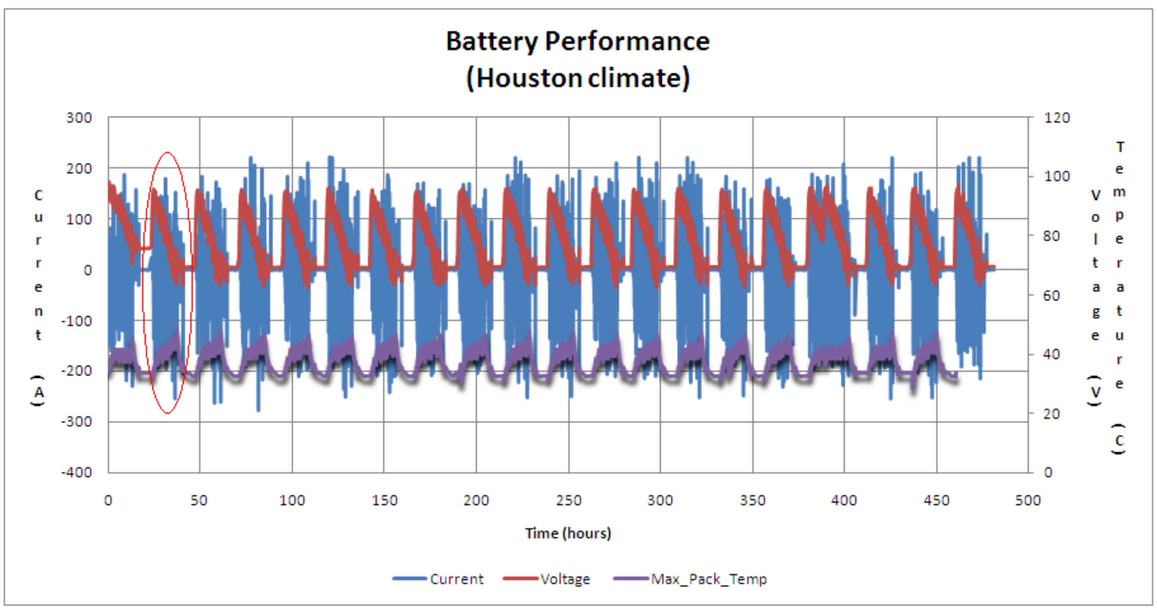


Figure 11. Chemistry 1 battery performance under Seattle climate (for detail see Figure 16)

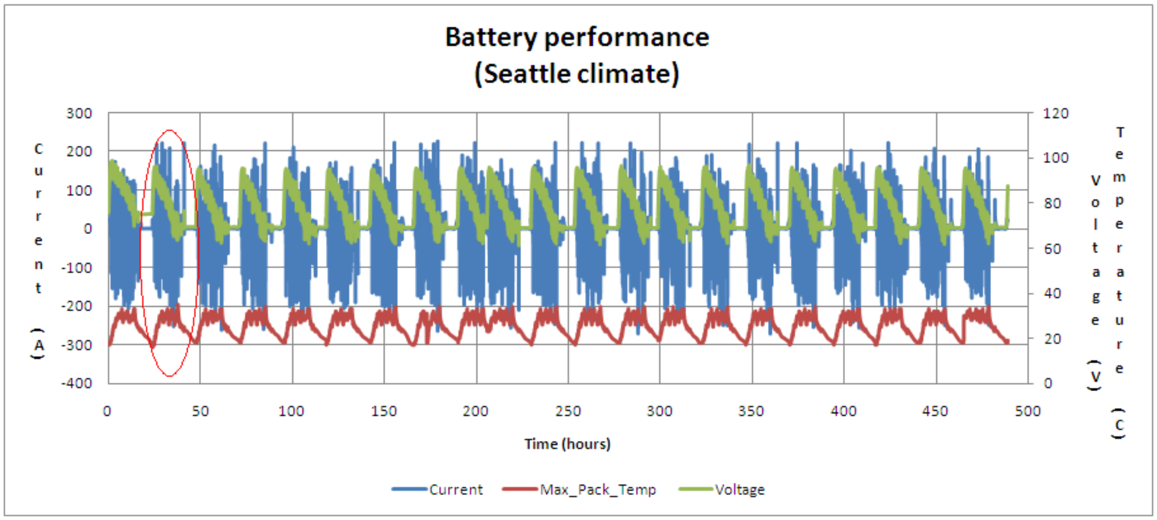


Figure 12. Chemistry 1 battery performance under Minneapolis climate (for detail see Figure 18)

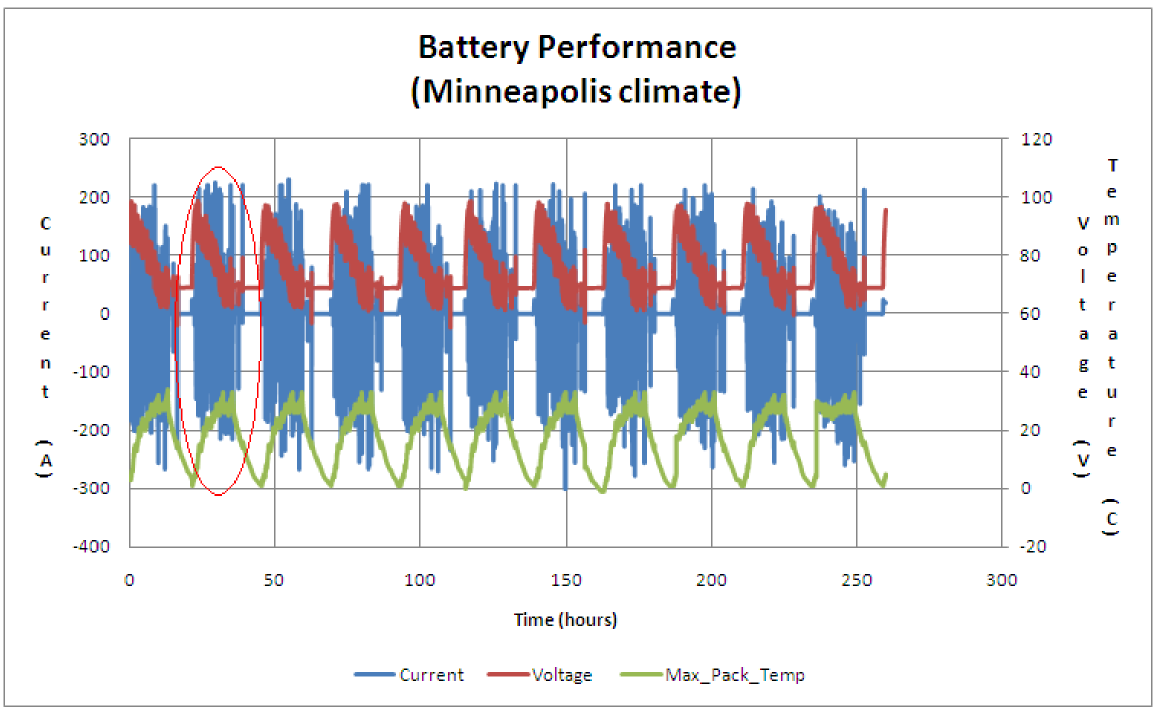


Figure 13. Original drive cycle and “tunnel” mode profiles

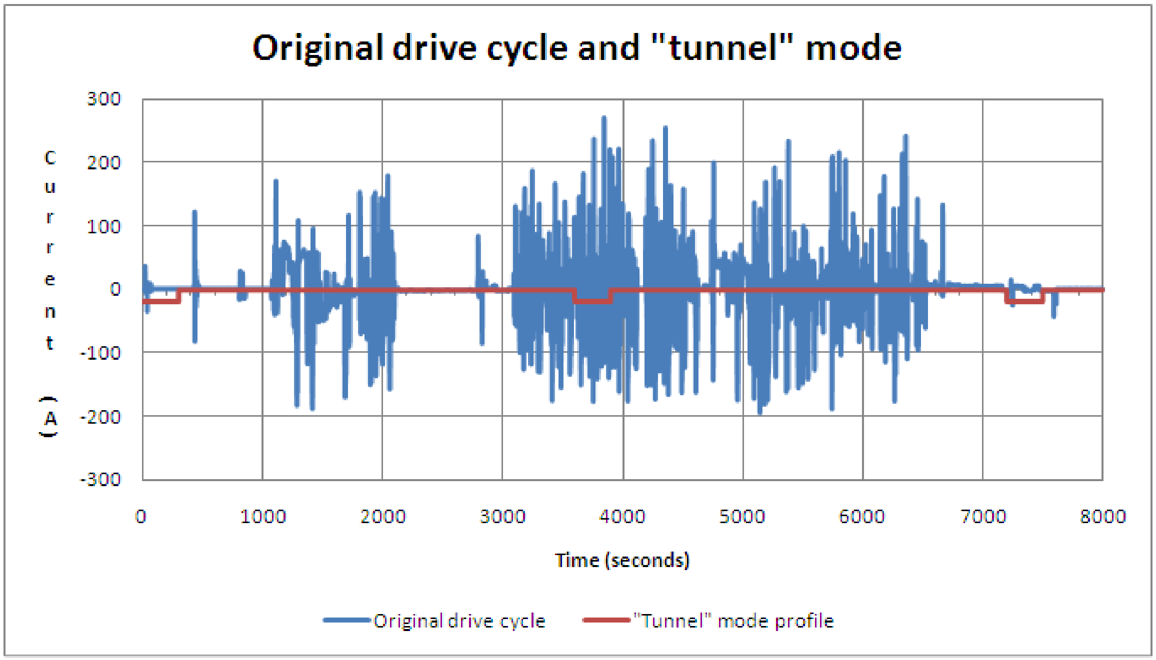


Figure 14. Chemistry 1 battery performance, 20 hour segment under Houston climate (for detail, see Figure 15)

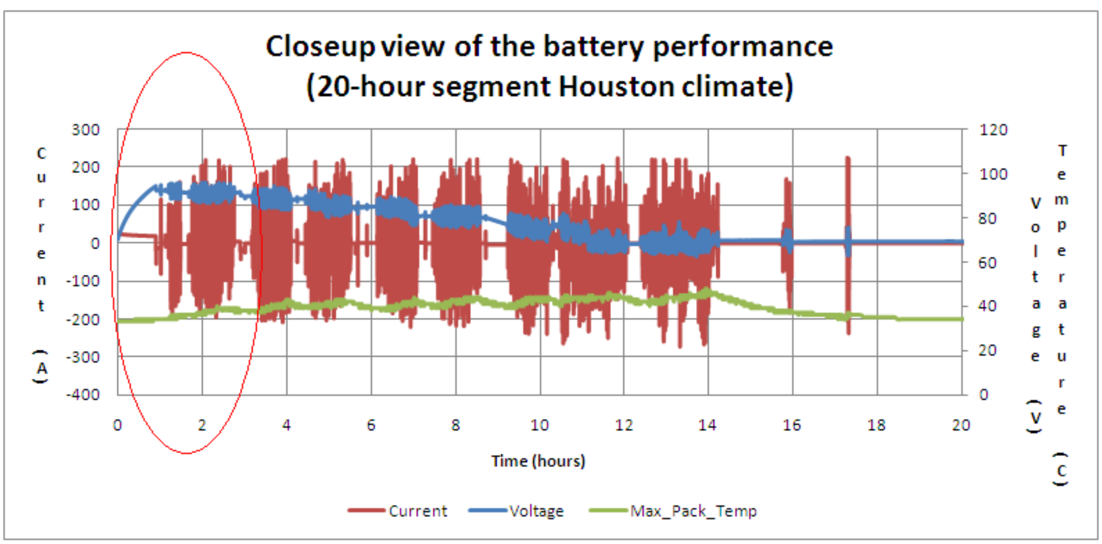


Figure 15. Chemistry 1 battery performance, 3 hour segment under Houston climate

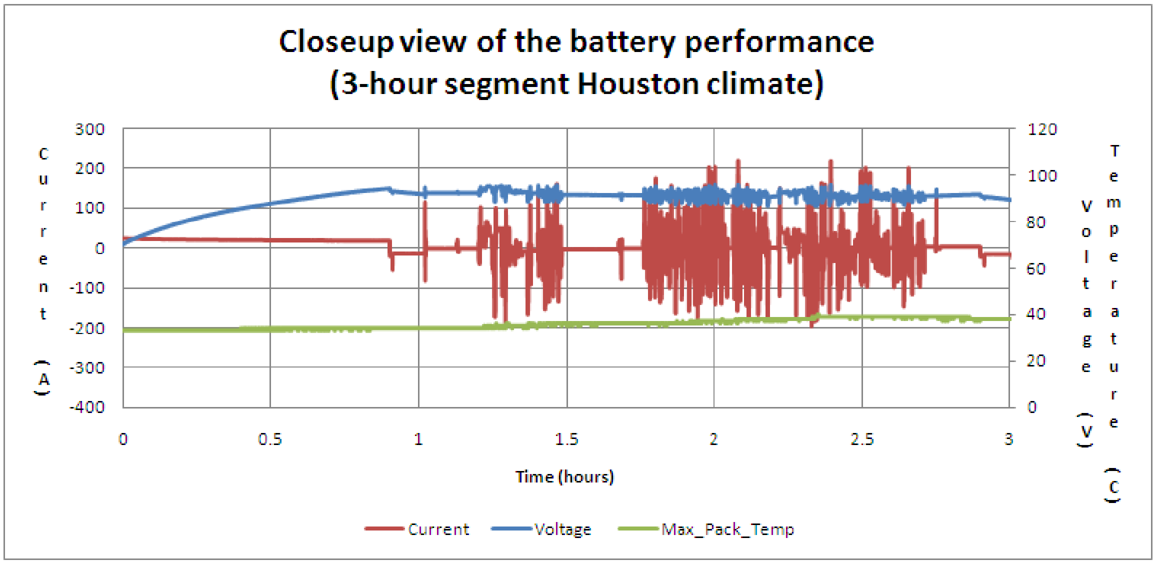


Figure 16. Chemistry 1 battery performance, 20 hour segment under Seattle climate (for detail, see Figure 17)

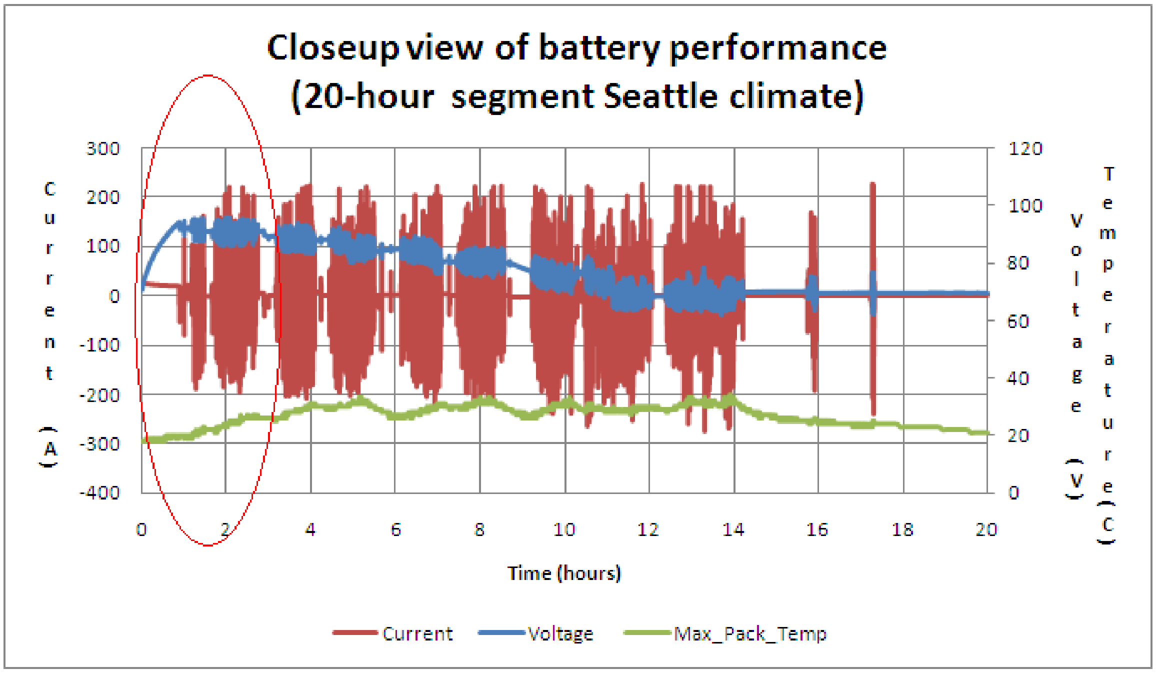


Figure 17. Chemistry 1 battery performance, 3 hour segment under Seattle climate

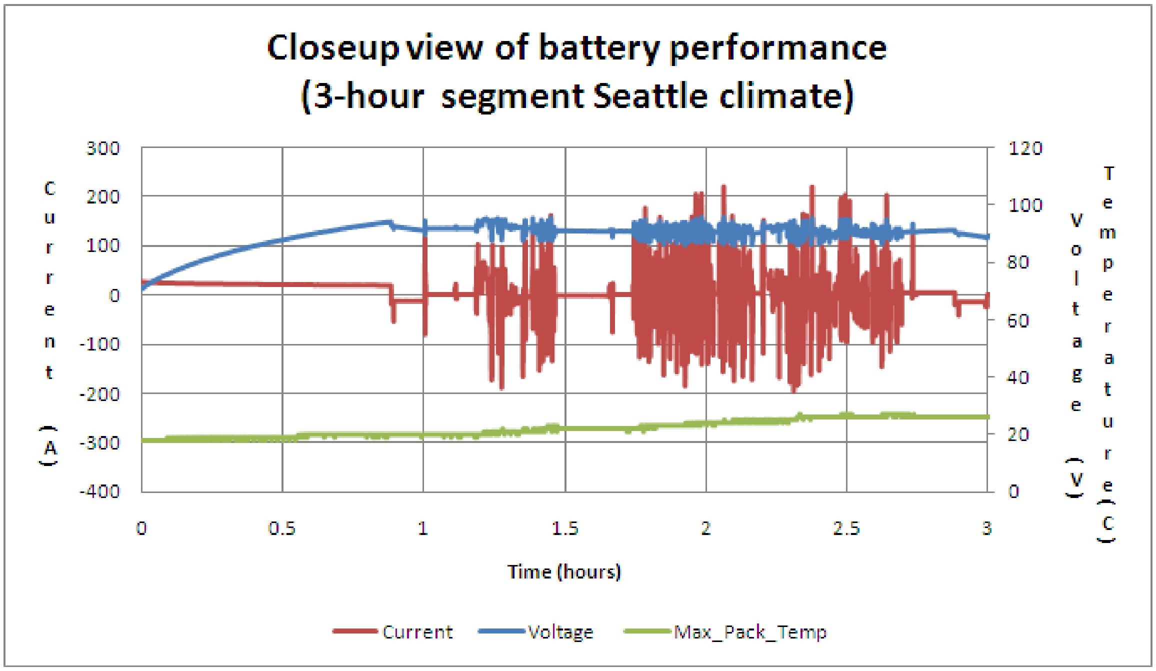


Figure 18. Chemistry 1 battery performance, 20 hour segment under Minneapolis climate (for detail, see Figure 19)

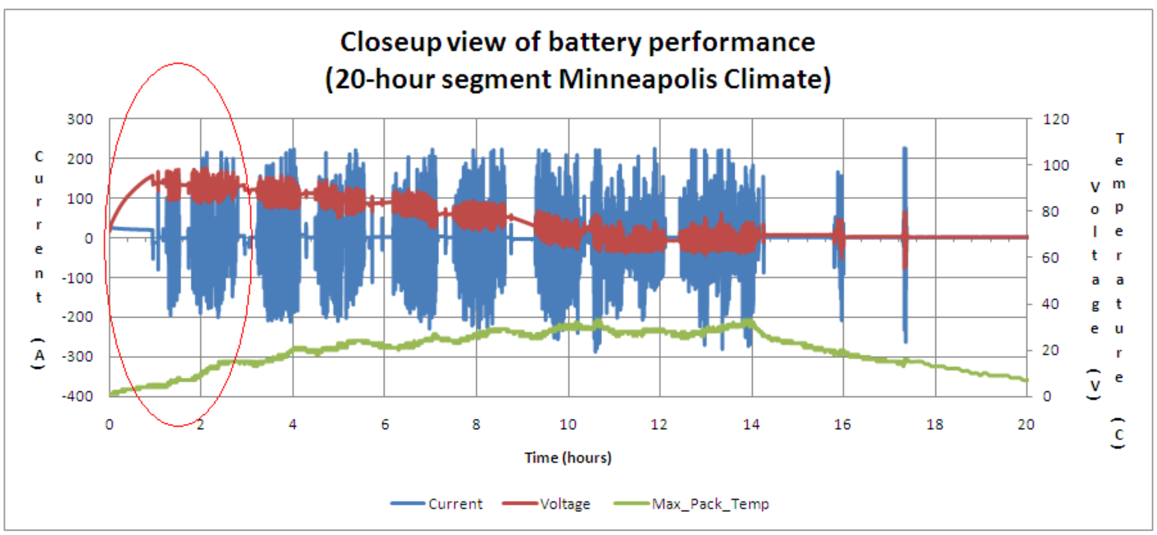


Figure 19. Chemistry 1 battery performance, 3 hour segment under Minneapolis climate

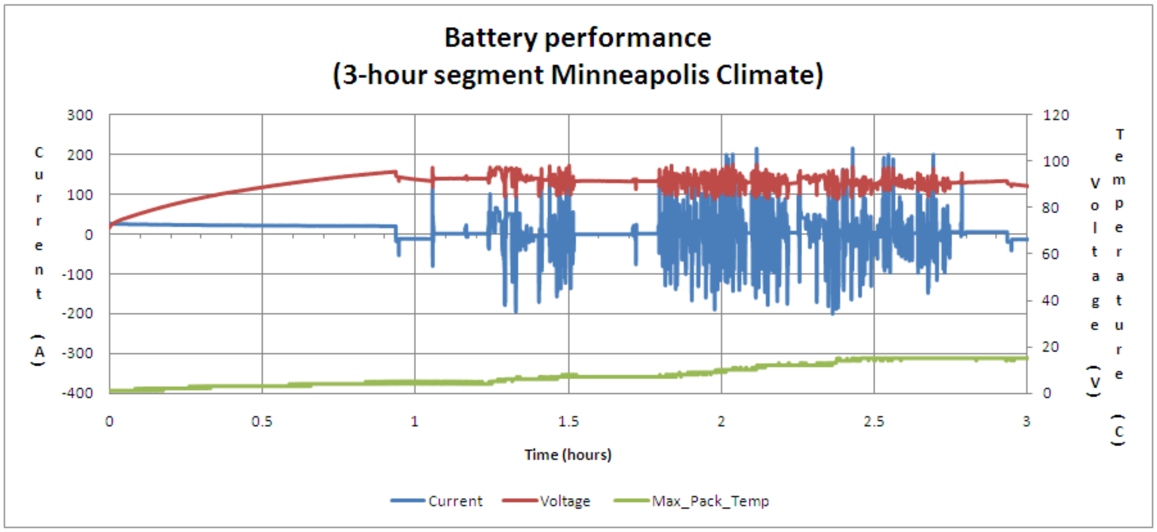


Figure 20. 15 minute segment of the desired current versus time drive cycle

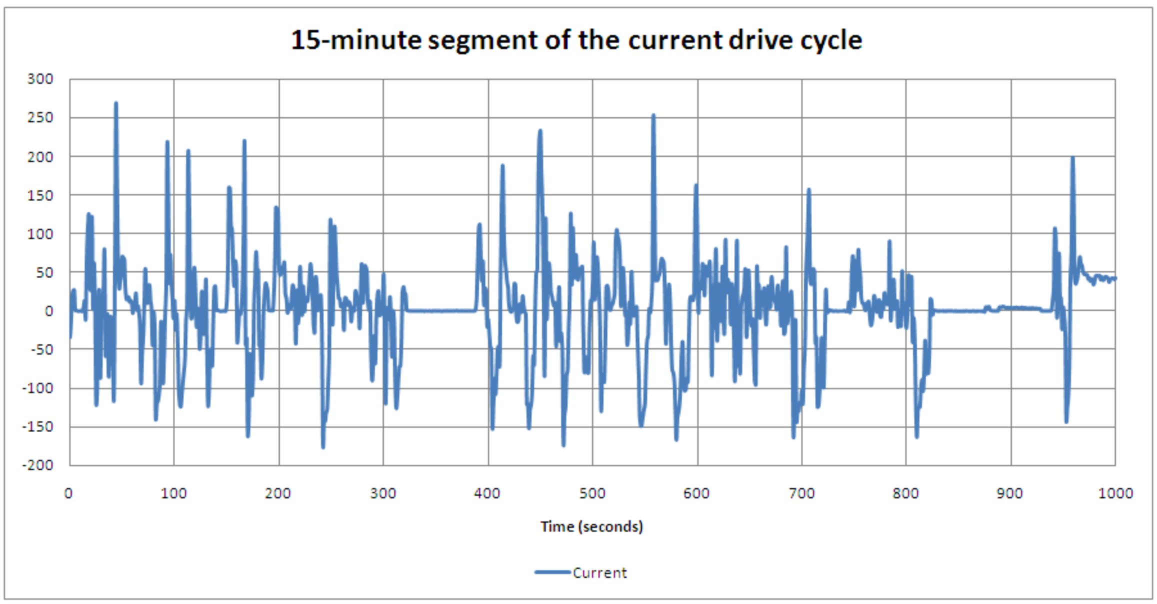


Figure 21. 15 minute segment of the current versus time drive cycle under Houston climate

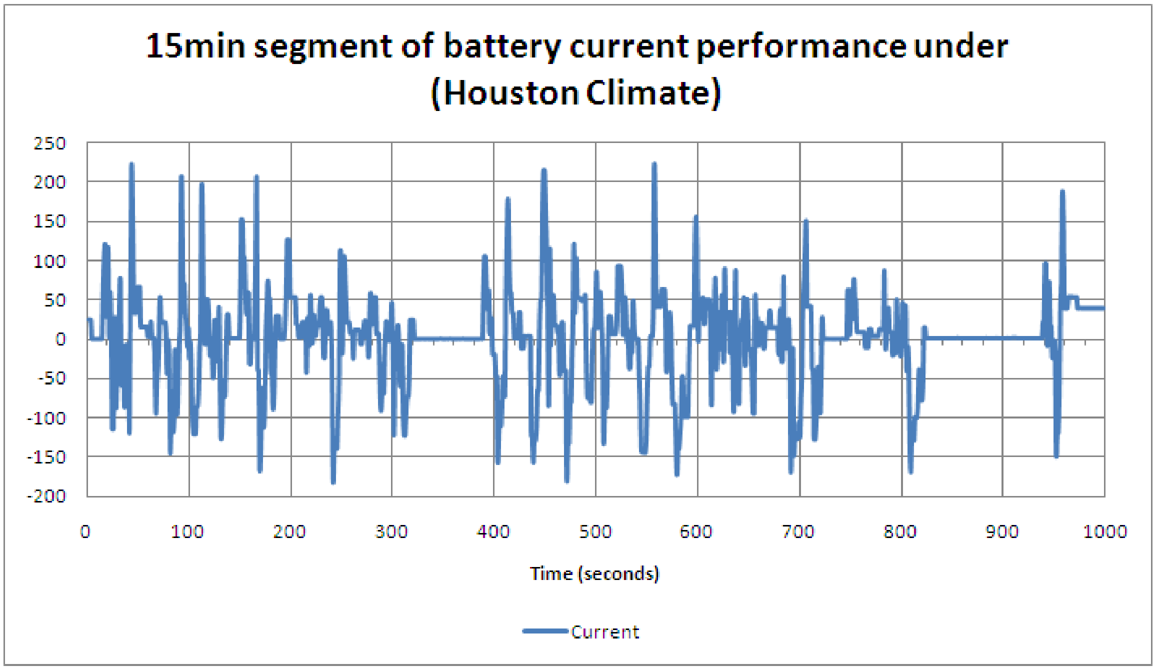


Figure 22. 15 minute segment of the current versus time drive cycle under Seattle climate

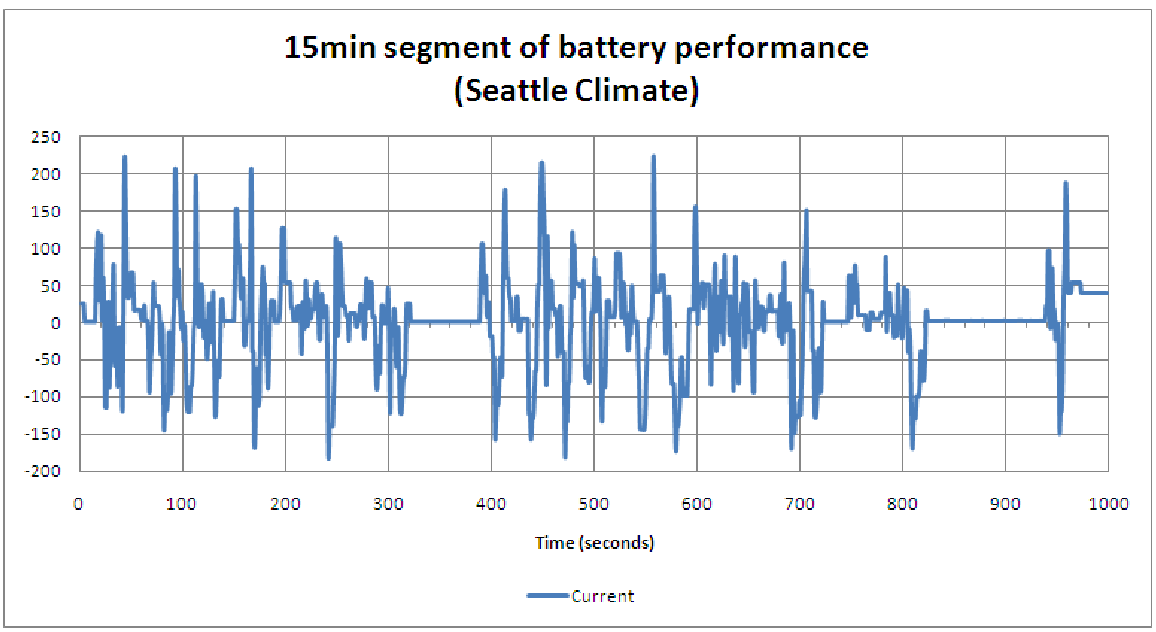


Figure 23. 15 minute segment of the current versus time drive cycle under Minneapolis climate

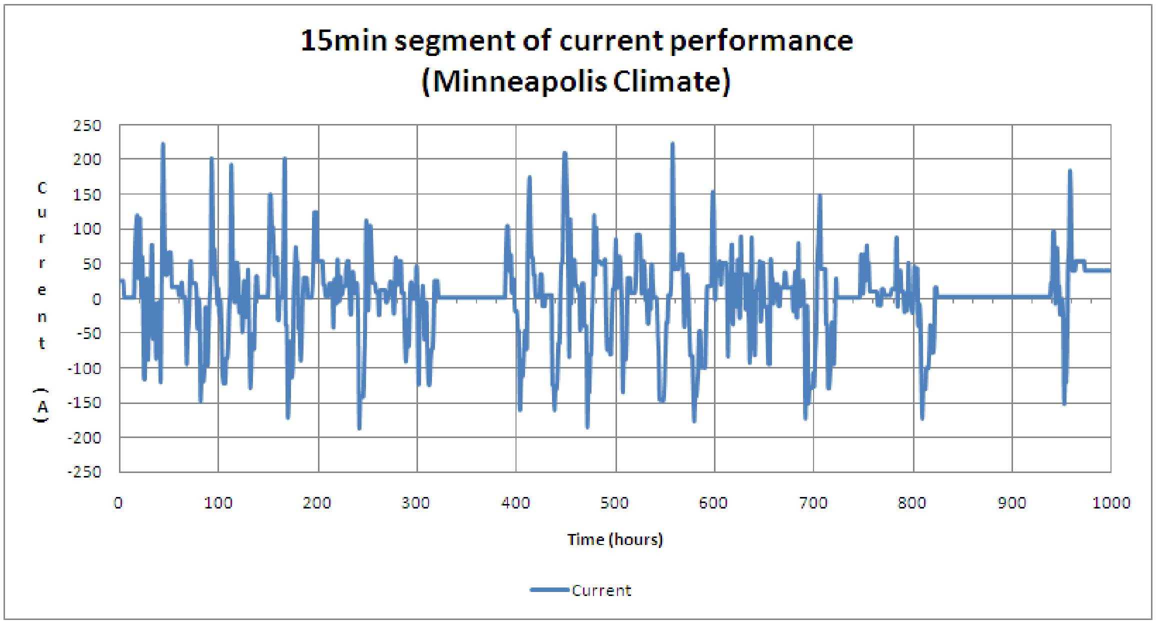


Figure 24. Chemistry 2 battery performance under Houston climate

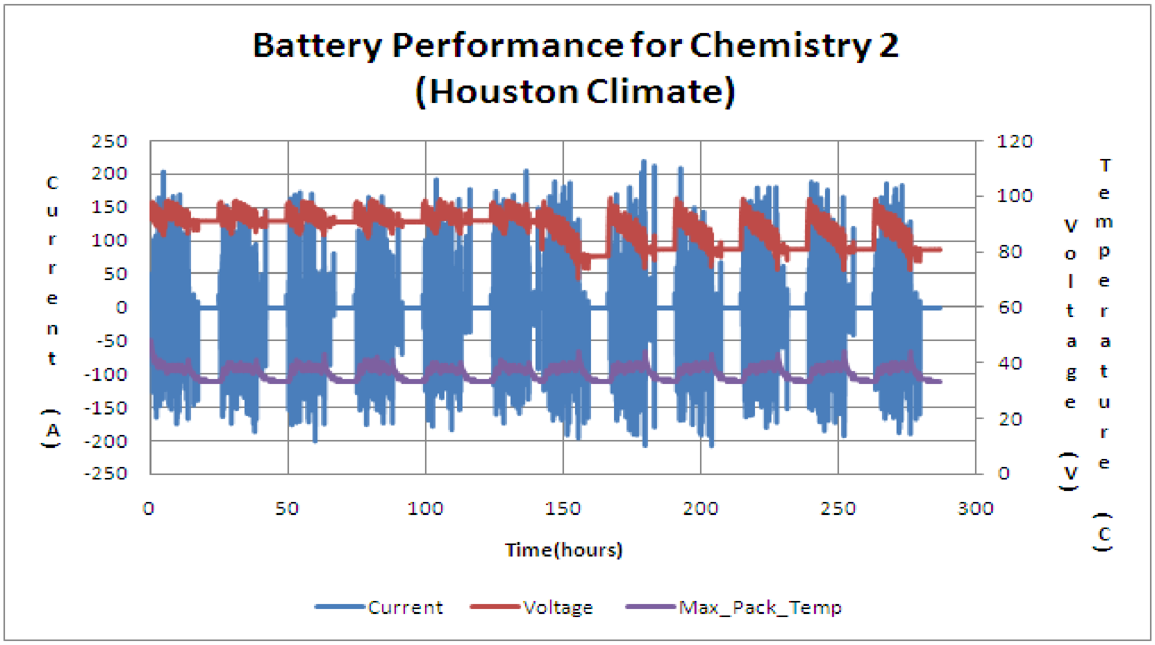


Figure 25. Chemistry 2 battery performance under Seattle climate

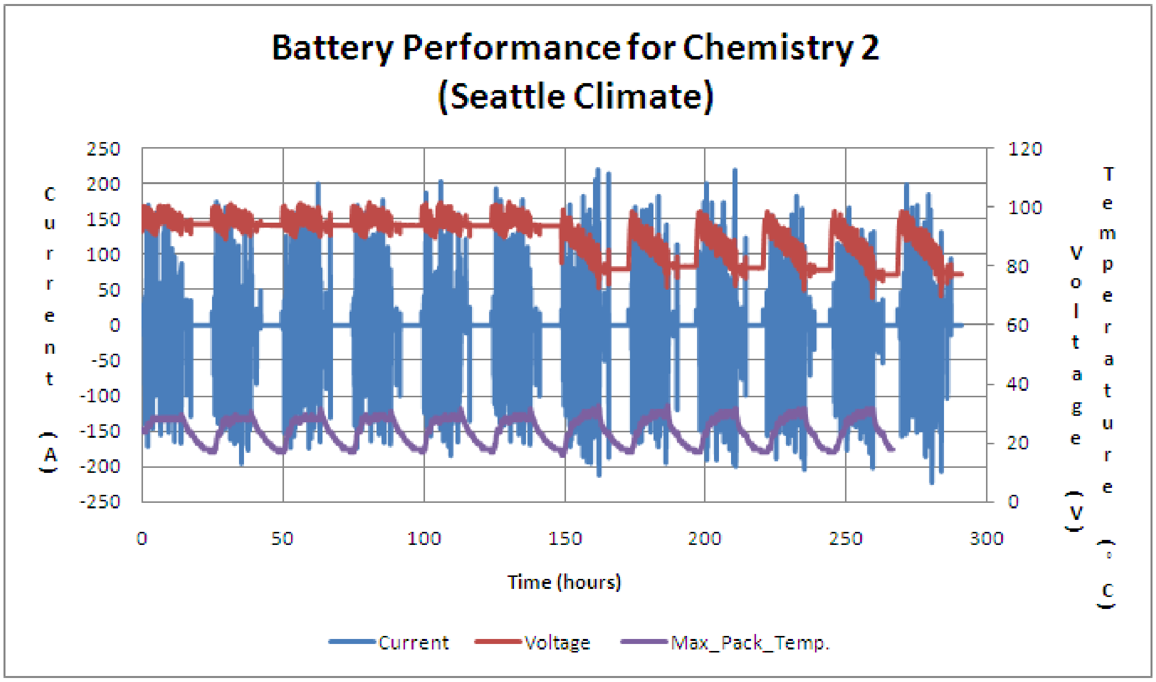


Figure 26. Chemistry 2 battery performance under Minneapolis climate

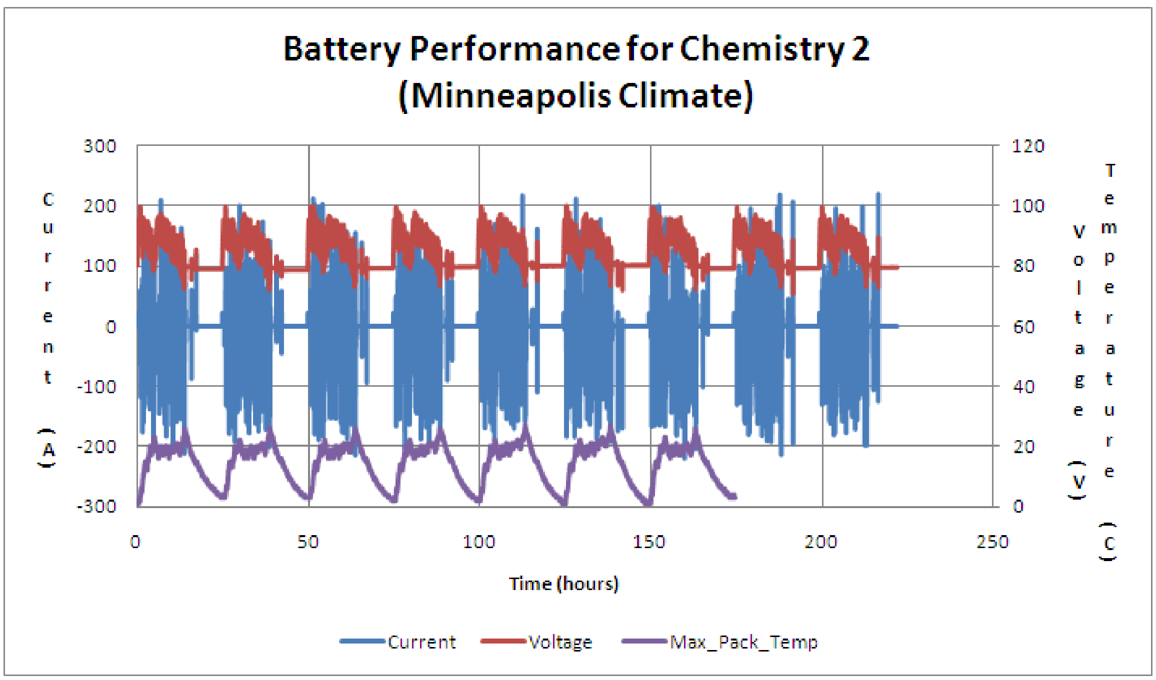


Figure 27. Chemistry 2 packs, voltage comparison as a function of climate

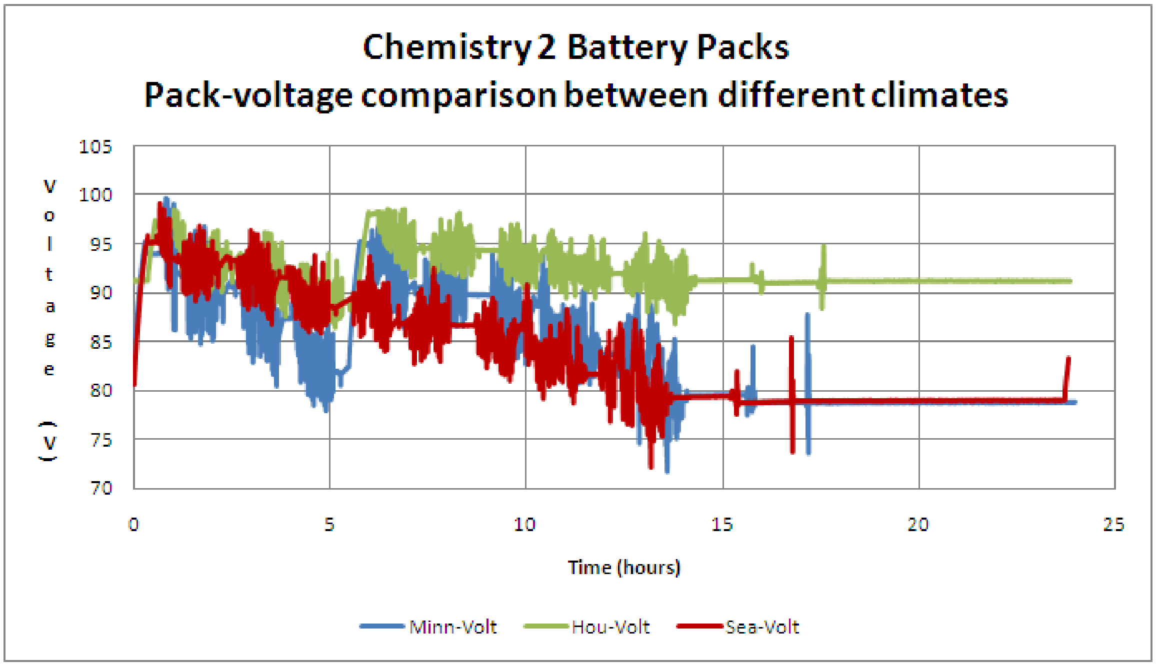


Figure 28. Chemistry 1 packs, voltage comparison as a function of climate

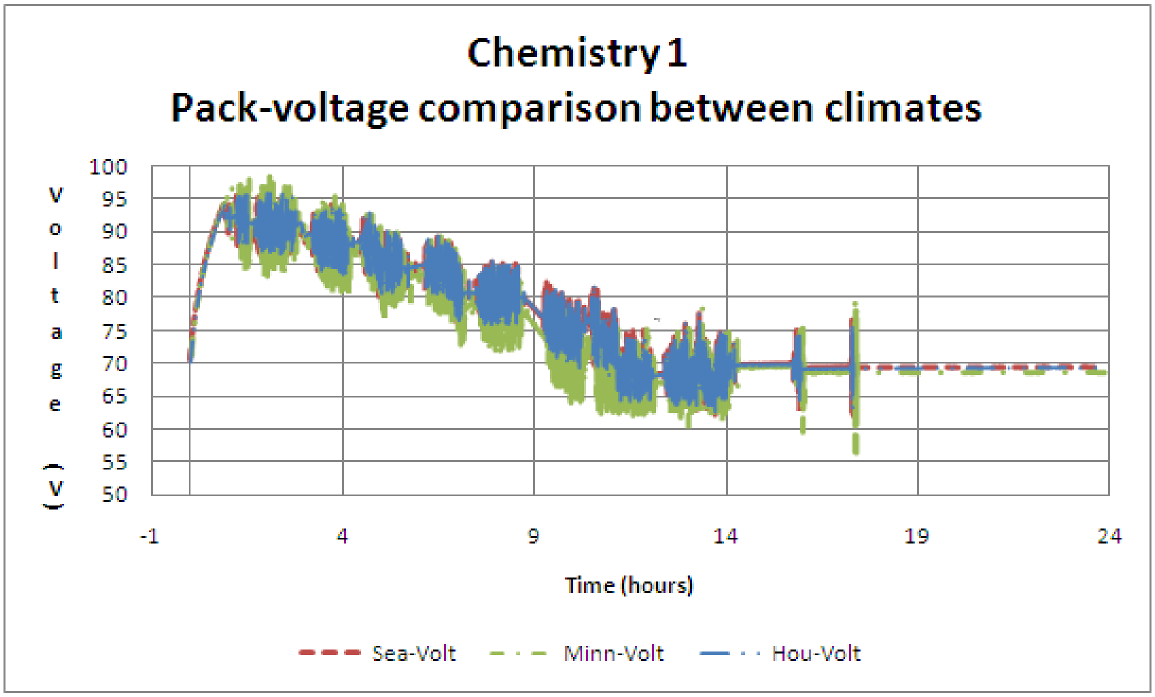


Figure 29. Chemistry 2 battery packs, pack temperature as a function of climate

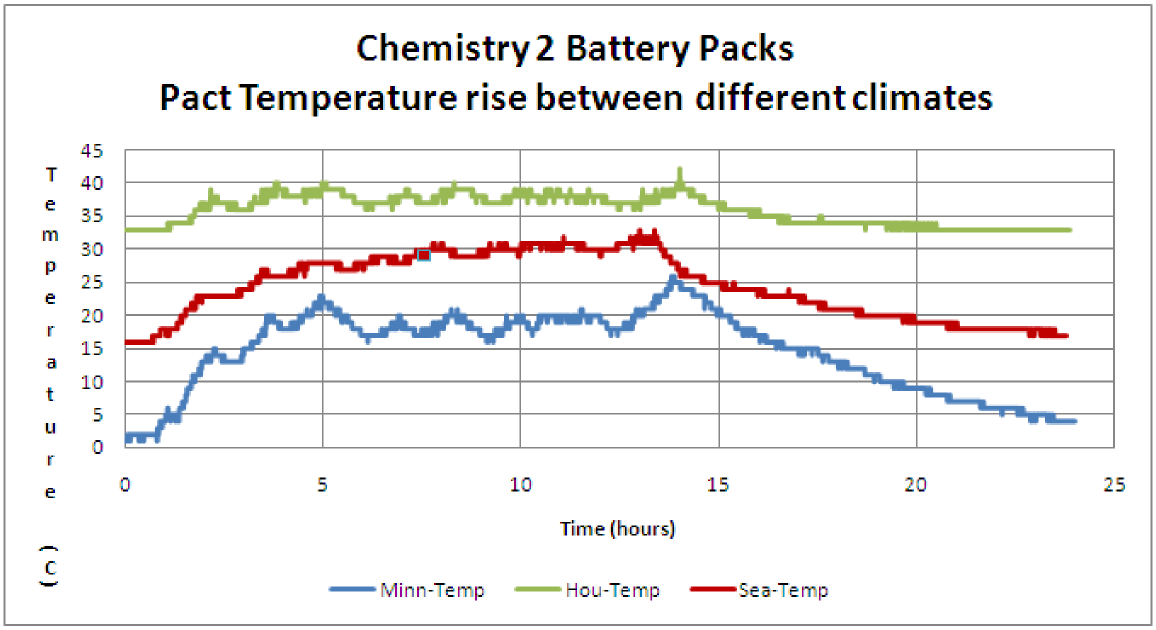


Figure 30. Chemistry 1 battery packs, pack temperature as a function of climate

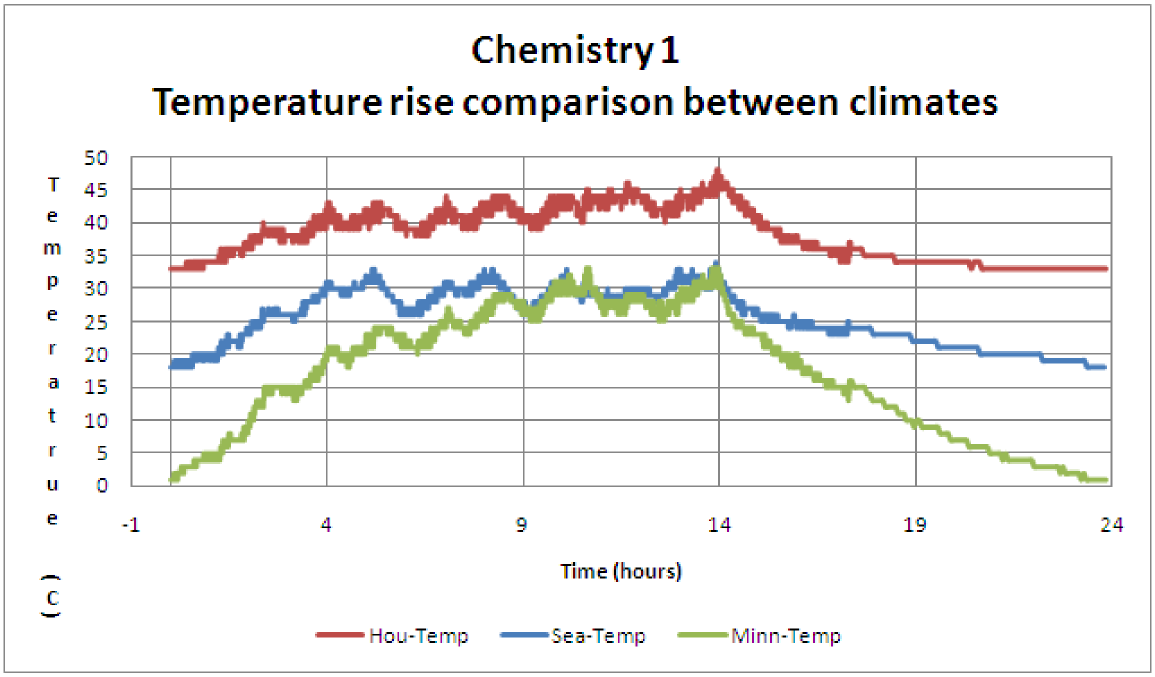


Figure 31. Pack temperature under Houston climate as a function of chemistry

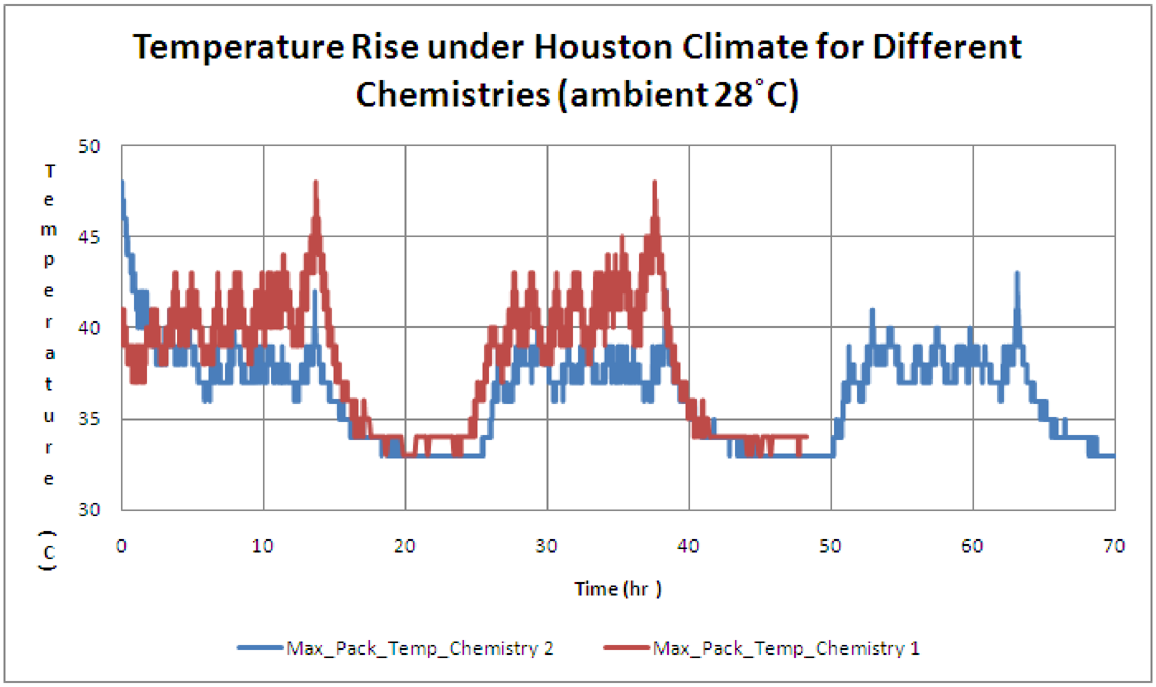


Figure 32. Pack temperature under Seattle climate as a function of chemistry

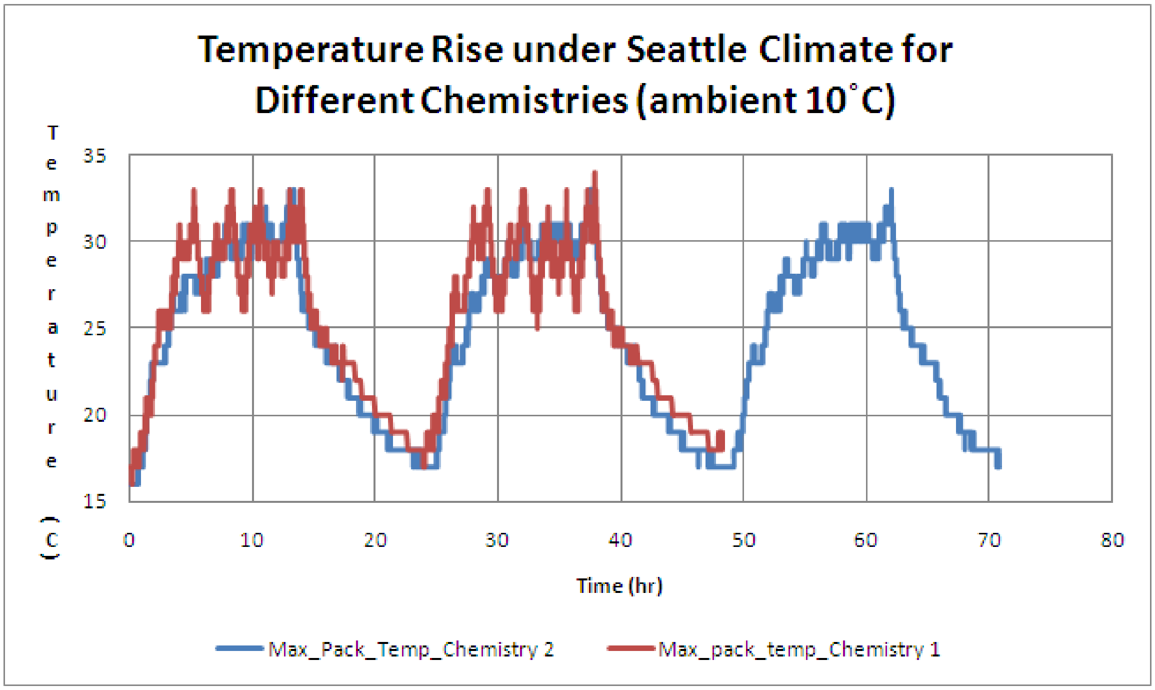


Figure 33. Pack temperature under Minneapolis climate as a function of chemistry

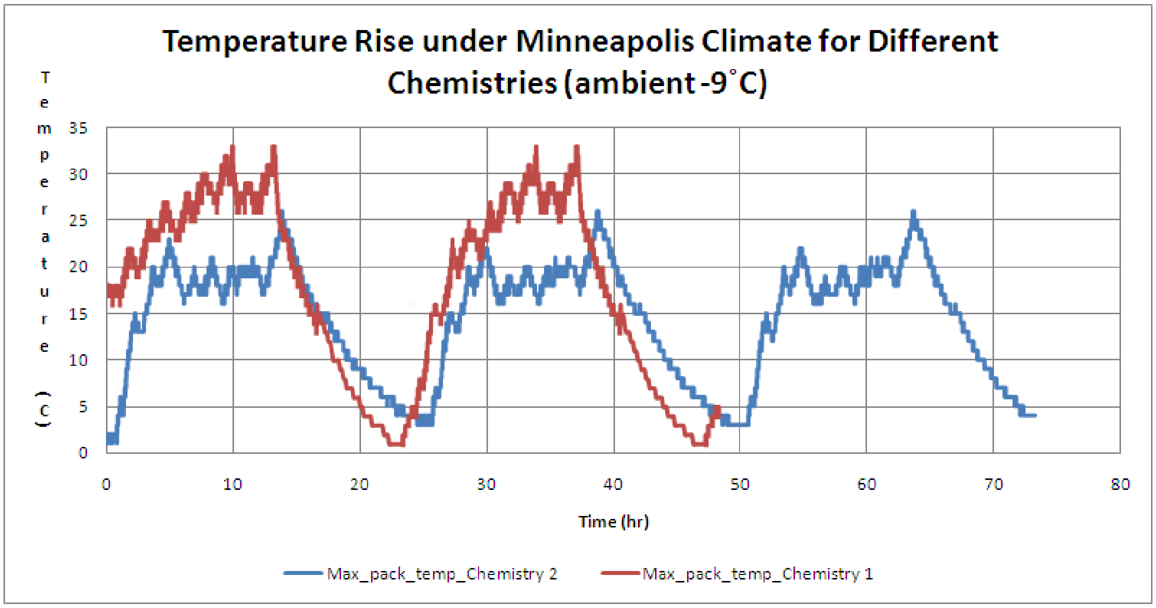


Figure 34. Discharge curve for Chemistry 1 (NMC – HC) module.

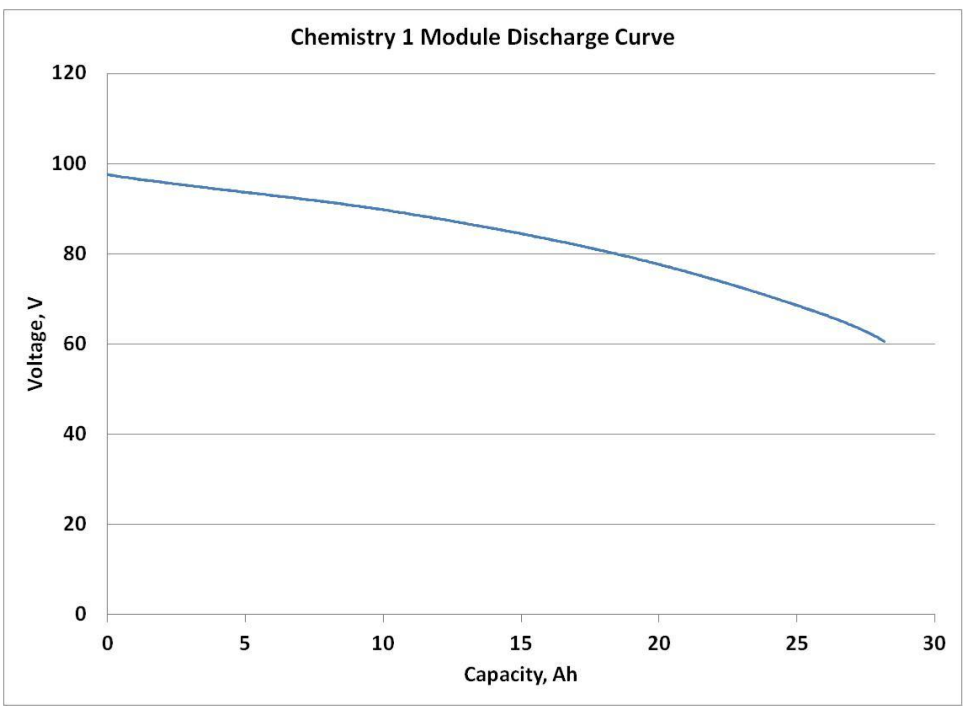


Figure 35. Discharge curve for Chemistry 2 (LMO – HC) module.

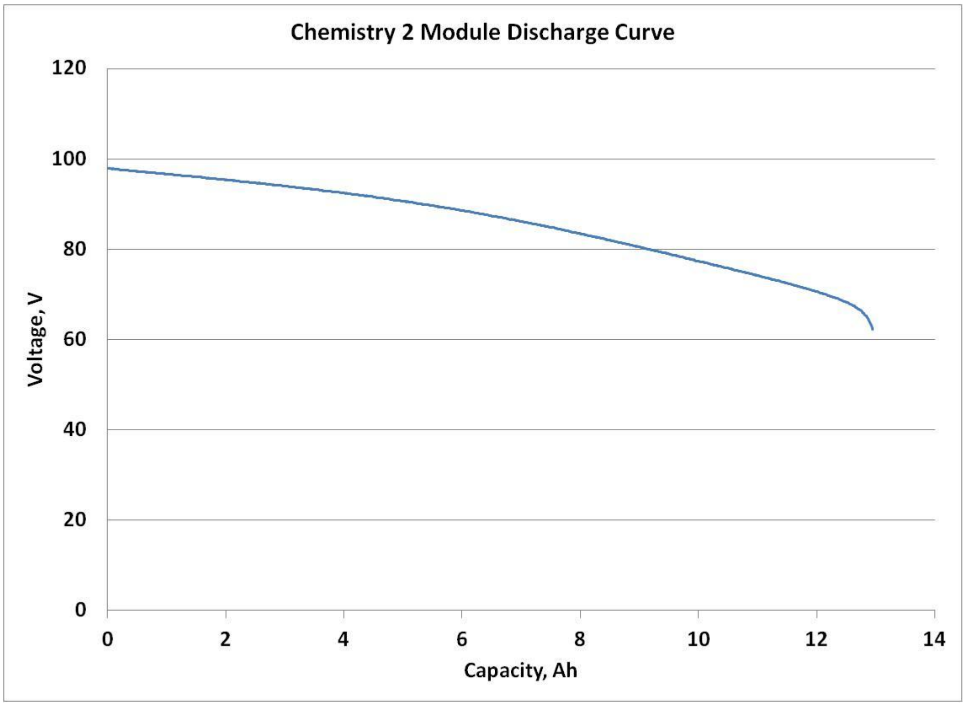


Figure 36. Discharge curve for Chemistry 3 (LMO – LTO) cell.