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Development and Testing of an UltraBattery-Equipped Honda Civic

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EXCUTIVE SUMMARY

The UltraBattery Retrofit Project DP1.8 and Carbon Enriched Project C3, performed by ECOtality North America (ECOtality) and funded by the U.S. Department of Energy and the Advanced Lead Acid Battery Consortium (ALABC), are to demonstrate the suitability of advanced lead battery technology in hybrid electric vehicles (HEVs).

A profile, termed the Simulated Honda Civic HEV Profile (SHCHEVP), has been developed in Project DP1.8 in order to provide reproducible laboratory evaluations of different battery types under real-time HEV conditions. The cycle is based on the Urban Dynamometer Driving Schedule and Highway Fuel Economy Test cycles and simulates operation of a battery pack in a Honda Civic HEV. One pass through the SHCHEVP takes 2,140 seconds and simulates 17.7 miles of driving. A complete NiMH battery pack was removed from a Honda Civic HEV and operated under the SHCHEVP to validate the profile. The voltage behavior and energy balance of the battery during this operation was virtually the same as that displayed by the battery when in the Honda Civic operating on the dynamometer under the Urban Dynamometer Driving Schedule and Highway Fuel Economy Test cycles, thus confirming the efficacy of the simulated profile.

An important objective of the project has been to benchmark the performance of the UltraBatteries from both Furukawa Battery Co., Ltd., Japan (Furakawa) and East Penn Manufacturing Co., Inc. (East Penn). Accordingly, UltraBattery packs from both Furakawa and East Penn have been characterized under a range of conditions. Resistance measurements and capacity tests at various rates show that both battery types are very similar in performance. Both technologies, as well as a standard lead-acid module (included for baseline data), were evaluated under a simple HEV screening test. Both Furakawa and East Penn UltraBattery packs operated for over 32,000 HEV cycles with minimal loss in performance, whereas the standard lead-acid unit experienced significant degradation after only 6,273 cycles. The high-carbon, ALABC battery manufactured in Project C3, also was tested under the advanced HEV schedule. Its performance was significantly better than the standard lead-acid unit, but was still inferior compared with the UltraBattery. The batteries supplied by Exide as part of the C3 Project performed well under the HEV screening test, especially at high temperatures. The results suggest that higher operating temperatures may improve the performance of lead-acid based technologies operated under HEV conditions; it is recommended that life studies be conducted on these technologies under such conditions.

Individual Furakawa UltraBatteries have been operated according to the SHCHEVP under a range of state-of-charge windows and temperatures. Battery cycling was conducted using three different state-of-charge windows (i.e., 43 to 53%, 53 to 63%, and 63 to 73%) and three different battery temperatures (10°C [50°F], 30°C [86°F], and 58°C [136°F]). The results suggest that an adequate compromise between vehicle acceleration and charging efficiency during regenerative braking is provided with a state-of-charge window of 53 to 63%. Also, low operating temperatures severely decrease the energy returned by simulated regenerative braking. At 30°C (86°F), the number of simulated vehicle

miles covered before a simulated engine recharge is required is 142 miles; the number of miles drops to less than 18 miles at 10°C (50°F). As a result, operation in cooler climates, where trip distances are short (i.e., where there is insufficient time for batteries to heat up), will result in increased fuel usage. The lower temperatures also decrease the available discharge power, although this change is small relative to the effect on charging efficiency.

In another test, an individual 12-volt (V) East Penn UltraBattery was cycled for 167,700 simulated vehicle miles under the SHCHEVP at 30°C (86°F). While the discharge capacity decreased from 7.6 to 4.5 Ah, the battery was still capable of providing the power required for acceleration. Also, the battery's ability to accept energy from regenerative braking decreased significantly during the operating period. However, the effect of this behavior on fuel economy is not known. This aside, the result is considered very promising because the SHCHEVP used to cycle the battery has the same discharge/charge intensity and frequency that is used for the NiMH battery currently in the Honda Civic Hybrid (i.e., the power levels were not decreased for the UltraBattery). This result demonstrates that the UltraBattery packs can last the design life of modern HEVs.

A 12-V, NiMH module (from the Honda Civic vehicle) was tested for almost 80,000 simulated vehicle miles under the SHCHEVP at 30°C (86°F); its capacity and performance remained unchanged during the test period. It consistently delivered 159 simulated vehicle miles between simulated engine recharges. The performance of the NiMH module also decreases when the temperature is lowered, although this drop is not as severe as for the UltraBattery. For example, at 10°C (50°F), the NiMH battery is still capable of operating for 71 simulated vehicle miles between simulated engine recharges, compared to only 18 miles for the UltraBattery. Therefore, the fuel usage at low temperatures of a NiMH-based HEV is expected to be lower than that of an equivalent UltraBattery-powered HEV. However, the extent of such a difference is not known. An individual 12-V, high-carbon ALABC module also was operated under the SHCHEVP, but failed after providing 40,391 miles of simulated service.

A Furakawa UltraBattery pack operated trouble-free for 60,000 simulated miles under the SHCHEVP at 30°C (86°F), with a minimal drop in performance. A vehicle-sized pack of East Penn UltraBattery packs also delivered 60,000 miles under the SHCHEVP at 30°C (86°F). While there was an initial battery failure in this pack (at 10,000 miles), logging of individual 12-V modules has shown that all units were still very close in performance at the end of the cycling period. These results are very promising and, combined with the results for the individual module cycling, suggest that UltraBattery packs may be capable of lasting the design life of a modern HEV (e.g., 160,000 miles). In the C3 Project, a vehicle-sized pack of the high-carbon ALABC modules was operated under the SHCHEVP, although it failed after just 27,000 simulated miles. A vehicle-sized, high-carbon, lead-acid battery from Exide also was cycled under the SHCHEVP, but it failed after just 12,500 simulated miles.

The Project DP1.8 also consists of a retrofit of the original NiMH battery with a pack of 14 UltraBattery modules, manufactured by East Penn, in a new 2010 Honda Civic HEV. After completing the initial conversion, ECOtality tested the HEV in accordance with, and in cooperation with, the Advanced

Vehicle Testing Activity of the Department of Energy's FreedomCAR and Vehicle Technologies Program.

ECOtality conducted a full vehicle baseline characterization on the converted HEV. A full dynamometer evaluation (e.g., measurement of fuel economy under standard driving schedules on the dynamometer) was completed by Argonne National Laboratory. This approach allowed direct performance comparisons with the UltraBattery against the technologies used in the unaltered HEVs.

In October 2011, the converted HEV was put into ECOtality's fleet of test vehicles in Phoenix, Arizona, and it currently is still being tested. The converted HEV accumulates approximately 5,000 miles on a monthly basis and is experiencing a wide range of driving conditions. The monthly data being collected from the vehicle is an array of battery parameters, such as the following:

- Most restrictive temperature
- Pack voltage
- Power
- Vehicle parameters, such as speed.

The individual module voltages and cell/module voltage deviation are being measured separately on a monthly basis, as well as monitoring the health of individual battery modules. The mileage driven and gallons of gasoline used monthly are being recorded to monitor the vehicle average fuel economy for the month.

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FIGURES

TABLES

ACRONYMS

ALABC	Advanced Lead Acid Battery Consortium
BCM	battery control module
CAN	controller area network
CSIRO	Commonwealth Scientific and Industrial Research organization
EODV	end of discharge voltage
EPUB	East Penn UltraBattery
FUB	Furakawa UltraBattery
HEV	hybrid electric vehicle
HPPC	Hybrid Pulse Power Characterization
HWFET	Highway Fuel Economy Test
LEODV	lowest end of discharge voltage
MCM	motor control module
OCV	open circuit voltage
SHCHEVP	Simulated Honda Civic HEV Profile
SOC	state of charge
TOCV	top of charge voltage
UDDS	Urban Dynamometer Driving Schedule

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1. INTRODUCTION

With the population of hybrid electric vehicles (HEVs) increasing rapidly, the need for both low-cost replacement and original equipment manufacturer battery packs for full, mild, and micro HEVs has become acute.

Recent developments in advanced lead-acid battery technology have resulted in development of an advanced lead-acid battery that incorporates the properties of an asymmetric supercapacitor (also known as an ultracapacitor). Work conducted by the Advanced Lead Acid Battery Consortium (ALABC), Commonwealth Scientific and Industrial Research Organization (CSIRO), and Furukawa Battery Co., Ltd., Japan (Furakawa) has demonstrated very promising results for a version developed at CSIRO and branded as the "UltraBattery." A license to manufacture this battery in the United States has been secured by East Penn Manufacturing Co., Inc. (East Penn) and they currently are transferring the technology for production at their facility in Pennsylvania.

ALABC and Furukawa previously have demonstrated the capabilities of the UltraBattery by using it to replace the NiMH battery in a Honda Civic HEV. ALABC and East Penn now wish to prove the East Penn version of the UltraBattery technology in the same HEV that is tested according to the Department of Energy testing protocol.

ECOtality North America (ECOtality) tested the East Penn UltraBattery and the original CSIRO-Furakawa version in the laboratory under simulated schedules to assist with technology verification and transfer. In the C3 Project, valve-release lead-acid batteries, containing high levels of carbon in the negative electrode, are being designed, manufactured, and evaluated under laboratory-simulated test cycles. In order to streamline both research projects, the battery evaluation component of C3 has been combined with the current project (DP1.8). This report contains results from Projects DP1.8 and C3. Both projects were funded by the Department of Energy and ALABC.

2. OBJECTIVES

The objectives of the retro-fit program are as follows:

- Develop and optimize the UltraBattery operating protocols and test cycles
- Assemble and characterize the UltraBattery packs
- Compare performance of UltraBatteries manufactured by East Penn and Furakawa
- Convert a Honda Civic HEV to operate using an UltraBattery manufactured by East Penn
- Maintain a minimum vehicle payload of 800 lb (four passengers plus 200 lb)
- Provide packaging favorable to battery life, but not integral with existing vehicle dimensions
- Provide a fuel economy equivalent to the unconverted Honda Civic Hybrid
- Maintain vehicle emissions performance equal to, or better than, the base vehicle
- Obtain an "Experimental Vehicle" permit from the California Air Resources Board for the converted vehicle

- Install conversion components without violating vehicle Federal Motor Vehicle Safety Standard certification
- Baseline vehicle performance within the HEVAmerica test program
- Conduct fleet testing within the Advanced Vehicle Testing Activity.

3. WORK PROGRAM

The DP 1.8 work program is comprised of the following tasks:

- Task 1 Develop initial vehicle operating protocols for UltraBattery use
- Task 2 Assemble and characterize UltraBattery packs
- Task 3 Optimize the UltraBattery operating protocol and test cycle
- Task 4 Develop an UltraBattery Management System
- Task 5 Prepare a new Honda Civic HEV for installation of UltraBattery packs
- Task 6 Install UltraBattery packs and conduct vehicle startup
- Task 7 Benchmark converted vehicle performance
- Task 8 Conduct fleet testing of the converted Honda Civic.

4. DP1.8 PROJECT PROGRESS

The following subsections include details on each task in the work program.

4.1 Task 1 – The Simulated Honda Civic Hybrid Electric Vehicle Profile

ECOtality performed extensive studies on a fleet of standard Honda Civic HEVs. This included 160,000 mile road tests and operation on the dynamometer under multiple drive schedules to determine fuel economy. All relevant battery parameters were monitored during this testing and, as a result, ECOtality obtained a comprehensive understanding of how the batteries operate in such vehicles. The Honda Civic HEV battery pack comprises 132 NiMH cells in series, with each cell having a nominal cell voltage of 1.2 V and a rated capacity of 5.5 Ah.

Data obtained during dynamometer studies (Figure 1) and field operation of Honda Civic HEVs have been used as a basis to formulate a Simulated Honda Civic HEV Profile (SHCHEVP) (Figure 2), which simulates the power requirements of the batteries in these vehicles. The profile is based on data derived from one pass through the Urban Dynamometer Driving Schedule (UDDS) followed by one pass through the Highway Fuel Economy Test (HWFET) schedule (i.e., an average of five runs), as well as information from the field regarding the effect of air-conditioning, hill climbing, and so forth, on battery state of charge (SOC). The energy and power levels of the SHCHEVP are, on average, equivalent to that experienced by the battery when the vehicle is driven according to the UDDS and HWFET schedules. More specifically, the SHCHEVP mimics one pass through the UDDS, followed by one pass through the HWFET.

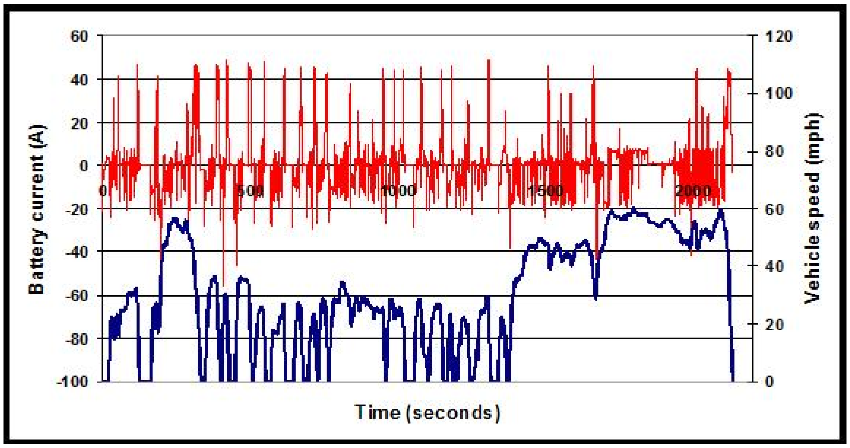

Figure 1. Actual battery current and vehicle speed logged during operation on the dynamometer during one pass through the UDDS, followed by one pass through the HWFET.

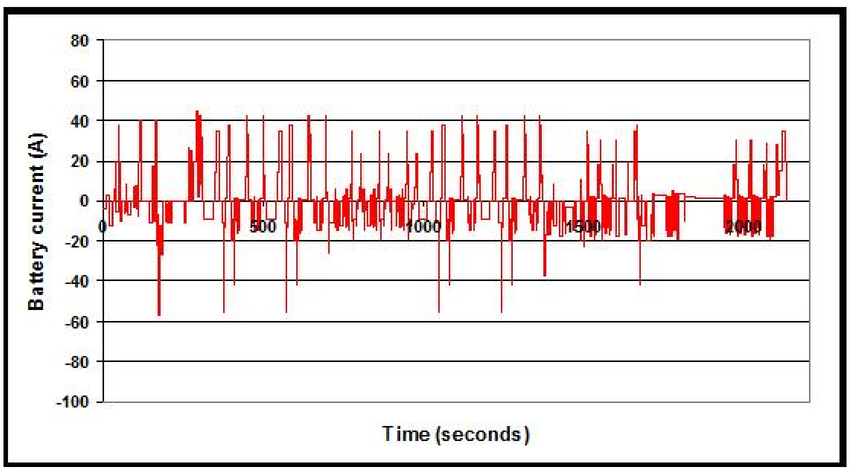

Figure 2. Battery current comprising the SHCHEVP.

The time required for one pass of the UDDS is 1,380 seconds. During this time, 7.5 simulated miles are covered at an average speed of 19.5 mph. One pass through the HWFET takes 760 seconds and simulates 10.2 miles of driving at an average speed of 48.5 mph. In summary, one pass through the SHCHEVP takes 2,140 seconds and provides 17.7 miles of operation at an average speed of 28.9 mph. Three months of duty under the profile provide greater than 64,000 miles of simulated driving.

In terms of energy delivery, one pass through the SHCHEVP (17.7 miles) requires the battery to deliver approximately 2.5 Ah. On average, each mile of driving requires 0.14 Ah of discharge energy. Over the design life of the vehicle (160,000 miles), the NiMH battery in the Honda Civic HEV would need to deliver 22,400 Ah, or the equivalent of approximately 4,000 complete-discharge cycles.

Comparative calculations performed by ECOtality for a Toyota Prius HEV battery pack indicate a delivery of almost 6,000 complete-discharge cycles over the same distance.

In order to further verify the efficacy of the profile, a standard Honda Civic NiMH battery pack was instrumented and its operation logged in a Honda Civic HEV on the dynamometer, performing consecutive passes though the UDDS and the HWFET schedules. A typical voltage profile is shown in Figure 3. These results were compared with those obtained when the same pack was operated under the SHCHEVP in the laboratory (Figure 4 and Figure 5). Figure 4 shows four repeats of the SHCHEVP followed by a simulated engine recharge. The engine recharge is required because the profile was designed so that there are slightly fewer Ah delivered during charge than discharge; therefore, a gradual reduction in capacity. When the battery SOC drops below a specified level, a charge equivalent to 10% of the nominal capacity is delivered. Figure 5 shows the second of these four SHCHEVP cycles.

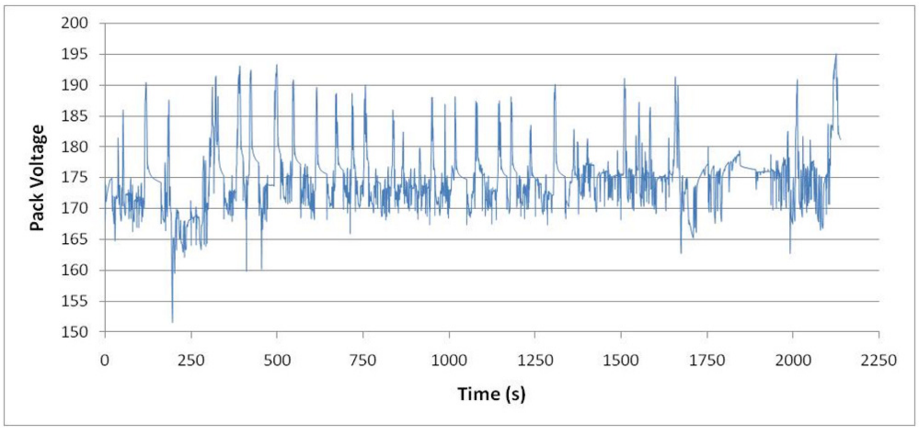

Figure 3. Typical voltage behavior of a NiMH battery pack in a Honda Civic on dynamometer during one pass through the UDDS followed by one pass through the HWFET.

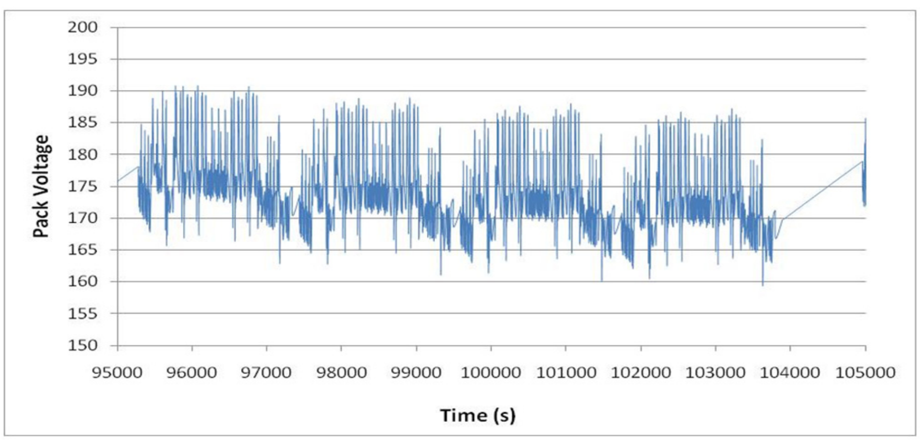

Figure 4. Voltage of NiMH pack in laboratory operating under four consecutive cycles of the SHCHEVP.

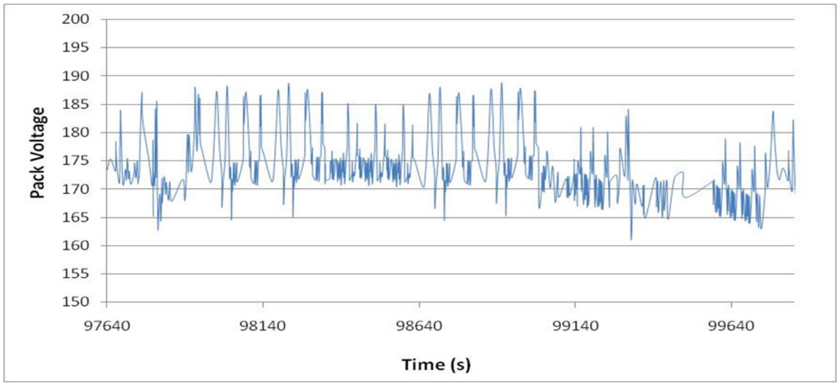

Figure 5. Voltage of NiMH pack in laboratory operating under one cycle of the SHCHEVP.

It can be seen that the voltage behavior of the battery operating in the vehicle (Figure 3) and in the laboratory under the simulated profile (Figure 4) and (Figure 5) are very similar. In addition, battery data from five independent dynamometer runs were averaged and compared with that obtained from the equivalent laboratory cycling. It was found that the energy delivered and accepted during both vehicle and laboratory operation was virtually identical, thereby confirming that the SHCHEVP mimics the drive cycles.

4.2 Task 2 – Assembly, Benchmarking, and Characterization of Furakawa and East Penn UltraBattery Modules

One of the goals of this project is to compare the performances of the UltraBattery modules from East Penn (EPUBs) with those from Furakawa (FUBs). Both battery types have been characterized according to the following schedule:

1. Determination of capacity at different rates of discharge
2. Determination of internal resistance
3. Long-term testing under a simple HEV screening test
4. Hybrid Pulse Power Characterization (HPPC) testing, both before and after the simple HEV screening test.

4.2.1 Task 2.1 – Capacity of UltraBattery Modules

Each of the 10 FUBPs and 16 EPUBs were subjected to the following cycling conditions:

1. Charge at 2.64 A for 10 hours (EPUB top-of-charge voltage (TOCV) = 13.98 V; FUB TOCV = 14.34 V)
2. Discharge at 8 A until 10.5 V
3. Repeat Steps 1 and 2.

Results are shown in Table 1, where it can be seen that the capacity of the EPUB modules (7.00 to 7.75 Ah) is very similar to that obtained for the FUBs (7.1 to 7.5 Ah). It should be noted that the EPUBs had a significantly higher float current for a given TOCV compared to the FUBs. As a result, a lower TOCV (13.98 V) was used for the former than was used for the latter (14.34 V).

Table 1. Capacity and open-circuit voltage of EPUB and FUB modules.

EPUB Module	Capacity (Ah) Measured at East Penn	Capacity (Ah) Measured at ECOtality[a]	Open-Circuit Voltage on Arrival (V)	FUB Module (Measured at ECOtality)	Capacity[a] (Ah)
A1	7.59	7.64	12.60	ETA-126	7.2
A2	7.41	7.54	12.60	ETA-127	7.2
A3	7.53	7.58	12.57	ETA-128	7.5
A4	7.68	7.47	12.63	ETA-129	7.3
A5	7.64	7.11	12.59	ETA-130	7.3
A6	7.62	7.23	12.60	ETA-131	7.5
A7	7.52	7.34	12.59	ETA-132	7.1
A8	7.41	7.12	12.61	ETA-133	7.3
A9	7.47	7.00	12.45	ETA-134	7.4
A10	7.64	7.75	12.58	ETA-135	7.3
A11	7.47	7.75	12.55	Average	7.3
A12	7.59	7.56	12.55		
A13	7.73	7.52	12.58		
A14	7.50	7.62	12.51		
A15	7.46	7.71	12.58		
A16	7.63	7.30	12.61		
Average	7.55	7.41	12.57		

a. The values shown are an average of three values (FUBs) and two values (EPUBs).

The capacity of an FUB and an EPUB module has been determined at various discharge rates; the results are shown in Table 2 and Figure 6. It can be seen that the values obtained in this study are in agreement with that obtained by CSIRO (Figure 6), although the capacity of the EPUB module is slightly higher than that of the FUB unit at higher discharge rates.

Table 2. Capacity of typical UltraBattery packs at different discharge rates.

Discharge Current (A)	End-of-Discharge Voltage (V)	Capacity FUB (Ah)	Capacity EPUB (Ah)
1.33	10.5	9.63	9.83
1.33	10.5	9.43	9.96
1.33	10.5	9.74	—
1.33	10.5	9.79	—
2.19	10.5	9.45	9.62
2.19	10.5	9.47	9.63
2.19	10.5	9.50	—
6.65	10.5	8.15	8.39
6.65	10.5	8.05	8.25
6.65	10.5	8.07	—
39.9	9.6	4.88	5.56
39.9	9.6	4.65	5.29
39.3	9.6	4.56	—

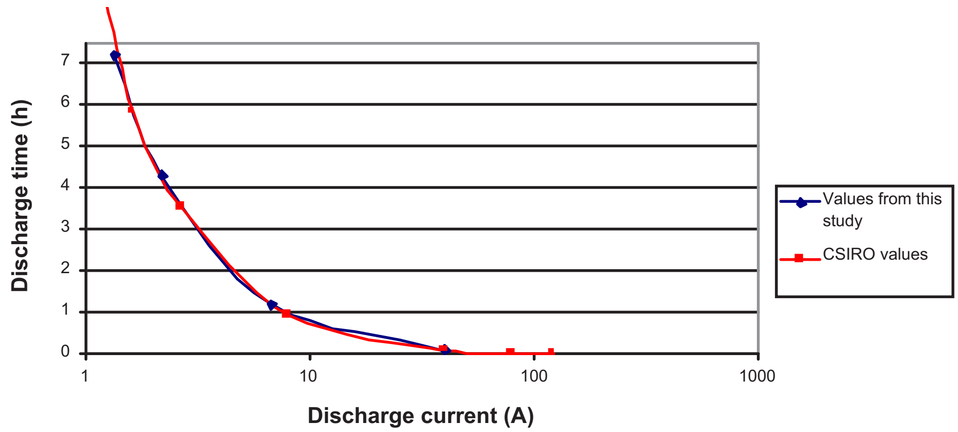

Figure 6. Discharge time of FUB modules for a range of discharge current.

4.2.2 Task 2.2 – Resistance and Open-Circuit Voltage–State of Charge Relationship of UltraBattery Packs

The discharge resistance and open-circuit voltage (OCV)-SOC relationship of the UltraBattery packs have been determined using the following procedure:

1. Charge at 2.64 A for 10 hours (TOCV FUB = 14.34 V; TOCV EPUB = 13.98 V)
2. Discharge at 8 A for 6 minutes
3. Rest for 90 seconds and measure OCV
4. Discharge at 40 A for 2 seconds and then calculate resistance
5. Repeat Steps 2 through 4 until 10.5 V reached during Step 2
6. Repeat Steps 1 through 5 a total of three times.

The OCV-SOC (after 90 seconds of rest) and resistance values determined are shown in Table 3 and Table 4. (Note that values did not vary significantly between batteries; therefore, data in Table 3 and Table 4 are for a typical module.) The internal resistance was calculated after a discharge step and is termed the discharge resistance. This is significant because resistance values calculated after a discharge will differ markedly from those calculated after a charge. The discharge resistance of both types of UltraBattery packs was very similar (as shown in Table 3 and Table 4). In a fully-charged state, the resistance of both technologies was between 14 to 15 m**Ω**. This did not change significantly until the SOC decreased to 40%, at which point it had increased to 16 to 18 m**Ω**. At 10% SOC, the resistance has increased to 26 to 28 m**Ω**. The resistance and OCV-SOC values are in good agreement with those obtained by CSIRO for the FUBs (Figure 7).

Table 3. Typical internal discharge resistance and OCV-SOC for an EPUB module and cell (determined by ECOtality).

Percent SOC	Resistance of Module (mΩ)	Resistance Per Cell (mΩ)	OCV
90	14	2.3	12.75
80	14	2.4	12.57
70	14	2.4	12.47
60	15	2.5	12.33
50	15	2.6	12.20
40	16	2.7	12.05
30	18	3.0	11.91
20	21	3.5	—
10	28	4.7	—

Table 4. Typical and internal discharge resistance and OCV-SOC for an FUB module and cell (determined by ECOtality).

Percent SOC	Resistance of Module (mΩ)	Resistance Per Cell (mΩ)	OCV
90	15	2.4	12.68
80	15	2.4	12.55
70	15	2.5	12.41
60	16	2.6	12.29
50	16	2.7	12.17
40	18	2.9	12.05
30	19	3.1	11.90
20	22	3.6	—
10	26	4.4	—

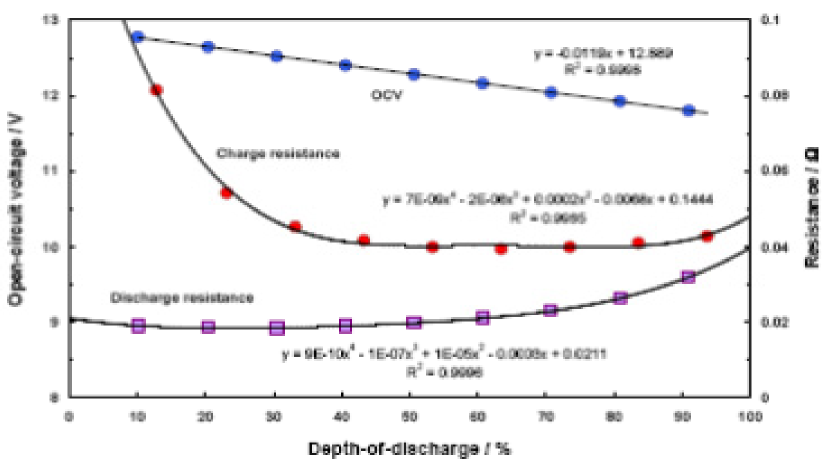

Figure 7. Internal resistance of an FUB module (measured at CSIRO).

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4.2.3 Task 2.3 – Benchmarking of UltraBattery Modules Under the Simple Hybrid Electric Vehicle Screening Test

UltraBattery modules have been tested under the simple HEV screening test that has the following steps:

1. Discharge at one cycle for 30 minutes (until approximately 50% SOC is reached).
2. Rest for 10 seconds.
3. Charge at two cycles for 60 seconds; terminate test if voltage hits 17.5 V.
4. Rest for 10 seconds.
5. Discharge at two cycle A for 60 seconds; if battery temperature exceeds 50°C (122°F), cycling is suspended until the temperature drops to 49.5°C (121.1°F).
6. Repeat Steps 2 through 5 until the voltage during Step 5 drops to 11.5 V (at approximately 40% SOC), then go to Step 7.
7. Rest for 10 seconds.
8. Charge at two cycles with a TOCV of 15 V until the equivalent of two cycles for 60 seconds has been returned.
9. Rest for 10 seconds.
10. Discharge at two cycles A for 59.1 seconds; if battery temperature exceeds 50°C (122°F), cycling is suspended until the temperature drops to 49.5°C (121.1°F).
11. Repeat Steps 7 through 10 one hundred times. Note that changing the discharge time from 60 seconds to 59.1 seconds results in the SOC of the cell increasing by 5% over the 100 repeats. Then go back to Step 2.

The schedule is based on a profile used extensively in past ALABC projects; however, in this work, it has an additional step that maintains the SOC above 40%, rather than allowing it to slowly decrease to 0%. This modification is considered to more closely mimic what happens to batteries in vehicles in the field and, therefore, allows a more accurate assessment of the susceptibility of batteries to the problem of negative electrode polarization. The results for the UltraBattery modules and a standard lead acid battery (i.e., the Genesis model manufactured by EnerSys) are shown in Figures 8 through 10Figure 10.

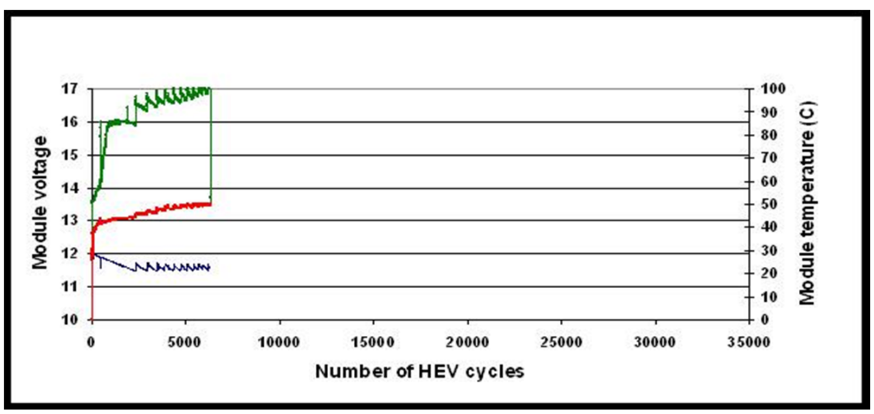


Figure 8. Voltage and temperature of Genesis module under the HEV screening test.

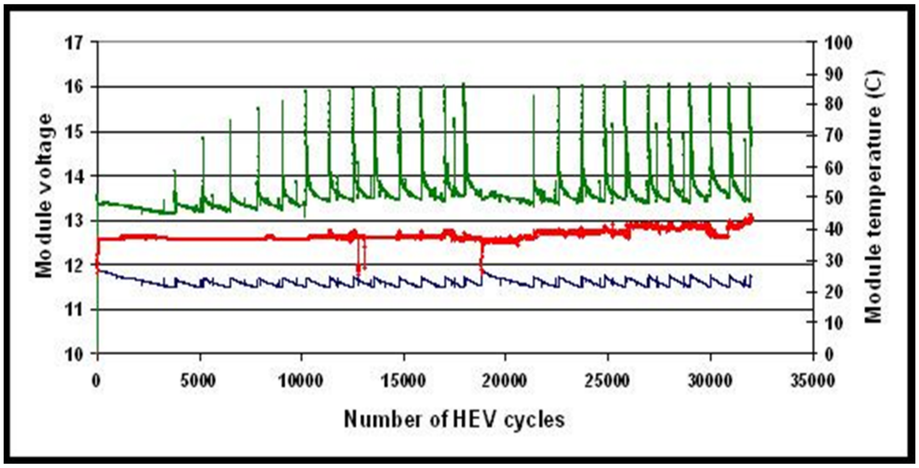


Figure 9. Voltage and temperature of FUB module under the HEV screening test.

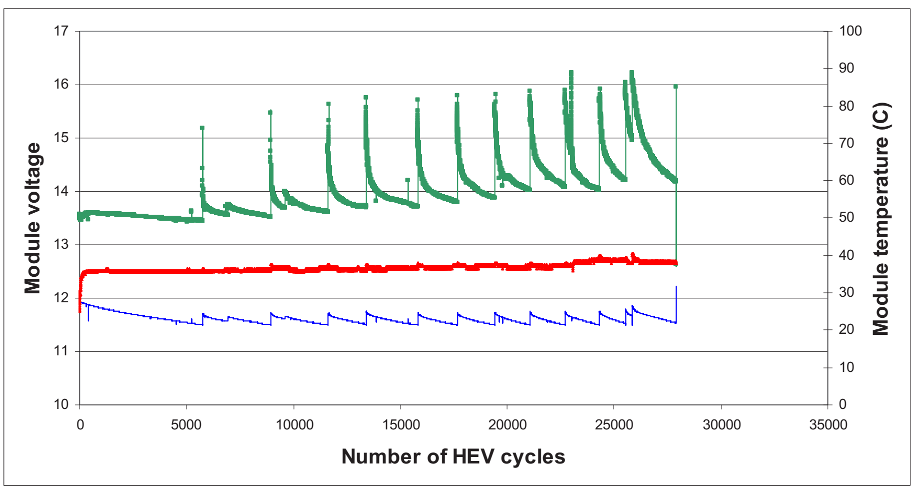


Figure 10. Voltage and temperature of EPUB module under the HEV screening test.

Figure 8 summarizes the results for the Genesis battery and displays three lines. The blue (bottom) line represents the battery voltage taken at the end of the 1-minute discharge periods (i.e., at the end of Step 5 or Step 10 above); this is termed end-of-discharge voltage (EODV). The red (middle) line is simply the temperature of the battery, as measured via a thermocouple attached to the side of the battery (and covered with a small piece of insulating foam). The green (top) line represents the battery voltage taken at the end of the 1-minute charge periods (i.e., the end of Step 3 or Step 8 above), which is the TOCV. The TOCV values are the highest voltages achieved during charging. These are significant because the level to which they rise is a direct indication of how susceptible the particular technology is to negative plate polarization. This polarization is important because it is the major problem with the use of lead-acid batteries in HEVs. If excessive, it results in a drop in the charging efficiency of the system, which causes an increase in fuel consumption.

The EODV (blue, bottom line) started at 12 V and slowly decreased during 2,700 cycles until it had reached 11.5 V (at approximately 40% SOC). At this point, Step 10 was activated, which resulted in a gradual increase in SOC of 5% over the following 100 cycles. (Note that for the sake of clarity, the data during these 100 steps are not shown.) When the profile re-started at Step 2, the EODV had risen by approximately 200 mV and the gradual decrease in EODV recommenced, although the time taken to reach 11.5 V was now less as the SOC started at approximately 45%, rather than the 50% at the commencement of cycling. This process continued for 11 of these SOC corrections, at which stage the TOCV reached 17.5 V (not shown on graph) and cycling was terminated (after 6,273 HEV cycles). In effect, the number of SOC corrections in relation to the total number of cycles performed (573 cycles/correction) can be used as a simple measure of the charging efficiency of the battery under these cycling conditions.

The temperature of the battery (red, middle line) was 25°C (77°F) at the start of cycling, but increased quickly to 40°C (104°F) within 170 cycles. The temperature then continued to rise gradually and had reached over 50°C (122°F) when cycling was stopped. Temperature monitoring performed by ECOtality in the field has shown that in-car temperatures can reach 60°C (140°F) if left in the sun on black tarmac during summer. Operating temperatures at this level will undoubtedly affect battery life; it is considered that effective temperature management will be a crucial aspect of ensuring the success of this technology in HEVs. Indeed, this issue will be even more important for lithium-ion battery systems.

The TOCV (green, top line) started at approximately 13.5 V and then increased to 16 V within the next 1,000 cycles. It then remained at approximately 16 V until the completion of 2,700 cycles, at which point the EODV had dropped to 11.5 V (approximately 40% SOC) and an SOC adjustment was activated (i.e., Step 10). When normal cycling restarted, the TOCV jumped immediately to 16.8 V and then decreased to 16.5 V over the next 50 cycles. During the 11 SOC corrections experienced by the battery, the TOCV continued this upward zigzag behavior, until the 17.5-V cut-off was activated after 6,273 cycles. The initial capacity of the battery was 9 Ah, but this had dropped to just 5.6 Ah at the completion of cycling.

The voltage behavior of the FUB and EPUB modules (Figure 9 and Figure 10) followed the same general trends as the Genesis battery (Figure 8). However, there were several notable differences:

1. The FUB and EPUB performed many more cycles than the Genesis and were still in good condition at the end of testing.

FUB:	32,000 cycles	Initial capacity = 7.3 Ah	Final capacity = 6.0 Ah
EPUB:	32,000 cycles	Initial capacity = 7.5 Ah	Final capacity = 7.0 Ah
Genesis:	6,273 cycles	Initial capacity = 9.0 Ah	Final capacity = 5.6 Ah

2. The FUB and EPUB performed more cycles before an SOC correction was required (especially the EPUB).

FUB:	24 corrections over 32,000 cycles	(1,333 cycles per correction)
EPUB:	12 corrections over 32,000 cycles	(2,666 cycles per correction)
Genesis:	11 corrections over 6,273 cycles	(570 cycles per correction)

3. The TOCV after an SOC correction and the overall average TOCV was much lower for the FUB and EPUB.

FUB:	Average TOCV less than 14.0 V	Maximum TOCV = 16 V
EPUB:	Average TOCV less than 14.5 V	Maximum TOCV = 16.2 V
Genesis:	Average TOCV greater than 16.0 V	Maximum TOCV = 17.5 V

In summary, the FUB and EPUB are very resistant to polarization during HEV duty relative to standard lead-acid valve-release lead acid technology. The capacity and overall performance of the UltraBattery packs changed little during cycling (32,000 cycles), whereas the Genesis battery was considered to have failed after just 6,273 cycles. However, the UltraBattery packs do still experience the phenomenon of polarization, especially after a charging SOC correction, albeit to a much lower extent than that of standard lead-acid technology. However, with proper SOC management, this effect could be controlled.

4.2.4 Task 2.4 – Hybrid Pulse Power Characterization Testing of UltraBattery Modules

The performance of FUB, EPUB, and Genesis 12-V modules have been evaluated according to the HPPC test schedule as used in the FreedomCAR and Advanced Vehicle Testing Activity program. The most relevant results are those for available charge and discharge power (these are shown in Figures 11 through 13), both before and after simple HEV testing. (Note that a complete summary of the HPPC test results is shown in the appendices of this report.)

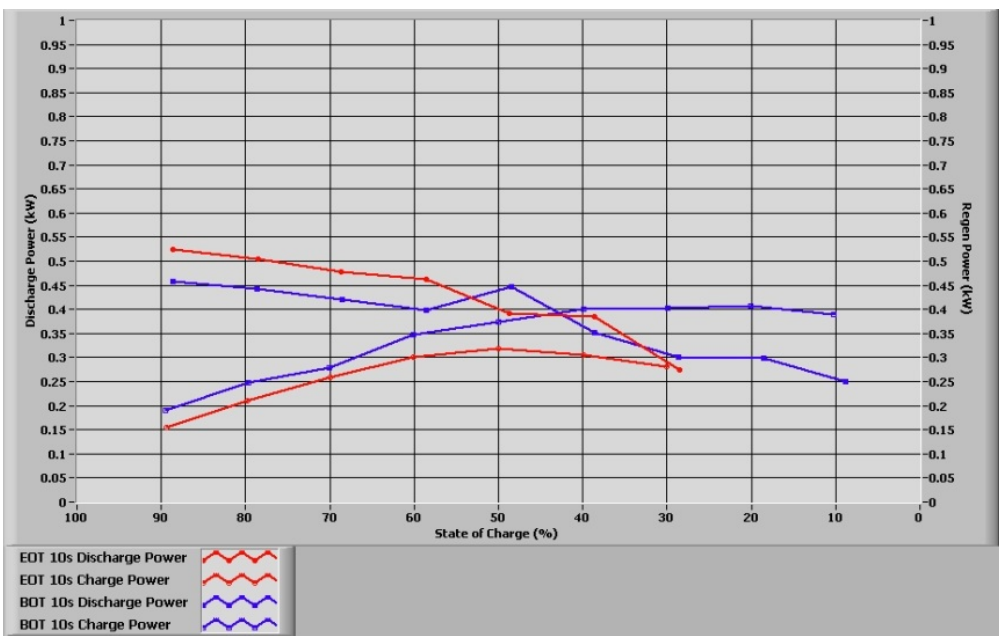


Figure 11. Discharge and charge power of the FUB module before and after HEV screening test.

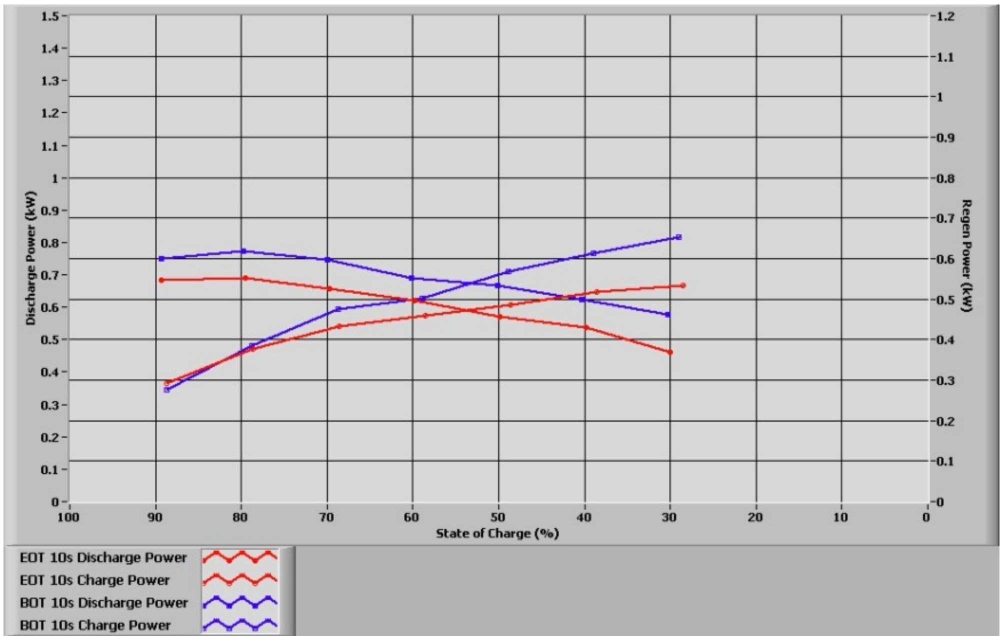


Figure 12. Discharge and charge power of an EPUB module before and after HEV screening test.

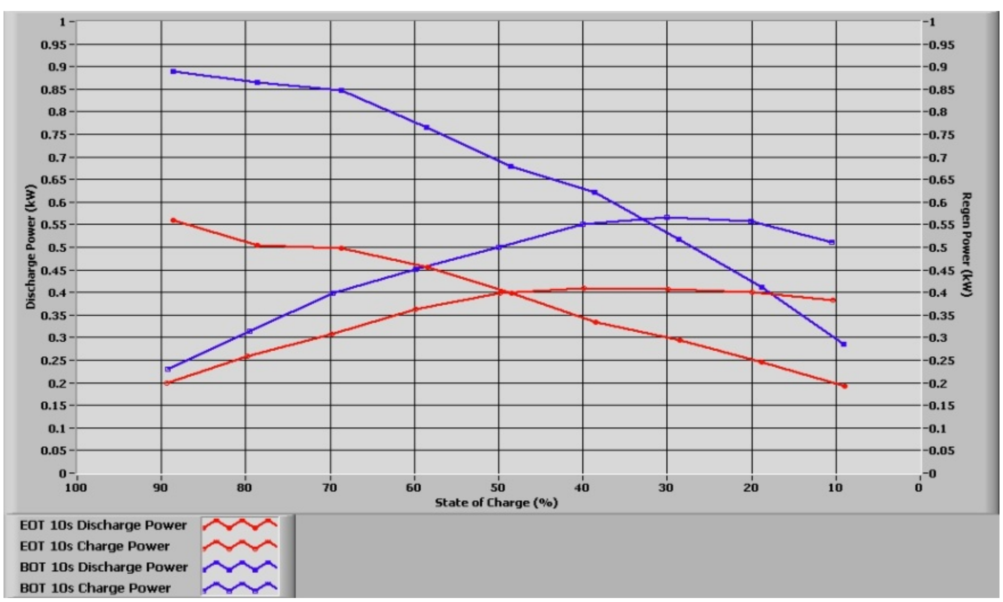


Figure 13. Discharge and charge power of a Genesis module before and after HEV screening test.

Figure 11 shows the available 10-second charge and discharge power for the FUB module at various SOCs. The two upper lines represent the 10-second discharge power that the battery can deliver both before and after testing, while the two lower lines show the 10-second charge power that could be accepted by the battery before and after testing. It can be seen that there is little difference within the pairs of lines (i.e., between the data obtained before and after HEV cycling). It can be concluded that minimal degradation of the battery has occurred as a result of the screening test, which is in agreement with the results described in Section 4.2.3. As expected, the performance of the EPUB module (Figure 12) was similar to that of the FUB module. By contrast, the Genesis module (Figure 13) deteriorated significantly as a result of the HEV screening test.

4.3 Tasks 3 – Optimize Operating Protocol for the UltraBattery

The following subsections include details on Task 3.

4.3.1 Characterization of 12-V FUB Modules Under the Simulated Honda Civic Hybrid Electric Vehicle Profile at Different State-of-Charge Windows

The best SOC window for an HEV battery is one that provides acceptable vehicle acceleration and allows full recovery of regenerative braking energy. Unfortunately, while a higher SOC window supports greater discharge power, a lower window allows for maximum charge acceptance/energy recovery. As a result, the positioning of the SOC window is always a compromise.

The SHCHEVP has been developed based on the requirement that slightly more Ah be delivered during discharge than returned during charge. This simulates the decrease in SOC that occurs between engine recharges in actual vehicle operation. Note that the energy recovered from regenerative braking is always less than that delivered by the battery for acceleration and vehicle accessories; therefore, frequent recharging by the engine is required. When the battery SOC has decreased to a specified level, a simulated recharge from the engine is activated, which returns 10% of the nominal capacity. In other words, the SHCHEVP employs a 10% SOC window. The number of cycles performed between each 10% engine recharge can vary significantly and depends on the charge acceptance of the battery. This charge acceptance is affected by a variety of parameters, including battery temperature, battery age, battery design, battery SOC, and the TOCV limit.

In order to examine the effect of the SOC window on battery performance, individual FUB modules have been cycled under the SHCHEVP using three different SOC windows (i.e., 43 to 53%, 53 to 63%, and 63 to 73% SOC). The batteries are first discharged down to the target SOC and then subjected to repeats of the SHCHEVP (e.g., the target SOC for the 43 to 53% SOC window is 53%). The results are summarized in Figures 14 through 19.

Figure 14 shows the voltage response of an FUB when operated between 43 and 53% SOC under the SHCHEVP, with a battery temperature of 30°C (86°F). Note that battery temperature generally increased by 5°C (41°F) during cycling; therefore, ambient temperature was 30°C (86°F). At commencement of cycling, the battery performed nine passes (159 simulated driving miles) through the SHCHEVP before the SOC dropped from 53 to 43% and a 10% simulated engine recharge was activated. Also, it can be seen that the TOCV limit of 14.7 V was activated during the first two of these nine cycles and the lowest end of voltage discharge (LEODV) was approximately 11.2 V.

The long-term behavior of the 43 to 53% SOC module during cycling is summarized in terms of OCV in Figure 15. Note that the OCV provides an estimate of SOC, as shown in Table 3 and Table 4. The OCV is measured during each repeat of the SHCHEVP at the end of a 90-second rest step that is preceded by a discharge step.

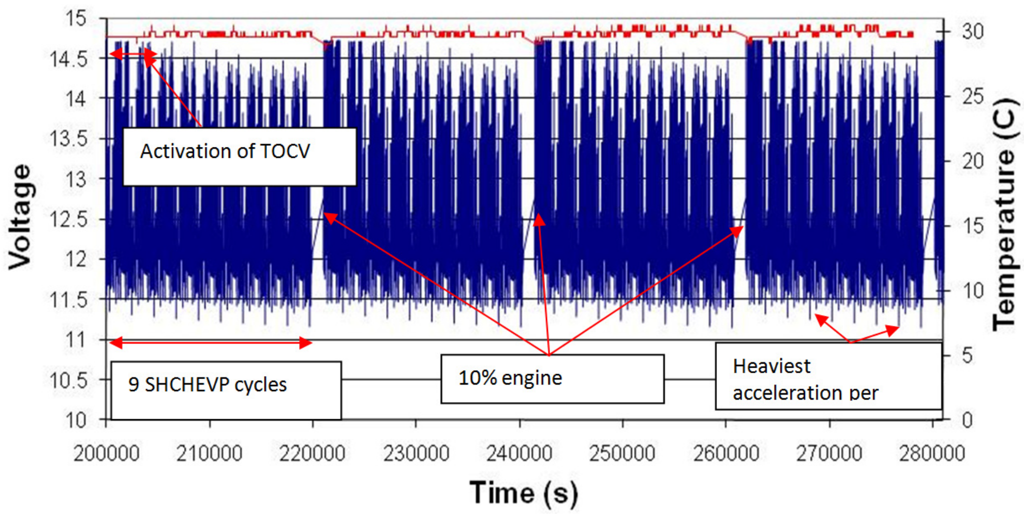


Figure 14. Typical voltage of an FUB (ETA-134) operating under the SHCHEVP, with a SOC window of 43 to 53% and battery temperature of 30°C.

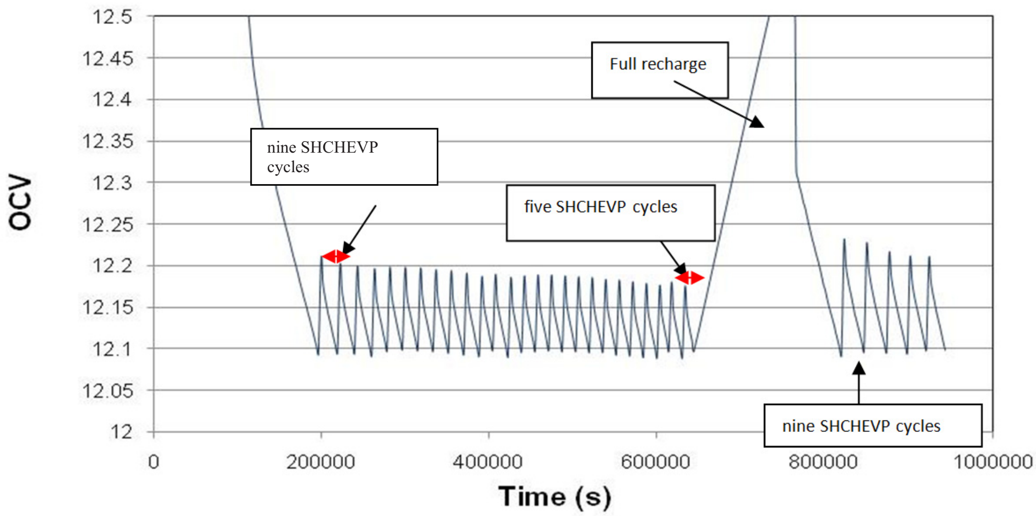


Figure 15. Typical open-circuit voltage of an FUB (ETA-134) operating under the SHCHEVP, with a SOC window of 43 to 53%.

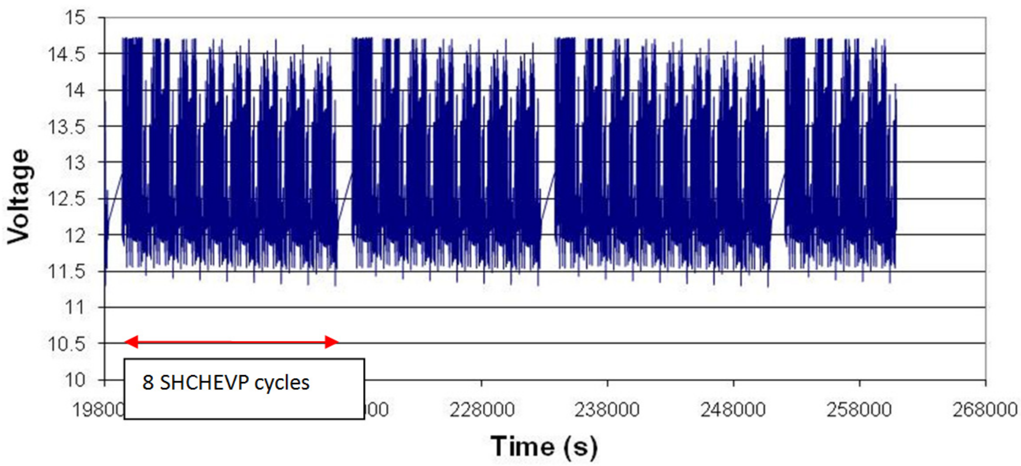


Figure 16. Typical voltage of an FUB (ETA-132) operating under the SHCHEVP, with a SOC window of 53 to 63%.

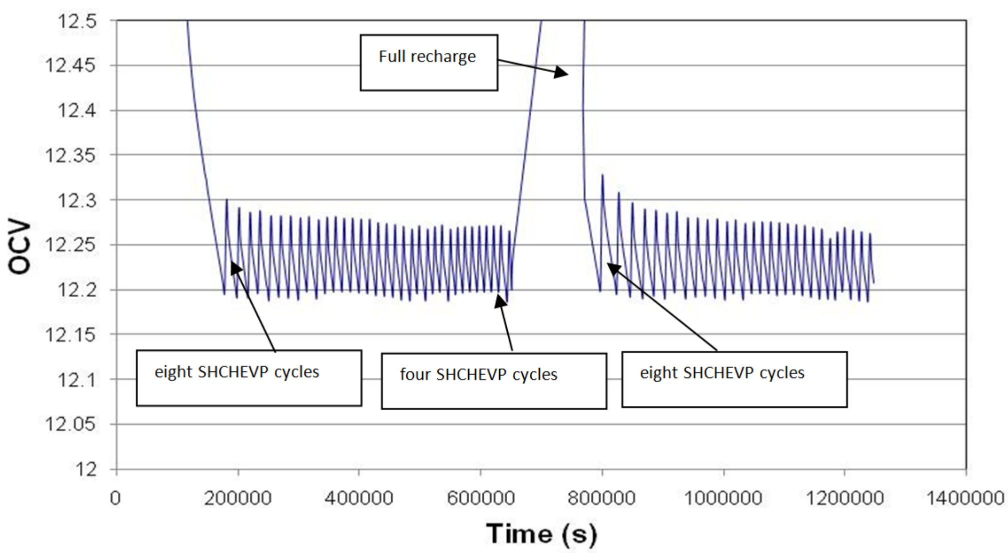


Figure 17. Typical open-circuit voltage of an FUB (ETA-132) operating under the SHCHEVP, with a SOC window of 53 to 63%.

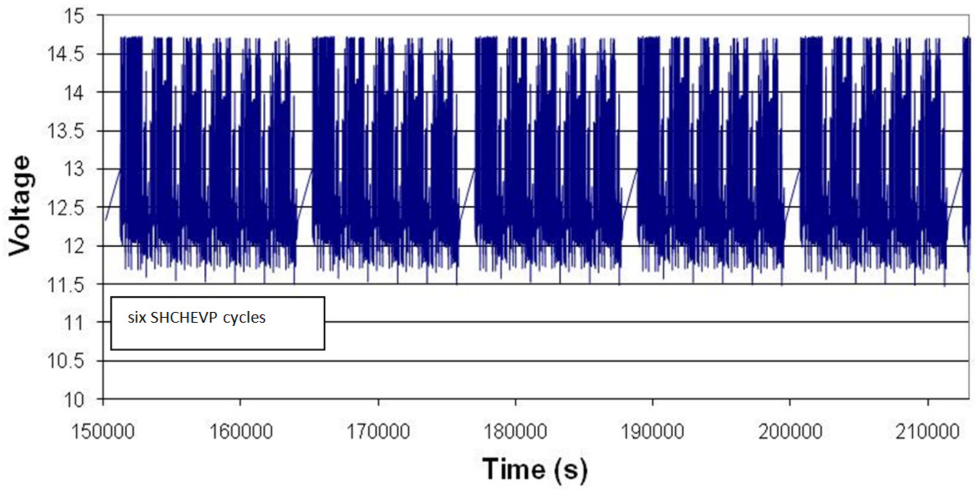


Figure 18. Typical voltage of an FUB (ETA-129) operating under the SHCHEVP, with a SOC window of 63 to 73%.

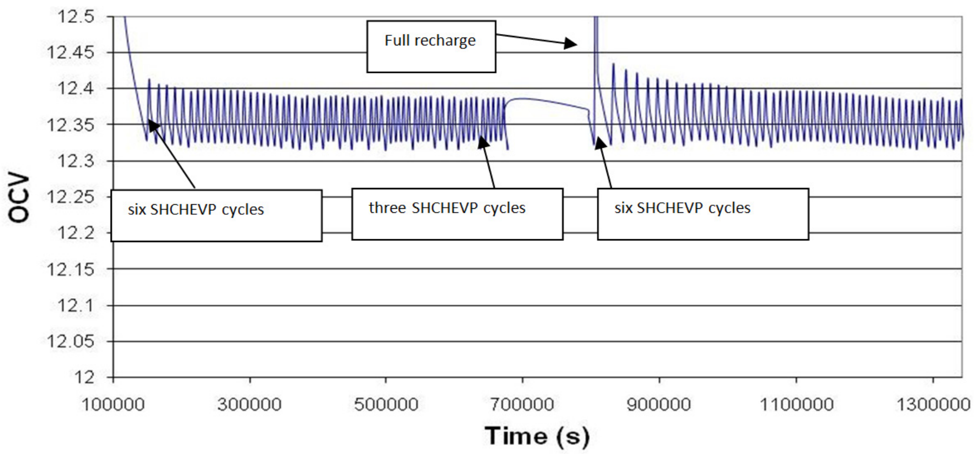


Figure 19. Typical open-circuit voltage of an FUB (ETA-129) operating under the SHCHEVP, with a SOC window of 63 to 73%.

The battery was first subjected to a characterization/capacity test procedure (0 to 200,000 seconds) followed by repetitive cycling under the SHCHEVP. During the latter operation, the OCV would start at 12.2 V and decrease slightly during each repeat of the SHCHEVP until it reached 12.1 V (43% SOC). At this point, a simulated 10% engine recharge was activated and the OCV returned to 12.2 V (53% SOC). At commencement of the SHCHEVP operation (i.e., 200,000 seconds), the battery was performing nine repeats (159 simulated driving miles) of the SHCHEVP between each 10% engine recharge (shown in Figure 15). However, after 650,000 seconds, this number had dropped to five (89 simulated driving miles). Given that the Ah delivered during discharge are constant, the walk down in capacity is attributed to a fall in the Ah delivered during charge, which is caused by a decrease in charge acceptance and an associated increase in the frequency/extent of activation of the TOCV limit. This behavior is consistent with the sulfation/degradation process that is known to occur in lead-acid battery systems. Interestingly, a full recharge/capacity test conducted at 670,000 seconds, included to routinely measure capacity, was found to ameliorate the negative affect and return the number of cycles completed between 10% engine recharges back to nine. This behavior suggests that a routine recovery charge can be beneficial for UltraBattery packs and standard lead-acid products.

The equivalent voltage and OCV graphs for an FUB operated within an SOC window of 53 to 63% are shown in Figure 16 and Figure 17, respectively. Raising the SOC window to 53 to 63% has resulted in the TOCV being activated during the first three SHCHEVP repeats of each cycle set instead of two for the 43 to 53% window. (Note that a cycle set is defined as the number of SHCHEVP cycles completed between 10% engine recharges.) The net result of this behavior is that the energy returned to the battery during regenerative braking is less and the number of SHCHEVP cycles per cycle set during initial cycling drops from nine for the 43 to 53% SOC window to eight for the 53 to 63% SOC window. Increasing the SOC window from 43 to 53% to 53 to 63% SOC also increased the LEODV from 11.2 to 11.35 V.

The OCV behavior of the module operated between 53 to 63% SOC (Figure 17) follows the same trend as the 43 to 53% SOC unit (Figure 15), although the number of SHCHEVP repeats per cycle set for the former decreased from eight (142 simulated driving miles) to four (71 simulated driving miles) during cycling, before being returned to eight by a full recharge.

The third SOC window investigated was 63 to 73% and the results are summarized in Figure 18 and Figure 19. As expected, the general behavior of the battery followed the same trend as that observed for those cycled between 43 to 53% and 53 to 63% SOC (i.e., although the number of SHCHEVP repeats completed within a cycle had fallen further to six [106 simulated driving miles] and the TOCV was activated during each repeat [Figure 18]). The LEODV also increased slightly, this time reaching 11.35 V. The behavior during longer-term cycling (Figure 19) also mimicked that of the lower SOC windows (i.e., the number of SHCHEVP repeats per cycle set decreased significantly from six at the start of cycling [150,000 seconds] to three [680,000 seconds], before increasing back to six following a recovery charge/capacity test [850,000 seconds]).

In summary, increasing the SOC window from 43 to 53% to 53 to 63%, then to 63 to 73%, increases the LEODV during acceleration from 11.2 to 11.5. This could provide a slight increase in the power during hard acceleration. However, moving to the higher SOC window causes a significant increase in the frequency of TOCV activation. This acts to decrease the amount of energy accepted by the battery during simulated regenerative braking, which, in turn, decreases the number of SHCHEVP repeats completed per cycle set from nine (159 simulated driving miles) to five (89 simulated driving miles). The net result of increasing the SOC window from 43 to 53% to 63 to 73% is that the number of simulated engine recharges increases by almost a factor of two, which will increase fuel consumption. Again, note that at this point it is not known to what extent fuel consumption would increase. The SOC window of 53 to 63% has been chosen for future cycling as it is considered to represent a suitable compromise between regenerative braking efficiency and available vehicle power. Finally, the results suggest that the charge acceptance of UltraBattery packs operated under HEV conditions can be improved/maintained through the use of a recovery charge. Such a charge may only need to be delivered every 5,000 miles, would require only 15 to 20 minutes, and could be delivered while the car is still running.

4.3.2 Characterization of 12-V FUB Modules Under the Simulated Honda Civic Hybrid Electric Vehicle Profile at Different Temperatures

It is well known that temperature can significantly affect both the charge acceptance and discharge power of lead-acid battery systems. In order to investigate this behavior, selected FUB modules have been operated under the SHCHEVP at different battery temperatures (i.e., 10°C [50°F], 30°C [86°F], and 58°C [136°F]). Figure 20 shows the voltage behavior of an UltraBattery operating at 30°C (86°F), whereas Figure 21 displays data for a battery initially operated at 58°C (136°F), followed by a period at 10°C (50°F) (of 290,000 seconds).

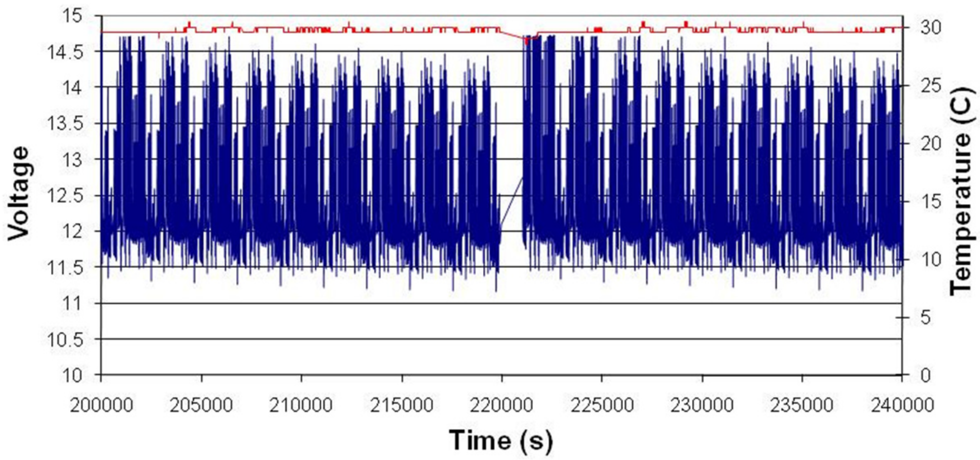


Figure 20. Typical voltage of an FUB (ETA-134) operating under SHCHEVP at a battery temperature of 30°C (86°F) (SOC window of 43 to 53%).

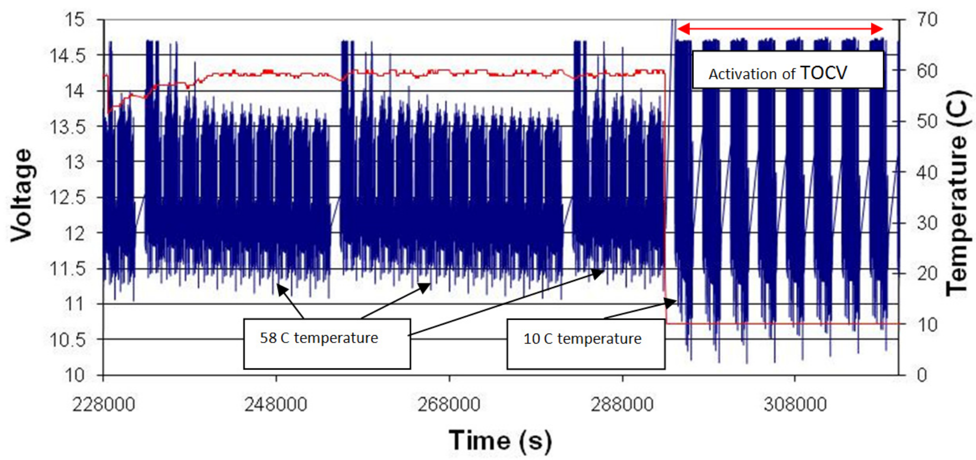


Figure 21. Typical voltage of an FUB (ETA-134) operating under SHCHEVP at battery temperatures of 58°C (136°F) and 10°C (50°F) (SOC window of 43 to 53%).

It can be seen that there is little change in the LEODV between a battery temperature of 30°C (86°F) (Figure 20) and 58°C (136°F) (Figure 21), but dropping the temperature to 10°C (50°F) decreases the LEODV markedly from 11.2 to 10.2 V (Figure 21). This drop is considered significant and may compromise vehicle performance somewhat during hard acceleration.

Charge acceptance of the FUB was found to decrease significantly with decreasing temperature. At an operating temperature of 58°C (136°F), the UltraBattery performed 12 SHCHEVP repeats (212 simulated vehicle miles) between simulated 10% engine recharges and only activated the TOCV during the first repeat (228,000 to 290,000 seconds; Figure 21). When the temperature was decreased to 10°C (50°F) (for a period greater than 290,000 seconds; Figure 21), the TOCV was activated during almost all the charge steps of SHCHEVP. The overall result of this behavior is that at 10°C (50°F), the amount of energy captured by the battery from the regenerative braking process is much reduced and simulated engine recharges are required every pass through the SHCHEVP (less than 18 simulated vehicle miles); this contrasts to 12 passes (212 simulated engine miles) at 58°C (136°F) or nine passes at 30°C (86°F). Obviously, this situation will result in an increase in fuel usage due to increased activity of the engine for battery charging.

In summary, decreasing the battery operating temperature drops both available power and charge acceptance. While the former is not expected to have a large effect on vehicle performance, the latter, with its associated increase in engine-run time, could increase fuel usage significantly.

4.3.3 Long-Term Testing of 12-V EPUB and 12-V NiMH Modules Under the Simulated Honda Civic Hybrid Electric Vehicle Profile

A 12-V EPUB module and a 12-V NiMH Civic module are being subjected to life testing under SHCHEVP (53 to 63% SOC and 30°C [86°F]). As the life cycle of individual modules generally exceeds that of long strings, the data from this study should represent the absolute maximum lifetime available from this technology under this duty. The results to date are summarized in Table 5.

Table 5. Performance of 12-V EPUB and NiMH insight modules under SHCHEVP duty (53 to 63% SOC and 30°C [86°F]).

Module	Operating Temperature	Simulated Miles Traveled	Number of Cycles	1-h Capacity 100% DOD (Ah)	No. of Miles Between Simulated Engine Recharges
EPUB	30°C	New battery	0	7.6	—
EPUB	30°C	8,850	500	7.6	—
EPUB	30°C	17,700	1,000	7.6	124
EPUB	30°C	26,550	1,500	7.5	—
EPUB	30°C	44,250	2,500	7.3	89
EPUB	30°C	61,950	3,500	7.1	89
EPUB	30°C	79,650	4,500	6.5	71
EPUB	30°C	97,350	5,500	6.0	71
EPUB	30°C	115,050	6,500	5.5	71
EPUB	30°C	132,750	7,500	5.0	53
EPUB	30°C	150,450	8,500	4.8	53
EPUB	30°C	167,700	9,500	4.5	44
NiMH from Civic	10°C	New battery[a]	0	6.0	71
NiMH from Civic	27°C	New battery[a]	0	6.0	159
NiMH from Civic	27°C	42,072	2,377	6.0	159

Table 5. (continued).

Module	Operating Temperature	Simulated Miles Traveled	Number of Cycles	1-h Capacity 100% DOD (Ah)	No. of Miles Between Simulated Engine Recharges
NiMH from Civic	27°C	78,712	4,447	6.0	159
FUB	10°C	New battery[a]	0	7.5	Less than 18[a]
FUB	30°C	New battery[a]	0	7.5	142[a]
FUB	58°C	New battery[a]	0	7.5	212[a]

a. These values were recorded when the battery was new. As a result, the number of miles obtained between simulated engine recharges was at a maximum. Note that the equivalent values recorded for the EPUB modules were taken some 16,000 miles after a capacity test and, as a result, are much lower than those for the FUB.

The 12-V EPUB module has completed almost 170,000 simulated driving miles, during which time its capacity has decreased from 7.6 to 4.5 Ah (as shown in Table 5). This decrease in capacity was accompanied by a drop in the number of simulated vehicle miles provided between simulated engine recharges and an associated increase in the polarization of the charging voltage. For example, after 44,250 simulated driving miles, a simulated recharge was required every 89 miles, but after 79,650 simulated driving miles, this number had dropped to 71 miles. This behavior indicates that the charging efficiency of the battery is decreasing as the battery ages and this outcome will increase engine activity and related fuel consumption of the vehicle.

The 12-V NiMH module from a Honda Civic has now completed 78,712 simulated miles (Table 5) and its capacity and voltage behavior are identical to that at the commencement of duty. Indeed, the battery has delivered 159 miles (9 cycles) between simulated engine recharges for the entire 78,712 miles (at the same temperature of 27°C [81°F]). The performance of the NiMH battery also has been evaluated at low temperatures (Figure 22). It was found that the number of simulated vehicle miles covered between simulated engine recharges fell from 159 to 71 miles when the operating temperature was lowered from 27°C (81°F) to 10°C (50°F). This is considered a significant reduction and could increase the vehicle fuel consumption noticeably.

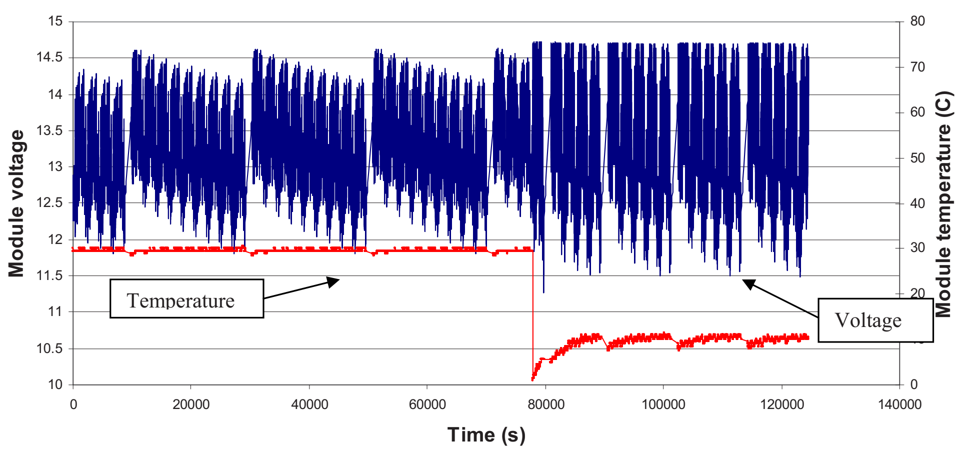


Figure 22. Voltage of Civic NiMH 12-V module under SHCHEVP at 27°C (81°F) and 10°C (50°F).

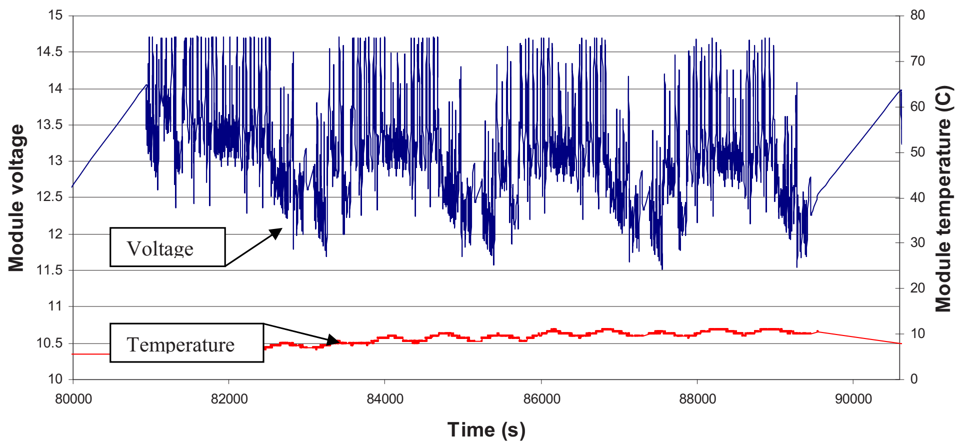


Figure 23. Voltage of Civic NiMH 12-V module under SHCHEVP at 10°C, expanded from Figure 22 (four cycles or 71 miles of simulated driving between simulated engine recharges).

In order to provide a direct comparison with the NiMH module, equivalent data for an FUB operated at different temperatures has been included in Table 5. It can be seen that at 30°C (86°F), an FUB-powered vehicle can be expected to travel for 142 simulated vehicle miles before a simulated engine recharge is required, whereas at 10°C (50°F), this number is reduced to 18 miles (Figure 24). This drop is likely to have a significant effect on fuel economy, because less of the energy available from regenerative braking is being accepted by the battery.

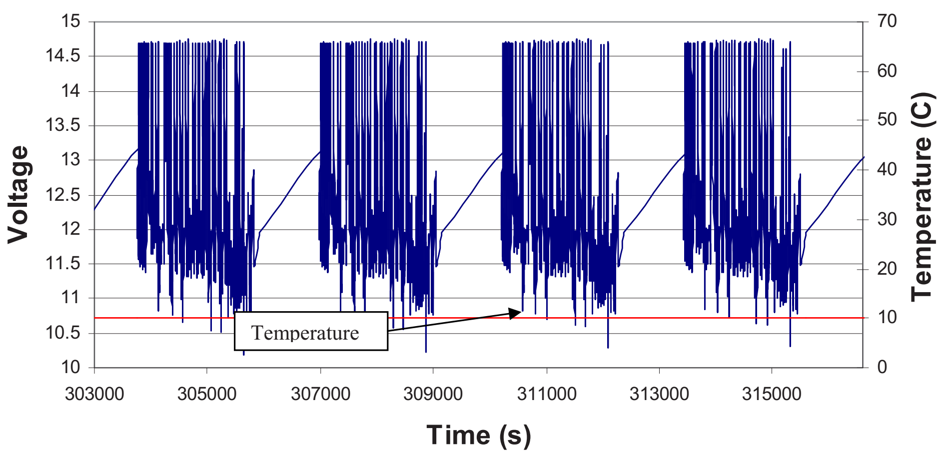


Figure 24. Voltage of an FUB 12-V module under SHCHEVP at an operating temperature of 10°C (50°F).

4.3.4 Operation of an FUB Pack (3, 12 V modules) Under the Simulated Honda Civic Hybrid Electric Vehicle Profile for 60,000 Miles

A pack consisting of three FUB modules connected in series has been cycled under the SHCHEVP (53 to 63% SOC and 30°C [86°F]) for the equivalent of 60,000 vehicle miles. The typical performance, in terms of voltage, is shown in Figure 25. Note that it was initially planned to operate a complete vehicle pack in series; however, only three 12-V modules were available. After 60,000 miles, the battery was providing trouble-free operation and was still above 90% of initial capacity.

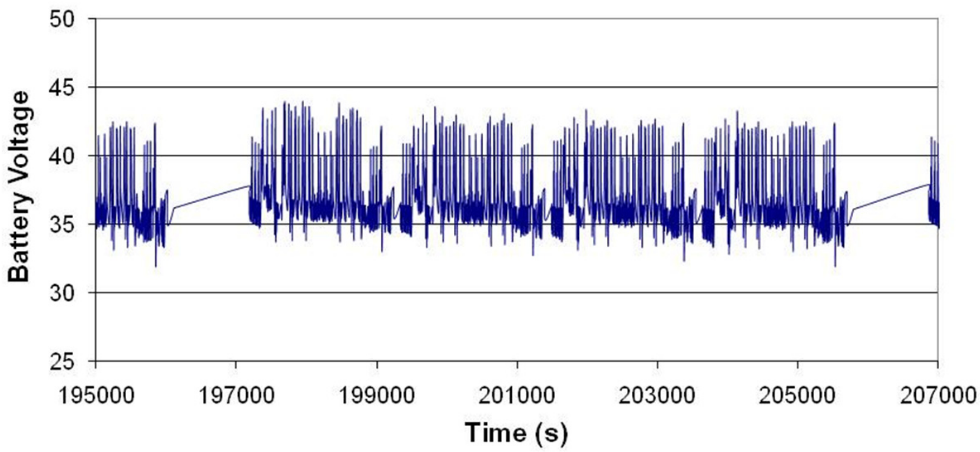


Figure 25. Voltage response of three FUB modules (53 to 63% SOC and 30°C [86°F]) after 60,000 miles of simulated service.

4.3.5 Operation of an EPUB Vehicle Pack (14, 12-V Modules) Under a Simulated Honda Civic Hybrid Electric Vehicle Profile for 60,000 Miles

A full vehicle-sized battery pack comprising of 14, 12-V EPUB modules (nominal 168 V) was provided by East Penn. It was first subjected to a capacity test (80% DOD, 6.3 Ah; 100% DOD, 7.5 Ah; as shown in Table 6) before commencing duty under SHCHEVP (53 to 63% SOC and 30°C [86°F]). After completion of 9,735 simulated miles (550 cycles), the voltage of the string dropped unexpectedly. On closer inspection, it was discovered that one module had failed. This failure may have been a result of a faulty module or related to the initial capacity tests, which were conducted to 100% DOD. It was decided that all future capacity tests would be conducted to 80% DOD.

The faulty module plus one other (which was required for use in the vehicle pack, as discussed in Section 4.4.6) were removed, and the remaining 12 modules were subjected to an equalization charge and capacity test (80% DOD, 6.6 Ah; as shown in Table 6) before being restarted under SHCHEVP.

The battery pack (which now comprises 12, 12-V modules in series) has now operated for the scheduled 60,000 miles. The capacity of the pack has decreased slightly during this period. However, the number of miles delivered between each simulated engine recharge remained stable at 53 miles until 62,835 miles were driven, when the number of miles between recharges began to drop slightly.

The individual voltages of the EPUB modules within the string have been monitored during operation. Figures 26 and 27 show the voltage of the weakest and the strongest module under the

SHCHEVP duty after both 10,000 and 45,135 simulated driving miles. After 45,135 miles, the difference in voltage between the two modules at the point of harshest acceleration (1,940 seconds in Figure 26; 165 seconds in Figure 27) is only 250 mV. In summary, the performance of the different modules within the pack is even and is considered very promising.

Table 6. Capacity of EPUB vehicle battery bank during simulated cycling (53 to 63% SOC and 30°C [86°F]).

Simulated Miles Travelled	Number of Cycles	Number of Modules in Series	1-h Capacity 100% DOD (Ah)	1-h Capacity 80% DOD (Ah)	No. of Miles Driven Before Simulated Engine Recharge Required
0	0	14	7.5	6.3	—
9,735	550	14	2 modules removed	2 modules removed	—
10,000	565	12	—	6.3	—
18,585	1,050	12	—	6.3	53
27, 435	1,550	12	—	6.4	53
36,285	2,050	12	—	6.1	53
45,135	2,550	12	—	5.9	53
53,985	3,050	12	—	5.9	53
62,835	3,550	12	—	5.8	48

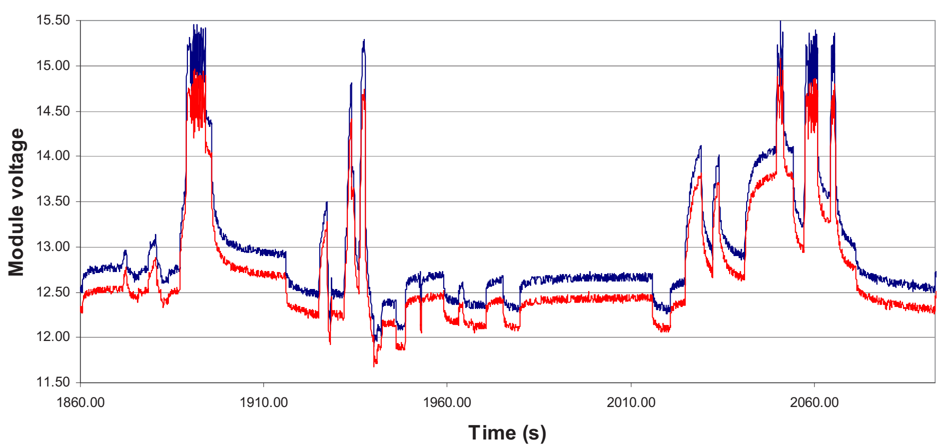


Figure 26. Voltage of weakest and strongest modules within the 12-module EPUB string during SHCHEVP duty (after 10,000 miles of simulated service; 50 to 60% SOC).

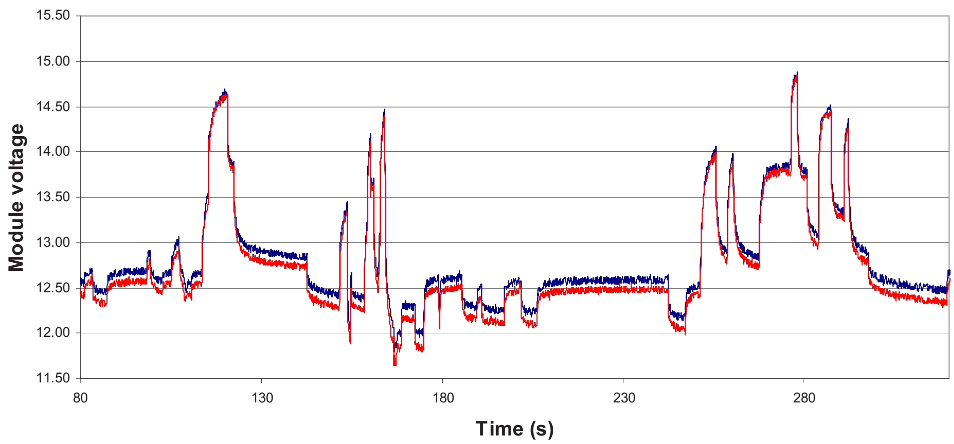


Figure 27. Voltage of weakest and strongest modules within the 12-module EPUB string during SHCHEVP duty (after 45,135 miles of simulated service; 50 to 60% SOC).

4.4 Tasks 4 to 8 – Vehicle Preparation and Battery Management System Development

In this task, a Honda Civic HEV has been retrofitted with an EPUB pack. The following sections describe progress both in vehicle construction and operation.

4.4.1 Honda System Overview

The HEV battery is controlled by a system combining a battery control module (BCM) in communication with a motor control module (MCM). The communication protocol between the BCM and MCM is a standard controller area network (CAN) messaging system. The BCM collects real-time information on the battery packs parameters, controls fan, and contactor operation. The battery pack parameters include voltage sensing at 11 sections of the battery pack (12 cells make up one section), current sensing, SOC, and temperature at three places in the battery pack.

The MCM controls the power flow of the motor to/from the battery pack, operation of the DC/DC converter, and air conditioning power module. Motor power is used to charge the battery pack (regeneration power) or assist in vehicle performance (drive power).

The battery parameters collected by the BCM are converted by multi-variable matrix tables into constraints that are sent to the MCM, which uses them to control power flow to/from the battery pack. CAN messages are used to send data containing drive power limits, regeneration and drive motor torque limits, real-time battery power, and SOC from the BCM to the MCM. It is not fully known how these messages are used within the MCM to control power flow, because the messages do not change with respect to one another (i.e., the drive power constraint does not go down with low SOC value) or fully constrain power levels at all times. This leads us to believe that the MCM also contains some form of matrix tables that take into account multiple variables at once.

4.4.2 UltraBattery Retrofit and Control Hardware Implementation

The ideal way of implementing the control changes in order to use the UltraBattery pack in place of the NiMH pack would be to reprogram the BCM with tables corresponding to the parameters of the UltraBattery. The second best way would be to replace the BCM entirely with another module that could perform all of the BCM's functions but include the necessary changes for the UltraBattery pack. However, without the ability to reprogram the BCM and no way of gaining full knowledge of all functionality performed by the BCM, the only way to control battery use is to control communication between modules. This entails intercepting the CAN messages sent by each module and altering the data within the messages to best possibly suit the actual battery use desired. In order to alter some messages, all messages must be intercepted and either passed through intact or altered accordingly.

In order to effectively intercept all messages, a device would need to be able to read all messages coming from both control modules, logically decide if any altering is needed, then send that message out to the other control module. This device would effectively cut the existing CAN bus into two with each side containing the same or similar messages. The CAN bus between the BCM and MCM has a very strict timing structure that is used to determine the quality of the connection and output a diagnostic trouble code to the main engine control unit if the quality is out of Honda's specifications. The way this diagnostic trouble code is transferred to the main engine control unit is unknown; therefore, the messaging structure must stay within the specifications for the vehicle to operate.

The BCM also outputs a diagnostic trouble code when the 11 voltage sensing leads are not present or are not within a range of approximately 10 V of the voltage measurement of the MCM. Because the voltage levels are outside of the range of a single UltraBattery module, a resistor network that takes in total pack voltage and divides by 11 (one for each input) must be in added into the hardware.

4.4.3 UltraBattery Control Strategy

The objective of the new control strategy is to be able to operate the Honda Civic Hybrid with an UltraBattery pack with little compromise in vehicle performance. Unfortunately, some trade-off will be required because complete access to the system control is unavailable. In order to effectively control the vehicle's use of the battery, the regeneration and drive power and torque constraints sent out by the BCM are modified, along with the SOC. The power and torque constraint messages are altered based on a proportional-integral feedback control scheme. This negative feedback control loop continuously alters the constraint messages based on pack voltage, which allows the batteries to operate within a desired voltage range. The control operates on a once-per-CAN message basis for which all necessary messages are updated every 10 minutes. The SOC sent to the MCM is the actual calculated SOC of the battery pack as determined through Ah-counting and a correction factor using OCV, following a rest period. This correction factor is needed because Ah-counting becomes inaccurate over time because the charge efficiency of the UltraBattery packs is always less than 100% and varies with SOC and rate of charge. With this knowledge, the SOC is based on Ah-counting while the vehicle is in use, then adjusted based on pack OCV divided by the number of modules converted to SOC (as shown in Table 7) every 10 times the vehicle turns on. This strategy was used because, without control of how the vehicle is being driven, the battery usage must be considered random; therefore, the only known time of open-circuit rest is during a vehicle off state. As such, when a vehicle key-on event occurs at the time immediately before the battery contacts are engaged, the battery OCV is sensed and used for SOC correction.

It has been demonstrated (as discussed in Section 4.3.1) that the performance of the UltraBattery packs is improved if some form of routine recovery charge can be delivered. The frequency of such a recharge would not have to be any greater than every 5,000-10,000 miles, and would not require more than 30 minutes.

Table 7. SOC correction table based on average module OCV.

SOC (%)	Average Module OCV (V)
90	12.68
80	12.55
70	12.41
60	12.29
50	12.17
40	12.05
30	11.90

4.4.4 Battery Management System

The battery management system performs the following functions:

- Intercepting CAN messages
- Logically deciding which messages to change and which to pass through
- Regeneration and drive power and motor torque constraint adjustments
- Ah counting and SOC correction.

The battery management system also monitors the following parameters during vehicle operation:

- Maximum temperature
- Pack voltage
- Current
- SOC.

4.4.5 Pack Configuration and Battery Enclosure

The battery pack contains 14 modules in a series string. There is space between each module to accommodate air flow for cooling purposes. The modules are configured to force air to flow over each module. The battery enclosure is made of six-gauge aluminum. It has enough space to hold up to 14 UltraBattery modules, the Junction box (shown in Figure 28), and the battery management system. The enclosure allows for use of the cooling system as designed by Honda, unless extra cooling is needed. This is possible by keeping the intake holes in the same place and sealing the area between the fabricated enclosure and the remaining Honda enclosure.

An enclosure and battery compartment for the EPUB has been designed and manufactured (shown in Figure 29). The enclosure fits into the same space as the standard Civic NiMH battery pack, with some extension into the vehicle trunk. The enclosure can hold up to 14 of the EPUB packs and the battery management system. It also has tabs for mounting what Honda refers to as a Junction Box, which normally is directly attached to the NiMH pack. The Junction Box contains current sensing circuitry, safety interlocks, and fuse protection, all of which are essential to the vehicle operating in its normal capacity.

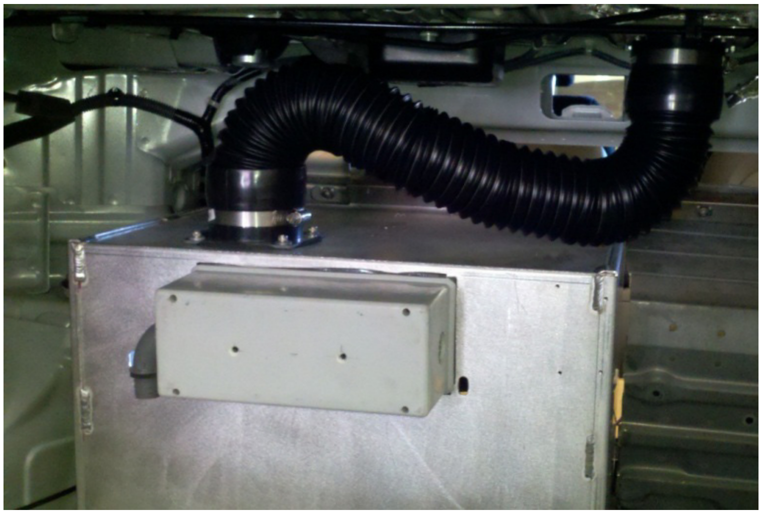


Figure 28. Junction box and the cooling duct.

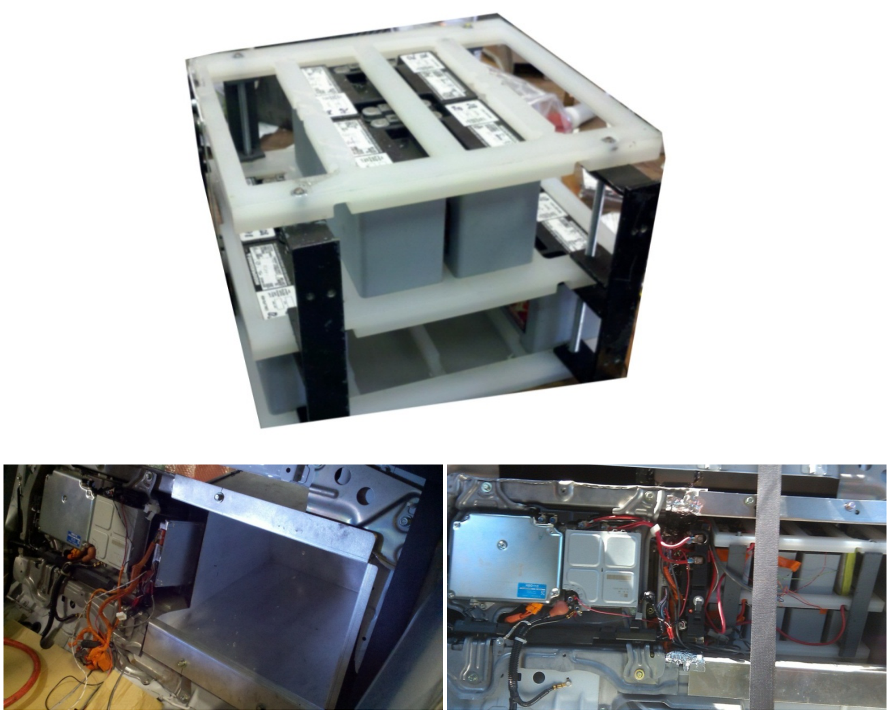


Figure 29. Battery compartment and its configuration in the vehicle.

4.4.6 Vehicle and Battery Operation in the Field

A new 2010 Honda Civic HEV was retrofitted with a pack of 14, 12-V East Penn UltraBattery modules (Figure 30), along with the appropriate control systems. After two weeks of preliminary driving, it was found that the capacity of two modules had dropped to 2 to 3 Ah. The modules were recharged and equalized, but the capacity could not be recovered. It is considered that either: (1) the modules were faulty; or (2) some damage was done to modules during the initial capacity tests to 100% DOD. As with the laboratory pack, capacity tests are now restricted to 80% DOD.

Figure 30. UltraBattery modified 2010 Honda Civic Hybrid.

One of the failed modules was replaced with the last remaining spare, while the second failed unit was replaced with a module from the laboratory pack (as discussed in Section 4.3.5). The battery pack then performed well for 1,500 miles, at which time it was shipped to Argonne for Dyno testing. Unfortunately, a small but continuous current drain on the battery occurred when the vehicle was stationary and waiting for tests, which damaged the batteries. A new battery pack was then fitted to the vehicle and the source of the current leak was removed. The voltages of the weakest and strongest modules within the new EPUB pack during a recent drive period are shown in Figure 31. It can be seen that there is a minimal difference between the voltages, both during an acceleration test (i.e., 150 to 450 seconds) and highway driving (i.e., 450 to 650 seconds). This indicates that all batteries are close in performance and capacity.

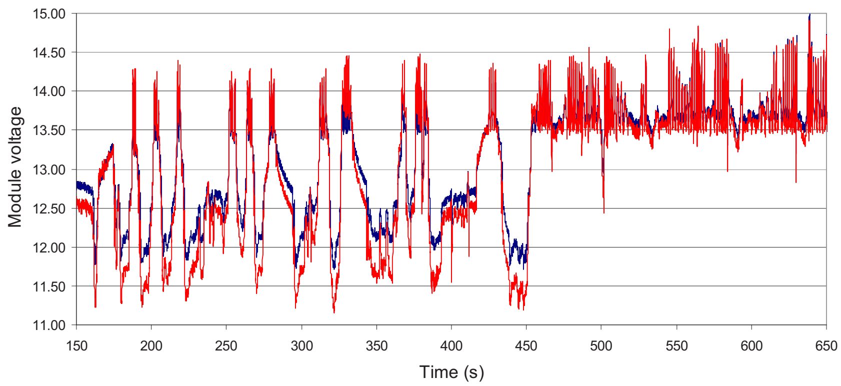


Figure 31. Voltage of weakest and strongest modules within the 14-module EPUB vehicle pack.

The acceleration and coast down baseline testing of the vehicle was conducted. Table 8 shows the acceleration performance comparison of the UltraBattery-modified Honda Civic versus its original hybrid model.

Table 8. Acceleration performance comparison of UltraBattery-modified 2010 Honda Civic HEV versus original 2006 Honda Civic HEV.

Tested Items	UB-Modified 2010 Civic Hybrid	2006 Honda Civic Hybrid[a]
0 to 60 mph(s):	14.7	13.6
Quarter mile (s):	21.1	19.6
Maximum speed (mph):	95.7	101.4
6% grade speed (mph):	74.7	80.9
3% grade speed (mph):	85.0	97.8
Maximum grade (%):	28.6%	31.0%

a. Acceleration test data on original Honda Civic HEV conducted by ECOtality in 2006.

Figures 32 and 33 show the charts of acceleration test on the 2006 Civic Hybrid and UltraBattery-modified 2010 Civic Hybrid. The blue lines give the voltage reading of the battery and the red lines give the speed reading during the test. These comparisons indicate that the UltraBattery-modified vehicle has a very similar performance versus the original one.

The coastdown testing of the converted UltraBattery Honda Civic, following SAE J1263, obtained the vehicle road load coefficients shown in Table 9. The modified vehicle uses 14 UltraBattery modules. The battery compartment weights roughly 124 lb, which is about 60 lb heavier than the weight of the NiMH battery pack the original Honda Civic contains. This moderate weight change in battery hardly affects the vehicle coastdown performance. The coastdown coefficients of the 2006 Honda Hybrid and Environmental Protection Agency standards are listed in the table as well. The table shows the UltraBattery-converted vehicle essentially has the same performance on coastdown compared with the original vehicle. The “B” coefficient is the only one the Honda Civic delivers smaller than the Environmental Protection Agency standards; however, because it generally is a small number, this variance is not expected to cause a big difference on vehicle performance. (The “A” coefficient roughly corresponds to the tire rolling resistance terms. The “B” describes higher order rolling resistance factors in addition to mechanical rotating friction losses. And “C” represents the air drag coefficient).

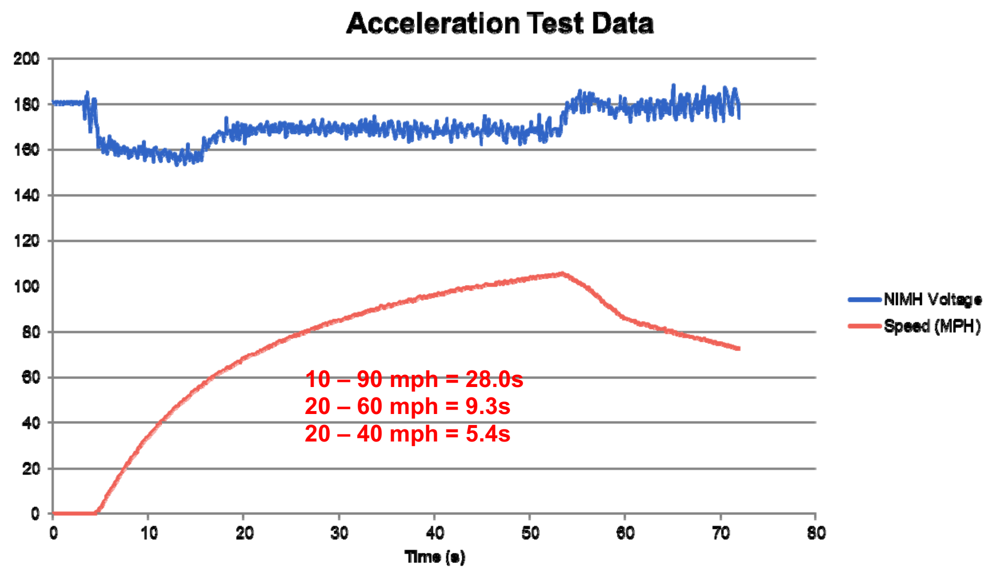


Figure 32. Acceleration test chart of original Honda Civic HEV with a NiMH battery.

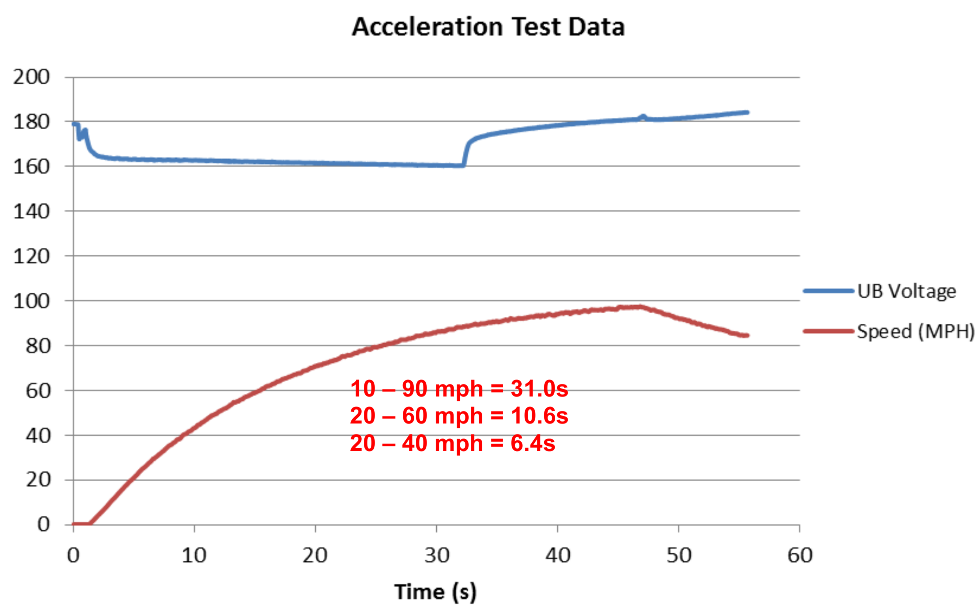


Figure 33. Acceleration test chart of UltraBattery-modified Honda Civic HEV.

Table 9. Coastdown coefficients comparison.

ECOtality-derived coastdown coefficients – 2010 UltraBattery Civic		
A	B	C
36.06	-0.25	0.022
ECOtality-derived coastdown coefficients – 2006 Civic Hybrid		
A	B	C
37.4	-0.17	0.020
Environmental Protection Agency-derived coastdown coefficients		
A	B	C
38.0	-0.045	0.022

Table 10 presents the coastdown test data comparison of the 2006 Honda Civic Hybrid and UltraBattery-modified 2010 vehicle.

Table 10. Coastdown test data comparison: 2006 Honda Civic HEV versus UltraBattery-Modified 2010 Honda Civic HEV.

	Original Honda Civic HEV[a]		UltraBattery-Modified Honda Civic HEV[b]	
Mileage Intervals (mph)	Calculated Coastdown Time Intervals (sec)	Measured Coastdown Time Intervals (sec)	Calculated Coastdown Time Intervals (sec)	Measured Coastdown Time Intervals (sec)
75 to 65	11.68	12.63	11.89	—
65 to 55	14.54	15.62	15.00	15.91
55 to 45	18.27	19.68	19.15	20.25
45 to 35	23.02	24.88	24.57	26.08
35 to 25	28.61	30.80	31.09	34.38
25 to 15	34.19	38.15	37.67	42.64

a. The test was conducted by ECOtality in 2006.

b. The test was conducted with a high-speed cutoff of 65 mile per hour.

Figures 34 and 35 present the velocity (mph) versus time (seconds) and force (lb) versus velocity (mph) curves during coastdown testing of the UltraBattery-modified 2010 Honda Civic HEV.

The vehicle currently was released to Argonne National Laboratory for dynamometer testing, based on SAE J1634, to determine fuel economy for a variety of different drive schedules: UDDS; HWFET; US06, and LA92, with and without air conditioning on. Table 11 indicates the UltraBattery-converted 2010 Civic delivers a very impressive fuel economy under all tested drive cycles.

The Honda Civic officially joined the test fleet in mid-October 2011. It is being operated by ECOtality in conjunction with EZ Messenger's courier fleet in Phoenix, Arizona. Around 5,000 miles are being accumulated per month during this fleet test. There are monthly data downloads that contain battery and vehicle information. The data being collected are an array of battery parameters such as most restrictive temperature, pack voltage, power, and vehicle parameters (such as speed). The individual module voltages and cell/module voltage deviation are being measured separately on the same monthly basis to monitor the health of the individual battery modules. The drive mileage and gallons of gasoline used during that month are being recorded to monitor the vehicle average fuel economy of the month.

An objective for the project, as stated in Section 3, is "To obtain an 'Experimental Vehicle' permit from the California Air Resources Board for the converted vehicle." The California Air Resources Board is no longer issuing experimental vehicle permits for hybrid vehicles. Because no modifications were made to the vehicle engine or chassis controller, such a permit is not required for vehicle licensing and will not be pursued.

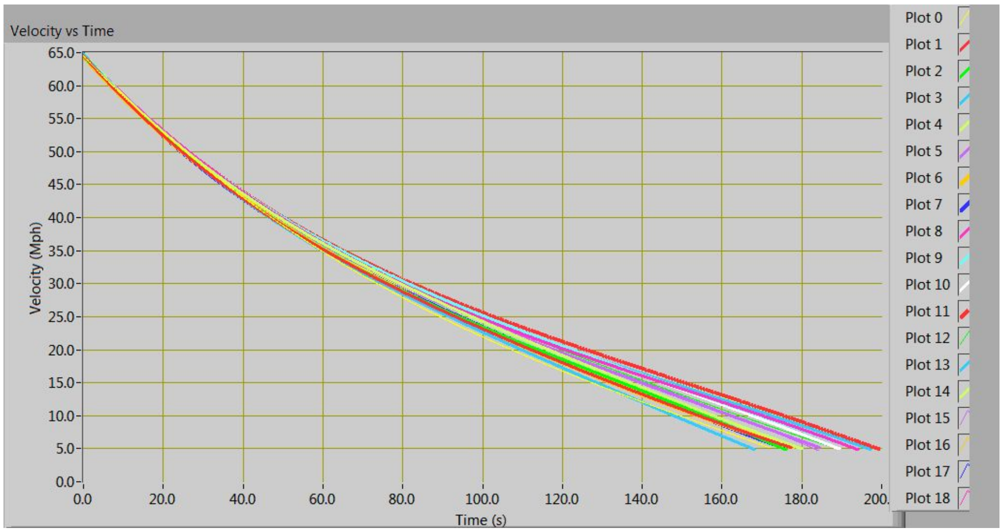


Figure 34. Coastdown test of the UltraBattery-modified 2010 Honda Civic HEV – velocity versus time.

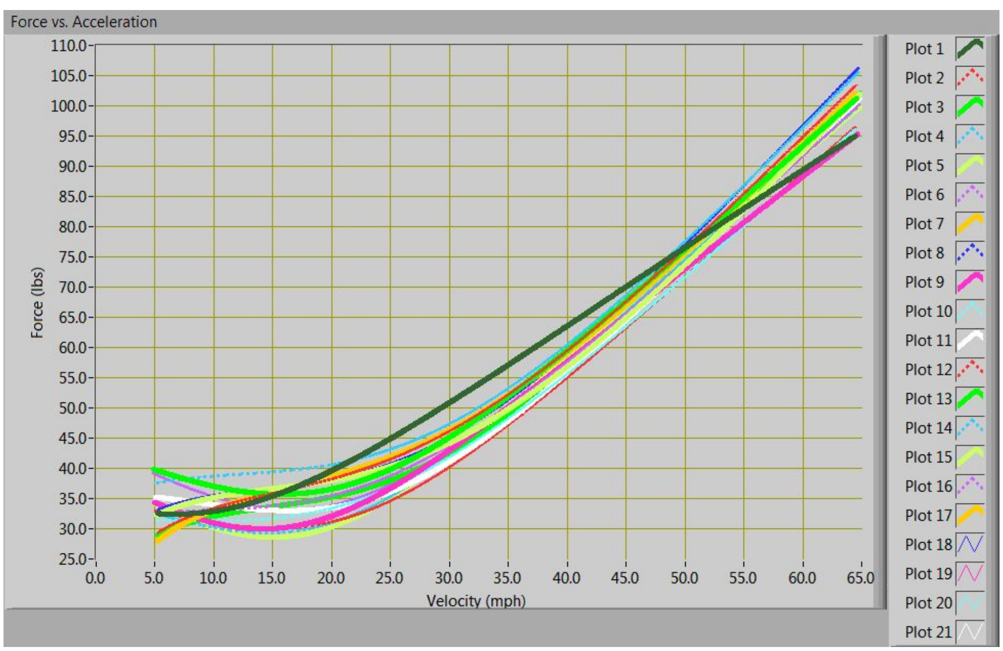


Figure 35. Coastdown test of UltraBattery-modified 2010 Honda Civic HEV – force versus velocity.

Table 11. Drive-cycle fuel economy comparison of UltraBattery-converted 2010 Civic Hybrid and 2006 Civic Hybrid.

Drive Cycle	2006 Honda Civic Hybrid	UltraBattery-Modified 2010 Civic*
UDDS (mpg)	53.1	61.7
Highway (mpg)	61.0	59.8
US06 (mpg)	37.0	35.6
LA92 (mpg)	Not performed	46.2
UDDS w/AC on (mpg)	36.0	49.8
Highway w/AC on (mpg)	47.7	45.9

* Environmental Protection Agency-estimated new MPG for 2010 Honda Civic Hybrid is 40 MPG city and 45 MPG highway.

Table 12. Accessory impact on UltraBattery-modified 2010 Civic drive-cycle fuel economy.

UltraBattery Civic without Accessories		UltraBattery Civic with Accessories	
Amp-hours out:	3.42 Ah	Amp-hours out:	4.39 Ah
Amp-hours in:	3.51 Ah	Amp-hours in:	4.32 Ah
Cycle fuel economy:	60.8 mpg*	Cycle fuel economy:	47.63 mpg*
Driving range:	747.8 miles	Driving range:	585.8 miles

* Cycle fuel economy is calculated using a combined drive where 55% is city driving (UDDS).

5. C3 PROJECT PROGRESS

5.1 Task 1 – Manufacture of Advanced Lead Acid Battery Consortium High-Carbon Batteries

The North Star Battery Co. manufactured a set of 75, 12-V, 10-Ah, high-carbon, HEV batteries (termed the ALABC high-carbon battery) for evaluation under SHCHEVP in this study. The design is based on ALABC research conducted previously at both Hammond and Axion Power and includes 2% (by weight) Ace Black carbon in the negative plates. A picture of the battery is shown in Figure 36.

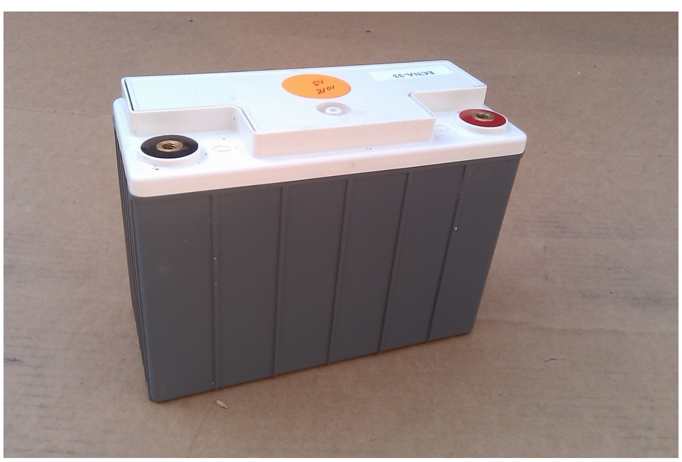


Figure 36. Picture of a 12-V, 10-Ah, ALABC high-carbon battery.

It also was planned to evaluate a battery pack from Axion Power (with a proprietary negative plate) under SHCHEVP. Unfortunately, production of this battery was cancelled and a carbon lead-acid technology from Exide was tested in its place. An Exide module (6 V, 10 Ah) is shown in Figure 37.

Figure 37. Picture of a 6-V, 10-Ah, Exide high-carbon battery.

5.2 Task 2 – Simulated Honda Civic Hybrid Electric Vehicle Profile

A simulated HEV duty cycle, termed the "Simulated Honda Civic HEV Profile" was developed in ALABC Project DP1.8 and was reprogrammed for use with the ALABC and Exide high-carbon batteries.

5.3 Task 3 – Performance of High-Carbon Advanced Lead Acid Battery Consortium and Exide Modules

5.3.1 Hybrid Electric Vehicle Screening Test

An ALABC high-carbon, 12-V module was operated for 35,000 cycles under the HEV screening procedure. At the end of testing, the capacity of the pack was approximately 50% of the initial value and the charging voltage was reaching 16 V after just 7,000 cycles (Figure 38). While this performance is far superior to that of standard lead-acid batteries (7,000 cycles to 50% capacity; 16-V after 1,000 cycles; Figure 8), it is much worse than that of the UltraBattery (see Section 4.2.3).

Two 6-V, spiral-wound modules from Exide were connected in series and operated under the HEV screening test. Based on the level of polarization experienced at the end of each charging period (Figure 38), the performance of the batteries was similar to that of the North Star Battery Co. units for the first 20,000 cycles. It is important to note, at this point, that for the same duty, the operating temperature of the Exide units was considerably lower than that of either the North Star Battery Co. or UltraBattery modules, presumably due to the spiral-wound nature of the design, allowing improved cooling. Given that higher temperatures have been shown to reduce the severity of polarization, it was decided to artificially heat the Exide modules. Accordingly, battery operating temperature was increased stepwise to 47°C (117°F), between cycles 20,000 to 33,000. As expected, polarization decreased, with the extent of the drop being much greater than anticipated.

The result raises the question as to the optimum operating temperature for lead-acid based batteries cycled under HEV conditions. Could high temperatures actually benefit battery performance and lifetime under such duty?

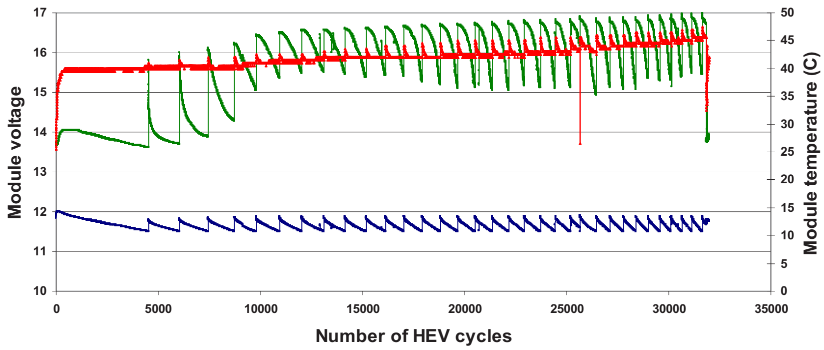


Figure 38. Performance of 12-V, 10-Ah, ALABC high-carbon module under the HEV screening test.

Traditional thinking would suggest that higher temperatures would result in premature failure as a result of positive-grid corrosion and perhaps active-material softening. Given that the average battery voltage during the high-temperature operation was around 13.5 V, corrosion may not be an issue under such conditions. Another important point is that the capacity of the modules was unaffected as a result of the higher-temperature operation between cycles 27,000 and 33,000; it was measured at 70% of initial at both points. This result is exciting given that both NiMH and lithium batteries (especially the latter) have significant disadvantages when operated at elevated temperatures. It is considered that life-time testing of lead-acid based technologies at elevated-temperature under real-time HEV conditions is a very important part in proving the technology suitable for use in HEVs.

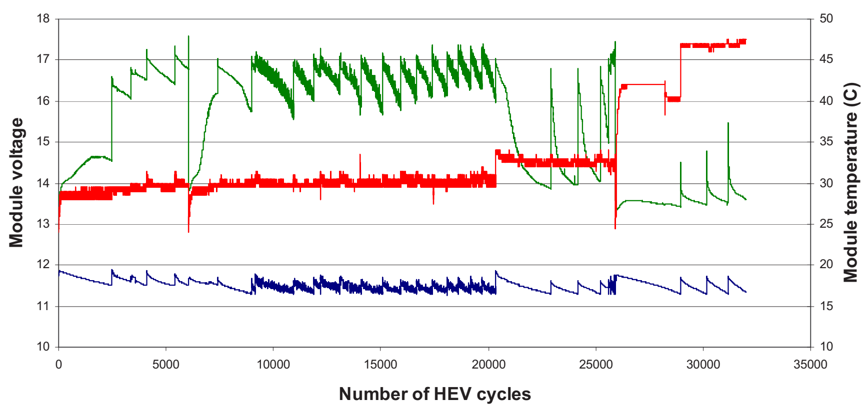


Figure 39. Performance of two 6-V Exide modules in series under the HEV screening test.

5.3.2 Simulated Honda Civic Hybrid Electric Vehicle Profile Test

An ALABC 12-V, high-carbon module was cycled under SHCHEVP (Figure 40). The module provided 40,391 miles of simulated service before failure. The capacity of the battery during this time dropped from 9.8 to 4.7 Ah during cycling, and toward the end of service, it could not support the required discharge power. Also, the battery-charging voltage was polarizing significantly, which indicates a significant reduction in charge acceptance. A second module was then operated under the SHCHEVP, but it also performed poorly and failed after approximately 40,000 simulated miles.

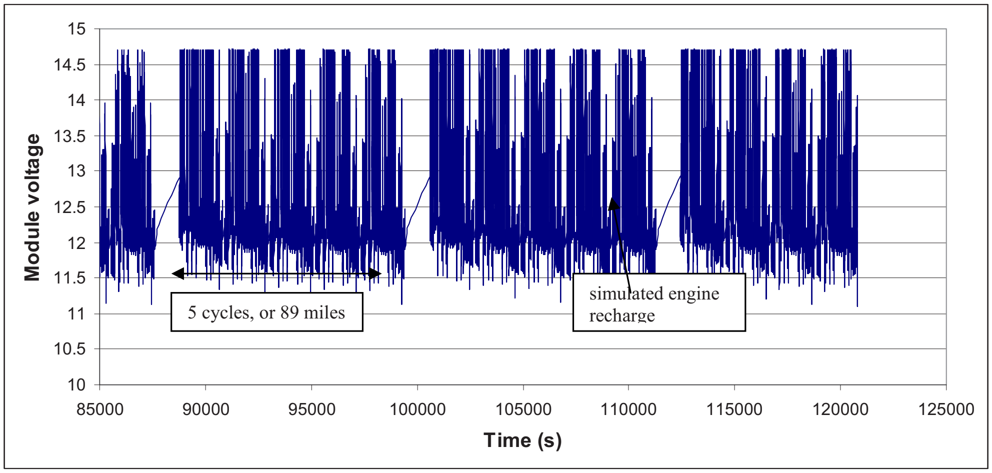


Figure 40. Voltage of a 12-V ALABC high-carbon module under SHCHEVP at the commencement of duty (note five cycles, or 89 miles, between simulated engine recharges).

5.4 Tasks 4, 5, 6, and 7 – Assemble, Commission, and Cycle Packs Under the Simulated Honda Civic Hybrid Electric Vehicle Profile

5.4.1 Advanced Lead Acid Battery Consortium High-Carbon Pack

A vehicle-sized pack comprising of 14, 12-V high-carbon ALABC modules has been assembled and fitted with a battery management system (shown in Figure 41). The performance of the pack was evaluated in terms of the strongest and weakest modules during operation under SHCHEVP (Figure 42).

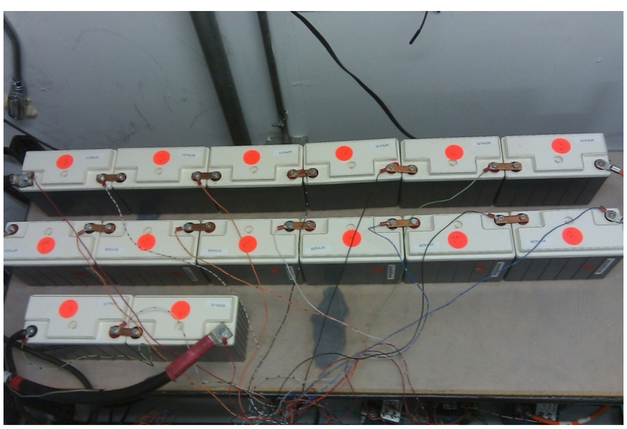


Figure 41. Picture of vehicle-sized ALABC high-carbon pack cycling in the laboratory.

It can be seen that the batteries were all well matched in performance, because their voltages differed by only 200 mV at the harshest acceleration point of the profile (i.e., approximately 800 seconds).

The pack delivered 27,000 simulated miles before failure. At this time, the capacity of 12 modules was around 80% of initial, while the remaining two were close to zero (0.3 Ahr). Logging of individual modules confirmed that two were low in capacity at the end of cycling (Figure 42).

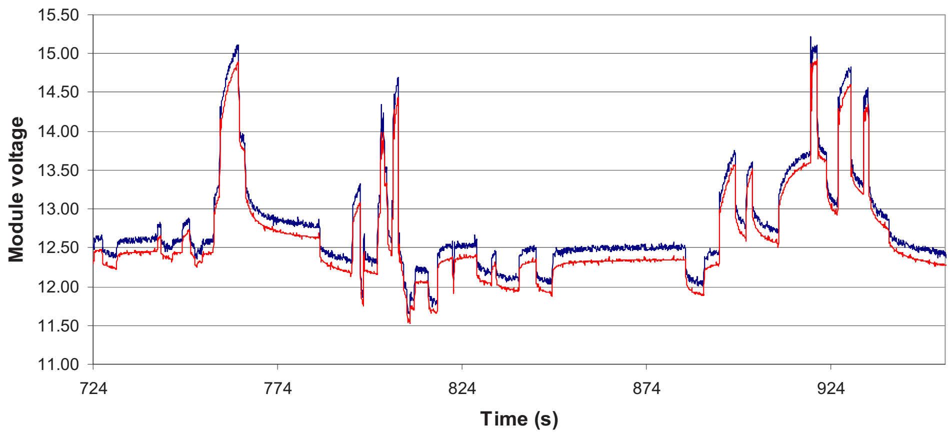


Figure 42. Voltages of the weakest and strongest modules in the ALABC carbon vehicle pack during operation under SHCHEVP.

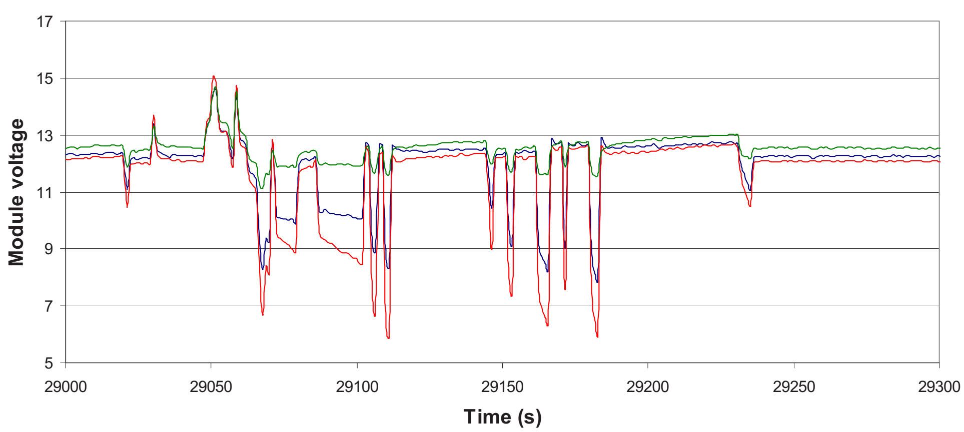


Figure 43. Voltages of the two weakest and the strongest modules in the ALAB carbon vehicle pack at the end of cycling under SHCHEVP.

5.4.2 Exide Pack

A set of 44, 6-V, 10-Ah modules was manufactured at Exide and shipped to ECOtality. Twenty-eight of these have been connected in series and operated under SHCHEVP duty as shown in Figure 44 (note these modules were selected from the rest based on capacity and open-circuit voltage).

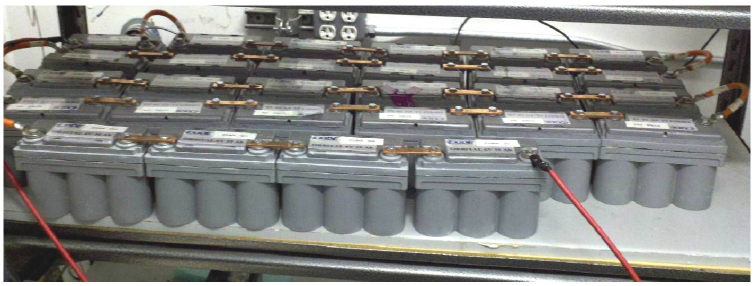


Figure 44. Picture of vehicle-sized Exide pack cycling in the laboratory.

The voltage of 12-V blocks (every two single Exide modules) within the pack was monitored during cycling. It can be seen in Figure 45 that the units were in balance at the commencement of duty. Unfortunately, two modules failed after completion of 6,100 simulated miles. These were then removed, the remaining modules recharged, and another two new, fully charged modules added. Cycling was recommenced, but another four modules failed after a total of 8,900 miles. These were replaced, but the pack failed again after a total of 12,500 miles, at which stage it was retired from service. The voltage of 12-V blocks from the pack at the end of cycling is shown in Figure 44. It can be seen that 7 of the 12 blocks had low voltages, which suggests that at least seven, 6-V modules were faulty. The capacity of the failed modules was about 3.2 Ahr.

In summary, the results to date suggest that both the ALABC high-carbon North Star Battery Co. and Exide technologies require further development before they are ready for use in HEVs. However, inconsistencies in cell manufacture may have contributed toward the reliability issues encountered in this study.

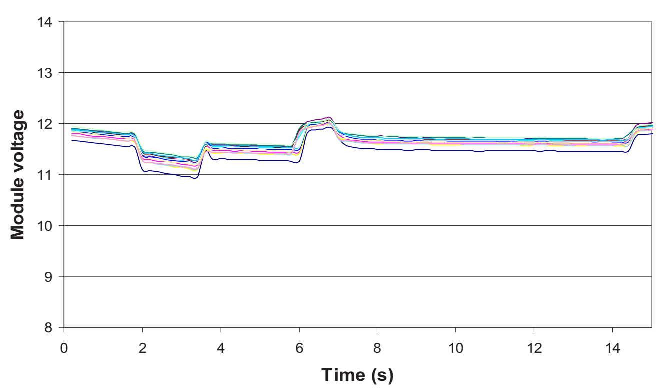


Figure 45. Voltages of each 12-V block within the Exide vehicle pack at commencement of cycling under SHCHEVP.

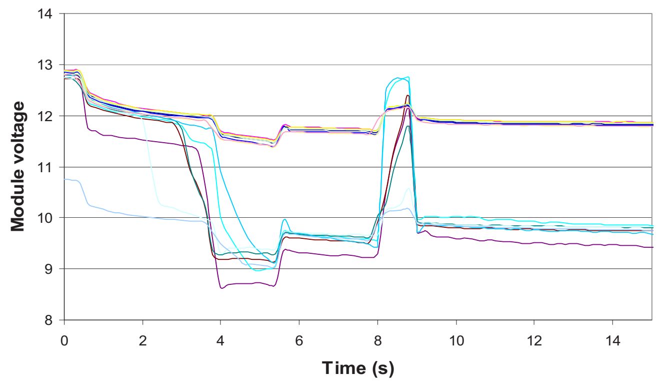


Figure 46. Voltages of each 12-V block within the Exide vehicle pack at the end of cycling under SHCHEVP.

6. CONCLUSION

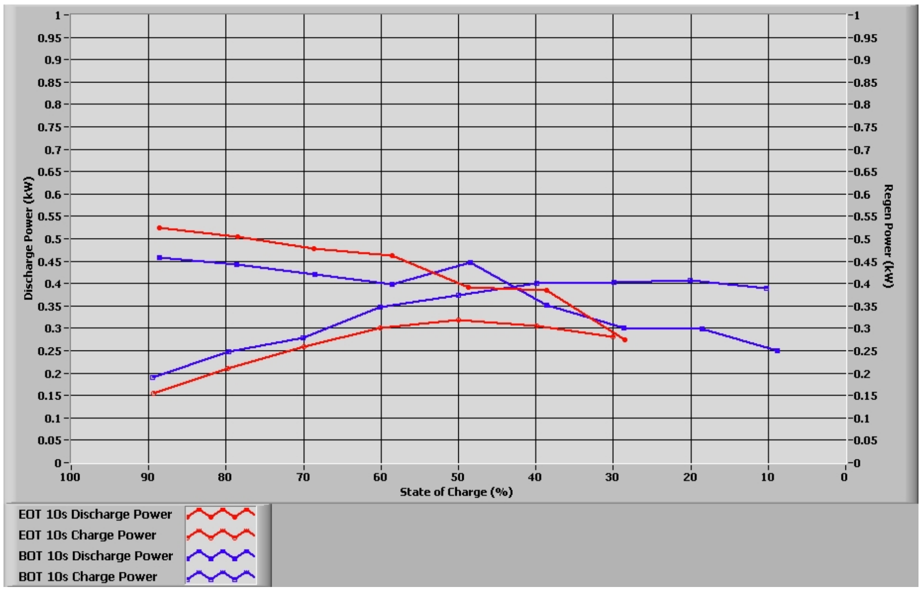
In summary, the data suggest that the East Penn UltraBattery packs are at least a match for the Furakawa UltraBattery packs in both capacity and HEV performance. Also, the life-cycle data under simulated HEV conditions suggest that the East Penn UltraBattery packs are capable of lasting the design life of modern HEVs. However, the fuel consumption of an UltraBattery-powered HEV may be higher than an equivalent NiMH vehicle at low temperatures and toward the end of vehicle life as a result of a reduction in charge acceptance of the UltraBattery. (Note that at present the extent of any increase in fuel consumption is not known.) Finally, the high-carbon, lead-acid ALABC battery from the C3 Project requires further development before it is suitable for duty in vehicles such as the Honda Civic HEV.

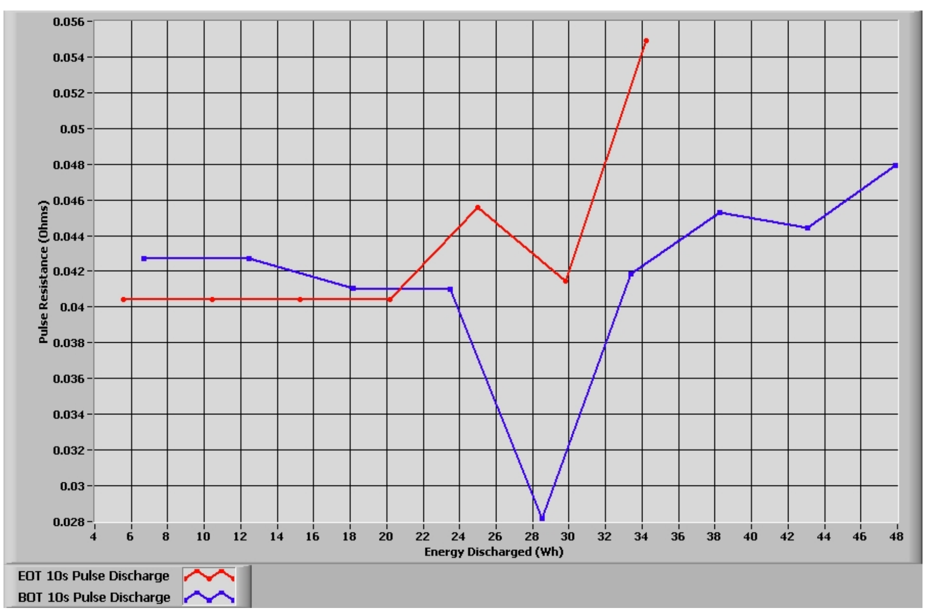
Appendix A

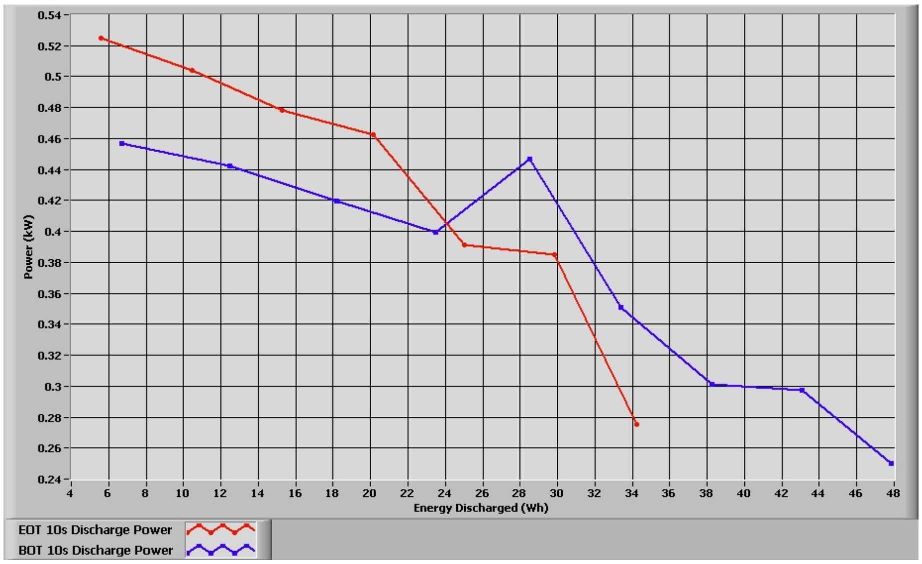
HPPC Results for Furakawa UltraBattery Module

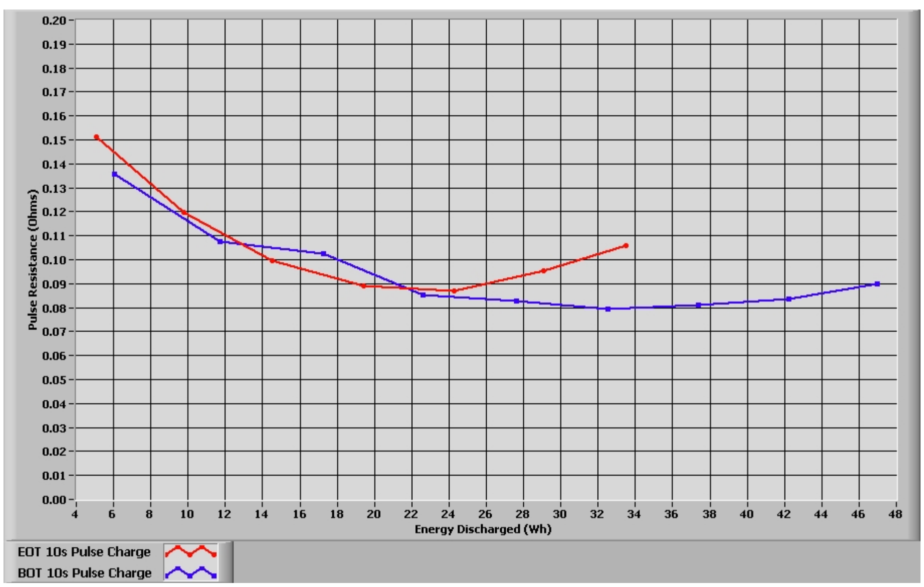
Appendix A

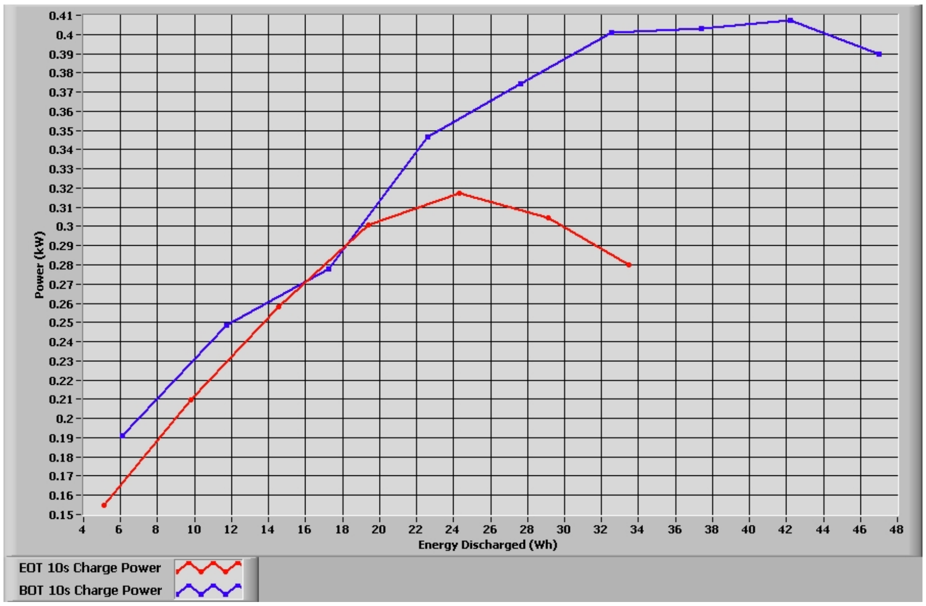
HPPC Results for Furakawa UltraBattery Module

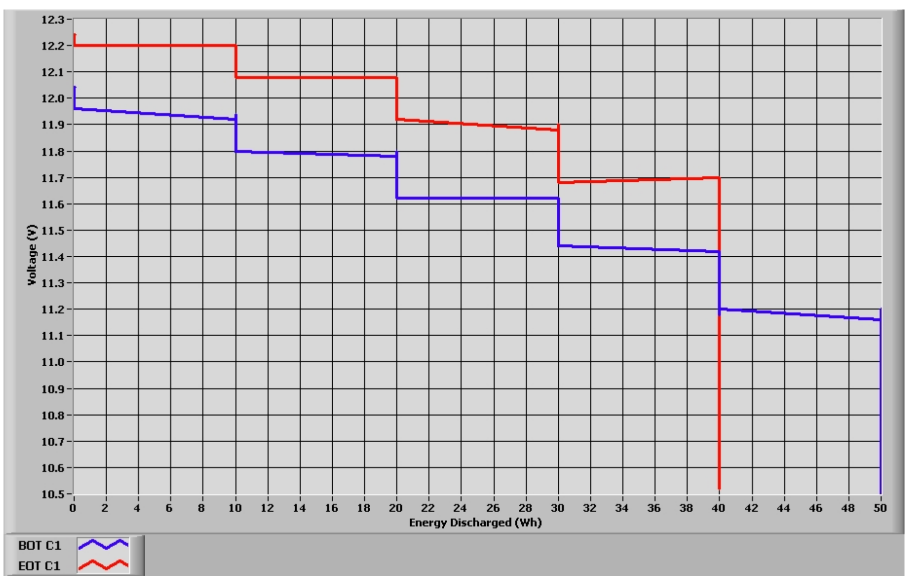


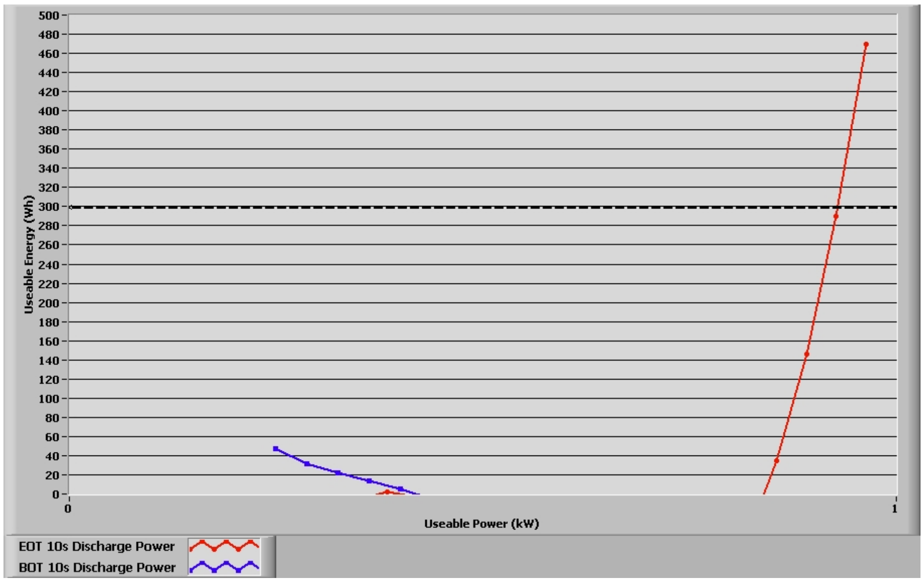



Power (kW)
Energy Discharged (Wh)
EOT 10s Discharge Power
BOT 10s Discharge Power


Pulse Resistance (Ohms)
Energy Discharged (Wh)
EOT 10s Pulse Charge
BOT 10s Pulse Charge


Power (kW)
Energy Discharged (Wh)
EOT 10s Charge Power
BOT 10s Charge Power


Voltage (V)
Energy Discharged (Wh)
BOT C1
EOT C1

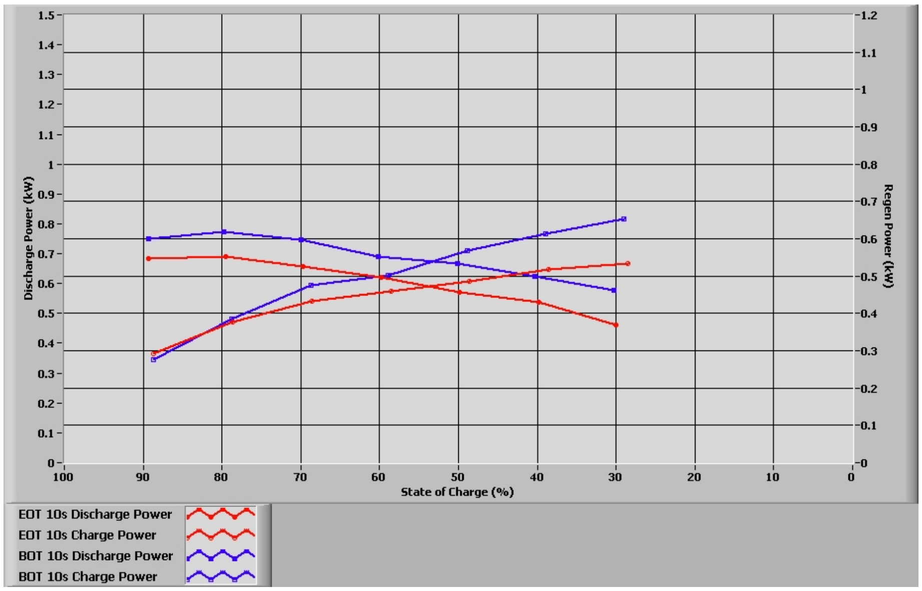

Useable Energy (Wh)
500
480
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0
1
Useable Power (kW)
EOT 10s Discharge Power
BOT 10s Discharge Power

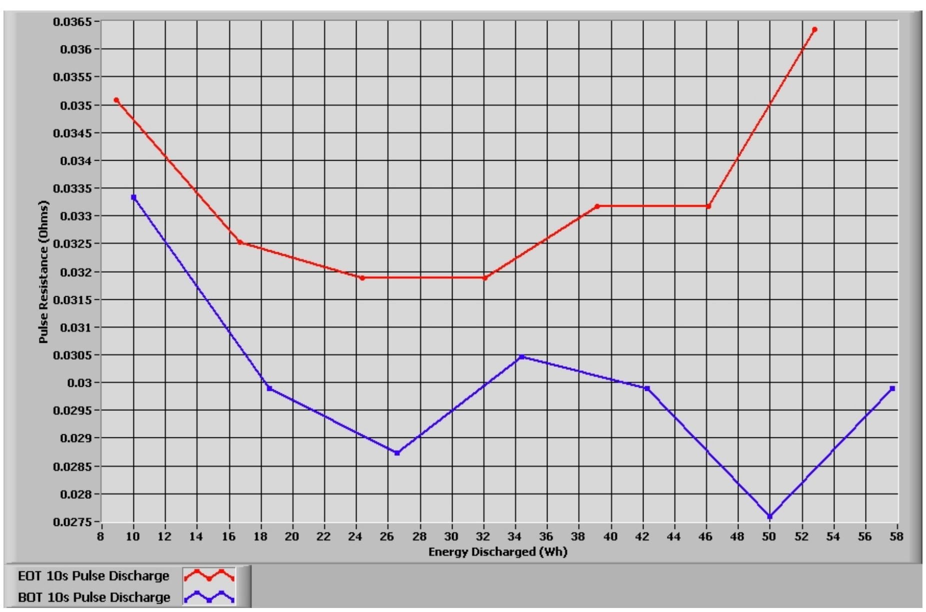
Appendix B

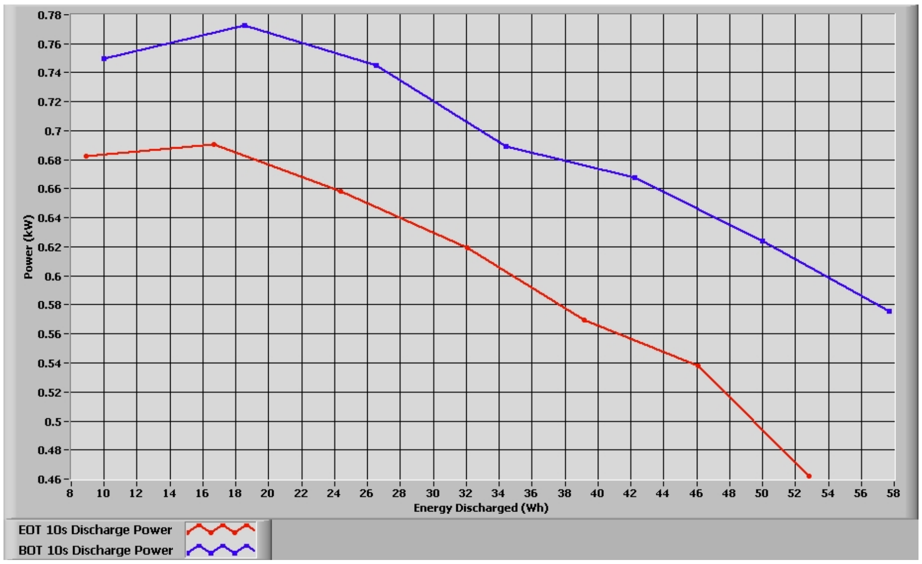
HPPC Results for East Penn UltraBattery Module

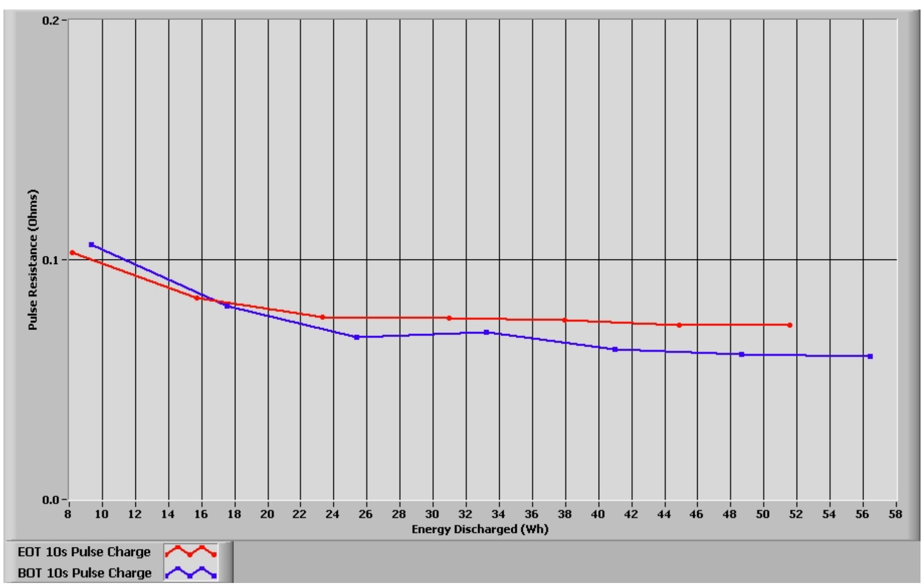
Appendix B

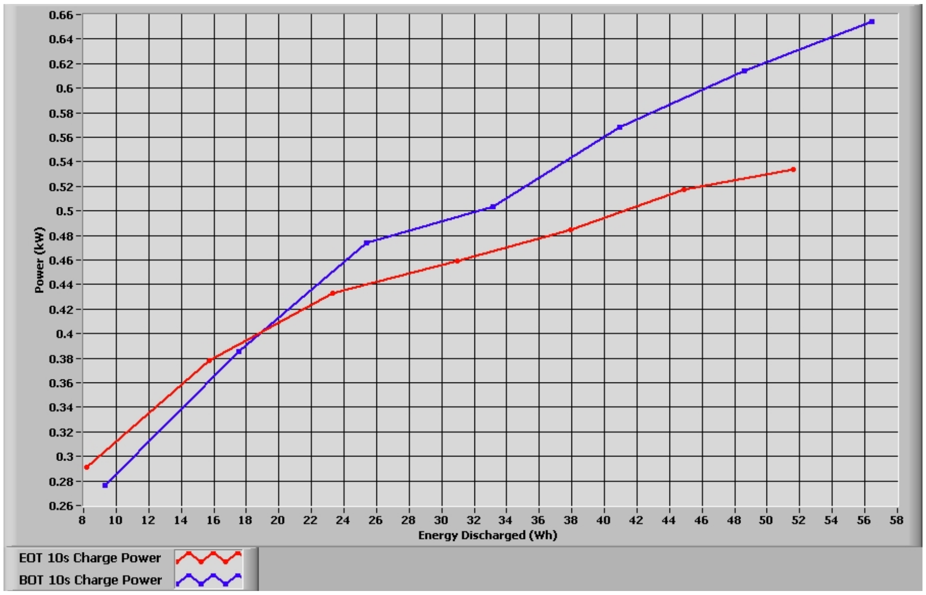
HPPC Results for East Penn UltraBattery Module

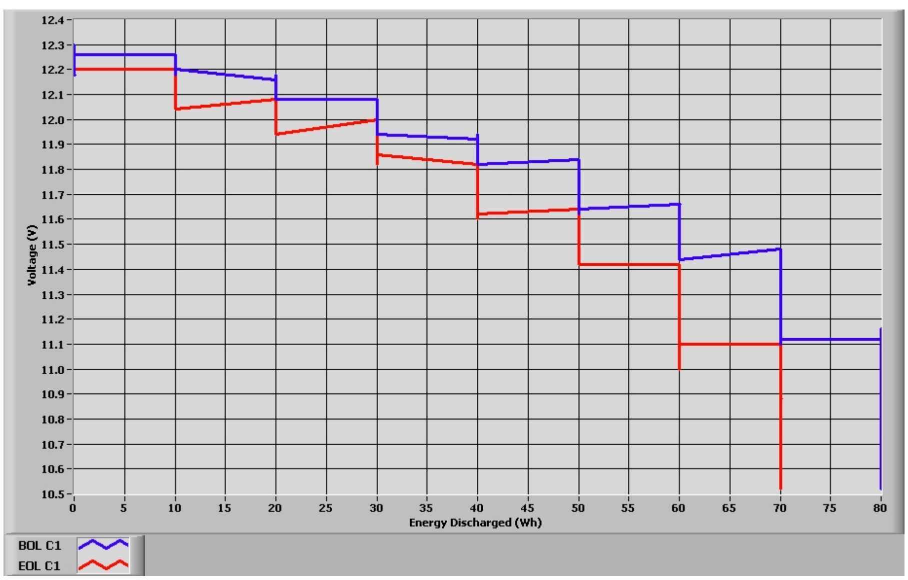


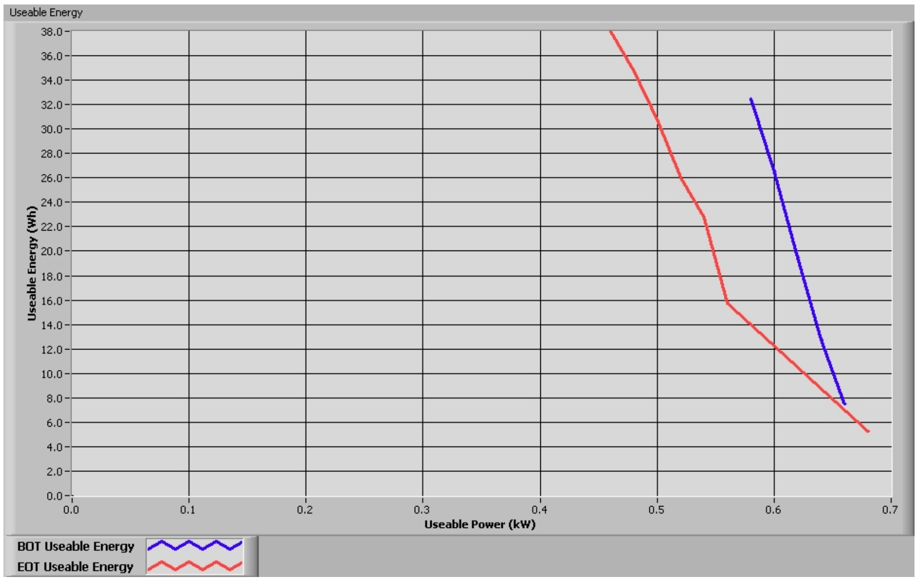



Power (kW)
Energy Discharged (Wh)
EOT 10s Discharge Power
BOT 10s Discharge Power


Pulse Resistance (Ohms)
Energy Discharged (Wh)
EOT 10s Pulse Charge
BOT 10s Pulse Charge


Power (kW)
Energy Discharged (Wh)
EOT 10s Charge Power
BOT 10s Charge Power


Voltage (V)
Energy Discharged (Wh)
BOL C1
EOL C1

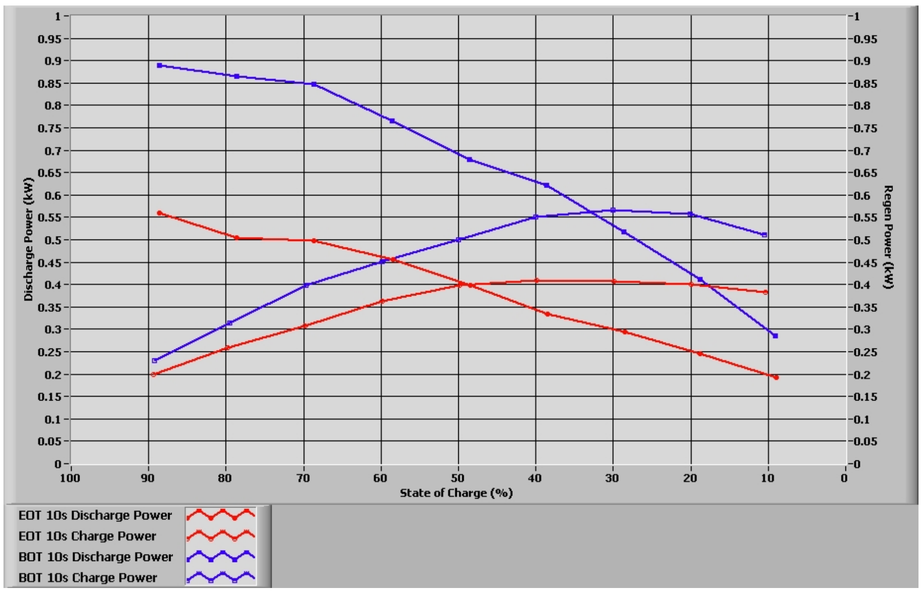

Useable Energy
Useable Energy (Wh)
38.0
36.0
34.0
32.0
30.0
28.0
26.0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Useable Power (kW)
BOT Useable Energy
EOT Useable Energy

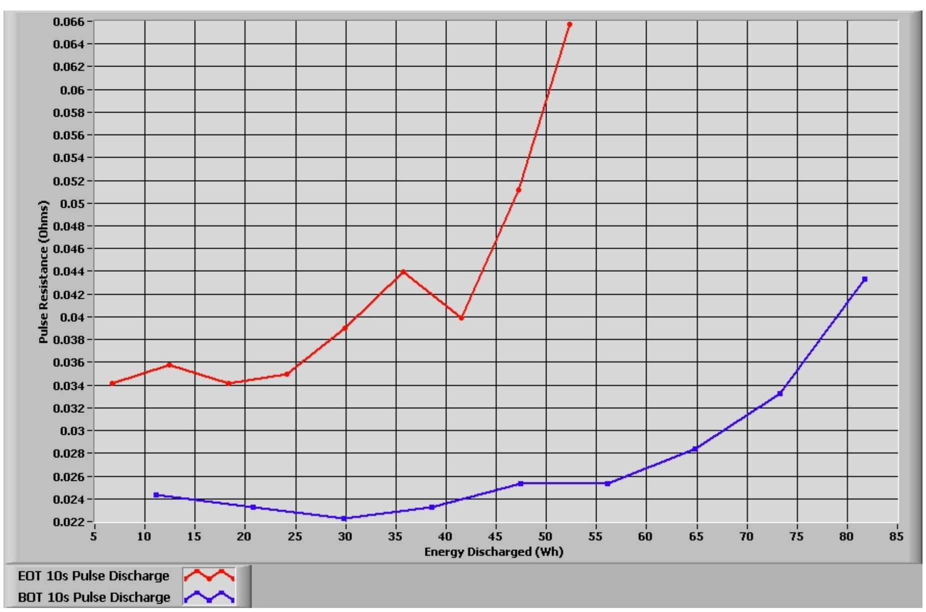
Appendix C

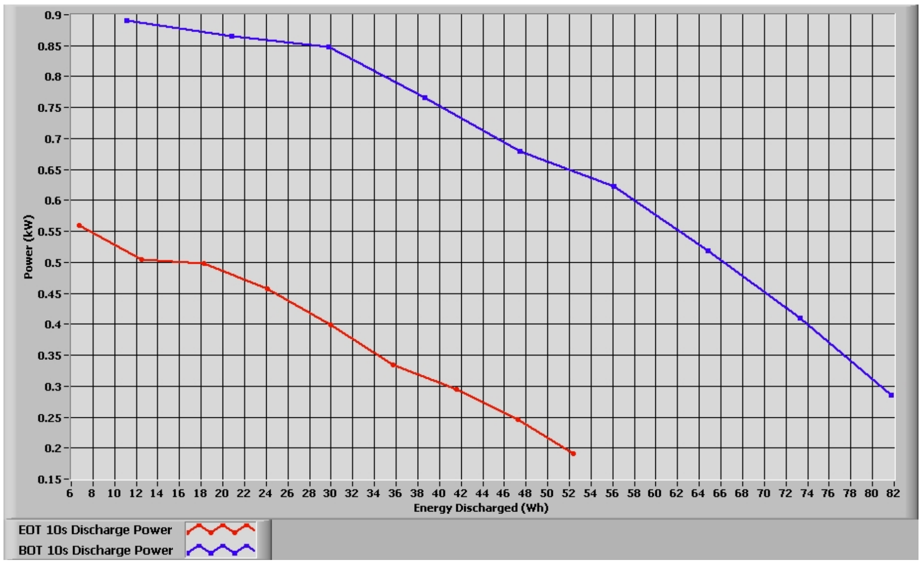
HPPC Results for Genesis Module

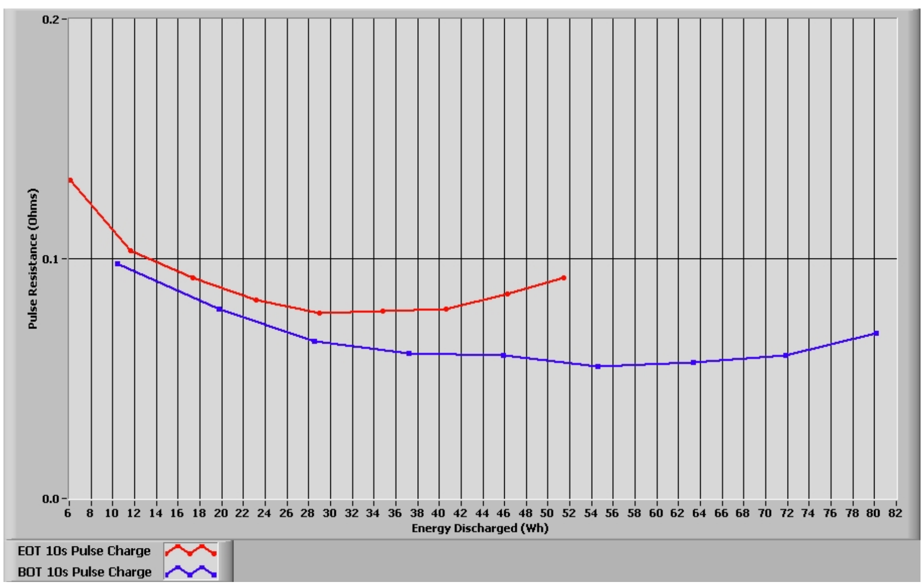
Appendix C

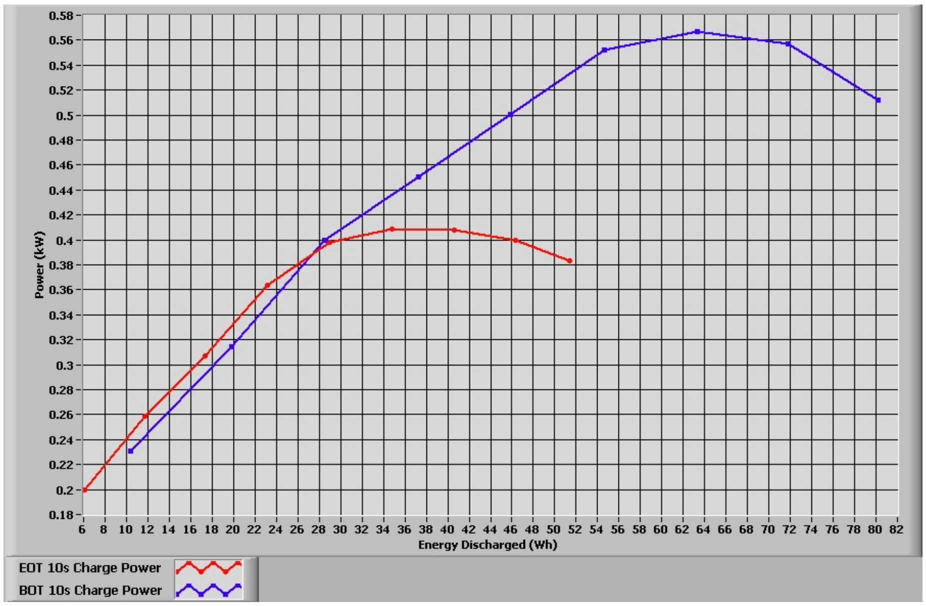
HPPC Results for Genesis Module

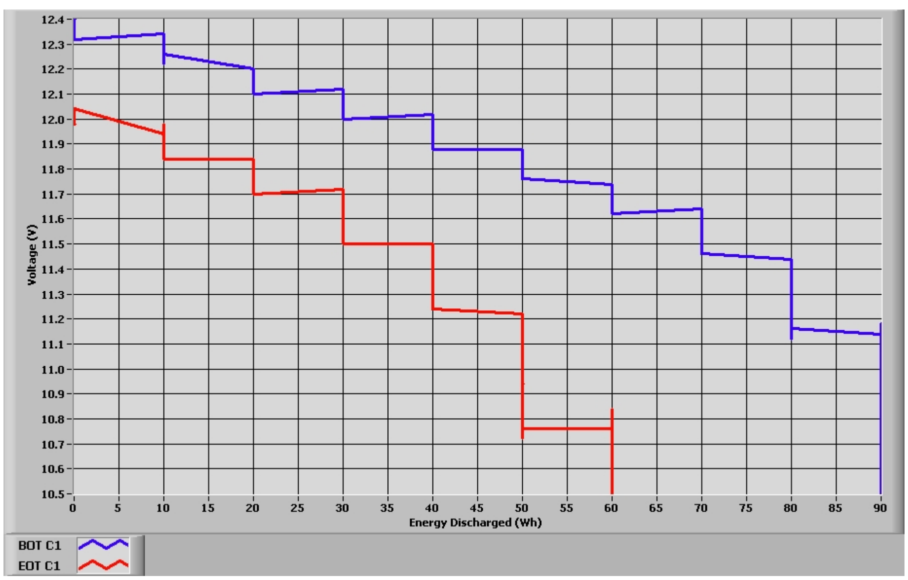


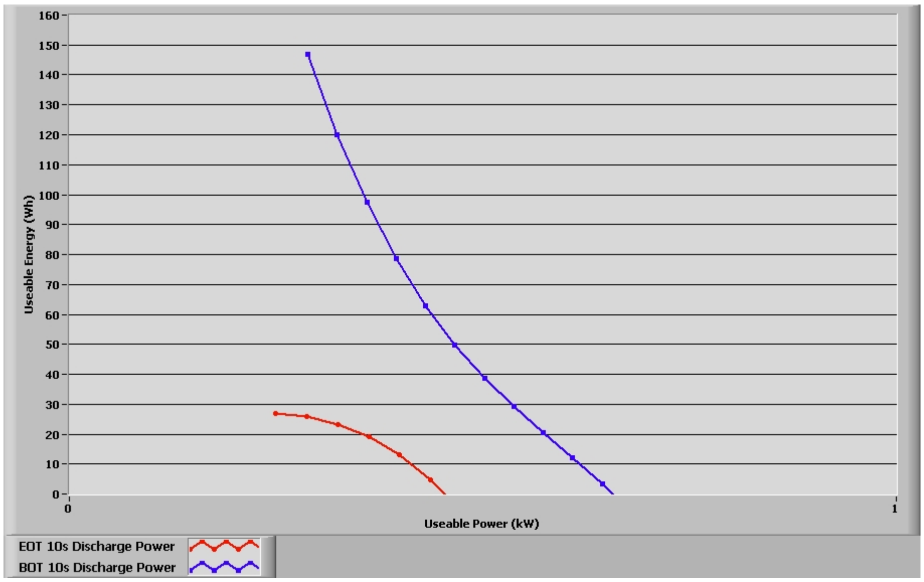



Power (kW)
Energy Discharged (Wh)
EOT 10s Discharge Power
BOT 10s Discharge Power


Pulse Resistance (Ohms)
Energy Discharged (Wh)
EOT 10s Pulse Charge
BOT 10s Pulse Charge


Power (kW)
Energy Discharged (Wh)
EOT 10s Charge Power
BOT 10s Charge Power


Voltage (V)
Energy Discharged (Wh)
BOT C1
EOT C1


Useable Energy (Wh)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
1
Useable Power (kW)
EOT 10s Discharge Power
BOT 10s Discharge Power