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U.S. Hybrid and Lithium Technology Corporation GAIA Battery: Initial System Characterization for the Plug-In Hybrid Electric Vehicle Yard Tractor

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Technical Update, March 2012

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THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Southern California Edison Electric Vehicle Test Center (EVTC)

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ABSTRACT

Diesel-powered tractors, called *yard tractors*, are used to shuttle cargo trailers from point to point within the confines of a port facility, terminal, or yard. A plug-in hybrid electric vehicle (PHEV) yard tractor design was proposed as a way to reduce operation emissions and diesel fuel use. The Electric Power Research Institute (EPRI) has designed and constructed a first-of-a-kind PHEV yard tractor.

Southern California Edison's (SCE's) Electric Vehicle Technical Center performed PHEV yard tractor battery and charger testing according to the Center's published procedures and in consultation with the battery manufacturer and the vehicle integrator. SCE evaluated the on-board charger by discharging the battery to a predetermined depth of discharge (DOD) level, and used the on-board charger to recharge the battery. SCE monitored the charger ac input and dc output to measure the overall system efficiency as well as the possible load impact on the grid and then repeated the test to validate the consistency of the data as well as to determine if the charger was properly charging the battery.

SCE concluded that during the charger test, the energy returned and the pack stop voltage were inconsistent. Ideally, the test should generate consistent results since the amount of energy removed was consistent. SCE was also unable to determine the cause of the erroneous state of charge values reported by the battery management system during the charger test.

SCE will use these results for future battery performance tracking. The capacity test results at this point were 84% of the rated capacity. The regenerative maximum power ranged from 76.92 to 110.22 kW, and the discharge maximum power ranged from 112.96 to 93.62 kW. The internal resistance calculated from the hybrid pulse power characterization (HPPC) ranged from 80.41 to 130.36 mOhm. No manufacturer ratings were available for maximum power and resistance because the battery system was integrated using single cells by U.S. Hybrid.

Keywords

Cargo handling equipment
Fleet vehicle
Lithium-ion battery
Plug-in hybrid electric vehicle (PHEV)
Port electrification
Yard tractor

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ON-BOARD CHARGER TEST

1.1 Introduction

SCE's Electric Vehicle Technical Center performed battery and charger testing according to its published procedures, and in consultation with the battery manufacturer and the vehicle integrator. SCE evaluated the on-board charger by discharging the battery to a pre-determine Depth of Discharge (DOD) level, and used the on-board charger to recharge the battery. SCE monitored the charger AC input and DC output to measure the overall system efficiency as well as possible load impact on the grid, then repeated the test to validate the consistency of the data as well as to determine if the charger was properly charging the battery.

1.2 On-Board Charger Test Setup

For the on-board charger test, the battery was discharged using an ABC-150 cycler to 75% DOD based on its rated capacity of 90 Ah, see Appendix A for battery pack and cell specifications. During the capacity test (Section 3) SCE noticed that the Battery Management System (BMS) State of Charge (SOC) parameter was resetting to 0% at around 15% SOC. The BMS SOC reset to 0% occurred when the minimum cell voltage reached 2.7V.

SCE set the battery pack to its original configuration after discharging the battery. The charger was energized and data acquisition equipment monitored the AC input and DC output. SCE allowed the charger to continue charging throughout the night.

The following morning, SCE connected the battery to the ABC-150 cycler and performed a charge, as specified in Section 3.1.1, followed by a discharge down to 75% DOD. The on-board charger test was then repeated again.

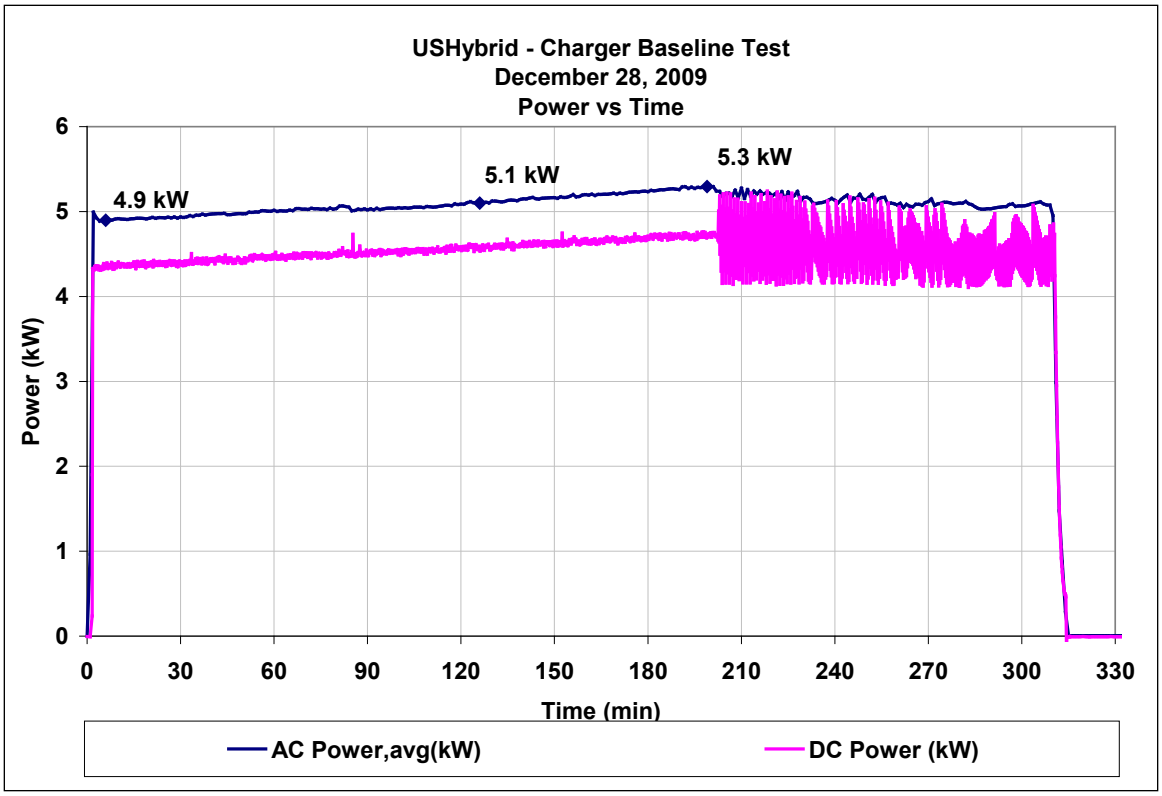

Figure 1-1
Charger Test 1 PQ Data Analysis Points

1.3 Charger Test Results

During the charger test, SCE installed a laptop with Vector CANAlyzer software to monitor the battery and charger CAN bus information. As soon as the charge started, the BMS reported a battery SOC of 95% in the first test, and 99% in the second test. SCE expected the reported BMS state of charge to be close to 15% SOC, as was reported to the ABC-150 cycler during the discharge portion of the test.

During the charger test on 12/28/09, the charger began to oscillate the output current, as shown in Figure 1-1. The AC data acquisition system also captured the oscillation, as can be seen in Figure 1-2. The same behavior was observed, only for a few minutes, during the charge performed on 12/29/09. Since the oscillation duration was not the same in both charger tests, SCE decided to only assess power quality during the stable part of the charge.

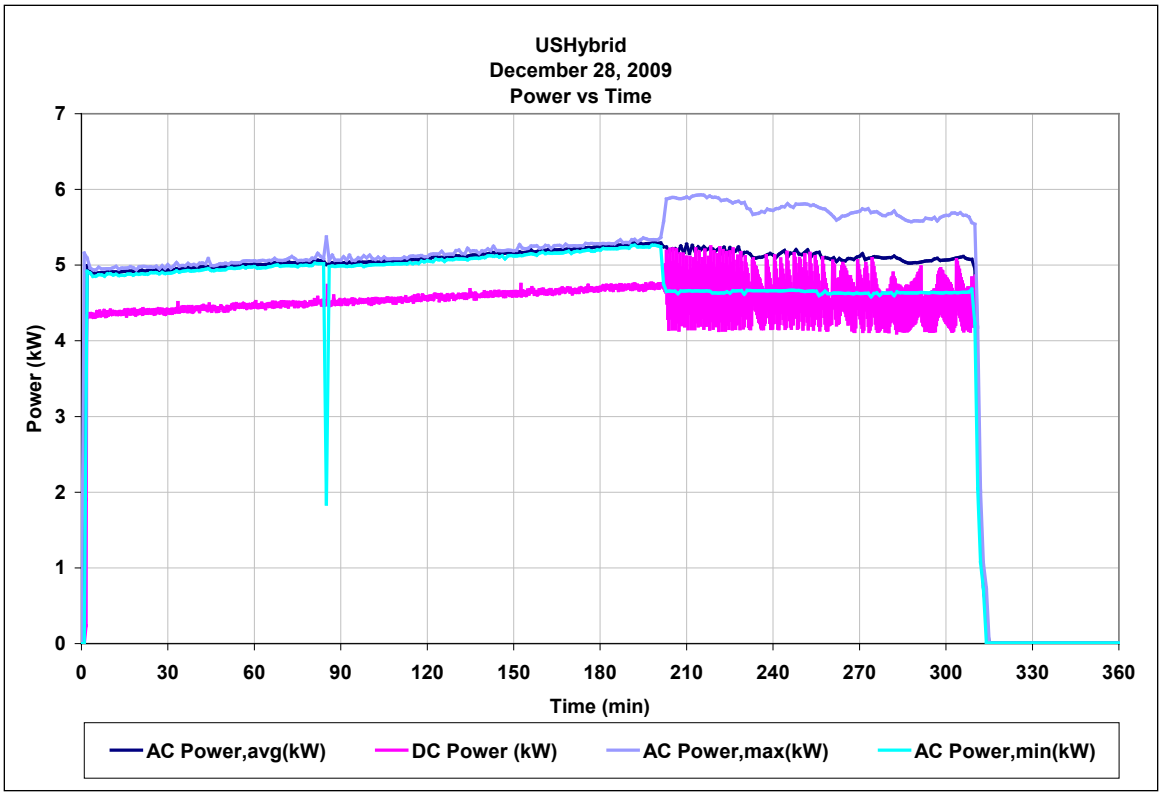

Figure 1-2
Charger Test 1 AC & DC Power vs Time

Another problem SCE encountered during the charger test was the charge return inconsistency. The energy removed from the battery on both tests was 67.5 Ah, 24.6 kWh, but the charge return between the two tests did not generate the same results; see Figure 1-3 and Table 3-2.

One problem was that the on-board charger did not stop at the same pack voltage; furthermore this voltage was not USHybrid's charge target pack voltage of 410V. For example, during the first charge the pack voltage reached 409V. During the second charge, the charger stopped when it reached 404V, as shown in Figure 1-3. SCE did not monitor cell voltage data when the charger was on, since it was not reported on the CAN Bus.

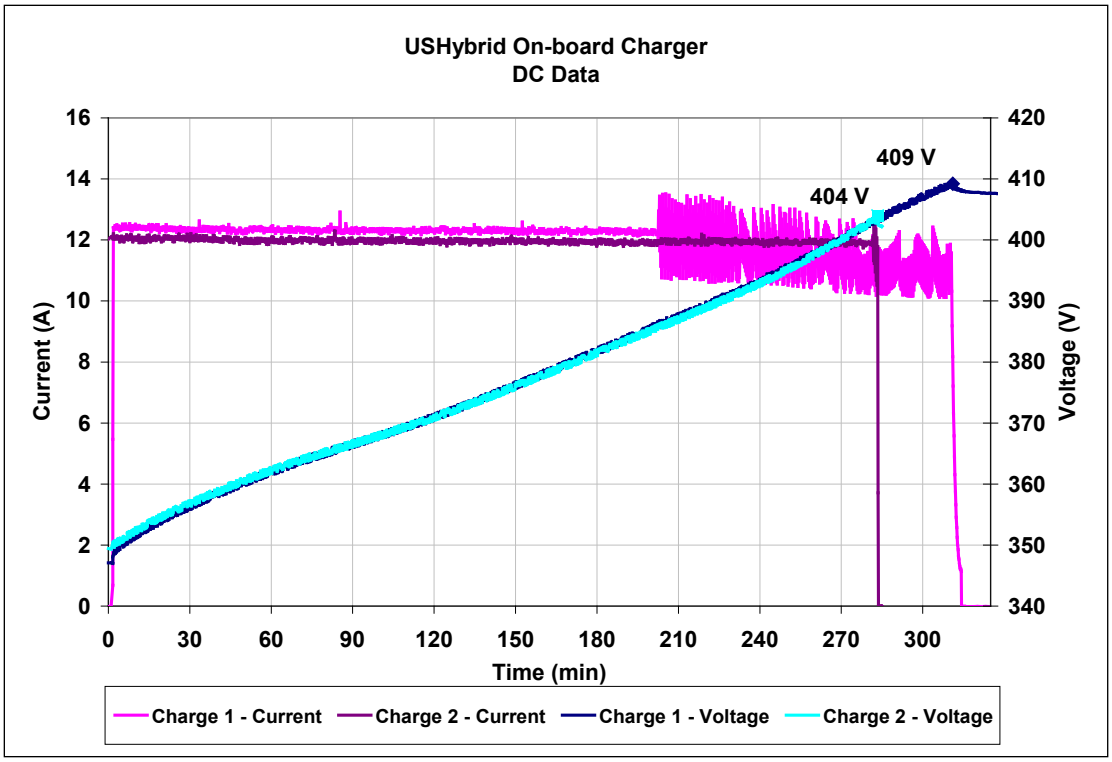

Figure 1-3
Charger Test 1 & 2 DC Data

1.3.1 On-board Charger Observations:

During the charger test, SCE encountered the following charger issues

Incorrect Sub ID Request:

ID 0x102 is requesting sub-ID 0x00 which is not defined. Based on the information USH provided on the charger, the system is capable of requesting cell voltages on ID 0x102 using sub-ID 0x18. Since the charger is requesting erroneous sub-ID the BMS does not respond to the data request on ID 0x102.

Erroneous SOC reporting:

During the first charger test, SOC on ID 0x100 Sub-ID 0x07 was reporting 95% when the battery voltage was 340V and the battery was actually discharged to 25% SOC.

Charge control:

- USH is requesting only the following info on ID 0x100:
- Sub-ID: 0x04 Temperature (max, min, avg)
- Sub-ID: 0x06 warning-error- status
- Sub-ID: 0x07 Short info (Vpack, I, Tavg, SOC, Delta V)
- Sub-ID: 0x08 Power forecast – Charge (I, P)
- Sub-ID: 0x09 Power forecast – Discharge (I, P)

2
POWER QUALITY (PQ) RESULTS

While monitoring the charger AC and DC behavior, SCE also collected power quality data. The only discrepancy between the two charges was during the oscillation portion of the charge. For that reason, SCE did not use the pulsing portion of the charge for the PQ analysis.

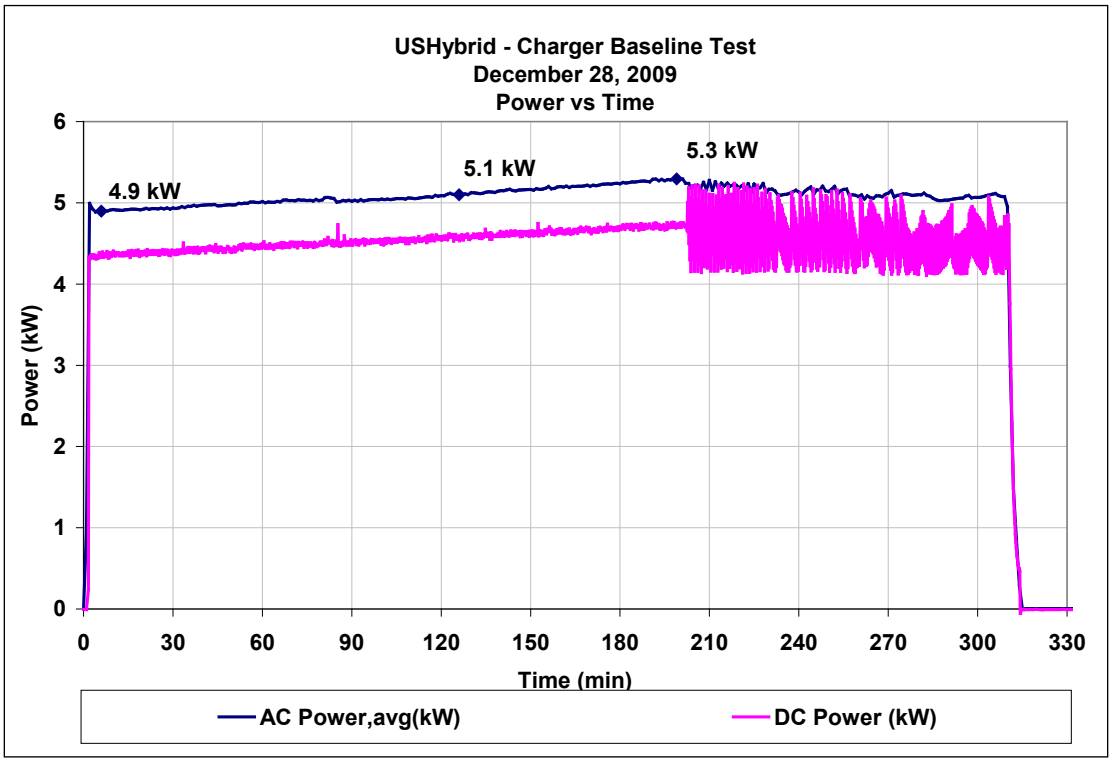

Figure 2-1
Power Quality Data Points (12/28/2009)

The data points selected for the PQ analysis are illustrated in Figures 2-1 and 2-2. The data points were averaged over a 5-minute interval and are listed in Table 2-1. No major issues were encountered during the stable portion of the charge.

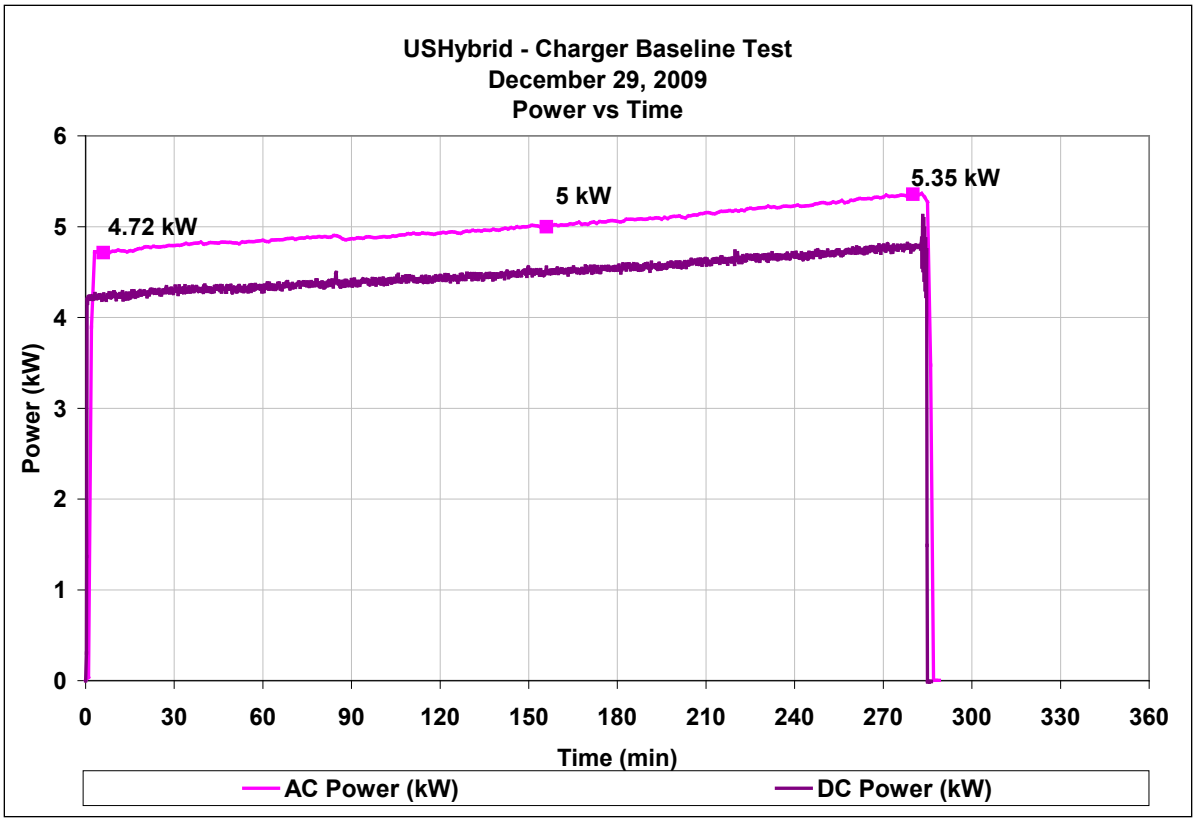

Figure 2-2
Power Quality Data Points (12/29/2009)

Table 2-1
Power Quality Results

Test Info		
Test date	12/28/2009**	12/29/2009
Nominal Voltage (V)	240	240
Energy Consumption (AC kWh)	26.34	23.76
Energy (DC kWh)	23.50	21.30
Min. Voltage (V)	236.10	240.53
Max. Voltage (V)	244.20	243.78

Power Quality Parameters	**Maximum Power**	**Avg. Power**	**Minimum Power**	**Maximum Power**	**Avg. Power**	**Minimum Power**
Voltage (V)	237.44	241.70	242.40	243.29	242.11	242.50
Current (A)	22.47	21.29	20.26	22.17	20.83	19.53
Frequency (Hz)	60.00	60	60.00	60.00	60.00	60.00
Active Power (kW)	5.30	5.10	4.90	5.35	5.00	4.72
Reactive Power (kVAR)	0.58	0.57	0.35	0.56	0.53	0.34
Apparent Power (kVA)	5.33	5.15	4.91	2.70	2.52	2.37
Power Factor	0.996	0.991	0.992	0.997	0.992	0.992
Max. Voltage thd (%)	1.48	1.37	1.33	1.35	1.30	1.35
Max. Current thd (%)	6.57	6.46	3.70	6.51	6.17	3.76

Note:

**All values are 5 min average around selected data point*

**Data calculated during non-pulsing portion of the charge

3
BATTERY REFERENCE PERFORMANCE TEST

3.1 Capacity Test Setup

SCE used cell voltage measurements to determine the end of the charge and discharge modes. A one hour break was allowed in-between the charge and discharge portion of the test. The pack level voltages for both tests are listed in Table 3-1. The rated capacity of the battery used for the tests is 90 Ah. The ABC-150 battery cycler used the following parameters for charging and discharging the USHybrid battery pack:

3.1.1 Charge Parameters

- Vcell,max = 4.2V
- Start Charge Current = 45A
- Stop Current = 2A
- Charge Algorithm: Constant Current – Constant Voltage (CC-CV)

3.1.2 Discharge Parameters

- Vcell,min = 2.7
- Current = 90A

Table 3-1
Capacity Test Pack Level Data

	Pack Voltage			Cell Voltage at End of Mode			
Test	Open Circuit Voltage Before Test	Last Recorded Voltage During Test	Open Circuit Voltage After Test	Vmax	Vmin	Vavg	Delta V
1C Discharge	415.38	305.96	328.98	3.209	2.699	3.062	0.51
C/2 Charge	337.3	416.5	416.46	4.197	4.135	4.166	0.062
1C Discharge	414.54	306.6	329.44	3.227	2.699	3.069	0.528
C/2 Charge	337.68	416.5	416.26	4.198	4.136	4.166	0.062

Delta V measured at the end on the charge/discharge

Table 3-2
Capacity Test Results - Discharge

Discharge										
Date	**Mileage**	**Test Type**	**Start Time**	**End Time**	**Duration (h)**	**Delta Cell Voltage at End of Mode (V) (1)**	**Start Temp. (1)**	**End Temp. (1)**	**Ah Out**	**kWh Out**
12/15/2009	552	C/1 Cap. Test	13:00	13:51	0:51	0.51	26	33	75.90	27.37
12/15/2009	552	C/1 Cap. Test	18:25	19:16	0:51	0.53	28	33	75.51	27.23
12/16/2009	552	HPPC	0:25	9:16	8:51	N/A	31	29	63.10	23.24
12/16/2009	552	HPPC	19:54	4:45	8:51	N/A	25	23	63.09	23.19
12/28/2009	556	Discharge to 75% DOD	11:35	12:20	0:45	0.21	25	28	67.50	24.60
12/29/2009	556	Discharge to 75% DOD	10:50	11:36	0:46	0.22	25	32	67.50	24.60
12/30/2009	556	C/1 Cap. Test - 85% DOD	12:38	13:26	0:48	0.5	23	32	71.63	25.60

Note:

(1) *Data gathered using manufacturer BMS – Calibration certificate not made available*

(2) *Calculation made using collected data from BMS*

Table 3-3
Capacity Test Results - Charge

Charge											
Date	Start Time	End Time	Duration (h)	Delta Cell Voltage at End of Mode (mV) (1)	Start Temp. (1)	End Temp. (1)	Ah In	kWh In	Ah Return (%)	Battery Efficiency (%)	Notes
12/15/2009	15:15	17:25	2:10	61	30	31	76.26	29.15	100.5%	93.9%	
12/15/2009	21:15	23:24	2:09	62	30	34	76.23	29.13	101.0%	93.5%	
12/16/2009	10:16	12:08	1:52	67	23.3	29	63.45	24.57	100.6%	94.6%	
12/17/2009	5:46	7:36	1:50	74	26	30	63.44	24.52	100.6%	94.6%	
12/28/2009	17:55	23:09	5:14	N/A	28	31	62.16	23.5	92.1%	N/A	Charged with on-board charger
12/29/2009	15:01	19:47	4:46	N/A	27	29	56.72	21.3	84.0%	N/A	Charged with on-board charger
12/30/2009	14:39	17:00	2:21	20	30	30	71.81	27.29	100.3%	93.8%	Charge pack voltage set to 410V

SCE measured the capacity over the two tests at 75.7 Ah (27.3 kWh) as seen in Table 3-2 and Table 3-3. The total Amp-hour removed was only 84% of the battery's rated capacity.

SCE performed an additional capacity test with the charge algorithm slightly modified, to compare with capacity test results that USHybid performed when it originally received the pack. The charger stop voltage was set to 410V. SCE set the charge to constant voltage when the target voltage was reached. The result from the modified capacity test was 71.63 Ah; US Hybrid reported 69 Ah and 70.53 Ah on the two tests they performed. The pack and cell level values are listed in Table 3-4. SCE did not obtain cell voltages in the data set that USHybrid provided.

Table 3-4
USHybrid and SCE Capacity Test Results

SCE Data							
85% DOD 410V charge Voltage							
Test	Open Circuit Voltage Before Test	Last Recorded Voltage During Test	Open Circuit Voltage After Test	Cell Voltage Max	Cell Voltage Min	Cell Voltage Avg	Delta Cell Voltage
1C Discharge	409.4	303.44	327.6	3.119	2.699	3.027	0.42
C/2 Charge	336.64	410	409.9	4.11	4.093	4.102	0.017
USHybrid Data							
Test	Open Circuit Voltage Before Test	Last Recorded Voltage During Test	Open Circuit Voltage After Test	Cell Voltage Max	Cell Voltage Min	Cell Voltage Avg	Delta Cell Voltage
1C Discharge	407	329	343	N/A	N/A	3.27	0.26
C/2 Charge	343	410	410	N/A	N/A	4.1	0.09
1C Discharge	409	325	338	N/A	N/A	3.21	0.26
C/2 Charge	338	410	410	N/A	N/A	4.1	0.09

3.2 HPPC Test

3.2.1 HPPC Test Setup

SCE performed an HPPC test using the FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles, and set up the test using the following parameters:

- Min. Cell Voltage for 18s (V) = 2.7V
- Max. Cell Voltage for 10s (V) = 4.2V
- Max. Discharge Current for 10s (A) = 155A
- Max. Regen Current for 10s (A) = 116.25A

3.2.2 HPPC Results

For calculating the maximum discharge/regen power, SCE used the maximum rating of the fuse (300 A) as the maximum allowable current for the battery system. The regen maximum power ranged from 76.92 to 110.22 kW and the discharge maximum power ranged from 112.96 to 93.62 kW (Figure 3-1). It should be noted that the maximum calculated power of the battery system is limited by the size of the fuse and wiring, not by the performance of the individual cells. The internal resistance calculated from the HPPC test ranged from 80.41 to 130.36 mOhm (Figure 3-2).

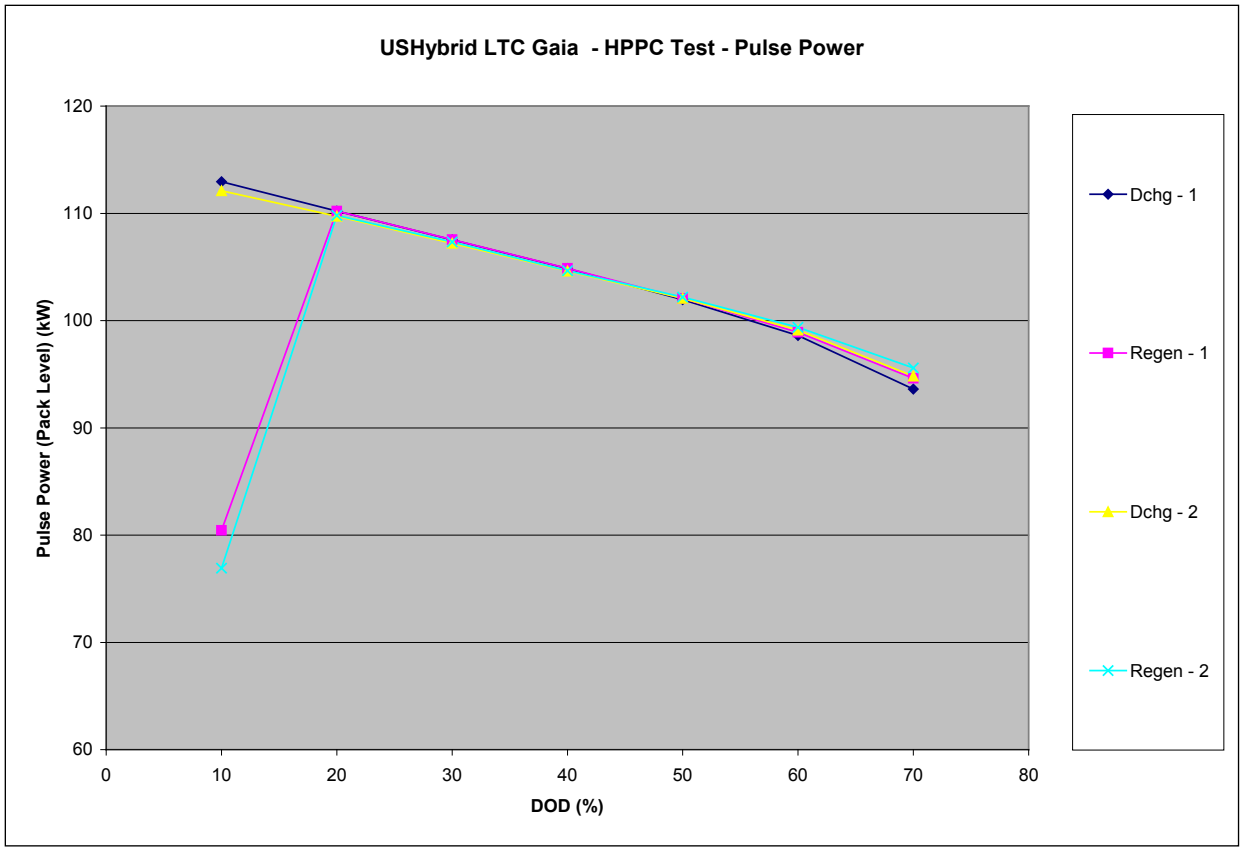

Figure 3-1
HPPC Results – Pulse Power

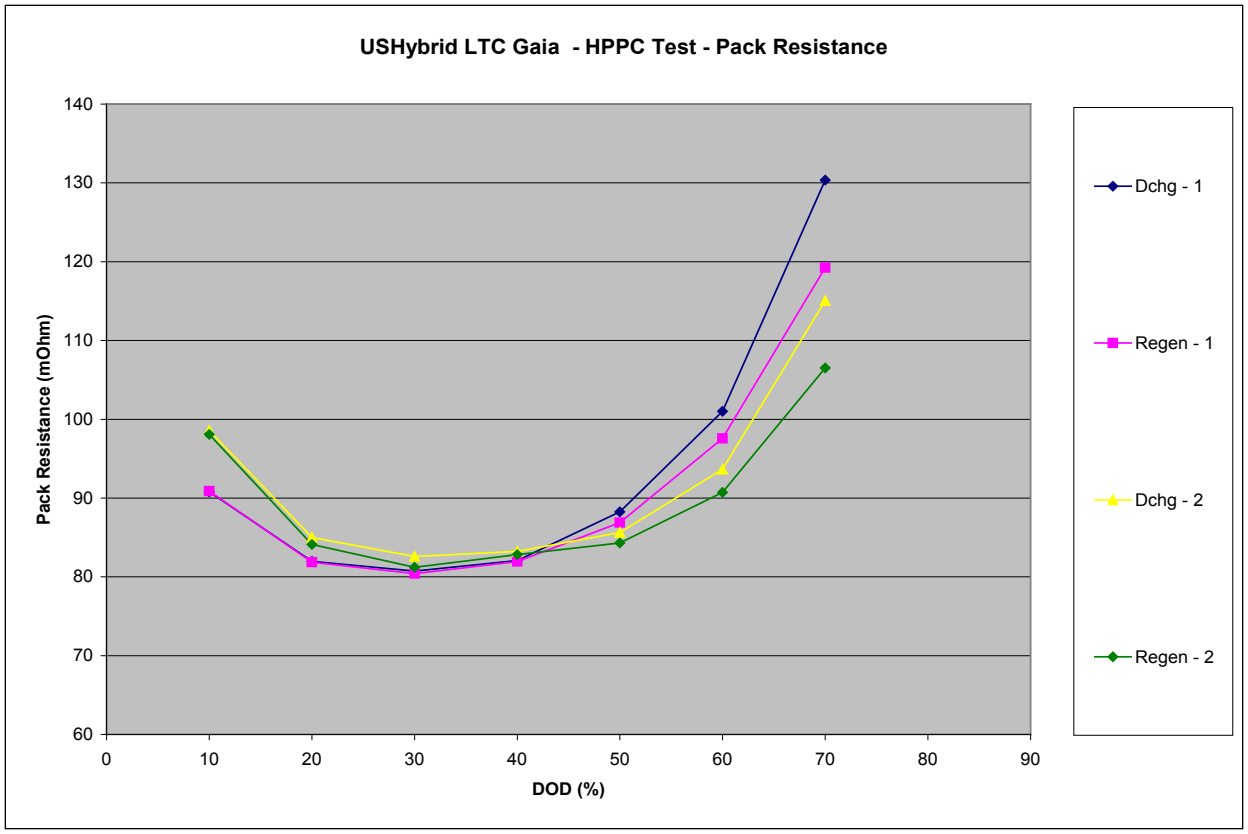

Figure 3-2
HPPC Results – Internal Resistance

4
CONCLUSION AND RECOMMENDATIONS

SCE concludes that during the charger test, the energy returned and the pack stop voltage were inconsistent. Ideally, the test should generate consistent results since the the amount of energy removed was consistent. SCE was also unable to determine the cause of the erroneous SOC values reported by the BMS during the charger test. The cause of this error should also be looked into by USHybrid.

SCE will use the results in this report for future battery performance tracking. The capacity test results at this point were 84% of the rated capacity. The regen maximum power ranged from 76.92 to 110.22 kW and the discharge maximum power ranged from 112.96 to 93.62 kW. The internal resistance calculated from the HPPC ranged from 80.41 to 130.36 mOhm. No manufacturer ratings were available for maximum power and resistance as the battery system was integrated using single cells by USHybrid.

Not implementing the BMS safety information is a safety concern. ID 0x100 contains the "Warning-Error-Status" messages that can be used to control the main contactor. Ideally, the BMS will act as the highest level safety device, while the hybrid system can operate somewhere in between the maximum safety values, for example using cell voltage limits set to 4.1V for charging and 2.8V for discharging. It is recommended that US Hybrid implement these measures immediately.

Some possible issues with battery safety are associated with the stop conditions used by the charger and vehicle hybrid systems. SCE does not recommend using pack voltage for battery safety, but recommends the hybrid/charger system incorporate cell voltage monitoring and not pack voltage.

This report will be provided to US Hybrid, and resolution of recommendations will be reported in the next RPT report.

A
BATTERY SPECIFICATION

BATTERY PACK CONFIGURATION	100 cells in series, 2 cells in parallel (100s2p)
BATTERY PACK CAPACITY	45 Ah
45 Ah HP-602040 Cell Specification	
PHYSICAL AND MECHANICAL CHARACTERISTICS	
DIAMETER	60 +/- 0.5 mm
HEIGHT	232 +/- 1 MM (204 +/- 1 mm WITHOUT TERMINALS
TERMINALS	POSITIVE TERMINAL Al M12 L: 14 mm
	NEGATIVE TERMINAL Cu M12 L: 14 mm
WEIGHT	APPROX. 1550 g
VOLUME WITHOUT TERMINALS	0.58 l
CASE MATERIAL	STAINLESS STEEL
CHEMICAL CHARACTERISTICS	
POSITIVE ELECTRODE	Li(NiCo) 02
NEGATIVE ELECTRODE	GRAPHITE
ELECTRICAL CHARACTERISTICS*	
NOMINAL VOLTAGE	3.6 V
NOMINAL CAPACITY AT 0.2 C	45 Ah
MINIMUM CAPACITY	42 Ah
AC IMPEDANCE (1 kHz)	< 0.5 mOhm
SPECIFIC ENERGY AT 0.2 C	105 Wh/kg
ENERGY DENSITY AT 0.2 C	281 Wh/l
SPECIFIC POWER (10 A PULSE DISCHARGE @ 28.9 C/ 90% SOC)	2510 W/kg
POWER DENSITY (10 A PULSE DISCHARGE @ 28.9 C/ 90% SOC)	6760 W/l
OPERATING CONDITIONS*	
RECOMMENDED CHARGE METHOD	CONSTANT CURRENT - CONSTANT VOLTAGE
MAXIMUM CHARGE VOLTAGE	4.2 V
RECOMMENDED CHARGE CURRENT	23 A (0.5 C)
MAXIMUM CHARGE CURRENT	90 A (2 C)
MAXIMUM PULSE CHARGE CURRENT (15 s)	270 A (6 C)
RECOMMENDED VOLTAGE LIMIT FOR DISCHARGE	3 V
LOWER VOLTAGE LIMIT FOR DISCHARGE	2.7 V
LOWER VOLTAGE LIMIT FOR PULSE DISCHARGE	2.1 V
RECOMMENDED DISCHARGE CURRENT	UP TO 90 A (2 C)
MAXIMUM DISCHARGE CURRENT	270 A (6 C)
MAXIMUM PULSE DISCHARGE CURRENT (10 s)	1300 A (28.9 C)
OPERATING TEMPERATURE	-30°C TO + 60 C°
RECOMMENDED CHARGE TEMPERATURE	0°C TO +40°C
STORAGE AND TRANSPORT TEMPERATURE	-40°C TO +60°C
CYCLE LIFE AT 20°C AND 100 % DOD	400 CYCLES TO 80% NOMINAL CAPACITY
(0.5 C CHARGE; 0.5 C DISCHARGE)	1000 CYCLES TO 60% NOMINAL CAPACITY
*REFERENCE TEMPERATURE 20°C	

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