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2007 Toyota Prius 8820 with Gen I Hymotion Prius Conversion Plug-In Hybrid Battery Test Results

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INL Idaho National Laboratory

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ABSTRACT

The U.S. Department of Energy (DOE) Advanced Vehicle Testing Activity (AVTA) consists of vehicle, battery, and infrastructure testing on advanced technology related to transportation. The activity includes tests on plug-in hybrid electric vehicles (PHEVs), including testing the PHEV batteries when both the vehicles and batteries are new and at the conclusion of 5,400 miles of accelerated on-road testing on specified routes. A 2007 Toyota Prius with VIN 8820 (VIN JTDKB20U577558820) was converted to a Gen I Hymotion Prius PHEV for testing. The battery testing was performed by the Electric Transportation Engineering Corporation (eTec) dba ECOtality North America (ECOtality). The Idaho National Laboratory (INL) and eTec collaborate on the AVTA for the Vehicle Technologies Program of the DOE.

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ACRONYMS

Ah	Amp-hour
AVTA	Advanced Vehicle Testing Activity
BOT	Beginning of Test
CD	Charge-Depleting
CS	Charge-Sustaining
DOE	U.S. Department of Energy
EOT	End of Test
eTec	Electric Transportation Engineering Corporation
HEV	Hybrid Electric Vehicle
HPPC	Hybrid Pulse Power Characterization
ICE	Internal Combustion Engine
INL	Idaho National Laboratory
kW	kilowatt
SOC	State of Charge
UDDS	Urban Dynamometer Drive Schedule
USABC	U.S. Advanced Battery Consortium
V	Volt
VDC	Volt Direct Current
VIN	Vehicle Identification Number
Vpc	Volt per cell
Wh	Watt-hour

1 TEST RESULTS

The U.S. Department of Energy's Advanced Vehicle Testing Activity conducts vehicle, battery, and infrastructure testing on several different vehicle technologies, including plug-in hybrid electric vehicles. This report provides test results for end-of-test (EOT) battery testing conducted on a first-generation Hymotion conversion of a 2007 Toyota Prius, number 8820 (VIN JTDKB20U577558820) in the battery test laboratory and during vehicle operations. The Hymotion conversion kit consists of a 5-kWh, Lithium-ion supplemental battery pack from A123 Systems. EOT testing is conducted after a vehicle has completed approximately 5,400 miles of on-road accelerated testing. The battery laboratory test results include those from the Static Capacity test and Constant Power Discharge test.[3] Vehicle test results include those from the acceleration testing and the fuel economy testing.[4] A summary of the test results is provided in Appendix A.

The battery and vehicle testing was performed by the Electric Transportation Engineering Corporation. The Idaho National Laboratory and the Electric Transportation Engineering Corporation conduct the Advanced Vehicle Testing Activity for the U.S. Department of Energy's Vehicle Technologies Program.

1.1 Static Capacity Test Results

Results from the laboratory EOT Static Capacity test are provided below in Table 1. BOT testing was not able to be conducted prior to the start of the accelerated mileage accumulation.

Table 1. Static capacity test results

	Test Date	Rated Capacity (Ah)	Measured Capacity (Ah)	Measured Energy (kWh)
EOT	March 17, 2009	25.3	22.4	3.94

Figure 1 shown below is a graph of battery voltage versus energy discharged for the EOT Static Capacity test. This graph illustrates voltage values during constant current discharge versus the cumulative energy discharged from the battery at a C/1 constant current discharge rate.

[3] Static Capacity and Constant Power Discharge test procedures were performed in accordance with the *FreedomCAR Battery Test Manual for Plug-In Hybrid Electric Vehicles*, DOE/ID-11069, October 2003, Procedures 3.2 and 3.3, respectively.

[4] Acceleration testing and fuel economy testing procedures were performed in accordance with the Advanced Vehicle Testing Activity PHEV America test procedures ETA-PHTP02 and ETA-PHTP03, respectively.

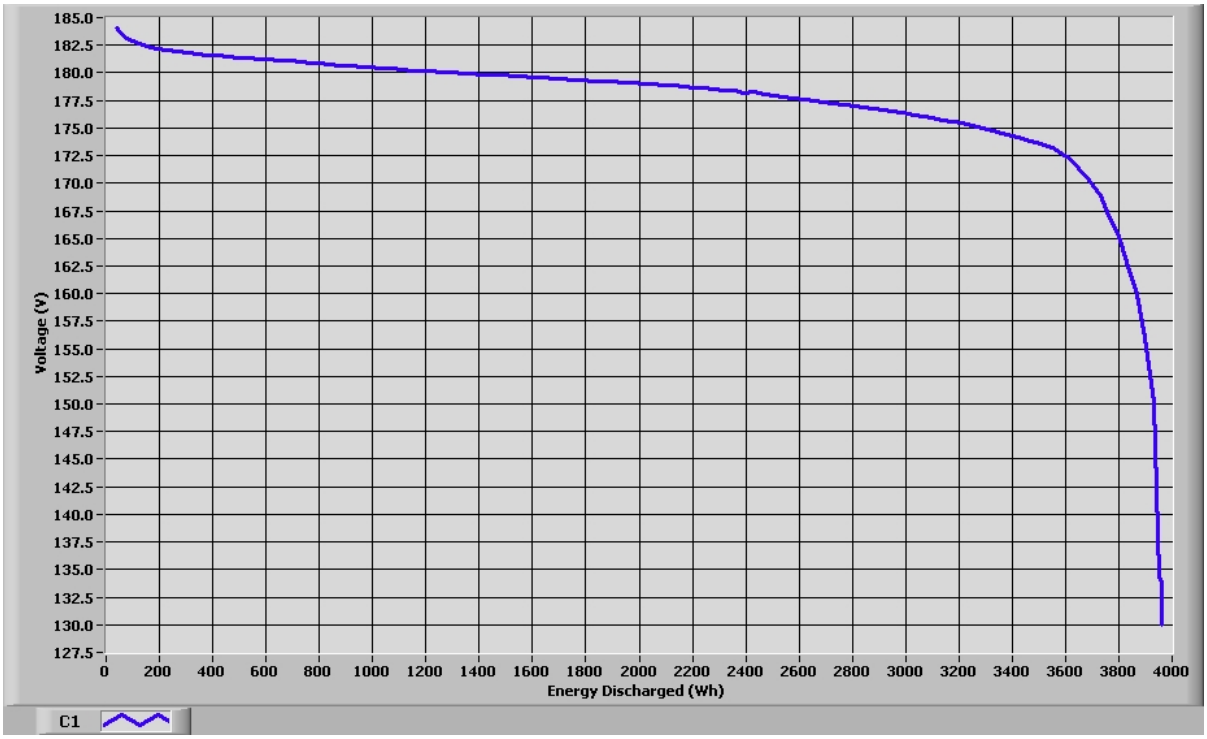

Figure 1. Voltage versus energy discharged during Static Capacity test

1.2 Constant Power Discharge Test Results

Results from the laboratory EOT Constant Power Discharge test results are provided in Table 2. The result of the EOT test was below the U.S. Department of Energy's available energy performance goal for charge-depleting operation of 3.4 kWh.

Table 2. Constant Power Discharge test results

	Capacity Discharged (Ah)	Energy Discharged (kWh)	Time to Completion (minutes)
EOT	18.76	3.10	18.72

1.3 Hybrid Pulse Power Characterization Test Results

A HPPC test was not performed for this plug-in battery pack because it is a supplemental pack that is connected in parallel to the manufacturer-designed, nickel-metal hydride (NiMH), hybrid electric vehicle battery pack. The supplemental pack assists the original equipment NiMH pack by delivering extra power to the system and allowing the vehicle to perform longer in all-electric or power-assist modes. This particular pack does not accept any charge from the vehicle during normal operation; therefore, the HPPC test is not relevant for this battery pack.

1.4 Acceleration Test Results

Results from vehicle on-track acceleration tests at BOT are shown in Table 3.

Table 3. Acceleration test results

	Average Discharge Power Over 10s (kW)	Energy Discharged at 1 Mile (Wh)	Capacity Discharged at 1 Mile (Ah)	Minimum Discharge Pack Voltage (V)	Minimum Discharge Cell Voltage (V)
BOT*	22.1	273	1.41	184.5	3.30

*All values represent only Hymotion conversion pack performance.

Figure 2 below shows the combined power of both battery packs in the converted vehicle versus time during the one-mile acceleration test. This graph is the basis for power calculations over the specified time interval and the cumulative discharged energy capacity during the duration of the test. Initially, during the acceleration test, the power quickly ramps up from about 0 kW to a peak value. This initial peak power is used as a reference point for the rest of the power analysis. Ideally, the power would remain constant; however, battery system dynamics, which may include battery control logic, cause the voltage to drop, resulting in an overall reduction in power.

Figure 2. Battery power versus time during acceleration test

Figure 3 shows the battery system voltage versus time during the one-mile acceleration test. The values are analyzed, where possible, to determine the battery control module's minimum allowable voltage. This graph also shows the impact of power electronics and the battery controller on the voltage response.

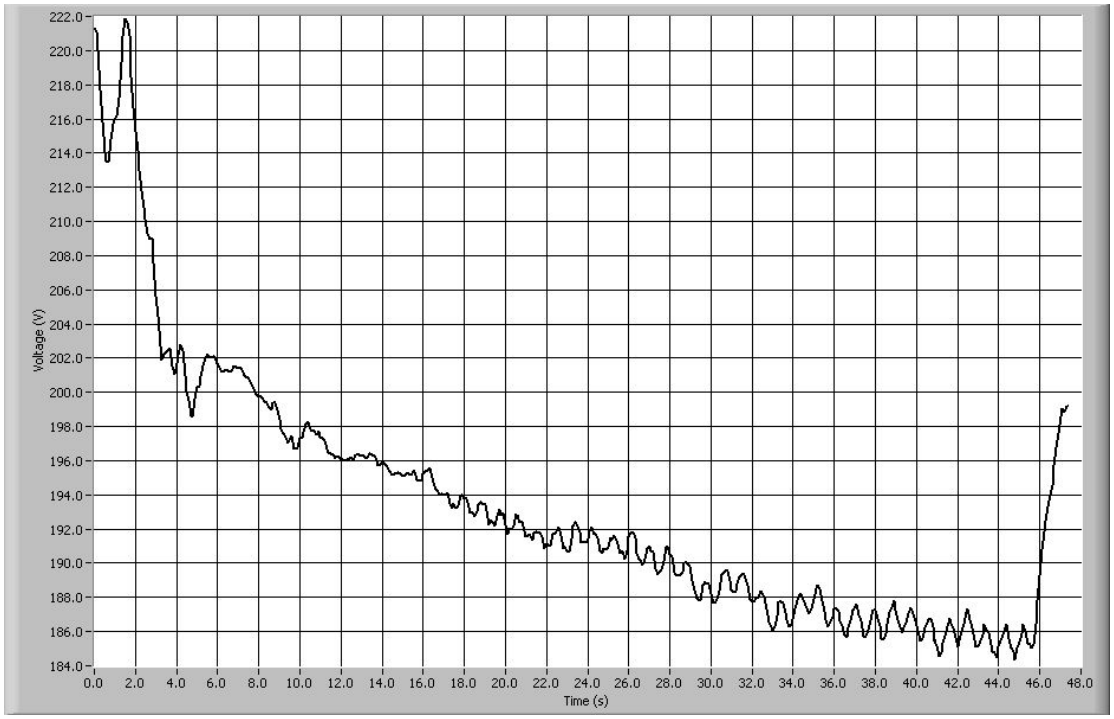

Figure 3. Battery voltage versus time during acceleration test

Figure 4 shows the combined current from both battery packs in the converted vehicle versus time during the one-mile acceleration test. This graph also is the basis for determining the cumulative discharged current capacity during the test run.

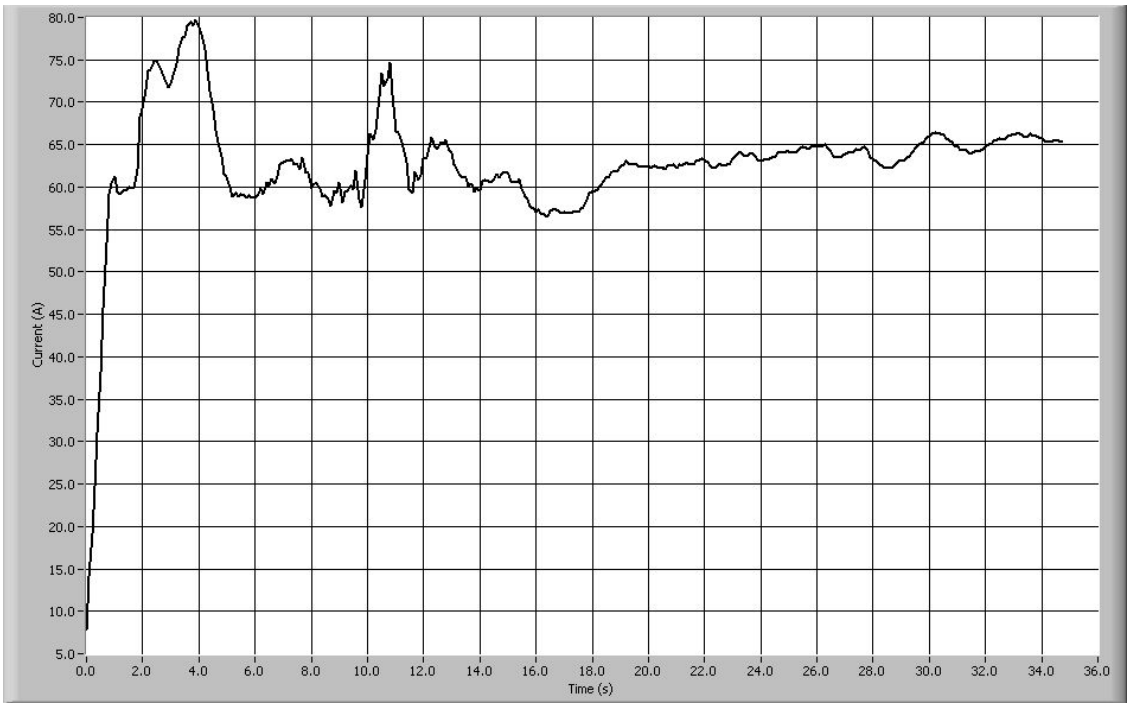

Figure 4. Battery current versus time during acceleration test

1.5 Fuel Economy Test Results

Results of battery testing that is conducted on a dynamometer during the Urban Dynamometer Drive Schedule[5] (UDDS) drive schedule at BOT are shown in Table 4.

Table 4. Dynamometer battery testing results

Peak Discharge Power (kW)	Measured Discharge Capacity (Ah)	Minimum Discharge Pack Voltage (V)	Minimum Discharge Cell Voltage (V)
15.8	21.8	186.8	3.34

1.6 On-Road Accelerated Testing Results

The per-cycle and cumulative fuel economy for on-road accelerated testing are shown below in Table 5. The leftmost column refers to the number of miles between vehicle recharges. As the distance between charges goes up, the electricity used decreases, as does the fuel economy. No obvious degradation in battery or vehicle performance was observed during testing.

Table 5. Results of on-road accelerated testing

Cycle (mi)	Urban (10 mi)	Highway (10 mi)	Charge (hr)	Reps (N)	Total (mi)	Electricity AC kWh	Gasoline	
							Gals	mpg
10	1	0	4	60	600	136.33	4.81	127.2
20	1	1	8	30	600	122.09	5.37	115.9
40	4	0	12	5	200	29.84	1.87	108.9
40	4	0	12	10	400	54.26	4.18	97.6
40	2	2	12	15	600	87.22	5.78	106.8
40	0	4	12	15	600	79.82	8.54	73.1
60	2	4	12	10	600	55.33	8.98	68.9
80	2	6	12	8	640	43.99	11.36	58.3
100	2	8	12	6	600	35.98	8.43	73.2
200	2	18	12	3	600	15.0	11.02	54.8
Total	**2,340**	**3,100**	**1,404**	**167**	**5,440**	**Weighted Average**		**86.4**

[5] The Urban Dynamometer Drive Schedule was performed as defined by the Environmental Protection Agency. The definition of the Urban Dynamometer Drive Schedule can be found at http://www.epa.gov/nvfel/methods/uddsdds.gif.

2 CONCLUSIONS

The 2007 Toyota Prius 8820 converted to a Gen I Hymotion Prius PHEV did not experience obvious degradation in battery capacity during the accelerated on-road testing. Without a BOT test to compare, some degradation may have occurred. The result of the EOT Constant Power Discharge test (3.10 kWh) was below the U.S. Department of Energy's available energy performance goal for charge-depleting operation of 3.4 kWh.

APPENDIX A – Vehicle Specifications and Test Results Summary

Vehicle Specifications	Battery Specifications
Manufacturer: Toyota Model: Prius Year: 2007 Number of Motors[a]: 1 Front Motor Power Rating[b]: 50 kW VIN #: JTDKB20U577558820	Battery Manufacturer: A123 Systems Generation: 1st Battery Type: Li-ion Number of Cells: 616 Nominal Cell Voltage: 3.3 V Nominal System Voltage: 185 V Nominal Pack Energy: 4.7 kWh
Beginning-of-Test Vehicle Baseline Performance Test Results[c]	
Acceleration Test	**Fuel Economy Test**
Peak Discharge Power @ 10 seconds[c]: 22.1 kW Peak Discharge Power @ 1 second[c]: 24.0 kW Energy Discharged @ 1 mile[d]: 273 Wh Capacity Discharged @ 1 mile[d]: 1.41 Ah Minimum Discharge Pack Voltage: 184.5 VDC Minimum Discharge Cell Voltage: 3.30 V	Peak Discharge Power: 15.7 kW Peak Charge Power: NA Measured Capacity Discharged[e]: 21.8 Ah Measured Capacity Regenerated: NA Battery Discharge/Charge Ratio: NA Maximum Charge Pack Voltage: 186.8 VDC Maximum Charge Cell Voltage: 3.34 Vpc Minimum Discharge Pack Voltage: 0 VDC Minimum Discharge Cell Voltage: 0 Vpc
Battery End-of-Test Laboratory Test Results	
Hybrid Pulse Power Characterization Test	**Static Capacity Test**
NA	Measured Average Capacity: 22.4 Ah Measured Average Energy Capacity: 3.94 kWh Date of Test: March 17, 2009
Constant Power Discharge Test	
Ahr Discharged: 18.76 Ah kWh Discharged: 3.10 kWh Time to Fully Discharge: 18.72 minutes	

Analysis Notes:

a. Motor refers to any motor capable of supplying traction power.

b Motor power rating refers to the manufacturer's peak power rating for the motor(s) supplying traction power.

c The peak power at a specified duration is the average power value over a specified interval beginning at the measured maximum power of the pulse.

d The capacity\energy value is defined as the net value over a 1-mile, full-throttle, acceleration test.

e. Cumulative capacity measurement over two hot start urban drive cycles and two hot start highway drive cycles.

Ah = amp-hour
kW = kilowatt
kWh = kilowatt-hour
VDC = volt direct current
Vpc = volt per cell
Wh = Watt-hour