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2008 Chevrolet Tahoe-5170 Hybrid Electric Vehicle Battery Test Results

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May 2010

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Disclaimers

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 hybrid electric vehicles (HEVs), including testing the HEV batteries when both the vehicles and batteries are new and at the conclusion of 160,000 miles of on-road accelerated testing. This report documents battery testing performed for the 2008 Chevrolet Tahoe HEV, number 5170 (VIN 1GNFC13568R215170). 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	kilo Watt
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

2008 Chevrolet Tahoe-5170
Hybrid Battery Test Results

1. TEST RESULTS

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 hybrid electric vehicles (HEVs), including testing the HEV batteries when both the vehicles and batteries are new and at the conclusion of 160,000 miles of on-road accelerated testing. This report provides test results for beginning-of-test (BOT) and end-of-test (EOT) battery testing conducted on a 2008 Chevrolet Tahoe HEV, number 5170 (VIN 1GNFC13568R215170) from both laboratory and on-road test configurations. BOT testing is conducted when a vehicle is new and EOT testing is conducted after a vehicle has accumulated approximately 160,000 miles of on-road accelerated testing. The battery laboratory test results include those from the Static Capacity Test and the Hybrid Pulse Power Characterization (HPPC) Test.[3] Vehicle test results include those from Acceleration Testing and the Fuel Economy Testing.[4]

The battery and vehicle 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.

1.1 Static Capacity Test Results

Results from the laboratory BOT and EOT static capacity test are provided below in Table 1. Static Capacity Test Results

Table 1. Static Capacity Test Results

	Test Date	Odometer (mi)	Rated Capacity (Ah)	Measured Capacity (Ah)	Measured Energy (Wh)
BOT	April 16, 2008	543	6.5	5.77	1,750
EOT	May 5, 2010	160,069	6.5	5.00	1,506
Difference	—	159,526	—	0.77 (13%)	244 (13%)

Figure 1 shows battery voltage versus energy discharged. This graph illustrates voltage values during constant-current discharge versus cumulative energy discharged from the battery at a C/1 constant-current discharge rate at BOT and EOT.

[3] Static Capacity and HPPC test procedures were based on the *FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles*, DOE/ID-11069, October 2003, Procedures 3.2 and 3.3, respectively. The measured capacity at the time of BOL testing was used to determine the magnitude of current during all HPPC test.

[4] Acceleration Testing and Fuel Economy Testing procedures were performed in accordance with the Advanced Vehicle Testing Activity HEVAmerica test procedures ETA-HTP02 and ETA-HTP03, respectively.

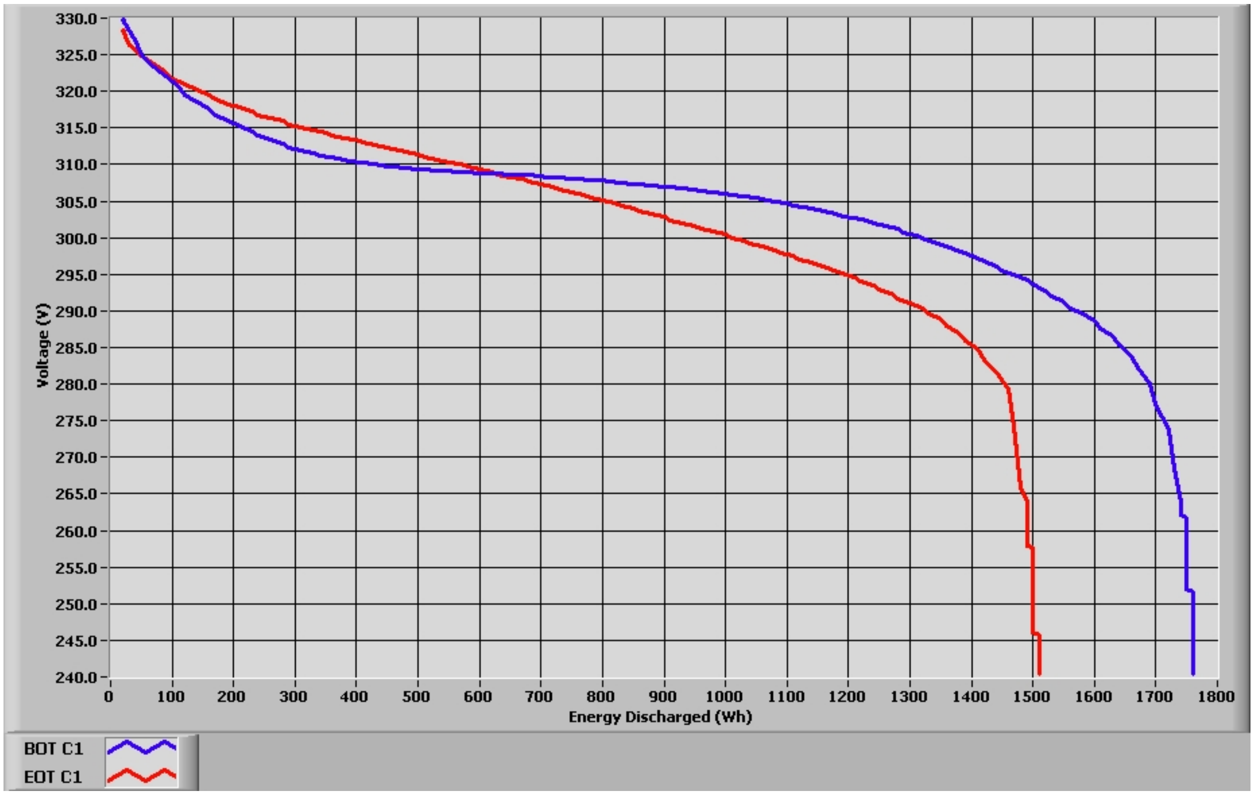

Figure 1. Voltage versus Energy Discharged During the Static Capacity Test

1.2 Hybrid Pulse Power Characterization Test Results

HPPC test results are summarized in Table 2, shown below.

Table 2. HPPC Test Results

	10 s Discharge Power (kW)	1 s Discharge Power (kW)	10 s Charge Power (kW)	1 s Charge Power (kW)	Maximum Cell Voltage (V)	Minimum Cell Voltage (V)
BOT	28.0	36.2	23.0	31.5	1.49	1.0
EOT	25.3	37.4	24.8	37.5	1.46	1.0
Difference	2.7 (9.6%)	-1.2 (-3.3%)	-1.8 (-7.8%)	-6.0 (-19%)	—	—

Figure 2 and Figure 4 illustrate charge and discharge pulse resistance graphs of the battery, respectively. The internal resistance is depicted over a range of 10 to 90% depth of discharge represented by the amount of energy discharged at each interval. Each curve represents the specified HPPC BOT or EOT resistance at the end of the 10-second pulse interval.

Figure 3 and Figure 5 illustrate the charge and discharge pulse power graphs of the battery, respectively. The power is depicted over a range of 10 to 90% depth of discharge represented by the amount of energy discharged at each interval. Each curve represents the specified HPPC BOT or EOT available power at the end of the 10-second pulse interval at the cell voltage limits.

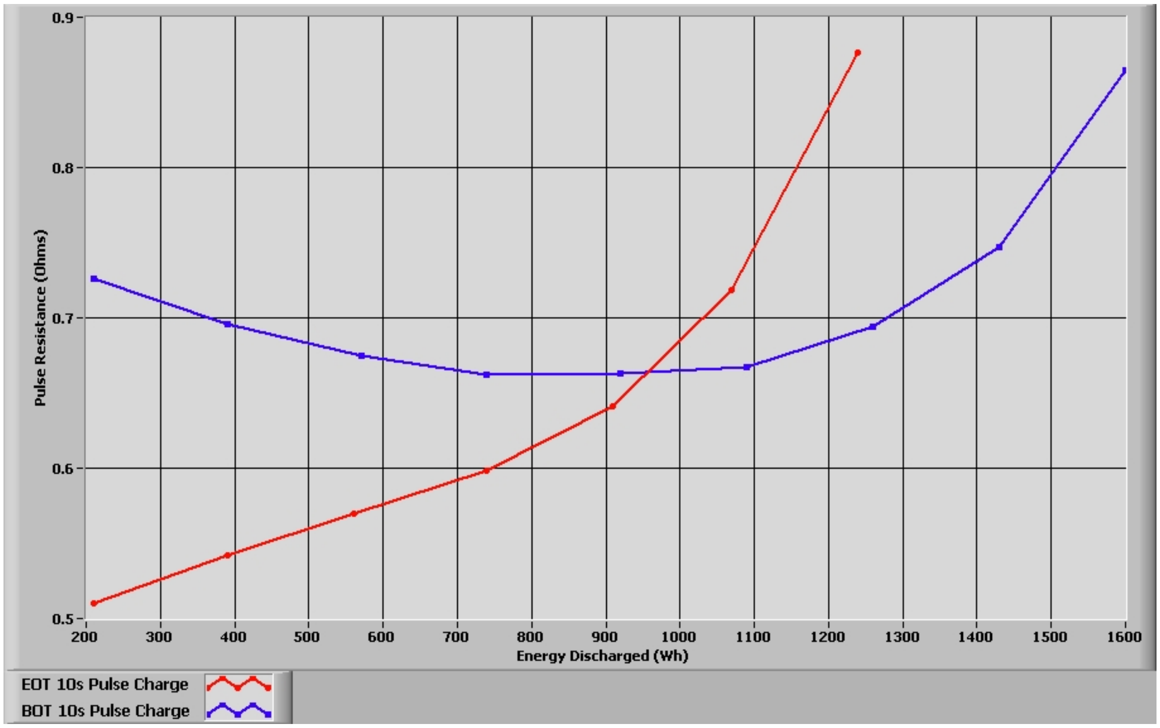

Figure 2. Ten-Second Charge Pulse Resistance versus Energy Discharged

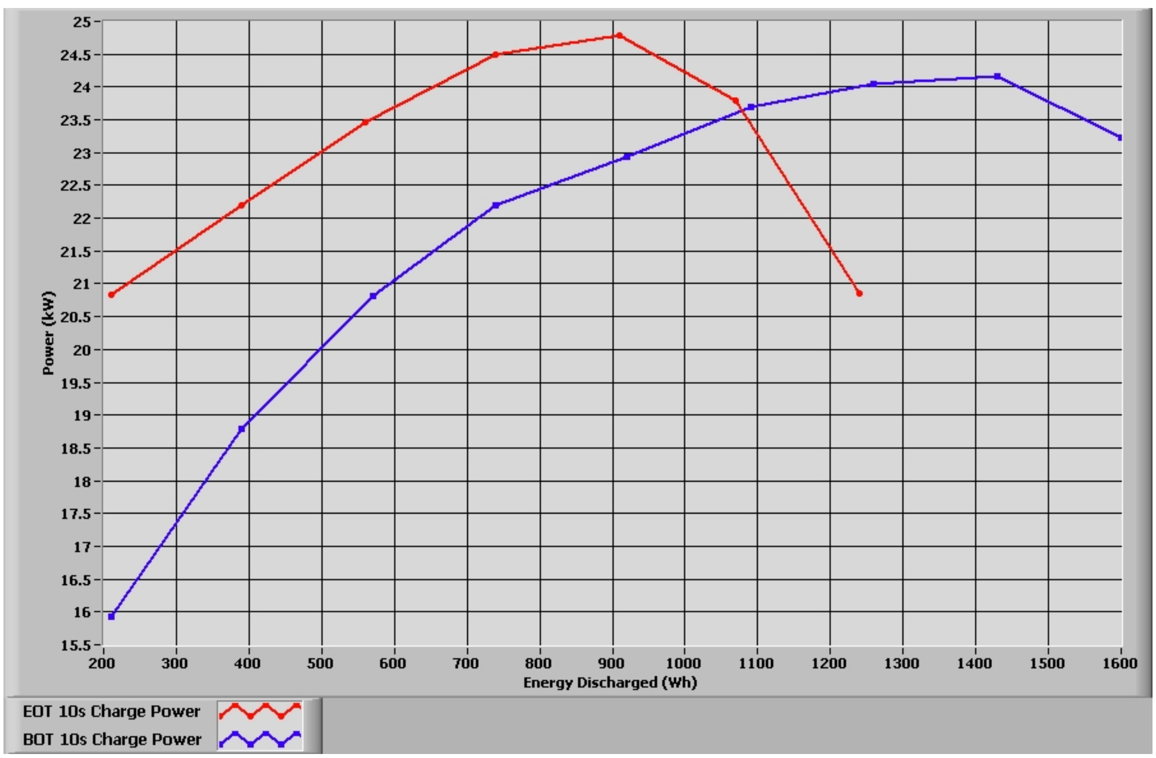

Figure 3. Ten-Second Charge Pulse Power versus Energy Discharged

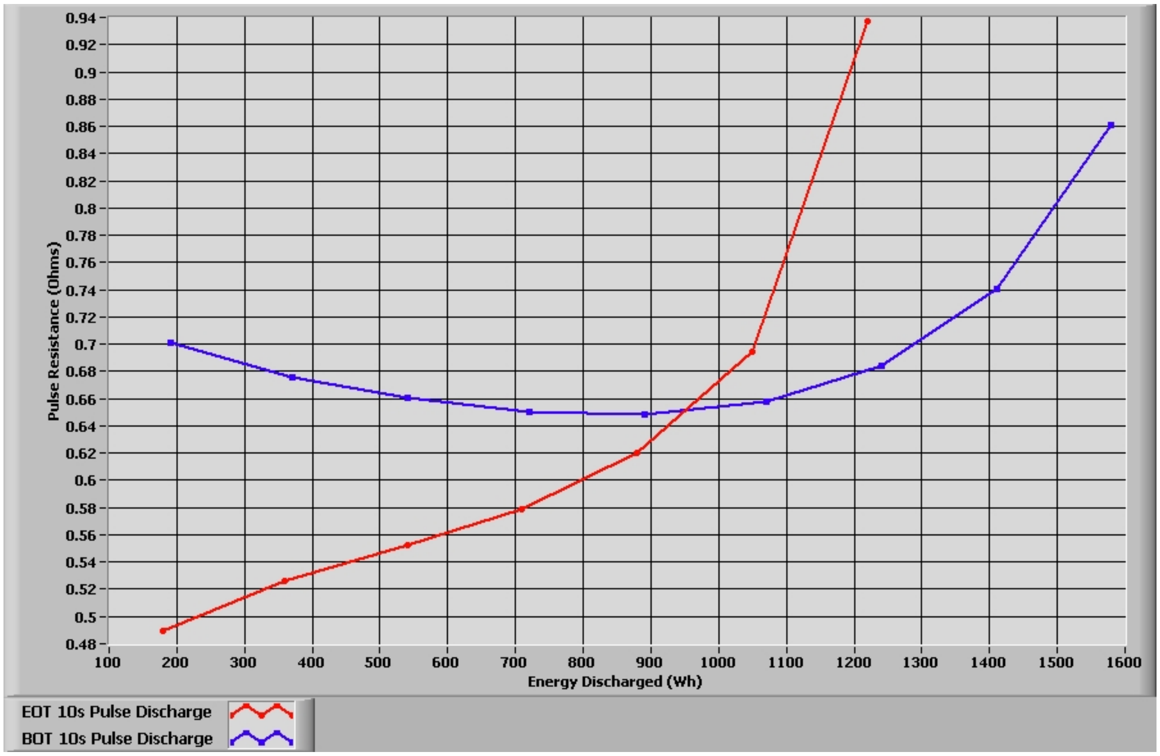

Figure 4. Ten-Second Discharge Pulse Resistance versus Energy Discharged

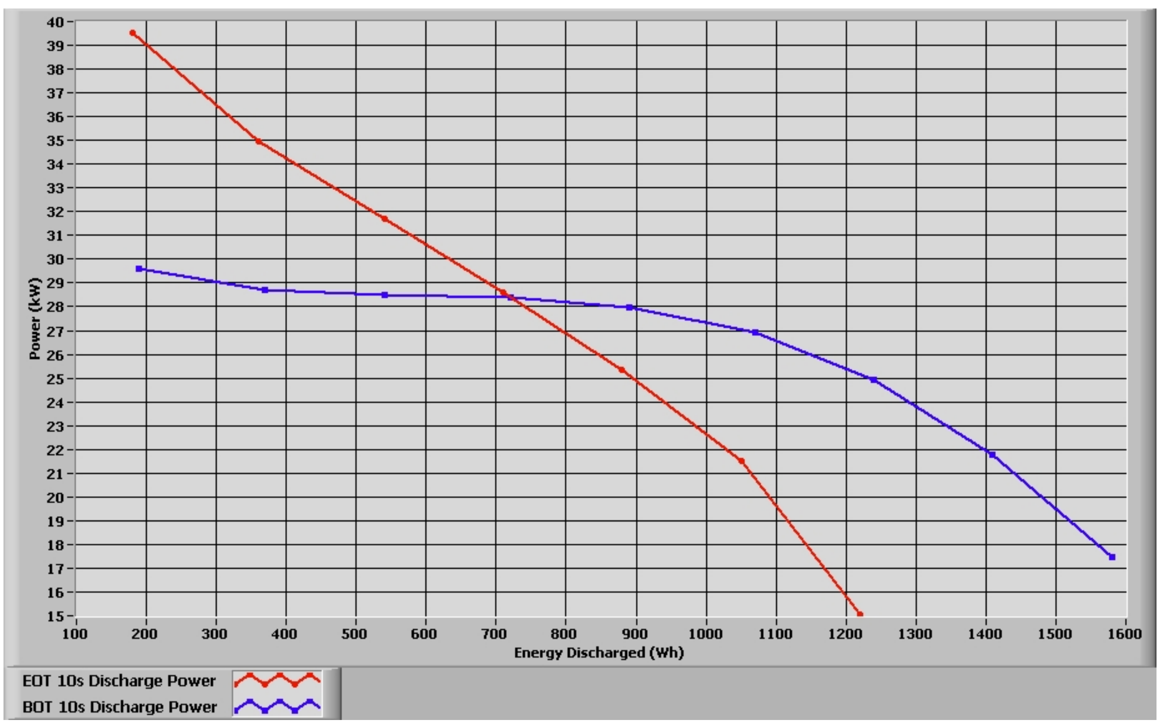

Figure 5. Ten-Second Discharge Pulse Power versus Energy Discharged

Figure 6 is a plot of the BOT and EOT HPPC 10-second pulse power values of the battery as a function of energy discharged. The graph shows the power values over the range of energy discharged and the DOE targets for a hybrid power assist battery for discharge power (25 kilo Watt (kW)) and regenerative power (20 kW) are included for comparative purposes. The BOT battery test meets DOE power targets for battery energy discharged range of 500 to 1240 Watt hour (Wh). The EOT battery test meets the DOE power targets for a battery energy discharged range of 210 to 890 Wh.

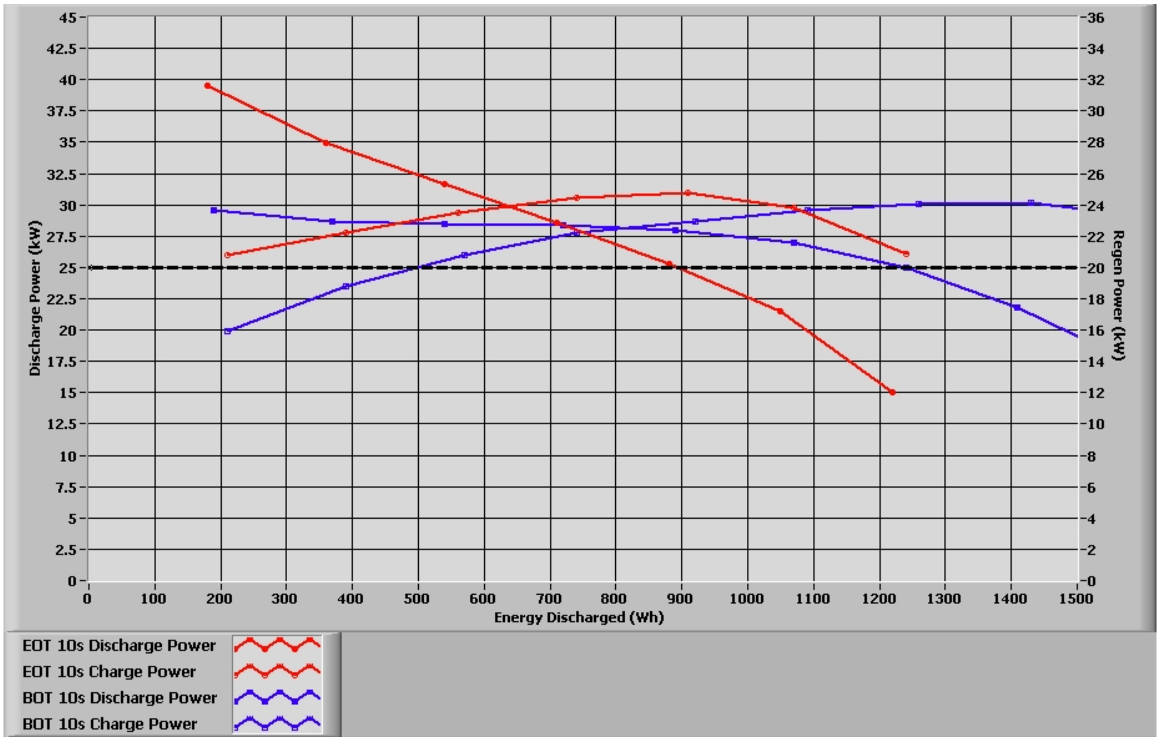

Figure 6. Peak Discharge and Regenerative Power versus Energy Discharged

Figure 7 is a plot of the BOT and EOT useable energy as a function of power of the battery. The x-axis indicates a desired discharge or charge power level and the y-axis indicates the useable energy at that power. The dashed horizontal line shows the DOE minimum power assist HEV energy target of 300 Wh. The dashed vertical line shows the DOE minimum power assist power target of 25 kW. The BOT useable energy curve of the Tahoe battery falls above and to the right of the intersection of DOE energy and power targets. The maximum power that can be delivered while meeting the DOE energy target is 27.4 kW at 300 Wh. The maximum energy that can be delivered while meeting the DOE power target is 725 Wh at 25 kW. This indicates that at the time of BOT testing, the Tahoe battery performance was above DOE targets. The EOT useable energy curve of the battery falls above and to the right of the intersection of the DOE energy and power targets. The maximum power that can be delivered while meeting the DOE energy target is 28.2 kW at 300 Wh. The maximum energy that can be delivered while meeting the DOE power target is 660 Wh at 26 kW. This indicates that at the time of EOT testing, the Tahoe battery performance was above DOE targets.

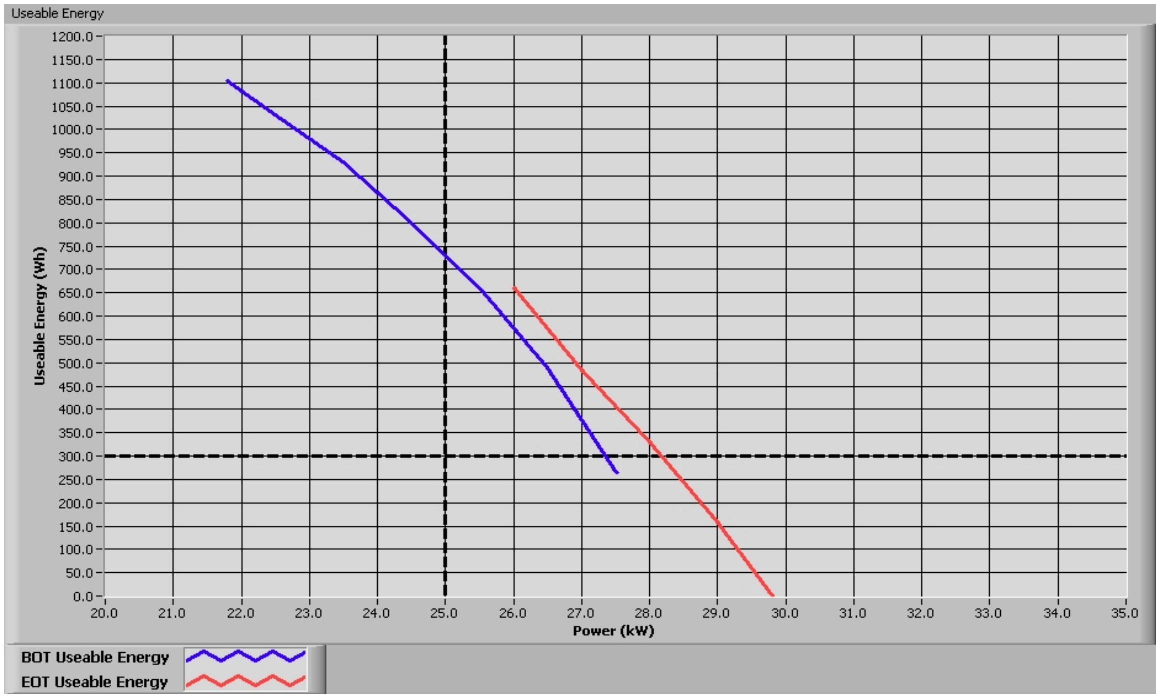

Figure 7. Useable Energy versus Power

1.3 Acceleration Test Results

BOT and EOT results from vehicle on-track acceleration tests are summarized in Table 3, shown below.

Table 3. Acceleration test results for BOT and EOT on-track acceleration tests

	Average Discharge Power Over 10 s (kW)	Energy Discharged at 1 Mile (Wh)	Capacity Discharged at 1 Mile (Ah)	Peak Power Over 1 Mile (kW)	Minimum Discharge Pack Voltage (V)	Minimum Discharge Cell Voltage (V)
BOT[5]	14.5	59.5	0.20	40.7	270.5	1.127
EOT[5]	13.8	20.1	0.08	38.2	276.3	1.151

Figure 8 shows battery power versus time during the one (1) mile acceleration test at EOT and BOT. 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. At the beginning of the acceleration test, the power quickly increases. Ideally, the power would remain constant; however, battery system dynamics, which may include battery control logic, cause the voltage to drop, resulting in a reduction in power.

Figure 9 shows the battery voltage versus time during the one (1) mile acceleration test at BOT and EOT. Values are analyzed to determine the minimum voltage allowed by the battery control module, if possible. Although the test may not yield a definitive minimum voltage value, it can

[5] BOT data is graphed in blue, while EOT data is graphed in red for all acceleration test results graphs.

provide an approximation for comparison to the HPPC analysis results. This graph also shows the impact of power electronics and battery controller on the voltage response.

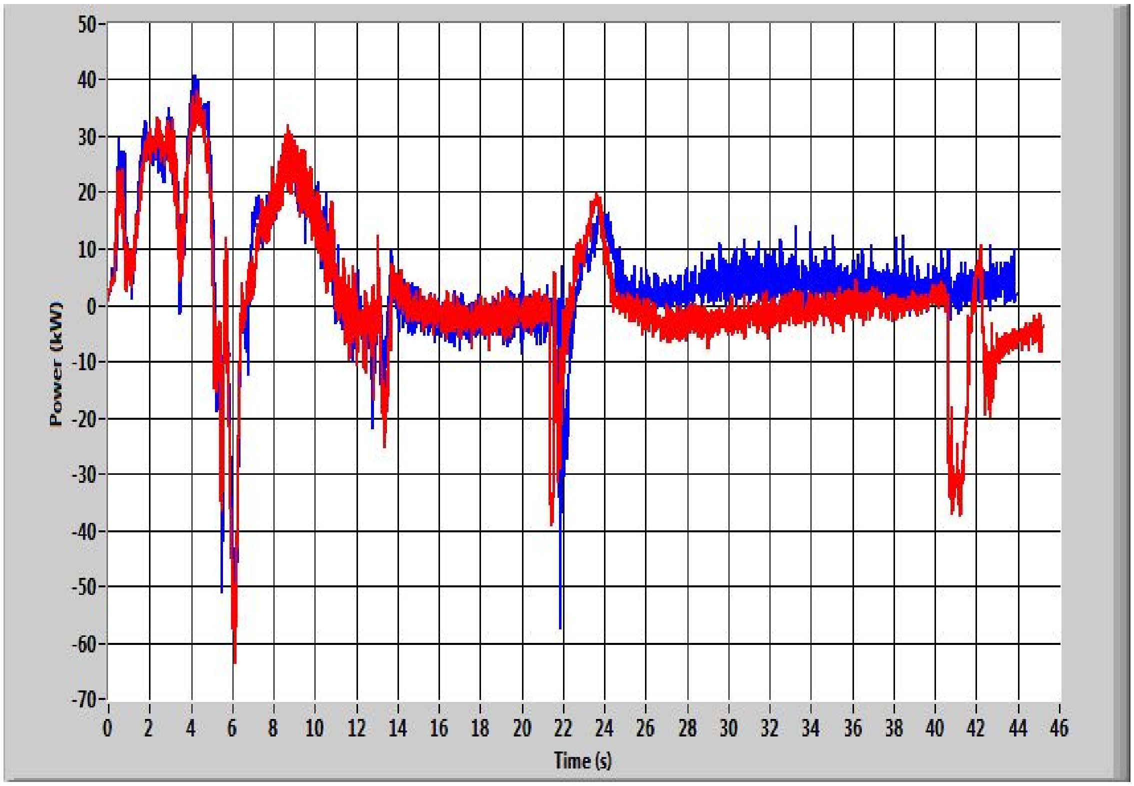

Figure 8. Battery Power versus Time

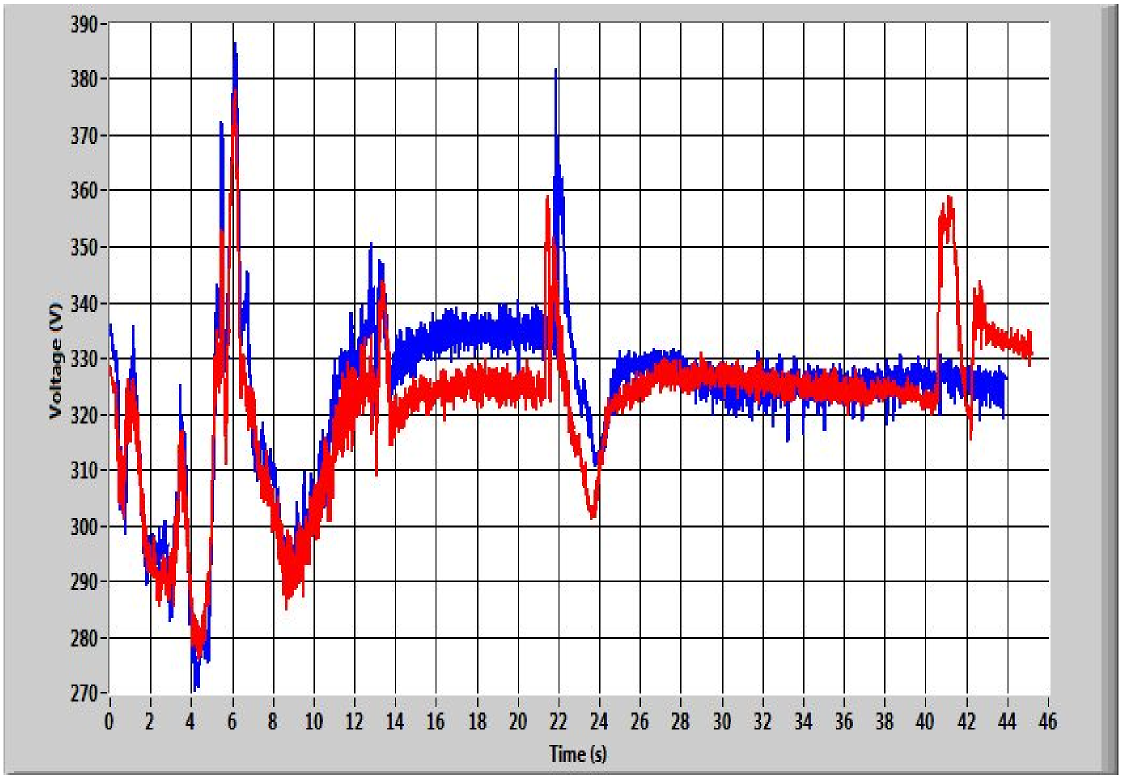

Figure 9. Battery Voltage versus Time

Figure 10 shows battery current versus time during the one (1) mile acceleration test at BOT and EOT. This graph also is the basis for determining the discharged capacity during the test run. Lastly, the power results in Figure can be obtained by simply multiplying the voltage values from Figure 9 by the current values in Figure 10.

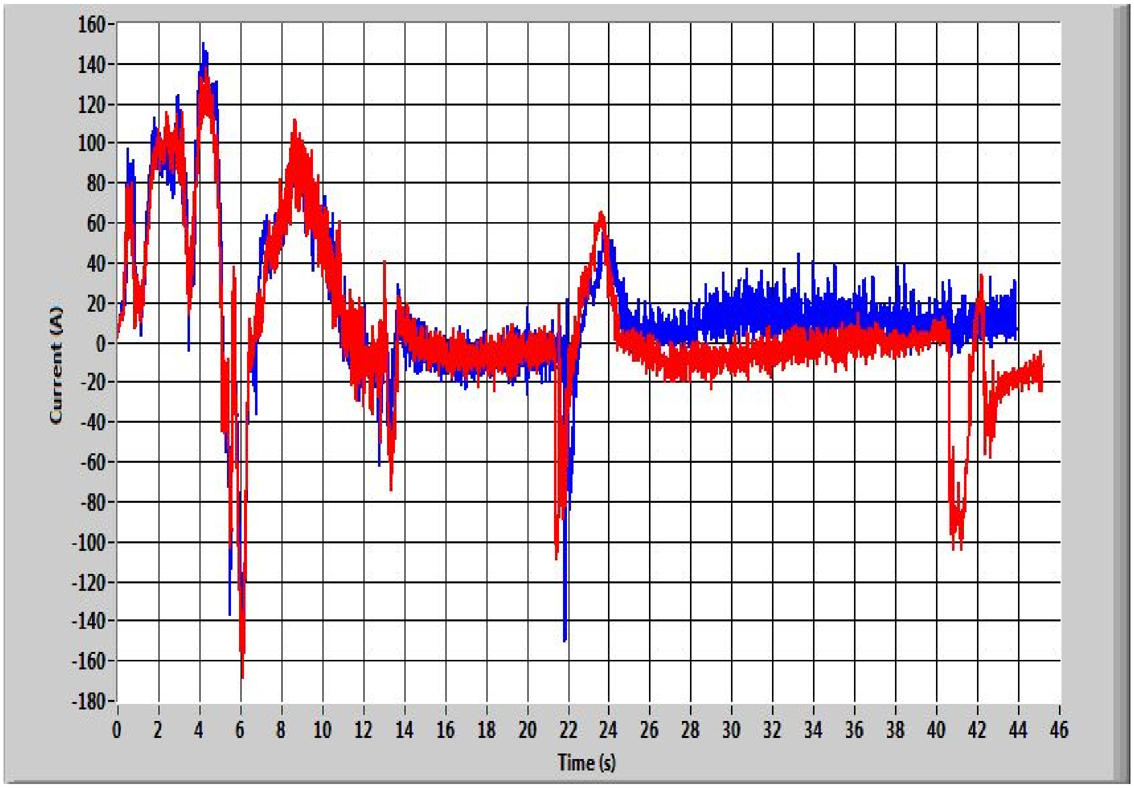

Figure 10. Battery Current versus Time

1.4 Fuel Economy Test Results

Battery performance results from testing conducted on a chassis dynamometer (using the Urban Dynamometer Drive Schedule (UDDS)[6]) at BOT and average fuel economy recorded while the vehicle was operating in an on-road fleet[7] approximately 50% in city and 50% in highway[8] types of routes are summarized in Table 4, as follows:

Table 4. Battery Performance Results on an Electric Dynamometer

Peak Discharge Power (kW):	37.4	Maximum Charge Pack Voltage (V):	363.7
Peak Regenerative Power (kW):	32.0	Maximum Charge Cell Voltage (V):	1.51
Measured Discharge Capacity (Ah):	10.32	Minimum Discharge Pack Voltage (V):	247.8
Measured Regenerative Capacity (Ah):	10.41	Minimum Discharge Cell Voltage (V):	1.03
Discharge/Charge Ratio:	0.991	Average Fuel Economy (mpg):	21.5

[6] 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.

[7] On-road fleet testing is performed by the Electric Transportation Engineering Corporation (in conjuncture with JP Morgan Chase Bank's courier services). The vehicles are driven a combination of city and highway routes by several different drivers to expedite the amount mileage needed to reach EOT.

[8] The type of on-road driving routes for the two Tahoe HEVs is summarized as 50% city and 50% highway in the Advanced Vehicle Testing Activity Final Fleet Testing Results fact sheet that can be found at http://avt.inel.gov/pdf/hev/finalfact2008ChevroletTahoe.pdf.

Figure 11 illustrates the vehicle motive power histogram throughout one of the tested drive schedules. Motive power is a calculated value representing instantaneous theoretical positive wheel power required to complete the urban drive cycle. The x-axis of the bar graph represents the center point of a particular power level. For example, the first bar on the graph with a power of 2 kW represents all power values between one (1) and three (3) kW (lower boundary is inclusive and upper boundary is non-inclusive). The corresponding y-value at this power level is the percentage of time at this particular power band throughout the entire drive cycle (regeneration power and zero power non-inclusive). Directly beside the vehicle motive power value is the same analysis performed on the battery output power for a particular power band. While the occurrences of vehicle motive power and battery discharge power in each power band in Figure are not necessarily coincident in time, it is possible to conclude from the overall shapes of the distributions that the battery provides a substantial fraction of the required vehicle motive power. Efficiency losses between the battery and wheels are not included in this figure, and they naturally reduce the contribution of the battery to vehicle motive power.

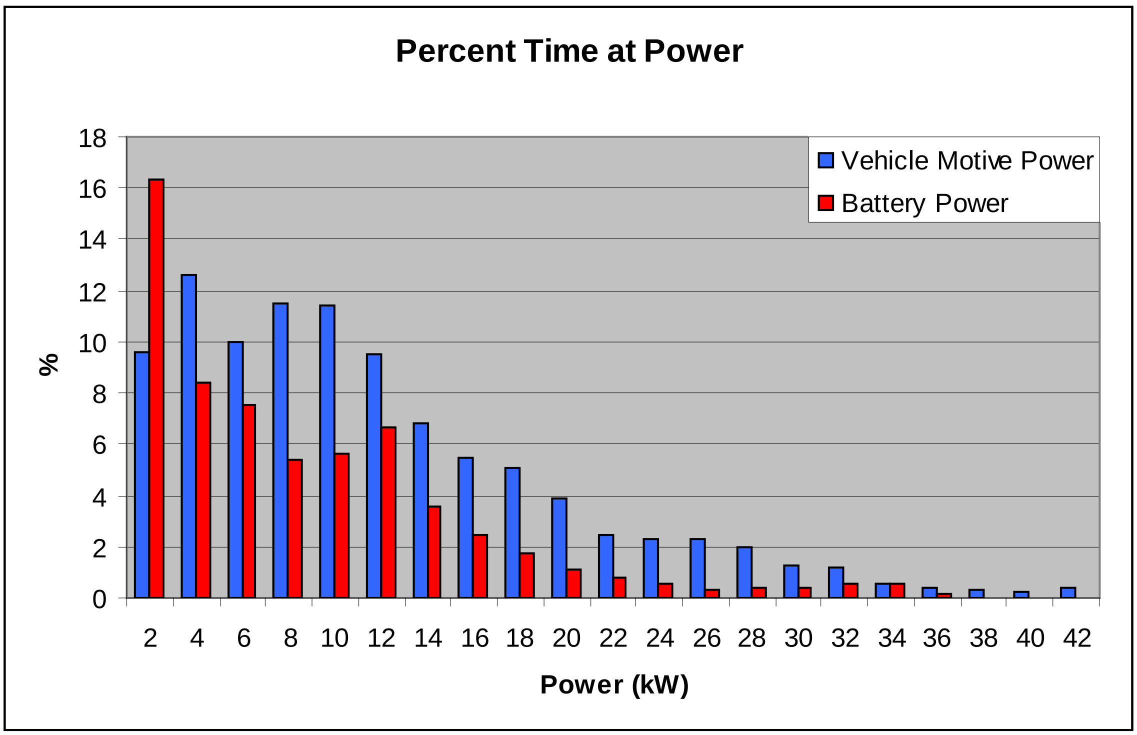

Figure 11. Percentage of Time at Motive Power Level

Figure 12 illustrates the vehicle regenerative braking power histogram throughout one of the tested urban drive cycles. Regenerative braking power is a calculated value that represents the theoretical negative wheel power required to decelerate the vehicle on the urban drive cycle. Figure compares the distributions of available braking power and actual battery charge power in a similar manner to Figure. The overall shapes of the distributions indicate that the battery captures a substantial fraction of the vehicle power available during braking.

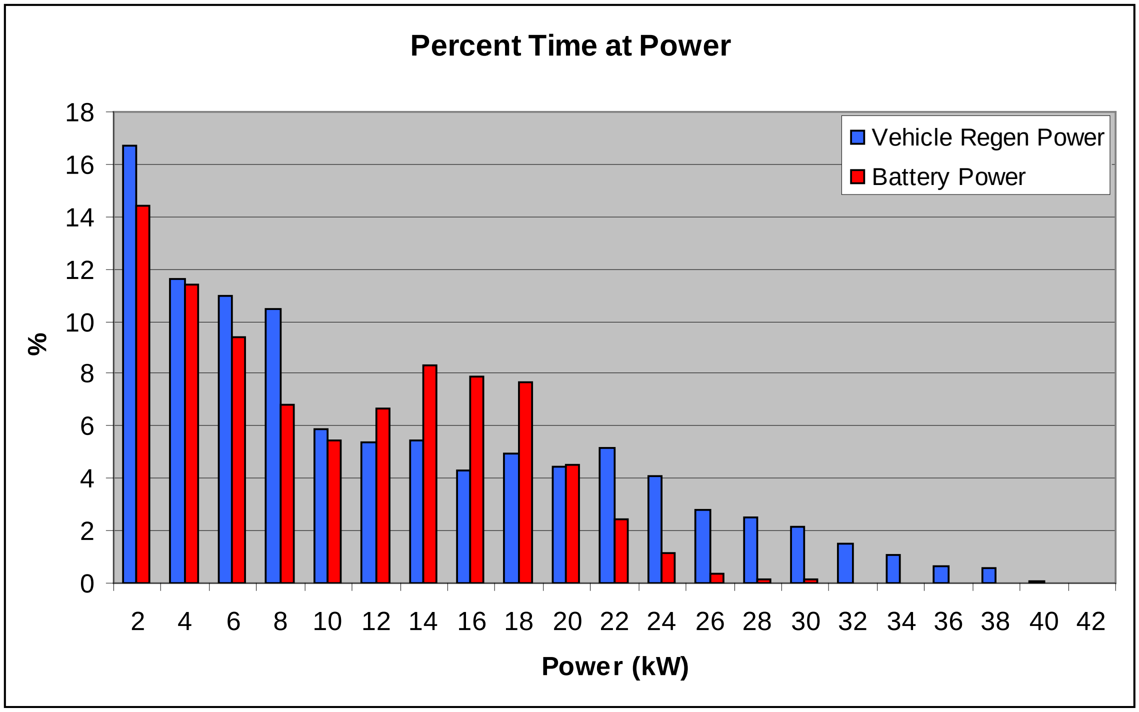

Figure 12. Percentage of Time at Regenerative Power Level

Figure 13 is a pie chart showing the sources of battery charging. The chart shows the percentages of battery charging time when the battery experienced ideal versus non-ideal charging. Ideal charging refers to regenerative braking during deceleration where the deceleration force is in excess of the vehicle drag forces. On a non-hybrid vehicle, this would require the brakes to be pressed and excess energy would be converted to heat at the brakes. In a hybrid vehicle, a portion of this excess energy can be captured and stored for later use. Because this charge method is capturing energy that is normally lost, the charge event is considered ideal. The second charging type is called non-ideal because the vehicle charges the battery by the use of the internal combustion engine (ICE) and generator. This can happen during acceleration, cruising, or deceleration when excess engine load is available or when the battery state of charge (SOC) has dropped below a minimum level. This is non-ideal because the ICE charges the battery. In some cases, this can be beneficial for overall fuel economy by maintaining optimum load on the engine to increase efficiency; however, it is still considered non-ideal (by definition) because gasoline is used to charge the batteries.

Figure 14 is a pie graph that shows the percentage of vehicle regeneration energy captured in the battery. By calculating total vehicle energy available at the wheels during an ideal charge event and performing a direct comparison of energy into the battery, the percent energy into the battery can be calculated. In addition, system losses can be determined as the difference between energy available from the vehicle and energy into the battery. Although each component of loss cannot be determined, the total system loss can be measured by this method. Also, it should be noted that this calculation does not take into account losses at the battery due to charge inefficiency. This measurement is merely a calculation of how efficiently the vehicle charging mechanism is able to capture regeneration energy during an ideal charge event. [9]

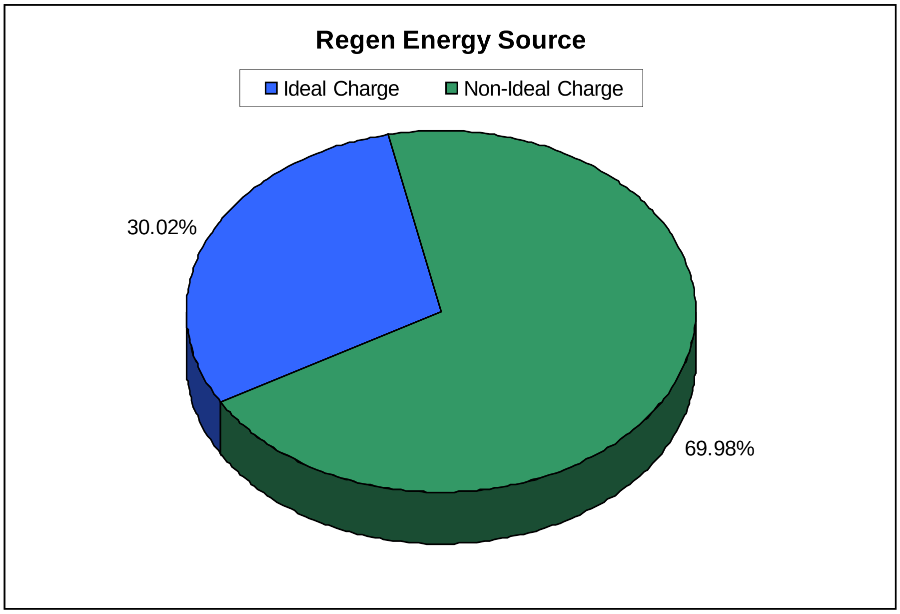

Figure 13. Regenerative Energy Source Comparison

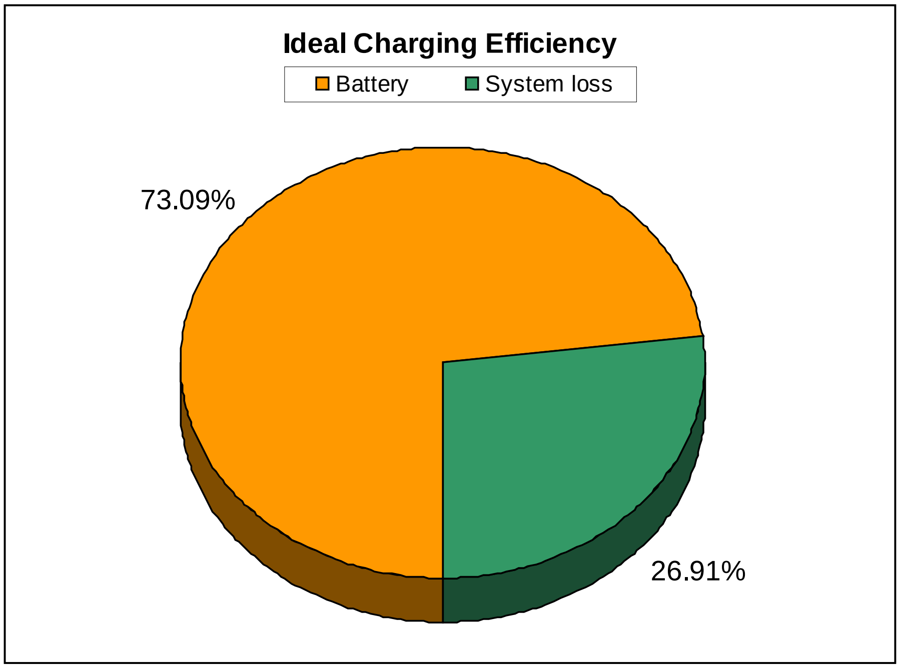

Figure 14. Regenerative Energy Efficiency

[9]Results shown in Figures 13 and 14 do not consider the case when non-ideal engine charging occurs during a regenerative braking event. The impact of this case during the UDDS test is assumed to be negligible.

Figure 15 represents the combined monthly fuel economy and cumulative fuel economy for two Tahoe HEVs, VIN 5170 and VIN 7400[10], that underwent on-road, accelerated testing. The monthly fuel economy is derived from the amount of fuel consumed, based on fleet fueling records, and the distance traveled, based on vehicle odometer readings, for each vehicle within that month. The cumulative fuel economy is a running total of each month's fuel consumption and distance traveled. While there is no way, with only these data, to directly correlate vehicle fuel economy to operation of the battery pack, it can be seen from Figure that fuel economy for these vehicles remained relatively unchanged over the last 18 months of testing, even with the battery degradation demonstrated by the EOT battery test.

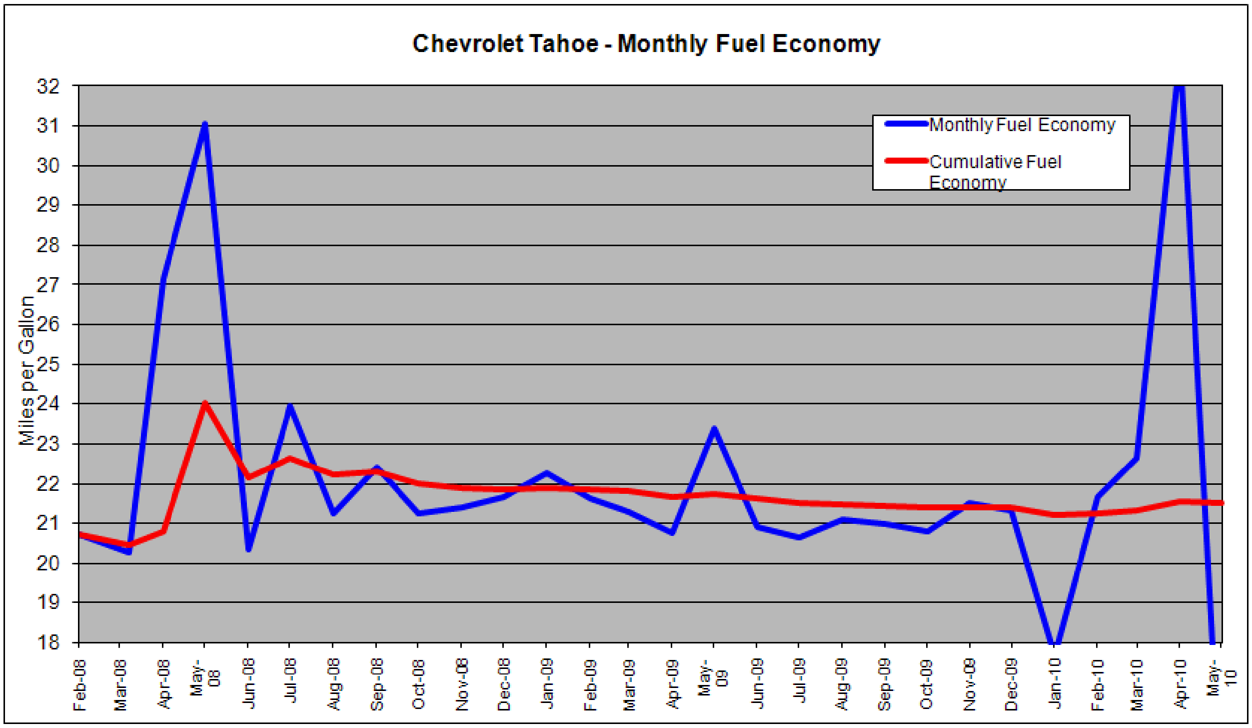

Figure 15. Monthly and Cumulative Fuel Economy

1.5 Conclusion

The Chevrolet Tahoe number 5170 experienced 13% degradation in battery capacity and stayed above DOE targets for all aspects of the HPPC test over the duration of 160,000 miles of accelerated durability testing.

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[10] On-road testing for two Tahoe HEV's, VIN 5170 and VIN 7400, is located at: Advanced Vehicle Testing Activity - Hybrid Electric Vehicles.

Appendix A

Vehicle Specifications and Test Results Summary

Vehicle Specifications	Battery Specifications
Manufacturer: Chevrolet Model: Tahoe Year: 2008 Motor Power Rating[a]: 120 kW VIN #: 1GNFC13568R215170	Manufacturer: Panasonic Battery Type: Nickel Metal Hydride Rated Capacity: 6.5 Ah Nominal Pack Voltage: 288 VDC Nominal Cell Voltage: 1.2 V Number of Cells: 240
Beginning-of-Test Vehicle Baseline Performance Test Results[b]	
Acceleration Test	**Fuel Economy Test**
Average Discharge Power Over 10 seconds[c]: 14.5 kW Peak Discharge Power Over one (1) mile: 40.7 kW Energy Discharged @ one (1) mile[d]: 59.5 Wh Capacity Discharged @ one (1) mile[d]: 0.20 Ah Minimum Discharge Pack Voltage: 270.5 VDC Minimum Discharge Cell Voltage: 1.127 V	Peak Discharge Power: 37.4 kW Peak Charge Power: 32.0 kW Measured Capacity Discharged[e]: 10.32 Ah Measured Capacity Regenerated[e]: 10.41 Ah Battery Discharge/Charge Ratio[f]: 0.991 Maximum Charge Pack Voltage: 363.7 VDC Maximum Charge Cell Voltage: 1.51 Vpc Minimum Discharge Pack Voltage: 247.8 VDC Minimum Discharge Cell Voltage: 1.03 Vpc
End-of-Test Vehicle Baseline Performance Test Results	
Acceleration Test	
Average Discharge Power Over 10 seconds[c]: 13.8 kW Peak Discharge Power Over one (1) mile: 38.2 kW Energy Discharged @ one (1) mile[d]: 20.1 Wh Capacity Discharged @ one (1) mile[d]: 0.08 Ah Minimum Discharge Pack Voltage: 276.3 VDC Minimum Discharge Cell Voltage: 1.151 V	
Battery Beginning-of-Test Laboratory Test Results	
Hybrid Pulse Power Characterization Test	**Static Capacity Test**
Peak Pulse Discharge Power @ 10 seconds[g]: 28.0 kW Peak Pulse Discharge Power @ one (1) second[g]: 36.2 kW Peak Pulse Charge Power @ 10 seconds[g]: 23.0 kW Peak Pulse Charge Power @ one (1) second[g]: 31.5 kW Maximum Cell Charge Voltage: 1.49 V Minimum Cell Discharge Voltage: 1.0 V	Measured Average Capacity: 5.77 Ah Measured Average Energy Capacity: 1,750 Wh Vehicle Odometer: 543 miles Date of Test: April 16, 2008

Battery End-of-Test Laboratory Test Results	
Hybrid Pulse Power Characterization Test	**Static Capacity Test**
Peak Pulse Discharge Power @ 10 seconds[g]: 25.3 kW Peak Pulse Discharge Power @ 1 second[g]: 37.4 kW Peak Pulse Charge Power @ 10 seconds[g]: 24.8 kW Peak Pulse Charge Power @ 1 second[g]: 37.5 kW Maximum Cell Charge Voltage: 1.46 V Minimum Cell Discharge Voltage: 1.0 V	Measured Average Capacity: 5.00 Ah Measured Average Energy Capacity: 1,506 Wh Vehicle Odometer: 160,069 miles Date of Test: May 5, 2010
Degradation of Battery Over Test Period[h]	
Hybrid Pulse Power Characterization Test	**Static Capacity Test**
Peak Pulse Discharge Power @ 10 seconds[g]: 2.7 kW (9.6%) Peak Pulse Discharge Power @ one (1) second[g]: -1.2 kW (-3.3%) Peak Pulse Charge Power @ 10 seconds[g]: -1.8 kW (-7.8%) Peak Pulse Charge Power @ one (1) second[g]: -6.0 kW (-19%)	Measured Average Capacity: 0.77 Ah (13%) Measured Average Energy Capacity: 244 Wh (13%)

Analysis Notes:

a. Motor power rating refers to the manufacturer's peak power rating for the motor(s) supplying traction power.
b. Vehicle test results are derived from baseline testing of Tahoe VIN: 7400.
c. The peak power at a specified duration is the average power value over a specified interval.
d. The capacity\energy value is defined as the net value over a one (1) mile, full-throttle acceleration test.
e. Cumulative capacity measurement over two (2) hot start urban drive cycles and two (2) hot start highway drive cycles.
f. Ratio is calculated as the ratio of measured capacity discharge to measured capacity regenerated. The initial and final states of charge are not specifically known, but are controlled by the battery management system and are within its normal range.
g. Calculated value based on selected battery voltage limits and at 50% SOC of measured capacity at the time of BOT testing.
h. All values are the degradation or difference in the battery from initial laboratory test to final laboratory test.