VEHICLE TECHNOLOGIES PROGRAM

2011 Nissan Leaf VIN 0356 Electric Vehicle Battery Test Results

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December 2016

The Idaho National Laboratory is a U.S. Department of Energy National Laboratory
Operated by Battelle Energy Alliance

INL/EXT-13-28025

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December 2016

Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

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Disclaimers

ABSTRACT

The U.S. Department of Energy (DOE) Advanced Vehicle Testing Activity (AVTA) program consists of vehicle, battery, and infrastructure testing on advanced technology related to transportation. The activity includes tests on electric vehicles (EVs), including testing the EV batteries when both the vehicles and batteries are new and at the conclusion of 12,000 miles of on-road fleet testing. This report documents battery testing performed for the 2011 Nissan Leaf (VIN JN1AZ0CP5BT000356). The battery testing was performed by the Electric Transportation Engineering Corporation (eTec) dba ECOtality North America. The Idaho National Laboratory and ECOtality North America collaborate on the AVTA for the Vehicle Technologies Program of the DOE.

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ACRONYMS

Ah	amp-hour
BOT	beginning of test
CD	charge-depleting
CS	charge-sustaining
DOD	depth of discharge
DOE	Department of Energy
EOT	end of test
EV	electric vehicle
EVPC	Electric Vehicle Power Characterization
EVSE	electric vehicle supply equipment
kW	kilowatt
PHEV	plug-in hybrid vehicle
SOC	state of charge
V	volt
VDC	volt direct current
VIN	vehicle identification number
Vpc	volt per cell
Wh	watt-hour
USABC	United States Advanced Battery Consortium

1 TEST RESULTS

The U.S. Department of Energy (DOE) Advanced Vehicle Testing Activity (AVTA) program consists of vehicle, battery, and infrastructure testing on advanced technology related to transportation. The activity includes tests on electric vehicles (EVs), including testing the EV batteries when both the vehicles and batteries are new (beginning-of-test, or BOT) and at the conclusion of 12,000 miles of accelerated on-road fleet testing (end-of-test, or EOT). The BOT testing takes place not immediately after vehicle receipt, but instead after the vehicle has been "broken in", meaning that its drivetrain components are sufficiently worn and functioning smoothly. The BOT testing for this vehicle occurred when the vehicle odometer registered 6,696 miles, beginning on May 5, 2012. The EOT testing occurred when the vehicle odometer registered 22,606 miles, beginning on March 5, 2013. This report provides test results for BOT and EOT battery testing conducted on a 2011 Nissan Leaf with VIN 0356 (Full VIN: JN1AZ0CP5BT000356) in both laboratory and on-road settings. The battery laboratory test results include those from the Static Capacity test[3], the Constant Power Discharge (CPD) test, and the Electric Vehicle Power Characterization (EVPC) test[4]. Vehicle test results include those from Acceleration Testing and Fuel Economy Testing.[5]

The battery and vehicle testing was performed by the Electric Transportation Engineering Corporation (eTec) dba ECOtality North America. The Idaho National Laboratory (INL) and ECOtality North America collaborate on the AVTA for the Vehicle Technologies Program of the DOE.

1.1 Static Capacity Test Results

Results from the laboratory beginning-of-test (BOT) and end-of-test (EOT) static capacity tests are provided below in Table 1. The rated capacity of the 2011 Nissan Leaf battery is 45 Ah.

Table 1. Static capacity test results

	Test Date	Odometer (mi)	Measured Capacity (Ah)	Measured Energy (kWh)
BOT	May 5, 2012	6,696	57.6	21.0
EOT[6]	March 5, 2013	22,606	49.4	17.9
Difference	—	15,910	8.2 (14.2%)	3.1 (14.8%)

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/3 constant-current discharge rate at BOT and EOT.

[3] Static Capacity and Constant Power Discharge test procedures are based on the USABC Electric Vehicle Battery Test Procedures Manual Rev 2, January 1996, Procedures 2 and 3, respectively.

[4] EVPC and CPD testing is based on the USABC Electric Vehicle Battery Test Procedures Manual Rev 2, publication pending.

[5] Acceleration Testing and Fuel Economy Testing procedures were performed in accordance with the AVTA PHEVAmerica test procedures ETA-PHTP02 and ETA-PHTP03, respectively.

[6] The 2011 Nissan Leaf VIN 0356 was in two separate accidents, both determined by certified Nissan technicians to have had no discernible affect on the battery pack; this vehicle was frequently charged using DC fast-chargers; and the vehicle was driven and charged in the elevated temperatures of the Pheonix, AZ area. All of these factors could have accelerated the degradation of the battery.

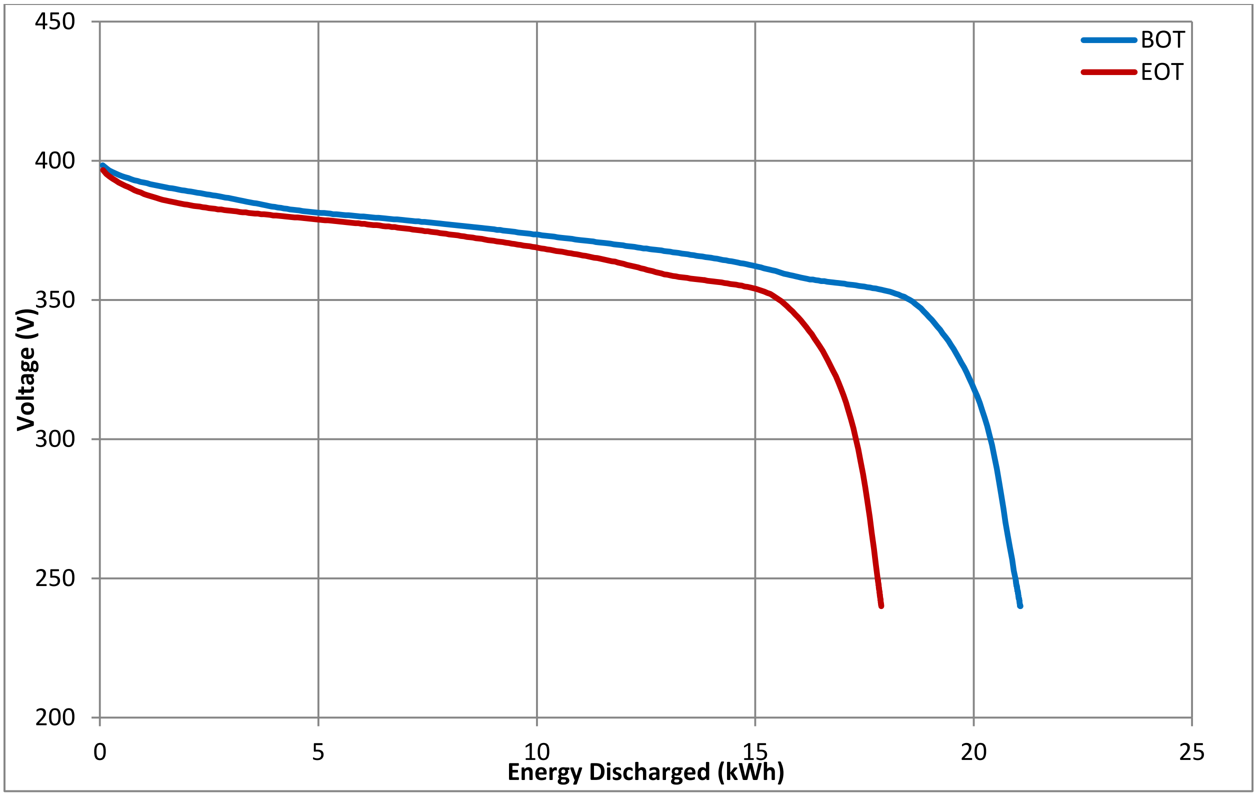

Figure 1. Voltage versus energy discharged during the Static Capacity test

1.2 Electric Vehicle Characterization Test Results

The EVPC Test commenced immediately following the Static Capacity test. The EVPC results are summarized below in Table 2.

Table 2. EVPC test results

	Discharge Power Capability @ 80% DOD (kW)	Discharge Resistance @ 80% DOD (Ω)	Charge Power Capability @ 20% DOD (kW)	Charge Resistance @ 20% DOD (Ω)
BOT	201.0	0.1380	71.2	0.1175
EOT	58.9	0.3413	63.4	0.1522
Difference	142.1 (70.7%)	-0.2033 (-147%)	7.8 (11.0%)	-0.0347 (-29.5%)

Figure 2 and Figure 3 illustrate the battery's charge and discharge pulse resistance graphs which show internal resistance at various depths of discharge (DODs). Each curve represents the resistance at the end of the specified pulse interval.

Figure 4 and Figure 5 illustrate the battery's charge and discharge pulse power capability graphs which show the calculated useable power at various DODs. Each curve represents the pulse power capability at the end of the specified pulse interval at the cell voltage limits.

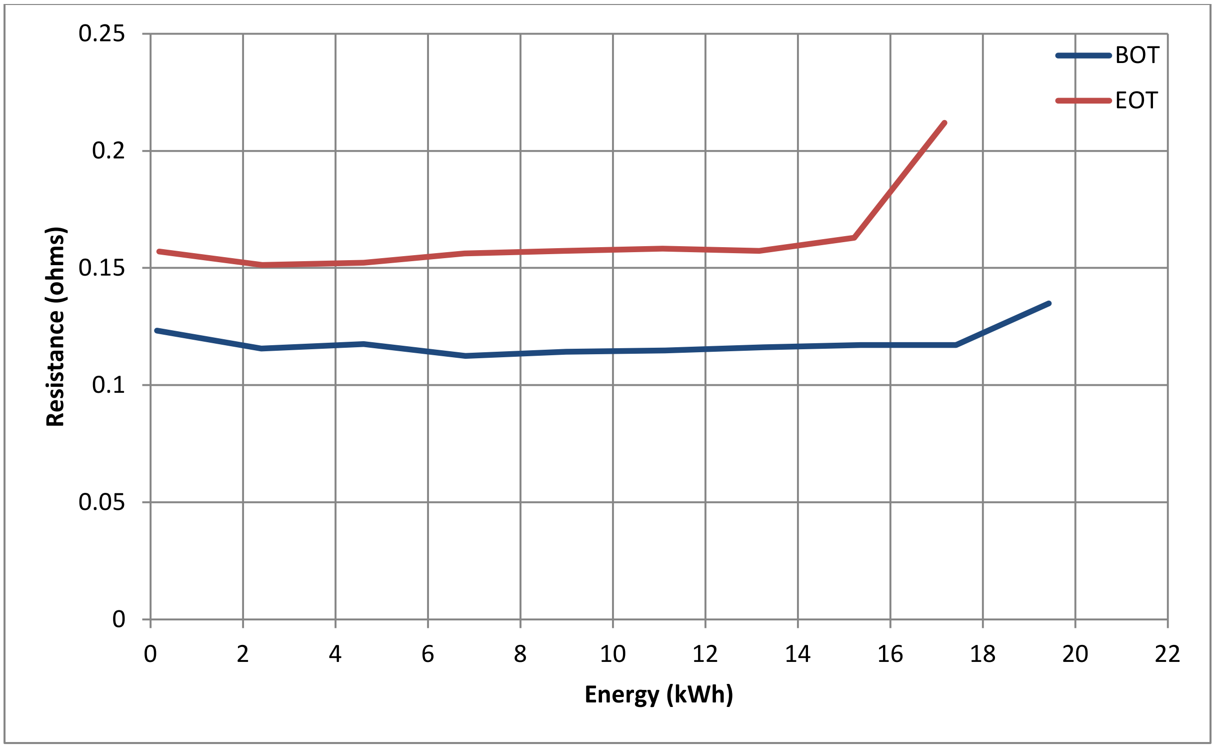

Figure 2. Charge pulse resistance versus energy discharged during the EVPC test

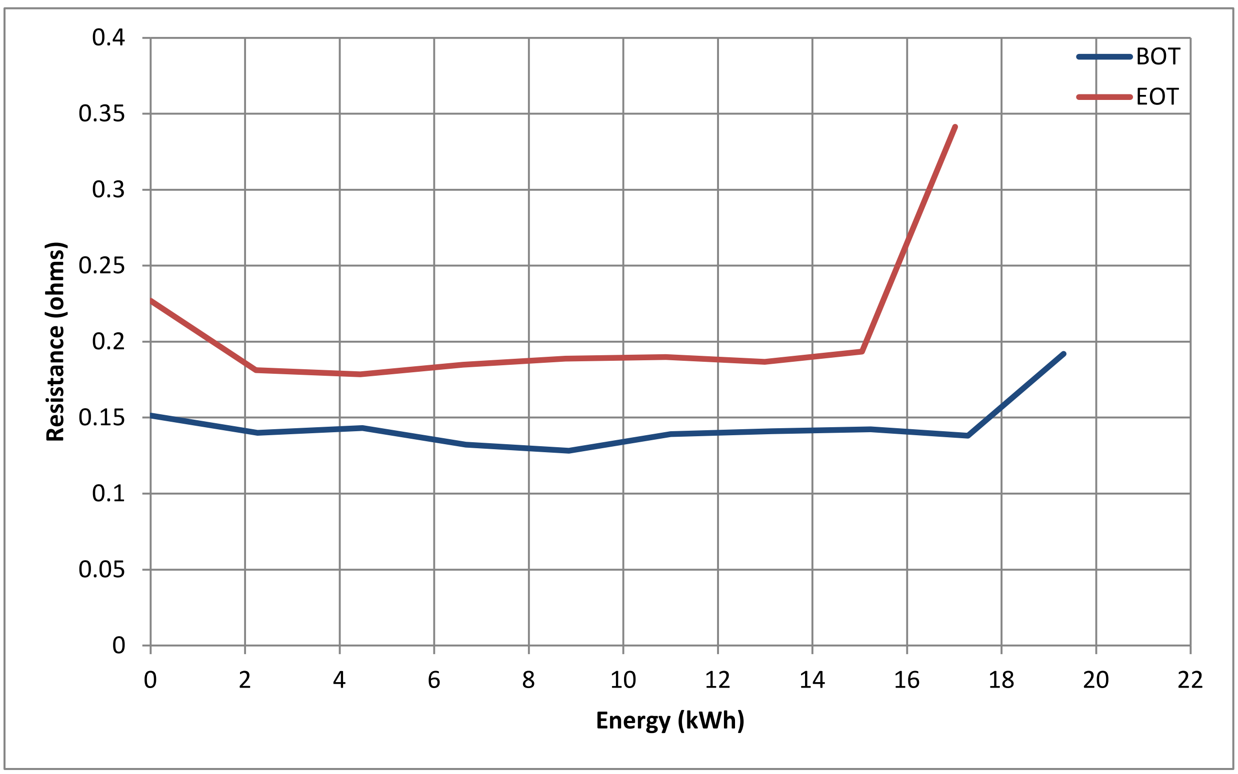

Figure 3. Discharge pulse resistance versus energy discharged during the EVPC test

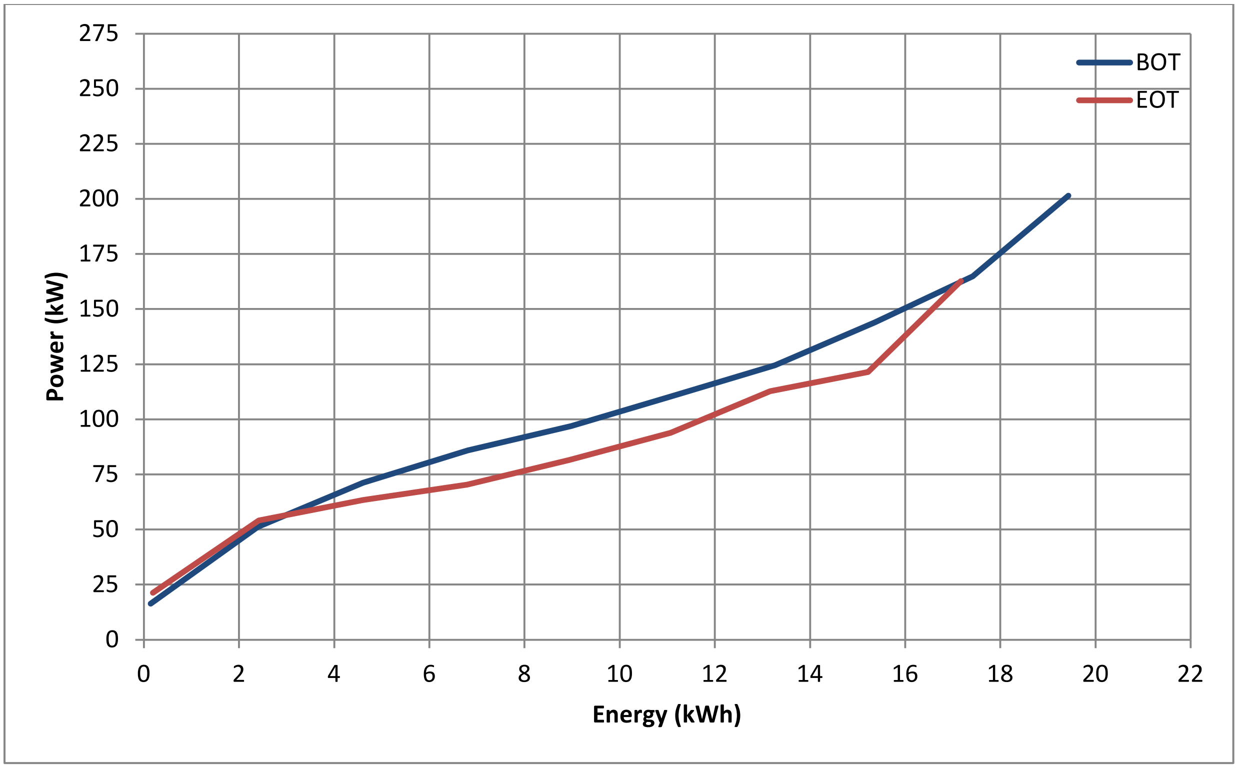

Figure 4. Charge pulse power capability versus energy discharged during the EVPC test

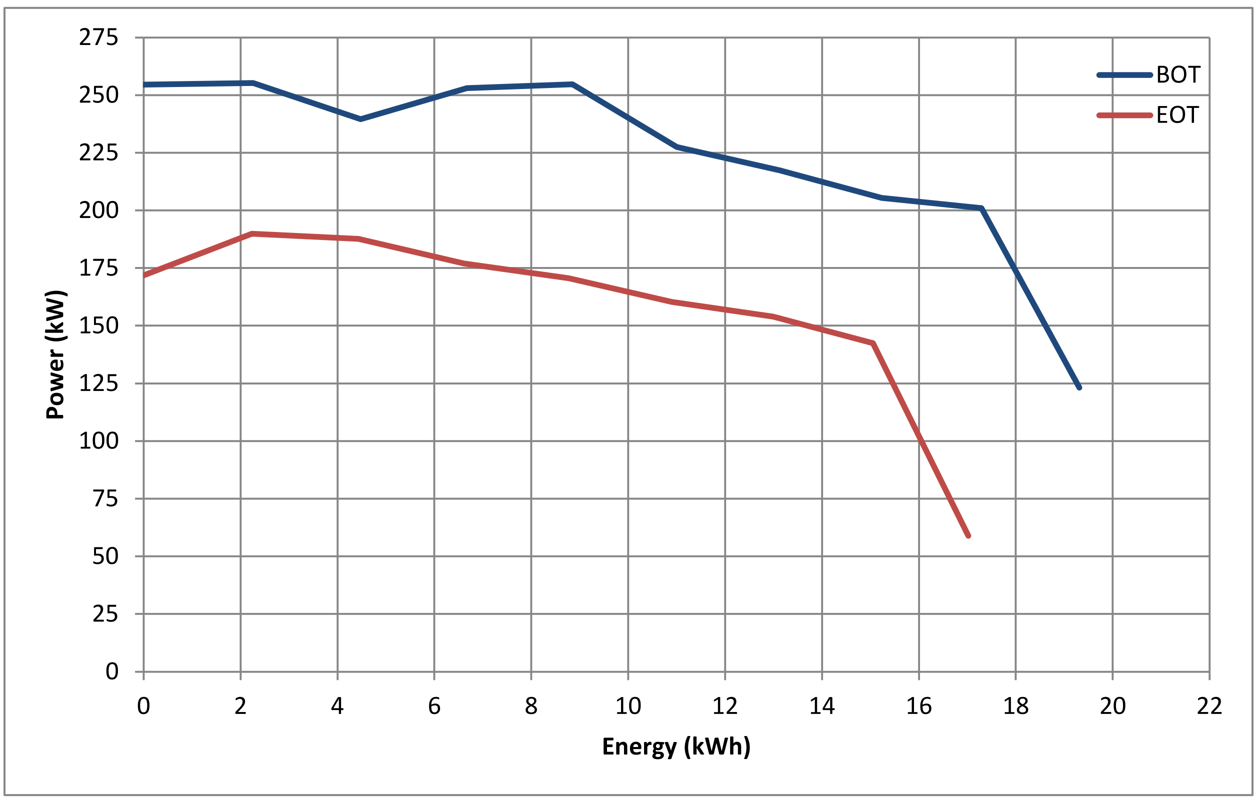

Figure 5. Discharge pulse power capability versus energy discharged during the EVPC test

1.3 Constant Power Discharge Test Results

The CPD test commenced immediately following the EVPC test. The CPD test results are summarized below in Table 3.

Table 3. Constant Power Discharge test results

	Capacity Discharged (Ah)	Energy Discharged (kWh)	Discharge Power Rate (kW)
BOT	56.8	20.0	37.05
EOT[7]	47.7	16.4	37.05
Difference	9.1 (16.0%)	3.6 (18.0%)	—

1.4 Acceleration Test Results

Acceleration testing took place beginning on February 6, 2012. BOT and EOT battery performance results from vehicle on-track acceleration tests are summarized below in Table 4. The discharge current and power refer to the energy out of the battery.

Table 4. Acceleration test results for BOT and EOT on-track acceleration tests

	Average Discharge Power Over Initial 30 s (kW)[8]	Energy Discharged Over Full Run (kWh)	Capacity Discharged Over Full Run (Ah)	Peak Discharge Power Over Full Run (kW)	Peak Discharge Current Over Full Run (A)
BOT	76.2	0.894	2.51	87.3	243.7
EOT[9]	NA	NA	NA	NA	NA

Figure 6 shows battery power versus time during the acceleration tests at BOT. This graph is the basis for power calculations over specified time or over the full test run and the cumulative discharged energy capacity during the duration of the test. At the beginning of the acceleration test, the power quickly increases from approximately 0 kW to the peak value. The power then remains relatively constant until vehicle system dynamics cause the power to adjust while holding a top speed.

[7] At the end of the constant power discharge, the voltage on two battery cell pairs fell below the point of being overdischarged and, as a result, the cell temperature increased to the point of the venting. This is likely a result of the significant battery degradation at the time of EOT testing.

[8] For acceleration testing, the average discharge power over the first 30 seconds is shown as an indirect metric comparable to the EVPC discharge pulse power capability. While limitations such as vehicle dynamics, conductor size, battery terminal size, etc., will rarely allow the battery to perform in-vehicle to the same power output levels shown capable in laboratory testing, the comparison of these values allows for a better understanding of the theoretical capability of the battery pack versus actual application.

[9] EOT acceleration testing was not performed due to the battery having two battery cell pairs fail at the end of the constant power test during laboratory testing.

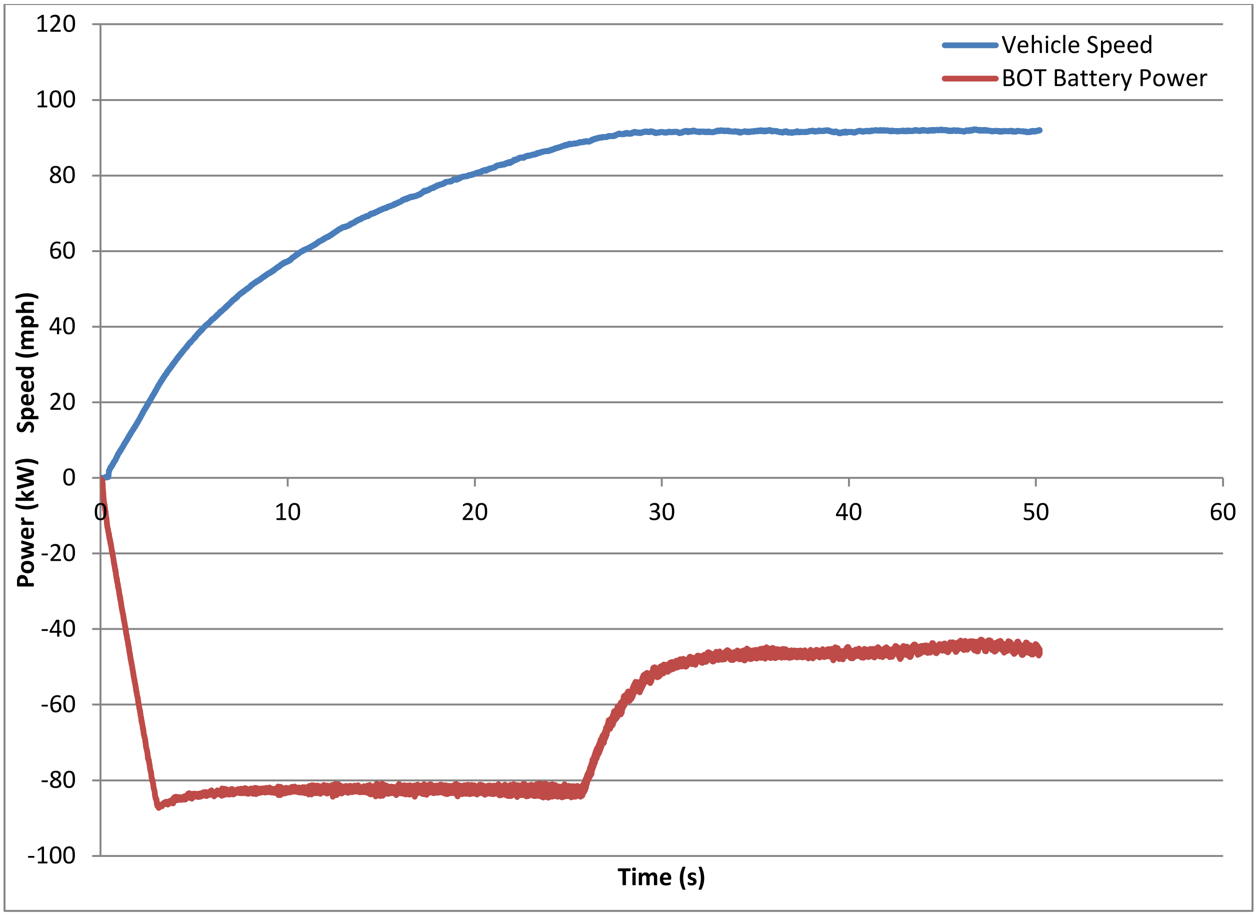

Figure 6. Battery power and vehicle speed versus time from BOT acceleration testing

Figure 7 show the battery voltage versus time plot during acceleration testing at BOT. This graph also shows the impact of power electronics and battery management system on the voltage response.

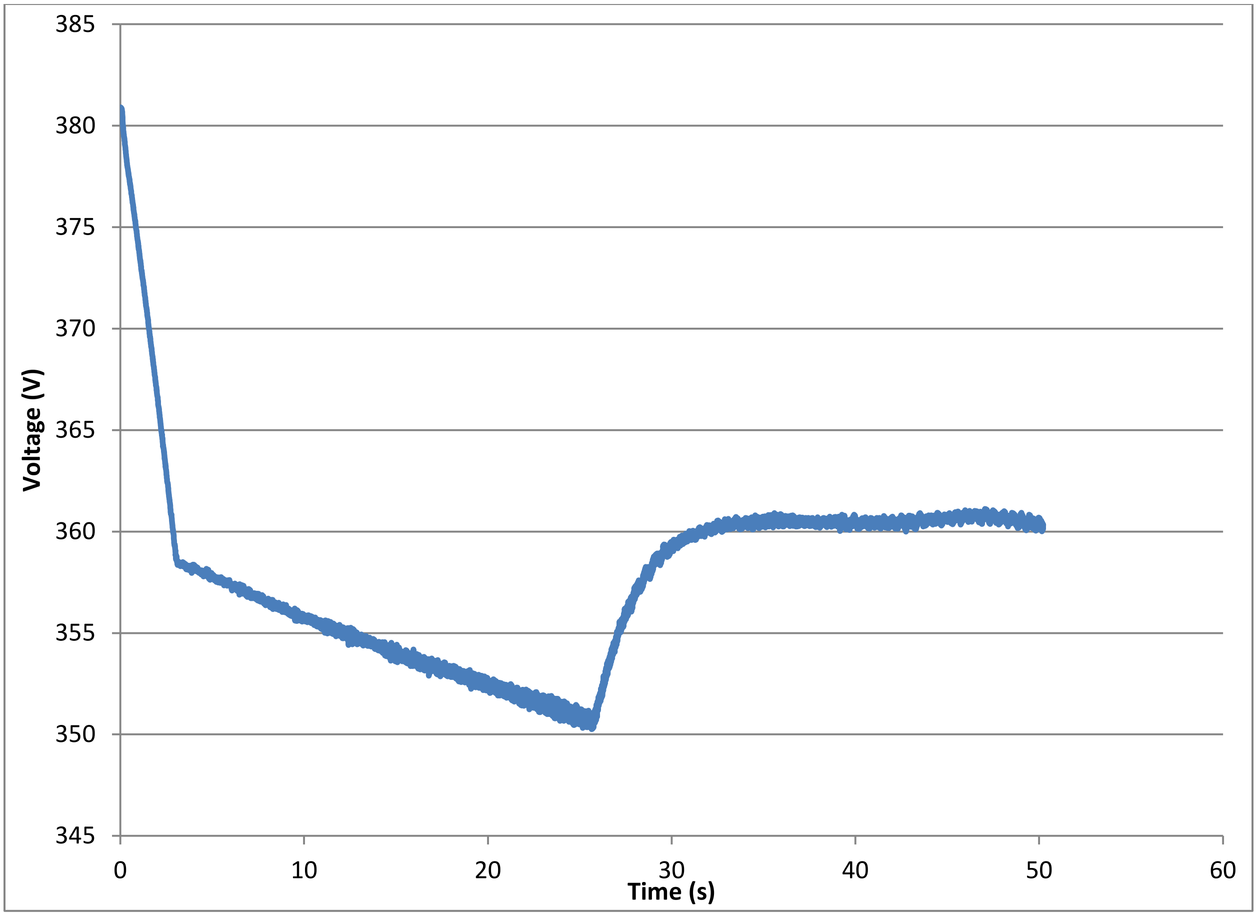

Figure 7. Battery voltage versus time from BOT acceleration testing

Figure 8 shows battery current versus time plots during acceleration testing at BOT. This graph also is the basis for determining the discharged capacity during the test run. Lastly, the power results in Figure 6 can be obtained by simply multiplying the voltage values from Figure 7 by the current values in Figure 8.

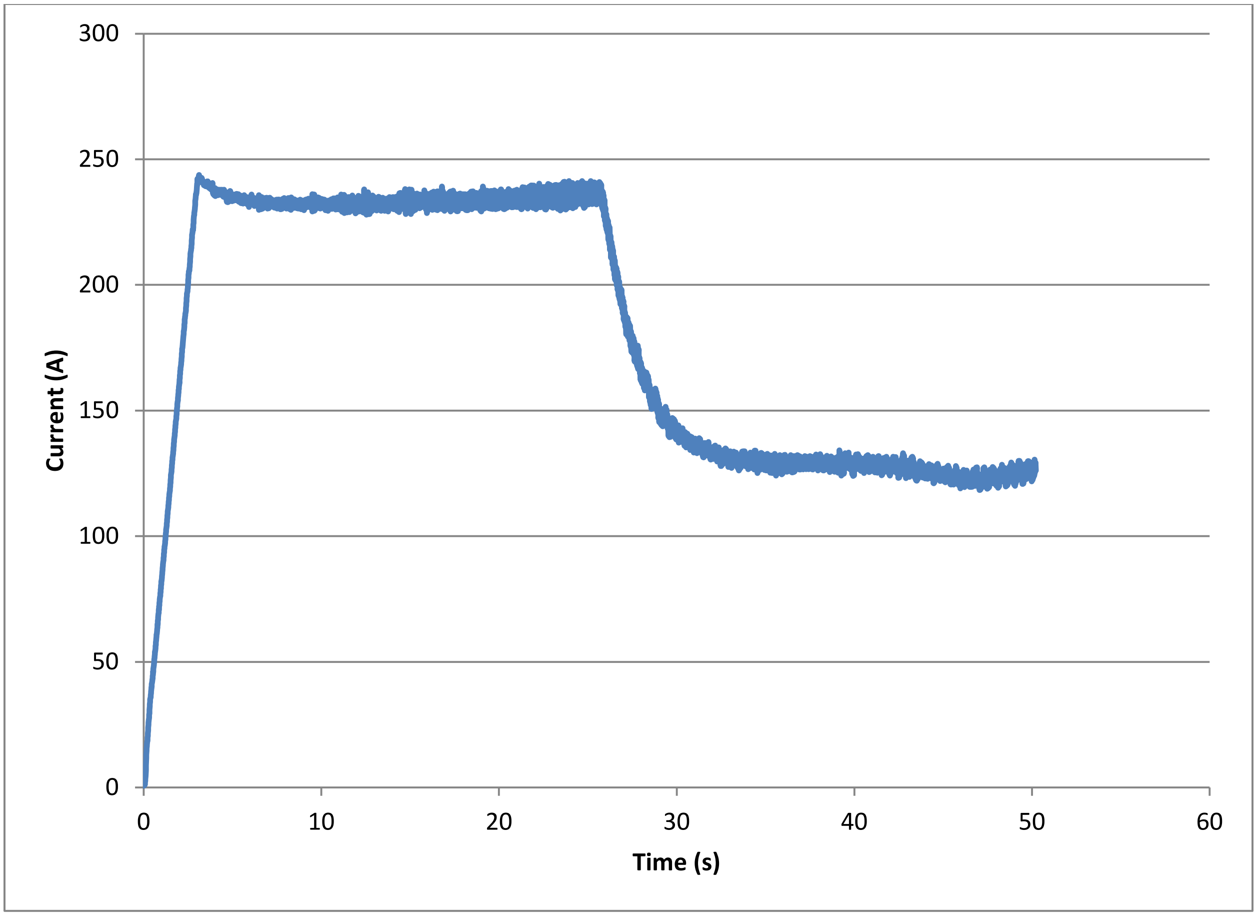

Figure 8. Battery current versus time from BOT acceleration testing

1.5 Dynamometer Test Results

This section contains battery performance testing conducted on a chassis dynamometer (using the Urban Dynamometer Drive Schedule (UDDS), Highway Fuel Economy Test (HFET), and US06[10]) at BOT Dynamometer data and calculations are summarized in Table 5.

Table 5. Battery performance results from dynamometer drive cycle testing11

	UDDS	HWY	US06
Net Capacity Discharge (Ah):	3.86	6.28	7.38
Total Net Energy (kWh):	1.45	2.37	2.67
Energy Consumption Rate (Wh/mile):	194.6	231.0	333.3
Max Drive Power (kW):	44.5	39.6	89.0
Max Drive Current (A):	120.4	106.1	255.3
Max Regenerative Power (kW):	29.4	29.3	35.6
Max Regenerative Current (A):	75.3	75.2	93.2
Average Current (A):	10.1	29.5	44.2

[10] Urban Dynamometer Drive Schedule, Highway Fuel Economy Test, and US06 were performed as defined by the Environmental Protection Agency. The definition of each drive schedule can be found at http://www.epa.gov/otaq/standards/light-duty/index.htm#3.

[11] These values were calculated by averaging the vehicles discharge capacity over multiple cycles for the given drive cycle.

2 Conclusion

The testing of Nissan Leaf 0356 included BOT and EOT battery tests and 15,910 miles of fleet testing. For vehicle battery packs, end-of-life (EOL) criteria is determined to be when the discharge capacity or discharge energy degradation exceeds 23% of the rated value, as specified in the USABC Electric Vehicle Battery Test Procedures Manual Rev 3 (publication pending). The Nissan Leaf with VIN 0356 experienced a degradation of 14.8% in battery capacity between BOT and EOT testing. This equates to 25.3% degradation from the 66.2 Ah rated capacity. The battery of Nissan Leaf 0356 is well beyond the EOL threshold. The battery of Leaf 0356 also had a degradation of 70.7% and 11.0% in discharge and charge power capability at 80% and 20% DOD, respectively, over the same duration of fleet testing.

Appendix A –Vehicle Specifications and Test Results Summary

Vehicle Specifications	Battery Specifications
Base Vehicle: 2011 Nissan Leaf VIN: JN1AZ0CP5BT000356 Propulsion System: BEV Electric Machine: 80 kW (peak), Permanent Magnet AC Synchronous, Air Cooled	Manufacturer: Automotive Energy Supply Corporation Type: Lithium-ion – Laminate type Cathode/Anode Material: $LiMn_2O_4$ with $LiNiO_2$/Graphite Pack Location: Under Center of Vehicle Number of Cells: 192 Cell Config.: 2 Parallel Strings of 96 in Series Nominal Cell Voltage: 3.8 V Nominal System Voltage: 364.8 V Rated Pack Capacity: 66.2 Ah Rated Pack Energy: 24 kWh Maximum Cell Charge Voltage[2]: 4.2 V Minimum Cell Discharge Voltage[2]: 2.5 V Thermal Mgmt.: Passive, Vacuum-Sealed Unit Pack Weight: 294 kg

Beginning-of-Test Vehicle Baseline Performance Test Results[2]
Acceleration Testing
Average Discharge Power Over 10 seconds: 76.2 kW Energy Discharged Over Full Run: 0.894 kWh Capacity Discharged Over Full Run: 2.51 Ah Peak Discharge Power Over Full Run: 87.3 kW Peak Discharge Current Over Full Run: 243.7 A
Fuel Economy Testing (UDDS, HWY, US06)
Single Cycle Net Capacity Discharge: 3.86 Ah, 6.28 Ah, 7.38 Ah Single Cycle Net Energy: 1.45 kWh, 2.37 kWh, 2.67 kWh Single Cycle Max Drive Power: 44.5 kW, 39.6 kW, 89.0 kW Single Cycle Max Drive Current: 120.4 A, 106.1 A, 255.3 A Single Cycle Max Regenerative Power: 29.4 kW, 29.3 kW, 35.6 kW Single Cycle Max Regenerative Current: 75.3 A, 75.2 A, 93.2 A Average Current: 10.1 A, 29.5 A, 44.2 A

Battery Beginning-of-Test Laboratory Test Results	
Electric Vehicle Power Characterization Test	**Static Capacity Test**
Discharge Power @ 80% DOD: 201.0 kW Discharge Resistance @ 80% DOD: 0.1380 Ω Charge Power @ 20% DOD: 71.2 kW Charge Resistance @ 20% DOD: 0.1175 Ω Maximum Cell Charge Voltage: 4.2 V Minimum Cell Discharge Voltage: 2.4 V	Measured Average Capacity: 57.6 Ah Measured Average Energy Capacity: 21.0 kWh
Battery End-of-Test Laboratory Test Results[2]	
Electric Vehicle Power Characterization Test	**Static Capacity Test**
Discharge Power @ 80% DOD: 58.9 kW Discharge Resistance @ 80% DOD: 0.3413 Ω Charge Power @ 20% DOD: 63.4 kW Charge Resistance @ 20% DOD: 0.1522 Ω Maximum Cell Charge Voltage: 4.2 V Minimum Cell Discharge Voltage: 2.4 V	Measured Average Capacity: 49.4 Ah Measured Average Energy Capacity: 17.9 kWh
Degradation of Battery Over Test Period[3]	
Electric Vehicle Power Characterization Test	**Static Capacity Test**
Discharge Power @ 80% DOD: 142.1 kW (70.7%) Discharge Resistance @ 80% DOD: -0.2033 Ω (-147%) Charge Power @ 20% DOD: 7.8 kW (11.0%) Charge Resistance @ 20% DOD: -0.0347 Ω (-29.5%)	Measured Average Capacity: 8.2 Ah (14.2%) Measured Average Energy Capacity: 3.1 kWh (14.8%)

Notes:

1. Motor power rating refers to the manufacturer's peak power rating for the motor(s) supplying traction power.
2. The BOT battery laboratory tests took place May 5, 2012, when the vehicle odometer was at 6,696 miles; the EOT battery laboratory tests took place on March 5, 2013, when the vehicle odometer was at 22,606 miles.
3. All values are the degradation or difference in the battery from initial laboratory test to final laboratory test.