Test Specification – Vehicle Energy Storage System Testing

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Revision History Log

Revision No.	Revisions Description	Effective Date	Revised/Reviewed By	Approved By
0	Initial release	11/23/2015	Tyler Gray	Jeremy Diez

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1 Objective

The objective of this Test Specification is to outline acceptable methods for the implementation of the test requirements of the various different battery test manuals (see references in Section 6) for specific electrified vehicle powertrains. This Test Specification establishes methods to quantitatively evaluate the capacity of an advanced vehicle battery as well as the battery's power capability over its useable range of current and voltage. The actual specific steps for the test conduct are listed and described as vehicles participating in the Advanced Vehicle Testing and Evaluation (AVTE) program or in other advanced vehicle testing activities. This Test Specification outlines the methods for experimental conduct and data analysis. The actual specific steps for the test conduct are listed and described in the associated Center for Evaluation of Clean Energy Technology. (CECET) internal Work Instruction document.

2 Test Conduct

Documentation resulting from usage of this Test Specification shall be consistent, easy to understand, easy to read, and readily reproducible. All documentation required to complete testing shall be completed, approved, and ready for issue prior to commencing the testing it addresses. The following will abide by company policy:

- Review and approval of test results
- Storage and retention of records during and following testing activities
- Recording of any deviation from the outlined procedures and the reason for the deviation

3 Initial Conditions & Prerequisites

Prior to conduct of any portion of the testing, the following initial conditions and prerequisites shall be met. Satisfactory completion of these items should be verified.

3.1 Personnel

Personnel conducting testing under this Test Specification, i.e., the Test or Project Engineer(s), shall be familiar with the requirements of this Test Specification, shall be trained in accordance with company policy, and shall be certified by a Mandated Reviewer prior to commencing any testing activities. This requirement includes training in all aspects of the Vehicle Energy Storage System Testing including its automatic shutdowns and safety procedures.

3.2 Manufacturer Information

The tests and conditions outlined in Section 5 are based on the manufacturer's specifications of the battery pack. Hence, the following information must be obtained from the manufacturer:

3.2.1 Recommended charge rate (i.e. current magnitude $C_{1/x}$ where x equals amount of time (in hours) needed to reach the top-of-charge voltage (TOCV)).

3.2.2 The TOCV limit when charging the battery at the $C_{1/x}$ constant charge current rate.

3.2.3 Recommended TOCV adjustment due to battery temperature

3.2.4 Recommended discharge capacity rate ($C_{1/y}$ where y equals the amount of time (in hours) needed to reach the end-of-discharge voltage (EODV)).

3.2.5 The EODV limit when performing a capacity test discharge at the $C_{1/y}$ constant discharge current rate.

3.3 Instrumentation

3.3.1 All instrumentation used during testing shall be calibrated. The calibration shall be performed and documented in accordance with company policy.

3.3.2 All instrumentation shall have the accuracies and resolutions noted. Unless specific exceptions have been made by the Test Manager, the following identifies the minimum instrumentation specification that shall be installed and employed during the testing:

3.3.2.1 Temperature

Accuracy: ± 1 °C

3.3.2.2 Battery Current

Accuracy: ± 1 A

3.3.3 Battery Voltage

Accuracy: ± 1 V

4 Test Activity Requirements

This section addresses testing required to meet the stated objective of this Test Specification. To this end, specific tests are selectively utilized. For ease of use and consistency of format with other Test Specifications, this section is divided into subsections for each ESS type, then further divided by major test. Unless otherwise noted, each section may be completed independent of all the other sections.

4.1 Collected Test Data

The following data shall be collected during conduct of the various tests specified by this procedure. Overall error in recording or indicating instruments shall not exceed ±2% of the maximum value of the variable being measured. Periodic calibration shall be performed and documented to ensure compliance with this requirement.

4.1.1 ESS voltage versus time

4.1.2 ESS current versus time

4.1.3 ESS power versus time

4.1.4 ESS capacity versus time

4.1.5 ESS energy versus time

4.1.6 ESS temperature versus time

4.1.7 Ambient temperature versus time

4.2 General Test Conditions

4.2.1 Units of charge and discharge: The charge and discharge of batteries in all test profiles will be based on current, with units of amperes (A). Negative current will correspond to a discharge and positive current will relate to a charge for reporting purposes.

4.2.2 Ambient temperature control: The ambient temperature for all testing shall be controlled at a nominal temperature of 25 °C +/- 5°C. All tests shall be preceded by, at minimum, 4-hour soak at this temperature.

4.2.3 ESS temperature control: The ESS temperature must be monitored, at least, on or inside the ESS where the highest thermal rise is likely to occur. The test must stop if the temperature rises above the manufacturer's recommended maximum charging temperature. If no maximum charging temperature is available, a reasonable temperature for the type of ESS being tested shall be chosen and approved by a Mandated Reviewer. It is recommended that cooling techniques applied to the ESS during normal operation while within the vehicle be used during testing. If these techniques are not enough to sufficiently cool the ESS, additional cooling may be used but a note must be made to the test documentation.

4.3 ESS Charging

The conditions for ESS charging should be defined using the manufacturer's recommended procedure. If no manufacturer's specifications are available, the battery will be recharged based on literature data specific to the technology under test and the method will be approved by a Mandated Reviewer.

4.4 Battery Testing Protocols

This section outlines the testing sequence and protocols to be performed for each battery operated vehicle type. The testing sequence is shown in Table 5-1, All tests are to be performed in order from left to right.

Table 4-1. Battery testing protocol by vehicle type

Vehicle Type	Battery Test				
	Static Capacity	HPPC	EVPC	Constant-Power Discharge	Low Peak Power
HEV	X	X			
PHEV	X	X			
EV	X		X		X
NEV	X				
Idle-Stop	X				

4.4.1 Static Capacity Test

This test measures the capacity of the battery in Ah at a constant discharge current rate that corresponds to the manufacturer's rated capacity (C):

1. EVs and NEVs: C/3 rate
2. HEVs: C_1 rate
3. PHEVs: 10 kW-based current calculated using equations (1) and (2) below

$$V_{AVG} = \frac{V_{MAX} + V_{MIN}}{2} \text{ (V)} \qquad (1)$$

$$I_{PHEV} = \frac{10kW}{V_{AVG}} \text{ (A)} \qquad (2)$$

If no manufacturer's rated capacity is available, a discharge current shall be estimated based on the weight, volume, typical energy density of the specific technology under test that corresponds with the specifications above.

Discharge is terminated when the battery voltage has decreased to the manufacturer's specified EODV limit. If the manufacturer does not supply a value, a limit shall be derived from literature data specific to the battery technology under test.

4.4.2 Hybrid Pulse Power Characterization Test

Use of the HPPC test is intended to provide an estimate of the power capability (charge and discharge) of an ESS. This test is used for ESSs which supplement the power and energy of the primary vehicle propulsion system such as HEVs and PHEVs.

The primary objective of this test is to establish, as a function of depth-of-discharge (DOD), the following:

- V_{min} discharge power capability at the end of a 10-second discharge current pulse;
- V_{max} regeneration power capability at the end of a 10-second regeneration current pulse.

The test consists of a charge and discharge pulse power current (PPC) separated by 40 seconds at every 10% SOC decrement, starting at 90% and finishing at 10%. For HEVs, the current magnitude of the discharge pulse is equal to that of five times the one-hour capacity (C_1) rate and the charge pulse is equal to 75% of the discharge rate. For PHEVs, the discharge current is 2.5 times that of the static capacity current calculated in equation (2) above, while the charge current is again 75% of the discharge current. Refer to Table 5-3, Figure 5-1, and Figure 5-2 for further clarification.

Table 4-2. HPPC pulse sequence

Time Increment (s)	**Cumulative Time (s)**	**Current**	
		HEV	**PHEV**
10	10	$-5C_1$	$-2.5I_{PHEV}$
40	50	0	0
10	60	$0.75 * 5C_1$	$0.75 * 2.5I_{PHEV}$

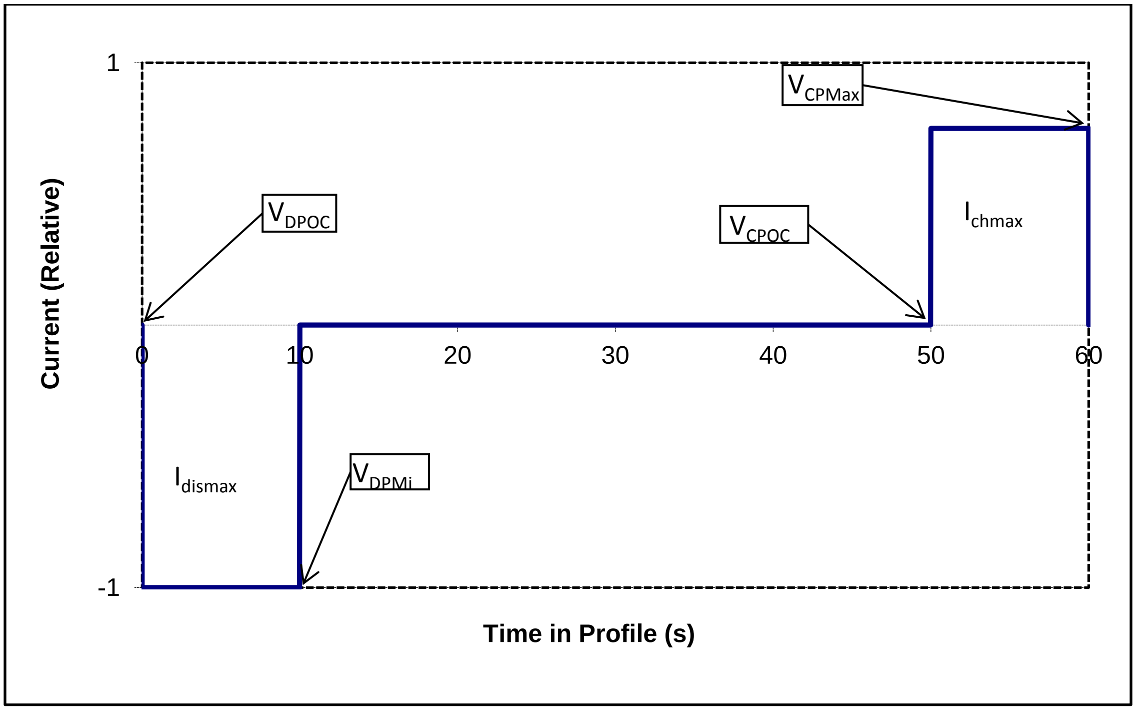

Figure 4-1. HPPC test profile

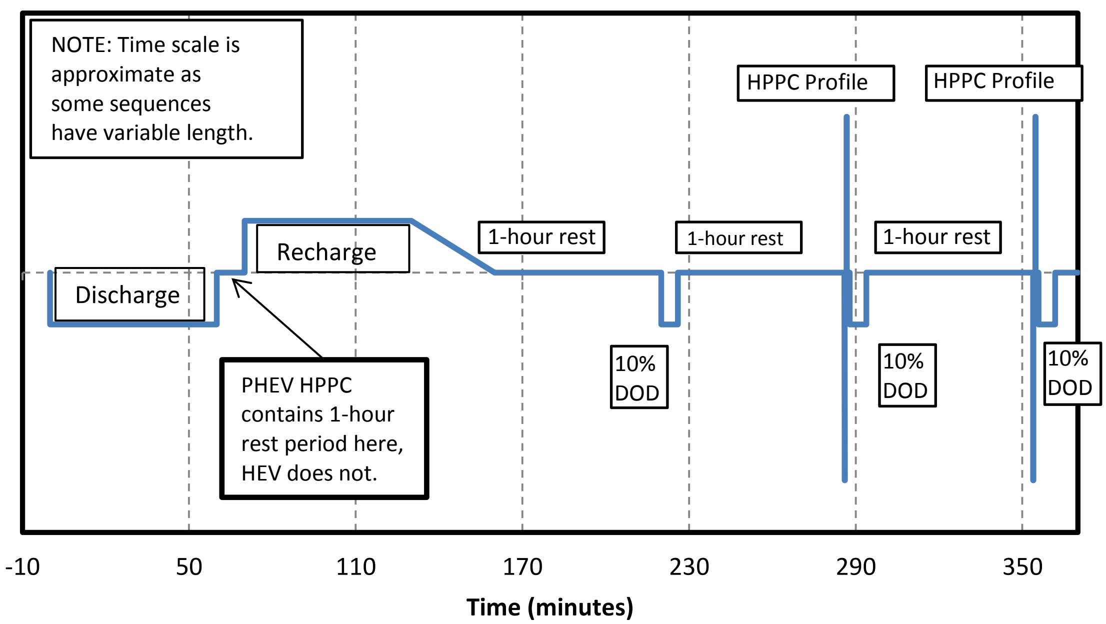

Figure 4-2. HPPC beginning test sequence

4.4.2.1 Calculating HPPC charge and discharge power capability

The charge and discharge power capability should be calculated for each SOC increment. To calculate the charge and discharge power capability for each pulse, the internal battery resistance must be calculated based on the open-circuit voltage immediately prior to the start of the pulse, V_{CPOC} or V_{DPOC}, subtracted by the voltage at the end of the pulse, V_{CPMax} or V_{DPMin}, all divided by the change in current . The internal battery resistances for both charge and discharge are calculated in equations (3) and (4), respectively.

$$\boldsymbol{R_{ch}} = \frac{\Delta V}{\Delta I} = \frac{V_{CPMax} - V_{CPOC}}{I_{CPMax} - I_{CPOC}} \ (\Omega) \qquad (3)^1$$

$$\boldsymbol{R_{dis}} = \frac{\Delta V}{\Delta I} = \frac{V_{DPOC} - V_{DPMin}}{I_{DPOC} - I_{DPMin}} \ (\Omega) \qquad (4)^1$$

With the internal battery resistance, the pulse power can then be calculated by using the power equations (5), (6) where VMin and VMax are the minimum and maximum total battery voltage limits used at the time of testing and VCPOC_I is the charge pulse open-circuit voltage interpolated from the discharge pulse open-circuit voltage versus capacity discharged curve based on the capacity discharge immediately prior to a discharge pulse. Instructions on finding VCPOC_I are shown in Appendix A.

$$\boldsymbol{P_{dis}} = \frac{V_{Min} * (V_{DPOC} - V_{Min})}{R_{dis} * 1000} \ (\text{kW}) \qquad (5)$$

$$\boldsymbol{P_{ch}} = \frac{V_{Max} * (V_{Max} - V_{CPOC\_I})}{R_{ch} * 1000} \ (\text{kW}) \qquad (6)$$

4.4.2.2 Calculating HPPC useable power and useable energy for HEVs

The useable power and energy for each battery pack are calculated from the charge and discharge power capability versus energy discharged values calculated in the previous section. A graphical representation of the charge and discharge power capability versus energy discharged values is shown in Figure 4-3.. The difference in energy for a given power value between the charge and discharge power capability curves must be calculated. The given power values have to be below the intersection point and have a single data point for each curve. Charge

[1] If, during any pulse, the current is reduced due to reaching a voltage limitation, the average current over the pulse duration is to be used in place of the difference between open-circuit and end-pulse current magnitudes for calculating resistance.

power shall be scaled with respect to the discharge power scale; therefore, all charge power values are to be multiplied by 5/4. The known power and energy points for each curve are then used with the energy value found by using a linear interpolation between two known points of the opposite curve. The known and numerically found energy values for each given power value are then subtracted from one another. The difference in energy is then graphed with respect to the power. An example of this calculation is shown in Appendix A.

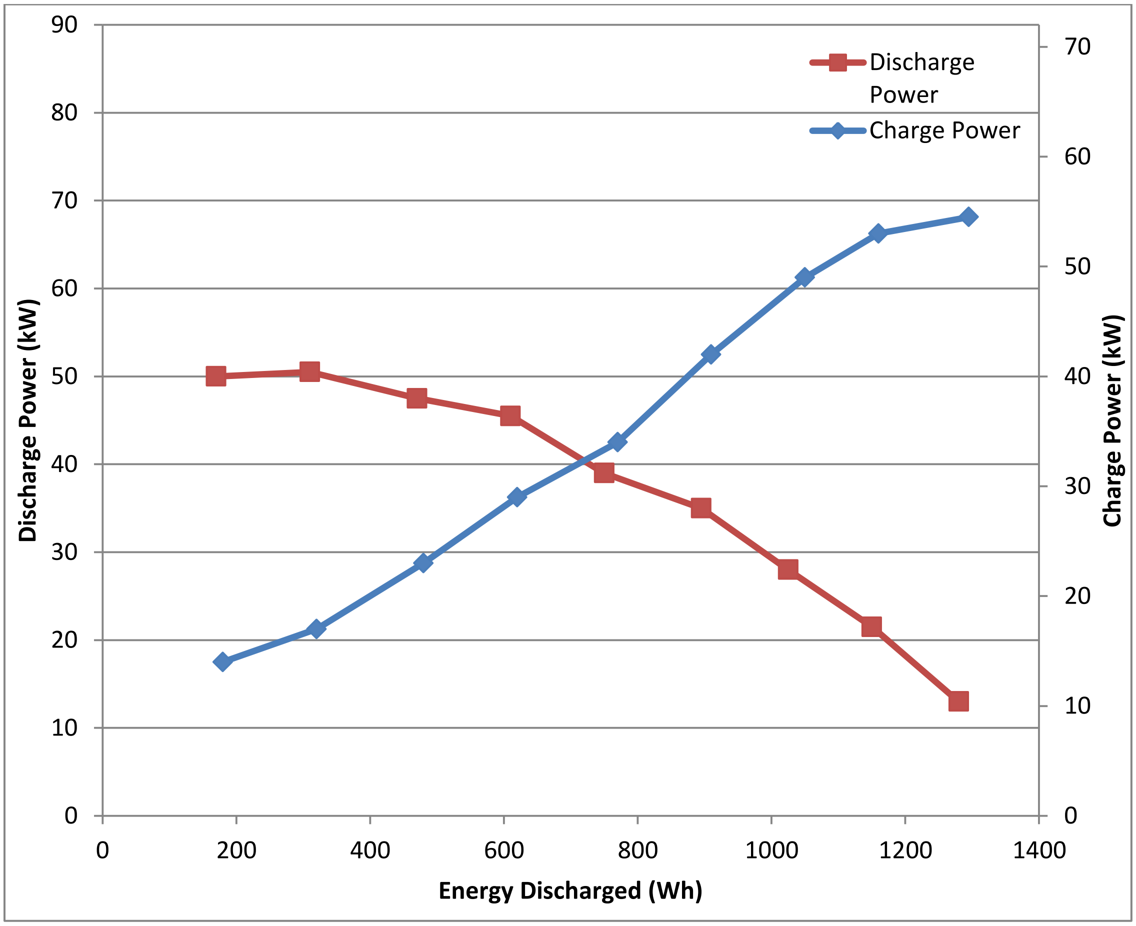

Figure 4-3. Example of calculated HPPC charge and discharge power versus energy discharged.

4.4.2.3 Calculating HPPC useable energy for PHEVs

Before calculations for useable energy can be made, a distinction of the type of PHEV battery must be made. For this testing, the type of battery is determined by approximating the battery pack energy available for charge-depleting mode within the vehicle to one of three values, 3.4 kWh, 5.8 kWh, or 11.6 kWh. Once this is established the category can be defined as a Minimum, Medium, or Maximum PHEV battery, respectively.

With the type of PHEV battery established, Equation 7 and Equation 8 can then be used to find the charge-depleting (CD) and charge-sustaining (CS) useable energy where $E_{PHEV\ Discharge}$ is the energy at a particular power on the discharge pulse power curve, $E_{PHEV\ Charge\ Target}$ is the energy that corresponds to 10% DOD, $AE_{CS\ Target}$ and $AE_{CD\ Target}$ are shown in Table 4-3. Values for $E_{PHEV\ Discharge}$ are bound by the intersection with the charge pulse power curve. An example of this calculation is located in Appendix A.

$$UE_{CD} = \left[E_{PHEV\ Discharge} - E_{PHEV\ Charge\ Target}\right] - {}^{1}/_{2}\, AE_{CS\ Target} \qquad (7)$$

$$UE_{CS} = \left[E_{PHEV\ Discharge} - E_{PHEV\ Charge\ Target}\right] - \left[AE_{CD\ Target} - \tfrac{1}{2}AE_{CS\ Target}\right] \qquad (8)$$

Table 4-3. Equation variables based on type of PHEV.

	Minimum PHEV	Medium PHEV	Maximum PHEV
$AE_{CD\ Target}$ (kWh)	3.4	5.8	11.6
$AE_{CS\ Target}$ (kWh)	0.5	0.3	0.3

4.4.3 Constant-Power Discharge Test

The Constant-Power Discharge test is designed to determine battery capacity and energy during a constant power discharge. The constant power rate is 10 kW. The discharge should be initiated after the battery is fully charged and stopped upon reaching a predetermined EODV. One-hour rest periods at open-circuit should precede and follow a constant power discharge.

4.4.4 Electric Vehicle Power Characterization Test

Use of the EVPC test is intended to provide an estimate of the power capability (charge and discharge) of an ESS. This test is used for ESSs which are the primary means of power and energy for a vehicle.

The primary objective of this test is to establish, as a function of depth-of-discharge (DOD), the following:

- V_{min} discharge power capability at the end of a 30 second discharge current pulse;
- V_{max} regeneration power capability at the end of a 10 second regeneration current pulse.

The current magnitude of the discharge pulse is equal to that of the one-hour capacity (C_1) rate and the charge pulse is equal to 75% of the C_1 rate measured during the Static Capacity test. Time increments and the cumulative time for these pulses are shown in Table 5-4. The test consists of a discharge and a regenerative current pulse separated by

40 seconds at every 10% SOC decrement, starting at 100% and finishing at 10%. Refer to Table 5-4, Figure 5-3 and Figure 5-4 for further clarification.

Table 4-4. EVPC pulse sequence

Time Increment (s)	Cumulative Time (s)	Current
30	30	C_1
40	70	0
10	80	$0.75 * C_1$

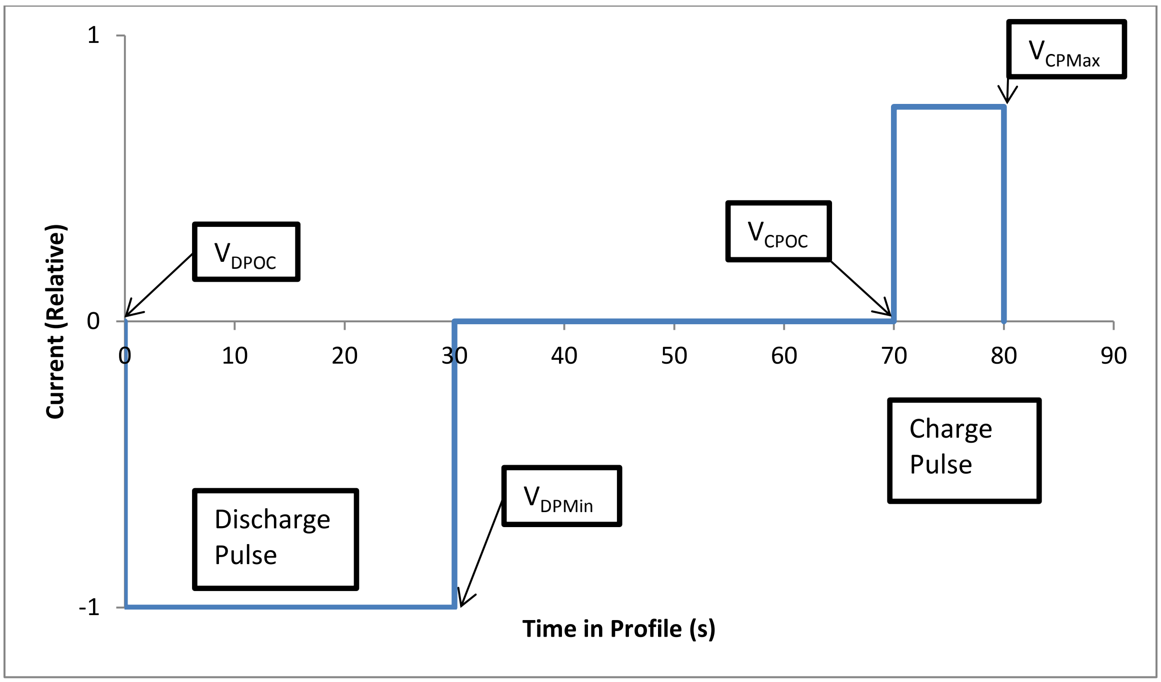

Figure 4-4. EVPC profile pulses

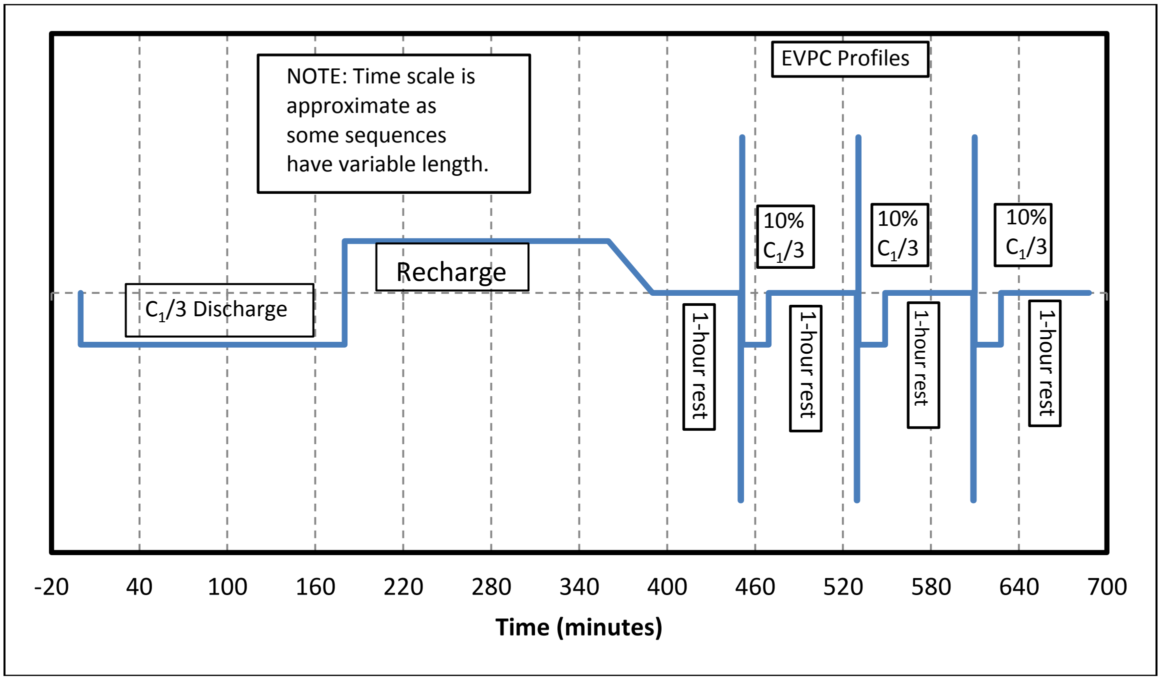

Figure 4-5. EVPC beginning pulse sequence

4.4.4.1 Calculating EVPC regeneration and discharge power capability

The regenerative and discharge power capability should be calculated for each SOC increment. To calculate the regenerative and discharge power capability for each pulse, the internal battery resistance must be calculated based on the open-circuit voltage immediately prior to the start of the pulse, V_{CPOC} or V_{DPOC}, subtracted by the maximum or minimum voltage at the end of the pulse, V_{CPMax} or V_{DPMin}, all divided by the average current throughout the duration of the pulse, as shown in equations (5) and (6).

$$\boldsymbol{R_{ch}} = \frac{\Delta V}{\Delta I} = \frac{V_{CPMax} - V_{CPOC}}{I_{CPMax} - I_{CPOC}}\ (\Omega) \qquad (9)^2$$

$$\boldsymbol{R_{dis}} = \frac{\Delta V}{\Delta I} = \frac{V_{DPOC} - V_{DPMin}}{I_{DPOC} - I_{DPMin}}\ (\Omega) \qquad (10)^2$$

With the internal battery resistance, the pulse power can then be calculated by using the power equations (7) and (8), where V_{Min} and V_{Max} are the minimum and maximum total battery voltage at the time of testing and V_{ED} is the voltage at the point during the initial, prior to applying any pulses, C/3 capacity discharge where

[2] If during any pulse the current is reduced due to reaching a voltage limitation, the average current over the pulse duration is to be used in place of the difference between open-circuit and end pulse current magnitude for calculating resistance.

the capacity discharged equals the capacity discharged immediately prior to each charge or discharge pulse.

$$P_{dis} = \frac{V_{Min} * (V_{ED} - V_{Min})}{R_{dis} * 1000} \text{ (kW)} \qquad (11)$$

$$P_{ch} = \frac{V_{Max} * (V_{Max} - V_{ED})}{R_{dis} * 1000} \text{ (kW)} \qquad (12)$$

4.4.5 Low Peak Power Test

The Low Peak Power test is used to determine an estimate for the maximum 30 seconds continual discharge power capability of a battery. To do this the battery is discharged at a constant base C/3 discharge rate until the capacity discharged reaches an increment of 10% of the rated capacity, at which time the discharge current magnitude is increased to a C1 rate for 30-seconds. This routine starts at 0% and finishes at 90% depth of discharge (DOD). Prior to the 0% DOD pulse the battery shall be discharged for 30-seconds at the base rate and after the 90% DOD pulse the battery shall be discharged at the base rate to 100% DOD, no 30-second C1 pulse is to be performed. Refer to Figure 5-5 for further clarification. If during a C1 pulse the battery voltage goes below the discharge limit voltage (DLV) or EODV, the voltage shall be held constant and the current lowered until the end of the pulse. If at any time the voltage cannot stay above the EODV limit while applying the base C/3 current, the test must be stopped.

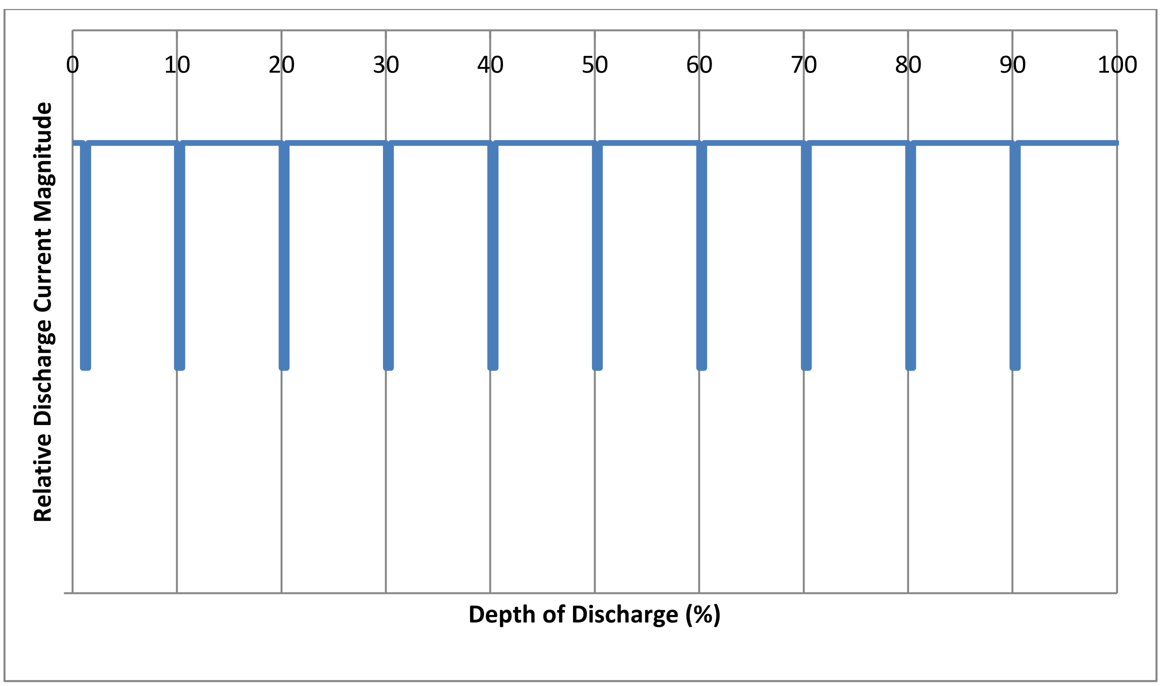

Figure 4-6. Low Peak Power test current pulse sequence

4.4.5.1 Calculating Low Peak Power test power capability

The power capability should be calculated for each DOD increment. To calculate the peak power, record the voltage and current immediately prior to the C_1 pulse (V_P and I_p) then again immediately before the current returns to the base $C_{1/3}$ current rate (V_D and I_D). Use these values with equation (9) and (10) to get the battery resistance (R) and to calculate the internal resistance free voltage (V_{IRFree}).

$$\boldsymbol{R_{LPP}} = \frac{\Delta \boldsymbol{V}}{\Delta \boldsymbol{I}} = \frac{|\boldsymbol{V_D} - \boldsymbol{V_P}|}{|\boldsymbol{I_D} - \boldsymbol{I_P}|} \quad (\Omega) \qquad (9)$$

$$\boldsymbol{V_{IRFree}} = \boldsymbol{V_D} - \boldsymbol{R_{LPP}} \boldsymbol{I_D} \quad (\mathrm{V}) \qquad (10)$$

Using these two values, the EODV and the maximum battery current from the manufacturer, the peak power can be calculated. Three separate equations, (11), (12), and (13), shall be used to calculate the estimated continuous 30-second peak power and the calculated value with the minimum negative value shall be used, unless the actual power3 at the end of a pulse is lower than each calculation. In the case where voltage or current limiting occurs the actual power at the end of the step shall be used.

$$\boldsymbol{P_1} = \left(-\frac{2}{9}\right) * \frac{(\boldsymbol{V_{IRFree}})^2}{\boldsymbol{R_{LPP}}} \quad (\mathrm{W}) \qquad (11)$$

$$\boldsymbol{P_2} = -(\boldsymbol{EODV}) * (\boldsymbol{V_{IRFree}} - \boldsymbol{EODV}) / \boldsymbol{R_{LPP}} \quad (\mathrm{W}) \qquad (12)$$

$$\boldsymbol{P_3} = \boldsymbol{I_{MAX}} * (\boldsymbol{V_{IRFree}} + \boldsymbol{R_{LPP}} * \boldsymbol{I_{MAX}}) \quad (\mathrm{W}) \qquad (13)$$

4.5 Capacitor Testing Protocols

This section outlines the testing sequence and protocols to be performed for each capacitor operated within a vehicle.

4.5.1 Reference Capacity Test

This test determines the discharge capacity and the discharge energy measured over the observed or manufacturer specified in-vehicle operating voltage range[4], V_{min} to V_{Max}, of the capacitor. To attain the aforementioned measurements the capacitor is discharged at a constant current equal to one of the following:

1. The manufacturer specified 5C rate;
2. The highest magnitude current observed in vehicle;
3. A 5C rate based on the equation $Q = [C(V_{Max} - V_{Min})]/3600$ where C equals the known capacitance in farads and Q is a resulting charge (C_1) in ampere-hours.

Once the current magnitude is defined and recorded the following steps can be taken:

[3] The actual power is only to be used if voltage or current limiting occurs during the current pulse.

[4] If the voltage range of the capacitor while operating in the vehicle includes V_{min} equal to zero then due to testing limitations for most power cyclers the minimum capacitor voltage can be equal to that of the lowest voltage allowed by the power cycler.

1. Charge[5] the capacitor to V_{Max}.
2. Allow the capacitor to rest at open circuit for 1-hour such that the device temperature and voltage stabilize.
3. Discharge the capacitor at the previously defined current magnitude until voltage reaches V_{Min}.
4. Rest for 1-hour at open circuit then repeat starting at step 1 until three consecutive cycles give capacity (Ah) measurements within 3% of one another.

4.5.2 Constant-Current Discharge and Charge Test

This test is used to determine the constant-current charge and discharge characteristics of a capacitor by running a sequence of consecutive discharge/charge cycles at various multiples of the current magnitude determined in the previous section. The current magnitude multiples are 0.1, 0.25, 0.5, and 0.75, and should be tested in the order shown. The following steps

1. Charge the capacitor to V_{Max} (this may require a constant voltage step).
2. Apply discharge current at the lowest current multiple, 0.1, until the voltage reaches V_{min}.
3. Rest at open circuit for 10 seconds to observe voltage behavior.
4. Apply charge current at the lowest current multiple until the voltage reaches V_{Max}.
5. Rest at open circuit for 10 seconds or until the device temperature returns to 25 °C ± 3 °C, whichever is longer.
6. Repeat steps 1 through 5 once at the this current magnitude.
7. Repeat steps 1 through 6 for each additional current multiple (0.25, 0.5, and 0.75).

From the data collect during this testing the following calculations can be completed:

a. The effective capacitance for each current multiple; $C_I = Q_I / (V_{Max} - V_{Min})$
b. The equivalent series resistance (ESR) for each current multiple; ESR = $\Delta V/\Delta I$ where the difference in each is a result of the instantaneous change in current from I = 0 to each current multiple.
c. Charge/discharge energy efficiency for each current multiple; Efficiency = $E_{discharge} / E_{charge}$

[5] The initial charge on a capacitor at zero volts may require an in-line current limiting resistor due to power cycler limitations.

5 Glossary

AVTE: Advanced Vehicle Testing and Evaluation

CECET: Center for Evaluation of Clean Energy Technology. (CECET)

Charge-Depleting (CD) Mode: An operating mode in which the energy storage system (ESS) state of charge (SOC) is depleted (not continuously, but the trend is depletion) while the vehicle is driven. May be ESS-Only (i.e., the vehicle operates solely on energy from the ESS) or Blended CD (i.e., the vehicle operates on energy from both the ESS and the consumable fuel energy converter (CFEC)).

Charge-Sustaining (CS) Mode: An operating mode in which the energy storage system (ESS) state of charge (SOC) is maintained within a prescribed range by operation of a consumable fuel energy converter (CFEC).

Consumable Fuel Energy Converter (CFEC): An engine which consumes fuel to produce work (either electrical or mechanical).

Curb Weight: The total weight of the vehicle including batteries, lubricants, and other expendable supplies but excluding the driver, passengers, and other payloads.

Effective Date: After a procedure has been reviewed and approved, the first date the procedure can be utilized official data collection and testing.

Energy Storage System (ESS): A component or system of components that stores energy and for which its supply of energy is rechargeable by an electric motor-generator system, an off-vehicle energy source, or both. Examples of ESSs include batteries, capacitors, and electromechanical flywheels.

ESS-Only Mode: An operator selectable vehicle operating mode in which the CEFC is disabled and the vehicle operates solely on energy from the ESS.

Gradeability: The maximum percent grade which the vehicle can traverse for a specified time at a specified speed. The gradeability limit is the grade upon which the vehicle can just move forward.

Initial Conditions: Conditions that must exist prior to an event occurring.

Initial State of Charge (SOC): ESS SOC at the beginning of a test.

Mandated Reviewer: The individual responsible for the implementation of the test program for any given vehicle undergoing advanced vehicle testing

Prerequisites: Requirements that shall be met or resolved prior to an event occurring.

Shall: This word is used to indicate an item which requires adherence without deviation. 'Shall' is used to identify the binding requirements in a statement. A go or no-go criterion.

Should: This word is used to identify an item, which requires adherence if at all possible. 'Should' statements identify preferred conditions.

State of Charge (SOC): The ESS SOC is defined as the present capacity, (amperes-hours or watt-hours or miles), expressed as a percentage of the total available.

Test/Project Engineer: The individual(s) assigned responsibility for the conduct of any given test.

Test Mass (Weight): The mass [weight] of the vehicle as tested, including driver and all instrumentation

<u>Tractive Force</u>: The force available from the driving wheels at the driving wheel/ground interface.

6 References

- FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles
- US DOE Battery Test Manual for Plug-in Hybrid Electric Vehicle
- USABC Electric Vehicle Battery Test Procedures Manual, Revision 2
- Electric Vehicle Capacitor Test Procedures Manual Oct. 1994

Appendix A – Vehicle Modes by Vehicle Type

HPPC: Calculating V_{CPOC_I}

V_{CPOC_I} is calculated by using a linear interpolation of the data between V_{DPOC} versus discharged capacity for two consecutively run HPPC pulse combinations. The following is an example of this calculation assuming a static capacity measurement of 5.0 Ah, discharge pulses at 10% and 20% DOD or 0.5 Ah and 1.0 Ah discharged, charge pulses[6] at 11.38% and 21.38% or 0.569 Ah and 1.069 Ah, and the V_{DPOC} for each DOD increment equal to 105 V and 100 V, respectively, therefore:

Point 1 = (0.5, 105);

Point 2 = (1.0, 100);

Use y = mx + b and $m = (y_1 – y_2)/ (x_1 – x_2)$ to interpolate between Points 1 and 2:

m = (105 – 100)/(0.5 – 1) = 10;

y = -10x + b therefore;

b = 110;

Insert the starting charge pulse capacity between 0.5 Ah and 1.0 Ah;

V_{CPOC_I} = 104.31 V

HPPC: HEV Useable Power and Energy Calculation Example

To calculate the HPPC test useable power and energy, the charge and discharge power versus energy discharged curve must be previously calculated as shown in Figure A-1. Using the values from Figure A-1, the charge power must be scaled to the discharge power by multiplying each individual calculation by 1.25. The discharge and charge power values (the latter having been scaled) that are below the intersection point are included below in Table A-1.

[6] The starting charge pulse capacities for the example are calculated by adding the capacity of a discharge pulse current ($5C_1$) assuming it is at full magnitude for the entire ten second pulse, i.e. (25 * 10 / 3600) + 0.5. This value should be measured prior to the charge pulse during actual testing.

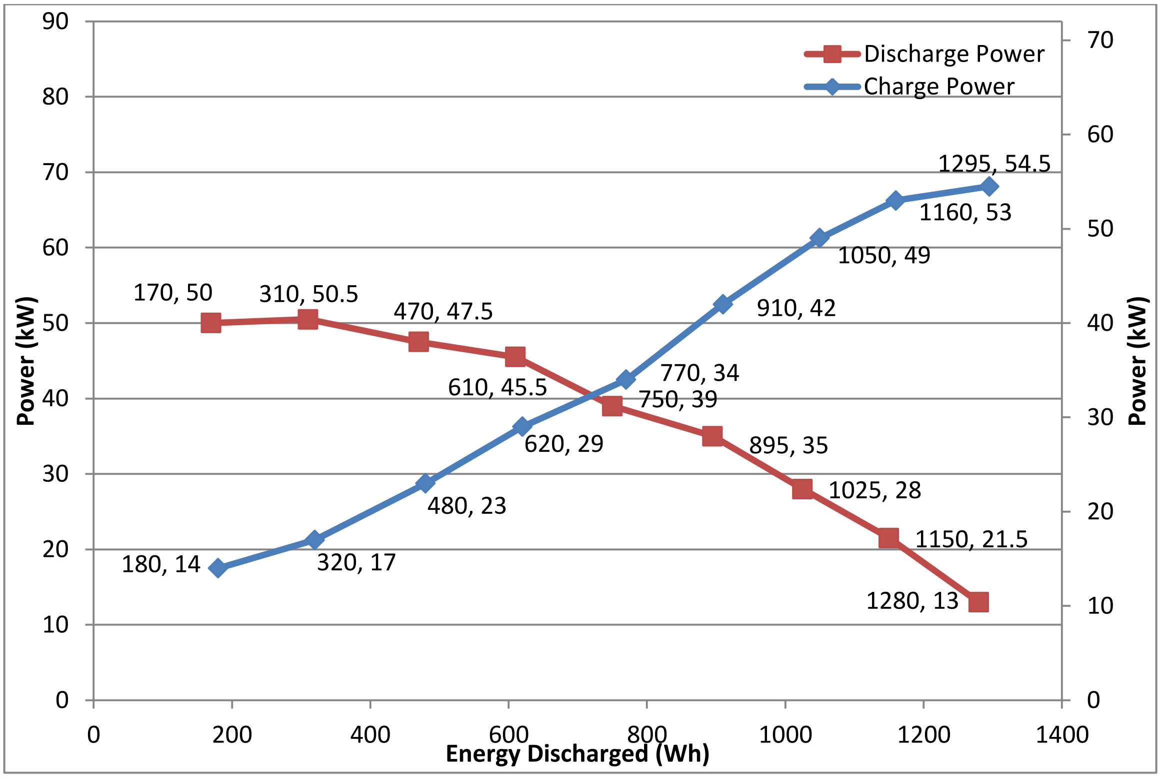

Figure A-1. HPPC charge and discharge power versus energy discharged with point dimensions

Table A-1. HPPC charge and discharge power coordinates used for calculating useable power and energy

Charge			Discharge	
Energy (Wh)	Power (kW)	Scaled Power (kW)	Energy (Wh)	Power (kW)
770	34	42.5	750	39
620	29	36.25	895	35
480	23	28.75	1025	28
320	17	21.25	1150	21.5
180	14	17.5	1280	13

Using discharge curve point (750, 39) as the known start point for calculating the useable energy versus useable power curve, a linear interpolation between charge curve points (770, 45.3) and (620, 38.7) is needed. In order for the function to be generated to output energy, the curve points' axes used must first be inverted; therefore, the points become:

(42.5, 770)

(36.25, 620)

Using the same method as A1, the function for these two points is

y = 24.0 x - 250

then, inserting y = 39 yields:

x = 627.5

Therefore, the first point of the useable energy versus useable power curve is ([750 - 686], 39) or (64, 39). The remaining calculated points for these data are shown in Table A-2 and the desired graph is shown in Figure A-2.

Table A-2. Complete calculations for useable power and energy example

Power	Discharge Energy or Function	Charge Energy or Function	Function Output	Energy Difference
39	750	y = 22.5x - 250	686	64
36.25	y = -36.25x + 2163.8	620	849.74	229.7
35	895	y = 18.667x - 56.667	596.68	298.3
28.75	y = -18.571x + 1545	480	1011.08	531.1
28	1025	y = 21.333x - 133.33	463.99	561.0
21.5	1150	y = 21.333x - 133.33	325.33	824.7
21.25	y = -15.294x + 1478.8	320	1153.80	833.8
17.5	y = -15.294x + 1478.8	180	1211.16	1031.2

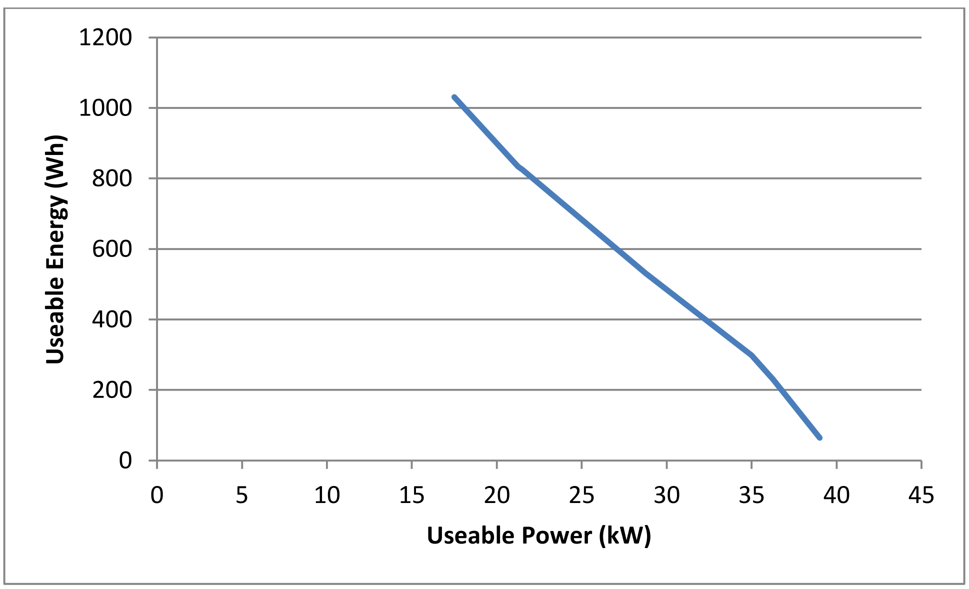

Figure A-2. HEV useable power and energy curve

HPPC: PHEV Charge-Depleting and Charge-Sustaining Useable Energy Calculation Example

Using the data shown in Figure A-1 and assuming that the vehicle in question for this data is a Minimum PHEV type, the values for $E_{PHEV\ Charge\ Target}$, $AE_{CS\ Target}$, and $AE_{CD\ Target}$ are170 Wh, 0.5

kWh, and 3.4 kWh, respectively. Also, values for $E_{PHEV\ Discharge}$ and the charge-depleting and charge-sustaining useable energy calculations are shown in Table A-3.

Table A-3. Complete calculations for CD and CS useable energy example

Power (kW)	E_{PHEV} Discharge (Wh)	UE_{CD} Calculation	UE_{CD} (Wh)	UE_{CS} Calculation	UE_{CS}
39	750	[750-170]-(0.5*500)	330	[750-170]-(3400-0.5*500)	-2570
35	895	[895-170]-(0.5*500)	475	[895-170]-(3400-0.5*0.500)	-2425
28	1025	[1025-170]-(0.5*500)	605	[1025-170]-(3400-0.5*500)	-2295
21.5	1150	[1150-170]-(0.5*500)	730	[1150-170]-(3400-0.5*500)	-2170
13	1280	[1280-170]-(0.5*500)	860	[1280-170]-(3400-0.5*500)	-2040

The negative numbers for UE_{CS} indicate that the battery in this example is not well suited for PHEV use, even at the Minimum PHEV values but this does not change the calculations within the example. A sample graph of the data shown in Table A-3 is shown in Figure A-3.

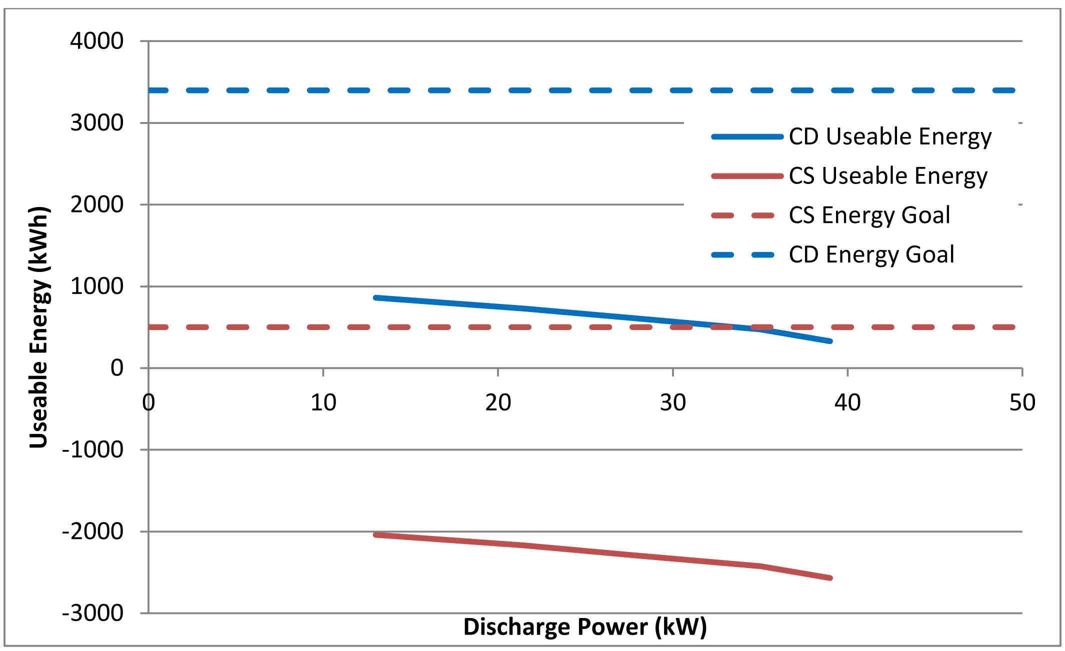

Figure A-3. Plot of example PHEV CD and CS useable energy with goals.