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United States Advanced Battery Consortium Battery Test Manual For Plug-In Hybrid Electric Vehicles

REVISION 3

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USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM LLC

United States Advanced Battery Consortium
Battery Test Manual
For Plug-In Hybrid Electric Vehicles

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SEPTEMBER 2014

Prepared for the
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FOREWORD

This battery test procedure manual was prepared for the United States Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Vehicle Technologies Office. It is based on technical targets for commercial viability established for energy storage development projects aimed at meeting system level DOE goals for Plug-in Hybrid Electric Vehicles (PHEV). The specific procedures defined in this manual support the performance and life characterization of advanced battery devices under development for PHEV's. However, it does share some methods described in the previously published battery test manual for power-assist hybrid electric vehicles.

Due to the complexity of some of the procedures and supporting analysis, future revisions including some modifications and clarifications of these procedures are expected. As in previous battery and capacitor test manuals, this version of the manual defines testing methods for full-size battery systems, along with provisions for scaling these tests for modules, cells or other subscale level devices.

The DOE-United States Advanced Battery Consortium (USABC), Technical Advisory Committee (TAC) supported the development of the manual. Technical Team points of contact responsible for its development and revision are Renata M. Arsenault of Ford Motor Company and Jon P. Christophersen of the Idaho National Laboratory.

The development of this manual was funded by the Unites States Department of Energy, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Office. Technical direction from DOE was provided by David Howell, Energy Storage R&D Manager and Hybrid Electric Systems Team Leader.

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ACRONYMS

AE	Available Energy
AE_{CS}	Available Energy for Charge-Sustaining
$AE_{CS\ Limit}$	Available Energy Limit where Charge-Sustaining starts
$AE_{CS\ Target}$	Available Energy Target for Charge-Sustaining
AE_{CD}	Available Energy for Charge-Depleting
$AE_{CD\ Target}$	Energy Target for Charge-Depleting
$AE_{Total\ Target}$	Total Energy Goal ($AE_{CD\ Target}$ + 1/2$AE_{CS\ Target}$)
AP_{CS}	Peak Pulse (available) Discharge Power (10 sec)
BSF	Battery Size Factor
BOL	Beginning-of-Life
CD	Charge-Depleting
CS	Charge-Sustaining
DOD	Depth-of-Discharge
EOL	End-of-Life
E_{regen}	Regen energy at any given power level
$E_{discharge}$	Discharge energy at any given power level
FreedomCAR	Freedom Cooperative Automotive Research
HEV	Hybrid Electric Vehicle
HPPC	Hybrid Pulse Power Characterization
I_{HPPC}	Hybrid Pulse Power Characterization Current
OCV	Open-Circuit Voltage
OSPS	Operating Set Point Stability
P_{CPD}	Constant Power Discharge Power
PHEV	Plug-in Hybrid Electric Vehicle
PNGV	Partnership for a New Generation of Vehicles
RPT	Reference Performance Test
SOC	State-of-Charge
UE	Useable Energy
UE_{CD}	Useable Energy for Charge-Depleting
UE_{CS}	Useable Energy for Charge-Sustaining
USABC	United States Advanced Battery Consortium

GLOSSARY

Available Energy [Wh] – the single energy point on the Useable Energy versus Power curve that precisely corresponds to the Pulse Power Discharge Target.

Available Energy for Charge Sustaining (AE_{CS}) [Wh]- the discharge energy available to maintain a charge sustaining operating mode at the Pulse Power Discharge Target. It is measured between the $AE_{CS\ Limit}$ and $E_{Discharge}$.

Available Energy Target for Charge Sustaining ($AE_{CS\ Target}$) [Wh] – the EOL target for CS mode shown in the Gap Analysis (300 Wh for all PHEV modes in Table 1).

Available Energy for Charge Sustaining Limit ($AE_{CS\ Limit}$) [Wh] – the point at which the discharge energy begins transitioning from a charge depleting mode to a charge sustaining mode. It is determined by subtracting half of the $AE_{CS\ Target}$ from the $AE_{CD\ Target}$ (see Section 4.3.4).

Available Energy for Charge Depleting (AE_{CD}) [Wh] – the discharge energy available to maintain a charge depleting operating mode at the Pulse Power Discharge Target. It is measured from $Vmax_{op}$ to $E_{Discharge}$ minus half of the $AE_{CS\ Target}$ energy.

Available Energy Target for Charge Depleting ($AE_{CD\ Target}$) [Wh] – the EOL target for CD mode shown in the Gap Analysis (5.8 / 11.6 / 14.5 kWh, respectively, for the PHEV modes in Table 1).

Battery Size Factor (BSF) – for a particular cell or module design, an integer which is the minimum number of cells or modules expected to be required to meet all the performance and life targets.

Beginning-of-Life (BOL) – the point at which characterization of the test article begins. The BOL HPPC is usually conducted to determine and/or confirm the BSF prior to life testing.

C_1/1 Rate [A]– a current corresponding to the manufacturer's rated capacity (in ampere-hours) for a one-hour discharge at BOL and 30°C between $Vmax_{100}$ and $Vmin_0$. For example, if the battery's rated one-hour capacity is 40Ah, then $C_1/1$ is 40A.

Charge – any condition in which energy is supplied to the device rather than removed from the device. Charge includes both recharge and regen conditions. Charge is indicated in this manual as a negative value (from the perspective of the battery).

Constant Power Discharge Power (P_{CPD}) [W] – the discharge rate set at 10kW based on the approximate power needed to propel a vehicle at a nominal speed of 30 miles per hour.

Default rest [h] – a fixed rest period determined at BOL, it is at least one hour or the time needed to achieve thermal and voltage equilibrium (e.g., rate of change less than 1°C/hour or less than 5 mV/h).

Depth-of-Discharge (DOD) [%]– the percentage of a device's rated capacity (Ah) removed by discharge relative to a fully charged condition from $Vmax_{100}$, normally referenced to a constant current discharge at the HPPC-Current rate (I_{HPPC}) or a $C_1/1$ rate.

Discharge – any condition in which energy is removed from the device rather than supplied to the device. Discharge is indicated in this manual as a positive value (from the perspective of the battery).

$E_{Discharge}$ [Wh] – at any given power level, $E_{Discharge}$ is the corresponding energy on the pulse power discharge curve. The value of $E_{Discharge}$ at the power target is the total Available Energy from which AE_{CD} and AE_{CS} are determined.

E_{Regen} [Wh] - at any given power level, E_{Regen} is the corresponding energy on the pulse power regen curve. The value of E_{Regen} at the power target is useful in differentiating between the regen limited and non-regen limiting portions of the total Available Energy.

End-of-Life (EOL) – a condition reached when the device under test is no longer capable of meeting the targets. This is normally determined from HPPC Test results scaled using the Battery Size Factor, and may not coincide exactly with the inability to perform the life test profile (especially if cycling is done at elevated temperatures).

End of Test – a condition where life testing is halted, either because criteria specified in the test plan are reached, or because it is not possible to continue testing.

Energy Goal [Wh] – alternate expression for *Available Energy Total Target* ($AE_{CD\ Target}$ + ½ $AE_{CS\ Target}$).

Fully Charged – the condition reached by a device when it is subjected to the manufacturer's recommended recharge algorithm. In most cases, a device is considered "fully charged" at $Vmax_{op}$, but in other cases (e.g., the static capacity test), the device could be recharged to $Vmax_{100}$.

HPPC-Current rate (I_{HPPC}) [A] – the constant current that is roughly equivalent to a BSF-scaled 10-kW constant power discharge rate (see Section 3.1.5).

Hybrid Pulse Power Characterization (HPPC) Test – a Reference Performance Test procedure that is used to determine the pulse power and energy capability as a function of aging for direct comparison with the targets in a Gap Analysis.

Maximum Rated Current (Imax)[A] – the maximum discharge current that a manufacturer will permit to be sustained by a device for 10 seconds or less. (This value need not be achievable over the full operating range).

Peak Discharge Pulse Power (AP_{CS}) [W] –the single point from the Useable Energy versus Power curve that precisely corresponds to the Total Energy Goal ($AE_{Total\ Target}$) for a given application (PHEV-20, PHEV-40 or xEV-50). This value represents Available Power, corresponds to CS mode and is the power value reported and tracked in the Gap Analysis.

Peak Regen Pulse Power [W] – the regen power that precisely corresponds to the Total Energy Goal ($AE_{Total\ Target}$) for a given application (PHEV-20, PHEV-40 or xEV-50). It can be calculated by scaling AP_{CS} by the regen to discharge power ratio.

Peak Discharge Pulse Power Target [kW] – the 2 second and 10 second discharge pulse power target defined in the Gap Analysis (for each application) and corresponding to the CS mode.

Peak Regen Pulse Power Target [kW] - The 10 second charge pulse power target defined in the Gap Analysis (for each application) and corresponding to the CS mode.

Power Fade [W] - the change in CS Available Power from RPT0 to the value determined at some later time, expressed as a percentage of the BOL value. (Similar definitions apply to Capacity Fade and CS or CD Available Energy Fade, although these are not included in this glossary).

Power Margin (W) – for a given HPPC test, the difference between the calculated available power (AP_{CS}) and the corresponding power target for a given application.

Profile – a connected sequence of pulses used as the basic 'building block' of many test procedures. A test profile normally includes discharge, rest and charge steps in a specific order, and each step is normally defined as having a fixed time duration and a particular (fixed) value of current or power.

Recharge – a charge interval corresponding to the sustained replenishment of energy by a continuous power source (such as an engine-generator or off-board charger).

Reference Performance Test (RPT) – periodic interruptions during calendar and cycle life aging to gauge degradation in the test article (see Section 3.13). Degradation rates are established by comparing results from the RPTs during life testing with respect to the initial RPT performed immediately prior to the start of life testing (usually referred to as RPT0).

Regen – a charge interval corresponding to the return of vehicle kinetic energy to a device (typically from braking). Because of physical limitations, high rates of regen can only persist for a few seconds at a time. Regen in this manual is indicated as a negative value (from the perspective of the battery).

Rest – the condition in which energy is neither supplied to the device nor removed from the device. Rest is indicated by zero current.

State- of-Charge (SOC) [%] – an estimate of the device charge capability expressed as a percentage of the BOL rated capacity and typically reached by obtaining specified voltages.

Useable Energy [Wh] – a set of available discharge energies at the scaled 10 kW rate between $Vmax_{op}$ and $E_{Discharge}$ at given power values. The total useable energy can be divided into Charge Depleting and Charge Sustaining modes for direct comparisons with the target values in a Gap Analysis.

Useable Energy for Charge-Depleting (UE_{CD}) [Wh] – the useable discharge energy at the scaled 10-kW rate required to maintain a charge depleting operating mode at various power levels between the crossover point and the lowest discharge pulse power capability on the power vs. energy curve. It is measured between the $Vmax_{op}$ and $E_{Discharge}$ minus half of the $AE_{CS\ Target}$ energy.

Useable Energy for Charge-Sustaining (UE_{CS}) [Wh] – the useable discharge energy at the scaled 10-kW rate required to maintain a charge sustaining operating mode at various power levels between the crossover point and the lowest discharge pulse power capability on the power vs. energy curve. It is measured between the $AE_{CS\ Limit}$ and $E_{Discharge}$.

Voltage limits [V] – numerous voltage limits are defined in the manual as follows:

$Vmax_{pulse}$ [V] – the regen voltage limit; maximum voltage allowed during regen pulses of 10s or less.

$Vmax_{100}$ [V] - manufacturer's specified voltage corresponding to 100% SOC and the basis for the rated capacity.

$Vmax_{op}$ [V] – corresponds to the upper end of the intended operating window, as specified by the manufacturer. This is the relevant upper voltage used in all testing unless otherwise specified (e.g., static capacity tests).

$Vmin_{op}$ [V] – (optional) corresponds to the lower end of the intended operating window. It is a variable parameter that will generally decrease as the test article ages and the minimum value is typically specified by the manufacturer.

$Vmin_0$ [V] – manufacturer's specified voltage corresponding to the minimum operating voltage ($Vmin_0$). It shall be limited to 0.55 times the maximum charge voltage limit ($Vmax_{100}$) or higher.

$Vmin_{pulse}$ [V] – minimum voltage allowed during discharge pulses of 10s or less.

$Vmin_{Low\ T}$ [V] – the minimum voltage allowable at less than or equal to 0°C set by the manufacturer and the technical program manager.

$V_{nominal}$ [V] – The nominal electrochemical voltage between $Vmax_{100}$ and $Vmin_0$. It is determined by the ratio between the total discharge energy and discharge capacity from the static capacity test (see Section 3.1.5).

Battery Test Manual
For Plug-In Hybrid Electric Vehicles

1. PURPOSE AND APPLICABILITY

This manual defines a series of tests to characterize aspects of the performance or life behavior of batteries for plug-in hybrid electric vehicle (PHEV) applications. Tests are defined based on the Vehicle Technologies Office targets for plug-in hybrid electric vehicles and it is anticipated that these tests may be generally useful for testing energy storage devices designed for this purpose. The test procedures in this manual are directly applicable to complete battery systems. However, most of these test procedures can also be applied with scaling of the test profiles to those appropriate for cells or modules. Much of the rationale for the test procedures and analytical methodologies utilized in this manual evolved from the USABC Electric Vehicle Battery Test Procedure Manual (Reference 1), the PNGV Battery Test Manual (Reference 2) and the FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles (Reference 3).

1.1 Energy Storage Targets For Plug-In Hybrid Electric Vehicles

The Department of Energy’s Vehicle Technologies Office Energy Storage Targets are the primary driving force for the test procedures and methods defined in this manual. The targets are outlined in Table 1 for a car having an equivalent electric range of 20, 40, and 50 miles for the PHEV-20, PHEV-40, and xEV-50 batteries, respectively. Establishing or verifying battery performance in comparison to these targets is a principal objective of the test procedures defined in this document. Unless otherwise stated, these targets all pertain to devices operating at 30°C.

This manual defines two primary operational modes for plug-in hybrid electric vehicles, Charge-Depleting (CD) and Charge-Sustaining (CS). The Charge-Depleting mode is intended to allow the vehicle to operate in hybrid mode (propulsion and accessories are powered by the electric drive and/or engine) and electric mode (propulsion and accessories powered by the electric drive and onboard electric energy storage), with a net decrease in battery state-of-charge (SOC). The Charge-Sustaining mode only allows the vehicle to operate in hybrid mode with a relatively constant battery state-of-charge. There is also a combined life cycle having both CD and CS cycle modes included.

Table 1. Energy Storage System Performance Targets for Plug-In Hybrid Electric Vehicles

Characteristics	Units	PHEV-20 Mile	PHEV-40 Mile	xEV-50 Mile
Commercialization Timeframe		**2018**	**2018**	**2020**
All Electric Range (AER)	**Miles**	**20**	**40**	**50**
Peak Discharge Pulse Power (10 sec)	**kW**	**37**	**38**	**110**
Peak Discharge Pulse Power (2 sec)	**kW**	**45**	**46**	**120**
Peak Regen Pulse Power (10 sec)	**kW**	**25**	**25**	**65**
Available Energy for CD (Charge Depleting) Mode	**kWh**	**5.8**	**11.6**	**14.5**
Available Energy for CS (Charge Sustaining) Mode	**kWh**	**0.3**	**0.3**	**0.3**
Minimum Round-trip Energy Efficiency	**%**	**90**	**90**	**90**
Cold cranking power at -30°C, 2 sec - 3 Pulses	**kW**	**7**	**7**	**7**
CD Life / Discharge Throughput	**Cycles/ MWh**	**5000/29**	**5000/58**	**5000/72.5**
CS HEV Cycle Life	**Cycles**	**300,000**	**300,000**	**300,000**
Calendar Life, 30°C	**year**	**15**	**15**	**15**
Maximum System Weight	**kg**	**70**	**120**	**150**
Maximum System Volume	**Liter**	**47**	**80**	**100**
Maximum Operating Voltage	**Vdc**	**420**	**420**	**420**
Minimum Operating Voltage	**Vdc**	**150**	**153**	**300**
Maximum Self-discharge	**%/month**	**<1**	**<1**	**<1**
System Recharge Rate at 30°C	**kW**	**3.3 (240V/16A)**	**3.3 (240V/16A)**	**6.6 (240V/32A)**
Maximum Discharge Pulse Current (≤10s)	**A**	**300**	**300**	**400**
Unassisted Operating Temp Range (10s)	**°C**	**-30 to +52**	**-30 to +52**	**-30 to +52**
30°-52°	**% Power**	**100**	**100**	**100**
0°	**% Power**	**50**	**50**	**50**
-10°	**% Power**	**30**	**30**	**30**
-20°	**% Power**	**15**	**15**	**15**
-30°	**% Power**	**10**	**10**	**10**
Survival Temperature Range	**°C**	**-46 to +66**	**-46 to +66**	**-46 to +66**
Max System Production Price @ 100k units/yr	**$**	**$2,200**	**$3,400**	**$4,250**

NOTES

i. Values correspond to End-of-Life (EOL).

ii. PHEV-20 and PHEV-40 targets correspond to commercialization goals in FY 2018; xEV targets correspond to commercialization goals in FY 2020.

iii. xEV cell is intended for architectures that require higher power levels than PHEV-20 and PHEV-40.

iv. The Peak Discharge Pulse Power and Peak Regen Pulse Power targets are applicable for the CS mode.

v. The HPPC-Current rate is used to approximate the required 10-kW rate during the Hybrid Pulse Power Characterization (HPPC) Test, Section 3.4.

vi. Maximum System Recharge Rate refers to the maximum power expected from a standard garage outlet. With the battery manufacturer's concurrence, an increase recharge rate can be used to accelerate life testing.

vii. The minimum operating voltage ($Vmin_0$) shall be limited to 0.55 times the maximum charge voltage limit ($Vmax_{100}$) or higher.

2. TEST PROFILES DERIVED FROM TARGETS

The test procedures described in this manual are intended for use over a broad range of devices at various stages of developmental maturity. Application of the procedures is further complicated by the existence of three different sets of performance targets. The approach taken for these procedures is to define a small set of test profiles based on the overall vehicle characteristics, independent of the size or capability of the device to be tested. These test profiles are specified in terms of the characteristics of vehicle power demand. They can be used in various combinations, with the appropriate scaling factors, to define specific performance, calendar or cycle life tests for cells, modules or battery systems. Each profile is defined within the respective procedure described, because there is essentially a one-to-one relationship between test profiles and test procedures.

3. TEST PROCEDURES

3.1 General Test Conditions and Scaling

In general, testing is divided into three broad phases, i.e., characterization, life, and reference performance testing. Characterization testing establishes the baseline performance and includes static capacity, hybrid pulse power characterization, self-discharge, cold cranking, thermal performance, and efficiency tests.[1] Life testing establishes behavior over time at various temperatures, states of charge and other stress conditions and includes both cycle life and calendar life testing. Reference Performance Tests establish changes in the baseline performance and are performed periodically during life testing, as well as at the start- and end-of-life testing. A generic test plan for testing is outlined in Appendix A; this outline can be used as a starting point for device-specific test plans.

3.1.1 Voltage Limits

Several voltage limits are defined in this manual for the purposes of testing and analysis (see Appendix C). The electrochemical voltage range between 100% SOC and 0% SOC are referred to as $Vmax_{100}$ and $Vmin_0$, respectively. Since energy storage devices in PHEV applications will rarely (if ever) operate at 100% SOC, the test protocols defined in this manual assume a maximum operating voltage, $Vmax_{op}$ which corresponds to the upper end of the intended operating window. For the purposes of this manual, a "fully charged device" is when the device has been charged to $Vmax_{op}$ using the manufacturer's recommended procedure, unless otherwise specified. The initial static capacity tests (Section 3.2) are generally the only condition in which a test article is discharged between $Vmax_{100}$ and $Vmin_0$ to ensure stability in the rated capacity. All subsequent tests should be conducted within the operating window between $Vmax_{op}$ and $Vmin_0$. Thus, the time spent at conditions higher than $Vmax_{op}$ for the sole purpose of testing (and not simulating the intended application strategy) is avoided, thereby minimizing any test-induced degradation mechanisms that may not be representative of the vehicle operation. The value for $Vmax_{op}$ should be supplied by the manufacturer but if not, it can be estimated by discharging 5% of the rated capacity (or another percentage specified by the manufacturer) from $Vmax_{100}$ at beginning of life, resting for 1 hour to ensure electrochemical equilibrium, and then observing the open circuit voltage.

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[1] In this manual, unless specifically stated otherwise, the desired test condition is typically established as a percentage of the rated capacity, which is always reached by removing the appropriate fraction of the rated capacity from a fully charged device (normally at a constant HPPC current discharge rate.) Also, the term "fully charged" means "charged in accordance with the manufacturer's recommended procedure" to $Vmax_{op}$ for operation.

In addition to the operating voltage limits, the maximum and minimum pulse voltage limits ($Vmax_{pulse}$, $Vmin_{pulse}$) should also be specified by the manufacturer for short duration (≤10s) charge or discharge pulses, respectively. A minimum voltage condition ($Vmin_{LowT}$) should also be specified for short duration pulses (≤10s) that are conducted at low temperatures (i.e., ≤0°C). All of these voltage limits must be carefully observed during performance testing to ensure proper operation of the energy storage device.

3.1.2 Temperature Control

Unless otherwise specified in a device-specific test plan, the ambient temperature for all tests should be controlled at a default nominal temperature of 30ºC. Also, to the extent possible, all testing should be conducted using environmental chambers. As a general practice, a rest of 60 minutes (or more if required) should be observed after each charge and each discharge prior to proceeding with further testing, to allow devices to reach stable voltage and temperature conditions. A longer rest is likely to be required for modules or packs.

3.1.3 Pressure control

Unless otherwise specified in a device-specific test plan, pouch or prismatic cell pressure should be established by placing the device between two plates with four to six bolts around the edges that are tightened using torque specifications provided by the manufacturer (or finger tightened if no specification is provided). Preferably, spacers between the two plates should be used to ensure a sufficient gap between the plates. As a general practice, once the pouch pressure has been set, the device should be placed in an environmental chamber and left undisturbed for the duration of the test period. The devices should occasionally be visually inspected periodically for any signs of swelling or leaking.

3.1.4 Scaling of Performance and Cycle Life Test Profile

With the exception of the Hybrid Pulse Power Characterization Test (HPPC) and Calendar Life Test, all performance and cycle life test profiles are defined in terms of required power levels at the system (i.e., full-size vehicle battery) level. Testing any device smaller than a full-size system requires a method for scaling these test profiles to a level appropriate to the size of the device (cell, module, or sub-battery) under test. This is done by using a *battery size factor*. For purposes of this manual, the Battery Size Factor (BSF) is defined as the minimum number of units (cells, modules or sub-batteries) of a given design required for a device to meet all targets, including cycle life and calendar life. Wherever possible, the Battery Size Factor will be specified by the manufacturer, based on the manufacturer's testing and best estimates of any allowances needed for system burdens and degradation over life.

If insufficient data exist to allow the manufacturer to determine a meaningful value, the Battery Size Factor will be determined from the beginning-of-life Low Current HPPC Test results using a $C_1/1$ rate for the HPPC-Current rate by applying the larger BSF from either a nominal CS power margin of 30% or a nominal CD Energy Margin of 20% to allow for degradation resulting from cycle life and calendar life effects. See Section 4.3.12 for details of this determination.[2]

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[2] In some cases, this value and/or the associated voltage limits may require modification to ensure that the round-trip efficiency targets are also met.

Once the Battery Size Factor is determined, it becomes a constant (i.e., fixed over life) scaling factor for all subsequent performance and cycle life tests. Any test profile (except HPPC or calendar life) is then scaled by dividing the nominal profile power levels by the Battery Size Factor. For example, if the Battery Size Factor is 100 for a particular cell design, the 7-kW Cold Cranking Test would then be performed at a pulse power level of 7000/100 = 70 W for such cells. Note that there is a different mode-specific Battery Size Factor for the PHEV-20 Mile, PHEV-40 Mile, and xEV-50 Mile Battery operation.

3.1.5 Scaling of HPPC-Current

The HPPC-Current is a constant current that will closely resemble the steady state current during the 10-kW Constant Power Discharge Test. To relate the energy removed at the 10-kW rate and the energy removed during the HPPC Test, the HPPC-current will primarily be used for discharging the device in 10% increments based on the rated capacity with constant current.

The HPPC-Current is calculated using the formula below.

$$I_{HPPC} = P_{CPD} / (V_{nominal} * BSF) \qquad (1)$$

where I_{HPPC} is the HPPC discharge current between pulses, P_{CPD} is the Constant Power Discharge target, and $V_{nominal}$ is the nominal electrochemical voltage between $Vmax_{100}$ and $Vmin_0$ (i.e., total energy divided by capacity). For example, if the total discharge capacity (rated) is 2 Ah and discharge energy is 7 Wh from the initial static capacity test, then $V_{nominal}$ = (Wh / Ah) = 3.5V. Given P_{CPD} = 10-kW and assuming BSF = 100, then I_{HPPC} = 10,000W / (3.5V * 100) = 28.6 A. Note that if the Battery Size Factor has not been determined, a $C_1/1$ rate can be used as an approximate rate for the HPPC-Current during the first iteration of the HPPC Test to determine an appropriate Battery Size Factor. Once the BSF is determined, this HPPC-Current value is used extensively for the HPPC tests[3].

3.1.6 Charging Procedure

The manufacturer is responsible for defining a reasonable charging procedure with the assistance of the Program Manager. This charging procedure should specify default rest periods before and after (at least 1 hour is recommended) charging is performed. During CD cycle life testing a rest period of 15 minutes can be used to accelerate testing before and after charging. This is a default value and can be adjusted based on the needs of the chemistry.

3.2 Static Capacity Test

This test measures device capacity in ampere-hours at a constant current discharge rate corresponding to the rated capacity. Discharge begins following a default rest from a fully-charged state to $Vmax_{100}$ and is terminated on a manufacturer-specified discharge voltage limit ($Vmin_0$), followed by a default rest at open-circuit voltage. If the manufacturer does not provide a discharge voltage limit, or if the provided limit is unrealistically low, either an appropriate value is determined from the literature or 55% of $Vmax_{100}$ is used. (This will automatically become the lowest possible value for full-size battery tests in any event because of the operating voltage ratio limits). The static capacity test can

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[3] The HPPC current should be compared with the average current for a scaled 10-kW discharge.

also be repeated using Vmax_{op} as the fully charged condition to ensure stable operating capacity as well.

3.3 Constant Power Discharge Tests (P_{CPD})

This test measures device capacity in ampere-hours and energy in watt-hours at a constant power discharge rate corresponding to a BSF-scaled 10-kW rate. Discharge begins following a default rest from a fully-charged operating state (Vmax_{op}) and is terminated on a manufacturer-specified discharge voltage limit (Vmin_0), followed by a default rest at open-circuit voltage. This test can also be performed using the HPPC-Current rate between Vmax_{op} and Vmin_0 for comparison with the constant power discharge.

3.4 Hybrid Pulse Power Characterization Test

The Hybrid Pulse Power Characterization (HPPC) Test is intended to determine dynamic power capability over the device's useable voltage range using a test profile that incorporates both discharge and regen pulses. The first step of this test is to establish, as a function of capacity removed or useable energy, (a) the Vmin_0 discharge power capability at the end of a 10-s discharge current pulse and (b) the Vmax_{op} regen power capability at the end of a 10-s regen current pulse.[4] These power and energy capabilities are then used to derive other performance characteristics such as Charge-Sustaining Available Energy and Available Power as well as the Charge-Depleting Available Energy for direct comparison with the targets specified in Table 1.

Additional data from the HPPC test include the voltage response curves, from which ~~are~~ the fixed (ohmic) cell resistance and cell polarization resistance as a function of capacity removed can be determined assuming sufficient resolution to reliably establish cell voltage response time constants during discharge, rest, and regen operating regimes. These data can be used to evaluate resistance degradation during subsequent life testing and to develop hybrid battery performance models for vehicle systems analysis.

3.4.1 Hybrid Pulse Power Characterization Test Profile

The objective of this test is to determine the 10-second discharge-pulse and the 10-second regen-pulse power capabilities at each 10% increment relative to the BOL rated capacity for the PHEV-20, PHEV-40, or xEV-50 Mile Targets (e.g., for a 2 Ah cell, power capabilities are assessed at 0.2 Ah increments between Vmax_{op} and Vmin_0). Between each pair of discharge and regen pulses, the device is discharged to the next 10% increment based on rated capacity using the HPPC-Current as determined in Section 3.1.3. The pulse profile is shown in Table 2 and Figure 1.

Note that the current values are relative, not absolute. The actual current values are determined as defined at the end of Section 3.4.2. Also, note that this manual uses positive values for discharge current and power, whereas charge or regen values are negative.

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[4] Vmin_0 and Vmax_{op} refer to the device minimum and maximum voltages that correspond to the operating voltage range for the purposes of this manual as defined in Section 3.1.1. For cells, the specific voltages can be any values appropriate to the technology as long as they fall within the BSF-scaled limits in Table 1. Expanded definition of voltages can be found in Appendix C.

Table 2. Hybrid Pulse Power Characterization Test Profile.

Time Increment (s)	Cumulative Time (s)	Relative Currents
10	10	1.00
40	50	0
10	60	-0.75

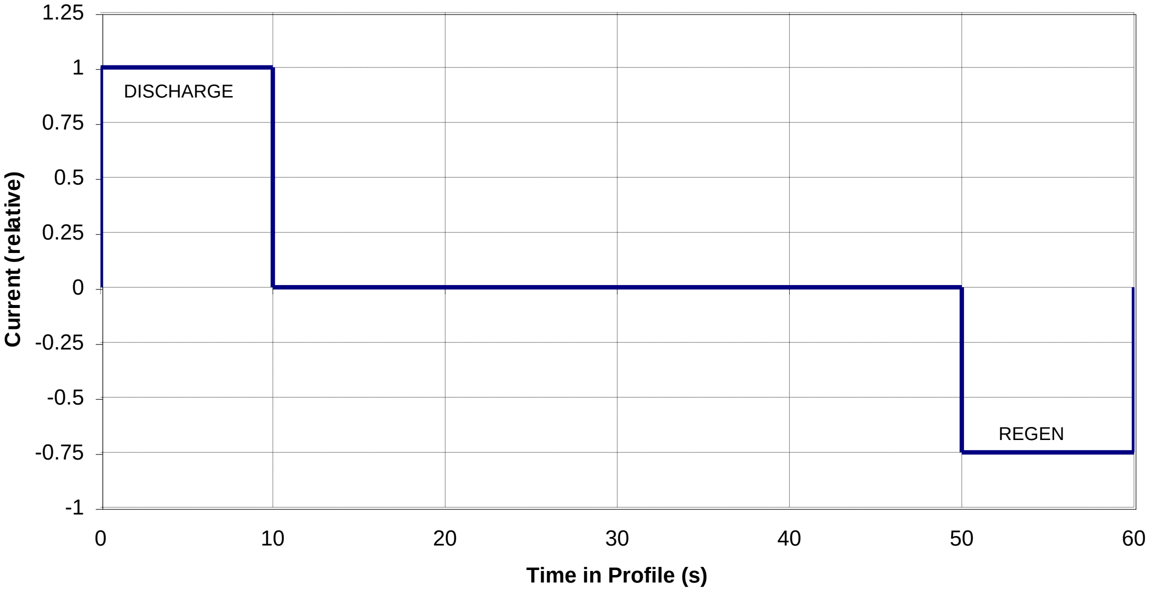

Figure 1. Hybrid Pulse Power Characterization Test Profile.

3.4.2 Test Procedure Description

The HPPC Test incorporates the pulse power characterization profile as defined in Section 3.4.1. Constant current steps are used in the ratios listed in Table 2. The test is made up of single repetitions of this profile, followed by discharge to the next 10% increment based on rated capacity point using I_{HPPC} (defined in Section 3.1.3),[5] each time followed by a default rest period to allow the cell to return to an electrochemical and thermal equilibrium condition before applying the next profile.

Note that battery developers typically specify a nominal capacity, which corresponds to a pair of voltage limits representing 0% and 100% SOC at beginning of life (BOL). These are defined as $Vmin_0$ and $Vmax_{100}$ for the purposes of this manual (see Section 3.1.1 and Appendix C). Separately, a developer will supply (or testing will determine) a recommended voltage range of operation, which will be less than the full 100% SOC span associated with the nominal capacity. The upper voltage limit of the intended operating window is defined as $Vmax_{op}$; it is fixed at BOL for all subsequent HPPC testing as the "fully charged" condition for operating mode and is used as the basis for determining the percentage of the rated capacity removed (i.e., 0% capacity removed at $Vmax_{op}$) for

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[5] Note that the energy of the pulse profile must be accounted for in determining the actual percentage of the rated capacity removed from $Vmax_{op}$ at which the profile was performed. The profile in Table 2 may remove several percent of the capacity from a typical device. The test should be programmed such that 10% of the rated capacity is removed in each test segment, including that removed by the pulse profile itself.

the Power vs. Energy curves from which parameters of interest are determined. Note that the manufacturer may also supply an alternative maximum and minimum voltage limit for short-duration pulse conditions (i.e., $Vmax_{pulse}$ and $Vmin_{pulse}$).

The HPPC test begins with a charged device up to $Vmax_{op}$ using the manufacturer recommended procedure. Following a default rest period (nominally a 1-hour rest), an HPPC profile is performed immediately followed by a discharge to the next 10% increment of the rated capacity at the I_{HPPC} rate (based on the established rated capacity at BOL) and a default rest. This sequence is repeated until the final profile at or near 90% of the rated capacity removed (or the maximum discharge specified by the manufacturer). For example, a 2 Ah cell (rated) having an I_{HPPC} of 28.6 A would require a total of 0.2 Ah removed (including the cumulative capacity removed after the HPPC pulse) using a discharge current of 28.6 A to reach the next 10% increment. The test terminates with a discharge of the device at the HPPC-Current rate to $Vmin_0$ and a final default rest. If at any point $Vmin_0$ is reached in the HPPC pulse then taper the current to finish the profile. If $Vmin_0$ is reached in the I_{HPPC} section, stop the test. The voltages during each rest period are recorded to establish the cell's OCV (open-circuit voltage) behavior. The sequence of rest periods, pulse profiles, and discharge segments is illustrated in Figures 2 and 3. These figures also illustrate a 10-kW discharge to be executed just prior to each HPPC Test.[6]

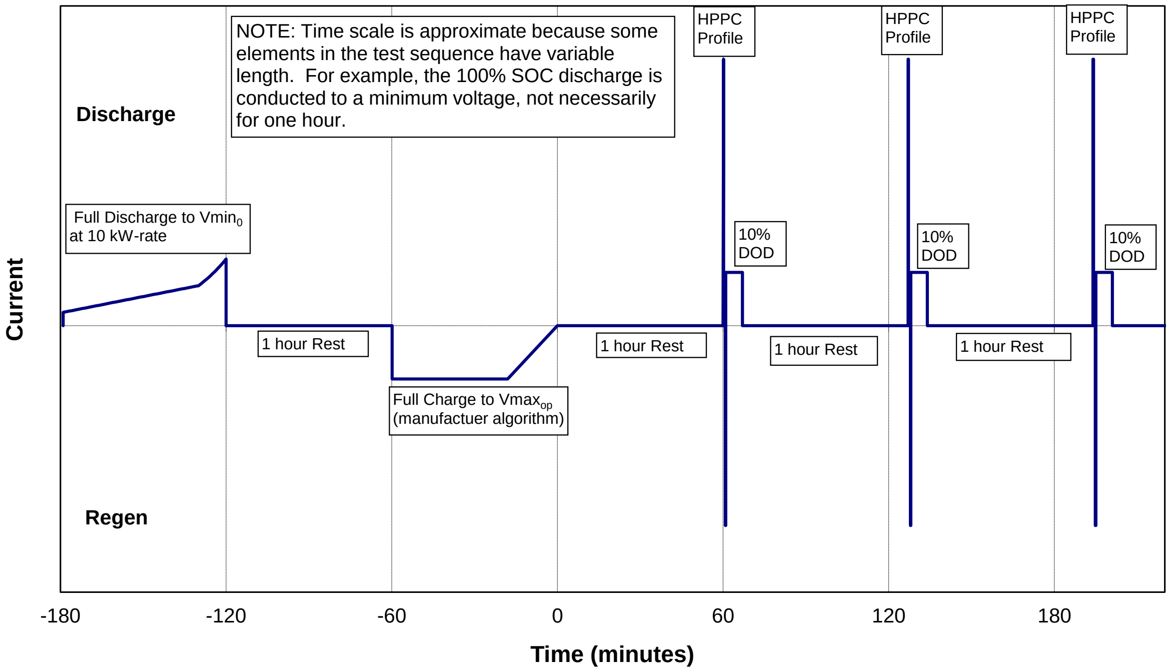

Figure 2. Hybrid Pulse Power Characterization Test (start of test sequence).

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[6] This HPPC-Current discharge is required because the HPPC results will eventually be reported as power capability versus energy removed at a 10-kW rate. The availability of linked HPPC-Current data facilitates this analysis and reporting; see Section 4.3.

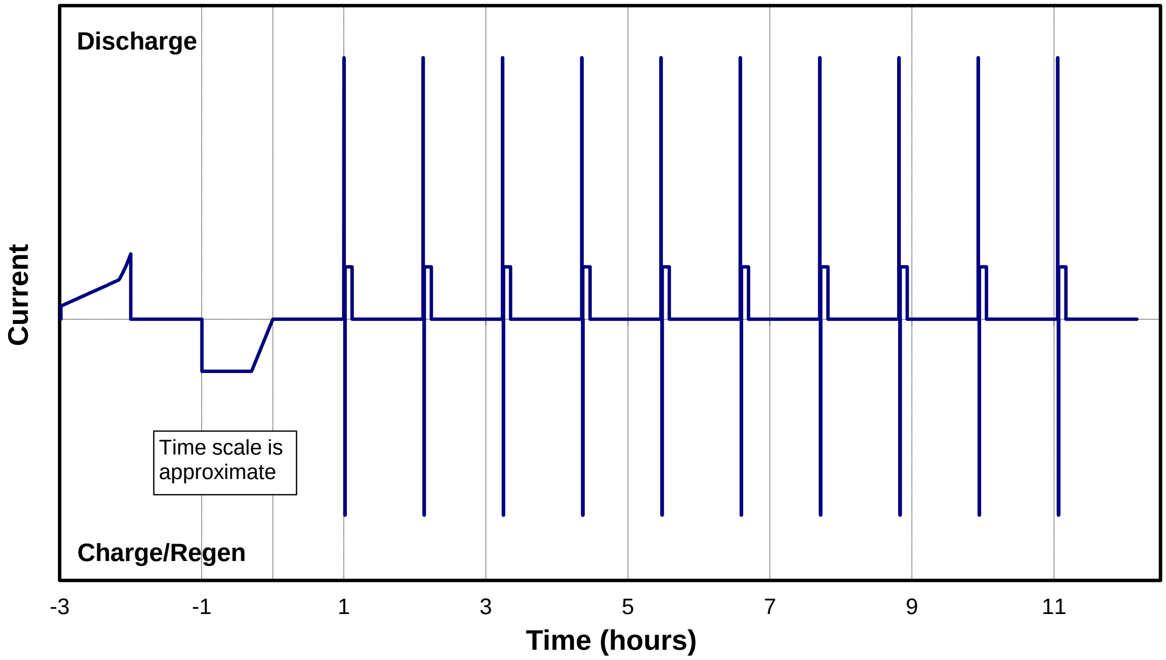

Figure 3. Hybrid Pulse Power Characterization Test (complete HPPC sequence).

The HPPC Test may be performed at the low-current level, the high-current level, or both. Each HPPC Test sequence is performed using peak currents scaled to one of the levels. Scaling of the levels is determined by the following criteria.

LOW CURRENT HPPC TEST—The pulse profile discharge current is equal to 2.5 times the HPPC-Current rating. If the BSF is unknown at the time of first testing, a $5C_1/1$ rate can be used to determine the BSF.

HIGH CURRENT HPPC TEST—The pulse profile discharge current is selected as 75% of I_{max} (the manufacturer’s absolute maximum allowable pulse discharge current for 10-s at some state-of-charge, which needs not be specified).

3.4.3 Charge-Sustaining Available Energy Verification Test

In general the HPPC Test produces slightly conservative results, because it is normally performed at power levels that are less than the target values. (At higher test currents, internal heating lowers the battery resistance and gives higher power capability). In some cases (e.g., when a new technology, a new cell design or a full-size battery design is tested for the first time), it may be desirable to verify the extent of this conservatism by performing a test at the actual target values. This is done using a special test sequence as follows:

1. From HPPC Test results, calculate (a) the minimum capacity removed (Ah_{MIN}) at which the regen pulse power target can be met and (b) the maximum capacity removed (Ah_{MAX}) at which the discharge pulse power target can be met. These values are calculated using Section 4.3.4 and 4.3.8 and graphically shown in Figure 23 of this manual.

2. Starting with a fully-charged battery (i.e., charge to $Vmax_{op}$ using the manufacturer recommended procedure), discharge to Ah_{MIN} at a constant 10-kW rate, followed by a default rest at open-circuit conditions.

3. Perform a 10-s regen pulse at the BSF-scaled Peak Regen Pulse Power target from Table 1. Remove the energy added to the battery from the regen pulse at the 10-kW rate.

4. Remove the Available Energy for Charge-Sustaining Mode from Table 1 by discharging the battery at a constant 10-kW rate, followed by a default rest at open-circuit conditions.

5. Perform a 10-s discharge pulse at the BSF-scaled Peak Discharge Pulse Power 10-s[7] target from Table 1.

The results of this test can be used to verify that the HPPC-predicted power capabilities and energy values are actually achievable and that they are not excessively conservative.

3.4.4 Charge-Depleting Available Energy Verification Test

This test will verify the Available Energy for the Charge-Depleting mode by direct measurement; secondarily, it will determine the charge range to be used for the Charge-Sustaining mode tests (i.e., that region where Charge-Sustaining operation will take place after Charge-Depleting energy is used). This test is performed in two steps.

1. Starting at manufacturer's specified $Vmax_{op}$, remove the Available Energy for Charge-Depleting Mode from Table 1 at the 10 kW rate.

2. Verify that the capacity removed is less than Ah_{MAX} by measuring coulombs removed as established in Section 3.4.3 by performing a 10-s, 37 kW (for the PHEV-20 Mile), 38kW (for the PHEV-40 Mile), or 110 kW (for the xEV-50 Mile) discharge pulse without violating the minimum voltage requirements.[8]

3.5 Self-Discharge Test

This test is intended to determine the temporary capacity loss that results from a cell or battery standing (i.e., at rest) for a predetermined period of time (i.e., 7 days at 30°C).

The test consists of the following sequence of activities:

1. Measure the actual cell capacity from full charge ($Vmax_{op}$) to the discharge voltage limit ($Vmin_0$) using a constant 10-kW discharge rate, and recharge it using the manufacturer's recommended charge algorithm.[9]

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[7] This same procedure can be used to verify the 2-second target by using a 2-second pulse at the associated power level for comparison with the target.

[8] If the discharge pulse cannot be completed without violating the minimum voltage requirements, this should be reported and program management will determine whether or not this constitutes an EOL criterion.

[9] Note that the measured capacity will be less than the rated value since the operating range uses a smaller voltage window.

2. Remove the Available Energy for Charge-Depleting Mode plus half the Available Energy for Charge-Sustaining Mode at the scaled 10-kW rate. Allow it to stand in an open-circuit condition for a nominal interval of 7 days.[10] (The actual stand period should be selected based on the expected stand loss rate, with the value chosen to yield an expected capacity loss of 5% or more over the interval). All measurement equipment may need to be disconnected from the cell during this period to reduce parasitic losses.

3. Discharge the cell to $Vmin_0$ for its remaining (residual) capacity at the 10-kW discharge rate.

4. Recharge the cell and fully discharge it again at the 10-kW discharge rate. If a loss of capacity is observed between (1) and (4), additional recharge/discharge cycles (up to 10 cycles) may be performed to return the cell to its nominal capacity.

3.6 Cold Cranking Test

The Cold Cranking Test is intended to measure 2-s power capability at low temperature (normally -30ºC) for comparison with the Cold Cranking Power targets in Table 1. The test is conducted where CS and CD Available Energy targets are met, i.e., after removal of the energy required by both targets. The test consists of the following sequence of activities:

1. Starting at manufacturer's specified $Vmax_{op}$, remove the Available Energy for Charge-Depleting Mode plus half the Available Energy for Charge-Sustaining Mode from Table 1 at the 10 kW rate.

2. Reduce the ambient temperature to –30ºC, and soak the device for a period of time adequate to ensure it has reached thermal equilibrium at this temperature (nominally 4 to 16 hours depending on the size and mass of the device).

3. Perform the Cold Cranking Test profile defined in Section 3.6.1. The pulse power level to be used is 7 kW divided by the Battery Size Factor as determined in Sections 3.1.4 and 4.3.11. Note that the manufacturer may specify a different minimum discharge voltage for cold cranking testing. This voltage, if specified, will be used for both test control and the subsequent calculation of cold cranking power capability, but it may not exceed the voltage ratio limits in Table 1. Note also that the profile pulses must be performed for the full 2-s duration (even if the test power has to be limited to stay within the minimum discharge voltage) to permit the later calculation of Cold Cranking power capability.

3.6.1 Cold Cranking Test Profile

The Cold Cranking Test Profile is a literal implementation of the Cold Cranking Power targets, which require the ability to provide 7 kW of discharge power for three 2-s pulses at 12-s intervals (i.e., 10 seconds between pulses). The profile is defined in Table 3 and illustrated in Figure 4 for the Plug-In Hybrid Battery targets.

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[10] Although the end of the CD Available Energy Target is the default nominal condition for this test, the actual value to be used is commonly defined in a device-specific test plan. The same test conditions that will be used for cycle life or calendar life testing are typical.

Table 3. Cold Cranking Test Profile for Plug-In Hybrid Targets.

Time Increment (s)	Cumulative Time (s)	System Power (kW)
2	2	7
10	12	0
2	14	7
10	24	0
2	26	7

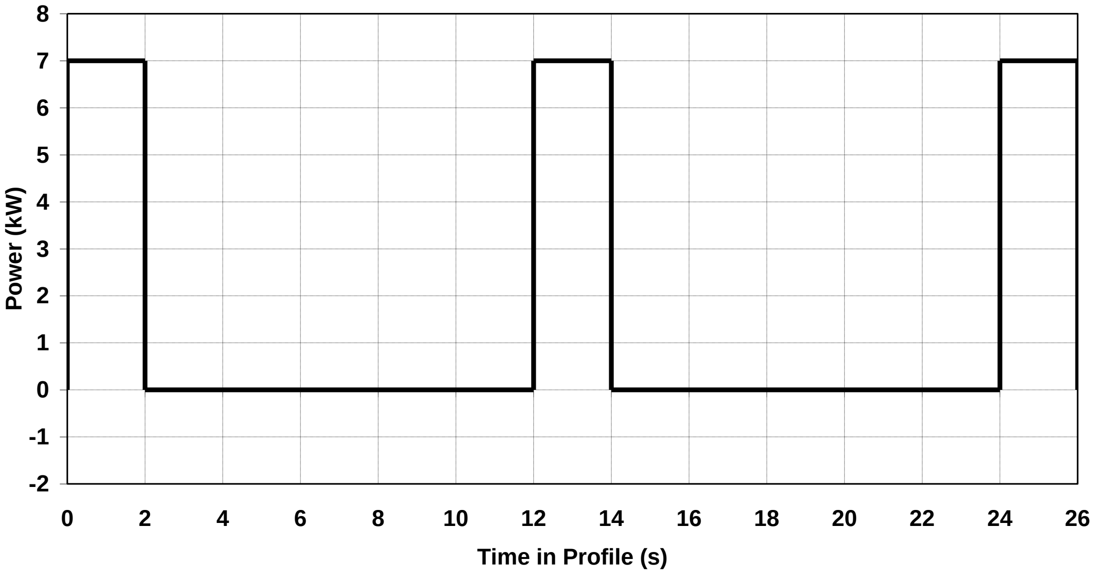

Figure 4. Cold Cranking Test Profile.

3.7 Thermal Performance Test

A primary objective of the thermal performance testing is to demonstrate the ability to meet some fraction of the CS Available Power target at various temperatures. The effects of environment (ambient temperature) on device performance will be measured as required by performing the Constant Power Test and Hybrid Pulse Power Characterization Test (either the low or high HPPC)[11] at various temperatures within the operating temperature target range (-30 to +52ºC). At the laboratory cell level, such testing has two targets: to characterize the performance of the technology as a function of temperature and to bound the likely constraints on thermal management of full-size cells or batteries. At the module and system level, the emphasis of thermal performance testing is increasingly on thermal management system design and behavior.

Unless otherwise specified in a device-specific test plan, initial charging should be performed at 30ºC during thermal performance testing. This implies a test sequence as follows: (1) fully charge the

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[11] Only one of the two HPPC test (low or high) should be used over a series of temperature tests for comparison with the targets. The HPPC current level will be invariant at all temperatures but the lower temperature tests may require lower voltage, but may not violate the $Vmin_0$.

device to $Vmax_{op}$ at 30ºC; (2) raise or lower the device ambient temperature to the target value; (3) wait a suitable soak period for thermal equalization, typically 4 to 16 hr depending on size and mass; and (4) execute the desired performance test. If self-discharge is a major concern during the soak period, the device can be clamped at a voltage during this period; however, this requires knowledge of the device OCV versus temperature behavior to ensure that the SOC is not changed inadvertently.

It may be necessary to adjust the rest intervals in the HPPC Test to ensure that thermal stability as well as voltage equilibrium is reached before each repetition of the pulse power characterization profile.

Complete thermal performance testing is conducted at BOL and at EOL if practical. At middle of life, two temperature conditions can be selected for the thermal performance test, the high temperature conditions and the lowest temperature condition that successfully passed the targets at BOL.

3.7.1 Survival Temperature Test

The survival temperature test is generally performed on a group of devices that will not be used for calendar and cycle life testing. This test may drastically affect or reduce the performance of the device. The effects of survival temperature on device performance will be measured as required within the USABC temperature target range (-46 to +66ºC). Unless otherwise specified in a device-specific test plan, charging should be performed at the reference temperature (30 ±3ºC). The device should generally be at beginning of life (BOL) conditions for this test and other tests shall not be performed at these storage temperature limits.

The cold storage test is performed as follows:

1. From a fully charged state at $Vmax_{op}$, perform a constant power discharge and charge test followed by a L-HPPC.

2. From a fully charged state at $Vmax_{op}$, bring the device to the voltage corresponding to $V_{nominal}$ at 30°C using the $C_1/1$ constant-current rate. Taper the current at $V_{nominal}$ following the manufacturer’s recommended procedure.

3. Ramp the thermal temperature chamber to the specified minimum survival temperature within 1-hr and then soak the device at open circuit for a 24-hr period (for a pack-level device, no fan should be running for this test).

4. Return to 30°C and rest for at least 4 to 16 hours (depending on the size of the device).

5. From a fully charged state at $Vmax_{op}$, perform a constant power discharge and charge test followed by a L-HPPC.

The hot storage test is performed as follows:

1. From a fully charged state at $Vmax_{op}$, perform a constant power discharge and charge test followed by a L-HPPC.

2. From a fully charged state at $Vmax_{op}$, bring the device to the voltage corresponding to $V_{nominal}$ at 30°C using the $C_1/1$ constant-current rate. Taper the current at $V_{nominal}$ following the manufacturer’s recommended procedure.

3. Ramp the thermal temperature chamber to the specified maximum survival temperature within 15-min and then soak the device at open circuit for a 24-hr period (for a pack-level device, no fan should be running for this test).

4. Return to 30°C and rest for at least 4 to 16 hours (depending on the size of the device).

5. From a fully charged state at $Vmax_{op}$, perform a constant power discharge and charge test followed by a L-HPPC.

Note that if the intent of the testing is to verify both the cold and hot storage, the HPPC test at the end of the cold storage test and/or the HPPC test at the start of the hot storage testing can be omitted.

3.8 Energy Efficiency Test

Charge sustaining efficiency is determined by a series of cycle-life pulse profiles and observing the energy throughput during discharge and regen. The Charge-Sustaining Test Profiles (Section 3.9.2) have been constructed for use in both efficiency and CS hybrid cycle life testing. They are 90-s in duration with a nominally charge-neutral pulse profile scaled to a level appropriate to verify the round trip energy efficiency target of 90% with a 50-Wh energy swing (75 Wh for the x-50 Mile Battery application). The test profile for the PHEV-20 Mile Battery is defined in Table 4 and illustrated in Figure 5, the PHEV-40 Mile Battery is defined in Table 5 and illustrated in Figure 6, and the profile for the xEV-50 Mile Battery is defined in Table 6 and Figure 7. The energy efficiency test is performed similarly to the Operating Set Point Stability (OSPS) Test in Section 3.9.3, as follows:

1. With the device at 30°C and fully charged at $Vmax_{op}$, discharge at the HPPC current (See Section 3.1.5) to the specified target voltage condition or cumulative capacity removed specified by the manufacturer[12] and then bring the cell to the specified test temperature.

2. Perform 100 efficiency test profiles.

3. Determine the change (if any) in the observed open-circuit voltage before and after the 100 profiles to gauge SOC swing. Allow a 1-hr rest period before and after the 100 profiles are performed to determine any change in open-circuit voltage.

4. If the initial and final SOC values are different (by 1% or more, unless otherwise directed by the Program Manager), or the data indicate that stable cycling was not achieved by the completion of 100 profiles, the OSPS test (Section 3.10.3) shall be conducted with implemented voltage control values or other limits, as appropriate.

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[12] If the manufacturer is unable to specify the test condition for the energy efficiency test, then use $Vmax_{op}$ as the default condition.

3.9 Life Testing

Life testing consists of cycle-life and calendar-life aging to ensure the device can meet the targets specified in Table 1 (i.e., 300,000 Charge Sustaining cycles; 5,000 Charge Depleting cycles, and 15 year calendar life). Cycle-life testing consists of repeating a test profile continuously for a sustained period of time for a Charge Sustaining mode (Section 3.10), Charge Depleting Mode (Section 3.11) or a combined CD/CS mode (Section 3.11.3). Calendar-life testing (Section 3.12) generally consists of resting the device under test at OCV using elevated test temperatures with a pulse profile applied once per day.

The life testing regime is interrupted approximately once per month and the devices are brought back to nominal operating temperature (i.e., 30° C) for reference performance tests (Section 3.13) to gauge degradation as a function of aging. Key parameters, e.g., CD and CS Available Energy and Power, and minimum voltage (or voltage margin) in the Cold Cranking Test (when it is performed), should be monitored. The corresponding end-of-life criteria for these parameters are: (1) CD and CS Available Energy or Power less than target energy or power; and (2) inability to complete the Cold Cranking Test within voltage limits.

Wherever possible, devices subjected to the same test conditions should be contained in the same test chamber or other environment, preferably using calibrated test channels with identical characteristics, and test intervals should be time-synchronized.

All devices that are part of a common test matrix should be subjected to reference testing at the same intervals if possible. Minimizing the fraction of time not spent at target temperatures is important for testing at elevated temperatures. However, in some cases rapid degradation may take place at very high temperatures; in such cases, the use of uniform test intervals will lead to a reduced number of data points for predicting trends over life. The reference test intervals have been selected to balance these conflicting needs but may need adjustment in special cases.

The general life test procedure is as follows (specific test sequences are provided in the sections below):

1. Characterize the device using the Static Capacity Test (Section 3.2), the Constant Power Discharge Test (Section 3.3) and the Hybrid Pulse Power Characterization Test (Section 3.4) and other reference tests as detailed in a device-specific test plan.

2. Conduct the initial reference performance test immediately prior to the start of life testing using the tests identified in Table 11 of Section 3.13. These tests establish the baseline performance from which degradation can be tracked and is typically referred to as RPT0.

3. Fully charge the device at 30°C to $Vmax_{op}$ using the manufacturer recommended procedure (i.e., fully charged) and rest at OCV for a default period (nominally 1 hour).

4. If necessary, discharge the device to the specified life test SOC condition or percent removed of rated capacity from $Vmax_{op}$. This can be done in one of two ways: (1) [default] remove the appropriate fraction of the cell's rated capacity at an HPPC-Current rate, or (b) if the open-circuit voltage corresponding to the target SOC is known, clamp the cell at this voltage while limiting discharge current to a HPPC-Current rate and then wait for the voltage and

current to stabilize.[13] . Note that the default method will typically reach the target condition more quickly. However, in some cases it may be desirable to use voltage (rather than fractional discharge) as the measure of SOC.

5. Rest at OCV for a default period (nominally 1 hour).

6. If aging is performed at an elevated temperature for accelerated aging, increase the ambient temperature and let the device soak for a sufficient duration to ensure thermal equilibrium (4 to 16 hours depending on the size and mass of the device).

7. Conduct the life aging sequence for ~32 days as specified in Sections 3.10 through 3.12 below.

8. If aging is performed at an elevated temperature, decrease the ambient temperature to the reference condition of 30°C and let the device soak for a sufficient duration to ensure thermal equilibrium (4 to 16 hours depending on the size and mass of the device).

9. Conduct the RPT as specified in Table 11 in Section 3.13.

10. Repeat Steps 6 through 9 until end of test or end of life.

The end-of-test criteria for life testing are normally specified in a device-specific test plan. A default (and generally mandatory) end-of-test condition is reached when the test profile cannot be executed within both the discharge and regen voltage limits.[14] Another default end-of-test condition also occurs if performance degrades to a point where the HPPC Reference Performance Test (RPT) yields insufficient information to show further degradation.[15] Other end of test criteria include: (a) a cycle life capability that meets the targets has been attained (i.e., the number of properly scaled test cycles exceeds the applicable target); or (b) the CD or CS Available Energy or Available Power drops below the target value. In case (a), the battery may not have reached end-of-life when testing stops, but further testing is not usually considered cost-effective. In case (b), end-of-life has occurred at some prior time.[16]

3.10 Charge-Sustaining Cycle Life Tests

Charge-Sustaining Cycle life testing for Plug-In Hybrid operation is performed using one of the Cycle Life Test Profiles defined in Section 3.10.2. Cycling is performed by repeating the selected test profile at a fixed state-of-charge (i.e., the profile is charge-neutral). Periodic reference performance tests will be conducted during cycle life testing to gauge degradation rates.

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[13] A value less than 1% of the HPPC current is probably adequate to meet this criterion, provided this is within the measurement capability of the test equipment.

[14] At this point, the device has insufficient available energy and capacity at the test conditions to execute the test, i.e., its capability is less than that required by the test profile.

[15] This would normally be the point where valid discharge and regen data are obtained at less than three DOD values using the Low-Current HPPC test.

[16] Note that *end-of-test* and *end-of-life* are not the same, and they may not even be related. See the glossary for more information on this distinction. The determination of End-of-Life and Cycle Life is discussed in Section 4.9.

3.10.1 Cycle Life Test Procedure Outline

The cycle life testing process consists of the following steps:

1. Scale the selected test profile (Table 4 for the PHEV-20 Mile Battery, Table 5 for the PHEV-40 Mile, or Table 6 for the xEV-50 Mile Battery) by dividing the nominal profile power values by the Battery Size Factor as described in Section 3.1.4.

2. From a fully charged condition ($Vmax_{op}$), bring the cell to the desired operating state-of-charge and test temperature for cycle life testing and perform the Operating Set Point Stability Test (Section 3.10.3) to verify stable operation at the selected SOC point. Make any needed adjustments to the test profile or test operating conditions.

3. Repeat the selected test profile(s) at the desired operating conditions the number of times specified in Table 11 (Section 3.13) or a device-specific test plan. If additional OSPS cycles are required to achieve stable cycling, these cycles should be included in the total.

4. After the specified number of repetitions, suspend cycling. If cycling is being done at other than 30ºC, return the cell to 30ºC. Observe the open-circuit voltage after a default rest. Remove the residual capacity at a constant HPPC-Current rate, and perform a Reference Performance Test to determine the extent of degradation in capacity and power capability. The reference tests are listed in Table 11. The intervals between repetitions of these reference tests are also specified in Table 11, though these may be adjusted somewhat if required for time synchronization of cells being tested under different test regimes.

5. If the residual capacity measured in Step 5 indicates an unacceptable drift during cycling (typically ±5% change in measured capacity), repeat Step 3 to re-establish the target cycling condition.

6. Repeat Steps 4 and 5 until an end-of-test condition is reached.

3.10.2 Charge-Sustaining Cycle Life Test Profiles

The Charge-Sustaining Cycle Life Test Profiles removes 50 Wh (PHEV-20 and PHEV-40 Mile application) or 75 Wh (xEV-50 Mile application) on discharge and is nominally charge-balanced. The test profiles are all defined at the battery pack level and can be scaled to the appropriate power levels for testing laboratory cells, full-size cells and module designs using the Battery Size Factor as described in Section 3.1.4. The objective of these test profiles is to demonstrate device life in the Charge-Sustaining mode when subjected to different energy use levels and patterns appropriate to the targets. Each profile is a 90-s pulse profile intended to demonstrate the ability to meet the cycle life target of 300,000 cycles. The profile families transfer about 15 million watt-hours (MWh) respectively in and out of the device over 300,000 cycles for the PHEV-20 and PHEV-40 Mile application; approximately 22.5 million watt-hours (MWh) are transferred over 300,000 cycles for the xEV-50 application.

The PHEV-20 Mile Battery profile is defined in Table 4 and illustrated in Figure 5, the PHEV-40 Mile Battery profile is defined in Table 5 and illustrated in Figure 6, and the xEV-50 Mile Battery profile is defined in Table 6 and illustrated in Figure 7.

3.10.2.1 PHEV-20 Mile Battery CS Profile

Table 4. Charge-Sustaining PHEV-20 Mile Battery (50 Wh) Cycle Life Test Profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
36	36	3	30.0	30.0
4	40	18	20.0	50.0
48	88	-3.13	-41.7	8.3
2	90	-15	-8.3	-0.1

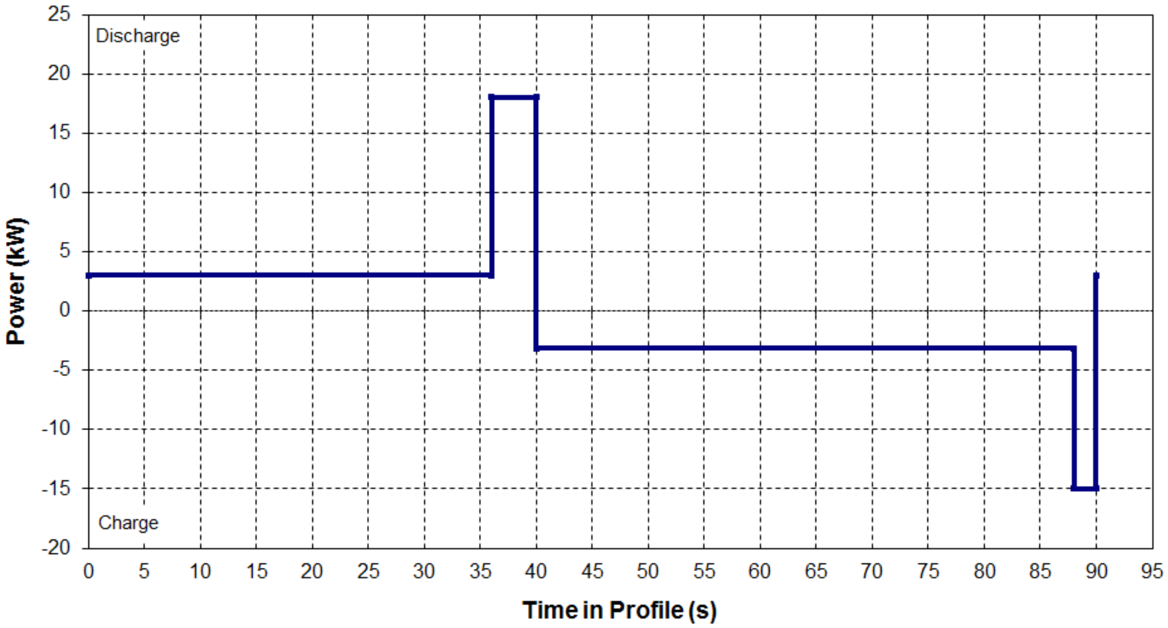

Figure 5. Charge-Sustaining PHEV-20 Mile Battery (50 Wh) Cycle Life Test Profile.

3.10.2.2 PHEV-40 Mile Battery CS Profile

Table 5. Charge-Sustaining PHEV-40 Mile Battery (50 Wh) Cycle Life Test Profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
37	37	3	30.8	30.8
3	40	23	19.2	50.0
48	88	-3.13	-41.7	8.3
2	90	-15	-8.3	-0.1

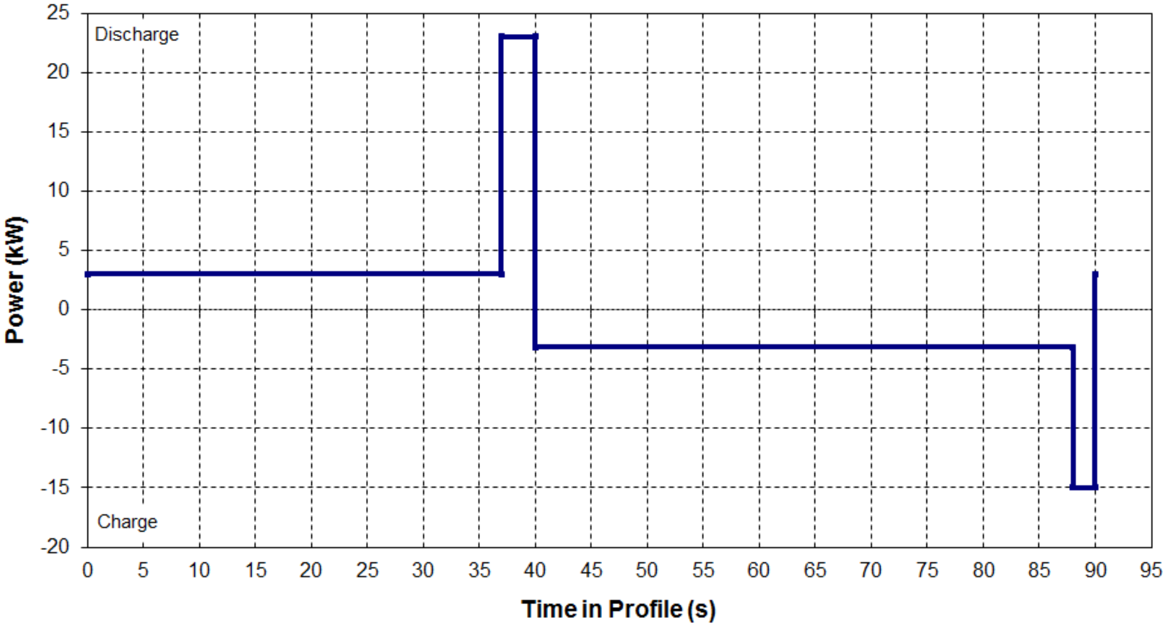

Figure 6. Charge-Sustaining PHEV-40 Mile Battery (50 Wh) Cycle Life Test Profile.

3.10.2.3 xEV-50 Mile Battery CS Profile

Table 6. Charge-Sustaining xEV-50 Mile Battery (75 Wh) Cycle Life Test Profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
30	30	5	41.7	41.7
2	32	60	33.3	75.0
56	88	-3.75	-58.3	16.7
2	90	-30	-16.7	0

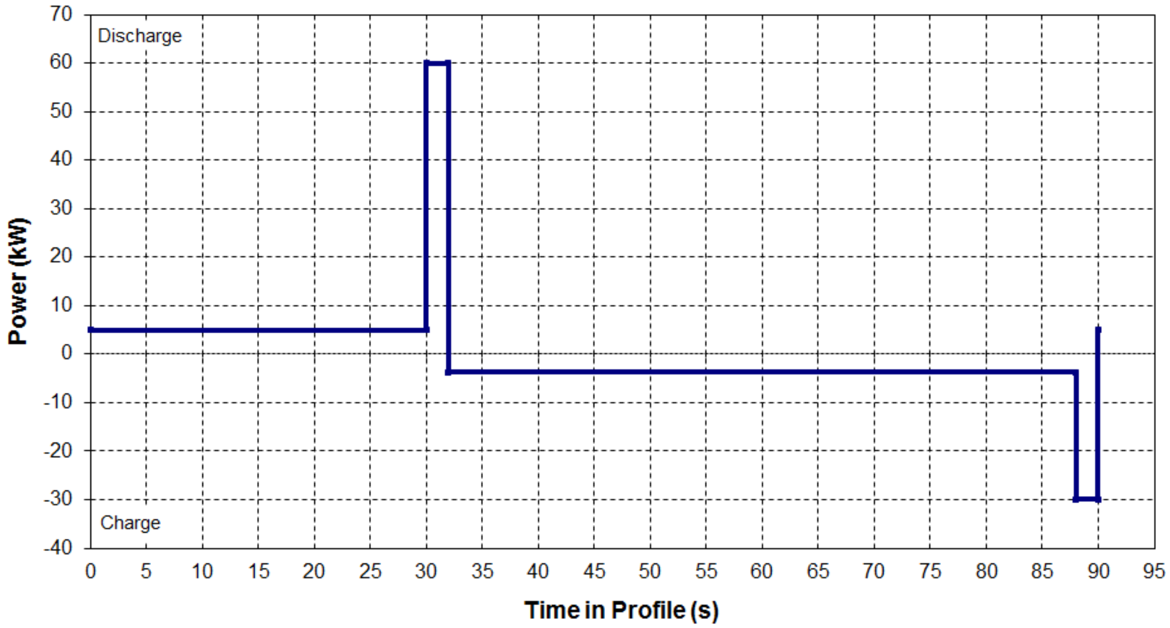

Figure 7. Charge-Sustaining xEV-50 Mile Battery (75 Wh) Cycle Life Test Profile.

3.10.3 Operating Set Point Stability Test

This test is a special case of the cycle life testing regime to be applied to a given device and should be performed immediately before the beginning of cycle life testing to determine that stable cycling will occur at the target SOC, or to adjust test conditions if necessary to ensure stability (charge neutrality). The target state-of-charge for the cycle life test is normally specified in a device-specific test plan based on projected use of the device.[17] Results from the energy efficiency test (Section 3.8) can be used to establish the initial operating set point parameters for this test.

With the cell at the selected state-of-charge value and all other conditions (e.g., operating temperature) as required for life cycling, apply the selected Cycle Life Test Profile for a period long enough to reach thermal equilibrium and to return to the target SOC.[18] Determine the change (if any) in the state-of-charge before and after the cycling interval. Allow a default rest before and after this cycling is performed to determine any change in open-circuit voltage. If the SOC is found to be more than ±1% SOC based on OCV (or a higher percent difference if directed by the Program Manager) then this test shall be repeated with updated control algorithms. The residual capacity can also be removed at a constant HPPC-Current rate to estimate the cumulative capacity removed (or restored) during the cycling interval.

3.10.3.1 Adjusting the Operating Set Point

If the device does not reach a voltage and temperature equilibrium during the cycling interval, upper or lower voltage constraints or other limits may be adjusted (within manufacturer limits) to provide stable cycling conditions, and this test may be repeated or extended if necessary. The test may also be repeated at the beginning of any cycle life testing interval if the device condition has changed significantly.

3.10.3.2 Controlling the State-of-Charge during the OSPS Test

The preferred approach to maintaining a target state-of-charge during the OSPS test and later cycle life testing depends on the test profile used and on test equipment capabilities. Guidelines for accomplishing can be called out in a device-specific test plan.

Note that achieving the target SOC and a stable cycling condition are related but have separate constraints. The maximum and minimum pulse voltages from profile to profile are usually the most sensitive indicators of stable cycling (unless the device resistance is changing appreciably during the cycling period), while the SOC during cycling must actually be measured after cycling stops. A voltage clamp during the last 10 seconds of the extended, low-power, regen portion of the profile (before the higher power regen pulse) is the default method to stabilize the cycling profiles. The intent of this test is to establish control parameter values, and if necessary to fine-tune the test profile, such that life cycling can be performed continuously over the intervals between reference tests specified in Table 11[19].

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[17] If the manufacturer is unable to specify the test condition for the energy efficiency test, then use $Vmax_{op}$ as the default condition.

[18] This typically requires approximately 100 complete pulse profiles.

[19] Using the voltage to stabilize the CS Cycle Life Profiles may not be appropriate for all chemistries. With the approval of the workgroup, other methods that are chemistry appropriate can be employed to stabilize the profile for long term cycling.

3.11 Charge-Depleting Cycle Life Tests

Charge-Depleting Cycle life testing is performed by repeating the designated test profile (Section 3.11.2) until the energy target for the Charge-Depleting mode from Table 1 is reached (e.g., a scaled 5.8 kWh energy removed for the PHEV-20 Mile Battery application, 11.6 kWh for PHEV-40, etc.). The device is then recharged at the Maximum System Recharge Rate listed in Table 1, unless otherwise specified by the manufacturer. RPTs are conducted periodically during cycle life testing.

3.11.1 Cycle Life Test Procedure Outline

The cycle life testing process consists of the following steps:

1 Scale the selected test profile by dividing the nominal profile power values by the Battery Size Factor as described in Section 3.1.4.

2 The device is first fully charged at 30°C to $Vmax_{op}$ using the manufacturer recommended procedure (i.e., fully charged).

3 Bring the device to the desired test temperature and soak for the appropriate duration. Repeat the designated test profile at the desired operating conditions until the net energy is equal to the scaled Charge-Depleting target energy. This will be about 12.9 profiles for the PHEV-20 Mile battery, about 25 profiles for the PHEV-40 Mile battery, or about 20 profiles for the xEV-50 Mile battery.

4 Rest at OCV for a default period of 15 minutes[20] and then recharge the device using the Maximum System Recharge Rate identified in Table 1 unless otherwise specified by the manufacturer. Rest at OCV for a default period of 15 minutes after the recharge. Steps 4 and 5 will be the equivalent of one Charge-Depleting Cycle.

5 Repeat the cycle (from steps 4 and 5) at the desired operating conditions the number of times specified in Table 11 or a device-specific test plan.

6 After the specified number of repetitions, suspend cycling. If cycling is being done at other than 30ºC, return the device to 30ºC and soak for the appropriate duration. Observe the open-circuit voltage after a 1-hr rest. Perform the Reference Performance Tests to determine the extent of degradation in capacity and/or power capability. The reference tests are listed in Table 11. The intervals between repetitions of these reference tests are also specified in Table 11, though these may be adjusted somewhat if required for time synchronization of cells being tested under different test regimes.

7 Repeat Steps 4 through 6 until an end-of-test condition is reached.

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[20] The manufacturer may specify an alternative rest period between the discharge and charge profiles. The rest interval should be specified in a device-specific test plan.

3.11.2 Charge-Depleting Cycle Life Test Profile

The objective of these test profiles is to demonstrate device life in the Charge-Depleting mode when subjected to energy use levels and patterns appropriate to the targets. Each profile is a series of constant power discharge/charge steps with a total duration of 360 seconds.

3.11.2.1 PHEV-20 Mile Battery CD Profile

The PHEV-20 Mile Battery profile is defined in Table 7 and illustrated in Figure 8. It is intended to demonstrate the ability to meet the Charge-Depleting cycle life target of 5,000 cycles (in sets of ~13 profiles per cycle) with a Charge-Depleting net energy of 5.8 kWh. The profile discharges 29 million watt-hours (MWh) respectively out of the device over 5,000 cycles.

Table 7. Charge-Depleting Cycle Life Test Profile for the PHEV-20 Mile Battery.

Step No	Step Time (sec)	Cum Time (sec)	% Power (%)	Power (W)	Net Energy (Wh)	Cum Dis Energy (Wh)
1	16	16	0	0	0.00	0.00
2	28	44	12.5	4625	35.97	35.97
3	12	56	25	9250	66.81	66.81
4	8	64	-12.5	-4625	56.53	66.81
5	16	80	2	740	59.82	70.09
6	24	104	12.5	4625	90.65	100.93
7	12	116	25	9250	121.48	131.76
8	8	124	-12.5	-4625	111.21	131.76
9	16	140	2	740	114.49	135.05
10	24	164	12.5	4625	145.33	165.88
11	12	176	25	9250	176.16	196.72
12	8	184	-25	-9250	155.61	196.72
13	16	200	2	740	158.89	200.01
14	36	236	12.5	4625	205.14	246.26
15	2	238	100	37000	225.70	266.81
16	6	244	50	18500	256.53	297.64
17	24	268	62.5	23125	410.70	451.81
18	8	276	-25	-9250	390.14	451.81
19	32	308	25	9250	472.37	534.03
20	8	316	-50	-18500	431.26	534.03
21	12	328	2	740	433.72	536.50
22	2	330	121	45000	458.72	561.50
23	5	335	2	740	459.75	562.53
24	2	337	-65.8	-25000	445.86	562.53
25	23	360	2	740	450.59	567.26

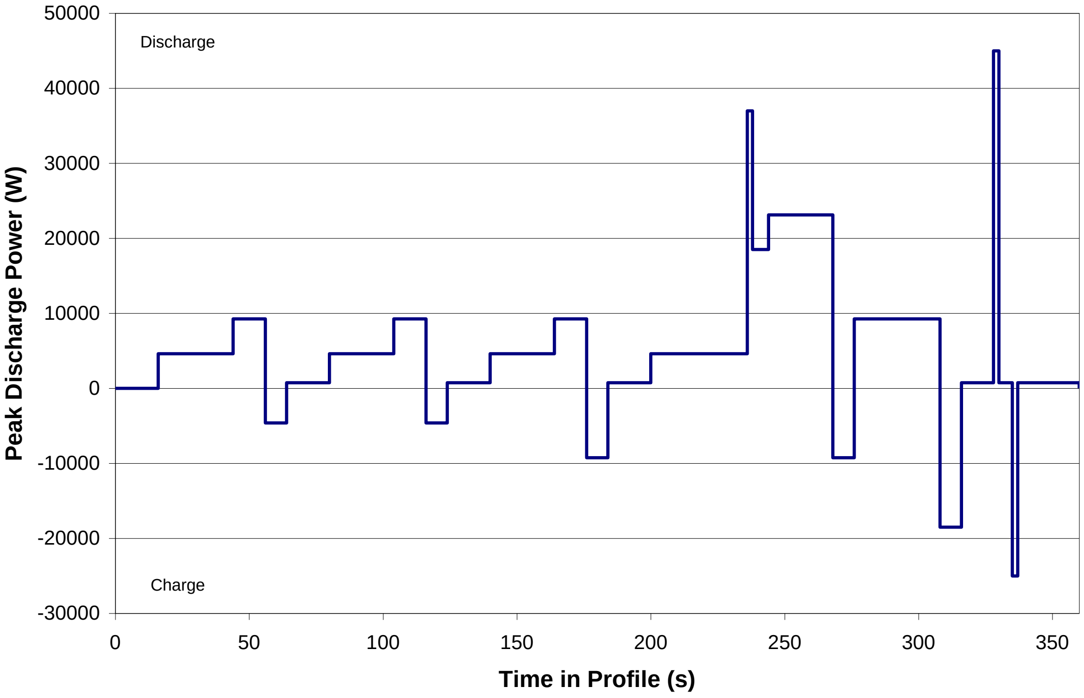

Figure 8. Charge-Depleting Cycle Life Test Profile for the PHEV-20 Mile Battery.

3.11.2.2 PHEV-40 Mile Battery CD Profile

The PHEV-40 Mile Battery profile is defined in Table 8 and illustrated in Figure 9. It is intended to demonstrate the ability to meet the Charge-Depleting cycle life target of 5,000 cycles (in sets of ~25 profiles per cycle) with a Charge-Depleting net energy of 11.6 kWh. The profile discharges 58 million watt-hours (MWh) respectively out of the device over 5,000 cycles.

Table 8. Charge-Depleting Cycle Life Test Profile for the PHEV-40 Mile Battery.

Step No	Step Time (sec)	Cum Time (sec)	% Power (%)	Power (W)	Net Energy (Wh)	Cum Dis Energy (Wh)
1	16	16	0	0	0.00	0.00
2	28	44	12.5	4750	36.94	36.94
3	12	56	25	9500	68.61	68.61
4	8	64	-12.5	-4750	58.06	68.61
5	16	80	2	760	61.43	71.99
6	24	104	12.5	4750	93.10	103.66
7	12	116	25	9500	124.77	135.32
8	8	124	-12.5	-4750	114.21	135.32
9	16	140	2	760	117.59	138.70
10	24	164	12.5	4750	149.26	170.37
11	12	176	25	9500	180.92	202.03
12	8	184	-25	-9500	159.81	202.03
13	16	200	2	760	163.19	205.41
14	36	236	12.5	4750	210.69	252.91
15	2	238	100	38000	231.80	274.02
16	6	244	50	19000	263.47	305.69
17	24	268	62.5	23750	421.80	464.02
18	8	276	-25	-9500	400.69	464.02
19	32	308	25	9500	485.13	548.47
20	8	316	-50	-19000	442.91	548.47
21	12	328	2	760	445.44	551.00
22	2	330	121	46000	471.00	576.56
23	5	335	2	760	472.06	577.61
24	2	337	-65.8	-25000	458.17	577.61
25	23	360	2	760	463.02	582.47

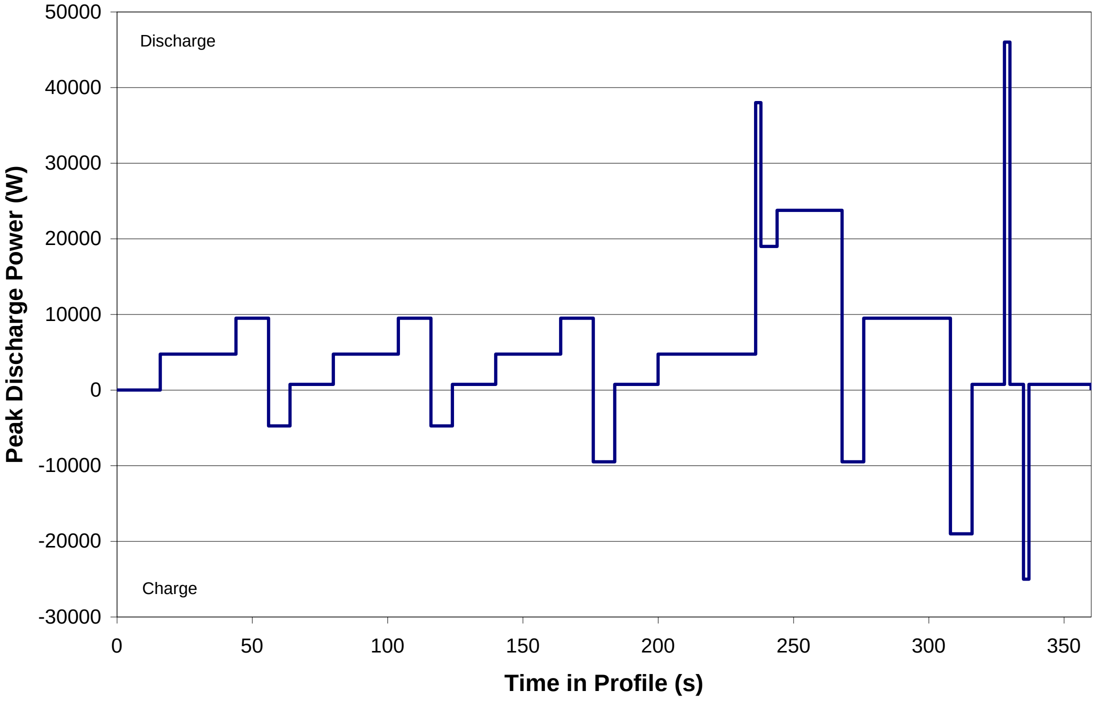

Figure 9. Charge-Depleting Cycle Life Test Profile for the PHEV-40 Mile Battery.

3.11.2.3 xEV-50 Mile Battery CD Profile

The xEV-50 Mile Battery profile is defined in Table 9 and illustrated in Figure 10. It is intended to demonstrate the ability to meet the Charge-Depleting cycle life target of 5,000 cycles (in sets of ~20 profiles per cycle) with a Charge-Depleting net energy of 14.5 kWh. The profile discharges 72.5 million watt-hours (MWh) respectively out of the device over 5,000 cycles.

Table 9. Charge-Depleting Cycle Life Test Profile for the xEV-50 Mile Battery.

Step No	Step Time (sec)	Cum Time (sec)	% Power (%)	Power (W)	Net Energy (Wh)	Cum Dis Energy (Wh)
1	16	16	0.0	0	0.00	0.00
2	28	44	9.8	10750	83.61	83.61
3	12	56	19.5	21500	155.28	155.28
4	8	64	-19.5	-21500	107.50	155.28
5	16	80	1.6	1720	115.14	162.92
6	24	104	9.8	10750	186.81	234.59
7	12	116	19.5	21500	258.48	306.26
8	8	124	-19.5	-21500	210.70	306.26
9	16	140	1.6	1720	218.34	313.90
10	24	164	9.8	10750	290.01	385.57
11	12	176	19.5	21500	361.68	457.23
12	8	184	-19.5	-21500	313.90	457.23
13	16	200	1.6	1720	321.54	464.88
14	36	236	9.8	10750	429.04	572.38
15	2	238	78.2	86000	476.82	620.16
16	6	244	-39.1	-43000	405.16	620.16
17	24	268	48.9	53750	763.49	978.49
18	8	276	-19.5	-21500	715.71	978.49
19	32	308	19.5	21500	906.82	1169.60
20	8	316	-39.1	-43000	811.27	1169.60
21	12	328	1.6	1720	817.00	1175.33
22	2	330	109.1	120000	883.67	1242.00
23	5	335	1.6	1720	886.06	1244.39
24	10	345	-54.5	-60000	719.39	1244.39
25	15	360	1.6	1720	726.56	1251.56

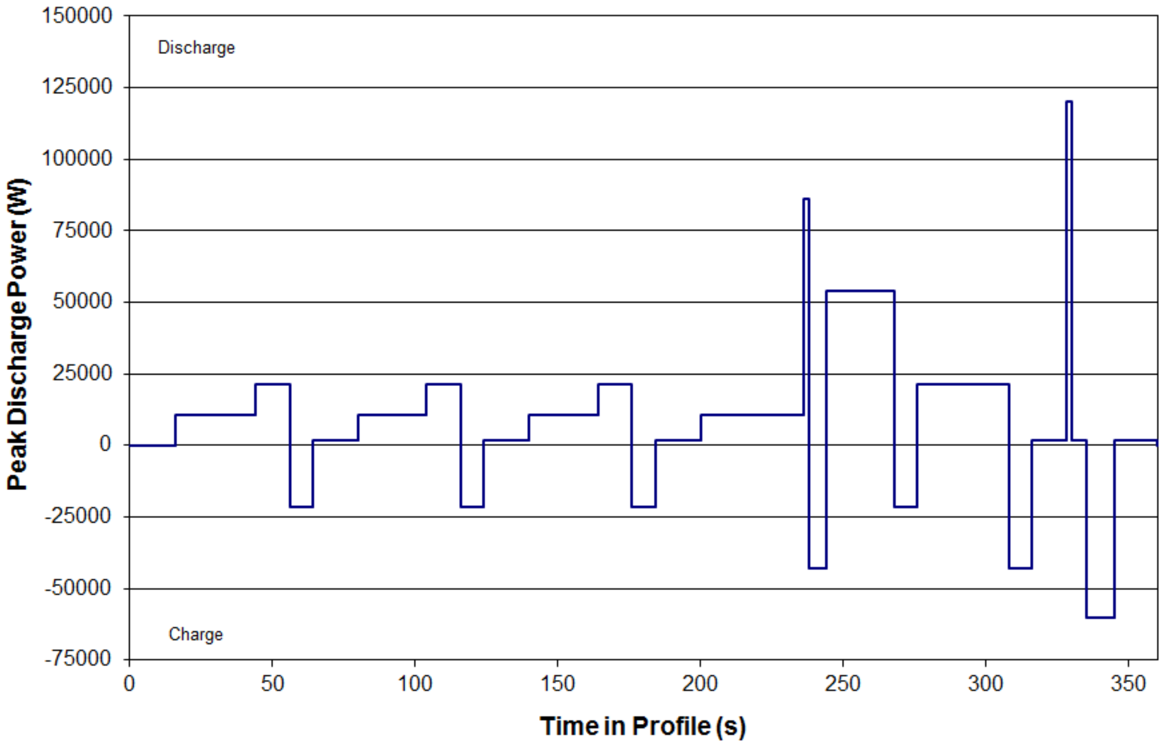

Figure 10. Charge-Depleting Cycle Life Test Profile for the xEV-50 Mile Battery.

3.11.3 Combined Cycle Life Test

The purpose of the combined cycle life test is to combine the appropriate number of Charge-Depleting Cycle Life Profiles with Charge-Sustaining Cycle Life Profiles such that both sets of cycle life targets are met at the end of testing. This test is not normally required by USABC but may be used as part of the development program test plan at the discretion of the program manager and the developer.

1. Scale the selected test profile by dividing the nominal profile power values by the Battery Size Factor as described in Section 3.1.4.

2. The device is first fully charged at 30°C to $Vmax_{op}$ using the manufacturer recommended procedure (i.e., fully charged).

3. Bring the device to the desired test temperature and soak for the appropriate duration. Perform one CD cycle by repeating the designated Charge-Depleting Cycle Life Test Profile at the desired operating conditions until the net energy is equal to the scaled Charge-Depleting target energy. This will be about 12.9 profiles for the PHEV-20 Mile battery, about 25 profiles for the PHEV-40 Mile battery, or about 20 profiles for the xEV-50 Mile battery.

4. Perform 60 successive Charge-Sustaining Cycle Life Test Profiles for the PHEV-20 Mile battery, PHEV-40 Mile battery, or the xEV-50 Mile battery. No rest period is required between the completion of the CD cycle and the start of the CS cycles.

5. Rest at OCV for a default period of 15 minutes and then recharge the device using the Maximum System Recharge Rate identified in Table 1 unless otherwise specified by the manufacturer. Rest at OCV for a default period of 15 minutes after the recharge.

6. Repeat Steps 3-5 the number of times required for 32-day intervals between RPTs.

7. If necessary, return the device to 30ºC and soak for the appropriate duration. Perform the Reference Performance Tests from Table 11.

8. Repeat Steps 1-7, ten times. (Note: Steps 6 and 8 can be modified to provide longer or shorter intervals between Reference Performance Testing).

3.12 Calendar Life Test

This test is designed to permit the evaluation of cell or battery degradation as a result of the passage of time with minimal usage. It is not a pure shelf life test because the devices are maintained at or near a target state-of-charge during the test. The devices will also be subjected to periodic RPTs.

In general, calendar life testing is performed using multiple cells over a range of test conditions.[21] It is commonly done at elevated temperatures in order to shorten the time required for obtaining useful results. Cells to be tested may be included in a matrix of test variables such as temperature and state-of-charge. This matrix may in turn be part of a larger cycle life test matrix where calendar life testing

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[21] The cell terminology in this section is not intended to prevent the calendar life testing of modules or complete batteries. It reflects only the fact that the vast majority of such testing is done at the cell level.

is considered a limiting cycle life test, i.e., one in which the state-of-charge swing during cycling is zero. Reference 5 provides more guidance on this subject. The calendar life test procedure assumes that the target test conditions for each cell or group of cells have been defined, typically in a device-specific test plan.

3.12.1 Calendar Life Test Planning

Careful planning and analysis of calendar life tests are critical to estimation of battery life with high confidence. Accurate life estimates are essential for assessing battery warranty risks and costs. Calendar life estimates are necessarily based on accelerated test methods. Test should be conducted at the most challenging SOC allowed by the manufacturer, representative of the most stressful condition within the operating window. The general approach is to store cells under open-circuit conditions at elevated temperatures to artificially increase their rates of performance deterioration. The key tradeoff in the selection of storage temperatures is to avoid introducing irrelevant failure modes at too high a temperature, while achieving high rates of deterioration to minimize test time and cost.

At a minimum, three temperatures should be selected. Optimally, five to seven elevated temperatures would be selected, but in many cases this proves impractical. The lowest temperature should be the baseline temperature for calendar life, while the highest temperature should result in an end-of-life condition at the desired test duration without introducing unrealistic failure mechanisms (e.g., two years or less). Other temperatures should be equally spaced between these extremes. At least three cells should be tested at each temperature, but for improved statistical results, additional cells should be used, especially at the lower temperatures. The cells under test should be stored in an open-circuit condition, but with voltage monitoring using sensing circuits that present negligible loads to the devices under test. If feasible, a daily pulse should be performed with a 5-minute voltage clamp after the pulse to maintain the appropriate SOC. Where it is not feasible to conduct a daily pulse, SOC should be periodically verified and maintained. For a test to be considered valid, the SOC may not be allowed to drop more than 5% below the target value. If a cell nears this level of drift, a taper charge to the target is permitted.

Wherever possible, cells subjected to the same test conditions should be contained in the same test chamber or other environment, preferably using calibrated test channels with identical characteristics, and test intervals should be time-synchronized.

All cells that are part of a common test matrix should be subjected to reference testing at the same intervals if possible. Minimizing the fraction of time not spent at target temperatures is important for testing at elevated temperatures. However, in some cases rapid degradation may take place at very high temperatures; in such cases, the use of uniform test intervals will lead to a reduced number of data points for predicting trends over life. The reference test intervals have been selected to balance these conflicting needs but may need adjustment in special cases.

3.12.2 Calendar Life Test Procedure

The outline of this test procedure for a particular cell is as follows:

1. The device is first fully charged at 30°C to $Vmax_{op}$ using the manufacturer recommended procedure (i.e., fully charged).

2. If necessary, discharge to the target condition (i.e., capacity removed or SOC) at 30ºC using the I_{HPPC} rate and rest for an hour.

3. Apply a single iteration of the Calendar Life Test Profile defined in Section 3.12.3. The nominal discharge current to be used for this profile is equal to the peak discharge current for the Low-Current HPPC Test.

4. Bring the cell to the target temperature at open-circuit condition and wait for the ambient temperature and voltage to stabilize (i.e., 4 to 16 hours based on cell or pack mass).

5. Apply a single iteration of the Calendar Life Test Profile defined in Section 3.12.3 at the same current level defined in Step 3. The device is then placed in an open-circuit state and the test continues at the target conditions.[22]

6. Once every 24-hours, and immediately before beginning Step 7, repeat Step 5. Note that data acquisition requirements during this pulse profile execution will be similar to those for HPPC Tests, even though other data may be required only infrequently during the 24-hour intervals.[23]

7. At intervals as specified in Table 11 or a device-specific test plan, return the cell to nominal temperature (e.g., 30ºC), observe its open-circuit voltage after a 1-hr rest, and apply a single iteration of the Calendar Life Test Profile before discharging its remaining capacity at the HPPC-Current rate. Conduct a single iteration of the required periodic Reference Performance Tests, and then return the cells to their test temperatures.

8. Repeat this test sequence until the cell reaches an end-of-test condition.

3.12.3 Calendar Life Test Profile

This test profile is intended for once-per-day execution during calendar life testing at the target temperature and state-of-charge. Additionally, this test profile is performed again at the target SOC but at 30°C, immediately before and immediately after each calendar life testing interval. The data provide daily information regarding the extent and rate of cell degradation during the intervals between periodic reference tests. This test profile differs from Cycle Life Test Profile in that it is not intended for continuous execution; instead, it is executed once during each 24-hr period while the cell under test is maintained at a given temperature and state-of-charge. The pulse profile is shown in Table 10 and illustrated in Figure 11.

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[22] In the event resources do not allow daily iteration, this step may be omitted with Manager approval and periodic voltage checks are conducted to ensure SOC stability.

[23] Intermittent charge increments may be required to compensate for self-discharge to keep the state-of-charge within an acceptable range until the next reference test. The method to be employed for doing this should be specified in a device-specific test plan. The suggested method is to clamp each device after the once-per-24-hours profile at its elevated-temperature OCV (as measured in Step 4) for a specified duration sufficient to compensate for increased self-discharge at the target temperature.

Table 10. Calendar Life Test Profile.

Step Time (s)	Cumulative Time (s)	Relative Current (Ratio)
10	10	1.0
60	70	0
10	80	-0.75
300	380	Voltage Clamp

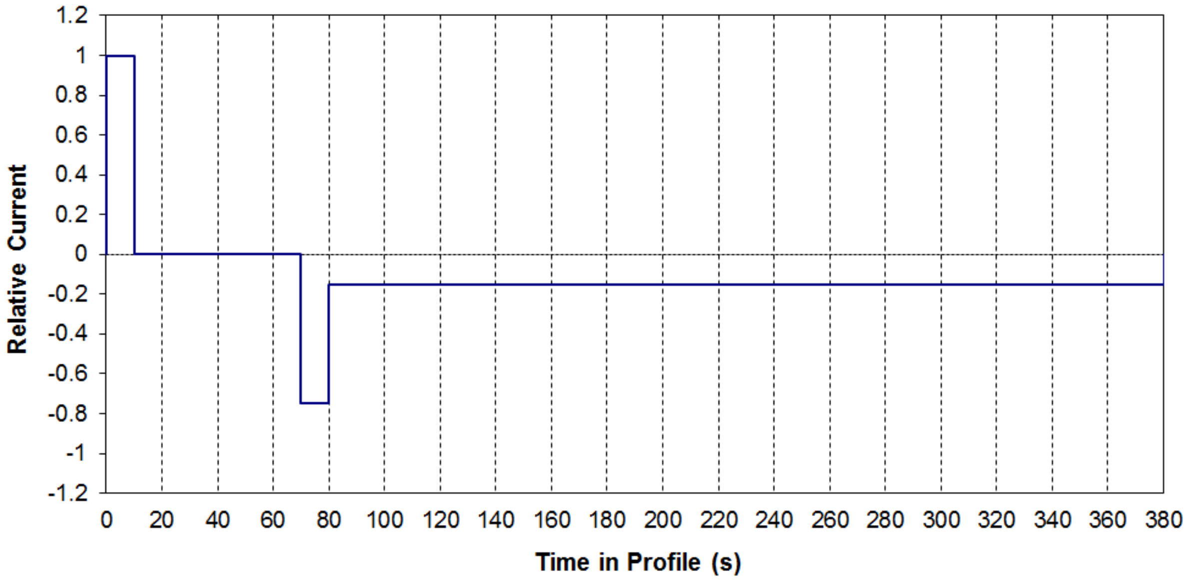

Figure 11. Calendar Life Test Profile.

3.12.4 Alternative Calendar Life Test

In some cases calendar life testing may be conducted without using the once-per-24-hr Calendar Life Test Profile. The most likely reason for this is a shortage of continuously available test channels for the number of devices to be tested. (If the 24-hr pulse profile is not performed, a test channel is required only for the periodic Reference Performance Tests and possibly for occasional charge increments). The earlier procedure can be used in this fashion by omitting the daily performance of the test profile specified in Step 6 in the preceding section. If testing is performed in this fashion, the device open-circuit voltage should be checked every 24 to 48-hours to verify that the state-of-charge remains in an acceptable region. To be a valid test the SOC should be monitored and prevented from drifting more than 1% from the target value (or a higher percent difference if directed by the Program Manager) by applying a taper charge to return the cell(s) to the target value.

3.13 Reference Performance Tests

Reference Performance Tests (RPTs) are a set of tests performed at periodic intervals during life testing to establish the condition and rate of performance degradation of devices under test. Except as modified by a device-specific test plan, these tests should be performed (a) prior to, and within two weeks of, the start of life testing; (b) at defined periodic intervals; and (c) at end of testing, for all devices undergoing either cycle life testing or calendar life testing. [24]

Table 11. Reference Performance Tests and Test Intervals for Life Testing.

Type of Life Testing	Interval Between RPTs	Reference Performance Tests
Charge-Sustaining Cycle Life Testing	30,000 cycle life profiles ~32 days,	10-kW Constant Power Discharge Test (This test is to precede the HPPC Test and generally included in the same data file as the HPPC Test for analysis purposes) Low-Current HPPC Test
Charge-Depleting Cycle Life Testing	300 to 600 cycles (This value should be adjusted to provide an RPT each month if the cycling lasts much longer than the anticipated 32 day period) ~32 days	
Calendar Life Testing	Approximately 32 days (consistent with CS cycle life RPTs)	
Combined Cycle Life Testing	~32 days	

A Reference Performance Test iteration consists of one repetition of each test listed in Table 11. It is recommended that these tests be performed in the order listed.[25] These tests are performed for all PHEV testing modes. Table 11 also lists typical intervals for reference tests during cycle life and calendar life testing. In practice, these intervals may have to be adjusted somewhat to synchronize reference testing for groups of multiple cells, especially where calendar life and cycle life cells are being tested in the same temperature chamber.

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[24] For battery chemistries that have a strong dependence of performance on temperature, it may be desirable to measure accurately the actual (ambient) temperature of the test article during the RPTs and adjust the performance results using the data from the Thermal Performance Tests (Section 3.7) to estimate the present performance at the nominal 30°C temperature. Performing such an adjustment is necessarily limited to those cases where the following conditions are satisfied: temperature data are available with accuracy better than the variations to be corrected (2°C or less); Thermal Performance Test data is available "near" the normal testing range, e.g., within ±5°C on either side of the nominal temperature; and the test whose data are to be adjusted is conducted within this limited range "near" the nominal temperature.

[25] The Cold Cranking Test is not included in the list of Reference Performance Tests, because it will not routinely be performed at the intervals specified in Table 9. However, it should typically be performed along with the Reference Performance Tests at each of three times over the life of a device: (1) as part of initial characterization testing, (2) about halfway through the projected life if the cell passed step 1, and (3) at the end-of-life testing, if practical.

4. ANALYSIS AND REPORTING OF TEST RESULTS

4.1 General

For purposes of consistency in test reporting (particularly between multiple testing organizations), a required minimum subset of information, based on the procedures and analysis defined in this manual, has been tabulated in Appendix B using the PHEV-40 Mile Battery application as an example. Corresponding data should also be reported for the other PHEV battery modes listed in Table 1, as appropriate. This is not intended to limit the reporting of other test results; the intent is rather to ensure that important test results are reported in a fashion that allows them to be compared to test results on hybrid energy storage devices performed at various locations and stages of development.

4.2 Static Capacity Test and Constant Power Discharge Test

Capacity in ampere-hours and energy in watt-hours at the specified discharge rates are reported based on manufacturer-specified discharge termination conditions. The Static Capacity Test is performed at a constant current discharge rate corresponding to the $C_1/1$ rate between $Vmax_{100}$ and $Vmin_0$, and the Constant Power Discharge Test is performed at a constant power discharge rate corresponding to a BSF-scaled 10-kW rate and/or the HPPC-Current between $Vmax_{op}$ and $Vmin_0$. (Note that the static capacity test will not generally be useable within operating conditions, and thus it does not reflect conformance to the Plug-In CS or CD Available Energy targets. However, it is still considered a useful measure of capacity at the laboratory cell stage to ensure stability and as a reference to the manufacturer's rated capacity).

Ampere-hours and watt-hours returned (and the corresponding overall charge/discharge efficiencies) may also be reported for the manufacturer-specified charge algorithm. Energy removed (watt-hours) is also reported as a function of capacity removed (expressed in percent of rated capacity). These data are used for the later calculation of CS and CD Available Energy.

4.2.1 Capacity Fade

For devices subjected to life testing, the change in constant power discharge capacity from the beginning-of-life values (measured just prior to the start of life testing) to some later point in time are to be reported periodically for each test as Capacity Fade, expressed as a percentage of the original (BOL) operating capacity between $Vmax_{op}$ and $Vmin_0$ as shown in Equation (2), where t_0 refers to RPT0 and t_1 refers to the time of the later RPT where capacity fade is to be determined.

$$Capacity\ Fade\,(\%) = 100 \times \left(1 - \frac{Capacity_{t1}}{Capacity_{t0}}\right) \tag{2}$$

4.3 Hybrid Pulse Power Characterization Test

Results from the HPPC test are generally aimed at comparing the performance of a device at a given RPT to the specified targets for PHEV-20, PHEV-40, or xEV-50 Mile application. Since these targets are expressed at the system level, most HPPC test results must be scaled using the Battery Size Factor (BSF) before such comparisons can be made (See Section 3.1.4). The BSF should be an integer value that aligns with all performance requirements and can be configured for series and/or parallel strings.

This section describes the HPPC analysis methodology using an illustrative dataset based on the PHEV-40 Mile application. The concepts and associated nomenclatures that are discussed in this analysis section have been defined in the glossary and summarized in Appendix B. Appendix B also describes how to use the HPPC test results to fill in a Gap Analysis.

4.3.1 Overall Analysis Approach

The primary purpose of the HPPC test is to periodically verify how the Peak Discharge Pulse Power, Peak Regen Pulse Power, Available Energy for CD (Charge Depleting) Mode, and Available Energy for CS (Charge Sustaining) Mode for a given test article compare to the appropriate targets identified in Table 1. To achieve this purpose, several calculations are required based on the acquired test data. At a minimum, the following data need to be captured during the HPPC test for successful comparison with the targets:

1. Temperature of the test article during the HPPC test.

2. Cumulative capacity (Ah) removed at the end of each 10% increment based on rated capacity, defined at beginning of life and fixed throughout life testing.

3. Cumulative capacity (Ah) removed at the end of each discharge pulse within the HPPC profile.

4. Measured voltages at the start and end of both the discharge and regen pulses within the HPPC profile.

5. Measured currents at the start and end of both the discharge and regen pulses within the HPPC profile.

From these data, the analysis methodology described herein can be used to determine the BSF-scaled values that are to be compared with the targets. Temperature data are useful to collect during HPPC testing, especially if the performance of the test articles is strongly affected by ambient conditions. Temperature is also a useful diagnostic tool if anomalous data are identified. The measured cumulative capacity data are related to the measured energy removed at a 10 kW rate from the Constant Power test (Section 4.2). The capacity data are also used to establish the percentage of rated capacity removed from $Vmax_{op}$. From the measured voltages and currents, pulse resistance values are calculated at each 10% increment and subsequently used to identify the corresponding pulse power capabilities. The pulse power capabilities at each 10% increment are then related to the cumulative energy removed at a 10-kW rate. Based on these results, useable energy curves are generated for both the CD and CS modes, from which the Peak Discharge Pulse Power, Peak Regen Pulse Power, Available Energy for CD (Charge Depleting) Mode, and Available Energy for CS (Charge Sustaining) Mode can be identified.

4.3.2 Pulse Resistance

From the HPPC pulse profile in Figure 1 (Section 3.4.1), resistance can be calculated using a ΔV/ΔI calculation at each 10% increment. Resistances are normally only calculated for completely unabated pulses, i.e., those with full duration and amplitude.[26] Equations 3a and 4a show the calculation for the 10-s discharge and regen pulse resistance, respectively, where the relevant time points are identified in Figure 12. Equations 3b and 4b show the corresponding discharge and regen pulse resistance calculations at 2-s. The illustrative test data described in this section is based only on the 10-s pulse resistance results, but the analysis methodology is the same when determining results based on the 2-s requirements.

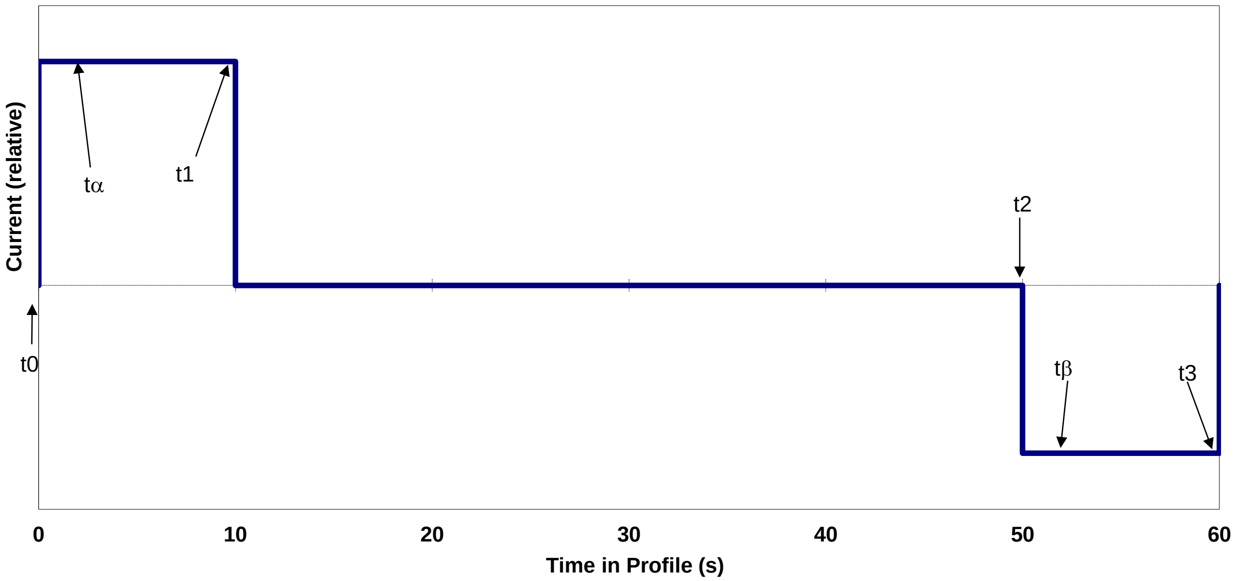

Figure 12. Resistance Calculation Time Points.

$$\mathrm{R}_{\mathrm{Discharge}}\ (10\mathrm{s}) = \frac{\Delta V_{discharge}}{\Delta I_{discharge}} = \left|\frac{V_{t1} - V_{t0}}{I_{t1} - I_{t0}}\right| \tag{3a}$$

$$\mathrm{R}_{\mathrm{Discharge}}\ (2\mathrm{s}) = \frac{\Delta V_{discharge}}{\Delta I_{discharge}} = \left|\frac{V_{t\alpha} - V_{t0}}{I_{t\alpha} - I_{t0}}\right| \tag{3b}$$

$$\mathrm{R}_{\mathrm{Regen}}\ (10\mathrm{s}) = \frac{\Delta V_{regen}}{\Delta I_{regen}} = \left|\frac{V_{t3} - V_{t2}}{I_{t3} - I_{t2}}\right| \tag{4a}$$

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[26] The HPPC test is required to continue to Vmin_0 (or until the constant current discharge rate cannot be sustained), however some data may be acquired during pulses where current limiting was encountered. Tests conducted indicate that pulse resistances calculated using such data will be somewhat different (probably higher) than the values calculated for pulses where limiting does not occur. While this current limited data may be useful as an indication of device behavior, it should not be used for direct comparisons to the targets.

$$R_{Regen}\ (2s) = \frac{\Delta V_{regen}}{\Delta I_{regen}} = \left|\frac{V_{t\beta} - V_{t2}}{I_{t\beta} - I_{t2}}\right| \tag{4b}$$

The discharge and regen resistances can then be plotted at each 10% increment between $Vmax_{op}$ and $Vmin_0$, as shown in Figure 13 for an illustrative set of 10-s data. The calculated percentage is based on the cumulative capacity removed divided by the rated capacity provided by the manufacturer. Note that charge removal from the discharge pulse has to be included when determining the percentage of rated capacity removed for the regen condition, which is why the 10-s regen resistances are slightly shifted to the right when compared to the discharge resistance data.[27] In addition to the resistance values, open-circuit voltage (OCV) can also be plotted at each 10% increment at time point t0 (from Figure 1), which is also shown in Figure 13. The OCV between the 10% increments can then be estimated by straight-line interpolation between the relevant data points or by fitting a curve through the measured data.

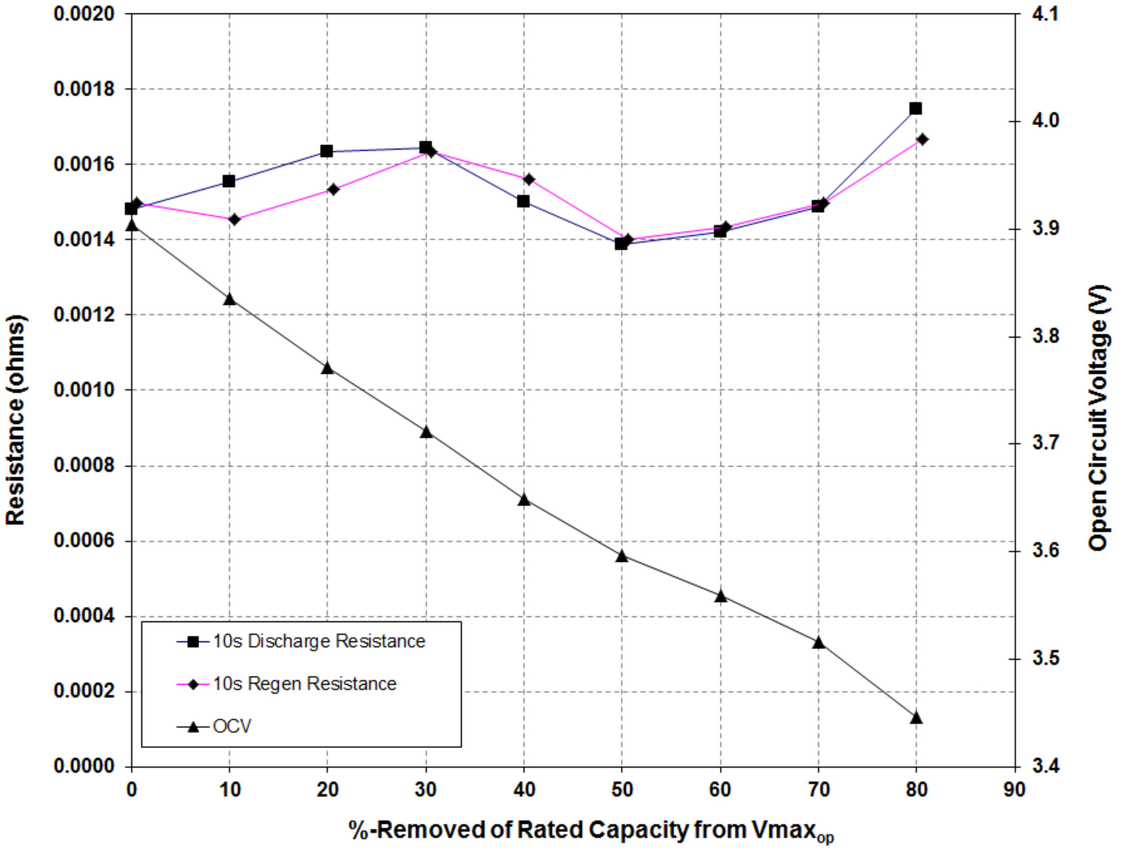

Figure 13. Open-Circuit Voltage and Pulse Resistances versus %-Capacity Removed.

4.3.3 Pulse Power Capability

The pulse resistance data are then used to calculate the pulse power capability at each 10% increment (defined at beginning of life and fixed throughout life testing), where the discharge power is relative to $Vmin_{pulse}$ and the regen power is relative to $Vmax_{pulse}$. (See Section 3.1.1 and Appendix C regarding allowable values for $Vmax_{pulse}$ and $Vmin_{pulse}$). These power capability values are used to

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[27] In this manual, plotted percentage values always represent the beginnings of their respective discharge or regen pulses.

determine the total available depth-of-discharge and energy swing that can be used (within the pulse voltage limits) for given discharge and regen power levels. Equations 5 and 6 show the pulse power capability calculation for the discharge and regen pulse, respectively. Figure 14 illustrates the resultant Pulse Power Capability curves as a function of the percent of rated capacity removed from $Vmax_{op}$.

$$\text{Discharge Pulse Power Capability} = Vmin_{pulse} \bullet (OCV_{dis} - Vmin_{pulse}) \div R_{discharge} \tag{5}$$

$$\text{Regen Pulse Power Capability} = Vmax_{pulse} \bullet (Vmax_{pulse} - OCV_{regen}) \div R_{regen}\text{ [28]} \tag{6}$$

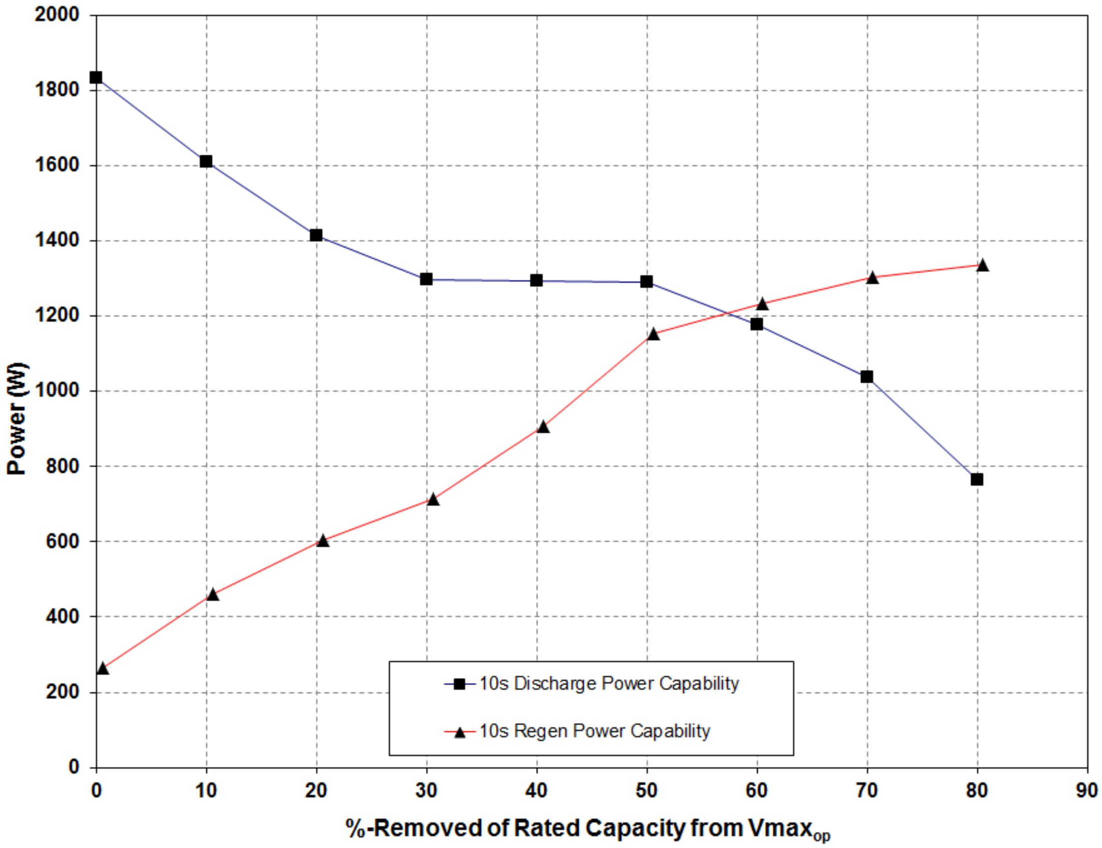

Figure 14. Pulse Power Capability versus %-Capacity Removed.

However, the pulse power capability must be related to the cumulative energy removed instead of the percent of rated capacity removed for successful comparison with the targets. The HPPC test is immediately preceded by a 10-kW constant power discharge test (Section 4.2), from which the cumulative energy removed at a 10-kW rate can be plotted against the calculated capacity removed as shown in Figure 15. Assuming that the measured capacity removed from the constant power

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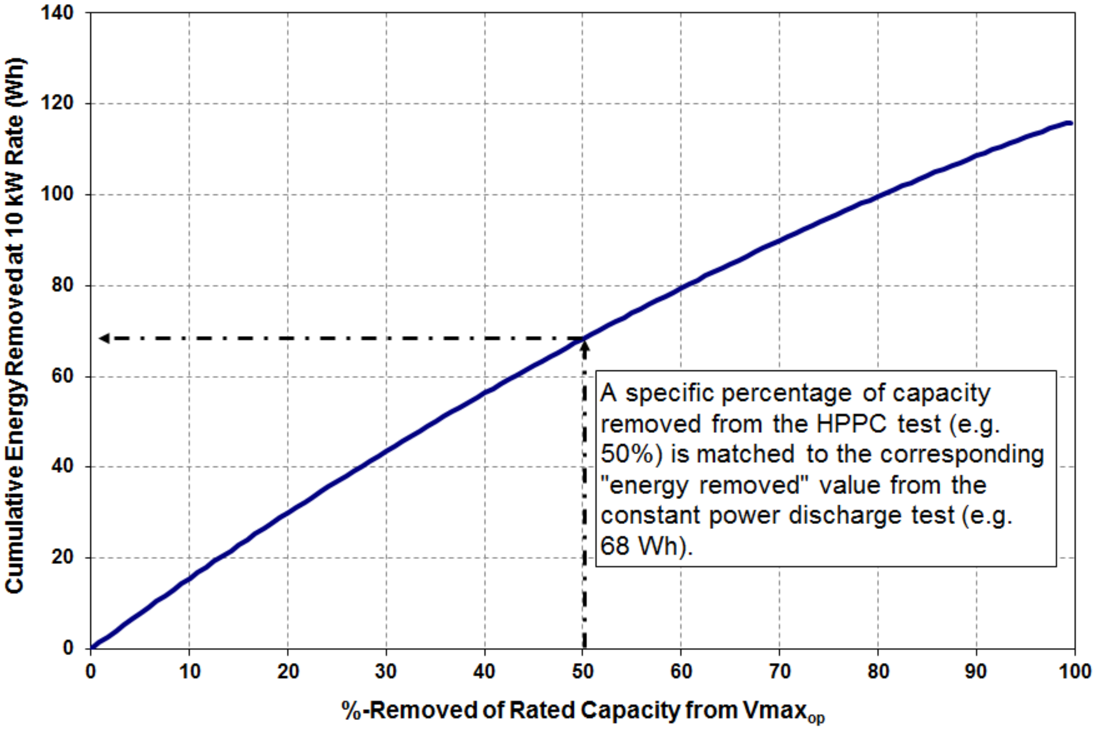
[28] Note that OCV at the start of each regen pulse must be interpolated from the OCV curve derived from the rest periods before each discharge pulse, accounting for the percentage of rated capacity removed by the discharge pulse (i.e., this is not the same OCV used for discharge calculations.) For example, if the discharge pulse starting at the 10% increment removes an additional 3% of the device capacity, the subsequent regen pulse OCV is interpolated starting at 13% of the rated capacity removed relative to $Vmax_{op}$.

discharge and the subsequent HPPC test are equivalent,[29] the cumulative capacity removed (expressed as a percentage relative to the rated capacity) from the HPPC test can be matched to the corresponding energy removed at the 10-kW rate (as indicated in Figure 15) and used to transform Figure 14 into Figure 16, where the pulse power capabilities at the cell level are now plotted as a function of cumulative energy removed.



A specific percentage of capacity removed from the HPPC test (e.g. 50%) is matched to the corresponding "energy removed" value from the constant power discharge test (e.g. 68 Wh).

Figure 15. Relationship Between Energy and %-Capacity Removed in a 10-kW Discharge.

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[29] This equivalence is not exact, because part of each 10% capacity increment removed in the HPPC test is due to the pulse profile. However, for high-power batteries the relationship is assumed to be sufficiently similar and it can be verified with the energy verification tests (Sections 3.4.3 and 3.4.4).

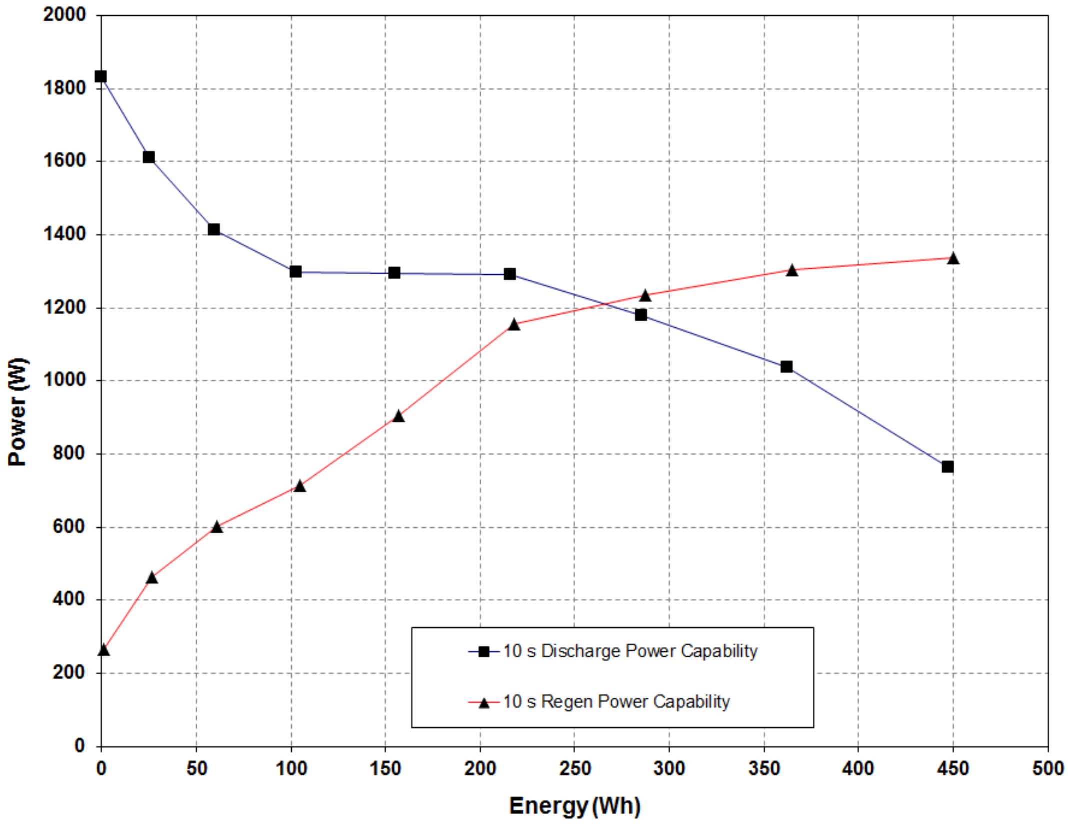

Figure 16. Unscaled HPPC Cell Power Capability vs. Energy Removed.

All calculated cell-level pulse power capability and energy removed values are then scaled by the given Battery Size Factor (BSF). To simplify the targets comparison, the regen power results should also be plotted on a secondary *y-axis* that is scaled by the ratio of required regen to discharge power, e.g., 25-kW regen and 38-kW discharge for the PHEV-40 Mile targets. Figure 17 illustrates the result of this scaling when applied to Figure 16 with an assumed BSF of 44, where the 25-kW regen target on the secondary *y-axis* is aligned with the 38-kW discharge target.

Note that the crossover point of the two power capability curves in Figure 17 is shifted in comparison to Figure 16 once the axes were scaled in proportion to the discharge and regen pulse power targets. Because of the way these pulse power values are calculated in Equations 5 and 6, changing the operating voltage limits $Vmax_{op}$ and/or $Vmin_0$ will also cause the curves to shift relative to each other. Thus the location of the useable energy range can be varied if desired by altering the operating voltage range (within the allowable voltage limits, where $Vmin_0 \geq 0.55 * Vmax_{100}$).

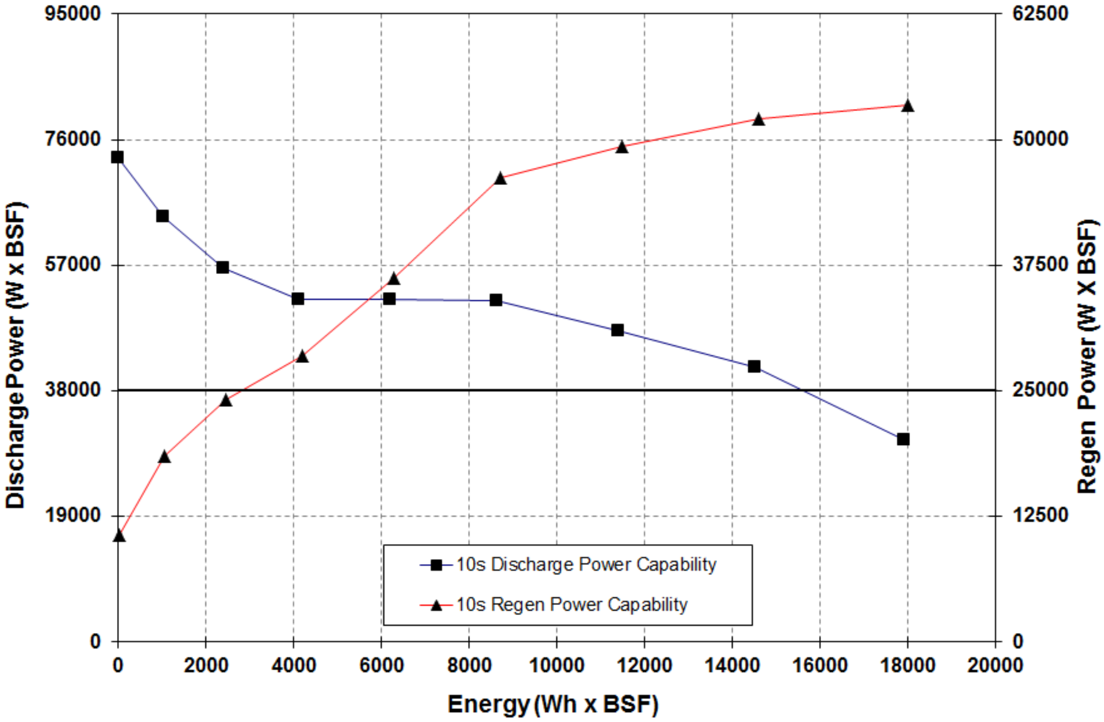

Figure 17. HPPC Power vs. HPPC-Current Discharge Energy Scaled by the Battery Size Factor.

4.3.4 Useable and Available Energies

The four primary values that must be determined from the HPPC test for comparison against respective targets are the Peak Discharge Pulse Power, Peak Regen Pulse Power, Available Energy for CD Mode (AE_{CD}) and Available Energy for CS Mode (AE_{CS}). The PHEV-40 Mile application, for example, requires 38 kW (at 10s), 25 kW (at 10s), 11.6 kWh, and 0.3 kWh, respectively, at end of life as shown in Table 1. To determine these values for a given test article, a series of calculations is required based on the data from Figure 17. First, both the Useable and Available energies for the CD and CS modes need to be defined and established.

Figure 18 illustrates the PHEV operating philosophy for Charge Depletion and Charge Sustaining modes where the targets are precisely met. Charge Depletion mode begins at the top of the operating window (set at $Vmax_{op}$), with the battery being discharged ‘in all-electric mode’ until a prescribed amount of energy has been removed. At that point, vehicle operation shifts to ‘power-assist’ mode, or Charge Sustaining (CS) mode. In this mode, the battery cycles over a narrow operating window between two limits, depicted as the dashed green and red lines, the $AE_{CS\ Limit}$ (beginning of CS mode) and the $AE_{Total\ Target}$ (end of CS mode). Note that the Charge Sustaining mode limits straddle the end point of the Charge Depletion mode target. Note also that the ‘full charge’ condition for the CD operating mode is at $Vmax_{op}$ (not $Vmax_{100}$). From Section 3.1.1, $Vmax_{100}$ corresponds to the theoretical 100% SOC level and the associated nameplate (i.e., rated) capacity. The range of operation is between $Vmax_{op}$ and $Vmin_0$ so as not to introduce degradation mechanisms that are not representative of vehicle operations. The operational usage between $Vmax_{op}$ and AE_{Total_Target} (identified by the red line in Figure 18) must provide sufficient energy to meet the targets at end of life. Note that the voltage corresponding to AE_{Total_Target} will be greater than $Vmin_0$ (i.e., full discharge) at end of life.

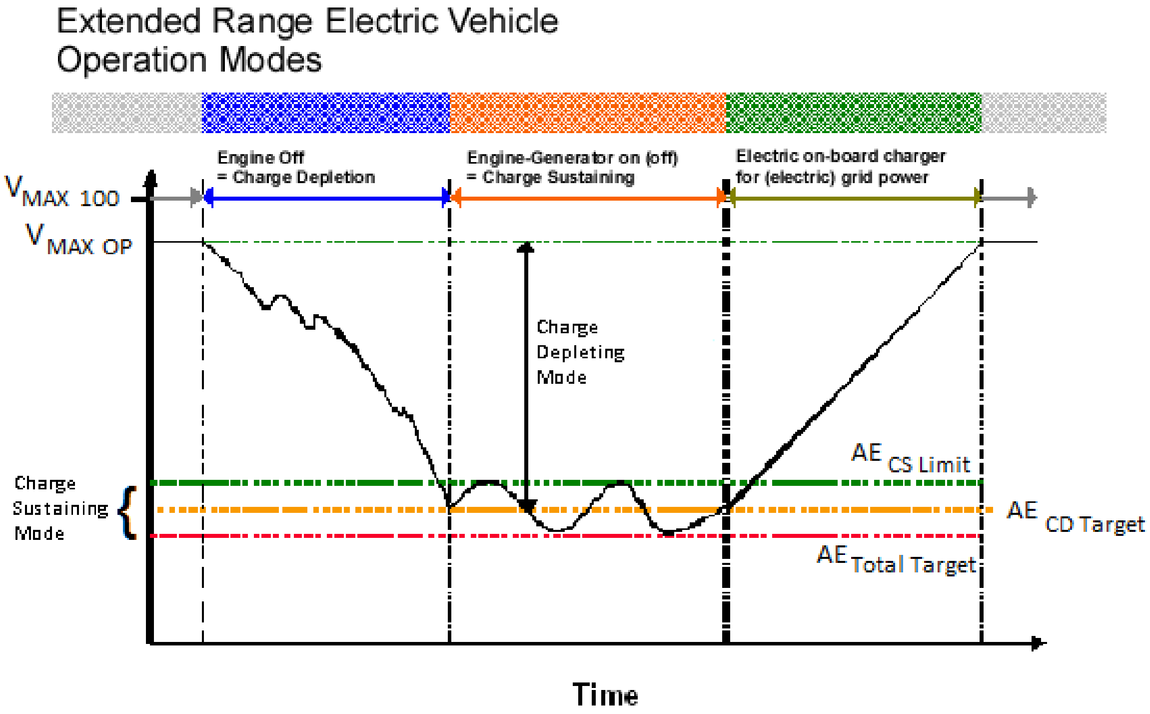

Figure 18. PHEV Operating Philosophy

Useable Energy (UE) is the total available discharge energy at the scaled 10-kW rate between the top of the operating window, or $Vmax_{op}$, and the Pulse Power Discharge curve (i.e., see Figure 17) at a given power value. It can therefore be represented by a set of horizontal lines originating at the *y-axis* and terminating at the point of intersection with the discharge curve. This point of intersection is defined as $E_{Discharge}$. Note also that the corresponding point on the regen curve is defined as E_{Regen}. The Useable Energy curve consists of two components, the charge depletion mode portion, UE_{CD}, and the charge sustaining mode portion, UE_{CS}.

Available Energy (AE) is the total available discharge energy at the scaled 10-kW rate between $Vmax_{op}$ and the Pulse Power Discharge curve evaluated at the Peak Discharge Pulse Power target~~.~~ (i.e., Available Energy is the point on the Useable Energy curve at the given target power defined in Table 1. Like Useable Energy, Available Energy consists of two components; the charge depletion mode portion, and the charge sustaining mode portion. These operating modes have their own specific energy targets for each application. The Charge Depleting Available Energy target (AE_{CD_Target}) at end of life for the PHEV-40 Mile application is 11.6 kWh, and the corresponding Charge Sustaining Available Energy target (AE_{CS_Target}) is 300 Wh. The calculated Available Energy for Charge Depleting mode (AE_{CD}) is the energy withdrawn from $Vmax_{op}$ to $E_{Discharge}$ at the power target minus half of the CS Energy Target. The calculated Available Energy for Charge Sustaining mode (AE_{CS}) is the energy required to sustain power assist operation (i.e., HEV mode) and ranges between the energy limit for CS mode, $AE_{CS\ Limit}$, and $E_{Discharge}$ at the power target.

Equations 7 and 8 define UE_{CD} and UE_{CS}, respectively, for a given power level, where $E_{Discharge}$ corresponds to the energy at the given discharge power level, AE_{CS_Target} refers to the Charge Sustaining Available Energy target, and AE_{CD_Target} is the Charge Depleting Available Energy target.

$$UE_{CD} = E_{Discharge} - \tfrac{1}{2}\, AE_{CS\_Target} \qquad (7)$$

$$UE_{CS} = E_{Discharge} - AE_{CS\ Limit} = E_{Discharge} - [AE_{CD\ Target} - ½\ AE_{CS\ Target}] \quad (8)$$

In the case where Equations 7 and 8 are evaluated at the Peak Discharge Pulse Power target (i.e., 38 kW for the PHEV-40 Mile application), UE_{CD} and UE_{CS} are equivalent to AE_{CD} and AE_{CS}, respectively, and these values are reported in the Gap Analysis as the Available Energy for CD Mode and Available Energy for CS Mode at a given point in life (see Appendix B). Figure 19 shows the illustrative Power vs. Energy curve with numerical values identified for evaluation at 38 kW discharge power target and 25 kW regen power target. From this given dataset, $E_{Discharge}$ is 15600 Wh, AE_{CD_Target} is 11.6 kWh, and AE_{CS_Target} is 300 Wh. Thus, Equations 7 and 8 are calculated as follows:

$$UE_{CD}\ (\text{at power target}) \equiv AE_{CD} = 15600\ \text{Wh} - ½\{300\ \text{Wh}\} = 15{,}450\ \text{Wh}$$

$$AE_{CS\ Limit} = [11{,}600 - ½\{300\ \text{Wh}\}] = 11{,}450\ \text{Wh}$$

$$UE_{CS}\ (\text{at power target}) \equiv AE_{CS} = 15600\ \text{Wh} - 11{,}450\ \text{Wh} = 4{,}150\ \text{Wh}$$

Because of the dual mode operation, the CD Energy can be regen limited (i.e., unable to accept complete regen at the lower end of the DOD range of operation). This portion of the CD Energy is between $Vmax_{op}$ (i.e., at 0 Wh) and E_{Regen} as indicated in Figure 19. The portion of the CD Energy that is not regen limited is between E_{Regen} and $E_{Discharge}$ minus half of the $AE_{CS\ Target}$. For example, in Figure 19, the regen limited portion of the CD energy curve is 2780 Wh and the non-regen limited portion is 12670 Wh (combining for an $AE_{CD\ (38\ kW)}$ sum total of 15450 Wh). It may be of additional value to track the regen limited portion of the CD Energy as a function of aging to gain a more comprehensive insight into the test article's capabilities. In contrast, the CS Energy must simultaneously meet the discharge and regen requirements, where AE_{CS} must be somewhere between $E_{Discharge}$ and E_{Regen}.

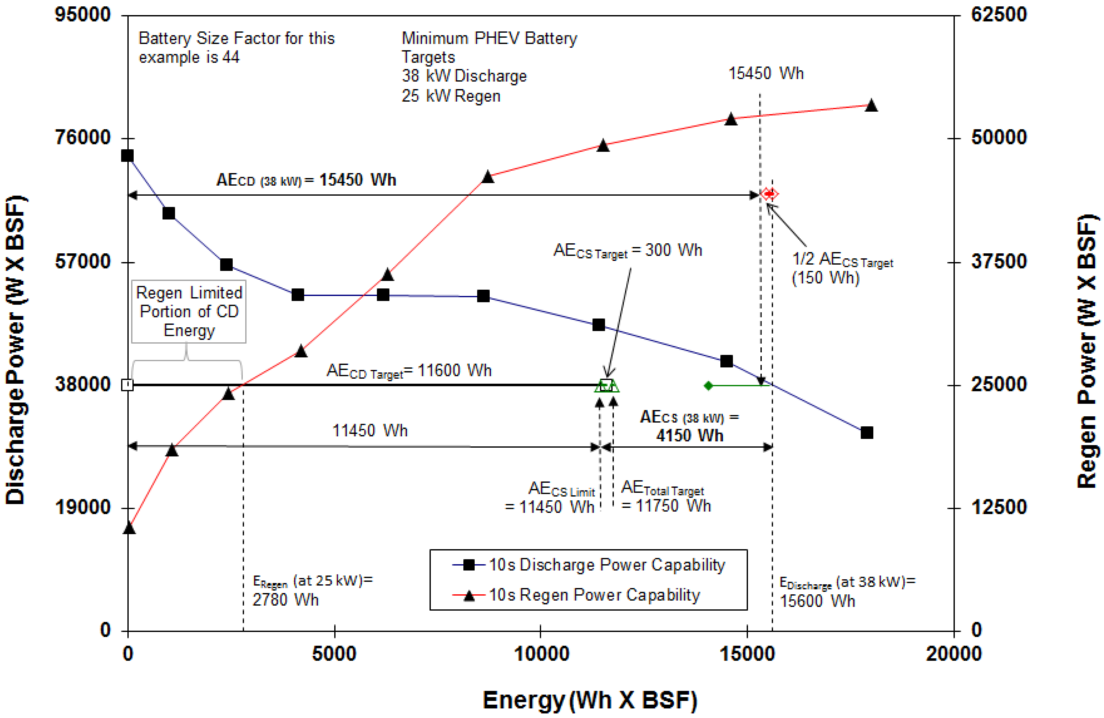

Figure 19. CS and CD Available Energy Determination.

4.3.5 Available Energy Margin

The CD and CS Available Energies at the Peak Discharge Pulse Power target reduce as a function of aging as the Useable Energy curves shift due to degradation in the power capability during calendar and/or cycle life. Once the Available Energies meet or fall below the targets, the test article has reached *end-of-life*, unless some other target criterion has already failed to be met (for example, the self-discharge rate might become unacceptably high). The energy margin is defined as the difference between the calculated Available Energy at a given point during calendar- or cycle-life aging and the corresponding target. Note that the CD and CS Available Energy margins will always be equivalent since both AE_{CD} and AE_{CS} are determined from $E_{Discharge}$. Consequently, the available energy margin can be calculated in one of two ways, as are defined in Equations 8 and 9, respectively, and illustrated in Figure 20. Thus, for a given AE_{CD} of 15,450 Wh and an AE_{CS} of 4,150 Wh, the resulting Available Energy margin for both cases is 3,850 Wh.

$$AE_{CD}\text{ margin} = [AE_{CD} - AE_{CD\text{ Target}}] \qquad (9)$$

$$AE_{CD}\text{ margin} = [15{,}450\text{ Wh} - 11{,}600\text{Wh}] = 3{,}850\text{ Wh}$$

$$AE_{CS}\text{ margin} = [AE_{CS} - AE_{CS\text{ Target}}] \qquad (10)$$

$$AE_{CS}\text{ margin} = [4{,}150\text{ Wh} - 300\text{ Wh}] = 3{,}850\text{ Wh}$$

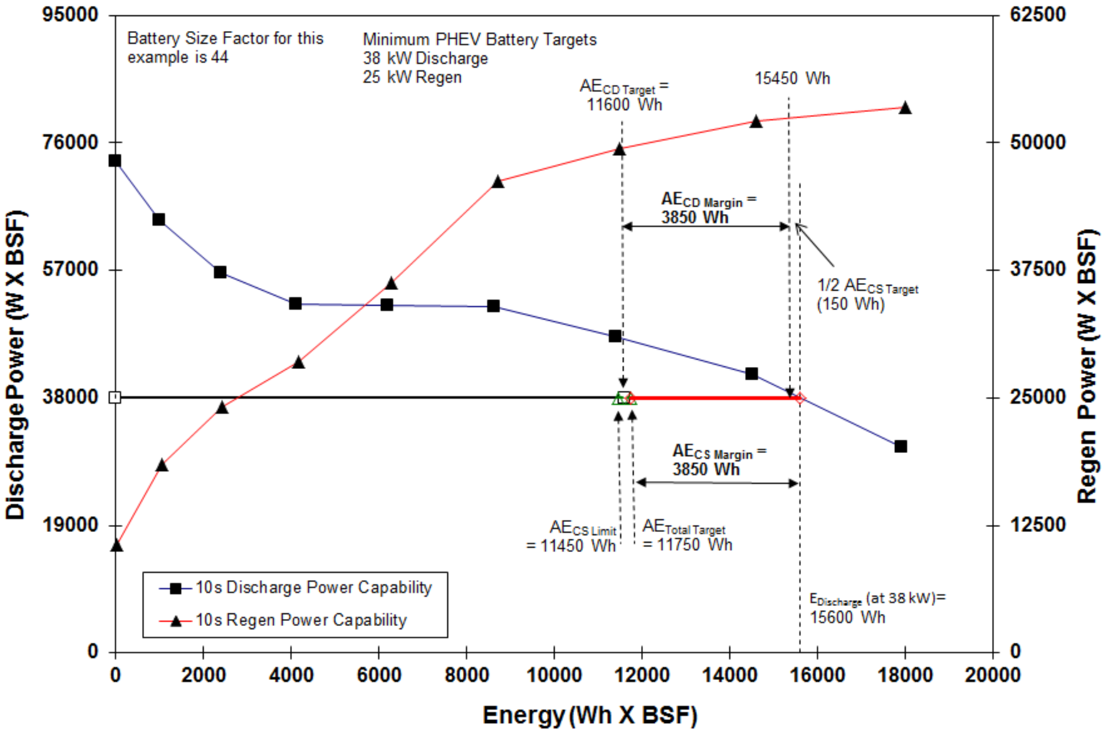

Figure 20. Charge-Depleting and Sustaining Useable Energy Margin Determination.

Figure 21 shows the shift in the Peak Discharge Pulse Power and Peak Regen Pulse Power curves at beginning-of-life (BOL) and at end-of-life (EOL) due to aging and the corresponding effect on energy margins, which are zero (by definition) at end-of-life.[30] Since the CD and CS Useable Energies are linked together, as the CS energy margin approaches zero (illustrated on Figure 21), the CD energy margin will also approach zero. This is one possible end-of-life condition.

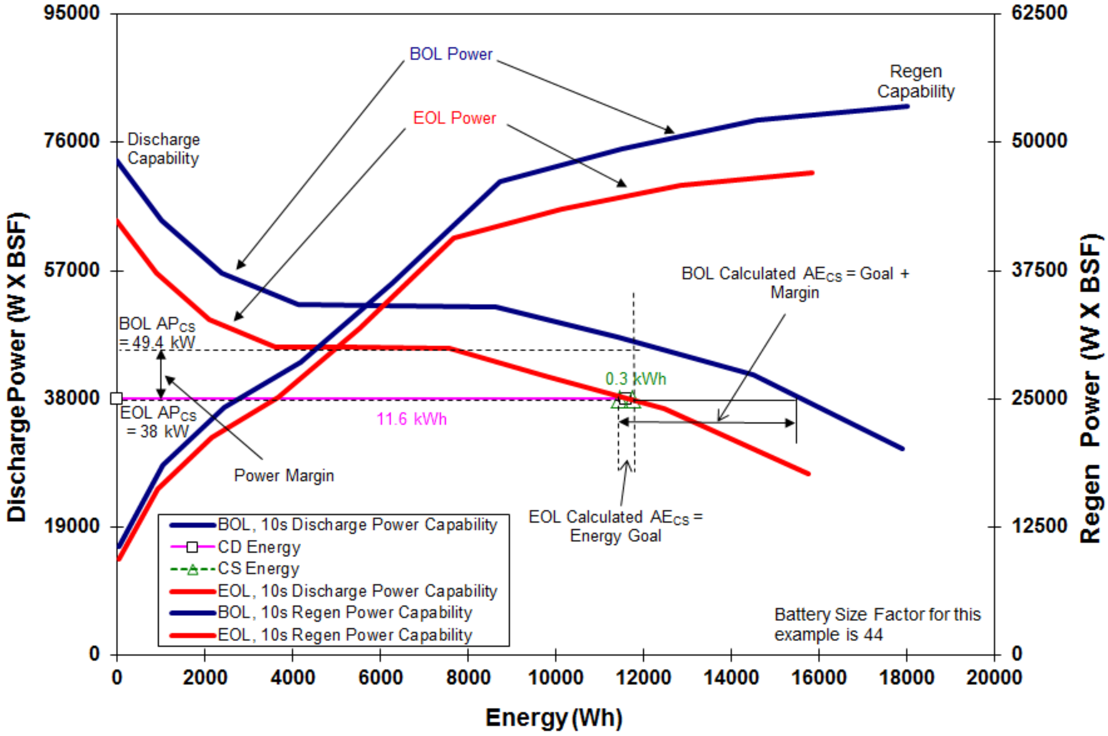

Figure 21. CD and CS Available Energy and Power Margins Over Life.

4.3.6 CS Available Power

The Charge Sustaining Available Power (AP_{CS}) is the discharge power capability level at the point where $E_{Discharge}$ is exactly equal to the total Available Energy target, $AE_{Total\ Target}$, where $AE_{Total\ Target}$ is $AE_{CD\ Target}$ plus half of $AE_{CS\ Target}$. This is reported in the Gap Analysis as the Peak Discharge Pulse Power (see Appendix B). The BOL and EOL AP_{CS} are illustrated in Figure 21 above. The AP_{CS} at BOL was calculated to be 49.4 kW and (in this example case) it is precisely equal to the discharge target power of 38 kW at EOL. Power Margin (also identified in Figure 21) is the difference in discharge power capability between AP_{CS} at a given point in time during life and the Peak Discharge Pulse Power target (38 kW for a PHEV-40 Mile application). The corresponding Peak Regen Pulse Power that is reported in the Gap Analysis is the AP_{CS} scaled by the power targets (i.e., AP_{CS} x [25 kW /3 8 kW] for the PHEV-40 Mile application, or 32.5 kW for a given AP_{CS} of 49.4 kW). Note that the power targets in Table 1 are specified for the CS mode only, so there is no available power value for the CD mode.

The Charge-Sustaining Available Power, Charge-Sustaining Available Energy and Charge-Depleting Available Energy represent complementary aspects in the performance of a test article at a given

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[30] These end-of-life data are theoretical; in practice, test data are seldom available *exactly* at the point in life where power and energy margins are zero because reference tests are performed only at periodic intervals. Thus this point normally occurs between two sets of reference tests. See Section 4.9 regarding the implications of this behavior on reported life.

point in time during life aging. These values can be graphically represented in a Useable Energy vs. Power curve as shown in Figure 22. The corresponding targets of the PHEV 40-Mile application are also identified with solid black lines to clearly identify the location of each relevant parameter on the useable energy curves that is reported in the Gap Analysis (see Appendix B).

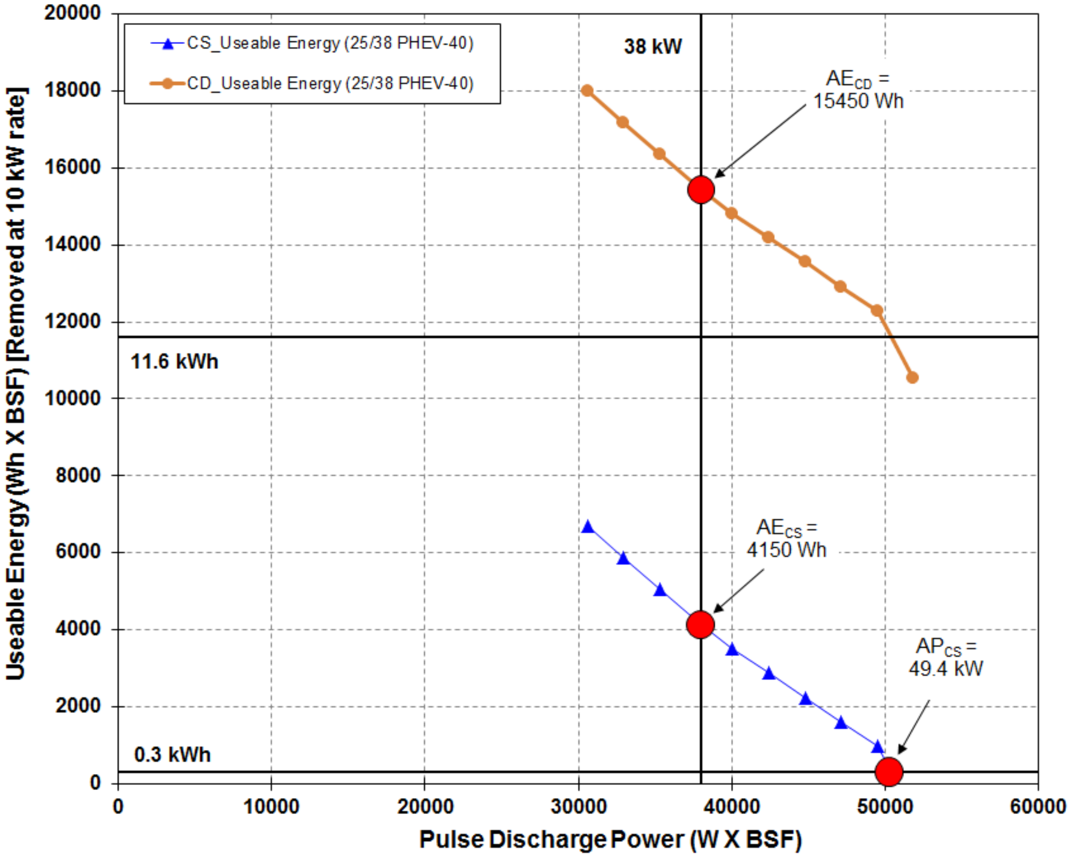

Figure 22. Useable Energy versus Power Curve

4.3.7 Power and Energy Fade

For devices subjected to life testing, the change in CS Available Power and CS and CD Available Energy from the beginning-of-life values (measured just prior to the start of life testing) to some later point in time are to be reported periodically as Power Fade and Energy Fade, both expressed as percentages of the original (BOL) values as shown in Equations 11 and 12.

$$Power\ Fade\ (\%) = 100 \times \left(1 - \frac{Available\ Power_{t1}}{Available\ Power_{t0}}\right) \tag{11}$$

$$Energy\ Fade\ (\%) = 100 \times \left(1 - \frac{Available\ Energy_{t1}}{Available\ Energy_{t0}}\right) \tag{12}$$

In both cases, *t0* refers to the Reference Performance Test conducted immediately prior to the start of life aging (i.e., RPT0) and *t1* refers to the time of the later RPT where power and energy fade are to be determined.

4.3.8 Minimum and Maximum Capacities Removed and Cold Crank Condition

Some characterization tests (e.g., the energy verification tests in Sections 3.4.3 and 3.4.4) require knowledge of the minimum and maximum capacities removed at which the corresponding power targets are exactly met (Ah_{MIN} and Ah_{MAX}, respectively), where Ah_{MIN} is located at E_{Regen} and Ah_{MAX} is located at $E_{Discharge}$ at the power target. A BSF-scaled representation of Figure 14 is shown in Figure 23, where the power capability curves are plotted as a function of the percent of rated capacity removed from $Vmax_{op}$ instead of cumulative energy removed. As shown, Ah_{MAX} is determined from the Peak Discharge Pulse Power target (e.g., 38 kW), which is approximately 74% of the rated capacity removed (e.g., for a 2 Ah cell, 1.48 Ah are removed). Likewise, Ah_{MIN} is approximately 24% of rated capacity removed (e.g., for a 2 Ah cell, 0.48 Ah are removed). Note that the location for Ah_{MIN} and Ah_{MAX} are typically fixed at BOL but the discharge and regen power curves shift as the test article ages. The values for Ah_{MIN} and Ah_{MAX} can be updated at the discretion of the Program Manager.

In addition to Ah_{MIN} and Ah_{MAX}, the capacity removed prior to the cold crank test (Section 3.6) can also be established from these data. Starting from full charge relative to $Vmax_{op}$, remove the amount of rated capacity equivalent to the Available Energy Target for the Charge-Depleting mode plus half the Available Energy for the Charge-Sustaining Mode from Table 1 at the 10 kW rate (e.g., 11.6 kWh + 150 Wh for the PHEV-40 Mile Battery Application). This is accomplished using the methodology discussed in Section 4.3.3 and Figure 15. The resulting capacity removed should be somewhere between Ah_{MIN} and Ah_{MAX}, as illustrated in Figure 23 with the dashed green line. In this example case, the cold crank test should be performed at 61% of rated capacity removed (e.g., for a 2 Ah cell, 1.22 Ah are removed). The cold crank test condition is typically fixed at BOL but can shift as a function of aging. The cold crank test condition can be updated at the discretion of the Program Manager. Note that when the cold crank test condition exceeds Ah_{MAX}, the test article can no longer successfully perform a cold crank test and has reached end of life.

4.3.9 Two-Second Discharge Target Verification

The 2-second discharge performance can also be verified by using the voltages and currents from the same HPPC discharge pulses, but after 2 seconds into the pulse instead of the 10-second values, as shown in Figure 12 and Equations 3b and 4b. The rest of the analysis is the same as previously discussed.

4.3.10 Other Laboratory Cell Performance Characteristics

Other laboratory cell performance characteristics can be calculated from the HPPC data to permit scale-up calculations to full-size cells and/or observe unique features in the specific cell chemistry. These include some or all of the following:

- Voltage response time constant estimates for discharge, regen, and rest periods derived from the current-driven HPPC Test data
- Ohmic and polarization resistances derived from lumped parameter equivalent circuit models

- Cell capacity and energy in area-specific, gravimetric, and volumetric units (mAh/cm^2, mWh/cm^2, Ah/kg, Wh/kg, Ah/liter, Wh/liter)

- Cell area-specific impedance in ohms-cm^2 for discharge and for regen from HPPC data. (Note: this requires specific knowledge of the active surface area of the cells).

The data acquired from HPPC cell testing are ultimately used for modeling cell characteristics and for the selection and design of full-size module and battery pack characteristics.

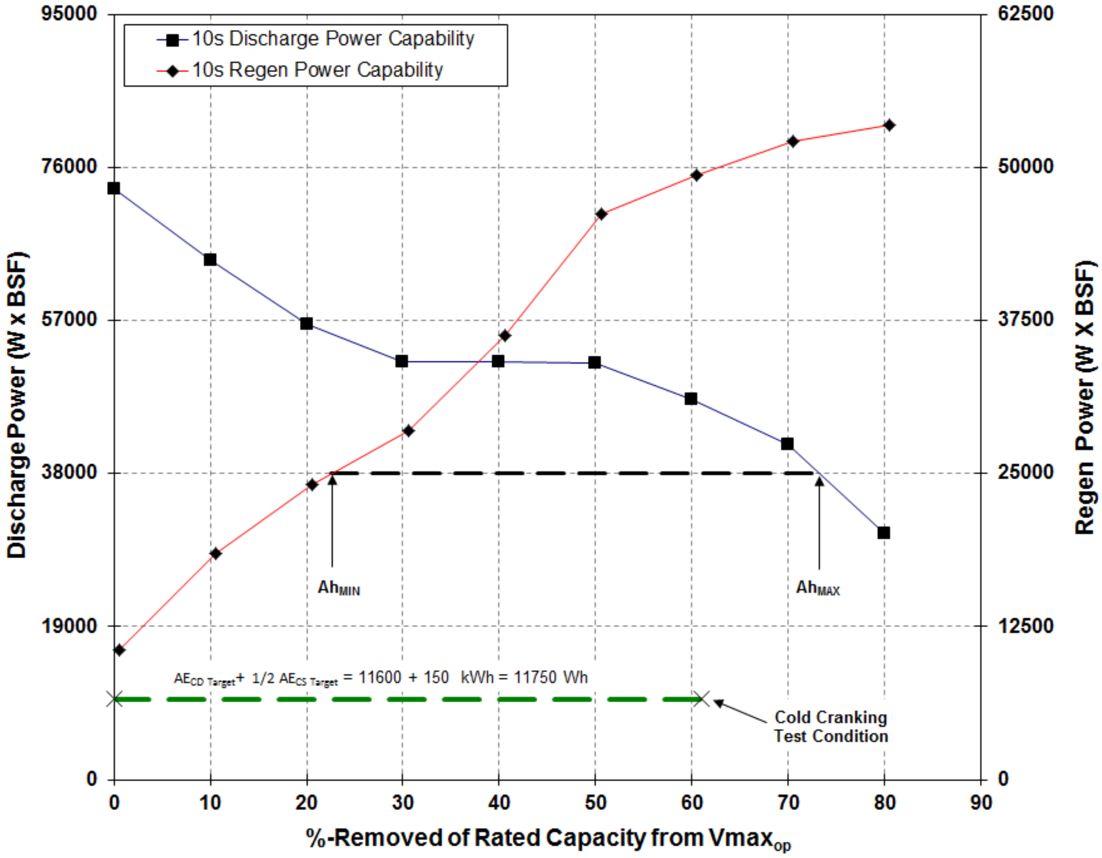

Figure 23. Minimum and Maximum Capacities Removed and Cold Crank Condition

4.3.11 Determining Battery Size Factor When Not Supplied By Manufacturer

If the device manufacturer is unable to supply a BSF, or if the provided BSF needs to be verified prior to life testing, an initial Low-Current HPPC test can be performed to establish the BSF. The discharge current between pulses (i.e., for the 10% increments) is at the C_1-rate and the magnitude of the discharge pulse is based on a $5C_1/1$ current. These conditions are used to approximate the HPPC-Current (I_{HPPC}) since it cannot be determined without a BSF. Additionally, the HPPC test is preceded by a constant current discharge at a C_1-rate to establish the relationship between capacity removed and cumulative energy removed (Figure 15). Once a BSF is determined using the methodology described herein, it should be validated by repeating the HPPC test using the HPPC-Current. If the results do not provide sufficient energy or power margin, a new BSF will need to be determined and validated. The BSF should typically provide at least a 20% AE_{CD} margin and 30% AP_{CS} margin at

BOL, though other ranges could be specified by a manufacturer if needed with approval from the technical program manager. If the validation testing supports the recommended BSF, then that value should be used for all future life testing of the test articles. A single typical or average value can be used for testing a group of identical devices.

Several steps are required to establish the BSF.[31] First, the unscaled power vs. energy curve is used to find the total Useable Energy of the individual test article. Figure 24 shows the illustrative power vs. energy curve, with the addition of a regen pulse power capability curve that is scaled by the power targets ratio of 25 kW to 38 kW (the green curve). As defined in Section 4.3.4, the total Useable Energy is the difference between $Vmax_{op}$ and $E_{Discharge}$ at various power levels as indicated by the horizontal lines. The resulting Useable Energy curve is shown in Figure 25 by the dashed green line with solid triangles.

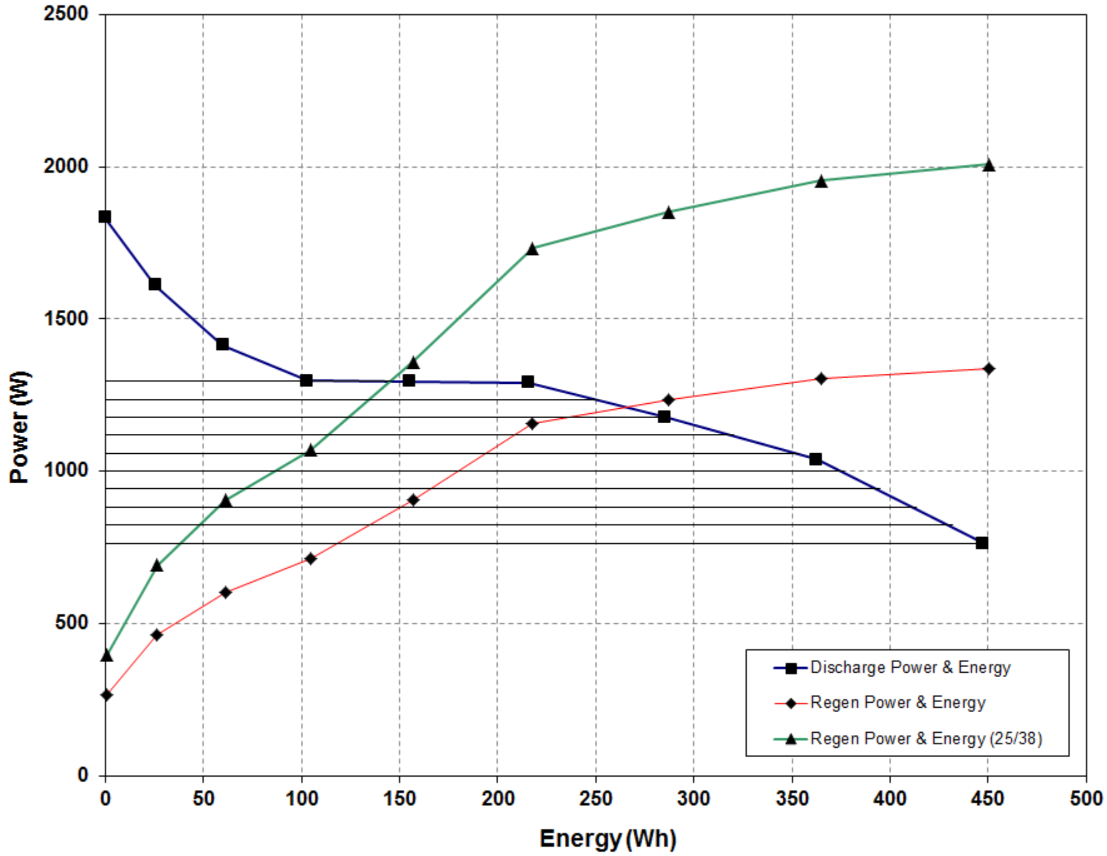

Figure 24. Finding the Useable Energy Using Device-Level Results.

Second, on the useable energy curve, draw a line from the origin having a slope equal to the ratio of the CD Available Energy target (i.e., 11.6 kWh) to the Peak Discharge Pulse Power target (i.e., 38 kW). This ratio is then multiplied by a factor of 1.2 to provide a 20% energy margin. For the PHEV 40-Mile application, the resulting slope of this line is 0.366; this is shown in Figure 25 with the solid green line. Next, determine the point at which this line intersects with the useable energy curve; this corresponds to 371 Wh of energy and 1012 W of power in Figure 25. A scaling factor is then calculated by dividing the numerator of the slope (i.e., 1.2 x 11.6 kWh) with the energy at the

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[31] This process is most accurately done using a spreadsheet with a macro. However, it is described graphically here for an understanding of the calculation method, and the graphical result may be accurate enough if done carefully.

intersection point; this corresponds to 13920 Wh / 371 Wh = 37.5. Note that the same value can be determined by dividing the Peak Discharge Pulse Power target with the power at the intersection point (38000 W / 1012 W = 37.5). This scaling factor is an estimate of the true scaling factor since it assumed only a CD mode, whereas the scaled useable energy must also account for the CS mode, half of which extends beyond the CD target (see Section 4.3.4).

If the Useable Energy curve does not intersect with the goals ratio slope, draw a horizontal line from the maximum Useable Energy curve value to the *y-axis* to identify the intersection point of the goals ratio slope. If this step is necessary, then the test article likely does not provide sufficient energy for the PHEV application and the technical program manager should be notified.

Third, to establish the actual BSF for the CD operating mode, take the useable energy curve in Figure 25 and add one-half of the CS Available Energy Target using the estimated scaling factor (i.e., the original useable energy curve is shifted by adding a factor of [½ x 300 Wh] / 37.5 = 4 Wh in this case). Figure 25 shows the adjusted useable energy curve with the dashed purple line with solid diamonds. Now, draw a line from the origin having a slope equal to the ratio of the CD Available Energy target plus one-half of the CS Available Energy Target (i.e., 11,600 Wh + 150 Wh = 11,750 Wh) to the Peak Discharge Pulse Power target (i.e., 38 kW). This ratio is then multiplied by a factor of 1.2 to provide a 20% energy margin. For the PHEV 40-Mile application, the resulting slope of this line is 0.371; this is shown in Figure 25 with the solid purple line. Determine the point at which this line intersects with the adjusted useable energy curve; this corresponds to 375 Wh of energy and 1012 W of power in Figure 25. The CD BSF is then calculated by dividing the numerator of the slope (i.e., 1.2 x 11,750 Wh) with the energy at the intersection point; this corresponds to 14100 Wh / 375 Wh = 37.6. For testing purposes, this BSF should be rounded to the next highest integer (i.e., BSF_{CD} = 38).

Fourth, now that the CD BSF has been established, the 30% available power margin for the CS operating mode must be established. The CS useable energy is determined by taking the total useable energy curve (i.e., the dashed green line with solid triangles in Figure 25) and subtracting the Available Energy Target minus one-half of the CS Available Energy Target and scaling by BSF_{CD} (i.e., 11,600 Wh - 150 Wh = 11,450 Wh / 38 = 301.3 Wh). The resulting CS useable energy curve is also shown in Figure 25 with the dashed blue line and solid circles. Draw a line from the origin having a slope equal to the ratio of the CS Available Energy target (i.e., 300 Wh) to the Peak Discharge Pulse Power target scaled by 1.3 to account for the 30% power margin at BOL (i.e., 38 kW x 1.3 = 49.4 kW). The resulting slope of this line is 0.006; this is shown in Figure 25 with the solid blue line. Determine the point at which this line intersects with the CS useable energy curve; this corresponds to 6.9 Wh of energy and 1136 W of power in Figure 25. The CS BSF is then calculated by dividing the CS energy target with the energy at the intersection point; this corresponds to 300 Wh / 6.9 Wh = 43.5. For testing purposes, this BSF should be rounded to the next highest integer (i.e., BSF_{CS} = 44). In practice, the larger BSF between the CS and CD modes should be used for life testing. In this illustrative case, a BSF of 44 is used to repeat the HPPC based on the HPPC-Current defined in Section 3.1.4. This is an example illustration, in other cases, the BSF_{CD} is the higher value.

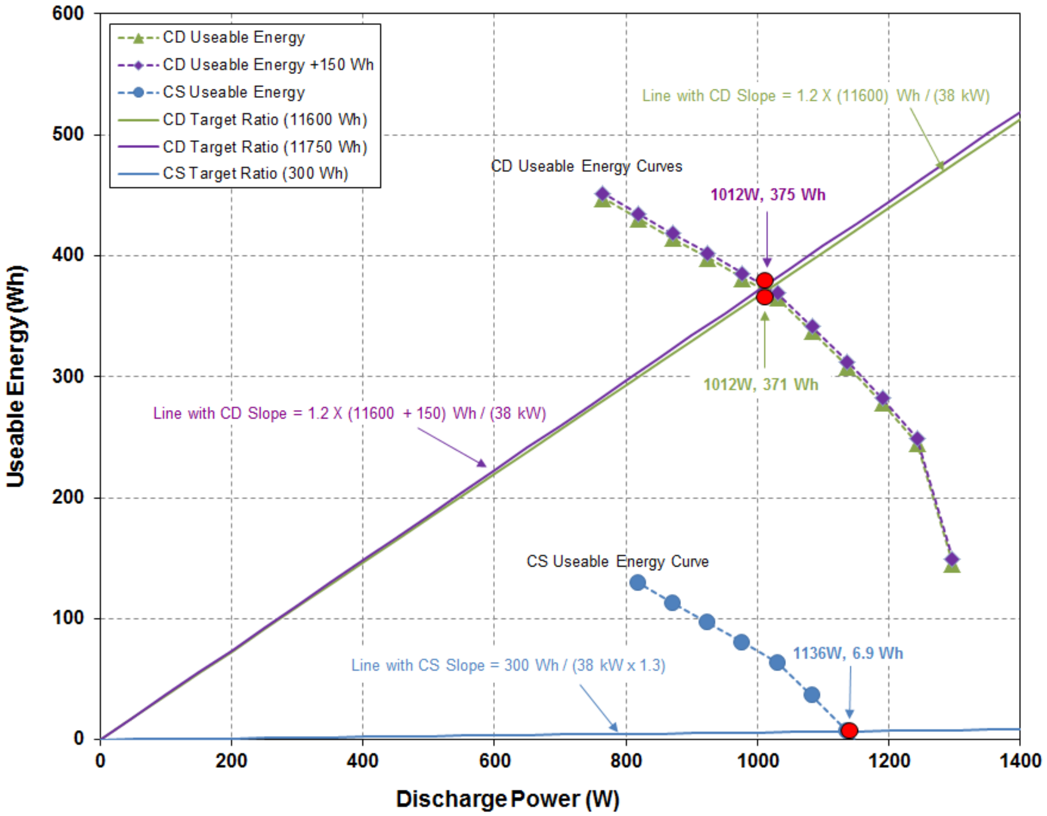

Figure 25. Finding a Battery Size Factor Using Device-Level Results.

4.4 Self-Discharge Test

Self-discharge rate is determined over a fixed period (nominally 7 days) at one or more intermediate test conditions that typically correspond to life testing conditions and/or $Vmax_{op}$. The difference between the energy (watt-hours) measured prior to the test and during the test is considered to be the energy loss reflecting self-discharge during the stand period. This energy loss is computed as the difference between the pretest HPPC-Current energy and the sum of the energies in the partial HPPC-Current discharges before and after the stand period. This value is then divided by the length of the stand period in days and multiplied by the appropriate Battery Size Factor for the applicable mode, as shown in Equation 13. Wh_{total} is the total energy available to be removed at top of charge as measured from the pretest. Wh_{part1} is the amount of energy removed from the cell to reach the initial target test condition for the self-discharge test, Wh_{part2} is amount of energy removed after completion of the self-discharge stand period.

$$\text{Self Discharge per month (\%)} = \frac{Wh_{\text{total}} - (Wh_{\text{part 1}} + Wh_{\text{part 2}})}{\text{Stand Time in Days x } Wh_{\text{total}}} \times BSF x 30 x 100 \qquad (13)$$

The result of this calculation is reported for comparison with the target of less than 1%/month.

4.5 Cold Cranking Test

The fundamental result of the Cold Cranking Test is the power capability at the end of any of the three 2-s pulses at -30°C, which is to be multiplied by the Battery Size Factor and compared to the target of 7 kW. The actual power achieved does not necessarily represent the maximum power capability; it merely shows whether the device was able to meet the target. (Some batteries may be capable of higher power than this). The maximum power capability may be calculated in a manner analogous to the normal pulse-power capability results, as follows:

1. Calculate discharge pulse resistance values using the voltage and current values at three pairs of time points [(t0, t1), (t2, t3), and (t4, t5), illustrated in Figure 26], using the same $\Delta V/\Delta I$ calculation (Equation 3b) used for discharge resistance in Section 4.3.2.

2. Calculate the discharge pulse power capability for each of the Cold Cranking Test pulses using Equation (5) as in Section 4.3.3. The current limitations must also be observed here. If the manufacturer specifies a minimum discharge voltage specifically for cold cranking, this voltage must be used for the calculation in place of the normal Minimum Discharge Voltage.

3. Multiply each of these three pulse power capability values by the Battery Size Factor and report the resulting power values for comparison with the target of 7 kW. The power achieved on the third pulse is typically reported in a Gap Analysis.

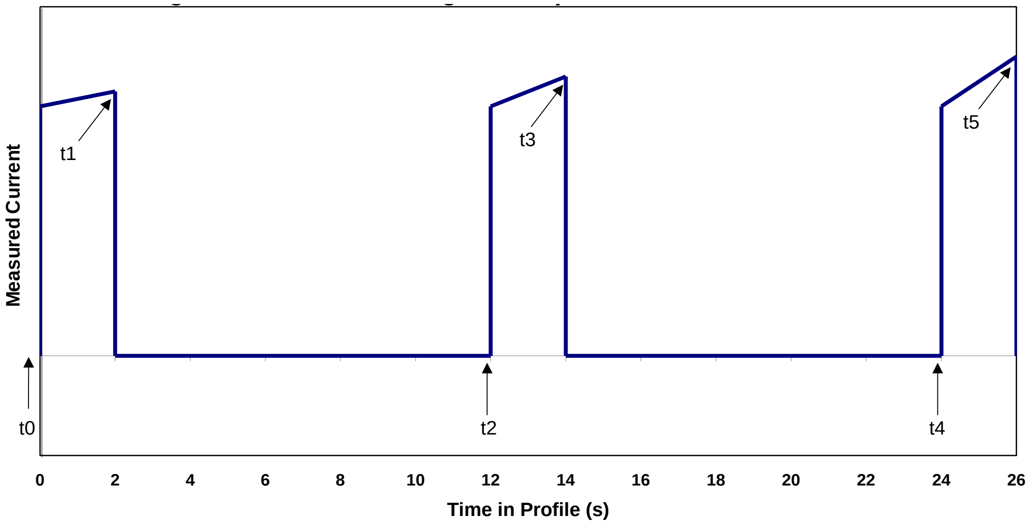

Figure 26. Cold Cranking Test Resistance Calculation Points.

4.6 Thermal Performance Tests

Measured capacity is reported over the range of temperatures at which the Constant Power Test is performed. Results of HPPC Testing at temperatures other than nominal are reported in the same formats defined in Section 4.3 except that the test temperature must accompany all data and graphs.

4.7 Energy Efficiency Test

Round trip energy efficiency is calculated from a select number of sequential test profiles of the Efficiency Test. The preferred approach is to use a group of 10 or more consecutive test profiles, both to reduce the impact of small profile-to-profile variations and to minimize numerical round-off effects. The calculation is performed as follows:

1. From an examination of the Efficiency Test data, choose a group of consecutive test profiles where the average SOC (as implied by temperature and peak voltage behavior) is relatively stable, normally at the end of the cycling period. The amount of time to reach this condition varies but will commonly be an hour or more after the start of cycling.

2. Integrate both the current and power for the discharge and regen intervals of these profiles (separately). Verify that the discharge ampere-hours and the regen ampere-hours are equal (within 1% or less). If this condition is not satisfied, either (a) cycling conditions were not sufficiently stable or (b) the cell is not 100±1% coulombically efficient at the cycling conditions. In the first case, the test must be repeated using additional test profiles as an OSPS test. In the second case, if a review of the data indicates that voltage and temperature conditions were stable, the results are reported but the charge imbalance must be noted.

3. Calculate round-trip efficiency as the ratio of discharge energy removed to regen energy returned during the profiles, expressed in percent as shown in Equation (14).

$$\text{Round - trip efficiency} = \frac{\text{watt} \cdot \text{hours (discharge)}}{\text{watt} \cdot \text{hours (regen)}} \times 100 \ \ (\%) \tag{14}$$

Round-trip efficiency may also be calculated if desired over a longer period of time (e.g., during life cycling) using any integral number of repeated test profiles for which the state-of-charge is stable, e.g., an entire block of several thousand profiles may be used instead of a small group.[32]

4.8 Operating Set Point Stability Test

No results are reported specifically from this test. The current, voltage, and residual capacity data are reviewed to establish the state-of-charge and other conditions are stable (and at their target values) for continuous cycle life testing, but otherwise this test is generally treated as part of cycle life testing.

4.9 Cycle Life Tests

For the selected life test profile, the cumulative number of test profiles executed prior to the most recent Reference Performance Tests is reported, along with any performance changes measured by these Reference Performance Tests. If testing is terminated due to the inability of the cell to perform the programmed test profile within the voltage limits or some other end-of-test condition, this is also reported. Detailed results of the reference tests are reported over life as described under these specific tests, including the magnitude of adjustments made (if any) due to the measured temperatures being above or below the nominal temperature. In addition, degradation of capacity, pulse power

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[32] The Efficiency Test and CS Cycle Life Test profiles are identical, so the Cycle Life Test data are directly useable for efficiency calculations if cycling is done at a constant SOC.

capability, CD and CS Available Energy, and Cold Cranking Power capability as a function of life (i.e., number of test profiles performed) should be reported graphically.

The value of cycle life to be reported for a device subjected to cycle life testing is defined as the number of test profiles performed before end-of-life is reached. In general an end-of-life condition is reached when the device is no longer able to meet the targets (regardless of when testing is actually terminated). The ability to meet the targets is evaluated based on the periodic Reference Performance Tests, particularly the HPPC Test results. When the power and energy performance of the device (scaled using the Battery Size Factor) degrades to the point that there is no power and energy margin (i.e., CS or CD Available Energy is less than the target value at the target power), the device has reached end-of-life. In addition, the inability to meet any of the other technical targets (e.g., the cold cranking power, efficiency or self-discharge target) also constitutes end-of-life. The basis for the reported cycle life value (i.e., the limiting target condition) should also be reported. [33] If the cycle life based on power and energy performance is very near the target, the end-of-life point may need to be interpolated based on the change in HPPC performance from the previous reference test.

4.10 Calendar Life Test

The raw data from calendar life testing are the periodic reference performance parameter measurements for all the batteries under test. The objective of this data analysis is to estimate battery calendar life under actual usage in a specified customer environment. Typically, the environmental specification will include a cumulative distribution of expected battery temperature over its 15-year life in, for example, the 90th percentile climate among the target vehicle market regions. These temperatures will vary, and will generally be substantially lower than the elevated temperatures used for (accelerated) calendar life testing. Note that for most (> 90%) of its 15-year life, the battery will typically be in a non-operating, vehicle-parked state.

Predicting battery life is a desired outcome of testing. There are various approaches to constructing a battery life model. One is theoretical, using various physical and chemical processes that may occur in the battery, which degrade its performance. A second is fitting a curve to the data. For an advanced treatment of interpreting calendar life test results with modeling and prediction, refer to the Battery Life Estimator (BLE) manual, Reference (5).

4.11 Reference Performance Tests

Results to be reported from the periodic Reference Performance Tests are defined in the previous sections on Cycle Life and Calendar Life Tests.

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[33] Efficiency and Self-Discharge are not necessarily measured at regular intervals during life testing, so the point during life cycling where such an end-of-life condition is reached cannot always be determined with high accuracy. Typically the test results showing that the targets are not met would be reported, without attempting to interpolate an end-of-life point using two test results widely separated in time.

4.12 Module Controls Verification Tests

Testing and analysis at the module level is similar to that employed for cells. However, standard tests are not defined in this manual for module control behavior, so analysis and reporting requirements for such tests must be detailed in device-specific test plans, as needed. Typically, these may include an understanding of the logic employed for electrochemically balancing the cells within the modules, and also understanding the thermal issues.

4.13 System-Level Testing

In general, the analysis and reporting of test results for complete battery systems is conducted similarly to comparable cell tests. Additional reporting requirements (e.g., detailed cell or module performance) should be specified in a battery-specific test plan that accounts for the specific design features of such a system. Test procedures and the associated reporting requirements are not defined in this manual for system-level thermal management load testing.

5. REFERENCES

1. *USABC Electric Vehicle Battery Test Procedures Manual*, Revision 2, DOE/ID-10479, January 1996.

2. *PNGV Battery Test Manual*, Revision 3, DOE/ID-10597, February 2001.

3. *FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles*, DOE/ID-11069, October 2003.

4. *Battery Test Manual for Plug-In Hybrid Electric Vehicles*, INL/EXT-07-12536, Rev. 0, March 2008.

5. *Battery Calendar Life Estimator Manual, revision 1:Modeling and Simulation* , INL-EXT-08-15136, October 2012.

APPENDIX A - SAMPLE TEST PLAN

This appendix provides a sample test plan based on the test requirements for this PHEV Manual. It is not intended to be a thorough representation, but an example format that can be useful in developing device-specific test plans for various deliverables.

VEHICLE TECHNOLOGIES OFFICE
PHEV TEST PLAN FOR TBD CELLS

1.0 Purpose and Applicability

The intent of the tests described in this test plan is to characterize the performance of TBD articles supplied by TBD for the TBD Battery mode. This testing will benchmark the performance capability of the articles relative to the TBD targets and is under the oversight of the Department of Energy, Vehicle Technology Office. TBD articles were received from TBD and TBD of them will be subjected to testing under this plan. The articles will be subjected to the performance test procedures defined for the PHEV Program and as outlined in Section 7.0.

2.0 References

2.1 Battery Test Manual for Plug-In Hybrid Electric Vehicles, INL/EXT-07-12536, Rev 3, September 2014.

3.0 Equipment

3.1 All testing is to be performed on test channels with current and voltage capabilities adequate for the specific test procedures to be performed.

3.2 Except where specifically noted otherwise, all tests will be performed within a temperature chamber capable of controlling the chamber temperature to within ±3 °C.

4.0 Prerequisites and Pre-Test Preparation

4.1 Actual weights and open circuit voltages of the articles as delivered shall be recorded.

4.2 If possible, 1 kHz impedance measurements shall be made prior to the start of testing with the articles as received.

5.0 Article Ratings, Test Limitations and Other Test Information

5.1 Ratings

Rated Capacity:	TBD A-h (C_1/1 rate)
Application:	PHEV-TBD Mile Battery
Battery Size Factor:	TBD articles
HPPC Pulse Power Voltage Calculation Ranges:	
Vmin_0	TBD V
Vmax_{op}	TBD V
I_{HPPC}	TBD A
Chemistry:	TBD

5.2 Temperature Ratings

Operating Temperature Range:	TBD°C to TBD°C
Discharge Temperature Range:	TBD°C to TBD°C
Charge Temperature Range:	TBD°C to TBD°C
Storage Temperature Range:	TBD°C to TBD°C
Cold Cranking Temperature	TBD°C to TBD°C

5.2 Nominal Values

Nominal Capacity:	TBD A-h
Nominal Weight:	TBD kg
Nominal Volume:	TBD L

5.4 Discharge Limits

Minimum Discharge Voltage	
Continuous rates ≤ C_1/1 rate (**Vmin_0**):	TBD V
≤10 s pulse (**Vmin_{pulse}**):	TBD V
≤10 s pulse and temp ≤0°C (**Vmin_{LowT}**):	TBD V

Maximum Discharge Current:	
Continuous rates ≤ C_1/1 rate:	TBD A
≤10 second pulse:	TBD A

5.5 Charge and Regen Limits

Maximum Charge and Regen Voltage	
Continuous rates ≤ C_1/1 rate (**Vmax_{100}**):	TBD V
Continuous rates ≤ C_1/1 rate (**Vmax_{op}**):	TBD V
≤10 second pulse (**Vmax_{pulse}**):	TBD V

Maximum Charge and Regen Current:	
Continuous ≤ C_1/1 rate:	TBD A
≤10 second pulse:	TBD A

5.6 Other Test Info:

Charge Procedure: TBD

5.7 End-of-Testing Criterion:

1. Completion of a number of properly scaled life cycle test profiles adequate to meet the PHEV life cycle target (as appropriate for the technology) or scheduled testing; or
2. Inability to perform the life cycle test profile at the programmed values at the required test condition without exceeding the voltage limits; or
3. Inability to give valid data from the HPPC Reference Performance Test; or
4. Inability to meet the PHEV power and energy targets or
5. When directed by the technical program manager.

6.0 Safety Concerns and Precautions

In general the safety issues with these articles are similar to those encountered previously with other similar technology tested for the Vehicle Technologies Office. Care is warranted due to the high power capability of these articles, as noted below.

6.1 Article Handling

- TBD

6.2 Other Safety Precautions

- TBD

7.0 Tests to be Performed Under this Test Plan

The articles to be tested under this test plan will be subjected to the performance test sequence in Table 1. The percent of rated capacity removed is to be established by discharging at a rated HPPC current for a fixed period of time from full charge to $Vmax_{op}$. Unless otherwise specified, the test temperature shall be 30 ± 3 °C. These Articles will be tested in a temperature chamber.

7.1 Performance Testing

Table 1. Performance Test Sequence

Item	Sequence of Initial Performance Tests for the Articles	No. Iterations
1	**Static Capacity Test** *(See Reference 2.1, Section 3.2)* Conduct this test on TBD articles at a constant rated $C_1/1$ discharge current (TBD A) between $Vmax_{100}$ and $Vmin_0$. Note: Test is to be terminated at manufacturer-specified cutoff voltage, NOT rated capacity. * Repeat discharge until measured capacity is stable within 2% for 3 successive discharges (maximum 10 discharges).	*
2	**Constant Power Discharge Test** *(Reference 2.1, Section 3.3)* Conduct this test on TBD articles at a BSF-scaled 10-kW discharge rate. Note: Test is to be terminated at manufacturer-specified cutoff voltage, NOT rated capacity.	1
3	**Hybrid Pulse Power Characterization Test** *(Reference 2.1, Section 3.4)* Perform the Low Current HPPC test on TBD articles. The peak discharge pulse current shall be TBD A and the HPPC Current (I_{HPPC}) is TBD A. For all articles, a 10 kW discharge shall be included in the same data file as the HPPC test for calculation purposes.	1
4	**Charge Depleting Energy Verification Test** *(Reference 2.1, Section 3.4.4)* Conduct this test on TBD articles at a 10 kW discharge rate starting at $\mathbf{Vmax_{op}}$. Conduct a 10-s discharge pulse at the BSF-scaled target power level. Test is to be terminated at the appropriate energy target. The remainder of the discharge will be completed using the HPPC current to the minimum voltage ($Vmin_0$).	1

5	**Self-Discharge Test** *(Reference 2.1, Sections 3.5)* Conduct this test on TBD articles for a 7-day stand interval at TBD condition. This value is consistent with the calendar/cycle life parameters. Note: If the final measured capacity is significantly less than the pre-test value, contact the technical program manager prior to beginning life testing.	1
6	**Cold Cranking Test** *(Reference 2.1, Sections 3.6)* Conduct this test on TBD articles at -30°C. For this test plan, the cold soak time at -30°C prior to pulse testing shall be at least TBD hours.	1
7	**Thermal Performance Test** *(Reference 2.1, Sections 3.7)* Perform a 10 kW Constant-Power Discharge Test and the Low-Current HPPC Test (see Items 2 and 3 above) at 0, -10, -20 ,-30, and 52°C on TBD articles. The sequence of tests is as follows: a) 0°C, b) -10°C, c) -20°C test **only if** the 0 and -10°C tests meet or exceed the performance goals, d) -30°C test **only if** the -20°C tests meet or exceed the performance goals, e) 52°C. **Use the cold crank voltage limit (i.e., $Vmin_{LowT}$) at 0°C and below.** Recharging for these tests is to be done at 30°C ambient temperature. A soak period of nominally TBD hours or longer is required at each temperature for all tests.	1
8	**Reference Performance Tests** *(Reference 2.1, Section 3.13)* Perform the 10 kW Constant Power Discharge Test and the Low Current HPPC Test as described above. These tests should be included in the same data file for calculation purposes. At the completion of life testing, perform the required Reference Performance Test as above. * During life testing, repeat the required Reference Performance Test every 32 days.	*
9	**Cycle Life Test** *(Reference 2.1, Sections 3.10 & 3.11)* *As directed.*	
10	**Calendar Life Test** *(Reference 2.1, Sections 3.12)* *As directed.*	

8.0 Measurement and Reporting Requirements

8.1 Measurements

TBD

8.2 Data Recording Intervals

TBD

8.3 Data Access

TBD

9.0 Anticipated Results

The purpose of this testing is to compare the performance of the technology against the PHEV targets.

9.1 Testing Deliverables

Test data and results will be generated as specified in the performance and life cycle test procedures in Reference 2.1. Quarterly progress summary information will be provided to the technical program manager.

10.0 Post-Test Examination, Analysis, and Disposition

TBD

11.0 Contact Persons

TBD

APPENDIX B - GAP ANALYSIS REPORTING

This appendix summarizes the key concepts and associated nomenclature that are used in Sections 3 and 4 of this manual, and is followed by a numeric example showing how the information obtained from the HPPC tests translates to the entries that are reported in the Gap Analysis. The Gap Analysis is the standard communication tool for USABC programs and is used to measure progress at regular intervals. It also supports direct comparisons between programs and technologies and as such it is critical that data interpretation and reporting are performed in a consistent manner across developers. This illustration is not intended to be a comprehensive description of a Gap Analysis, but an example based on the 10-s power data and the energy data from an HPPC test. Additional information, including results from other characterization testing and the 2-s HPPC evaluation, should also be included in a Gap Analysis for test articles.

Figure B.1 shows a BSF-scaled Power vs. Energy curve using the same example as in Section 4.0 based on a PHEV-40 Mile Battery Application. The *x-axis* represents the cumulative energy removed at the 10-kW rate starting from the upper end of the operating window which is defined as $Vmax_{op}$. The *y-axes* represent the calculated Peak Discharge Pulse Power (on the left side) and the Peak Regen Pulse Power (on the right side) at each 10% increment between $Vmax_{op}$ and $Vmin_0$. The energy targets, $AE_{CD\ Target}$ (11.6 kWh), $AE_{CS\ Target}$ (0.3 kWh) and $AE_{Total\ Target}$ (11.75 kWh) are defined in Table 1 and labeled in Figure B1 with the green text. The measured Available Energy for the CD and CD modes (AE_{CD} and AE_{CS}, respectively) for this dataset are highlighted in the red text. The CD Energy (AE_{CD}) is 15,450 Wh and the CS Energy (AE_{CS}) is 4,150 Wh. These values are reported in a Gap Analysis as shown in Table B.1 and tracked as a function of age against the EOL targets. The corresponding energy margins for the CD and CS modes are also shown in Figure B.1 for reference.

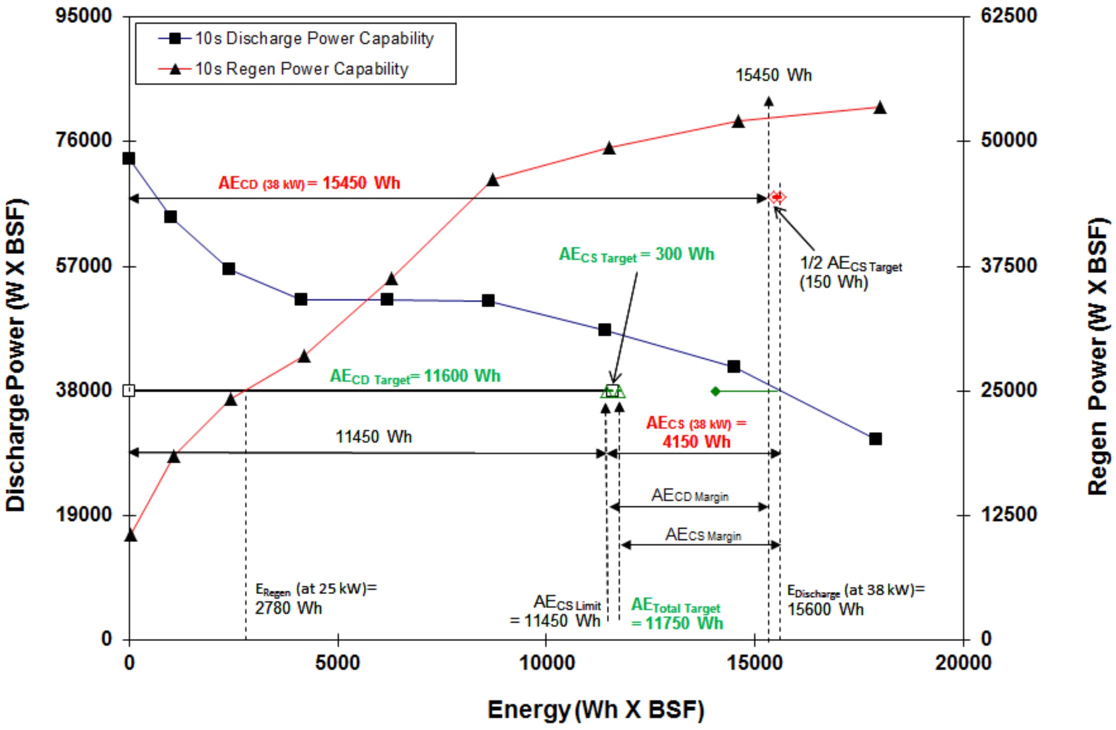


Figure B.1. Gap Analysis - Energy

To determine the Peak Discharge Pulse Power and Peak Regen Pulse Power capability of the test article, the data in Figure B.1 must be evaluated at the point where the CD and CS Available Energy targets are exactly met. Figure B.2 shows a zoomed-in view of Figure B.1 where the location of $AE_{Total\ Target}$ is found to intersect with $E_{Discharge}$ at a Peak Discharge Pulse Power of 49.4 kW. This power levels allows for a 30% power margin at BOL. The corresponding Peak Regen Pulse Power can be determined graphically as shown in Figure B.2 or it can be calculated based on regen to discharge power ratio (i.e, 25 kW / 38 kW = 0.658 * 49.4 kW = 32.5 kW). These values are reported in a Gap Analysis as shown in Table B.1 and tracked as a function of age against the EOL targets.

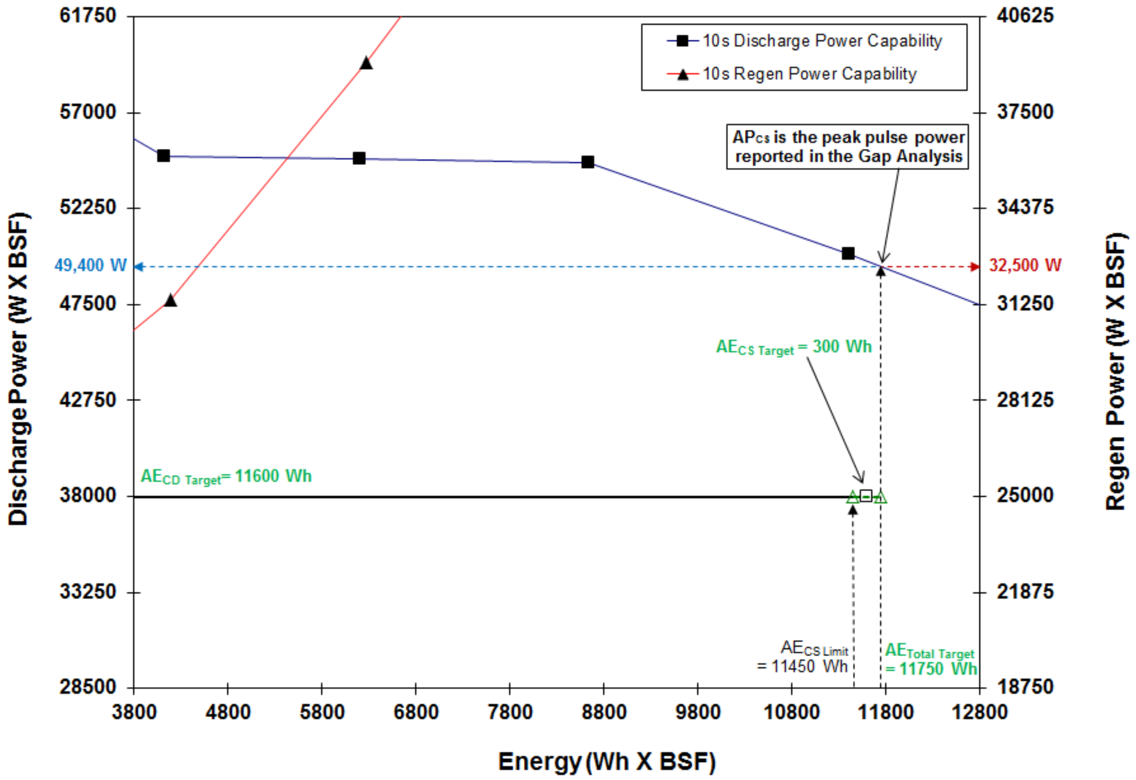


Figure B.2. Gap Analysis - Power

Alternatively, as described in Section 4.3.6, the power vs. energy curves can be translated into Useable Energy curves for evaluation. This approach requires generating a set of Useable Energies in Figure B.1 from the crossover point to the lower end of the discharge curve (on the *y-axis*) between $Vmax_{op}$ (i.e, 0 Wh) and $E_{Discharge}$ on the *x-axis*. The total Useable Energy is then separated into the CD and CS modes and plotted as a function of the discharge power as shown in Figure 22 and reproduced in Figure B.3. From these curves, the Available Energy for CD Mode, Available Energy for CS Mode, and the Peak Discharge Pulse Power values can be identified and reported in the Gap Analysis. The corresponding Peak Regen Pulse Power can then be determined by the regen to discharge power ratio based on the targets.

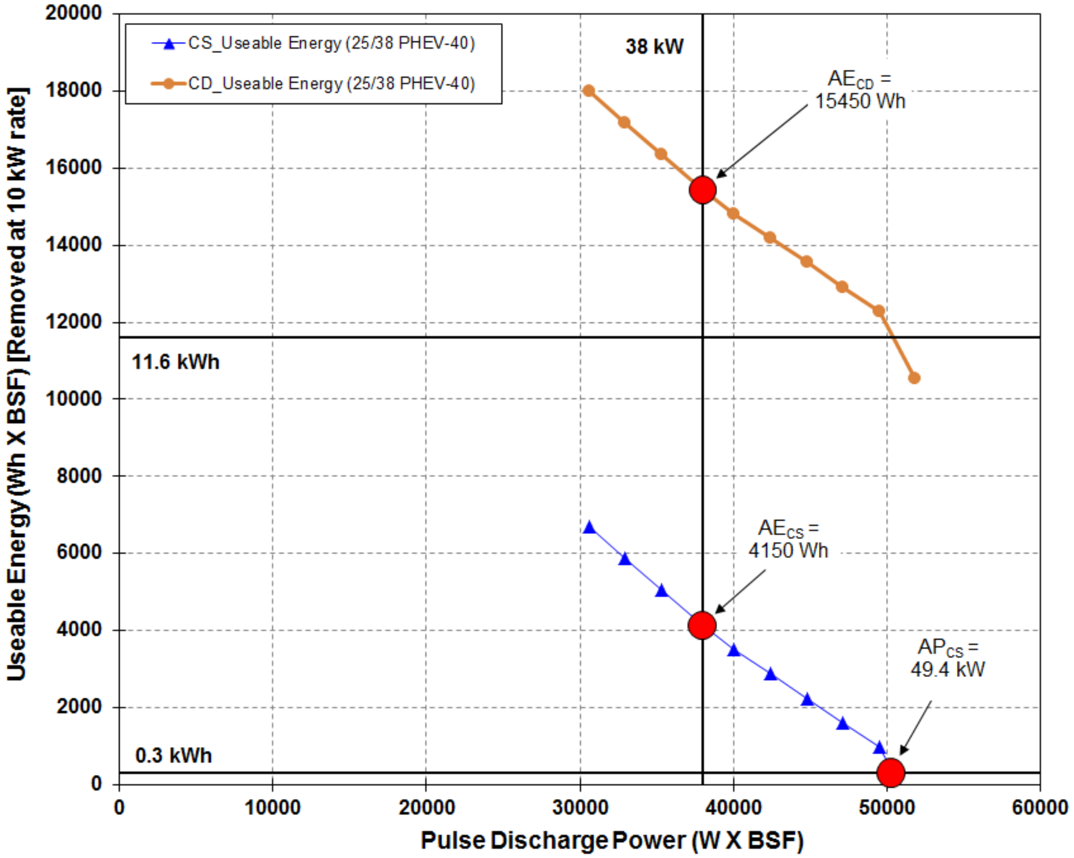


Figure B.3. Useable Energy versus Power Curve

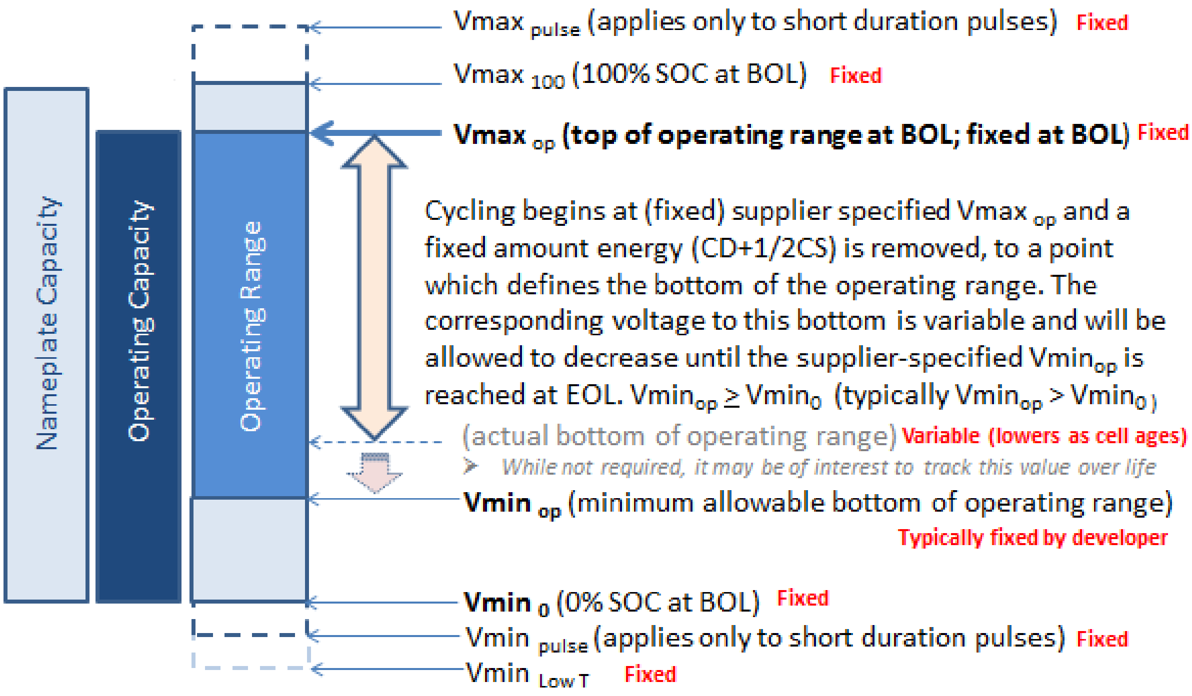
Based on these illustrative data, the Gap Analysis is shown in Table B.1. The Gap Analysis typically will include columns having the characteristics, units, targets for the given application (PHEV-40 Mile in this example), the data for a representative cell at beginning of life (often referred to as RPT0) and data for the same representative cell at its given point in life during calendar or cycle-life aging. If the test article demonstrates that a value exceeds the given target, the value is highlighted in green as shown in Table B.1. If the test article shows a value that is less than the target, but reasonably close (i.e., less than 15% of the target), the value in the Gap Analysis is then highlighted in yellow. If more than 15% of the target, then it is highlighted in red. The column with the most recent data is typically highlighted while earlier data (i.e., RPT0) is not highlighted. The Gap Analysis should be updated after each RPT and reported to the technical program manager if any metric falls below the target level.

Table B.1. Gap Analysis

Characteristics	Units	EOL Targets	PHEV-40 Mile	
			RPT0	RPT##
Peak Discharge Pulse Power (10 sec)	**kW**	**38**		49.4
Peak Regen Pulse Power (10 sec)	**kW**	**25**		32.5
Available Energy for CD Mode	**kWh**	**11.6**		15.45
Available Energy for CS Mode	**kWh**	**0.3**		4.15

APPENDIX C – VOLTAGE DEFINITIONS

This appendix provides a graphical description of the voltage limits defined in Section 3.1.1. Figure C.1 shows all of the voltage definitions and the associated range of operation. The test article is typically operated between Vmax_{op} and Vmin_{0} so as not to introduce any artificial degradation mechanisms that are not representative of vehicle operation. Pulse voltage limits on the upper and lower ends are also available (Vmax_{pulse} and Vmin_{pulse}, respectively) for short durations. Charge depleting cycle-life aging consists of a series of pulses starting from Vmax_{op} and ending after the target energy has been removed. The corresponding voltage is known as Vmin_{op} and it is a variable parameter that will generally decrease as the test article ages and the minimum value should be supplied by the manufacturer (typically, the lowest allowable voltage for Vmin_{op} is higher than Vmin_{0}). The value of Vmin_{op} can be tracked at the request of the technical program manager.



Vmax_{pulse} (applies only to short duration pulses) Fixed

Vmax_{100} (100% SOC at BOL) Fixed

Vmax_{op} (top of operating range at BOL; fixed at BOL) Fixed

Cycling begins at (fixed) supplier specified Vmax_{op} and a fixed amount energy (CD+1/2CS) is removed, to a point which defines the bottom of the operating range. The corresponding voltage to this bottom is variable and will be allowed to decrease until the supplier-specified Vmin_{op} is reached at EOL. $\mathrm{Vmin}_{op} \geq \mathrm{Vmin}_{0}$ (typically $\mathrm{Vmin}_{op} > \mathrm{Vmin}_{0}$)

(actual bottom of operating range) Variable (lowers as cell ages)

- *While not required, it may be of interest to track this value over life*

Vmin_{op} (minimum allowable bottom of operating range)
Typically fixed by developer

Vmin_{0} (0% SOC at BOL) Fixed

Vmin_{pulse} (applies only to short duration pulses) Fixed

$\mathrm{Vmin}_{Low\ T}$ Fixed

Figure C.1. Voltage Definitions and Key Concepts

APPENDIX D – DEVELOPER / NATIONAL LABORATORY DELIVERABLE CHECKLIST

The following is a list of “Best Practices” that are strongly recommended for developers and testing labs prior to shipping and upon receiving deliverables. These practices are to ensure the integrity of a deliverable and that testing can be started and conducted safely.

Developer Deliverable Checklist

The Developer shall ensure the following items have been completed prior to shipping to the National Laboratory:

- A test plan has been developed and approved by the Developer, USABC Working Group, and the testing lab (National Laboratory). The test plan must include the following items.
    - Detailed charging protocol with the following parameters:
        - Maximum taper current time (default 1 hour unless otherwise specified)
        - Constant voltage taper current cutoff (default C/20 if not otherwise specified)
        - Maximum % over the constant current charge capacity done during the constant voltage charge (default 5% if not otherwise specified)
        - Maximum allowable change in temperature above ambient during charge (default 10°C if not otherwise specified)
    - Fixture Requirements (Fixtures should replicate conditions that would be seen in the vehicle):
        - Clamping Force / Torque / Pressure
        - Fixture Drawings / Specifications / Materials if fixtures are not to be provided
        - Any other data about fixtures that could impact safety or performance.
- A cell chemical composition sheet, and chemical safety data sheet (SDS). Below is an example of a chemical composition sheet, the sheet should contain any material that is an environmental, or health and safety hazard.

Cell Chemical Composition:

Constituents*	% by weight
Anode	
Si based nano (example)	xx
Cathode	
NMC	xx
Electrolyte	
EC	xx
EMC	xx
Other solvents and additives	xx
LiPF6	xx
Total electrolyte weight	xx
Other	
RCAC Metals (Arsenic, Barium, Cadmium, Chromium, Mercury, Selenium, Lead, Silver)	Include Quantity

*please note any non-traditional constituents that might have additional handling hazards. Total electrolyte weight is needed for environmental release calculations

- Perform a Static Capacity Test as outlined in the program specific USABC testing manual within 30 days prior to shipping to the testing lab.
  - Data from static capacity shall be supplied to the testing lab.
- Collect the following data within 7 days prior to shipping to the testing lab. The data shall be relayed to the testing lab and the USABC Workgroup.
  - Open Circuit Voltage
  - AC Impedance (at 1kHz)(if available)
  - Battery weight without fixture
  - Battery weight with fixture (if fixture is provided)
- Fixtures and interface methods should be consistent with the end use automotive application.

Test Laboratory Deliverable Checklist

The testing laboratory shall ensure the following items have been completed upon receipt and prior to the start of testing of deliverables at the National Laboratory:

- A visual inspection with photo documentation shall be conducted, and it should include the following items.

  - Packaging as received, which include outer package and how the batteries are arranged in package (document any damage of abnormalities)
  - Batteries as received (document any damage of abnormalities)
  - Polarity and connection methods
  - Fixture
  - Other hardware

- Measurement of the following parameters during the receipt check in.
  - Open Circuit Voltage
  - AC Impedance (at 1kHz)
  - Battery weight without fixture
  - Battery weight with fixture (if fixture is provided)
  - Cell dimensions using the USABC guidance method.

- The testing lab will analyze the data from the developer and compare it to the data taken at the lab to identify anomalies.

- Record fixture installation parameter (torque, pressure, force, etc.)

- Perform the Static Capacity Test as outlined in the USABC Testing manual prior to any other testing.

- The following limits will be imposed
  - Maximum taper current time (default 1 hour unless otherwise specified)
  - Constant voltage taper current cutoff (default C/20 if not otherwise specified)
  - Maximum % over the constant current charge capacity done during the constant voltage charge (default 5% if not otherwise specified)
  - Maximum allowable change in temperature above ambient during charge (default 10°C if not otherwise specified)