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Revision 1

Battery Test Manual For 12 Volt Start/Stop Vehicles

Jeff Belt

May 2015

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

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Energy Efficiency and Renewable Energy

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U.S. Department of Energy Vehicle Technologies Program

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Assistant Secretary for Energy Efficiency and Renewable Energy (EERE)
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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 12V Start/Stop Vehicles (12V S/S). The specific procedures defined in this manual support the performance and life characterization of advanced battery devices under development for 12V S/S applications.

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 Brian Cunningham (DOE), Oliver Gross (Fiat Chrysler Automobiles), Scott Jorgensen (General Motors), and Matt Denlinger (Ford Motor Company). Jon P. Christophersen from Idaho National Laboratory was the primary author for the manual.

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_{Margin}	Available Energy Margin at 6 kW ($E_{Discharge} - AE_{Total\ Target}$)
$AE_{Total\ Target}$	Total Available Energy Target (360 Wh)
BOL	Beginning Of Life
BSF	Battery Size Factor
$E_{discharge}$	Discharge energy at any given power level
EOL	End Of Life
FreedomCAR	Freedom Cooperative Automotive Research
HPPC	Hybrid Pulse Power Characterization
I_{HPPC}	Hybrid Pulse Power Characterization Current
INL	Idaho National Laboratory
OCV	Open-Circuit Voltage
OSPS	Operating Set Point Stability
P_{CPD}	Constant Power Discharge Power
PNGV	Partnership for a New Generation of Vehicles
SOC	State Of Charge
S/S	Start/Stop
RPT	Reference Performance Test
UE	Useable Energy
USABC	United States Advanced Battery Consortium

GLOSSARY

Available Energy (AE) [Wh] – the single energy point on the Useable Energy versus Power curve that precisely corresponds to the Discharge Pulse power target.

Available Energy Margin (AE_{Margin}) [Wh] – for a given HPPC test, the difference between the calculated available energy (AE) and the corresponding energy target ($AE_{Total\ Target}$).

Available Energy for Total Target ($AE_{Total\ Target}$) [Wh] – the total discharge available energy at end-of-life; this corresponds to the target available energy of 360 Wh based on the targets in Table 1.

Available Power [kW] – the discharge pulse power at which the useable energy is equal to the Available Energy target ($AE_{Total\ Target}$).

Battery Size Factor (BSF) –an integer which is the minimum number of cells or modules expected to be required to meet all the performance and life targets in a parallel and/or series combination. Note that there may be some cases where the BSF is not required to be an integer (*e.g.*, when prototype cell designs have different electrode surface areas than the final design).

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. This is distinguished from the HPPC immediately prior to the start of life testing, which is typically denoted RPT0 (see below).

C_1/1 Rate [A]– a current corresponding to the manufacturer's rated capacity (in ampere-hours) for a one-hour discharge at BOL between $Vmax_{100}$ and $Vmin_0$. For example, if the battery's rated one-hour capacity is 10Ah, then C_1/1 is 10A.

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 750 W based on the approximate power needed for the vehicle.

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.

Device – a cell, module, sub-battery or battery pack, depending on the context. The generic term "device" is normally used in test procedures except where a specific type of device is meant. (Most test procedures are intended to apply to any of these types.)

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 the AE_{Margin} is determined.

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.

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 750-W 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 0.5 seconds or less. (This value need not be achievable over the full operating range).

Operating Capacity [Ah] – the useable capacity at a $C_1/1$ rate over the full operating range of the device between $Vmax_{op}$ and $Vmin_0$. The operating capacity should be provided by the manufacturer, or it is established at BOL and remains fixed during life aging.

Power Fade [W] - the change in Available Power from RPT0 to the value determined at some later time, expressed as a percentage. (Similar definitions apply to Capacity Fade and 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 and the corresponding power target.

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.

Rated Capacity [Ah] – the useable capacity at a $C_1/1$ rate over the full electrochemical range of the device between $Vmax_{100}$ and $Vmin_0$. The rated capacity should be provided by the manufacturer, or it is established at BOL and remains fixed during life aging.

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 3.12). 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 750 W rate between $Vmax_{op}$ and $E_{Discharge}$ at given power values.

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.

$Vmin_{pulse}$ [V] – minimum voltage allowed during discharge pulses of 1s 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).

USABC Battery Test Manual
For 12 Volt Start/Stop Vehicles

1. PURPOSE AND APPLICABILITY

This manual defines a series of tests to characterize aspects of the performance or life behavior of batteries for 12 Volt Start/Stop (12V S/S) vehicle applications. Tests are defined based on the Vehicle Technologies Office targets for 12 V micro-hybrid 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), the FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles (Reference 3), and the Battery Test Manual for Plug-In Hybrid Electric Vehicles (Reference 4). Deviations from the test or analysis procedures defined in this manual must be approved by the USABC technical program manager.

1.1 USABC Energy Storage Targets For 12 Volt Start/Stop Vehicles

The Department of Energy's Vehicle Technologies Office Energy Storage Targets for 12 Volt Start/Stop Vehicles are the primary driving force for the test procedures and methods defined in this manual. These targets are outlined in Table 1. Note that two operating environments are covered, "Not under hood" and "Under hood," which impact operating and survival temperature ranges and system cost. Establishing or verifying battery performance in comparison to these targets is a principal objective of the test procedures and analysis methodologies defined in this manual.

Table 1. USABC Energy Storage System Performance Targets for 12 Volt Start/Stop Vehicles.

End of Life Characteristics	Units	Target	
		Under hood	Not under hood
Discharge Pulse, 1s	kW	6	
Max discharge current, 0.5s (minimum design)	A	900	
Cold cranking power at -30 °C (three 4.5-s pulses, 10s rests between pulses at min SOC)	kW	6-kW for 0.5s followed by 4 kW for 4s	
Min voltage under cold crank	Vdc	8.0	
Available energy (750W accessory load power)*	Wh	360	
Peak Recharge Rate, 10s **	kW	2.2	
Sustained Recharge Rate	W	750	
Cycle life, every 10% life RPT with cold crank at min SOC ***	Engine starts/miles	450k/150k at 45°C	450k/150k at 30°C
Calendar Life at 30°C, 45°C if under hood	Years	15 at 45°C	15 at 30°C
Minimum round trip energy efficiency	%	95	
Maximum allowable self-discharge rate	Wh/day	2	
Peak Operating Voltage, 10s – Max	Vdc	15.0	
Sustained Operating Voltage - Max	Vdc	14.6	
Minimum Operating Voltage under Autostart	Vdc	10.5	
Operating Temperature Range - to allow 6-kW (1s) pulse	°C	-30 to + 75	-30 to +52
30 °C – 52 °C	Wh	360 (to 75°C)	360
0 °C	Wh	180	
-10 °C	Wh	108	
-20 °C	Wh	54	
-30 °C	Wh	36	
Survival Temperature Range (24 hours)	°C	-46 to +100	-46 to +66
Maximum System Weight	kg	10	
Maximum System Volume	L	7	
Maximum System Selling Price (@250k units/year)	$	$220	$180

NOTES

* The United States Advanced Battery Consortium has decided that the Available Energy can be regen limited (unable to accept complete regen at the upper end of the SOC range) when verifying peak recharge rate.

** Normally refers to any device charge interval corresponding to the return of vehicle kinetic energy to a device (typically from braking.) However, since 12 Volt Start/Stop vehicles do not utilize regenerative braking, the term regen used throughout the manual will be synonymous with a short term recharge from the engine-generator, <10 seconds.

*** Note that the minimum state-of-charge (min SOC) condition corresponds to the energy removed on the pulse power discharge curve at the power target.

2. TEST PROFILES DERIVED FROM USABC TARGETS

The test procedures described in this manual are intended for use over a broad range of devices at various stages of developmental maturity. 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 and energy 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.

3. TEST PROCEDURES

3.1 General Test Conditions and Scaling

In general, USABC testing is divided into three broad phases, *i.e.*, characterization, life, and reference performance testing. Characterization testing establishes the baseline performance and includes 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 at the beginning of life and are performed periodically during life testing, as well as at the start and end of life testing. A generic test plan for USABC 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% state of charge (SOC) and 0% SOC are referred to as $Vmax_{100}$ and $Vmin_0$, respectively. Since energy storage devices in 12V Start/Stop 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 charge (≤10s) or discharge (≤1s) 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

To the extent possible, all testing should be conducted using environmental chambers. When changing the ambient temperature, the test article should be soaked for a period of time to ensure thermal equilibrium (4 to 16 hrs, depending on size and mass of the device). Unless otherwise specified in a device-specific test plan, the ambient temperature for all tests shall be controlled at a default nominal temperature of 30ºC ± 3°C. For "Under Hood" applications, the default nominal temperature for calendar- and cycle-life testing shall be 45°C± 3°C.[2] 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.

3.1.3 Pressure Controls (Pouch Cells)

Unless otherwise specified in a device-specific test plan, pouch pressure should be established by placing the device between two thermally non-conductive 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 remain 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 for Constant Power Test Profiles

Testing any device smaller than a full-size system (*i.e.*, full-size vehicle battery) 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 USABC 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 (using a $C_1/1$ current instead of the 750-W rate) results by applying a nominal power margin of 30% to allow for degradation resulting from cycle life and calendar life effects. See Section 4.4.11 for details of this determination.[3]

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

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2. Reference performance testing for "Under Hood" applications, however, shall also be at 30°C.

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

scaled by dividing the nominal profile power levels by the Battery Size Factor. For example, if the Battery Size Factor is 3 for a particular cell design, the 6-kW Cold Cranking test would then be performed at a pulse power level of 6000/3 = 2000 W for such cells. The number of cells should typically be rounded to an integer value that aligns with all performance requirements and can be configured for series and/or parallel strings. However, there may be some cases where the BSF is not required to be an integer (*e.g.*, when prototype cell designs have different electrode surface areas than the final design).

3.1.5 Scaling of HPPC-Current

The HPPC-Current is a constant current that will closely resemble the steady state current during the 750-W Constant Power Discharge Test. To relate the energy removed at the 750-W 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.

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

where I_{HPPC} is the HPPC discharge current between pulses, P_{CPD} is the Constant Power Discharge target, and $V_{nominal}$ is the average electrochemical voltage between $Vmax_{100}$ and $Vmin_0$ (*i.e.*, total energy divided by capacity). For example, if the total discharge capacity is 2 Ah and discharge energy is 7 Wh from the initial static capacity test, then V_{avg} = (Wh/Ah) = 3.5V. Given P_{CPD} = 750-W and assuming BSF = 10, then I_{HPPC} = 750W/(3.5V * 10) = 21.4 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. This HPPC-Current value is used extensively once the BSF is determined for the Capacity and HPPC tests.[4]

3.1.6 Charging Procedure

The manufacturer is responsible for defining a reasonable charging procedure with the assistance of the technical program manager. This charging procedure should specify rest periods before and after charging is performed (at least 1 hour is recommended, but it be adjusted based on the needs of the chemistry).

3.2 Capacity Test

This test measures device capacity in ampere-hours at a $C_1/1$ 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 measured capacity is significantly different from the rated (*i.e.*, more than ±10%), notify the technical program manager before continuing testing and determine if the capacity needs to be re-rated.[5] The static capacity test is to be performed until three consecutive discharge capacities are stable within ±2% up to a maximum of 10 discharges. If the device is unable to

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4. The HPPC current should be compared with the average current for a scaled 750-W discharge.

5. If initial Capacity Tests indicate that the manufacturer's rated capacity is clearly not representative of the device's actual capacity, the value to be used as the rated capacity may be re-defined by USABC program management before testing continues. Use of a reasonably representative capacity value is important for high quality HPPC test results.

reach stability after 10 discharges, the technical program manager should be notified. The static capacity test can also be repeated using $Vmax_{op}$ as the fully charged condition to ensure stable operating capacity as well.

3.3 Constant Power Discharge and Charge Tests

This test measures device capacity in ampere-hours and energy in watt-hours at a constant power discharge rate corresponding to a BSF-scaled 750-W rate. Discharge begins following a one-hour rest from a fully-charged state ($Vmax_{op}$) and is terminated on a manufacturer-specified discharge voltage limit ($Vmin_0$), followed by a one-hour rest at open-circuit voltage. Recharge the device using the 750-W rate to $Vmax_{op}$. Once $Vmax_{op}$ is reached, use the manufacturer's recommended procedure to ensure the device is "fully charged" at $Vmax_{op}$. 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 $Vmin_{pulse}$ discharge power capability at the end of a 1-s discharge current pulse and (b) the $Vmax_{pulse}$ regen power capability at the end of a 10-s regen current pulse.[6] These power and energy capabilities are then used to derive other performance characteristics such as Available Energy and Available Power for direct comparison with the targets specified in Table 1.

Additional data from the HPPC test include the voltage response curves, from which 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 1-second discharge-pulse and the 10-second regen-pulse power capabilities at each 10% increment relative to the beginning of life (BOL) rated capacity for the "Under Hood" and "Not Under Hood" 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 (I_{HPPC}) as determined in Section 3.1.5. 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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6. $Vmin_{pulse}$ and $Vmax_{pulse}$ refer to the device minimum and maximum voltages that correspond to the pulse 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
1	1	1.00
40	40	0
10	51	-0.33

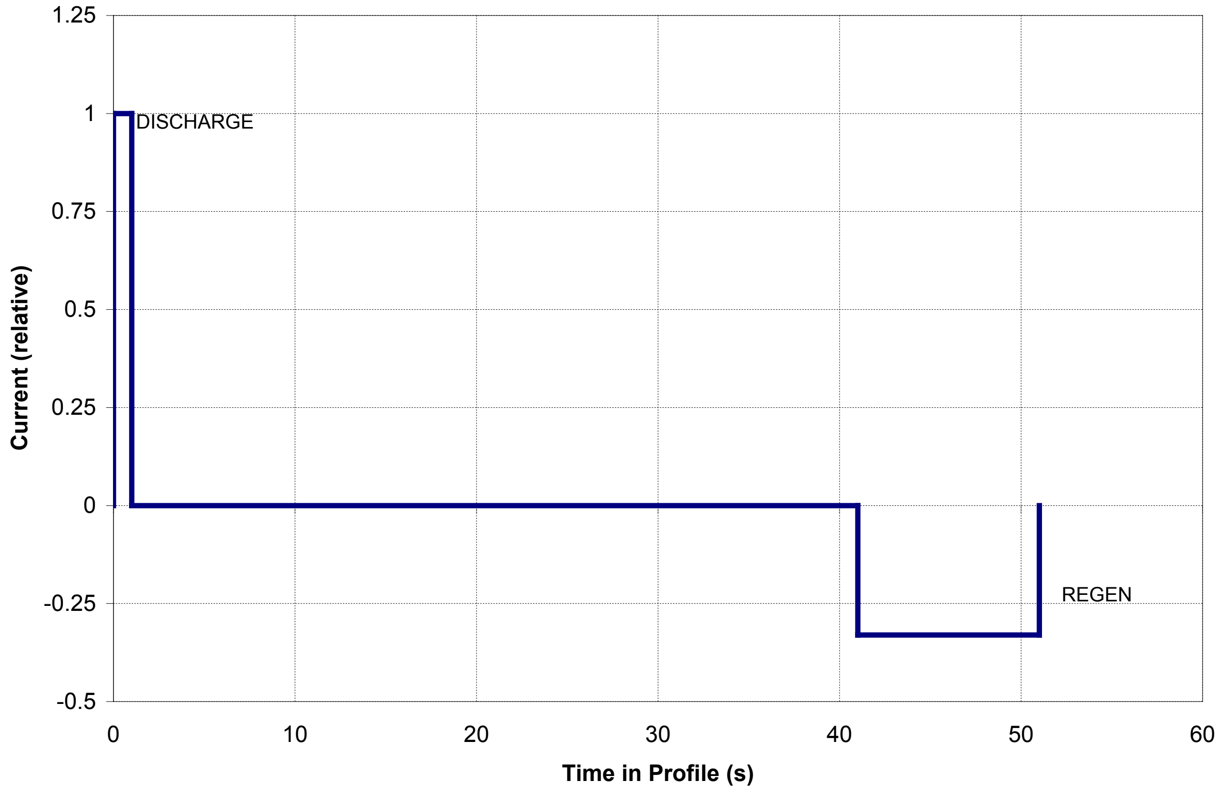

Figure 1. Hybrid Pulse Power Characterization Test profile.

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 a discharge to the next 10% increment based on rated capacity using I_{HPPC} (defined in Section 3.1.5),[7] each followed by a default rest period to allow the cell to return to an electrochemical and thermal equilibrium condition before applying the next profile.

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7. Note that the capacity of the pulse profile must be accounted for in determining the actual state of charge at which the profile was performed. The profile in Table 2 restores more capacity than it takes out of a device. The test should be programmed such that a total of 10% of the rated capacity is removed in each test segment, including the capacity that was restored by the pulse profile itself.

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 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). 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 750-kW discharge to be executed just prior to each HPPC Test.[8]

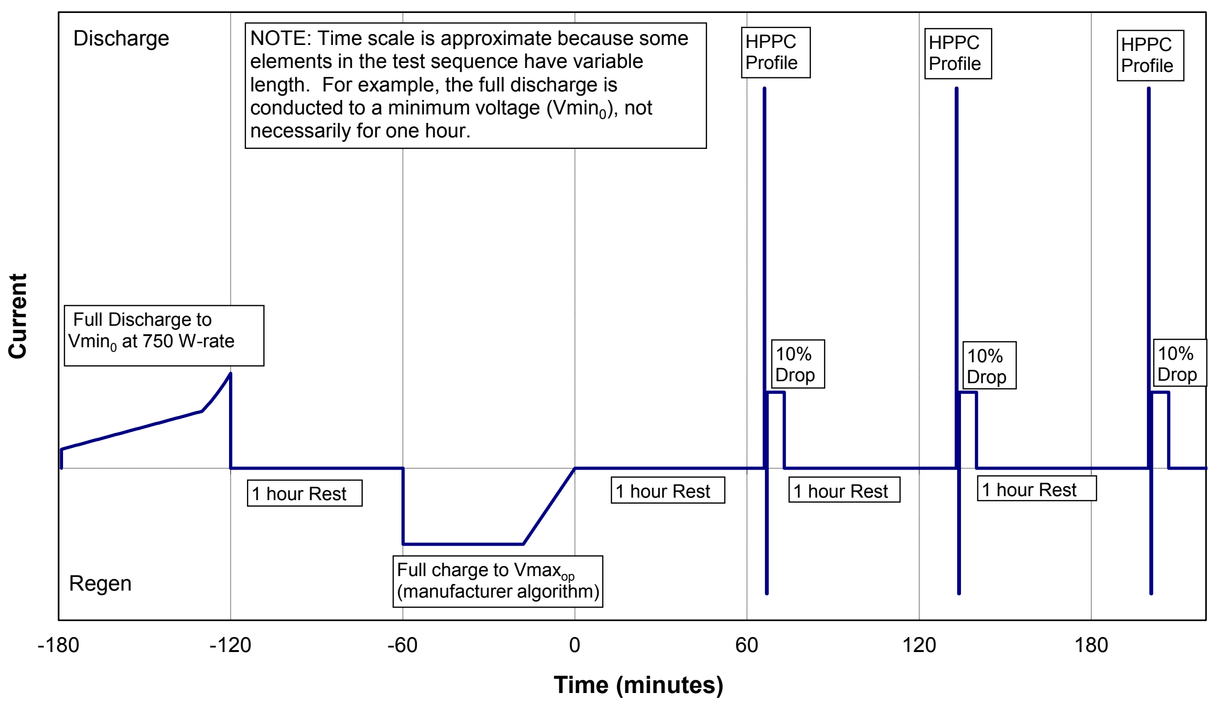

Figure 2. Hybrid Pulse Power Characterization Test (start of test sequence).

8. This HPPC-Current discharge is required because the HPPC results will eventually be reported as power capability versus energy removed at a 750-W rate. The availability of linked HPPC-Current data facilitates this analysis and reporting; see Section 4.4.

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. A $5C_1/1$ rate is used in place of the 750-W rate and the HPPC-Current, see Section 4.4.11.

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 1-s at some state-of-charge, which needs not be specified). The purpose of this test is to evaluate the power and energy capability of the device at current levels consistent with actual use, which will take into account any reduction in resistance that results from thermal effects arising from higher current levels see Section 3.4.3.

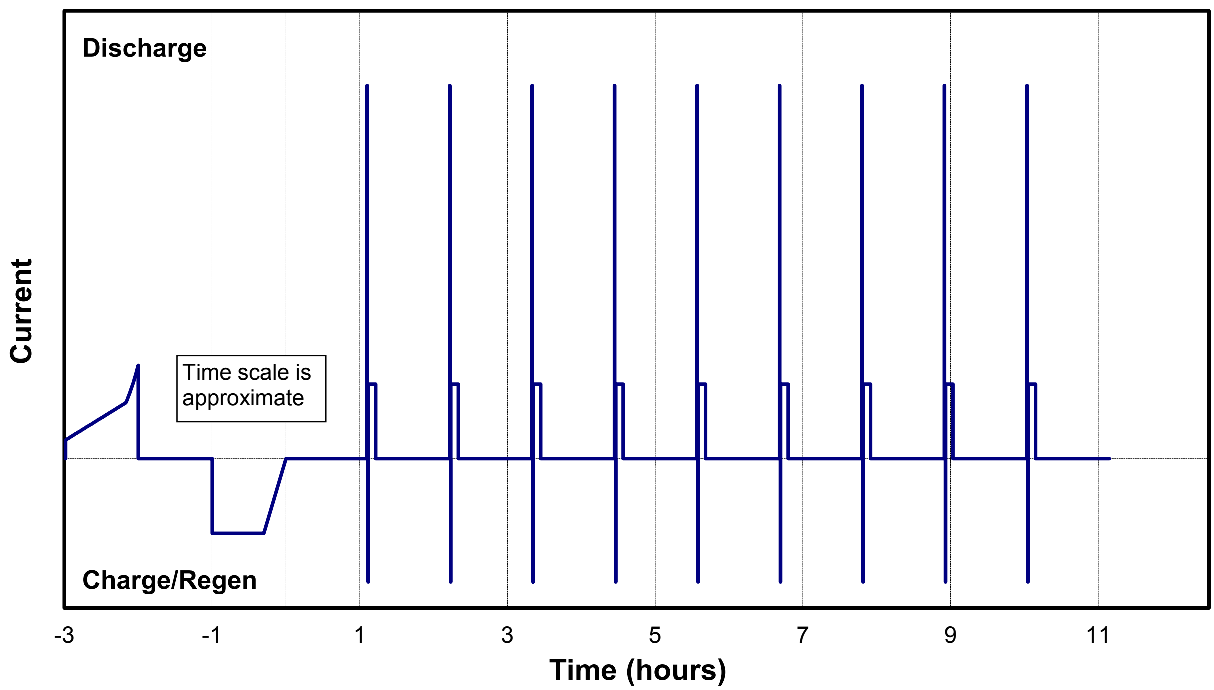

Figure 3. Hybrid Pulse Power Characterization Test (complete HPPC sequence).

3.4.3 HPPC Verification Test (Optional)

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. Starting with a fully-charged battery at $Vmax_{op}$ followed by a one-hour rest at open-circuit conditions, perform a regen pulse at the BSF-scaled target power from Table 1.

2. Recharge the device to $Vmax_{op}$ using the manufacturer's recommended procedure and rest for one hour at open-circuit conditions.

3. Remove the energy corresponding to the Discharge Pulse target ($E_{Discharge}$, as defined in Section 4.4.8) at a 750W constant power rate, and then rest for one hour at open-circuit conditions.

4. Perform a discharge pulse at the BSF-scaled target power 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 Max Current Verification Test

This test is intended to determine capability of the device to meet the maximum discharge current requirements based on the targets identified in Table 1. The test consists of the following sequence of activities:

1. Perform an HPPC test on the device to establish the initial performance.

2. Recharge the device to $Vmax_{op}$ using the manufacturer's recommended procedure and rest for one hour at open-circuit conditions.

3. Perform a 500 ms pulse at the maximum current (*i.e.*, 900 A[9]) that is scaled based on the parallel/series combinations of cells (*e.g.*, if the scaling factor results in 2 devices wired in parallel, then perform the pulse at 450 A). If the minimum voltage is reached before the end of test, immediately stop the test (within the next clock cycle).

4. Rest for one hour at open-circuit conditions and then recharge the device using the manufacturer's recommended procedure.

5. Perform another HPPC test to quantify any change in performance.

3.5 Self-Discharge Test

3.5.1 Standard 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. The test consists of the following sequence of activities:

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9. Note that the 900-A requirement in Table 1 is a design minimum for the battery hardware. The manufacturer can specify a larger maximum current as well and this should be specified in a device-specific test plan.

1. Recharge the device to $Vmax_{op}$ using the manufacturer's recommended procedure and rest for one hour at open-circuit conditions.

2. Discharge the device to $Vmin_0$ at a $C_1/1$ rate and rest for one hour at open-circuit conditions. Record the actual discharge capacity from this step.

3. Recharge the device to $Vmax_{op}$ using the manufacturer's recommended procedure and then rest for one hour at open-circuit conditions.

4. Remove 360 Wh from the cell at the $C_1/1$ constant-current discharge rate and allow it to stand in an open-circuit condition for a nominal interval of 7 days. All measurement equipment may need to be disconnected from the cell during this period to reduce parasitic losses.

5. Discharge the cell for its remaining (residual) capacity at a $C_1/1$ discharge rate.

3.5.2 Extended Stand Test

This test is intended to determine the capacity loss and cold cranking capability that results from a cell or battery standing (*i.e.*, at rest) for a 30 days at 30°C. The test consists of the following sequence of activities:

1. Recharge the device to $Vmax_{op}$ using the manufacturer's recommended procedure and rest for one hour at open-circuit conditions.

2. Discharge the device to $Vmin_0$ at a $C_1/1$ rate and rest for one hour at open-circuit conditions. Record the actual discharge capacity from this step.

3. Recharge the device to $Vmax_{op}$ using the manufacturer's recommended procedure and then rest for one hour at open-circuit conditions.

4. Remove 360 Wh from the cell at the 750-W rate and allow it to stand in an open-circuit condition for an interval of 30 days at 30°C. All measurement equipment may need to be disconnected from the cell during this period to reduce parasitic losses.

5. Perform the Cold Cranking Test as described in Section 3.6.

6. Discharge the cell for its remaining (residual) capacity at a $C_1/1$ discharge rate.

3.6 Cold Cranking Test

The Cold Cranking test is intended to measure the 4.5-s power capability at low temperature (normally -30ºC) for comparison with the USABC Cold Cranking Power target(s) in Table 1. The test is conducted where the USABC Available Energy target is just met or at the residual capacity level determined during the extended stand test (Section 3.5.2). The test consists of the following sequence of activities:

1. At normal ambient temperature, bring the device to the cold cranking condition using one of the following approaches:

a. From a fully charged condition, remove a BSF-scaled 360 Wh at a $C_1/1$ constant current discharge rate.

b. From the Extended Stand test (Section 3.5.2), the device is already at the cold cranking condition.

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

3. Perform the Cold Cranking Test profile defined in Section 3.6.1. The pulse power level to be used is 6-kW and 4-kW divided by the Battery Size Factor as determined in Sections 3.1.4 and 4.4.10. 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 USABC voltage ratio limits in Table 1. Note also that the profile pulses must be performed for the full 4.5-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. This test may also be performed at other SOC conditions with approval from the technical program manager.

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 capability to provide 6-kW of discharge power for 0.5-s followed by 4-kW for 4-s for a total of three 4.5-s pulses at 14.5-s intervals (*i.e.*, 10 s between pulses.) The profile is defined in Table 3 and illustrated in Figure 4.

Table 3. Cold Cranking Test profiles.

Time Increment (s)	Cumulative Time (s)	System Power (kW)
0.5	0.5	6
4	4.5	4
10	14.5	0
0.5	15	6
4	19	4
10	29	0
0.5	29.5	6
4	33.5	4
10	43.5	0

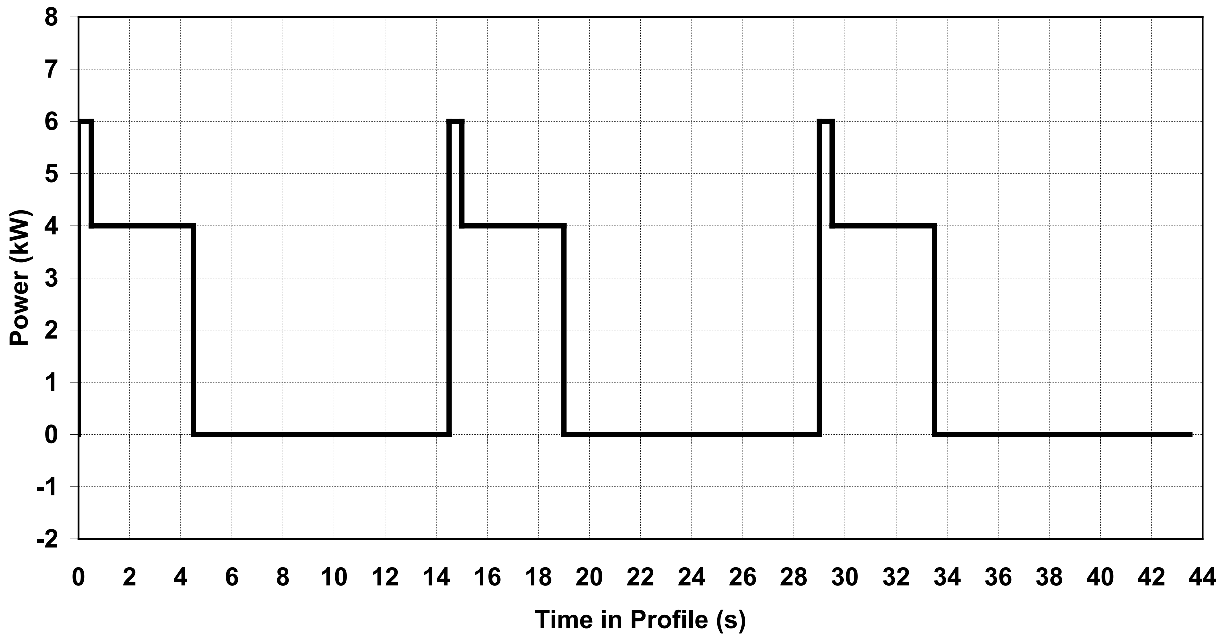

Figure 4. Cold Cranking Test profiles.

3.7 Thermal Performance Test

The effects of environment (ambient temperature) on device performance will be measured as required by performing the Constant Power Test, Low-Current Hybrid Pulse Power Characterization Test, and/or Cold Cranking Test at various temperatures within the USABC operating temperature target range for "Under Hood" (-30 to +75ºC) and "Not Under Hood" (-30 to +52ºC) applications. At the 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 dependent 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 device 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 hrs depending on size and mass of the device; 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 cell OCV-versus-temperature behavior to ensure that the SOC is not changed inadvertently. Typical temperatures for the thermal performance test consist of 75 or 52°C (depending on the application), followed by 0, -10, -20, and -30°C. Thermal testing at temperatures below 0°C should not be conducted once the test article demonstrates and inability to meet the targets.

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.

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 for "Under Hood" (-46 to +100ºC) and "Not Under Hood" (-46 to +66ºC) applications. Unless otherwise specified in a device-specific test plan, charging should be performed at the reference temperature (*i.e.*, 30ºC). The device should generally be at 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 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 hrs (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 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 hrs (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

Round-trip efficiency is determined at the cell level by calculation from a charge-balanced pulse profile. The efficiency test profile is defined in Section 3.8.1. This profile has been constructed for use in both efficiency and cycle life testing. This test is performed similarly to the Operating Set Point Stability (OSPS) Test, as follows:

1. Bring the device to a specified target SOC value and operating temperature using the $C_1/1$ constant-current rate.

2. Perform 100 profiles as defined in Section 3.8.1.

3. Determine the change (if any) in the state of charge before and after the 100 profiles. 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 technical program manager), or the data indicate that stable cycling was not achieved by the completion of 100 profiles, the OSPS test (Section 3.9) shall be conducted with implemented voltage control values or other limits, as appropriate.

3.8.1 12 Volt Start/Stop Efficiency Test Profile

The 12 Volt Start/Stop efficiency test profile is a 120-s, nominally charge-neutral pulse profile (also used as the 12V S/S Cycle Life Test profile) that is scaled to a level appropriate to verify the round trip energy efficiency target of 95%.[10] This test profile is defined in Table 4 and illustrated in Figure 5.

Table 4. 12 Volt Start/Stop Cycle Life Test profile.

Time Increment (s)	Cumulative Time (s)	Current (A)	Capacity Removed (A-s)	Cumulative Capacity (A-s)
59	59	60	3540	3540
1	60	300	300	3840
60	120	-100 tapered to target voltage	~3840	~0*

*Note: The profile will be controlled by the target voltage and the coulombic efficiency will be monitored.[11]

10. These profiles are calculated to be charge-neutral for a device that is about 95% energy efficient. Note that the Efficiency Test may also serve as the initial OSPS Test if the same SOC value and temperature are used.

11. Alternatively, the profile can be controlled with 100% coulombic efficiency while monitoring the voltage drift with approval from the technical program manager.

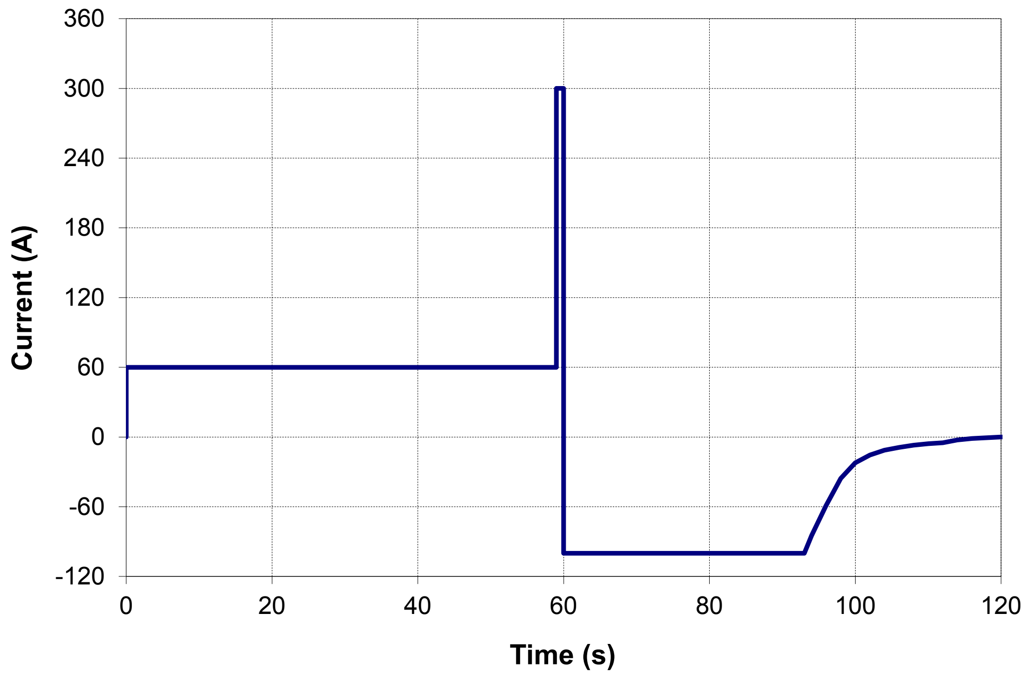

Figure 5. 12 Volt Start/Stop Cycle Life Test profile.

3.9 Operating Set Point Stability Test

This test is a special case of the cycle life testing regime to be applied to a given cell or battery. Since cycle life testing is normally done at an intermediate state of charge, it is necessary to determine that stable cycling will occur at the target SOC, and to adjust test conditions if necessary to ensure that this will be the case. The target state of charge for the cycle life test(s) defined in Section 3.10 is normally specified in a device-specific test plan based on projected use of the device.[12] This test should be performed immediately before the beginning of cycle life testing.

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.[13] Determine the change (if any) in the state of charge before and after the cycling interval. Allow the device to cool to +3°C of the target temperature with at least a 1-hr rest before and after this cycling is performed to determine any change in open-circuit voltage. The residual capacity can also be removed at a $C_1/1$ constant-current rate to verify the depth of discharge at the end of the cycling interval if the final SOC values are different by 1% or more.

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12. There is no "default nominal" state of charge for life cycling. However, if the appropriate value is not known in advance of the start of testing, the range of useable target SOC values can be determined from the HPPC test results (see Section 4.4) based on the peak discharge and regen powers planned for cycle life testing.

13. This typically requires approximately 100 complete pulse profiles.

3.9.1 Adjusting the Operating Set Point

If the cell 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 cell condition has changed significantly.

3.9.2 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 this and the specific method to be used can be called out in a device-specific test plan.

Note that achieving the target SOC and a stable cycling condition are related but 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 during the cycling period), while the SOC during cycling must actually be measured after cycling stops. 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 7.

3.10 Cycle Life Test

Cycle life testing is performed using the Cycle Life Test profile defined in Section 3.10.2. The test sequence is performed by repeating this profile at a fixed state of charge (*i.e.*, the profile is charge-neutral). Control of the state of charge is addressed in detail in Section 3.9.2.

3.10.1 Cycle Life Test Procedure Outline

The cycle life testing process consists of the following steps:

1. Scale the test profile by adjusting the nominal profile current (based on the parallel/series combination of cells) by the Battery Size Factor.

2. Bring the device to a specified target SOC value and operating temperature using the $C_1/1$ constant-current rate.

3. If necessary, conduct the Operating Set Point Stability Test (Section 3.9) to ensure stable operaton at the selected SOC condition. Make any needed adjustments to the test profile or test operating conditions as necessary.

4. Once stable operation has been established, repeat the test profile at the desired operating conditions the number of times specified in Table 7 or a device-specific test plan.

5. 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 suitable rest period to ensure electrochemical and thermal equilibrium (4 to 16 hours depending on the size of the device). Remove the residual capacity at a $C_1/1$ constant-current rate to verify the cycling depth of discharge, and perform one or more Reference Performance Tests to determine the extent of degradation in capacity and/or power capability. The reference tests are listed in Table 7. The intervals between repetitions of these reference tests are also

specified in Table 7, though these may be adjusted somewhat if required for time synchronization of cells being tested under different test regimes.

6. If the residual capacity measured in Step 5 indicates an unacceptable drift during cycling, repeat Step 3 to re-establish the target cycling condition.

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

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 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]

3.10.2 12 Volt Start/Stop Cycle Life Test Profile

The objective of this test profile is to demonstrate device life when subjected to different energy use levels and patterns appropriate to the USABC targets. The 12 volt start/stop profile is a 120-s pulse profile intended to demonstrate the ability to meet the USABC cycle life target of 450,000 cycles. The profile transfers about 0.48 million amp-hours (MAh) respectively in and out of the device over 450,000 cycles. Although the discharge pulses are constant current, the charge pulse is a constant current until it reaches a target voltage, when the current is tapered for the remaining time. The target voltage should be chosen to ensure a charge neutral profile.

These test profiles are all defined at the battery pack level. They are scaled to the appropriate current levels for testing cells and module designs using the Battery Size Factor based on the parallel/series combinations of cells as described in Section 3.1.3.

Each of the Cycle Life Test profiles remove 1.067 Ah on discharge and is nominally charge-balanced for a device that just satisfies the 95% energy efficiency target (note that the capacity is shown in this table and not the energy). The profile is listed here as Table 5 and is illustrated in Figure 6.

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 pulse profiles 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 4.10.

Table 5. 12 Volt Start/Stop Cycle Life Test profile.

Time Increment (s)		Cumulative Time (s)		Current (A)		Capacity Removed (A-s)		Cumulative Capacity (A-s)
59		59		60		3540		3540
1		60		300		300		3840
60		120		-100 tapered to target voltage		~3840		~0*

*Note: The profile will be controlled by the target voltage and the coulombic efficiency will be monitored.[17]

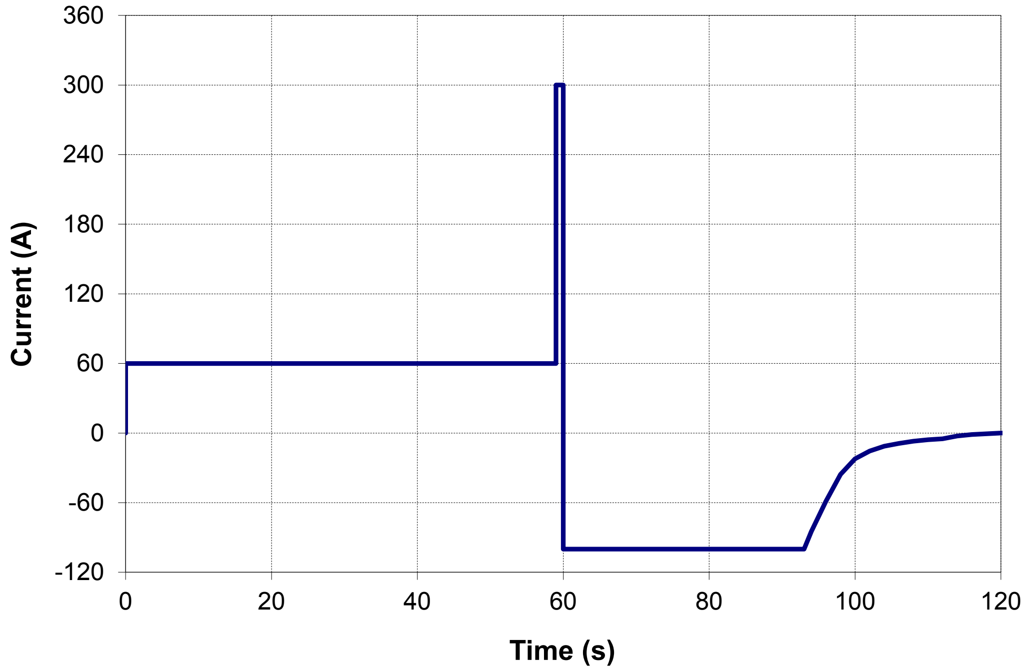

Figure 6. 12 Volt Start/Stop Cycle Life Test Profile.

3.11 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 under test are maintained at or near a target state-of-charge during the test. They must also be periodically subjected to reference discharges to determine the changes (if any) in their performance characteristics.

In general, calendar life testing is performed using multiple cells over a range of test conditions.[18] It is commonly done at elevated temperatures in order to shorten the time required for obtaining useful results.

17. Alternatively, the profile can be controlled with 100% coulombic efficiency while monitoring the voltage drift with approval from the technical program manager.

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 is considered a limiting cycle life test, *i.e.*, one in which the state-of-charge swing during cycling is zero. The design of experiments for such a larger test matrix is not described in this manual, but can be found in the Technology Life Verification Testing (TLVT) manual (Reference 5). 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.

3.11.1 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, in turn, essential for assessing battery warranty risks and costs.

Calendar life estimates are necessarily based on accelerated test methods. The general approach is to store cells or batteries 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 least three elevated temperatures should be selected in addition to the reference temperature. The lowest of these elevated temperatures should result in approximately half of the target life of 15 years, while the highest temperature should result in an end of life condition at the desired test duration (*e.g.*, two years). Other temperatures should be equally spaced between these extremes. At least three cells should be tested at each elevated temperature.

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. Periodically, based on criteria for acceptable decay in open-circuit voltages, the cells should be brought back to nominal operating temperature (*e.g.*, 30° C) and their performance measured. Such performance tests should be done at least monthly on each cell.

Key parameters should be monitored by the periodic performance tests, *e.g.*, available energy and power, and minimum voltage (or voltage margin) in the Cold Cranking test procedure. The corresponding end of life criteria for these parameters are: (1) available energy or power < target energy or power; and (2) inability to complete the cold cranking test within voltage limits when performed during the RPT as specified in Section 3.12. The test-to-test repeatability of these parameters should be no worse than one percent of the target values (to one standard deviation).

Other guidelines to improve test consistency for multiple cell tests include the following:

- Wherever possible, cells subjected to the same test conditions should be contained in the same test chamber or other environment, preferably using identical test channels, 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

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18. 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.

important for testing at elevated temperatures. However, 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.

3.11.2 Calendar Life Test Procedure

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

1. Characterize the cell using the Capacity Test (Section 3.2) and Hybrid Pulse Power Characterization Test (Section 3.4) and other reference tests as appropriate.

2. Discharge the fully charged cell to the target test condition at 30ºC. This can be done in one of two ways: (1) remove the appropriate fraction of the cell's rated capacity at a $C_1/1$ rate, or (b) [default] if the open-circuit voltage corresponding to the target test condition is known, clamp the cell at this voltage while limiting discharge current to a $C_1/1$ rate and then wait for the voltage and current to stabilize.[19] Note that the default method will typically reach the target test condition more slowly. In some cases it may be desirable to use voltage (rather than fractional discharge) as the measure of SOC.

3. Apply a single iteration of the Calendar Life Test Profile defined in Section 3.11.3. The nominal discharge current to be used for this profile is equal to the peak discharge current for the Low-Current HPPC Test (*i.e.*, 2.5 x I_{HPPC}).

4. Bring the cell to the target temperature at open-circuit condition and wait for the ambient temperature and voltage to stabilize.

5. Apply a single iteration of the Calendar Life Test profile defined in Section 3.11.3 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.

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. Data acquisition requirements during the 24 hour intervals (if desired) should be specified in a device-specific test plan.[20]

7. At intervals as specified in Table 7 or a device-specific test plan, return the cell to nominal temperature (*e.g.*, 30ºC), observe its open-circuit voltage after a suitable rest period to ensure electrochemical and thermal equilibrium (4 to 16 hours depending on the size of the device), and apply a single iteration of the Calendar Life Test profile before discharging its remaining

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19. A value less than 1% of the $C_1/1$ current is probably adequate to meet this criterion, provided this is within the measurement capability of the test equipment.

20. 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. One 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.

capacity at the $C_1/1$ 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. Default end-of-test conditions are generally analogous to those for cycle life testing in Section 3.10.1: (a) the Calendar Life Test profile cannot be performed within the voltage limits; (b) the HPPC reference test yields insufficient information to show further degradation; (c) calculated Available Energy is less than the target; or (d) sufficient data is acquired to project calendar life at 30ºC with a predetermined degree of confidence. Note that condition (d) may take precedence over condition (c) in some cases.

3.11.3 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. 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 profiles 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 6 and illustrated in Figure 7. This should be a charge-neutral profile, but the voltage limits shall not be violated. Thus, the 60-s discharge step at the end of the profile can include a taper current if a voltage limit is reached. In the case where calendar-life aging is performed at full charge and $Vmax_{op}$ is reached during the 10-s charge, then the 60-s discharge step can be a taper charge step instead.

Table 6. Calendar Life Test profile.

Step Time (s)	Cumulative Time (s)	Relative Current (Ratio)	Relative Net Charge (A-s/A)
1	1	1.0	1.0
40	41	0	1.0
10	51	-0.33	-2.3
9	60	0	-2.3
60	120	0.0383	0

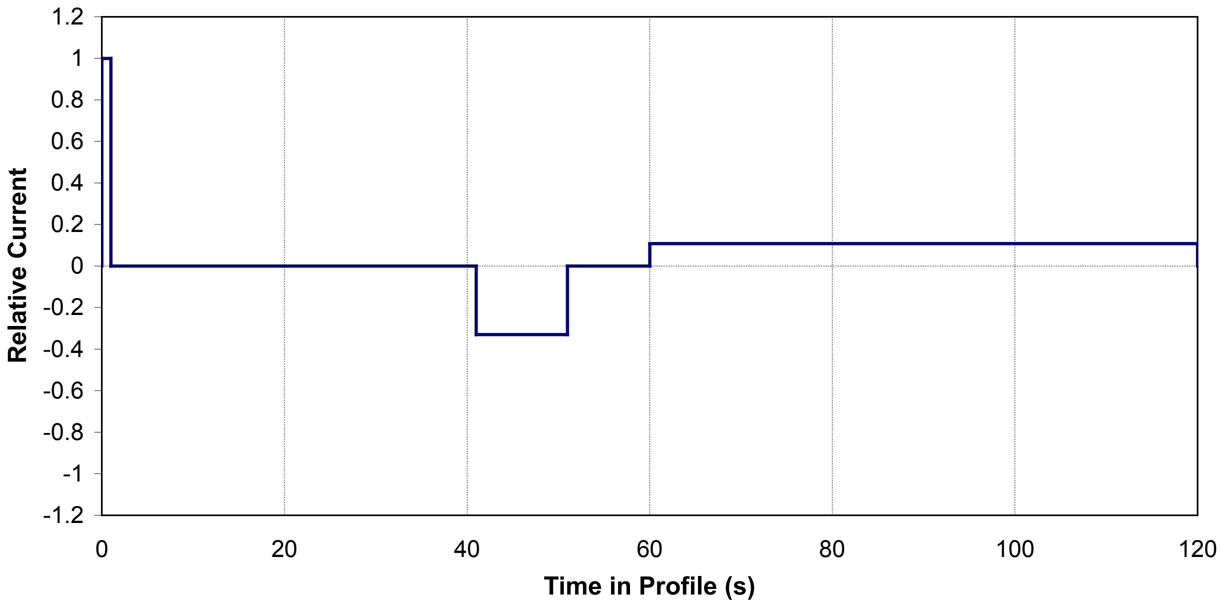

Figure 7. Calendar Life Test profile.

3.11.4 Alternative Calendar Life Test

In some cases calendar life testing may be conducted without using the once-per-day 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. 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.

3.12 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 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. [21]

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21. 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 are available "near" the normal testing range, *e.g.*, within ±5°C on either side of the nominal temperature; and the test whose data is to be adjusted is conducted within this limited range "near" the nominal temperature.

A Reference Performance Test iteration consists of one repetition of each test listed in Table 7. It is recommended that these tests be performed in the order listed.[22] Note that the reference temperature for the RPTs shall be 30±3°C for both "Not Under hood" and "Under Hood" applications.

Table 7. Standard Reference Performance Tests and Test Intervals for Life testing.

Type of Life Testing	Interval Between RPTs	Reference Performance Tests
Cycle Life Testing	23,040 cycle life profiles	**Constant-Power Discharge Test** **Low-Current HPPC Test** **Cold Cranking every 10% life RPT (for Cycle Life)**
Calendar Life Testing	Approximately 32 days	
Other Life Tests	10% of expected life	

Table 7 also lists typical intervals for reference tests during cycle life and calendar life testing. In practice, these intervals may have to be adjusted somewhat by the technical program manager 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.

22. The Cold Cranking Test is performed every 10% life increment for cycle life aging but no requirement is identified in the targets for calendar-life aging and should be specified in a device-specific test plan. If cycle- and calendar-life devices are placed in the same chamber, the calendar-life devices should also be subjected to the Cold Crank Test every 10% life increment. If not, another typical option is to perform the Cold Crank Test at least three times over the life of a device during calendar aging: (1) as part of initial characterization testing, (2) about halfway through the projected life, and (3) at the end of life testing.

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 a “Not Under Hood” application as an example. Corresponding data should also be reported for the other 12V S/S battery mode 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 Capacity Test

Capacity in ampere-hours and energy in watt-hours removed at the specified constant current discharge rate are reported based on manufacturer-specified termination conditions. (Note that all of this capacity will not generally be useable within USABC operating conditions, and thus it does not reflect conformance to the USABC Available Energy target. However, it is still considered a useful measure of capacity at the laboratory cell stage.) Energy removed (watt-hours) is reported as a function of depth of discharge (in percent of rated capacity). These data are used for the later calculation of Available Energy. Ampere-hours and watt-hours returned (and the corresponding overall charge/discharge efficiencies) are also reported for the manufacturer-specified charge algorithm.

4.2.1 Capacity Fade

For devices subjected to life testing, the change in capacity from the beginning-of-life value (measured just prior to the start of life testing) to some later point in time is to be reported periodically as Capacity Fade, expressed as a percentage of the original (BOL) capacity as shown in Equation (1).

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

where *t0* refers to the time of the initial (BOL) RPT and *t1* refers to the time of the later RPT where capacity fade is to be determined.

4.2.2 Energy Fade

For devices subjected to life testing, the change in energy from the beginning-of-life value (measured just prior to the start of life testing) to some later point in time is to be reported periodically as Energy Fade, expressed as a percentage of the original (BOL) capacity as shown in Equation (2).

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

where *t0* refers to the time of the initial (BOL) RPT and *t1* refers to the time of the later RPT where energy fade is to be determined.

4.3 Constant Power Discharge and Charge Tests

Capacity in ampere-hours and energy watt-hours removed at the specified constant power discharge rate are reported based on manufacturer-specified discharge termination conditions. (Note that all of this capacity will not generally be useable within USABC operating conditions, and thus it does not reflect conformance to the USABC Available Energy target. However, it is still considered a useful measure of capacity at the laboratory cell stage.) Energy removed (watt-hours) is reported as a function of depth of discharge (in percent of rated capacity). These data are used for the later calculation of Available Energy.

Ampere-hours and watt-hours returned (and the corresponding overall charge/discharge efficiencies) are also reported for the manufacturer-specified charge algorithm.

The same methodology to determine capacity and energy fade for the Capacity Test in Section 4.2 is used for the Constant Power Discharge and Charge Tests.

4.4 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 an "Under Hood" or "Not Under Hood" 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. 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.

4.4.1 Overall Analysis Approach

The primary purpose of the HPPC test is to periodically verify how the 1s Discharge Pulse, 10s Peak Recharge Rate, and Available Energy 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 750 W rate from the Constant Power test (Section 4.3). 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 750 W rate.

4.4.2 Pulse Resistance

From the HPPC pulse profile in Figure 1 (Section 3.4.1), resistance can be calculated using a $\Delta V/\Delta I$ calculation at each 10% increment. Resistances are normally only calculated for completely unabated pulses, *i.e.*, those with full duration and amplitude.[23] Equations 3 and 4 show the calculation for the 1-s discharge pulse and 10-s regen pulse resistance, respectively, where the relevant time points are identified in Figure 8.

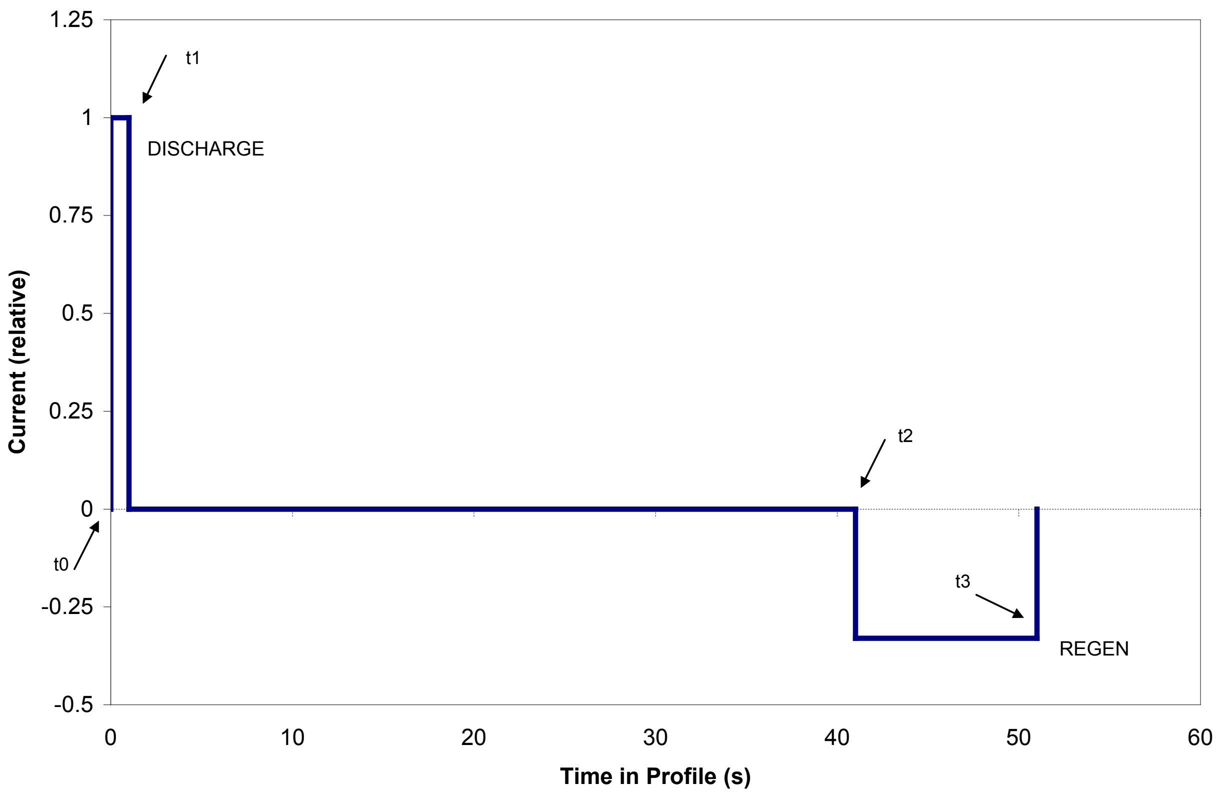

Figure 8. Resistance calculation time points.

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23. 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.

$$\text{Discharge Resistance} = \frac{\Delta V_{discharge}}{\Delta I_{discharge}} = \left| \frac{V_{t1} - V_{t0}}{I_{t1} - I_{t0}} \right| \tag{3}$$

$$\text{Regen Resistance} = \frac{\Delta V_{regen}}{\Delta I_{regen}} = \left| \frac{V_{t3} - V_{t2}}{I_{t3} - I_{t2}} \right| \tag{4}$$

The discharge and regen resistances can then be plotted at each 10% increment between $Vmax_{op}$ and $Vmin_0$, as shown in Figure 9 for an illustrative set of 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.[24] 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 9. 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.

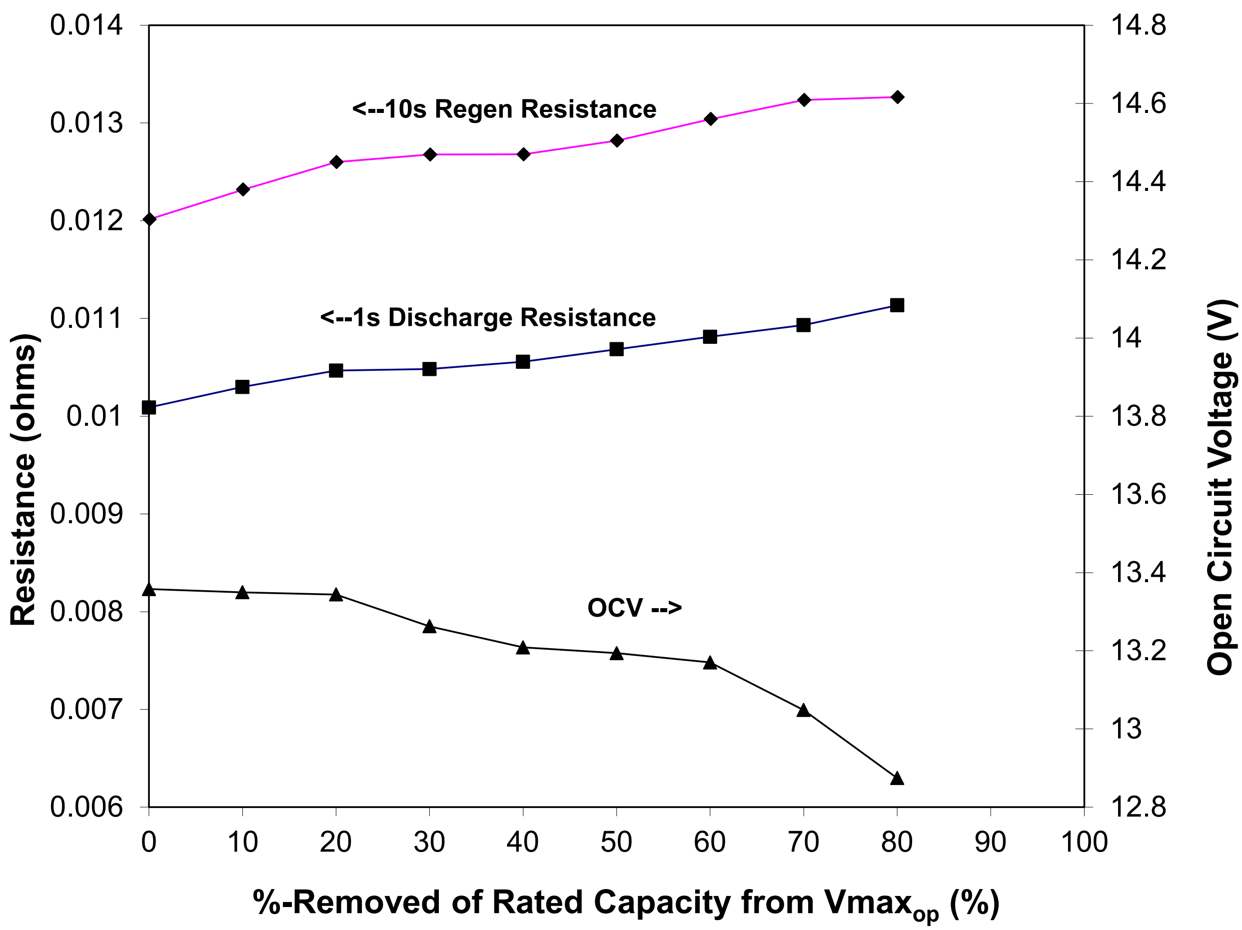

Figure 9. Open-circuit voltage and pulse resistances versus capacity removed.

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

4.4.3 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 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 10 illustrates the resultant Pulse Power Capability curves as a function of the percent of rated capacity removed from $Vmax_{op}$.

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

$$Regen\ Pulse\ Power\ Capability = Vmax_{pulse} \bullet (Vmax_{pulse} - OCV_{regen}) \div R_{regen} \quad (6)$$ [25]

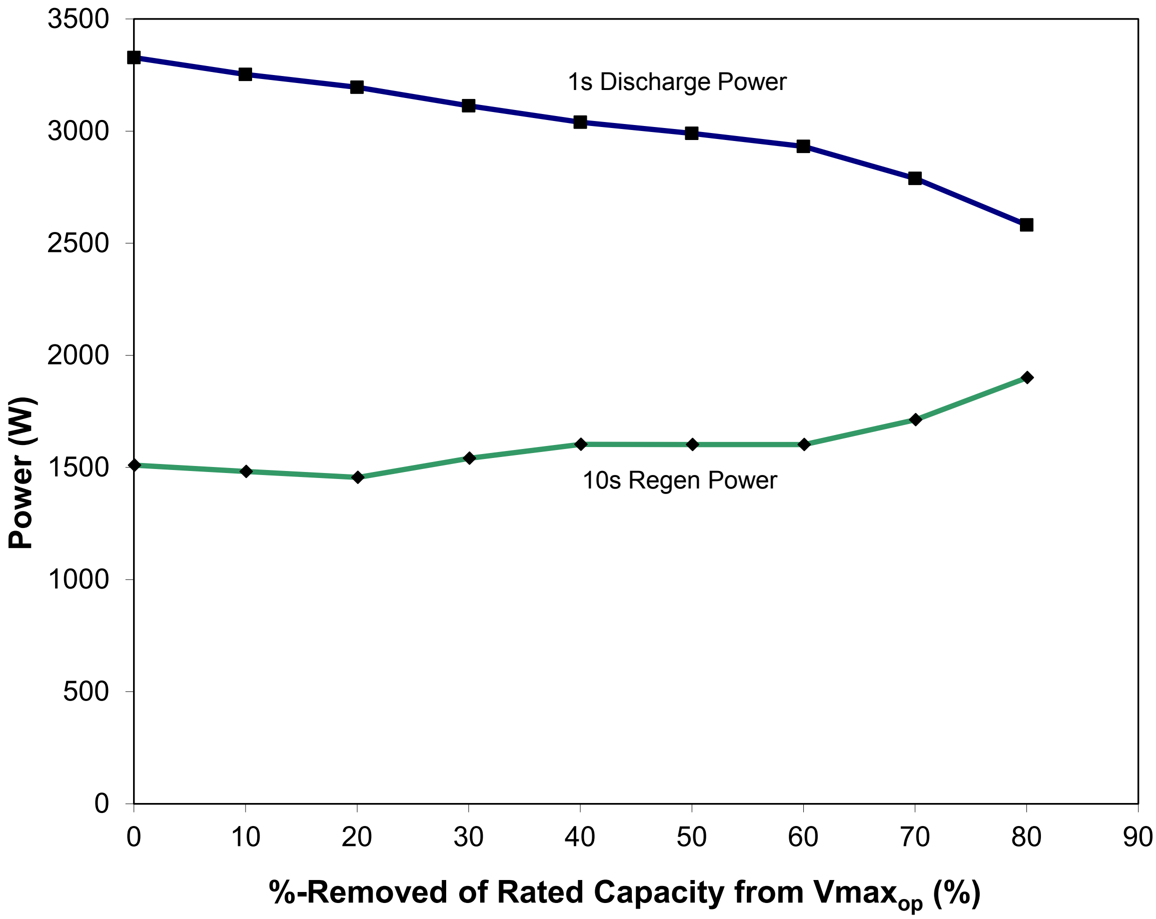

Figure 10. Pulse power capability vs depth of discharge.

25. 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 percent 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 10% of rated capacity removed removes 3% of the device capacity, the subsequent regen pulse OCV is interpolated starting at 13% of rated capacity removed.

However, the pulse power capability must first be plotted relative 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 750 W constant power discharge test (Section 4.3), from which the cumulative energy removed at a 750 W rate can be plotted against the calculated capacity removed as shown in Figure 11. Assuming that the measured capacity removed from the constant power discharge and the subsequent HPPC test are equivalent,[26] 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 750 W rate (as indicated in Figure 11) and used to transform Figure 10 into Figure 12, where the pulse power capabilities at the cell level are now plotted as a function of cumulative energy removed. Note that the data in Figure 11 must be generated each time an HPPC test is performed since the energy removed as a function of discharge capacity will likely change with aging.

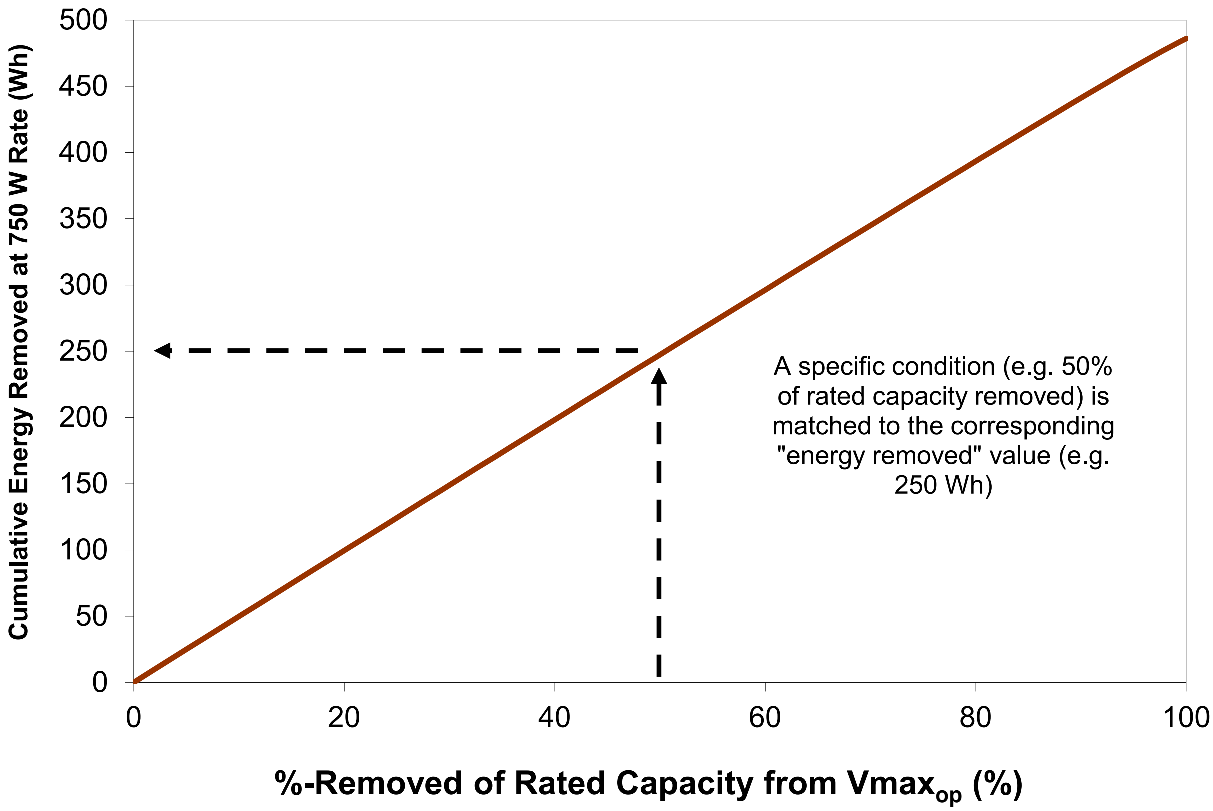

Figure 11. Relationship Between Energy and %-Capacity Removed in a 750 W Discharge

26. 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).

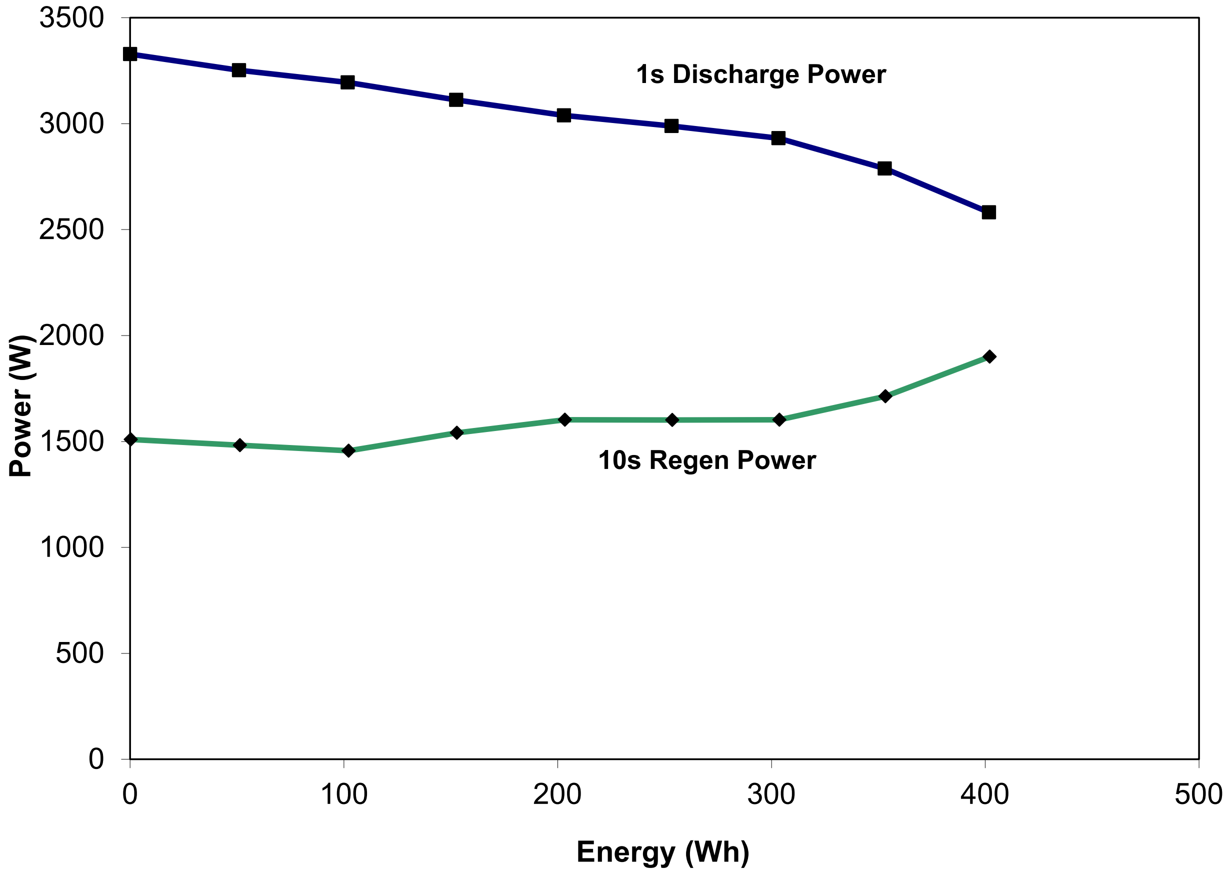

Figure 12. Unscaled HPPC Cell Power Capability vs. Energy Removed.

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 targets, *e.g.*, 2.2-kW regen and 6-kW discharge. Figure 13 illustrates the result of this scaling when applied to Figure 12 with an assumed BSF of 3 (to ensure at least a 30% power margin at beginning of life, see Section 4.4.11)[27], where the 2.2-kW regen target on the secondary *y-axis* is aligned with the 6-kW discharge target.

27. Note that the Battery Size Factor should be an integer value, however, it can be a non-integer for early-stage development of a device chemistry).

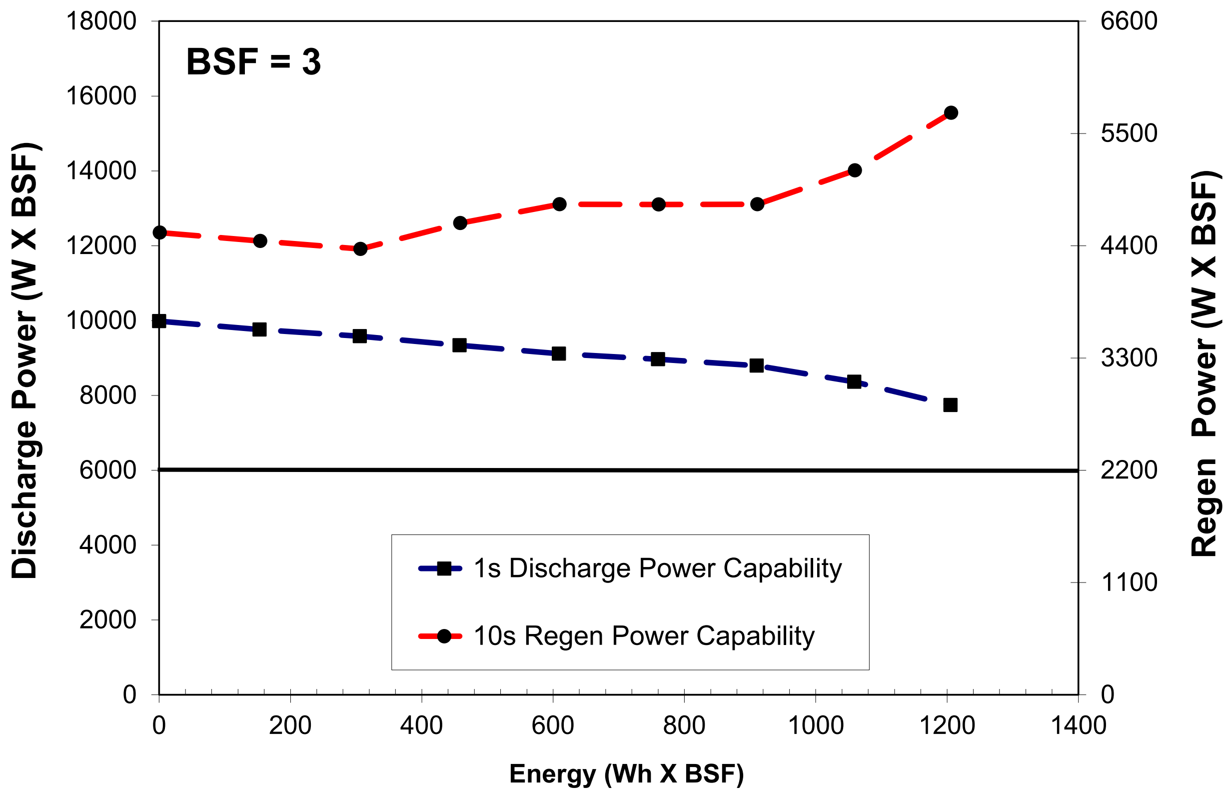

Figure 13. HPPC Power vs. HPPC-Current Discharge Energy Scaled by the Battery Size Factor.

4.4.4 Useable and Available Energies

The 12 Volt Stop/Start targets include a 1-s Discharge Pulse power target and an Available Energy target, both of which must be simultaneously satisfied. Normally the Peak Recharge Rate target is included in the energy calculation with the Discharge Pulse power. However, USABC has decided for this manual that the energy can be regen limited (*i.e.*, unable to accept complete regen at the upper end of the SOC range). This regen limit is dubbed the Charge Target and has been chosen to be at $Vmax_{op}$ by the USABC. However, this example shows that there would be no point at which regen would be limited.

Given the power target requirements, it is not anticipated that the discharge and regen power curves will crossover eachother. Thus, the energy assessment is based solely on the discharge power curve. Useable Energy (UE) is the total available discharge energy at the scaled 750-W rate between the top of the operating window, or $Vmax_{op}$, and the Pulse Power Discharge curve (*i.e.*, see Figure 13) 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 $E_{Discharge}$. Available Energy (AE) is the total available discharge energy at the scaled 750-W 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). In the case where the last point on the discharge curve exceeds the 6-kW target, then the Available Energy is defined as the energy removed prior to the final discharge pulse from the HPPC. Equation (7) defines UE, where $E_{Discharge}$ corresponds to the energy at a given power level along the discharge curve.

$$UE = \{E_{Discharge}\}_P \tag{7}$$

In the case where Equation (7) is evaluated at the discharge power target of 6 kW, UE becomes the available energy (AE) and this value is reported in the Gap Analysis as the "Available Energy (750 W accessory load power)" as defined in Appendix B. Figure 14 shows the illustrative Power vs. Energy curve with a numerical value identified at 6 kW. For this given dataset, the ninth discharge pulse still exceeded the 6 kW discharge power target, so the total AE is at the 9th pulse, or 1205 Wh.

UE (at power target) = AE = 1205 Wh

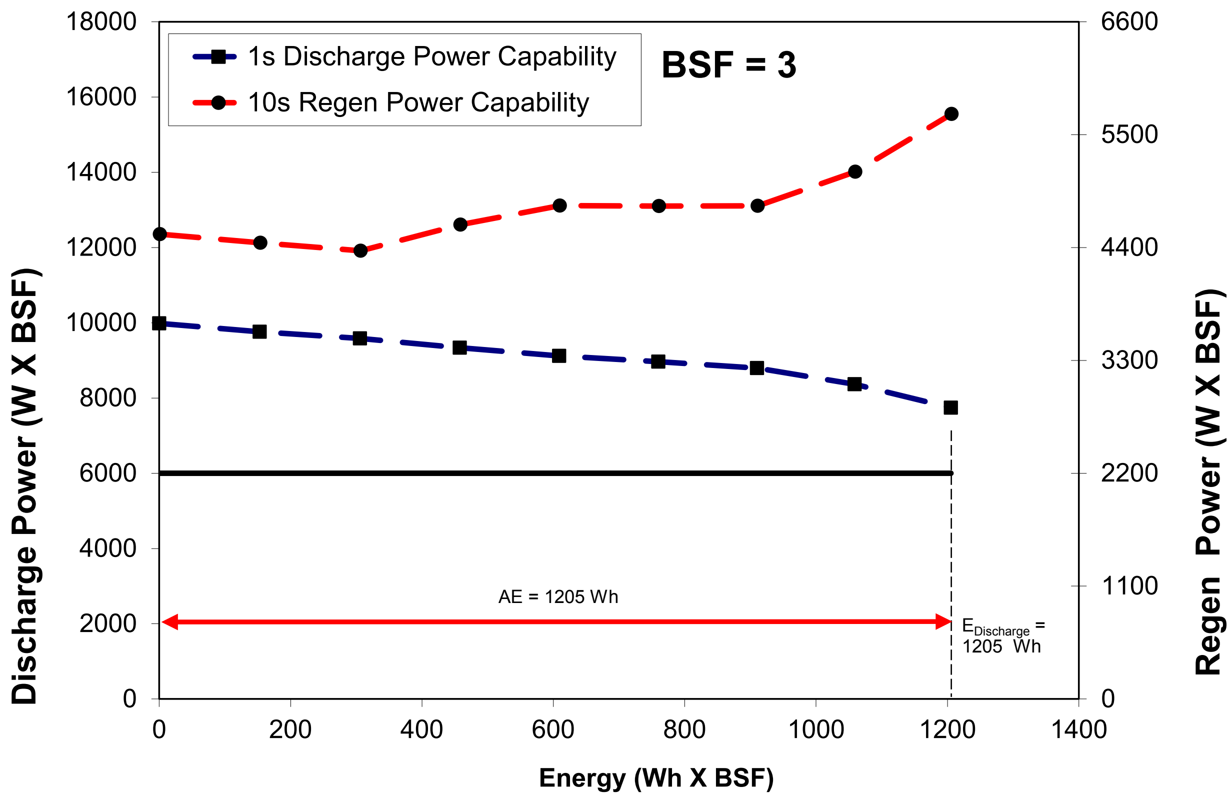

Figure 14. Available Energy Determination.

4.4.5 Available Energy Margins

The Available Energy at the 6-kW discharge pulse power target reduces as a function of aging as the Useable Energy curve shifts due to degradation in the power capability during calendar and/or cycle life. Once the Available Energy meets or falls below the target, 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. The available energy margin is calculated as defined in Equation 8 and illustrated in Figure 15, where $AE_{Total\ Target}$ is the specified available energy target specified in Table 1 (*i.e.*, 360 Wh). Thus, for a given AE of 1,205 Wh, the resulting Available Energy margin is 845 Wh. Figure 15 also shows the shift in the Peak Discharge

Pulse Power 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.[28]

$$AE_{Margin} = AE - AE_{Total\ Target} = 1205\ Wh - 360\ Wh = 845\ Wh \quad (8)$$

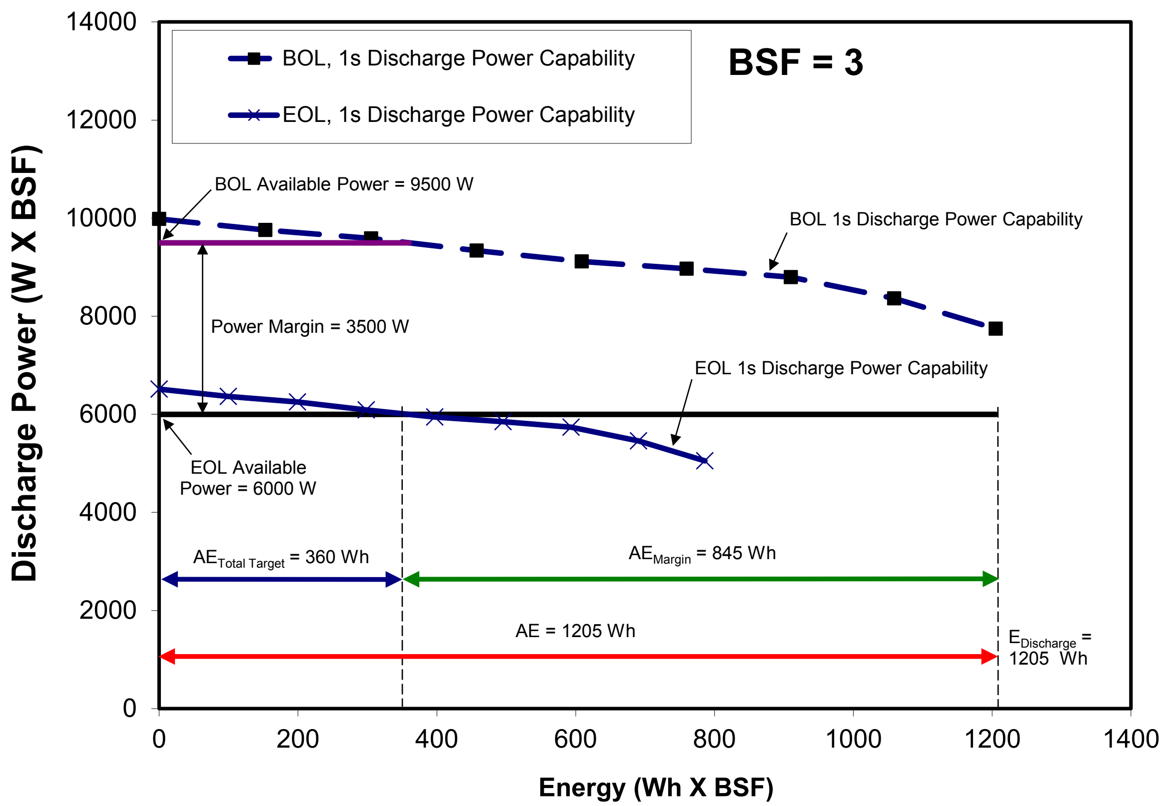

Figure 15. Available Energy and Power Margins Over Life.

4.4.6 Available Power

Available Power 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 360 Wh for 12V S/S applications. This is reported in the Gap Analysis as the Discharge Pulse capability (see Appendix B). The BOL and EOL Available Power are illustrated in Figure 15 above. At BOL, the Available Power was calculated to be 9.5 kW and (in this example case) it is precisely equal to the discharge target power of 6 kW at EOL. Power Margin (also identified in Figure 15) is the difference in discharge power capability between the Available Power at a given point in time during life and the Peak Discharge Pulse Power target of 6 kW.

The Available Power and Available Energy represent complementary aspects in the performance of a test article at a given point in time during life aging. These values can be graphically represented in a Useable Energy vs. Power curve as shown in Figure 16. The corresponding targets of the 12V S/S application are

28. 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.

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).

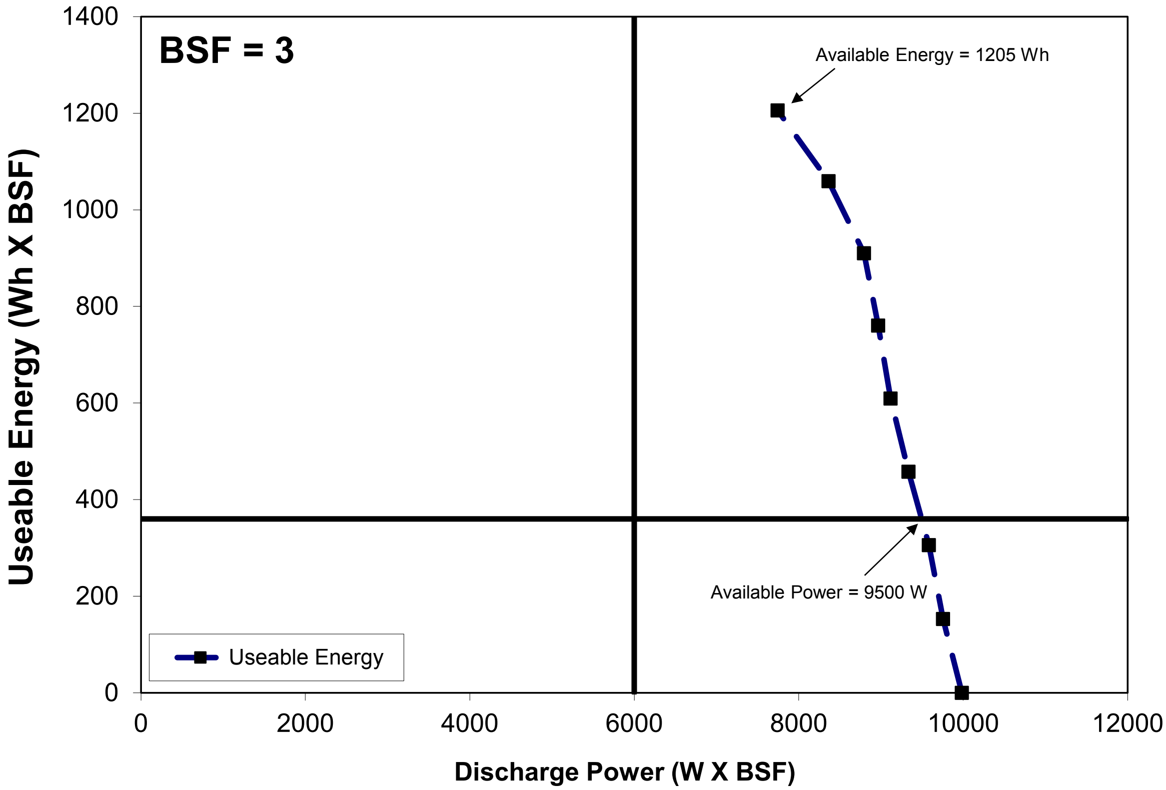

Figure 16. Useable Energy versus Power Curve.

4.4.7 Power and Energy Fade

For devices subjected to life testing, the change in Available Power and 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 (9) and (10).

$$\text{Power Fade}\,(\%) = 100 \times \left(1 - \frac{\text{Available Power}_{t1}}{\text{Available Power}_{t0}}\right) \tag{9}$$

$$\text{Energy Fade}\,(\%) = 100 \times \left(1 - \frac{\text{Available Energy}_{t1}}{\text{Available Energy}_{t0}}\right) \tag{10}$$

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.

4.4.8 Minimum and Maximum Capacities Removed and Cold Crank Condition

Some characterization tests (*e.g.*, the energy verification test in Section 3.4.3) require knowledge of the minimum and maximum capacities removed at which the corresponding power targets are exactly met. A BSF-scaled representation of Figure 10 is shown in Figure 17, 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, the maximum capacity removed is determined from $E_{Discharge}$ at the Peak Discharge Pulse Power target (*e.g.*, 6 kW), which is 80% of the rated capacity removed (*e.g.*, for a 2 Ah cell, 1.6 Ah are removed). Likewise, the minimum capacity removed is, by definition at 0% of rated capacity removed (*i.e.*, $Vmax_{op}$). Note that the location for these conditions are typically fixed at BOL but the discharge power curve shifts as the test article ages. The values for the minimum and maximum capacities removed can be updated at the discretion of the technical program manager.

In addition to the maximum and minimum values, 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 from Table 1 at the 750 W rate (*e.g.*, 360 Wh)[29]. This is accomplished using the methodology discussed in Section 4.4.3 and Figure 11. The resulting capacity removed should be somewhere between the minimum and maximum capacities, as illustrated in Figure 17. In this example case, the cold crank test should be performed at 23.5% of rated capacity removed (*e.g.*, for a 2 Ah cell, 0.47 Ah are removed). Note that when the cold crank test condition exceeds the maximum capacity removed, the test article can no longer successfully perform a cold crank test and has reached end of life.

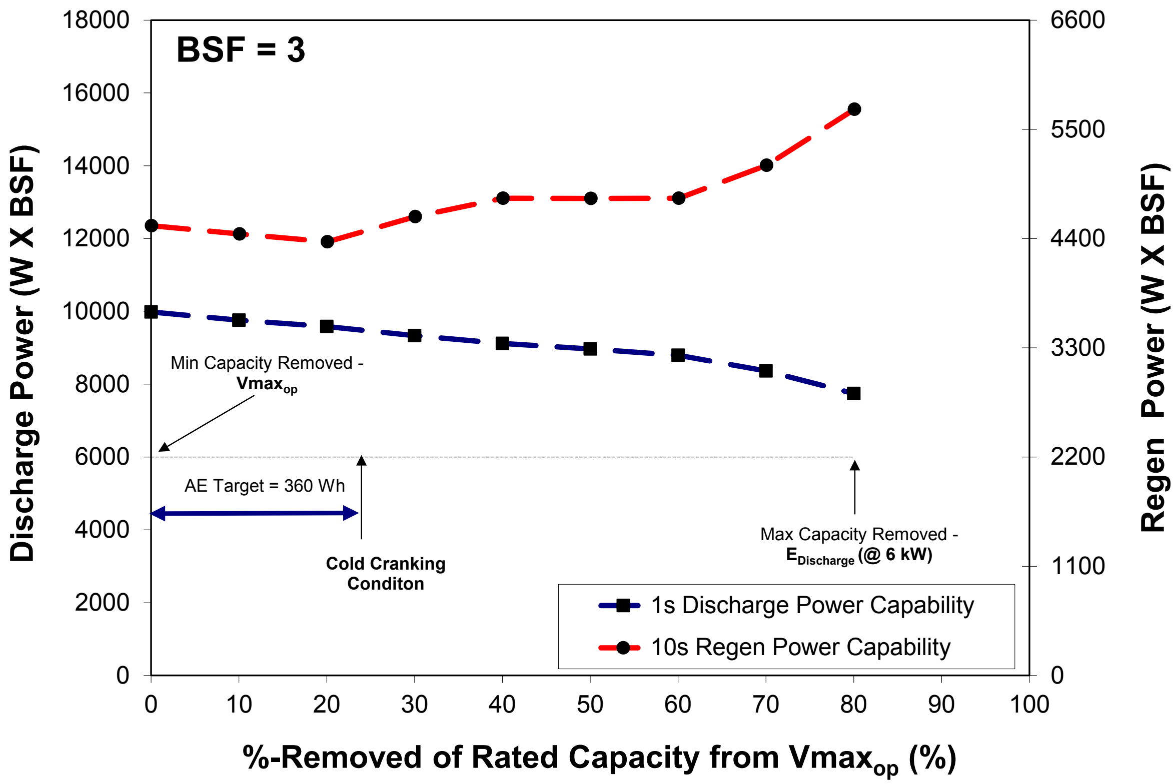

Figure 17. Minimum and Maximum Capacities Removed and Cold Crank Condition.

29. Note that this is referred to as minimum state-of-charge (min SOC) condition in the targets in Table 1.

4.4.9 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 $ohms\text{-}cm^2$ for discharge and for regen from HPPC data for 12 Volt Start/Stop applications. (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.

4.4.10 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 11). 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 30% power 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.[30] First, the unscaled power vs. energy curve is used to find the total Useable Energy of the individual test article. Figure 18 shows the illustrative power vs. energy curve (unscaled). As defined in Section 4.4.4, 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 19.

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30. 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.

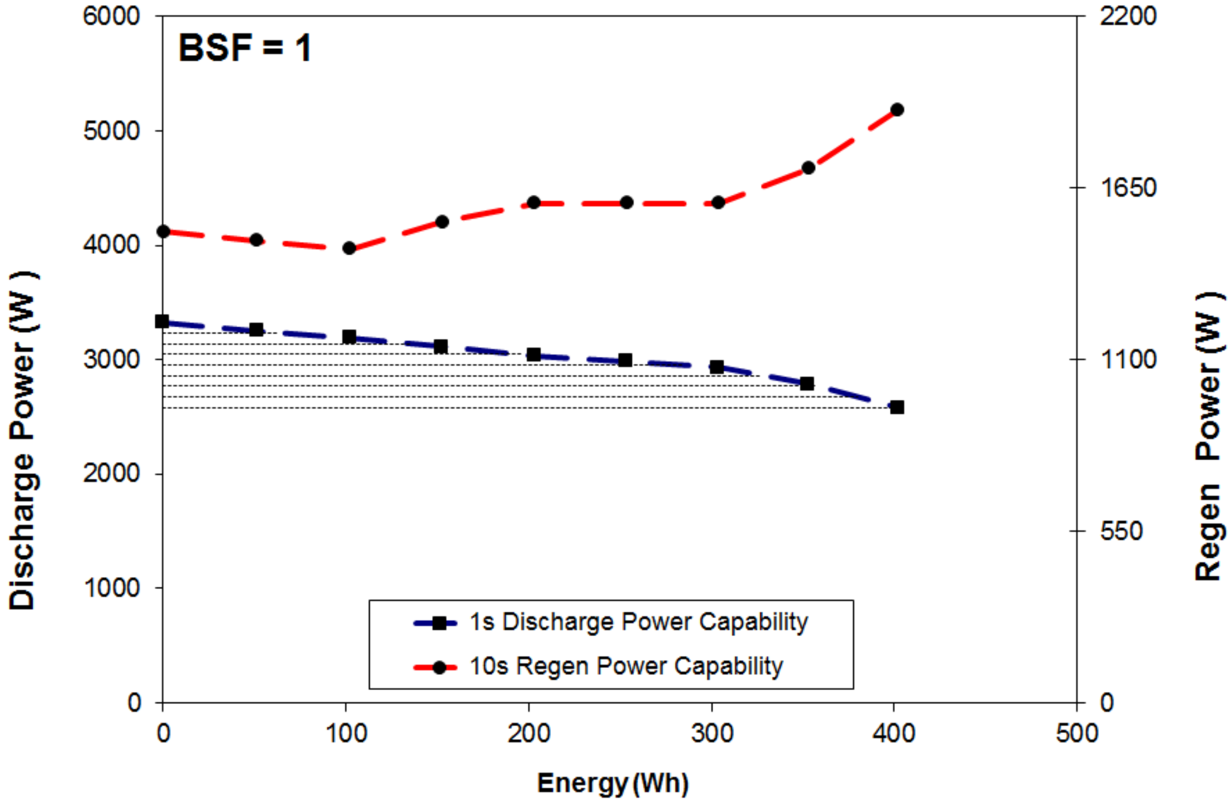

Figure 18. Finding the Useable Energy Using Device-Level Results.

Second, on the useable energy curve, draw a line from the origin having a slope equal to the ratio of the Available Energy target (*i.e.*, 360 Wh) to the Discharge Pulse power target (*i.e.*, 6 kW). This ratio is then multiplied by a factor of 1/1.3 (0.77) to provide a 30% power margin. For the 12V S/S application, the resulting slope of this line is 0.046; this is shown in Figure 19 with the solid green line. Next, determine the point at which this line intersects with the useable energy curve; this corresponds to 144 Wh of energy and 3126 W of power in Figure 19. A scaling factor is then calculated by dividing the numerator of the slope (*i.e.*, 360 Wh) with the energy at the intersection point; this corresponds to 360 Wh / 144 Wh = 2.5. Note that the same value can be determined by dividing the Discharge Pulse power target with the power at the intersection point (6000 W x 1.3 / 3126 W = 2.5). For testing purposes, this BSF should be rounded to the next highest integer (*i.e.*, BSF = 3), but it can be a non-integer for early stage development of a device chemistry with concurrence from the technical program manager. In this illustrative case, a BSF of 3 is used to repeat the HPPC based on the HPPC-Current defined in Section 3.1.5.

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 12V S/S application and the technical program manager should be notified.

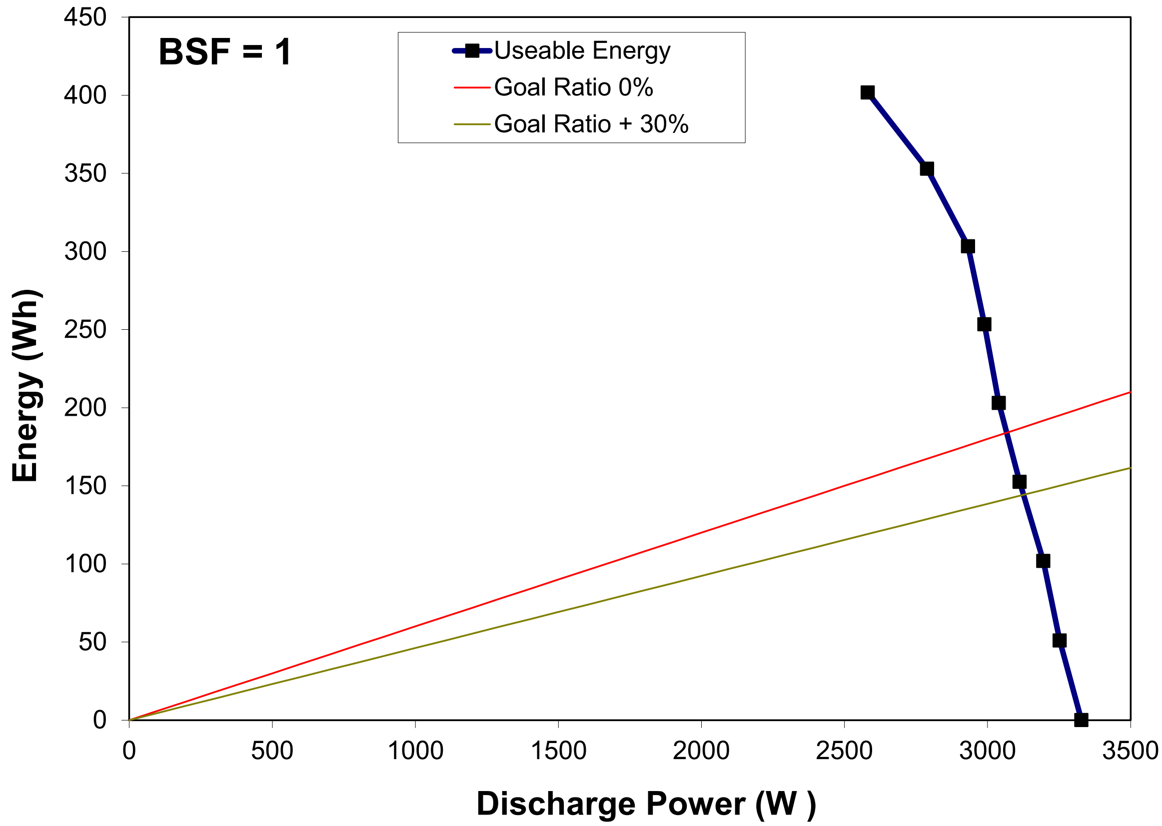

Figure 19. Finding a Battery Size Factor Using Device-Level Results.

4.5 Self-Discharge Test

Self-discharge rate is determined over a fixed period (nominally 7 days) at one or more intermediate test conditions (nominally after removing a 360 Wh). 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 $C_1/1$ energy and the sum of the energies in the partial $C_1/1$ 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, as shown in Equation (11).

$$\text{Self Discharge} = \frac{Wh_{C/1\ \text{before test}} - (Wh_{\text{part 1}} + Wh_{\text{part 2}})}{\text{Stand Time in Days}} \times \text{BSF} \qquad (11)$$

The result of this calculation is reported for comparison with the USABC target of no more than 10 Wh per day. (Note: The self-discharge test for a module with electronic cell balancing circuit etc should be reported to show the cell self-discharge and any parasitic drain on the module.)

4.6 Cold Cranking Test

The fundamental result of the Cold Cranking Test is that the device must maintain voltage at or above 8.0 V while simultaneously meeting both the 6 kW and 4 kW portions of the pulse profile for all three cranks at -30°C. The power capability for the test article is to be multiplied by the Battery Size Factor and compared to the corresponding USABC targets. 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), (t0,t2), (t3, t4), (t3, t5), (t6, t7) and (t6, t8), illustrated in Figure 20, using the same ΔV/ΔI calculation (Equation [3]) used for discharge resistance in Section 4.4.2.

2. Calculate the discharge pulse power capability for each of the Cold Cranking Test pulses using Equation (5) as in Section 4.4.3. The current limitations described in the footnote to this section 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 pulse power capability values by the Battery Size Factor and report the resulting power values for comparison with the USABC targets of 6 kW and 4 kW.

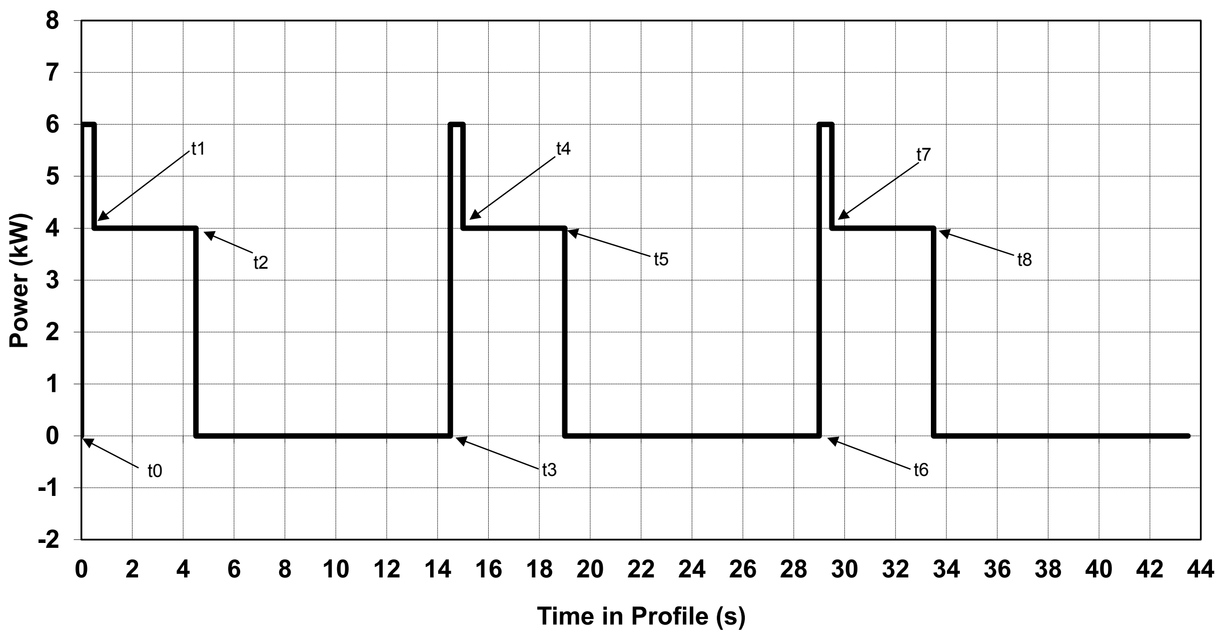

Figure 20. Cold Cranking Test resistance calculation points.

4.7 Thermal Performance Tests

Measured capacity at the 750W rate is reported over the range of temperatures at which the Capacity Test is performed. Results of HPPC testing at temperatures other than nominal are reported in the same formats defined in Section 4.4, except that the test temperature must accompany all data and graphs. The results of the thermal performance test will show the available energy at each temperature.

4.7.1 Survival Temperature Test

The survival temperature test is designed to evaluate degradation at the extreme upper and lower temperatures. The result of this test is reported for comparison with the USABC target of no more than 5% capacity or power loss after the upper and lower temperature test.

4.8 Energy Efficiency Test

Round trip energy efficiency is calculated from an integral number of test profiles of the Efficiency Test. The preferred approach is to use a group of 10 or more consecutive test profiles within the 100 profiles that were performed, 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 cell average SOC (as implied by temperature and peak voltage behavior) is 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% coulombically efficient at the cycling conditions. In the first case, the test must be repeated using additional test profiles. 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 at least one of the profiles, expressed in percent as shown in Equation (12).

$$\text{Round-trip efficiency} = \frac{\text{watt} \cdot \text{hours (discharge)}}{\text{watt} \cdot \text{hours (regen)}} \times 100 \ \ (\%) \tag{12}$$

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.[31] The efficiency is calculated after it is verified that the profile was charge-neutral.

31. The Efficiency Test and Cycle life Test profiles are identical, so Life Test data are directly useable for efficiency calculations if cycling is done at a constant SOC.

4.9 Operating Set Point Stability Test

No results are reported specifically from this test. The current, voltage, and residual capacity data are reviewed to determine that 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.

4.10 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 reported. However, the number of profiles performed is not necessarily the cycle life and should not be reported as such.[32] 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 capability, 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.[33] In general an end of life condition is reached when the device is no longer able to meet the USABC 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 or energy margin (*i.e.*, 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 USABC 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. [34] 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.

4.11 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

32. If the cell can't do the profile, that is the end of life. However, the cell may fail the performance requirements in the middle of the cycle life test, but it won't be caught until the RPT.

33. If the RPT shows that the device has past the end of life, then the cycle life reported is from the prior RPT.

34. 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.

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. The following discussion is limited to the latter approach and is meant to illustrate a general approach to construct a reasonable, data-based model. For a more advanced treatment of life test results, refer to Battery Life Estimator Manual (Reference 6).

4.12 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.

4.13 Module Controls Verification Tests

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.

4.14 System-Level Testing

In general, the analysis and reporting of test results for complete battery systems is conducted similarly to comparable cell tests, with the exception that the BSF will be 1 by definition. Additional reporting requirements (*e.g.*, detailed cell or module performance) should be specified in a device-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. *Battery Test Manual for Electric Vehicles*, Revision 3, INL/EXT-15-34184, June 2015.

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-14-32849, Rev. 3, September 2014

5. *Battery Technology Life Verification Test Manual,* INL/EXT-12-27920, Rev. 1, December 2012

6. *Battery Calendar Life Estimator Manual,* INL-EXT 08-15136, Rev. 1, October 2012

APPENDIX A - SAMPLE TEST PLAN

This appendix provides a sample test plan based on the test requirements for this 12V S/S 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
12V START/STOP TEST PLAN FOR TBD DEVICES

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 12V S/S Program and as outlined in Section 7.0.

2.0 References

2.1 Battery Test Manual for 12 Volt Start/Stop Vehicles, INL/EXT-12-26503, Rev. 1, June 2015

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 Cell Ratings, Test Limitations and Other Test Information

5.1 Ratings

Rated Capacity:	TBD A-h ($C_1/1$ rate)
Application:	TBD 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

5.3 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
≤1 s pulse (**$Vmin_{pulse}$**):	TBD V
≤1 s pulse and temp ≤0°C (**$Vmin_{LowT}$**):	TBD V
Maximum Discharge Current:	
Continuous rates ≤ C_1/1 rate:	TBD A
≤1 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 12 Volt Start/Stop 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 12 Volt Start/Stop 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	**Capacity Test** *(See Reference 2.1, Section 3.2)* Conduct this test on TBD articles at a constant rated $C_1/1$ discharge current. 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 750-W 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 test on TBD articles. The Low Current Test is performed at a peak discharge current of TBD. HPPC Current = TBD.	1

	For all Articles, the HPPC Current discharge will be included in the same data file as the HPPC test for calculation purposes.	
4	**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
5	**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
6	**Thermal Performance Test** *(Reference 2.1, Sections 3.7)* Perform a 750 W 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.*, $\mathbf{Vmin_{LowT}}$) 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
7	**Reference Performance Tests** *(Reference 2.1, Section 3.13)* Perform the 750 W 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. Also include a cold crank every 10% of life increment. 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.	*

8	**Cycle Life Test** *(Reference 2.1, Sections 3.10)* *As directed.*	
9	**Calendar Life Test** *(Reference 2.1, Sections 3.11)* *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 12V Start/Stop 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 1-s discharge power data and the energy data from an HPPC test.

Figure B.1 shows a BSF-scaled Power vs. Energy curve using the same example as in Section 4.0 based on the 12V S/S Application. The *x-axis* represents the cumulative energy removed at the 750-W rate starting from the upper end of the operating window which is defined as $Vmax_{op}$. The *y-axis* represents the calculated 1-s Discharge Pulse power at each 10% increment between $Vmax_{op}$ and $Vmin_0$. The energy target, $AE_{Total\ Target}$ (360 Wh) is defined in Table 1 and labeled in Figure B1 with the blue arrow. The measured Available Energy for this dataset (1205 Wh) is identified by the red arrow. 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 margin (AE_{Margin}) is also shown in Figure B.1 for reference.

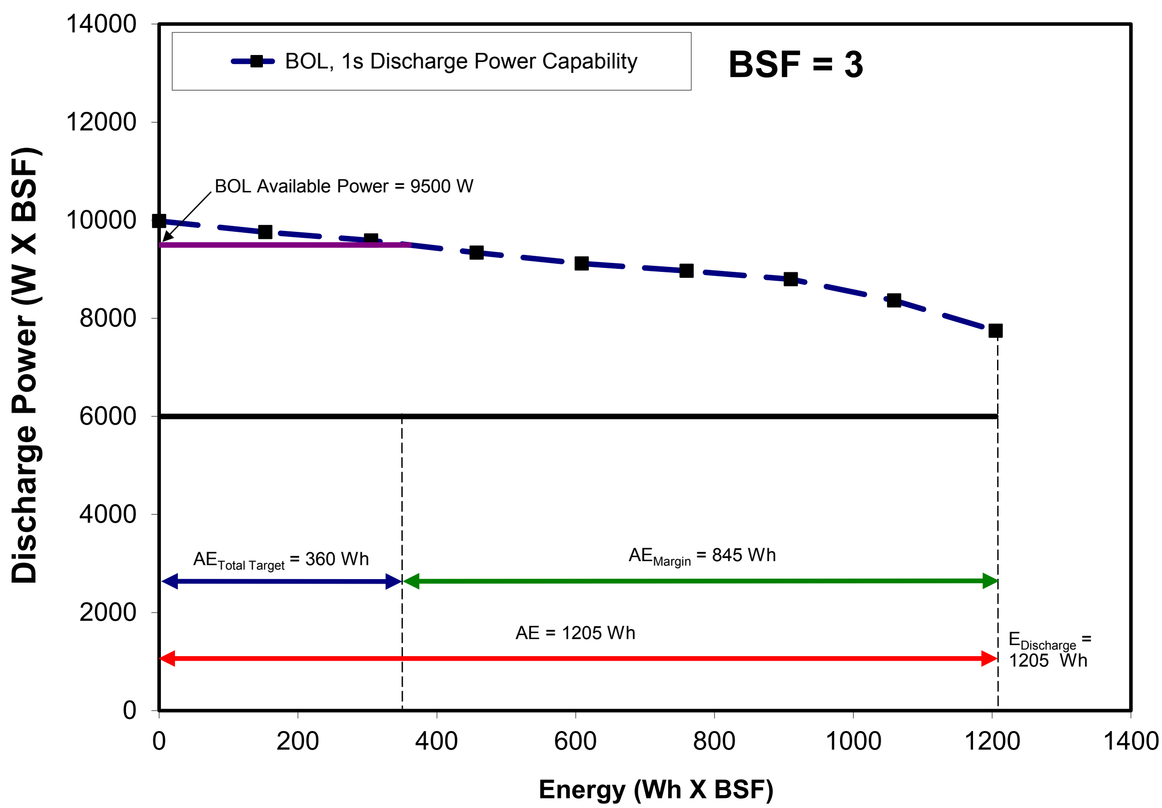

Figure B.1. Gap Analysis – Energy

Alternatively, as described in Section 4.4.6, 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 between $Vmax_{op}$ (i.e, 0 Wh) and $E_{Discharge}$ on the *x-axis* and plotted as a function of the discharge power as shown in Figure 16 and reproduced in Figure B.2. From these curves, the Available Energy and the Discharge Pulse power values can be identified and reported in the Gap Analysis.

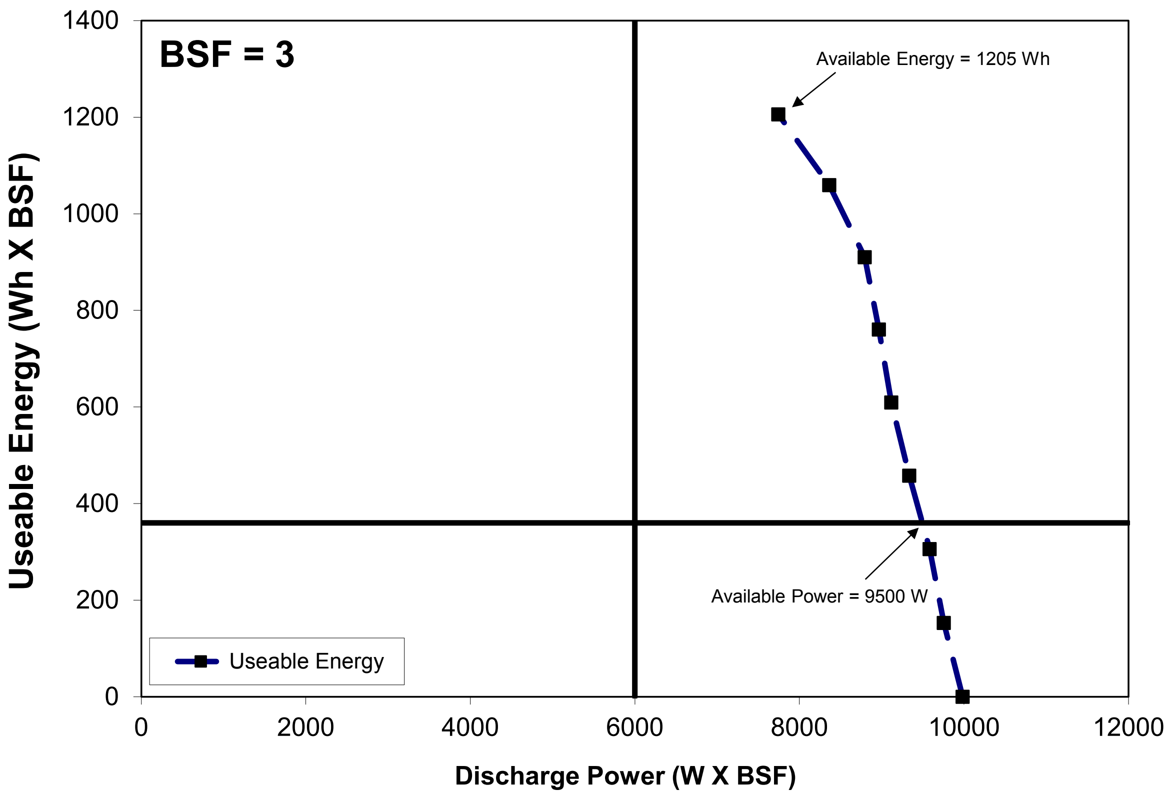

Figure B.2. Useable Energy versus Power Curve

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 ("Not Under Hood" 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.*, within 15% of the target), the value in the Gap Analysis is then highlighted in yellow. Otherwise 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	Not Under Hood	
			RPT0	RPT##
Discharge Pulse (1s)	**kW**	**6**		9.5
Max discharge current, 0.5s	**A**	**900**		
Cold cranking power at -30 °C	**kW, 0.5s**	**6**	TBD	
	kW, 4.0s	**4**	TBD	
Available Energy (750 W)	**Wh**	**360**		1205

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. $Vmin_{op}$ 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.

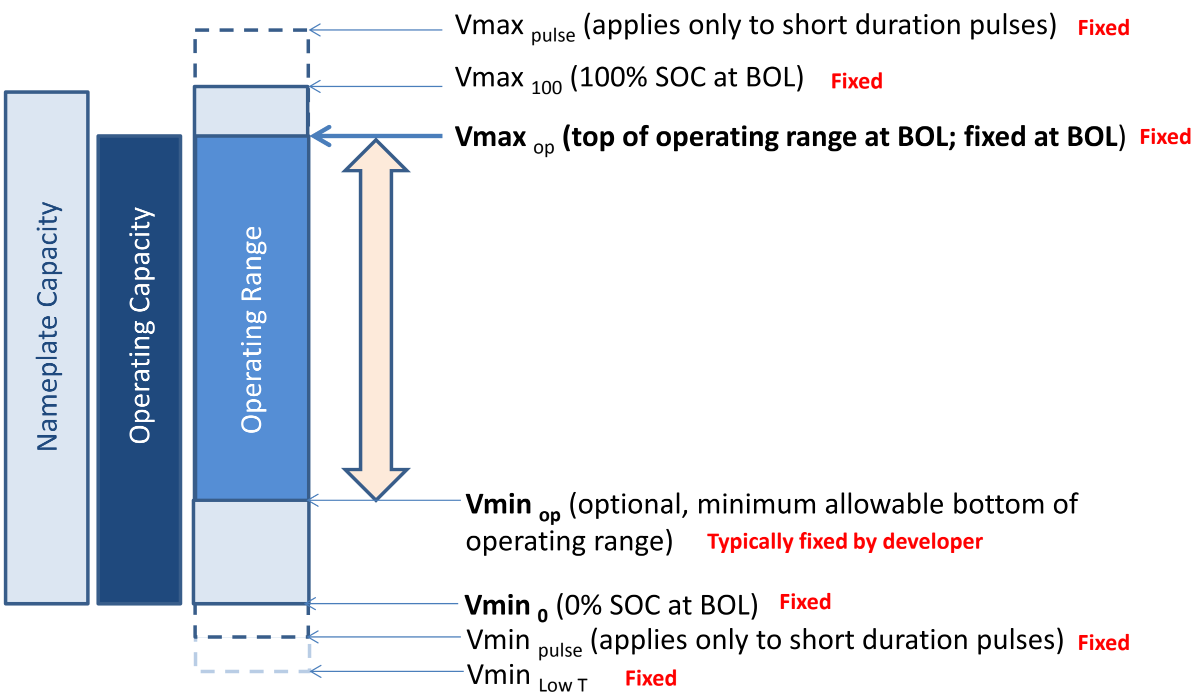

Figure C.1. Voltage Definitions and Key Concepts