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Battery Test Manual For 12 Volt Start/Stop Vehicles

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For 12 Volt Start/Stop Vehicles

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Prepared for the
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Assistant Secretary for Energy Efficiency and Renewable Energy (EERE)
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FOREWORD

This manual was prepared by and for the United Stated Advanced Battery Consortium (USABC) Technical Advisory Committee. It is based on the targets established for 12 Volt Start/Stop energy storage development and is similar (with some important changes) to earlier manuals for the former FreedomCAR program. The specific procedures were developed primarily to characterize the performance of energy storage devices relative to the USABC requirements. However, it is anticipated that these procedures will have some utility for characterizing 12 Volt Start/Stop hybrid energy storage device behavior in general. Scott W. Jorgensen of General Motors Corporation and Harshad S. Tataria of General Motors Corporation assisted in the development of the manual. Jeffrey R. Belt was the primary author for the manual.

A continuing need to improve these procedures is expected. This first published version of this manual defines testing methods for full-size energy storage systems, along with provisions for scaling these tests for cells, modules or other subscale devices. Suggestions or comments should be directed to Jon P. Christophersen, jon.christophersen@inl.gov.

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ACRONYMS

AC	Alternating Current
AE	Available Energy
Ah	Ampere-Hours
BOL	Beginning Of Life
BSF	Battery Size Factor
CPDT	Constant Power Discharge Test
DOD	Depth Of Discharge
EMI	Electromagnetic Interference
EOL	End Of Life
EV	Electric Vehicle
HPPC	Hybrid Pulse Power Characterization
INL	Idaho National Laboratory
OCV	Open-Circuit Voltage
OSPS	Operating Set Point Stability
PHEV	Plug-In Hybrid/Electric Vehicle
SOC	State Of Charge
SOE	State of Energy
RPT	Reference Performance Test
UE	Useable Energy
USABC	United States Advanced Battery Consortium

GLOSSARY[a]

Available Energy –the discharge energy available from top of charge to the DOD where the USABC discharge power target is precisely met.

Available Power –the discharge pulse power at which the useable energy is equal to the Available Energy target.

Battery Size Factor (BSF) – for a particular cell or module design, an integer which is the minimum number of cells or modules expected to be required to meet all the USABC performance and life targets in a parallel and/or series combination. If this value cannot be determined prior to testing, the Battery Size Factor is chosen as the minimum number of cells that can satisfy the USABC energy targets with a 30% power margin at beginning of life or as specified by the manufacturer.

Beginning of Life (BOL) – the point at which life testing begins. A distinction is made in this manual between the performance of a battery at this point and its initial performance, because some degradation may take place during early testing prior to the start of life testing. Analysis of the effects of life testing is based on changes from the BOL performance.

C_1/1 Rate – a current corresponding to the manufacturer's rated capacity (in ampere-hours) for a one-hour discharge at the beginning of life. 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.

Depth of Discharge (DOD) – the percentage of a device's rated capacity removed by discharge relative to a fully charged condition, normally referenced to a constant current discharge at the 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.)

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

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

Energy Margin – for a given HPPC test data set, the difference between the Available Energy and the energy target for a given application.

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[a] Only selected terms specific to this manual or those frequently misunderstood in the context of this manual are defined here. A more comprehensive list of battery-related terms is found in the USABC Electric Vehicle Battery Testing Manual, Reference [1].

Fully Charged – The condition reached by a device when it is subjected to the manufacturer's recommended recharge algorithm. This state is defined as 100% State of Charge, or 0% Depth of Discharge.

Hybrid Pulse Power Characterization (HPPC) Test – a test procedure whose results are used to calculate pulse power and energy capability under USABC operating conditions.

Maximum Rated Current (Imax) – the maximum discharge current that a manufacturer will permit to be sustained by a device for 0.5s, 1s, or continuous based on the test at hand. (This value need not be achievable at all DOD values.)

Power Fade—the change in Available Power from the beginning of life value to the value determined at some later time, expressed as a percentage of the BOL value. (Similar definitions apply to Resistance Rise, Capacity Fade and Available Energy Fade, although these are not included in this glossary.)

Power Margin – for a given HPPC test data set, the difference between the maximum power at which the applicable energy target can be met and the power target for a given application.

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

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

Regen – 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.

State of Charge (SOC)—the available capacity in a battery expressed as a percentage of rated capacity. (Handbook of Batteries, 3rd Edition)

Useable Energy –an amount of energy (calculated from HPPC test results) that represents the discharge energy available over a DOD range between full charge and the corresponding USABC discharge power target. Available Energy is the value of useable energy at the actual USABC discharge power target value.

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 cycle/calendar life behavior of batteries for 12 volt start/stop vehicle applications. The test procedures defined in this manual are specifically based on the United States Advanced Battery Consortium (USABC) program targets for 12 volt start/stop vehicles (see Section 1.1) and are directly applicable to complete battery systems. However, most of these procedures can also be applied with appropriate scaling to the testing of cells, modules or less-than-full-size batteries. Much of the rationale for the test procedures and analytical methodologies utilized in this manual evolved from the Battery Test Manuals [1, 2, 3, and 4]

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

The USABC 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 Power-Assist 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	A	900	
Cold cranking power at -30 °C (three 4.5-s pulses, 10s rests between pulses at lower 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 cycles (engine starts) /150k miles	
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	Vdc	15.0	
Sustained Operating Voltage - Max	Vdc	14.6	
Minimum Operating Voltage under Autostart	Vdc	10.5	
Operating Temperature Range (available energy to allow 6-kW (1s) pulse)	°C	-30 to + 75	-30 to +52
30 °C – 75 °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

*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.

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 battery characteristics, i.e., independent of the size or capability of the device to be tested. These 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 or cycle life tests for cells or modules.

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.[2] 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 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 "Not Under Hood" applications. For "Under Hood" applications, the default nominal temperature shall be 45°C± 3°C. However, in some cases, it may be preferred to conduct

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2. In this manual, unless specifically stated otherwise, the desired state of charge for a test is established as a depth-of-discharge (DOD) value, which is always reached by removing the appropriate fraction of the rated capacity from a fully charged device (normally at a $C_1/1$ constant-current discharge rate.) Also, the term "fully charged" means "charged in accordance with the manufacturer's recommended procedure".

full charges and discharges to the designated state of charge condition at 30ºC ± 3°C for "Under Hood" applications so as not to induce artificial degradation mechanisms on the test articles. The disadvantage to this method, however, is the additional thermal cycling during testing as well as the extended test time due to the soak periods. The methodology to set the state of charge condition for an "Under Hood" application should be specified in a device-specific test plan. 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.

3.1.2 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.

3.1.3 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 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 be an integer value that aligns with all performance requirements and can be configured for series and/or parallel strings.

3.1.4 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 be used for the 10% DOD (depth-of-discharge) constant current discharge segments.

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[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.

The HPPC-Current is calculated using the formula below.

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

where I_{HPPC} is the HPPC discharge current between pulses, P_{CPD} is the Constant Power Discharge target, and V_{avg} is the average electrochemical voltage between V_{max} and V_{min} (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].

3.2 Capacity Test

This test measures device capacity in ampere-hours at a constant current discharge rate corresponding to the manufacturer's rated $C_1/1$ capacity in ampere-hours (e.g., if the rated one-hour discharge capacity is 10 Ah, the discharge rate is 10 A.) Discharge is terminated on a manufacturer-specified discharge voltage limit. The one-hour rate ($C_1/1$) is used as the reference for capacity and energy measurement and as a 'standard' rate for module and system-level testing. The slower rates more commonly used for electric vehicle (EV) batteries are unrealistically low for 12 volt start/stop hybrid applications.[5]

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 and is terminated on a manufacturer-specified discharge voltage limit, followed by a one-hour rest at open-circuit voltage. Recharge the device using the 750-W rate.

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 DOD range using a test profile that incorporates both discharge and regen pulses. The primary objective of this test is to establish, as a function of depth of discharge, (a) the V_{MIN} discharge power capability at the end of a 1-s discharge current pulse and (b) the V_{MAX} regen power capability at the end of a 10-s regen current pulse.[6] These power capabilities are then used to derive other performance characteristics such as Available Energy and Available Power. Secondary objectives when used for cell testing are to derive from the voltage response curves the fixed (ohmic) cell resistance and

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[4] The HPPC current should be compared with the average current for a scaled 750-W discharge. An alternate method to determine the HPPC current is as follows (HPPC Current = 750-W / (BSF *(Device Energy/ Device Capacity)).

[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.

[6] V_{MIN} and V_{MAX} refer to the cell minimum and maximum voltages that correspond to the USABC operating voltage range as defined in Table 1. For cells, the specific voltages can be any values appropriate to the technology as long as they fall within the BSF-scaled Table 1 limits.

cell polarization resistance as a function of state of charge (SOC) with sufficient resolution to reliably establish cell voltage response time constants during discharge, rest, and regen operating regimes. The resistance calculations will 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 profile is to demonstrate the discharge pulse and regen pulse power capabilities at various depth of discharge (DOD) values for the targets (1-s discharge, 10-s regen). The normal test protocol uses constant current (not constant power) for the HPPC current. Between each pair of discharge and regen pulses, the device is discharged to the next 10% DOD increment using the HPPC-Current (I_{HPPC}) as determined in Section 3.1.3. The characterization profile is shown in Table 2 and Figure 1.

Table 2. Hybrid Pulse Power Characterization Test profile.

Time Increment (s)	Cumulative Time (s)	Relative Currents
1	1	1.00
40	41	0
10	51	-0.33

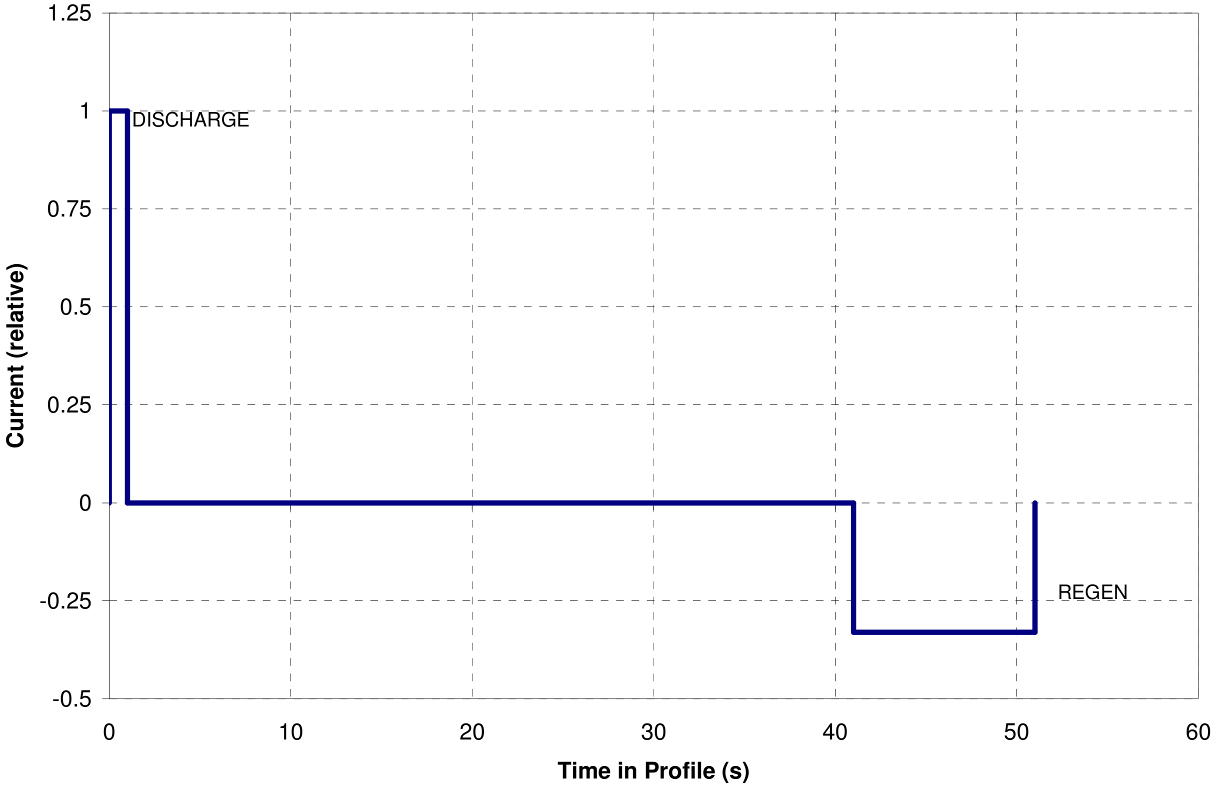

Figure 1. Hybrid Pulse Power Characterization Test profile.

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

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, separated by 10% DOD constant current discharge segments,[7] each followed by a 1-hr rest period to allow the cell to return to an electrochemical and thermal equilibrium condition before applying the next profile. The constant current used during these segments i.e., between the pairs of discharge and regen pulses is the HPPC-Current as determined in Section 3.1.3. The test begins with a fully charged device after a 1-hr rest and terminates after completing the final profile at 90% DOD, followed by a discharge of the cell at the HPPC-Current rate to 100% DOD, and a final 1-hr rest.[8] 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

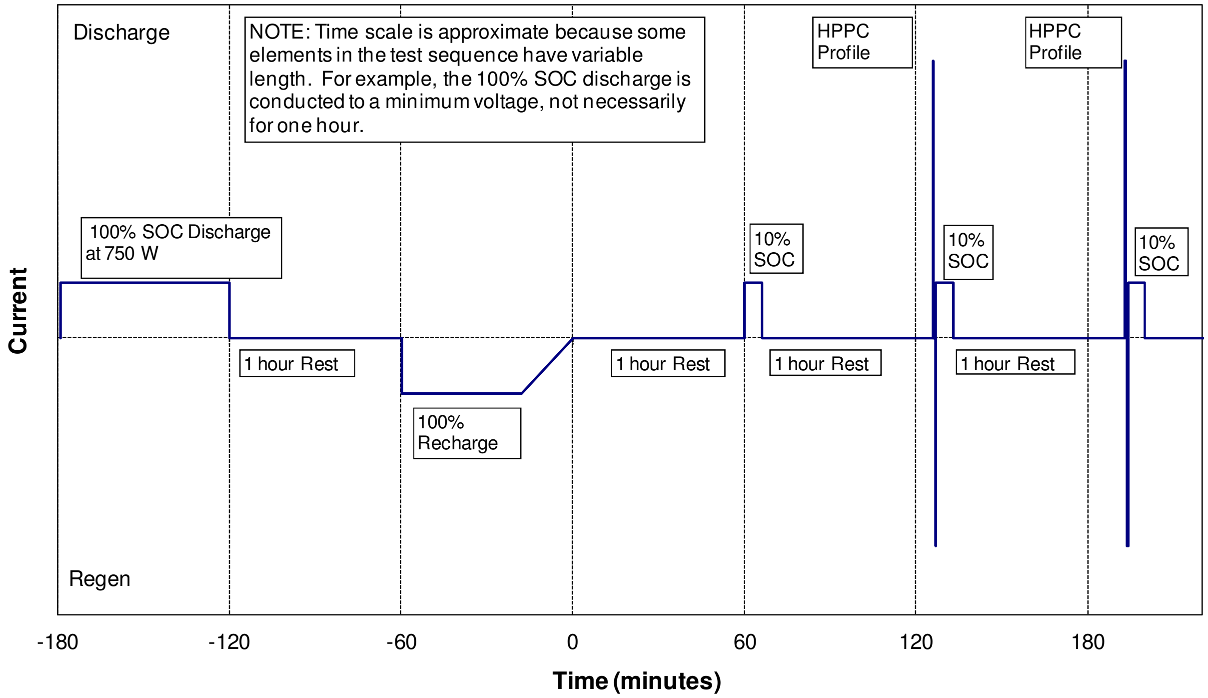

Figure 2. Hybrid Pulse Power Characterization Test (start of test sequence).

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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.

[8] Note that the manufacturer's limits must be observed during all test procedures. If the discharge voltage limit is reached during the actual pulse profiles, discharge or regen steps shall be voltage-clamped to stay within limits, and the test sequence shall continue if the discharge rate can be sustained to the next 10% DOD increment.

illustrate a 750-W constant power discharge to be executed just prior to each HPPC test.[9] 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 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.

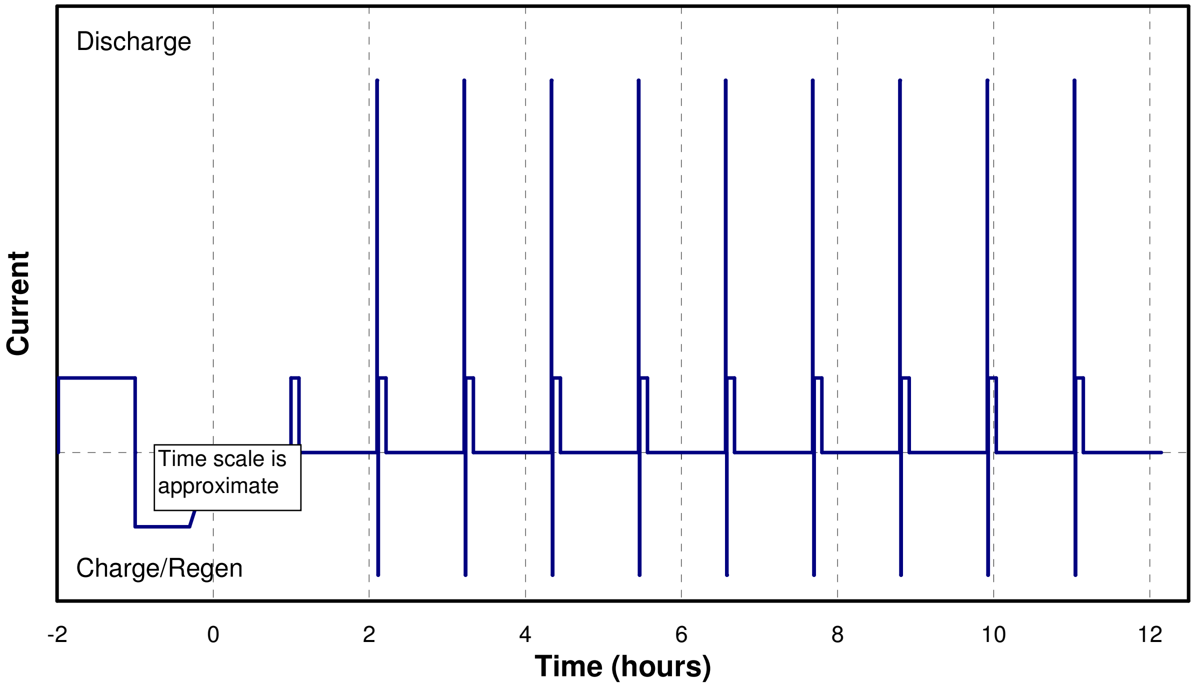

Figure 3. Hybrid Pulse Power Characterization Test (complete HPPC sequence).

3.4.3 HPPC Verification Test

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

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[9] 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.

of this conservatism by performing a test at the actual target values. This is done using a special test sequence as follows:

The HPPC Verification Test can be performed in one of two ways. If the power-versus-energy data plot (calculated using Section 4.4.3) does not show crossover between the discharge power capability curve and the regen power capability curve, then the test sequence is as follows:

1. Starting with a fully-charged battery, discharge to a manufacturer-recommended minimum DOD (DOD_{MIN}) at a 750W constant power rate, and then rest for one hour at open-circuit conditions. If the manufacturer does not provide a value for DOD_{MIN}, then determine a value based on the HPPC test results such that removing an additional 360 Wh of energy does not result in a full discharge (e.g., 0% DOD).

2. Perform a regen pulse at the BSF-scaled target power from Table 1.

3. Recharge the device using the manufacturer's recommended procedure.

4. Discharge to DOD_{MIN} at a 750W constant power rate, and then rest for one hour at open-circuit conditions.

5. Discharge an additional 360 Wh of energy at a 750W constant power rate, and then rest for one hour at open-circuit conditions.

6. Perform a discharge pulse at the BSF-scaled target power from Table 1.

If the power-versus-energy data plot (calculated using Section 4.4.3) does show crossover between the discharge power capability curve and the regen power capability curve, then the test sequence as follows:

1. From HPPC test results, calculate (a) the minimum DOD value DOD_{MIN} at which the regen pulse power target can be met, (b) the maximum DOD value DOD_{MAX} at which the discharge pulse power target can be met, and (c) the Available Energy, which is the energy discharged at a HPPC-Current rate between DOD_{MIN} and DOD_{MAX}. These values are calculated using Section 4.8.8 of this manual.

2. Starting with a fully-charged battery, (Perform this step only if DOD_{MIN} is not 0% DOD)discharge to DOD_{MIN} at a 750W constant power rate, and then rest for one hour at open-circuit conditions.

3. Perform a regen pulse at the BSF-scaled target power from Table 1.

4. Recharge the device using the manufacturer's recommended procedure.

5. Discharge to DOD_{MAX} at a 750W constant power rate, and then rest for one hour at open-circuit conditions.

6. 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

1. Perform an HPPC test on the device to establish the initial performance.
2. Recharge the device using the manufacturer's recommended procedure.
3. Perform a 500 ms pulse at the maximum current (i.e., 900 A) 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. 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:

1. Measure the actual cell capacity from full charge to the discharge voltage limit using a $C_1/1$ constant-current discharge rate, and recharge it using the manufacturer's recommended charge algorithm.
2. Discharge 30% of the rated capacity at a $C_1/1$ rate (i.e., 30% DOD) from the cell, and allow it to stand in an open-circuit condition for a nominal interval of 7 days.[10] (The actual stand period should be selected based on the expected stand loss rate, with the value chosen to yield an expected capacity loss of 5% or more over the interval.) All measurement equipment may need to be disconnected from the cell during this period to reduce parasitic losses.
3. Discharge the cell 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:

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[10] Although 30% DOD is the default nominal condition for this test, the actual value to be used is commonly defined in a device-specific test plan. The DOD value that will be used for cycle life or calendar life testing is a typical value.

1. Measure the actual cell capacity from full charge to the discharge voltage limit using a $C_1/1$ constant-current discharge rate, and recharge it using the manufacturer's recommended charge algorithm.

2. Discharge 30% of the rated capacity at a $C_1/1$ rate (i.e., 30% DOD) from the cell, and allow it to stand in an open-circuit condition for an interval of 30 days at 30°C.[11] All measurement equipment may need to be disconnected from the cell during this period to reduce parasitic losses.

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

4. Discharge the cell for its remaining (residual) capacity at a $C_1/1$ discharge rate (This can be used to determine the SOC after the test was complete).

5. Recharge the cell using the manufacturer's recommended charge algorithm and discharge using a $C_1/1$ constant-current 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 at the maximum DOD (~minimum state of charge) where the USABC Available Energy target is just met, this DOD point is based on BOL HPPC data and is invariant,[12] 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 DOD (the maximum DOD) using one of the following approaches:

    a. From the HPPC test, discharge the fully charged device at a $C_1/1$ constant current discharge rate to the maximum DOD value (minimum state of charge) as defined in Section 4.4.8. A simpler method to find the cold cranking DOD is to remove a BSF scaled 360 Wh (determined as above in Section 3.4.3) for the standard cold cranking test.

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

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 3.1.3 and 4.4.11. Note that the manufacturer may specify a different minimum discharge voltage for cold cranking testing.

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[11] Although 30% DOD is the default nominal condition for this test, the actual value to be used is commonly defined in a device-specific test plan. The DOD value that will be used for cycle life or calendar life testing is a typical value.

[12] The analysis procedure to determine this DOD value is described in Section 4.4.8.

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.

3.6.1 Cold Cranking Test Profile

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

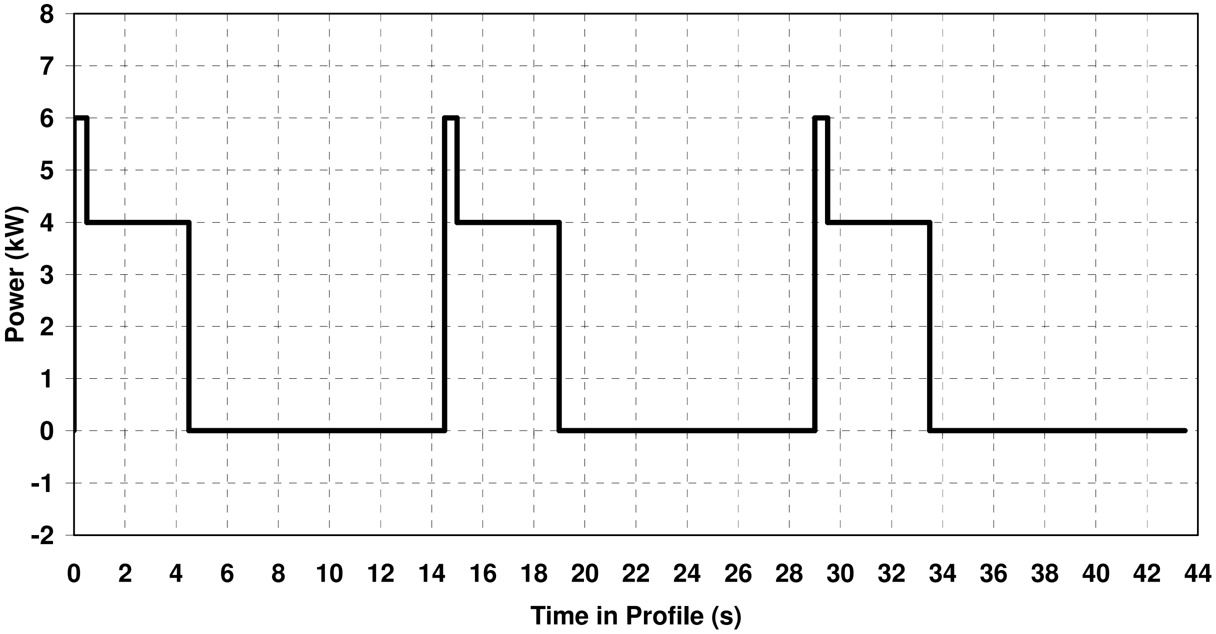

Figure 4. Cold Cranking Test profiles.

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.

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 (-30 to +75ºC), under hood and (-30 to +52ºC), not under hood. 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.

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 (-46 to +100ºC), under hood and (-46 to +66ºC), not under hood. Unless otherwise specified in a device-specific test plan, charging should be performed at the reference temperature (30 ±3ºC). The device should generally be at 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, perform a constant power discharge and charge test followed by a L-HPPC.

2. Bring the device to 50% DOD at 30°C using the $C_1/1$ constant-current rate.

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, 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, perform a constant power discharge and charge test followed by a L-HPPC.
2. Bring the device to 50% DOD at 30°C using the $C_1/1$ constant-current rate.
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, 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 5% or more), or the data indicate that stable cycling was not achieved by the completion of 100 profiles, repeat the test with different SOC control values or additional profiles, as appropriate.

3.8.1 12 Volt Start/Stop Efficiency Test Profile

The 12 volt start/stop efficiency test profile is a 240-s, nominally charge-neutral pulse profile (also used as the 12 volt start/stop Cycle Life Test profile) that is scaled to a level appropriate to verify the round trip energy efficiency target of 95%.[13] This test profile is defined in Table 4 and illustrated in Figure 5.

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[13] 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 OSPS Test if the same SOC value and temperature are used.

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
120	240	0		

*Note: The profile will be charge-neutral profile and tweaked periodically (e.g. every week) to validate the target Voltage (SOC) maintenance.

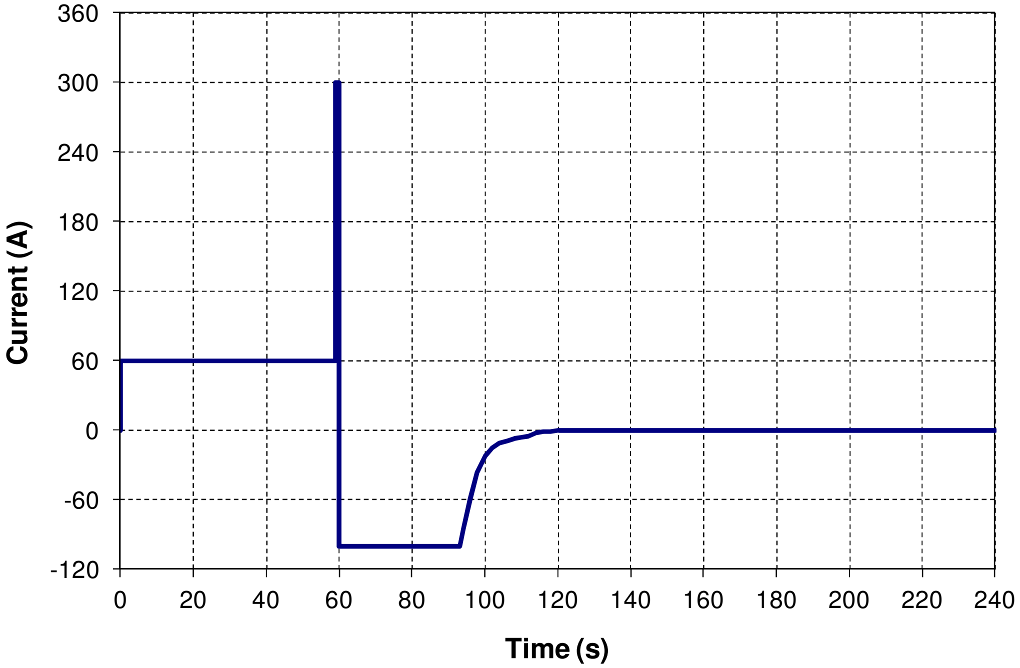

Figure 5. 12 Volt Start/Stop Cycle Life Test profile.

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.[14] This test should be performed immediately before the beginning of cycle life testing.

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[14] 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 4.3) based on the peak discharge and regen powers planned for 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.[15] 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 5% or more.

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. Determine end-of-test criteria for cycle life testing. These are normally specified in a device-specific test plan. A default (and generally mandatory) end-of-test condition is

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

reached when the test profile cannot be executed within the discharge and regen voltage limits.[16]

Another default end-of-test condition also occurs if performance degrades to a point where the HPPC reference test yields insufficient information to show further degradation.[17]

End of test is normally chosen to occur when one of the following conditions exists: (a) cycle life meeting the USABC targets has been attained (i.e., the number of properly scaled test cycles exceeds the applicable USABC target); or (b) Available Energy 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.[18]

4. Select the desired operating state of charge for cycle life testing and perform the Operating Set Point Stability Test (Section 3.9) to verify stable operation at the selected SOC point. Make any needed adjustments to the test profile or test operating conditions.

5. Repeat the selected test profile at the desired operating conditions the number of times specified in Table 7 or a device-specific test plan.[19]

6. 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 1-hr rest. 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.

7. If the residual capacity measured in Step 5 indicates an unacceptable drift in DOD during cycling, repeat Step 4 to re-establish the target cycling condition.

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

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 240-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

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16. At this point, the cell 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.

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

18. Note that *end of test* and *end of life* are not the same, and they may not even be related. See the Glossary for more information on this distinction. The determination of End of Life and Cycle Life is discussed in Section 4.9.1.

[19] More definition of the sequencing of the three test profiles will be provided later.

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.

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
120		240		0				

*Note: The profile will be charge-neutral profile and tweaked periodically (e.g. every week) to validate the target Voltage (SOC) maintenance.

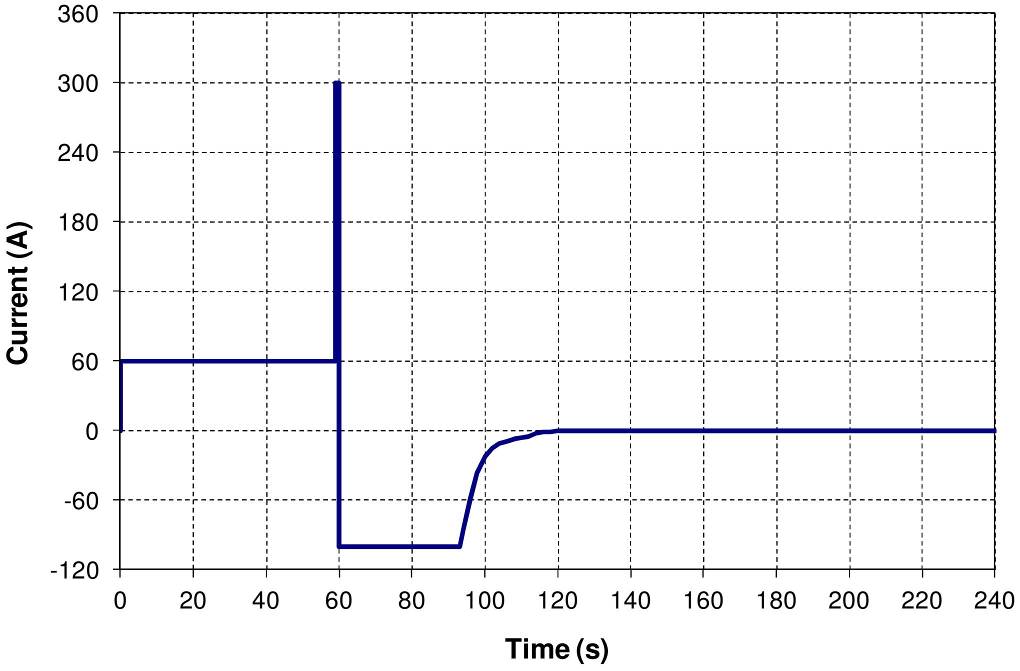

Figure 6. 12 Volt Start/Stop Cycle Life Test Profile.

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.[20] It is commonly done at elevated temperatures in order to shorten the time required for obtaining useful results. Cells to be tested may be included in a matrix of test variables such as temperature and state of charge. This matrix may in turn be part of a larger cycle life test matrix where calendar life testing 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 [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 (and the corresponding SOE), the cells should be brought back to nominal operating temperature (i.e., 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).

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20. 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.

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 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 DOD/SOC value 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 DOD/SOC 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.[21] Note that the default method will typically reach the target DOD 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., 5 X HPPC Current.)

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.[22]

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[21] 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.

[22] 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

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 1-hr rest, and apply a single iteration of the Calendar Life Test profile before discharging its remaining 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.

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
47	120	0.1083	0

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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.

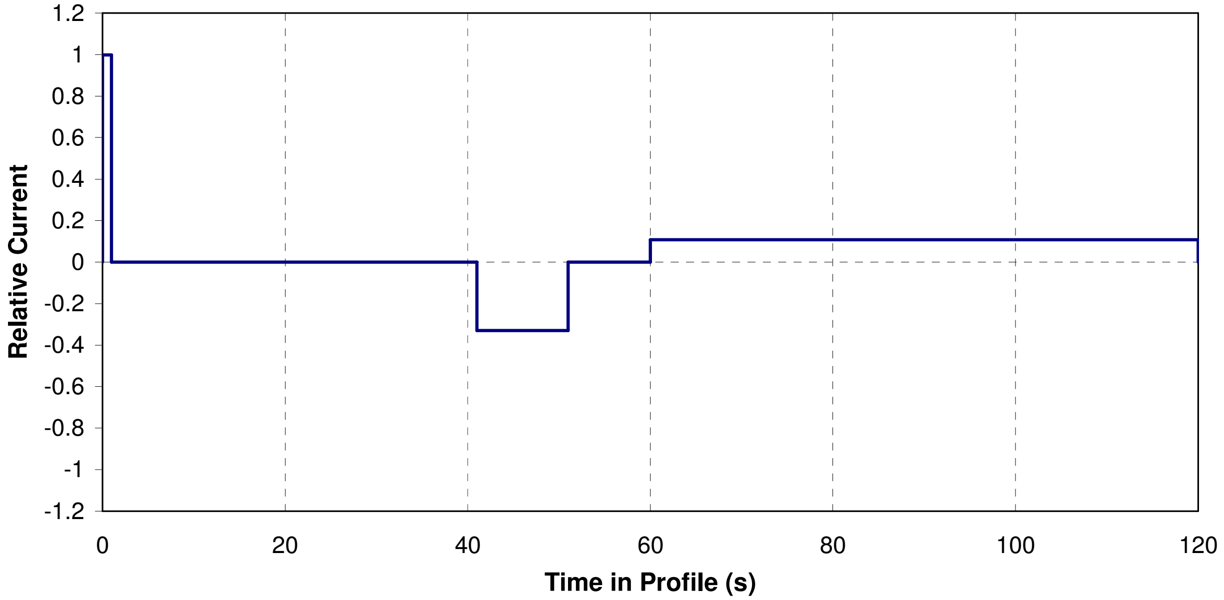

Figure 7. Calendar Life Test profile.

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. [23]

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[23] 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.[24] Note that for "Not under hood" applications, the reference temperature for the RPTs shall be 30±3°C and for "Under hood" applications, the reference temperature for the RPTs shall be 45±3°C.

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

Type of Life Testing	Interval Between RPTs	Reference Performance Tests
Cycle Life Testing	11,520 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 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.

3.13 Impedance Spectrum Measurements

For cells, it may be useful to measure AC impedance values at various points during life. These measurements are generally made with the cell at open-circuit conditions, i.e., not under load. Thus, they are not considered *tests* in the sense commonly used in this manual but are instead treated as special measurements. No standard measurement procedures are defined for this use. However, the following measurement practice is recommended, especially for cells that are to be life-tested:

1. An initial measurement should be made when a cell is received for testing, as a gross check on the condition of the device. This measurement can be taken at the state of charge at which the device is received, so that it can be done prior to the cell's installation in a testing station. A simple 1-kHz AC impedance meter can be used for this measurement.

2. A full-spectrum complex impedance measurement scan should be made prior to the start of life testing, and then repeated when life testing is concluded. This measurement will not normally be performed during life testing because it requires disconnecting the device from the testing equipment. However, this can be required in a device-specific test plan if data are needed for a particular use.

A list of specific issues to be considered for such testing, along with some suggested default values for test conditions, is included in Appendix A.

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24. The Cold Cranking Test is performed every 4th RPT 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 4th RPT. 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.

3.14 Module Controls Verification Tests (Module-Level Testing)

Standard tests have not been defined for the verification of battery module control behavior, in part because the functions provided by such controls are not standardized. Such verification can be performed through use of special testing requirements in device-specific test plans. Candidate functions to be tested include the following (where appropriate to specific module designs):

Electrical Behavior	- Power and energy required for module controls
	- Electromagnetic interference (EMI) generation and susceptibility
	- Cell balancing behavior and energy use
Thermal Behavior	- Effectiveness of thermal control (cooling and/or heating) with ambient temperature variation
	- Energy required for thermal control (cooling and/or heating) with ambient temperature variation

3.15 Thermal Management Load (System-Level Testing)

Verification of overall thermal behavior is necessarily done at the system level due to the broad operating temperature range (-30 to +75ºC), under hood and (-30 to +52ºC), not under hood specified by the USABC targets. Most battery technologies will require active thermal management to maintain acceptable performance and life while operating over this range, and this may impose substantial penalties in overall system energy efficiency. The internal operating and storage temperatures selected for various battery technologies (for performance and life reasons) will interact with the USABC operating temperature range in a manner that is influenced by the statistics of annual climatic (i.e., in-vehicle) conditions in various geographic locations.

A process for evaluating the effects of these interactions (primarily in terms of energy losses) has been defined and is described in Appendix F, of the *FreedomCAR Battery Test Manual for Power-Assist Hybrid Electric Vehicles [3*. This process is analytical in nature, but its use requires test data on battery efficiency, battery heat capacity and other physical characteristics, as well as the intended operating and storage temperature conditions. (Operating and storage temperature targets may be different due to the tradeoff that often exists between performance and calendar life, as well as practical limits on maintaining battery temperature during non-operating states.) Most of the required performance and life data will be gathered at the cell or module level, and basic energy costs for module control and conditioning will be determined by module testing. However, overall tradeoffs must be made in the context of a complete system design (or at least an assumed design), and experimental verification of thermal effects (including control effectiveness) at the system level is highly desirable.

3.16 System-Level Combined Life Verification Test

Once the cycle life and calendar life of a battery have been established through testing of relevant designs, it will be necessary to verify that both the cycle and calendar life targets will be met concurrently in the same battery. This should be done using a test protocol that combines cycling operation and storage at elevated temperatures, with the objective of validating a battery system life model at accelerated stress conditions. This testing, conducted concurrently on multiple complete systems, should be sufficiently robust to enable battery life projections, using the validated model, over a wide range of intended in-vehicle usage conditions. The target duration for such testing should be no more than one year. Note that it may not be necessary to have reached the batteries' end-of-life condition, merely to have reached a level of deterioration sufficient to validate the battery life model.

In principle such a test regime consists of a calendar life test performed as in Section 3.11, interspersed with periodic (typically daily) intervals of life cycling. The number of life cycles to be performed each day is determined by dividing the total cycle life target by the predicted calendar life (in days) at the test temperature. For example, if the projected calendar life of a battery at 50°C is 300 days, the 450,000-cycle life target could be demonstrated by performing 1500 cycle life test profiles each day.

In practice there are other issues to be considered. The 450,000-cycle life target is considered to apply at the battery's nominal operating temperature (30°C by default), while calendar life testing is normally done at significantly elevated temperatures to accelerate the testing. Thus the effects of cycling at elevated temperatures cannot be assumed to be the same as at normal temperature. The preferred way to address this problem is to have an "equivalent" cycle life at the calendar life test temperature, based on cycle life testing previously performed at the same temperature. This temperature-equivalent number of cycles is then distributed over the calendar life testing. Under such conditions, this combined life test can be expected to show whether and to what extent there is a deleterious interaction between calendar life and cycle life performance.

In the absence of one of these inputs (predicted calendar life and cycle life at the test temperature), battery degradation due to the two types of stress is likely to proceed at different rates, and a detailed analysis of the results will be impractical. In such a case it is very important that conventional calendar life under similar conditions (but with no life cycling) is conducted in parallel with this test to provide control data.

4. ANALYSIS AND REPORTING OF TEST RESULTS

4.1 General

For purposes of test reporting consistency (particularly between multiple test organizations), the sample test plan in Appendix A includes a list of required information for successful USABC testing based on the procedures defined in this manual. This is not intended to limit the reporting of other test results where appropriate. Instead, the purpose is to ensure that hybrid energy storage devices at various stages of development that are aged at different locations will yield comparable results.

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

Analysis and reporting of the results of the Hybrid Pulse Power Characterization Test (HPPC) test is generally aimed at comparing the present performance of a cell to the USABC targets. Since the USABC targets are all expressed at the system level, most results must be scaled using the Battery Size Factor before such comparisons can be made. (See Sections 3.1.3 and 4.4.11.)

4.4.1 Open-Circuit Voltage

Open-circuit voltage (OCV) is measured and plotted as a function of depth of discharge (DOD) at the end of each HPPC rest period, as shown in Figure 9. From these data, OCV at other DOD values can be estimated by straight-line interpolation or by fitting a curve through the measured data.

4.4.2 Calculated Resistance Characteristics as a Function of Depth of Discharge

Calculated resistance characteristics as a function of depth-of-discharge are derived from the pulse profile test data as follows:

1. Discharge resistance 1 s after start of discharge pulse
2. Regen resistance 10 s after start of regen pulse.

Discharge and regen resistances are determined using a $\Delta V/\Delta I$ calculation for each iteration of the test profile, in accordance with Equations (3) and (4) and Figure 8. Resistances are normally only calculated for completely unabated test profile pulses, i.e., those with full duration and amplitude.[25]

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[25] Because the HPPC test is required to continue to 100% DOD (or until the constant current discharge rate cannot be sustained), some data may be acquired during pulses where current limiting was encountered. Tests conducted by INL 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 USABC 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 signs of all terms in these equations have been chosen to agree with the manual convention that discharge current is positive and regen current is negative, thus assuring that the calculated resistance is always a positive quantity. These discharge and regen resistances are plotted as a function of depth of discharge, as shown in Figure 9. Also it may be informative to plot open-circuit voltage on this same figure as shown here.

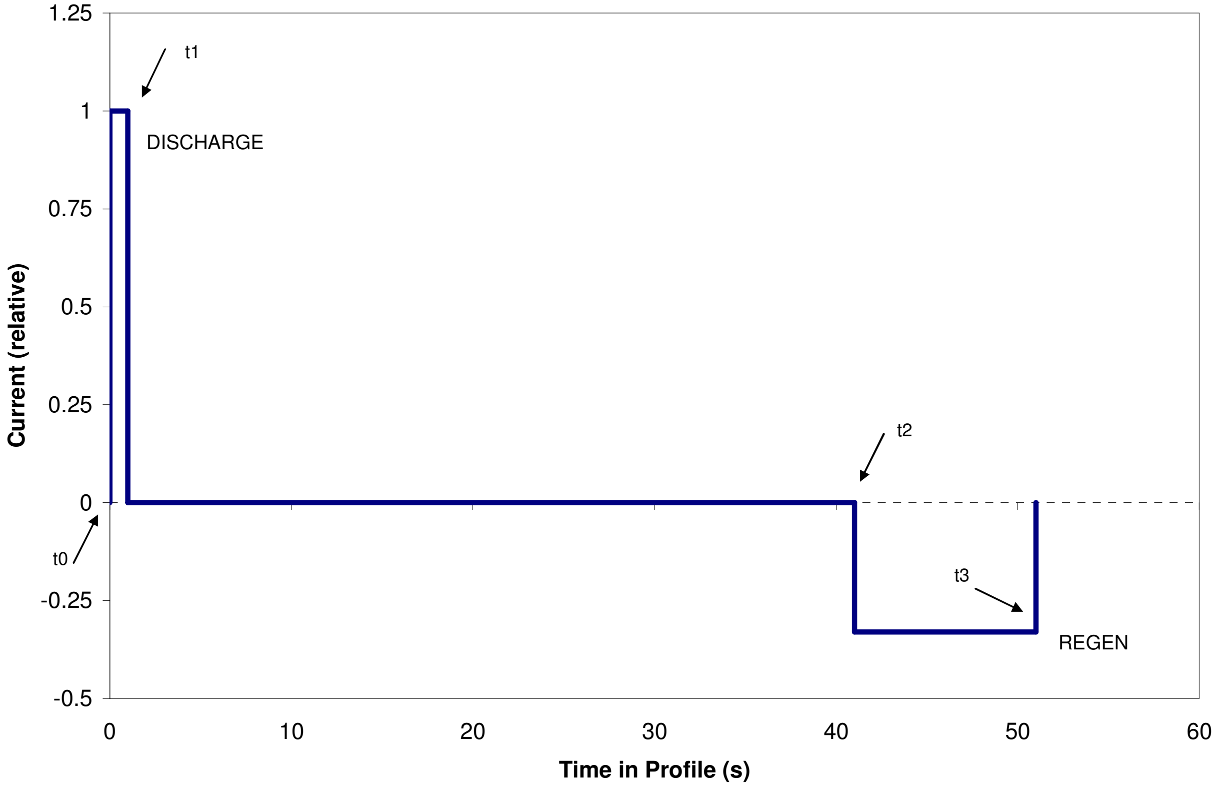

Figure 8. Resistance calculation time points.

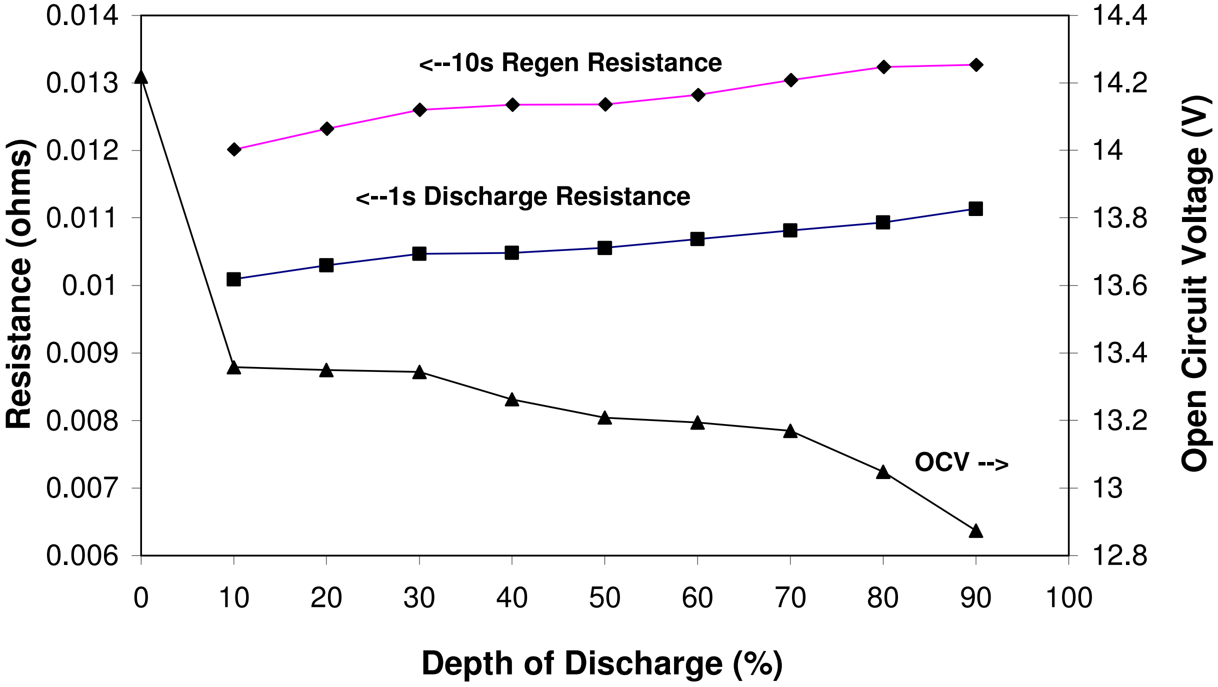

Figure 9. Open-circuit voltage and pulse resistances versus depth of discharge.

4.4.3 Pulse Power Capability

Pulse power capability is defined and plotted from the voltage and resistance characteristics, showing the V_{MIN} discharge capability and V_{MAX} regen capability at each DOD tested, i.e. the open-circuit voltage and resistance determined for that DOD (as shown in Figure 9), using Equations (5) and (6). (See footnote [6] in Section 3.4 regarding allowable values for V_{MAX} and V_{MIN}.)

$$\textit{Discharge Pulse Power Capability} = V_{MIN} \bullet (OCV_{dis} - V_{MIN}) \div R_{discharge} \tag{5}$$

and

$$\textit{Regen Pulse Power Capability} = V_{MAX} \bullet (V_{MAX} - OCV_{regen}) \div R_{regen}\,^{26} \tag{6}$$

These power capability values are used to determine the total available depth of discharge and energy swing that can be used (within the USABC operating voltage limits) for specified discharge and regen power levels. Note that profile charge removal has to be accounted for in determining DOD.[27] An example of the power capability versus DOD plot is shown in Figure 10. (Power values shown are for illustration only.)

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[26] 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 DOD 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% DOD removes 3% of the device capacity, the subsequent regen pulse OCV is interpolated starting at 13% DOD.

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

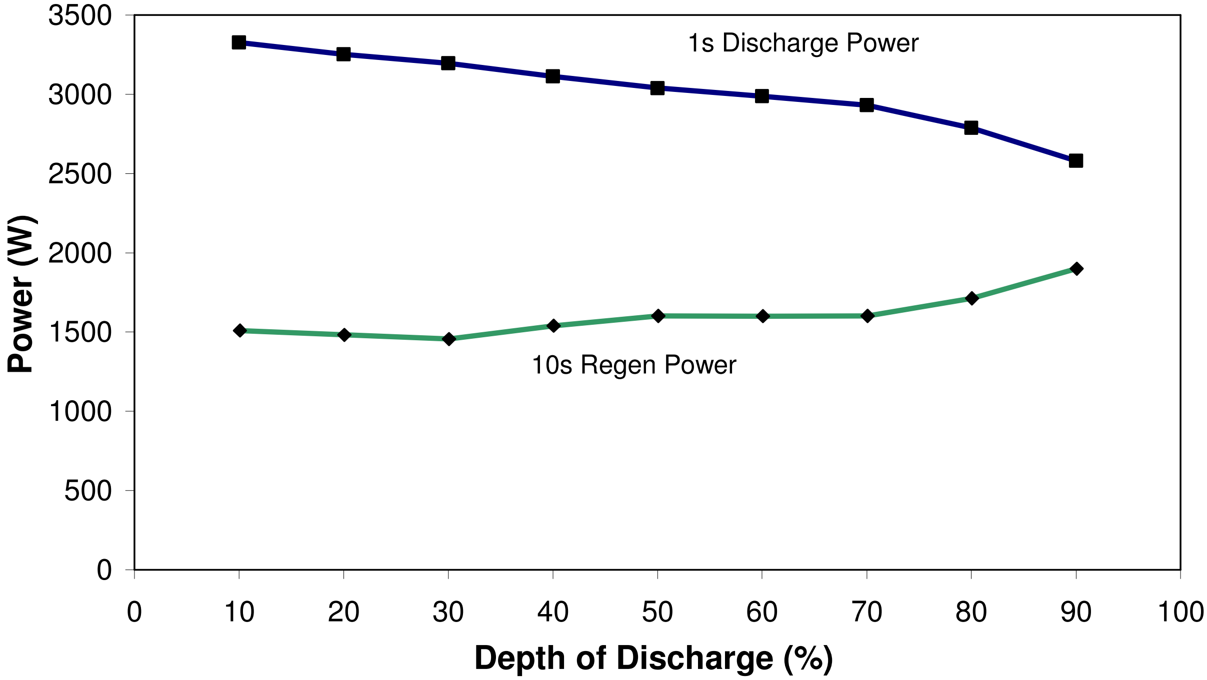

Figure 10. Pulse power capability vs depth of discharge.

To compare the HPPC results with the 12 Volt Start Stop Targets, Figure 10 must be transformed such that the *x-axis* becomes the Cumulative Discharge Energy Removed and the *y-axis* is scaled by the appropriate Battery Size Factor (based on the parallel/series combinations of cells). This is accomplished as follows:

1. Establish relationship between DOD (as a function of capacity) and energy removed from the scaled750-W constant power discharge as shown in Figure 11.
2. With each DOD increment in the HPPC test, relate the cumulative capacity removed to the energy removed at the scaled 750-W rate.
3. Scale both the energy and power results using the Battery Size Factor.

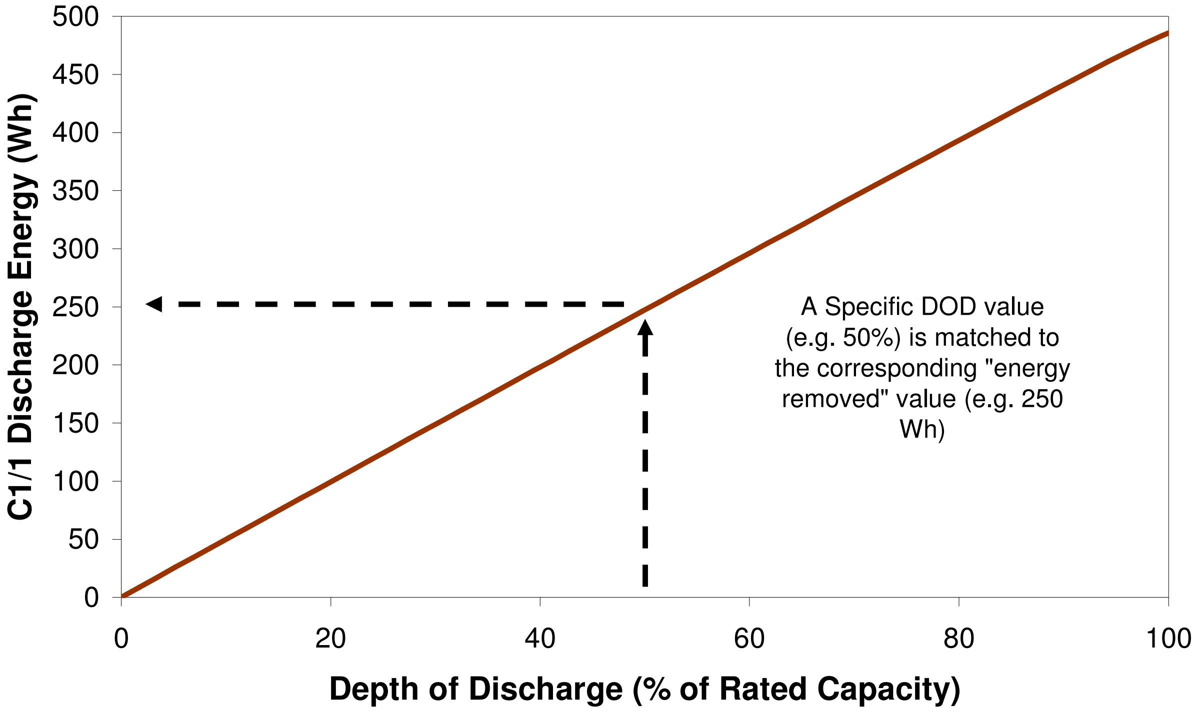

Figure 11. Relationship Between Energy and DOD in a $C_1/1$ Discharge.

HPPC power capability and $C_1/1$ or (750-W) discharge energy values are related by assuming that the corresponding measured DOD values in a pair of such tests are equivalent.[28] With this assumption, Figure 10 can be transformed to a power-versus-energy plot by replacing each DOD value from the HPPC data with the energy value at that DOD from a corresponding $C_1/1$ or (750-W) discharge test. Figure 11 shows a $C_1/1$ equivalence, and Figure 12 illustrates the resulting HPPC power versus $C_1/1$ equivalent energy plot for cell-level data.[29] (Power and energy values are illustrative only).

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[28] 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 corresponding DOD values are assumed to represent the same state-of-charge in both tests.

[29] In Figure 12 and the following figures, the data markers continue to correspond to data taken at 10% DOD intervals.

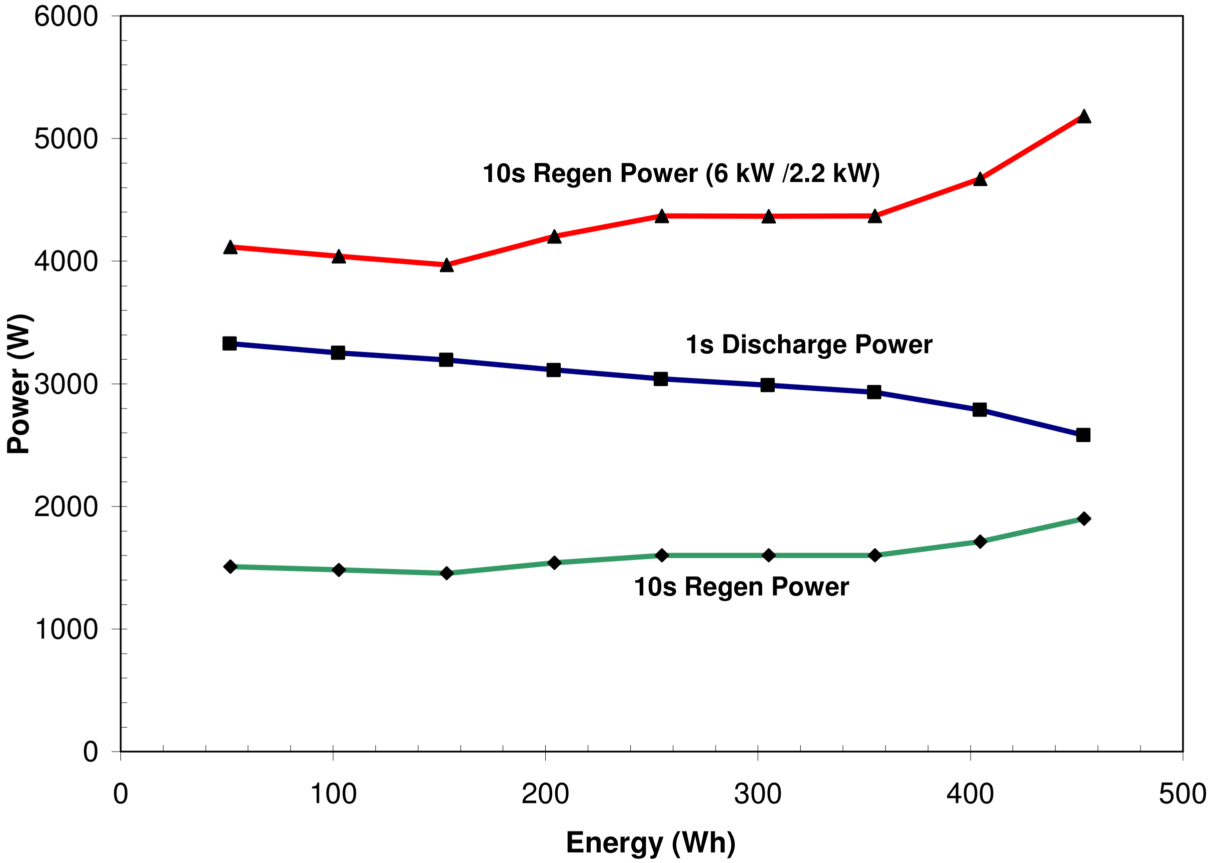

Figure 12. Unscaled HPPC Cell Power Capability vs. Energy Removed.

The power-versus-energy data plot can now be scaled by the Battery Size Factor for comparison with the targets. This is performed by multiplying all cell-level power and energy values by the Battery Size Factor. To simplify the targets comparison, the regen power results are then plotted on a second y-axis scaled by the ratio of required regen to discharge power, e.g., 2.2-kW regen and 6-kW discharge for the targets. Figure 13 illustrates the result of this scaling applied to Figure 12, for a Battery Size Factor of 2.44 with the Regen Power now plotted on a secondary y-axis. In this case the Battery Size Factor had been determined to be 2.44 to provide a 30% power margin. (This value is for calculation purposes only. It is assumed the Battery Size Factor costing would be an integer.)

Note that in Figure 12, the location of the regen curves shifts from below the discharge curve to above the discharge curve when the axes are scaled in proportion to the discharge and regen pulse power targets. Because of the way these pulse power values are calculated in Equations (5) and (6), changing the operating voltage limits V_{MAX} and/or V_{MIN} will also cause the curves to shift relative to each other. Thus the location of the useable energy range can be varied if desired by altering the operating voltage range (within the allowable voltage limits).

The comparison of these results to the targets can be performed graphically in several steps as shown in the next sections.

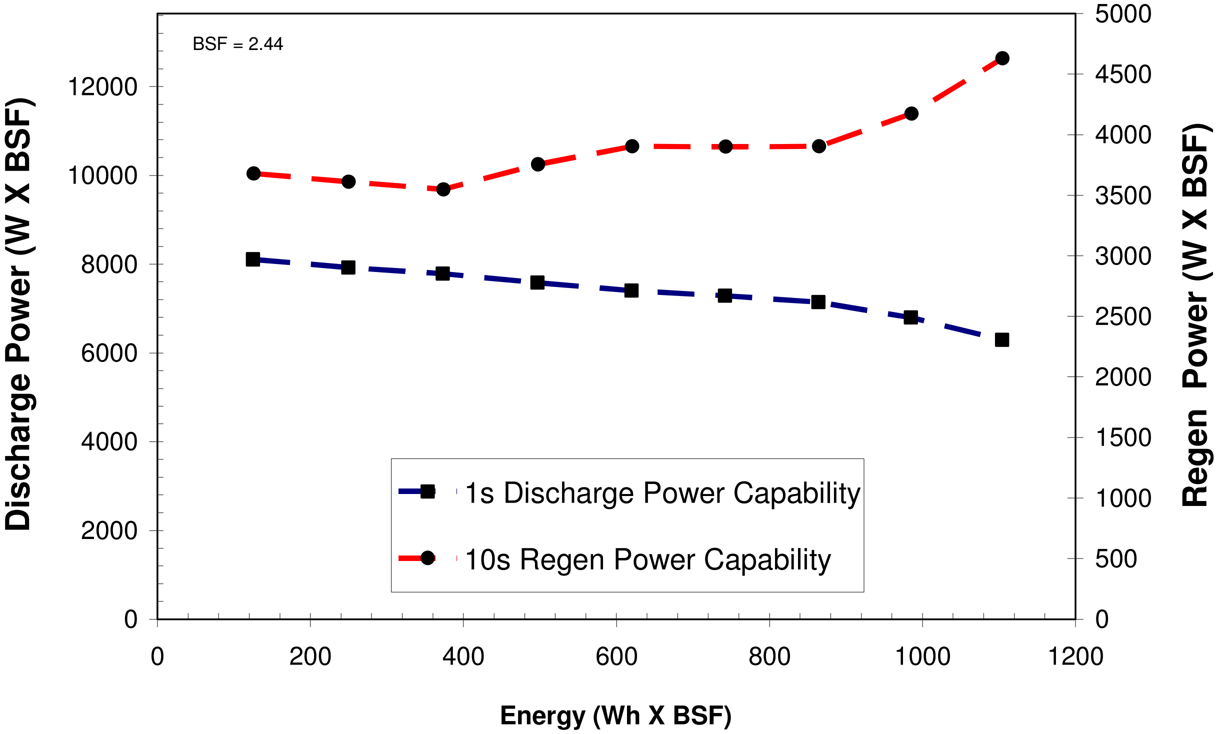

Figure 13. HPPC Power vs. HPPC-Current Discharge Energy Scaled by the Battery Size Factor.

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 0% DOD by the USABC, which is the same terminology used in Rev 2 of the Plug-In Hybrid Electric Vehicle Battery Test Manual (Reference 4) and has been chosen to be 0% DOD by the USABC for 12V Start/Stop applications. However, this example shows that there would be no point at which regen would be limited.

To assess the energy and power capabilities of the battery at Beginning of Life (BOL) and how these change with usage and time, several new terms are defined. In general (but with some correction terms), Useable Energy is the discharge energy at the scaled 750-W rate (based on $C_I/1$ rate in this example) between the Charge Target and the Pulse Power Discharge curve for any given power level. In contrast, Available Energy is the single point on the Useable Energy versus power curve that precisely corresponds to the Pulse Power Discharge Target. These terms are defined in Equation (7) and discussed extensively later in this section. Similarly, Available Power is the single point from the same Useable Energy Curve that precisely corresponds to the Available Energy Target.

The following equation defines UE, the Useable Energy.

$$UE = [E_{\text{Discharge}} - E_{\text{Charge Target}}] \tag{7}$$

At a selected discharge power level, $E_{\text{Discharge}}$ is the corresponding energy on the pulse power discharge curve; $E_{\text{Charge Target}}$ is the energy that corresponds to the Charge Target of 0% DOD; AE_{Target} is the Available Energy Target (i.e., 360 Wh). In Equation (7), when UE is evaluated at precisely the Peak Discharge Pulse Power Target (i.e., at 6-kW), it is by definition equal to AE, i.e., the corresponding Available Energy.

In the example shown in Figure 14, $E_{\text{Discharge}}$ = 1104 Wh; $E_{\text{Charge Target}}$ = 0 Wh; and the selected evaluation power is the Peak Discharge Pulse Power Target of 6-kW. Thus,

$$UE = AE = [1104 \text{ Wh} - 0 \text{ Wh}] = 1104 \text{ Wh}$$

Please note that this methodology is consistent with the customary method to calculate Useable and Available Energies for conventional hybrid electric vehicles and the methodology Rev 2 of the Plug-In Hybrid Electric Vehicle Battery Test Manual (Reference 4).

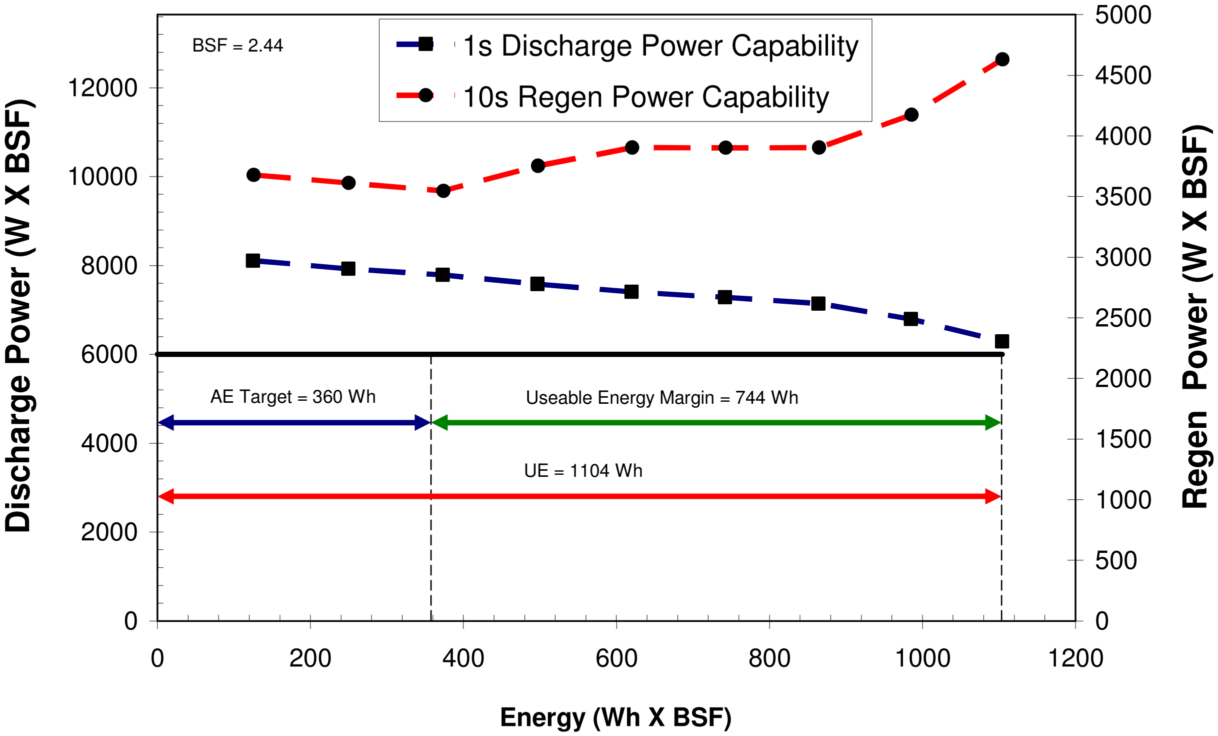

Figure 14. Useable Energy Determination.

4.4.5 Available Energy Margins

The Useable Energy is the measure of the energy available for different points in life and also how much that energy exceeds the target. As stated earlier and repeated here for emphasis, the Available Energy is the Useable Energy at precisely the Discharge Power Target of 6-kW. The value can easily be determined from Equation 7 or graphically from Figure 14.

The Useable Energy margins are defined as the differences between their respective Useable Energies and the corresponding Available Energy Targets as defined in Equation (8) and as shown in Figure 14.

$$UE_{Margin} = [UE - AE_{Target}] \tag{8}$$

Continuing this example, UE = 1,104 Wh and AE_{Target} = 360 Wh. Thus,

$$UE_{Margin} = [1{,}104 \text{ Wh} - 360 \text{ Wh}] = 744 \text{ Wh}$$

Some margin is necessary at beginning-of-life to allow for the degradation of power capability and Available Energy that occurs over both life cycling and calendar life. Because the power and energy targets are required to be met at end-of-life, the point in life where this energy margin decreases to zero is the *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 variations of energy and power margin over life are illustrated in Figure 15. This figure shows the energy margin and power margin at beginning-of-life, how they change over life, and that these margins are zero (by definition) at end-of-life.[30] This is one possible end-of-life condition.

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[30] These end-of-life data are theoretical; in practice, test data are seldom available *exactly* at the point in life where power and energy margins are zero because reference tests are performed only at periodic intervals. Thus this point normally occurs between two sets of reference tests. See Section 4.10 and 4.11 regarding the implications of this behavior on reported life.

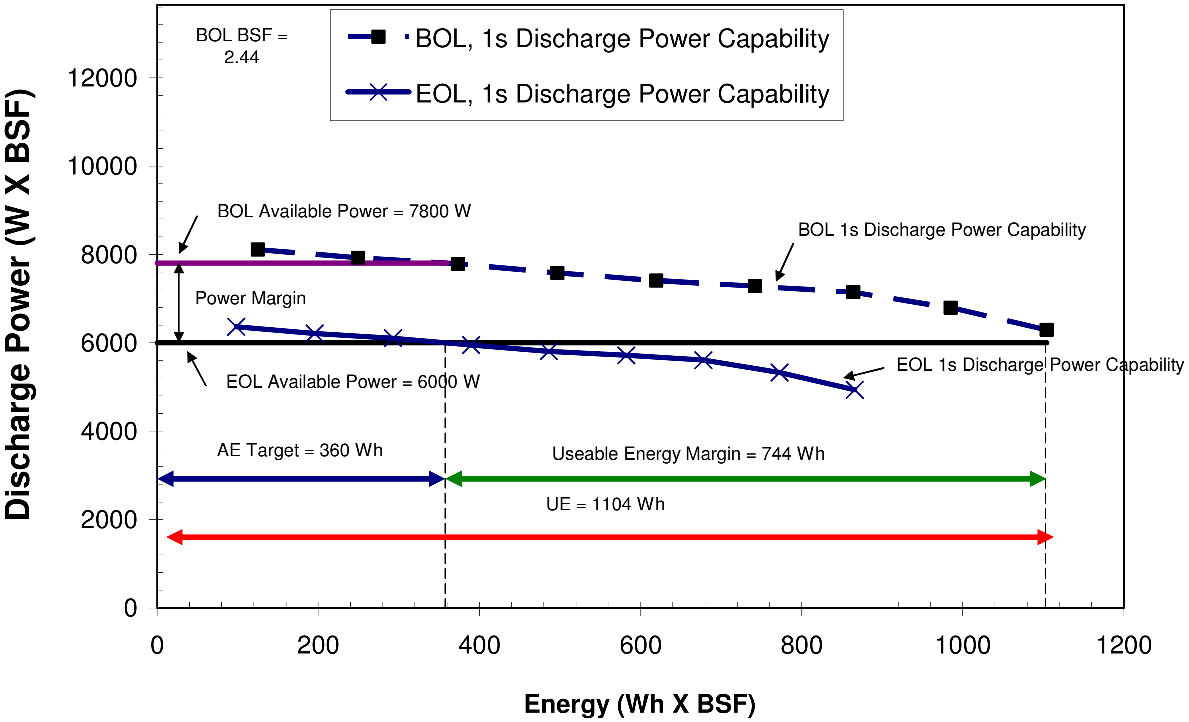

Figure 15. Available Energy and Power Margins Over Life.

4.4.6 Available Power

Available Power is the discharge power capability at which useable energy is equal to the Available Energy Target . In effect it is the maximum discharge power capability at which the Available Energy Target, 360 Wh, is precisely met. Available Power is illustrated at both beginning-of-life (BOL) and end-of-life (EOL) conditions in Figure 15. Available Power at EOL is precisely equal to the discharge target power, 6-kW. This parameter is defined primarily for reporting battery degradation over life. In fact, Available Power and Available Energy represent two complementary aspects in the performance of a battery at any point in time and must be tracked and reported over life.

The useable energy is calculated using Equation (7) as a function of the associated discharge pulse power. In this context, the numerical example depicted in Figure 14 illustrates one such specific energy value which happens to be calculated at a power equal or nearest but greater than the discharge pulse power target of 6-kW. A more complete representation of the energy and power behavior is represented by the example of the Useable Energy versus Discharge Power curve illustrated in Figure 16. The Figure also illustrates the location of the Available Energy and the Available Power.

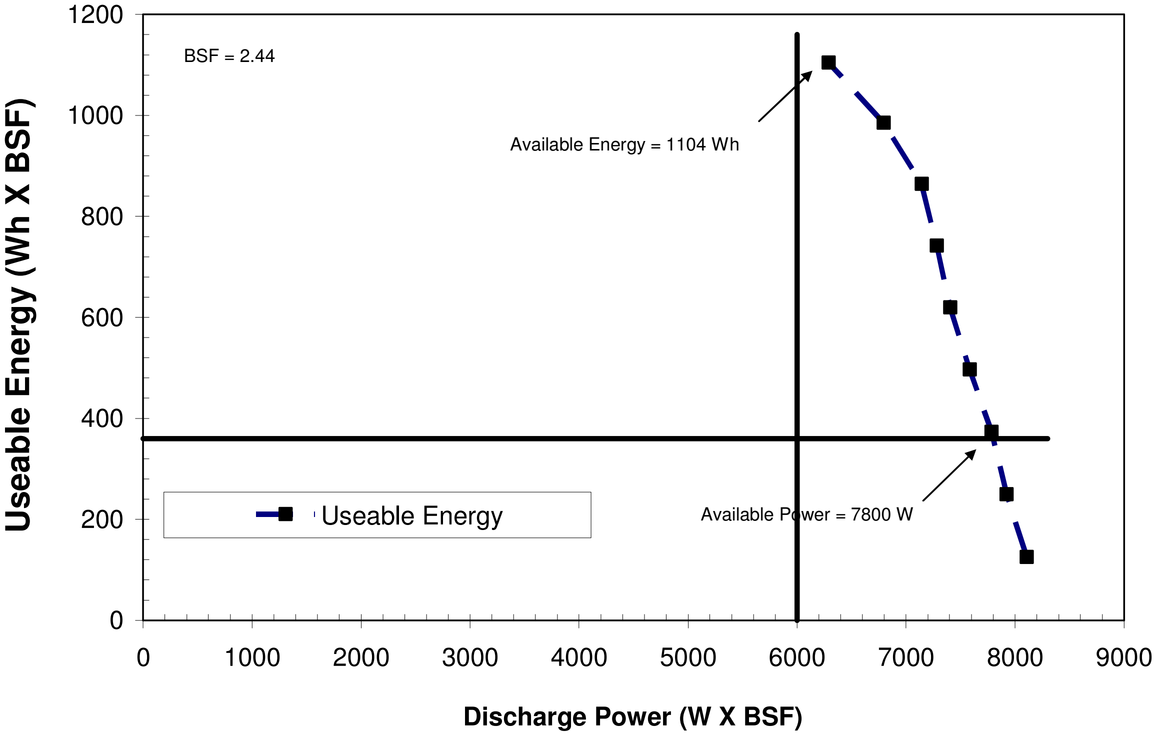

Figure 16. Useable Energy versus Power Curve.

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).

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

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

In both cases *t0* refers to the time of the initial (BOL) RPT 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 DOD Values

Minimum and maximum DOD values where the power targets can be met may be needed for other test purposes. These values can be determined by using the same HPPC data and scaling factors as in Figure 13, but plotted against the original DOD values from the HPPC Test (i.e., DOD values are not converted to the $C_1/1$ or 750-W equivalent energy values). Figure 17 shows the results of this scaling applied to the same example data as previously shown. This graph shows that the minimum and maximum DOD values corresponding to the 6-kW Pulse Power Discharge Target and the 2.2-kW Pulse Power Regen Target are approximately 0% and 90% respectively and the cold cranking DOD at 28.9%.

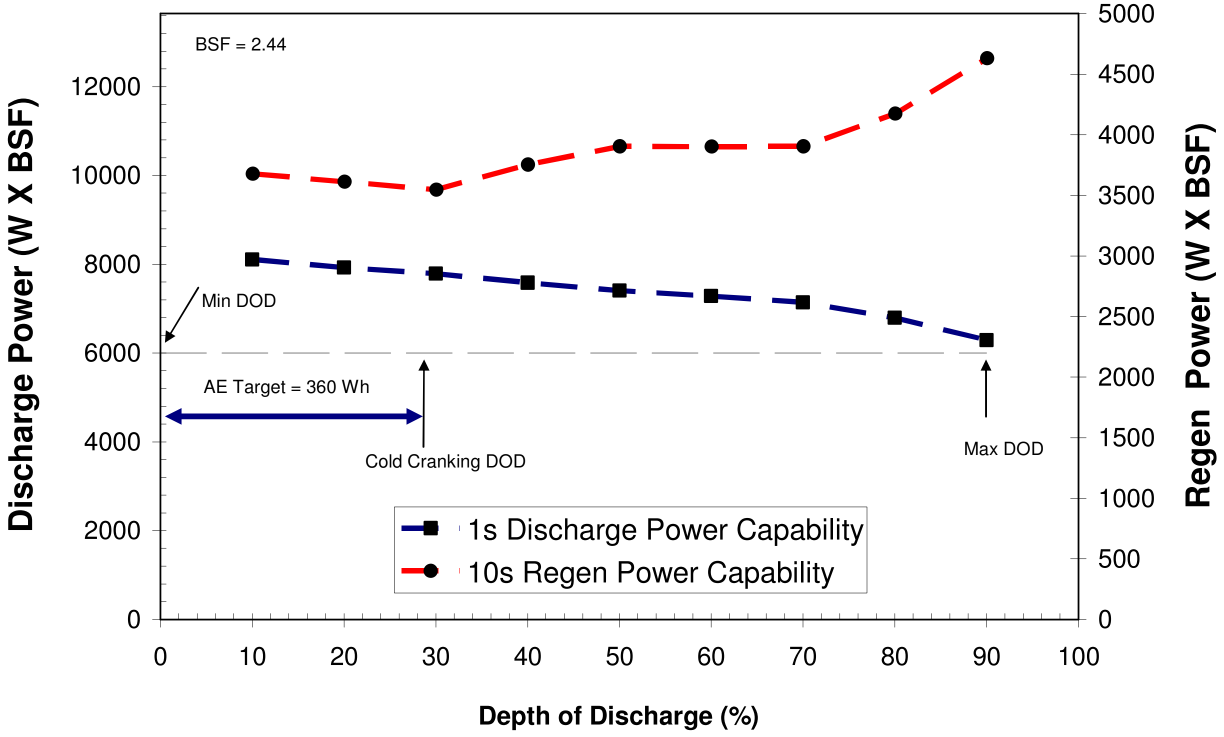

Figure 17. Minimum and Maximum DOD Values Where Targets Are Met.

The Cold Cranking Test DOD value can be determined from full charge or the Charge Target and removing the scaled Available Energy Target of 360 Wh and then reading the corresponding DOD value as also illustrated in Figure 17.

4.4.9 Pulse Power Characterization Profile Voltage Response

Voltage response to the associated current stimulus may be shown by graphing the measured voltage and current as functions of time during one or more executions of the HPPC pulse profile or for the entire HPPC Test sequence.

4.4.10 Other Laboratory Cell Performance Characteristics

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

- Voltage response time constant estimates for discharge, regen, and rest periods derived from the current-driven HPPC Test data
- Ohmic and polarization resistances derived from lumped parameter equivalent circuit models
- Cell capacity and energy in area-specific, gravimetric, and volumetric units (mAh/cm^2, mWh/cm^2, Ah/kg, Wh/kg, Ah/liter, Wh/liter)
- Cell area-specific impedance (ASI) in ohms-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.

4.4.11 Determining Battery Size Factor When Not Supplied By Manufacturer

Section 3.1.3 discusses the special case where the device manufacturer is unable to supply a Battery Size Factor in advance of testing. In this case, the minimum Battery Size Factor is calculated directly from the initial Low Current HPPC Test results. Since the BSF scaling factor is not yet known, the magnitude of the HPPC pulses is calculated relative to the $5C_1/1$ current and the C_1-rate current is used in lieu of the scaled HPPC current. Once the BSF is determined, the process should be repeated using the HPPC test in Section 3.4, using the HPPC Current to validate the choice of BSF. The method for doing this is effectively an inversion of the Available Energy calculation process described in Section 4.4.4, with steps as follows.[31]

1. Establish the relationship between the HPPC discharge and regen powers versus DOD similar to Figure 10. Plot the Energy Removed at a C_1-rate versus DOD similar to Figure 11. Transform the *x-axis* in Figure 10 to Energy similar to Figure 12.

2. From Figure 12, draw a vertical line at the 0% DOD point. (Note that this analysis can be performed from any DOD point, but 0% DOD is the recommended point for the 12V Start Stop application). Calculate the useable energy between the vertical (0% DOD) line and the discharge curve. Repeat this calculation at various power levels until reaching the lowest power point on the end of the discharge curve, as shown in Figure 18. (Note: While this appears to be trivial, this methodology allows useable energies to be determined at other values other than 0% DOD or to determine the useable energies with respect to a Regen power capability curve).

3. Plot the useable energy versus useable power as shown in Figure 19.

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

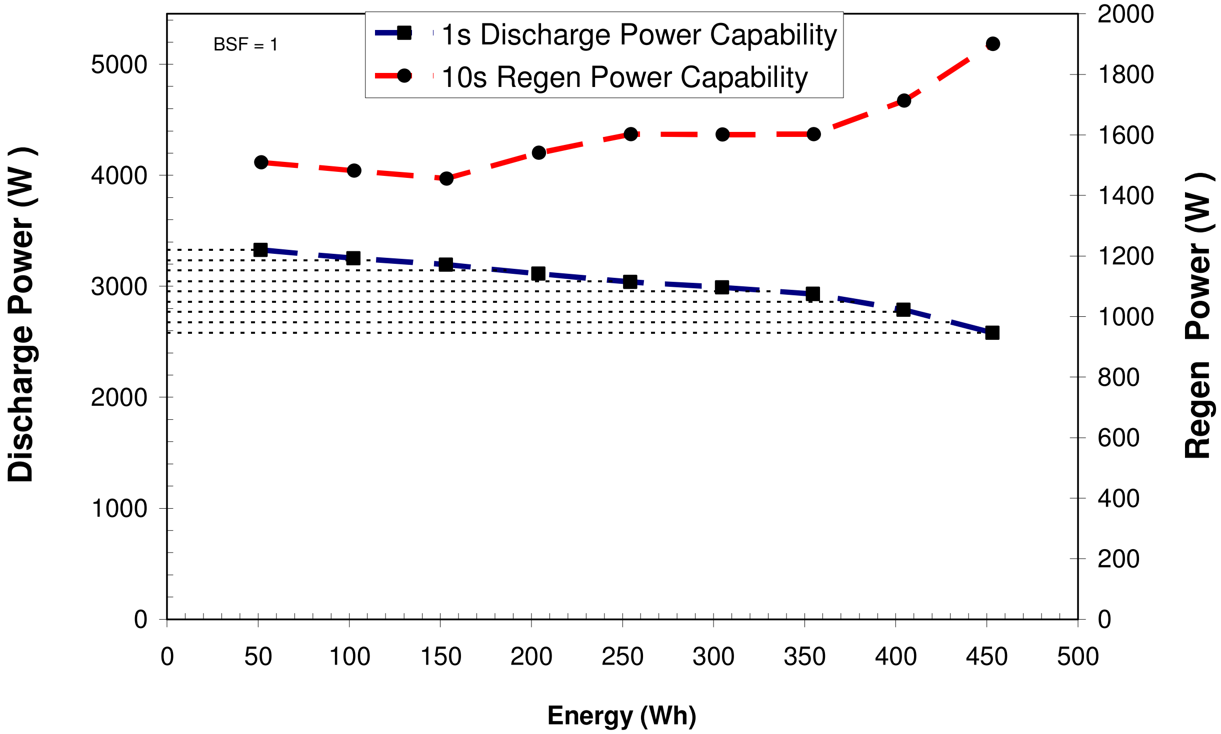

Figure 18. Finding the Useable Energy Using Device-Level Results.

4. On this Useable Energy graph, draw a line from the origin having a slope equal to the ratio of the Available energy target (i.e., 360 Wh) to the 1-sec discharge power target (i.e., 6-kW) times 1.3 to provide a 30% power margin. This line is labeled the Goal Ratio + 30%. This slope would be 0.046154 Wh/W, [i.e., (360 Wh ÷ (1.3 * 6 kW))].

5. Determine the value of the energy and power at the point where this line intersects the Useable Energy curve. This is about 147.7 Wh in this example and the power is 3201.1 W.

6. Divide this power value into the power target including the 30% energy margin (i.e. [6000 x 1.3] / 3201.1 = 2.4366). This is the BSF.

7. Steps 1-8 should be performed again using the results from the HPPC Current version of the HPPC test to validate the approximated BSF determined from the $C_1/1$ version of the HPPC test.

8. This method, steps 1-8 can also be used to determine the BSF with no 30% margin, which is also shown in Figure 19 by the intersection of the Goal Ratio 0% line and the Useable Energy Curve.

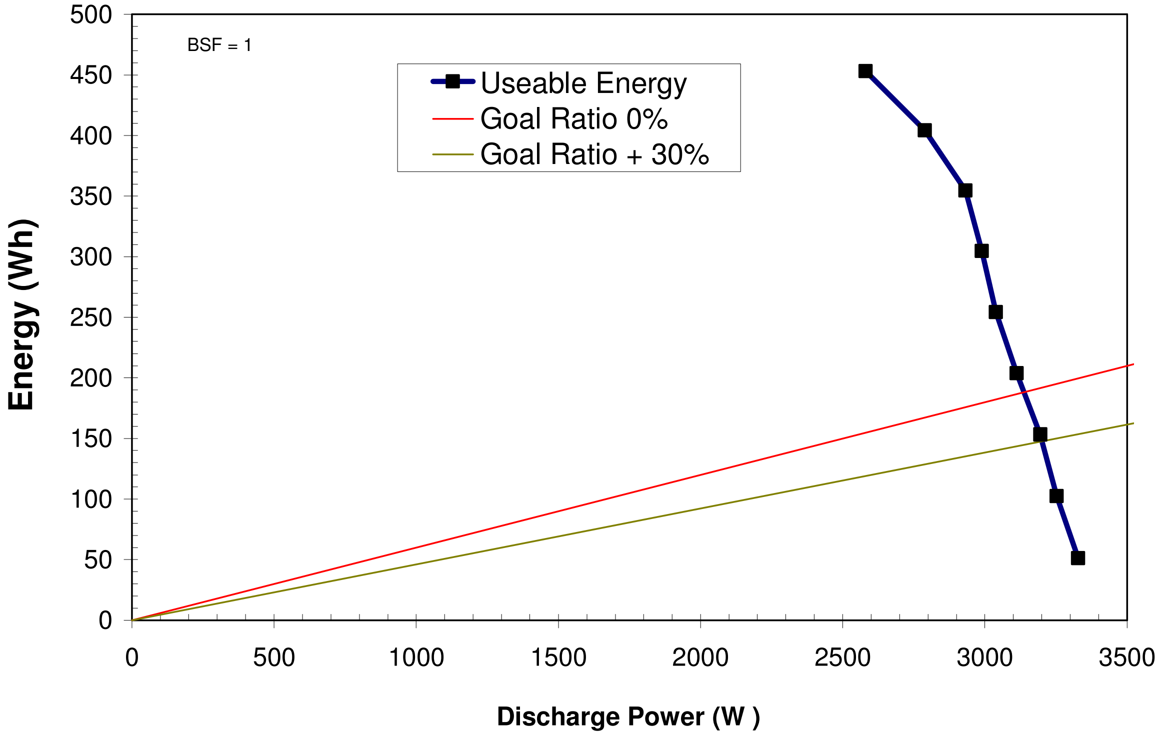

Figure 19. Finding a Battery Size Factor Using Device-Level Results.

9. On this Useable Energy graph, draw a line from the origin having a slope equal to the ratio of the Available energy target (i.e., 360 Wh) to the 1-sec discharge power target (i.e., 6-kW) provide a 0% power margin. This line is labeled the Goal Ratio 0%. This slope would be 0.06 Wh/W, [i.e., (360 Wh ÷ 6 kW)].

10. Determine the value of the energy and power at the point where this line intersects the Useable Energy curve. This is about 188.3 Wh in this example and the power is 3138.6 W.

11. Divide this power value into the power target (i.e. 6000 / 3138.6 = 1.91167). This is the BSF for a 0% margin.

12. Verify that this Battery Size Factor is still expected to give round-trip efficiency values within the targets at end-of-life. This can be done by executing the Efficiency Test at a current level scaled at 130% of the normal value (i.e., test current = full system current divided by Battery Size Factor and multiplied by 1.3). [32] If the applicable efficiency target(s) are not met using this scaling factor, the multiplier must be increased appropriately.

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[32] The logic behind this approach is to increase the testing "stress level" (power) by a percentage equal to the BOL power margin, to give results that approximate those expected at end-of-life when the power margin has declined to zero.

13. The BSF resulting from this process is used for all future testing. (A single typical or average value can be used for testing a group of identical devices. If the HPPC test is shown to be overly conservative, the BSF will need to be adjusted using a different combination of parallel and/or series cells, see Sections 3.4.3 and 3.4.4).

4.5 Self-Discharge Test

Self-discharge rate is determined over a fixed period (nominally 7 days) at one or more intermediate DOD conditions (nominally 30% DOD). 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).

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

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 $\Delta V/\Delta I$ calculation (Equation [2]) 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.

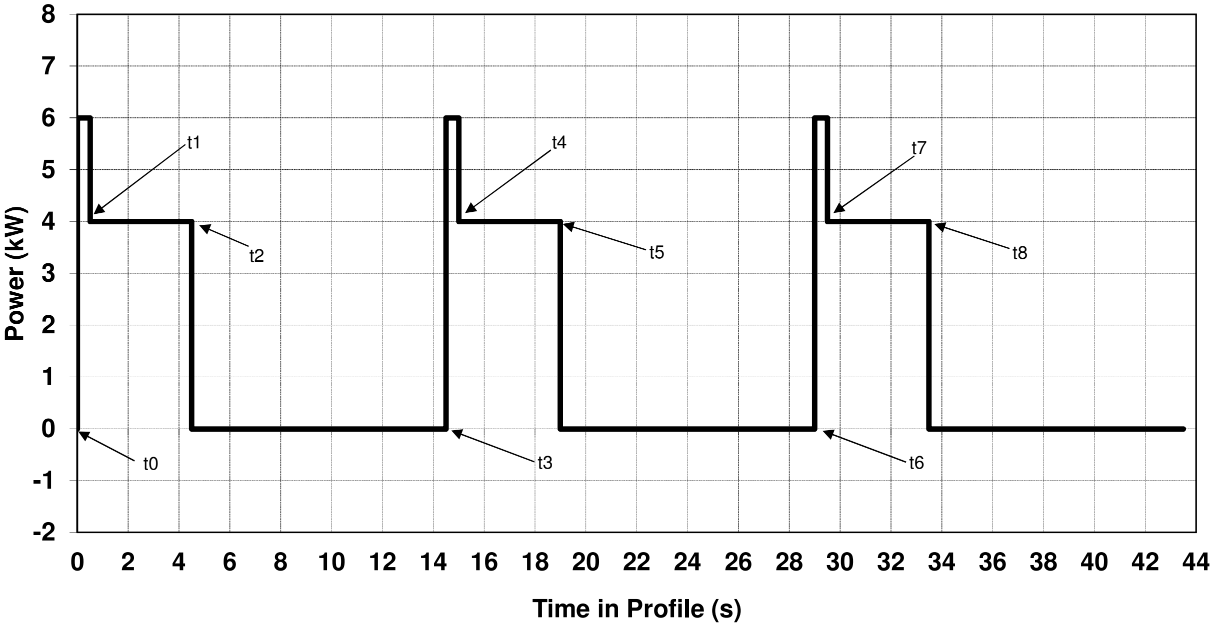

Figure 20. Cold Cranking Test resistance calculation points.

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).

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

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

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[34]. 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

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33. 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.

34 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.

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.[35] 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. [36] 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 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 Calendar Life Estimator Manual*, Reference [6].

Curve fitting may be applied to resistance, power, energy, and capacity data and is transparent to battery chemistry and technology. It is an interpretative, deductive approach to understanding the performance degradation process. Assuming that the battery test was performed with a number of different

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

[36] 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.

temperatures over a number of reference performance tests, the most general curve fit allows for a linear combination of temperature and time dependencies, as given in Equation (13),

$$Q = f(T)g(t), \tag{13}$$

where Q is the property of interest, $f(T)$ is the temperature-dependent part of the degradation process and $g(t)$ is the time-dependent part of the degradation process. An important assumption in constructing a curve-fit model is that there was no important change in mechanism of the degradation process with temperature and time. Temperature- and time-based changes can be accommodated, but the exact treatment of these cases is beyond the scope of this discussion.

The two main approaches for describing temperature dependence of the degradation process are linear and Arrhenius. Linear-with-temperature processes are very rare in battery testing. They usually occur in the early part of a longer test and are not truly indicative of the actual degradation process. Arrhenius-like temperature dependence is common. It occurs when there is an activation energy barrier which must be overcome for the process to occur. The activation energy barrier, in this case, is a thermally activated process. The temperature-dependent part of Equation (13) above then can be written as given in Equation (14),

$$f(T) = Ae^{-E_a/RT}, \tag{14}$$

where A is a constant, E_a is the activation energy for the process in J/mol, R is the universal gas constant, 8.314 J/mol-K, and T is the absolute temperature in Kelvin.

Many life-limiting processes in a battery typically follow either a (t^z) or ln(t) time dependence. The exponent z is a constant that is determined by curve fitting. The form of the time-dependent part of Equation (13), $g(t)$, is germane and it can also be determined by curve fitting. The simpler forms of the fit are usually preferable if the values of r^2 are approximately the same.

For example, if $Q = Ae^{-E_a/RT}t^z$, the data may be fit to the linearized form of Q, Equation (15), using the Microsoft Excel function LINEST.

$$\ln(Q) = \ln(A) + (-E_a/RT) + z\ln(t), \tag{15}$$

Care must be taken when t=0. These data points should be excluded from the initial fit. If the process depends on ln(t), as shown in Equation (15), the data at t=0 cannot be used.

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

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

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

4. *Battery Test Manual for Plug-In Hybrid Electric Vehicles,* INL/EXT-07-12536, Rev. 2, March 2010

5. *Advanced Technology Development Program for Lithium-Ion Batteries: Battery Technology Life Verification Test Manual,* INEEL/EXT 0401986, February 2005

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

6. APPENDIX A

Sample Test Plan

VEHICLE TECHNOLOGIES PROGRAM
12VOLT START/STOP TEST PLAN FOR TBD CELLS

1.0 Purpose and Applicability

The intent of this test plan is to characterize the performance, of TBD cells supplied by TBD for the TBD Battery mode. This testing will support the proposed program and provide baseline data for comparison with previous technologies and future cell developments. This testing is under the oversight of the Department of Energy, Office of Vehicle Technology. These Articles will be subjected to the performance test procedures defined for the 12 Volt Start/Stop Program.

2.0 References

2.1 Battery Test Manual for 12 Volt Start/Stop Vehicles, INL/EXT-12-26503, Rev 0, April 2013

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

4.2 Actual weights and open circuit voltages of the Articles as delivered shall be recorded.

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 cells
HPPC Pulse Power Voltage Calculation Ranges:
  Vmin TBD V
  Vmax TBD V

5.2 Temperature Ratings

Operating Temperature Range: TBD
Discharge Temperature Range: TBD
Charge Temperature Range: TBD
Storage Temperature Range: TBD
Cold Cranking Temperature TBD

5.2 Nominal Values
Nominal Capacity: TBD A-h

Nominal Weight: TBD kg
Nominal Volume: TBD L

5.4 Discharge Limits

Minimum Discharge Voltage
- ≤1 second pulse: TBD
- ≤ C_1/1 rate: TBD
- ≤1 second pulse and temp ≤0°C: TBD

Maximum Discharge Current: TBD

5.5 Charge and Regen Limits

Maximum Regen Voltage for ≤10s: TBD
Continuous rates ≤ C_1/1 rate: TBD
Maximum Regen Current (10 sec): TBD
≤10 second pulse and temp ≤0°C: TBD

5.6 Other Test Info:

Charge Procedure: TBD

5.6 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 DOD 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 Vehicle Technologies Program Manager.

6.0 Safety Concerns and Precautions

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

6.1 Cell Handling
- TBD

6.2 Other Safety Precautions
- TBD

7.0 Tests to be Performed Under this Test Plan

The Cells to be tested under this test plan will be subjected to the performance test sequence in Table 1. The depth of discharge is to be established by discharging at a rated HPPC current for a fixed period of time from full charge. 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 Cells	No. Iterations
1	Capacity Test *(See Reference 2.1, Section 3.2)* Conduct this test on TBD cells 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	Hybrid Pulse Power Characterization Test *(Reference 2.1, Section 3.4)* Perform the Low test on TBD cells. The Low Current Test is performed at a peak discharge current of TBD. HPPC Current = TBD. For all Articles, the HPPC Current discharge will be included in the same data file as the HPPC test for calculation purposes.	1
3	Constant Power Discharge Test *(Reference 2.1, Section 3.3)* Conduct this test on TBD cells at a BSF-scaled 750-W discharge rate. Note: Test is to be terminated at manufacturer-specified cutoff voltage, NOT rated capacity	1
4	Self-Discharge Test *(Reference 2.1, Sections 3.5)* Conduct this test on TBD cells	1
5	Cold Cranking Test *(Reference 2.1, Sections 3.6)* Conduct this test on TBD cells at -30°C. For this test plan, the cold soak time at -30°C prior to pulse testing shall be four hours.	1
6	Thermal Performance Test *(Reference 2.1, Sections 3.7)* Perform a Constant-Power Discharge Test and the Low-Current HPPC Test (see 2 above) at 0, –10, –30, and 50°C on TBD of the cells.	1

	Recharging for these tests is to be done at 30 °C ambient temperature. A soak period of nominally four hours or longer is required at each temperature for all tests.	
7	Cycle Life Test *(Reference 2.1, Sections 3.10)* *As directed.*	
8	Calendar Life Test *(Reference 2.1, Sections 3.11)* *As directed.*	

7. APPENDIX B

Table 8. Gap Table Example for an Under Hood Device.

End of Life Characteristics	**Target**	**BOL**	**Present**
	Under hood		
Discharge Pulse, 1s [kW]	6		
Max discharge current, 0.5s [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 cycles (engine starts /150k miles		
Calendar Life at 30°C, 45°C if under hood [Years]	15 at 45°C		
Minimum round trip energy efficiency [%]	95		
Maximum allowable self-discharge rate [Wh/day]	2		
Peak Operating Voltage, 10s [Vdc]	15.0		
Sustained Operating Voltage - Max [Vdc]	14.6		
Minimum Operating Voltage under Autostart [Vdc]	10.5		
Operating Temperature Range (available energy to allow 6-kW (1s) pulse) [°C]	-30 to + 75		
30 °C – 52 °C [Wh]	360 (to 75°C)		
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		
Maximum System Weight [kg]	10		
Maximum System Volume [L]	7		
Maximum System Selling Price (@250k units/year) [$]	$220		