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Battery Test Manual For Low-Energy Energy Storage System for Power-Assist Hybrid Electric Vehicles

Revision 0

APRIL 2013

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Prepared for the
U.S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy (EERE)
Idaho Operations Office
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FOREWORD

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

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

The DOE-United States Advanced Battery Consortium, Electrochemical Energy Storage Technical Team supported the development of the manual. Technical Team members responsible for its development and revision are Scott W. Jorgensen of General Motors Corporation and Jeffrey R. Belt of the Idaho National Laboratory.

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

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CONTENTS

FIGURES

TABLES

ACRONYMS

ac	alternating current
Ah	ampere-hours
ASI	area-specific impedance
BOL	beginning of life
BSF	Battery Size Factor
DOD	depth of discharge
EMI	electromagnetic interference
EOL	end of life
EV	electric vehicle
HEV	hybrid/electric vehicle
HPPC	hybrid pulse power characterization
INL	Idaho National Laboratory
OCV	open-circuit voltage
OSPS	operating set point stability
PNGV	Partnership for a New Generation of Vehicles
SOC	state of charge
USABC	United States Advanced Battery Consortium

GLOSSARY[A]

Available Energy –the discharge energy available over the DOD range where both the LEESS discharge and regen pulse power targets are precisely met. This energy is measured using a $C_1/1$ constant current discharge rate, and the limiting power conditions are calculated using a procedure defined in this manual.

Available Power –the discharge pulse power at which the usable 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 LEESS performance and life targets. If this value cannot be determined prior to testing, the Battery Size Factor is chosen as the minimum number of cells or modules that can satisfy the LEESS energy targets with a 30% power margin at beginning of life or as specified by the manufacturer. Battery Size Factor is determined separately for each mode.

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. 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 LEESS 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 LEESS 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.

[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 LEESS operating conditions.

Maximum Rated Current (Imax) – the maximum discharge current that a manufacturer will permit to be sustained by a device for 10s. (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 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 LEESS 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.)

Regen – any device charge interval corresponding to the return of vehicle kinetic energy to a device (typically from braking.) Because of physical limitations, regen can only persist for a few seconds at a time.

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

Usable Energy – a value (calculated from HPPC test results) that represents the discharge energy available over a DOD range corresponding to any pair of discharge and regen power values whose ratio is that of the corresponding LEESS power targets. Available Energy is the value of usable energy at the actual LEESS power target values. (Usable energy has been frequently but inaccurately called Available Energy.)

Battery Test Manual For Low-Energy Energy Storage System for Power-Assist Hybrid Electric Vehicles

1. PURPOSE AND APPLICABILITY

This manual defines a series of tests to characterize aspects of the performance or cycle life behavior of batteries for hybrid electric vehicle applications. Tests are defined based on the LEESS program targets for power-assist hybrid electric vehicles, though it is anticipated these tests may be generally useful for testing energy storage devices for hybrid vehicles. The test procedures in this manual are directly applicable to complete battery systems. However, most 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 former PNGV Battery Test Manual (Reference 2).

1.1 LEESS Targets For Power-Assist Hybrid Electric Vehicles

LEESS Targets are the primary driving force for the test procedures and methods defined in this manual. These targets are outlined in Table 1 for levels of Power-Assist performance specified for the LEESS Program. Note that this table of LEESS targets is presented as the primary basis for this test manual. Establishing or verifying battery performance in comparison to these targets is a principal objective of the test procedures defined in this document.

Table 1. USABC Requirements at End of Life for LEESS PA-HEV

End of Life Characteristics	Unit	PA (Lower Energy)	
2s / 10s Discharge Pulse Power	kW	55	20
2s / 10s Regen Pulse Power	kW	40	30
Maximum current	A	300	
Available Energy (@ C1/1 rate)	Wh	26	
Energy Efficiency	%	95	
Maximum allowable self-discharge rate	Wh/day	5	
Cycle-life	Cycles	300,000 (HEV)	
Cold-Cranking Power at -30ºC (after 30 day stand at 30^{o}C)	kW	5	
Calendar Life	Years	15	
Maximum System Weight	kg	20	
Maximum System Volume	Liter	16	
Maximum Operating Voltage	Vdc	≤400	
Minimum Operating Voltage	Vdc	≥0.55 V_{max}	
Unassisted Operating Temperature Range	ºC	-30 to +52	
30 ^{o} -52^{o}C	%	100	
0^{o}C (% of Available Power)	%	50	
-10^{o}C (% of Available Power)	%	30	

-20°C (% of Available Power)	%	15
-30°C (% of Available Power)	%	10
Survival Temperature Range	ºC	-46 to +66
Selling Price/System @ 100k/yr)	$	400

2. TEST PROFILES DERIVED FROM LEESS TARGETS

The test procedures described in this manual are intended for use over a broad range of devices at various stages of developmental maturity. The approach taken for these procedures is to define a small set of test profiles based on the overall vehicle characteristics, 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 demand. They can be used in various combinations, with the appropriate scaling factors, to define specific performance or calendar/cycle life tests for cells, modules or battery systems. Because there is essentially a one-to-one relationship between test profiles and test procedures, each profile is defined within the respective procedure described.

3. TEST PROCEDURES

3.1 General Test Conditions and Scaling

In general, LEESS testing is divided into three broad phases, i.e., characterization, life, and reference performance testing. Characterization testing establishes the baseline performance and includes static capacity, hybrid pulse power characterization, self-discharge, cold cranking, thermal performance, and efficiency tests.[B] Life testing establishes behavior over time at various temperatures, states of charge and other stress conditions and includes both cycle life and calendar life testing. Reference Performance Tests establish changes in the baseline performance and are performed periodically during life testing, as well as at the start and end of life testing.

3.1.1 Temperature Control

Unless otherwise specified in a device-specific test plan, the ambient temperature for all tests shall be controlled at a default nominal temperature of 30±3ºC. Also, to the extent possible, all testing should be conducted using environmental chambers. As a general practice, a rest of 60 minutes (or more if required) should be observed after each charge and each discharge prior to proceeding with further testing, to allow devices to reach stable voltage and temperature conditions.

3.1.2 Scaling of Performance and Cycle Life Test Profiles

With the exception of the Hybrid Pulse Power Characterization Test (HPPC) and Calendar Life Test, all performance and cycle life test profiles are defined in terms of required power levels at the system (i.e., full-size vehicle battery) level. Testing any device smaller than a full-size system

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[B]. 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”.

requires a method for scaling these test profiles to a level appropriate to the size of the device (cell, module, or pack) 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 pack) of a given design required for a device to meet all LEESS targets, including cycle life and calendar life. Wherever possible, the Battery Size Factor will be specified by the manufacturer, based on the manufacturer's testing and best estimates of any allowances needed for system burdens and degradation over life.

If insufficient data exist to allow the manufacturer to determine a meaningful value, the Battery Size Factor will be determined from the beginning-of-life Low Current HPPC test results by applying a nominal power margin of 30% to allow for degradation resulting from cycle life and calendar life effects. . [C]

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 40 for a particular cell design, the 5-kW Cold Cranking test would then be performed at a pulse power level of 5000/40 = 125 W for such cells.

3.2 Static 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. If the manufacturer does not provide a discharge voltage limit, or if the provided limit is unrealistically low, either an appropriate value is determined from the literature or 55% of the maximum charge voltage is used. (This will automatically become the lowest possible value for full-size battery tests in any event because of the LEESS operating voltage ratio limits.) The one-hour rate ($C_1/1$) is used as the reference for static 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 hybrid applications.[D]

3.3 Hybrid Pulse Power Characterization Test

The Hybrid Pulse Power Characterization (HPPC) Test is intended to determine dynamic power capability over the device's useable charge and voltage 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 10-s discharge current pulse and (b) the V_{MAX} regen power capability at the end of a 10-s regen current pulse.[E] 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

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

[D]. If initial Static 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 LEESS program management before testing continues. Use of a reasonably representative capacity value is important for high quality HPPC test results.

[E]. V_{MIN} and V_{MAX} refer to the cell minimum and maximum voltages that correspond to the LEESS 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.

voltage response curves the fixed (ohmic) cell resistance and cell polarization resistance as a function of state of charge with sufficient resolution to reliably establish cell voltage response time constants during discharge, rest, and regen operating regimes. The resistance measurements will be used to evaluate resistance degradation during subsequent life testing and to develop hybrid battery performance models for vehicle systems analysis.

3.3.1 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 both the targets (10-s discharge, 10-s regen). The normal test protocol uses constant current (not constant power) at levels derived from the manufacturer's maximum rated discharge current or the rated capacity. 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
10	10	1.00
40	50	0
10	60	-0.75

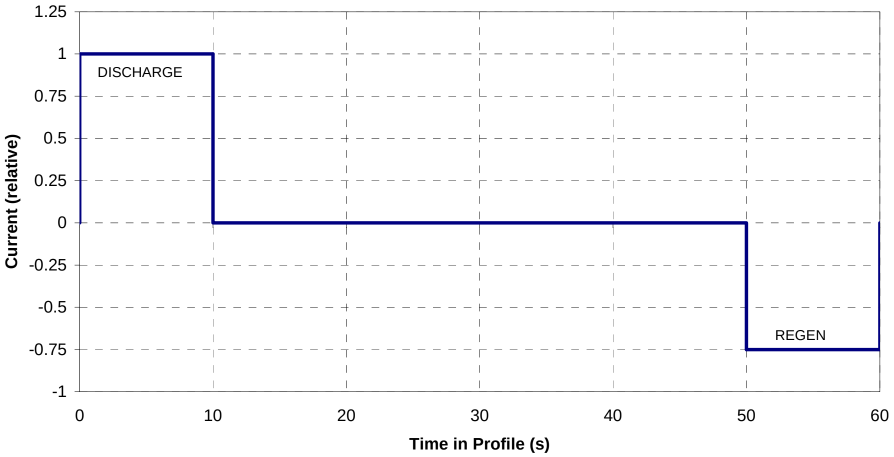

Figure 1. Hybrid Pulse Power Characterization Test profile.

Note that the current values are relative, not absolute. The actual current values are determined as defined in Section 3.3.2. Also, note that this manual uses positive values for discharge current and power, whereas charge or regen values are negative.

3.3.2 Test Procedure Description

The HPPC test incorporates the pulse power characterization profile as defined in Section 3.3.1. 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 (depth of discharge) constant current $C_1/1$

discharge segments,[F] 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 test begins with a fully charged device after a 1-hr rest and terminates after completing the final profile at 90% DOD, discharge of the cell at a $C_1/1$ rate to 100% DOD, and a final 1-hr rest. [G] 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 $C_1/1$ discharge segments is illustrated in Figures 2 and 3. These figures also illustrate a $C_1/1$ discharge to be executed just prior to each HPPC test.[H]

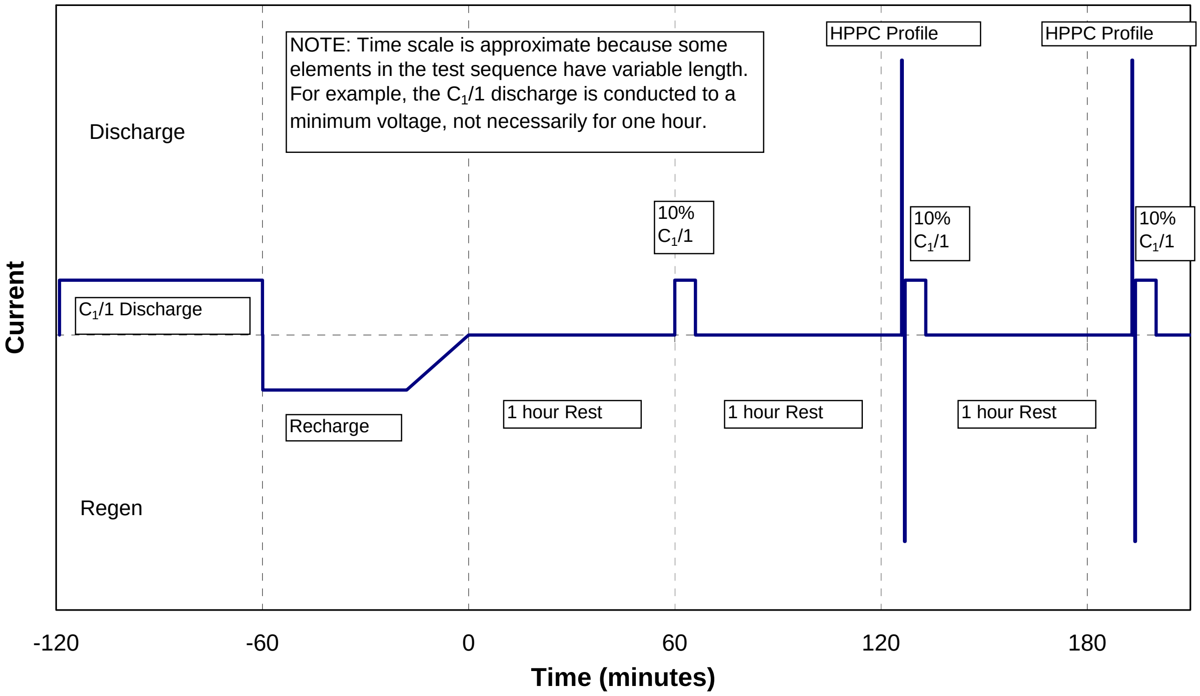

Figure 2. Hybrid Pulse Power Characterization Test (start of test sequence).

[F]. Note that the energy 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 may remove several percent of the capacity from a typical device. The test should be programmed such that 10% of the rated capacity is removed in each test segment, including that removed by the pulse profile itself.

[G]. 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 $C_1/1$ discharge rate can be sustained to the next 10% DOD increment.

[H]. This $C_1/1$ discharge is required because the HPPC results will eventually be reported as power capability versus energy removed at a $C_1/1$ rate. The availability of linked $C_1/1$ data facilitates this analysis and reporting; see Section 4.3.

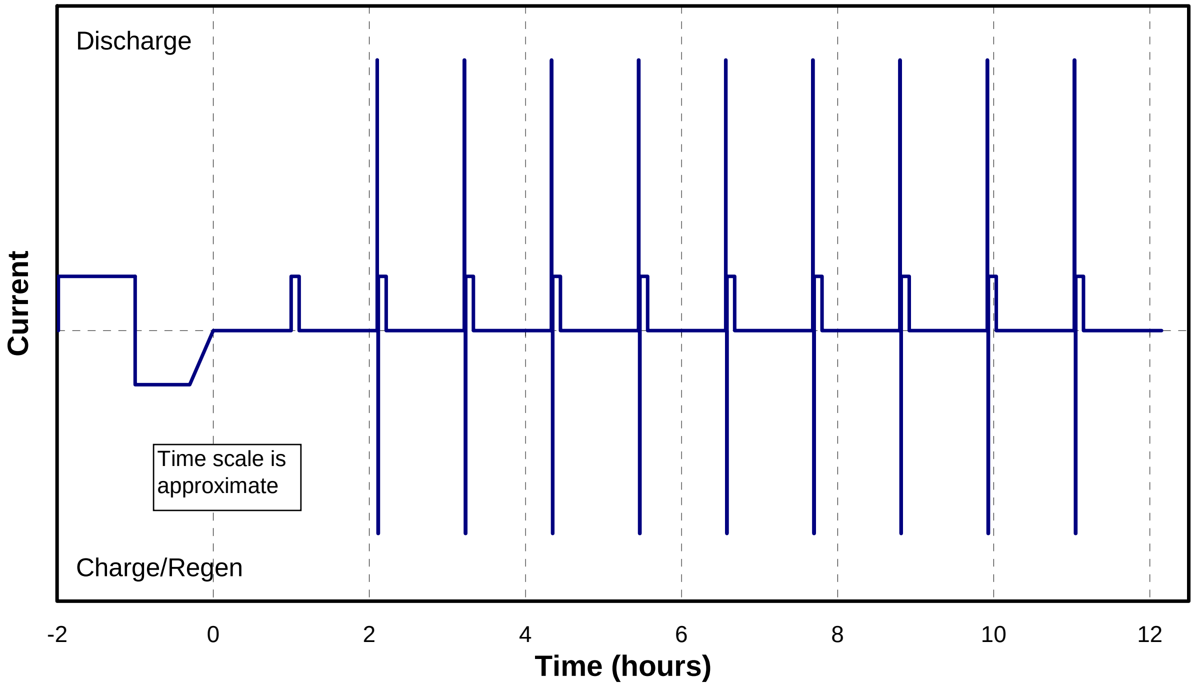

Figure 3. Hybrid Pulse Power Characterization Test (complete HPPC sequence).

The HPPC test sequence is performed using peak currents scaled to two different levels, with the complete test performed for each level. Scaling of the levels is determined by the following criteria.

LOW CURRENT HPPC TEST—The pulse profile discharge current is 25% of I_{max}, where I_{max} is the manufacturer's absolute maximum allowable pulse discharge current for 10 s (at some state of charge, which need not be specified). The test current selected must be at least a 5C rate, i.e., a discharge current (in amperes) greater than or equal to five times the manufacturer's ampere-hour capacity rating.[I]

HIGH CURRENT HPPC TEST—The pulse profile discharge current is selected as 75% of I_{max} (as defined previously).[J]

3.3.3 Special 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

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[I]. If the manufacturer does not specify I_{max} as defined here, the Low-Current test is performed at a 5C rate.

[J]. If the manufacturer does not specify I_{max} as defined here, it is calculated from the Low-Current HPPC Test results using the discharge resistance and OCV curves from Sections 4.3.1 and 4.3.2 and the manufacturer's discharge voltage limit V_{DVL}, using the equation

$I = (OCV-V_{DVL}) \div R_{discharge}$.

The largest value of current calculated at any 10% DOD value is defined as I_{max}.

new technology, a new cell design or a full-size battery design is tested for the first time), it may be desirable to verify the extent of this conservatism by performing a test at the actual target values. This is done using a special test sequence as follows:

1. From HPPC test results, calculate (a) the minimum 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 $C_1/1$ rate between DOD_{MIN} and DOD_{MAX}. These values are calculated using Section 4.3.4 and 4.3.7 of this manual.

2. Starting with a fully-charged battery, discharge to DOD_{MIN} at a $C_1/1$ constant current 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 battery.

5. Discharge to DOD_{MAX} at a $C_1/1$ constant current 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 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 the cell for 30% of the rated capacity at a $C_1/1$ rate, and allow it to stand in an open-circuit condition for a nominal interval of 7 days (1 week).[K] (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.

[K]. 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.

4. Recharge the cell and fully discharge it again at a $C_1/1$ rate. If a loss of capacity is observed between (1) and (4), additional recharge/discharge cycles may be performed to return the cell to its nominal capacity.

3.5 Cold Cranking Test

The Cold Cranking test is intended to measure 2-s power capability at low temperature (normally -30ºC) for comparison with the LEESS Cold Cranking Power target(s) in Table 1. The test is conducted after a 30 day stand at 30°C from the fully charged condition. The test consists of the following sequence of activities:

1. Fully charge the device, allow it to stand for 30 days at 30°C.

2. Reduce the ambient temperature to –30ºC, and soak the device for a period of time adequate to ensure it has reached thermal equilibrium at this temperature.

3. Perform the Cold Cranking Test profile defined in Section 3.5.1. The pulse power level to be used is 5 kW divided by the Battery Size Factor as determined in Sections 3.1.2. Note that the manufacturer may specify a different minimum discharge voltage for cold cranking testing. This voltage, if specified, will be used for both test control and the subsequent calculation of cold cranking power capability; but it may not exceed the LEESS voltage ratio limits in Table 1. Note also that the profile pulses must be performed for the full 2-s duration (even if the test power has to be limited to stay within the minimum discharge voltage) to permit the later calculation of Cold Cranking power capability.

3.5.1 Cold Cranking Test Profile

The Cold Cranking Test profile is a literal implementation of the Cold Cranking Power targets, which require the ability to provide either 5 kW of discharge power for three 2-s pulses at 12-s intervals (i.e., 10 s between pulses.) The profile is defined in Table 3 and illustrated in Figure 4 for both the targets.

Table 3. Cold Cranking Test profiles for targets.

Time Increment (s)	Cumulative Time (s)	System Power (kW)
2	2	5
10	12	0
2	14	5
10	24	0
2	26	5

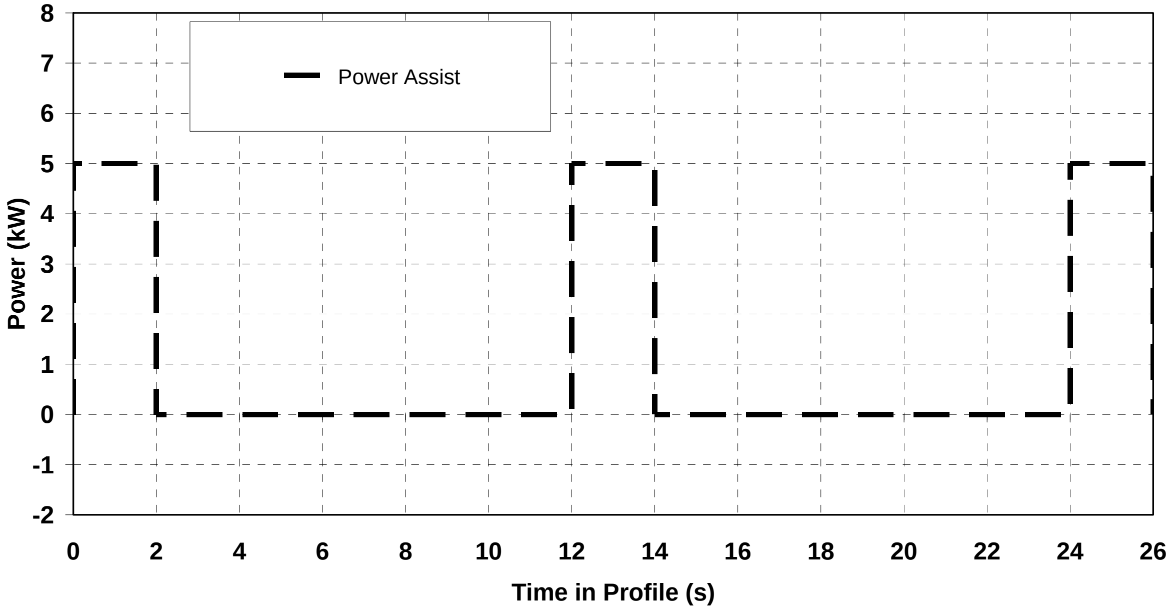

Figure 4. Cold Cranking Test profiles.

3.6 Thermal Performance Test

The effects of environment (ambient temperature) on device performance will be measured as required by performing the Static Capacity Test, Low-Current Hybrid Pulse Power Characterization Test, and/or Cold Cranking Test at various temperatures within the LEESS operating temperature target range (-30 to +52ºC). 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 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 cell at 30ºC; (2) raise or lower the cell ambient temperature to the target value; (3) wait a suitable soak period for thermal equalization, typically 4 to 8 hr; and (4) execute the desired performance test. If self-discharge is a major concern during the soak period, the cell 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 Energy Efficiency Test

Round-trip efficiency is determined at the cell level by calculation from a charge-balanced pulse profile. 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 cell to a specified target state of charge value and operating temperature.

2. Perform 100 efficiency test profiles while controlling state of charge as described in Appendix B under “Continuous Life Cycling at a Fixed Target SOC/DOD Value.”

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.

3.7.1 Efficiency Test Profile

The Efficiency Test Profile is a 90-s, nominally charge-neutral pulse profile (also used as the 25-Wh Cycle Life Test profile) that is scaled to a level appropriate to verify the round trip energy efficiency target of 90% for a 25-Wh energy swing.[L] This test profile is defined in Table 4 and illustrated in Figure 5.

Table 4. 25 Wh Efficiency and Cycle Life Test profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
20	20	3.00	16.67	16.67
2	22	15.00	8.33	25.00
66	88	-1.15	-21.11	3.89
2	90	-12.00	-6.67	-2.78

[L]. This profile is calculated to be charge-neutral for a device that exactly meets the 90% efficiency target. Appendix B explains in detail how to adjust it to a charge balanced state in the case where the efficiency is higher than the target. Efficiency lower than the target is not anticipated, but the Appendix B procedure is easily modified to accommodate this as well. Note that because the Efficiency Test and Cycle Life Test profiles are identical, the Efficiency Test may also serve as the OSPS Test if the same SOC value is appropriate.

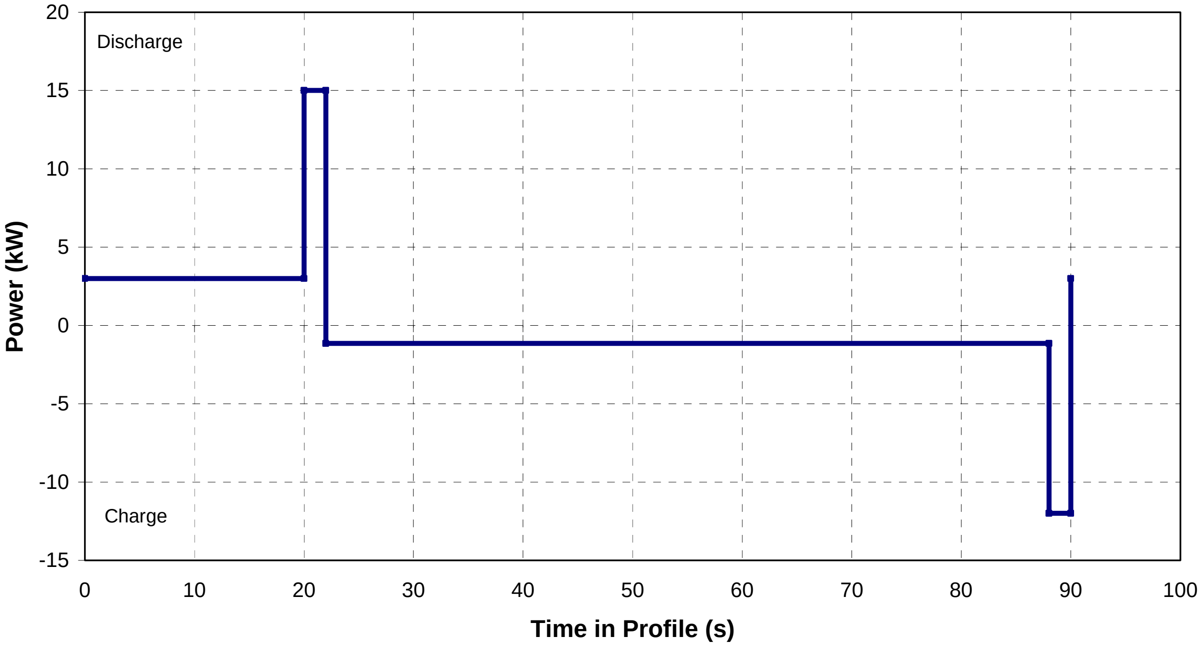

Figure 5. (25 Wh) Efficiency and Cycle Life Test profile.

3.8 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 3.9 is normally specified in a device-specific test plan based on projected use of the device.[M] This test should be performed immediately before the beginning of cycle life testing.

With the cell at the selected state-of-charge value and all other conditions (e.g., operating temperature) as required for life cycling, apply the Cycle Life Test profile for a period long enough to reach thermal equilibrium and to return to the target SOC.[N] Determine the change (if any) in the state of charge before and after the cycling interval. Allow 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.

3.8.1 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

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[M]. 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 usable 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.

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

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.

3.8.2 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 are provided in Appendix B, 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 9.

3.9 Cycle Life Tests

Cycle life testing is performed using the Hybrid Cycle Life Test profile defined in Section 3.9.2 for Power-Assist operation. Cycle life testing is performed by repeating the test profile at a fixed state of charge (i.e., the profiles are charge-neutral). Control of the state of charge is addressed in detail in Appendix B.

3.9.1 Cycle Life Test Procedure Outline

The cycle life testing process consists of the following steps:

1. Scale the test profile by dividing the nominal profile power values by the Battery Size Factor as described in Section 3.1.2.

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

   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.[P]

   End of test is normally chosen to occur when one of the following conditions exists: (a) cycle life meeting the LEESS targets has been attained (i.e., the number of properly scaled test cycles exceeds the applicable LEESS target); or (b) Available Energy drops below the target value. In case (a) the battery may not have reached end of life when

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[O]. 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.

[P]. 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.

testing stops, but further testing is not usually considered cost-effective. In case (b), end of life has occurred at some prior time.[Q]

3. Select the desired operating state of charge for cycle life testing and perform the Operating Set Point Stability Test (Section 3.8) to verify stable operation at the selected SOC point. Make any needed adjustments to the test profile or test operating conditions.[R]

4. Repeat the selected test profile(s) at the desired operating conditions the number of times specified in Table 9 or a device-specific test plan.[S]

5. After the specified number of repetitions, suspend cycling. If cycling is being done at other than 30ºC, return the cell to 30ºC. Observe the open-circuit voltage after a 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 9. The intervals between repetitions of these reference tests are also specified in Table 9, though these may be adjusted somewhat if required for time synchronization of cells being tested under different test regimes.

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

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

3.9.2 Power-Assist (25 Wh) 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 LEESS targets.

The 25Wh Power-Assist profile is a set of 90-s pulse profiles intended to demonstrate the ability to meet the LEESS cycle life target of 300,000 cycles with a 25-Wh swing. The profile transfer about 7.5-million watt-hours (MWh) respectively in and out of the device over 300,000 cycles.

This test profile is defined at the battery pack level. It is scaled to the appropriate power levels for testing laboratory cells, full-size cells and module designs using the Battery Size Factor as described in Section 3.1.2.

Each of the Power-Assist (25 Wh) Cycle Life Test profiles remove 25 Wh on discharge and is nominally charge-balanced for a device that just satisfies the 90% efficiency target using the profile. The profile is identical to the Power-Assist Efficiency Test profile defined in Section 3.7.1. The Power Assist profile is listed here as Table 5 and is illustrated in Figure 6.

[Q]. 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.

[R] Because there are large differences in average heating rate for the three profiles in each family, it may be necessary to perform the OSPS separately for each profile.

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

Table 5. Power-Assist (25 Wh) Cycle Life Test profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
20	20	3	16.67	16.67
2	22	15	8.33	25
66	88	-1.15	-21.11	3.89
2	90	-12	-6.67	-2.78

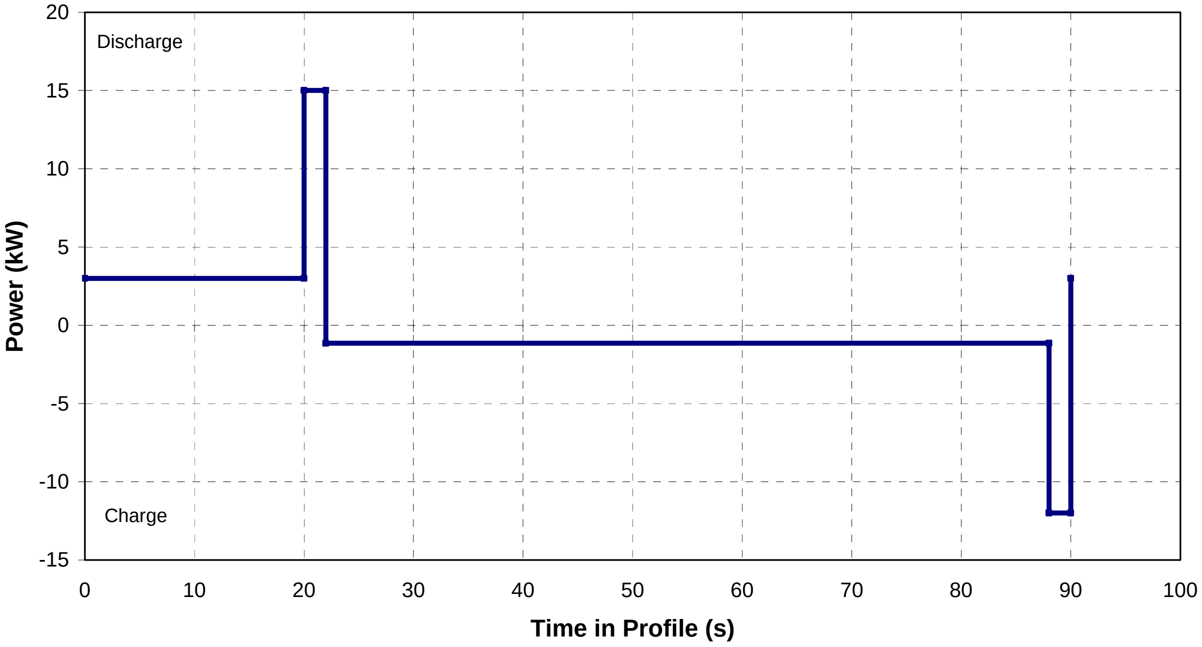

Figure 6. Power-Assist (25Wh) Cycle Life Test Profiles

3.10 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.[T] 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. 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.

3.10.1 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.

Five to seven elevated temperatures should be selected. The lowest temperature 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 SOC), 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. The test-to-test repeatability of these parameters should be no worse than one percent of the target values (to one standard deviation).

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

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

- All cells that are part of a common test matrix should be subjected to reference testing at the same intervals if possible. Minimizing the fraction of time not spent at target temperatures is important for testing at elevated temperatures. However, in some cases rapid degradation may take place at very high temperatures; in such cases, the use of uniform test intervals will lead to a reduced number of data points for predicting trends

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[T]. 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.

over life. The reference test intervals have been selected to balance these conflicting needs but may need adjustment in special cases.

3.10.2 Calendar Life Test Procedure

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

1. Characterize the cell using the Static Capacity Test (Section 3.2) and Hybrid Pulse Power Characterization Test (Section 3.3) 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) [default] remove the appropriate fraction of the cell's rated capacity at a $C_1/1$ rate, or (b) 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.[U] Note that the default method will typically reach the target DOD more quickly. However, 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 3.10.3. 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., 25% of I_{max} or 5C, whichever is smaller.)

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 3.10.3 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, even though other data may be required only infrequently during the 24 hour intervals.[V]

7. At intervals as specified in Table 9 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 3.9.1: (a) the Calendar Life Test profile cannot be performed within the voltage limits; (b) the

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[U]. 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.

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

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.

3.10.3 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)
9	9	1.0	9.0
60	69	0	9.0
2	71	-1.0	7.0
2	73	0	7.0
47	120	-0.149	0

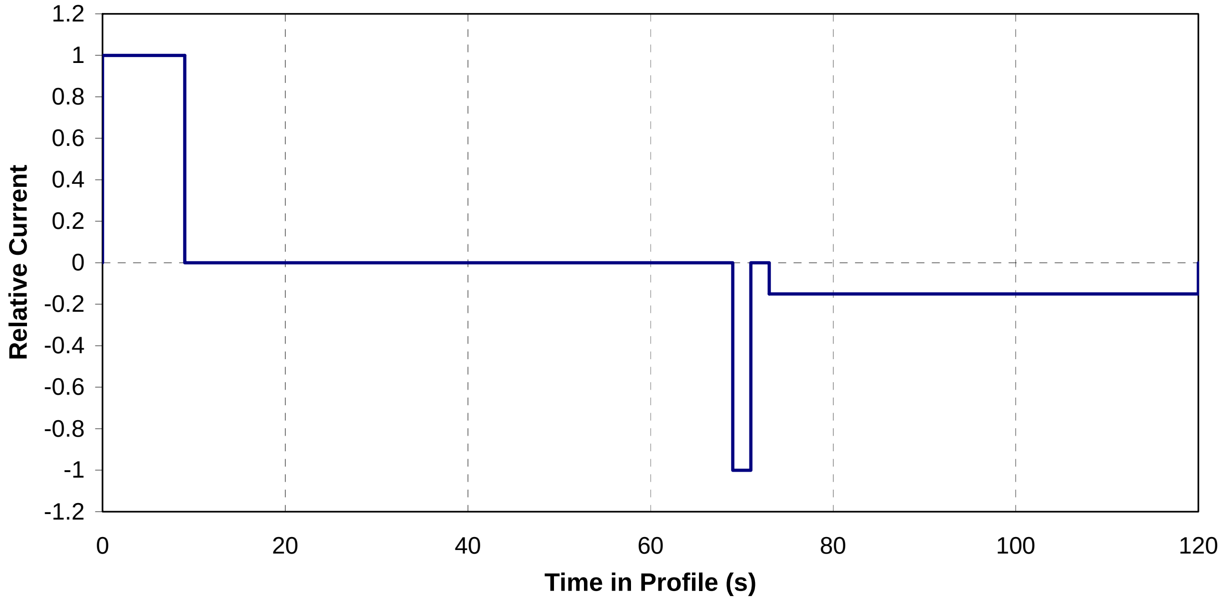

Figure 7. Calendar Life Test profile.

3.10.4 Alternative Calendar Life Test

In some cases calendar life testing may be conducted without using the once-per-24 hr Calendar Life Test profile. The most likely reason for this is a shortage of continuously available test channels for the number of devices to be tested. (If the 24-hr pulse profile is not performed, a test channel is required only for the periodic Reference Performance Tests and possibly for occasional charge increments.) The earlier procedure can be used in this fashion by omitting the daily performance of the test profile specified in Step 4. 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.

3.11 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. [W]

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. These tests are performed for all HEV testing modes.

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

Type of Life Testing	Interval Between RPTs	Reference Performance Tests
Cycle Life Testing	30,000 cycle life profiles	C_1/1 Constant-Current Discharge Test Low-Current HPPC Test
Calendar Life Testing	Approximately 32 days (750 hours)	
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.

[W]. 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 3.6) to estimate the present performance at the nominal 30°C temperature. Performing such an adjustment is necessarily limited to those cases where the following conditions are satisfied: temperature data are available with accuracy better than the variations to be corrected (2°C or less); Thermal Performance Test data is available "near" the normal testing range, e.g., within ±5°C on either side of the nominal temperature; and the test whose data are to be adjusted is conducted within this limited range "near" the nominal temperature.

3.12 Impedance Spectrum Measurements

For cells, it may be useful to measure ac impedance values at various points during their 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.

3.13 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

3.14 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 (-30ºC to +52ºC) specified by the LEESS 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 LEESS operating temperature range in a manner that is influenced by the statistics of annual climatic (i.e., in-vehicle) conditions in various geographic locations.

3.15 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 3.10, 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 300,000-cycle life target could be demonstrated by performing 1000 cycle life test profiles each day.

In practice there are other issues to be considered. The 300,000-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 FOR LEESS SYSTEMS

4.1 General

For purposes of test reporting consistency (particularly between multiple testing organizations), a required minimum subset of information, based on the procedures in this manual, has been compiled for testing and is tabulated in Appendix A. This is not intended to limit the reporting of other test results where appropriate; the intent is rather to ensure that important test results are reported in a fashion that allows them to be compared to test results on hybrid energy storage devices performed at various locations and stages of development.

4.2 Static Capacity Test

Capacity in ampere-hours and watt-hours at the specified discharge rate are reported, based on manufacturer-specified discharge termination conditions. (Note that all of this capacity will not generally be useable within the LEESS operating conditions, and thus it does not reflect conformance to the LEESS Available Energy target. However, it is still considered a useful measure of capacity at the laboratory cell stage.)

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

4.2.1 Capacity Fade

For devices subjected to life testing, the change in static 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 t_0 refers to the time of the initial (BOL) RPT and t_1 refers to the time of the later RPT where capacity fade is to be determined.

4.3 Hybrid Pulse Power Characterization Test

Analysis and reporting of the results of the HPPC test is generally aimed at comparing the present performance of a cell to the LEESS targets. Since the LEESS 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 Section 3.1.2). The Battery Size Factor for a cell is necessarily specific to Power-Assist targets.

4.3.1 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.

4.3.2 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: 10 s after start of discharge pulse
2. Regen resistance: 10 s after start of regen pulse.

The same process that is used to evaluate 10 s can be used to evaluate the 2 s resistance and power. Discharge and regen resistances are determined using a ΔV/ΔI calculation for each iteration of the test profile, in accordance with Equations (2) and (3) and Figure 8. Resistances are normally only calculated for completely unabated test profile pulses, i.e., those with full duration and amplitude.[x]

$$\text{Discharge Resistance} = \frac{\Delta V_{discharge}}{\Delta I_{discharge}} = \frac{V_{t1} - V_{t0}}{-\left(I_{t1} - I_{t0}\right)} = \frac{V_{t1} - V_{t0}}{I_{t0} - I_{t1}} \tag{2}$$

$$\text{Regen Resistance} = \frac{\mathit{\Delta} V_{regen}}{\mathit{\Delta} I_{regen}} = \frac{V_{t3} - V_{t2}}{-\left(I_{t3} - I_{t2}\right)} = \frac{V_{t3} - V_{t2}}{I_{t2} - I_{t3}} \tag{3}$$

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.

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[x]. 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 targets.

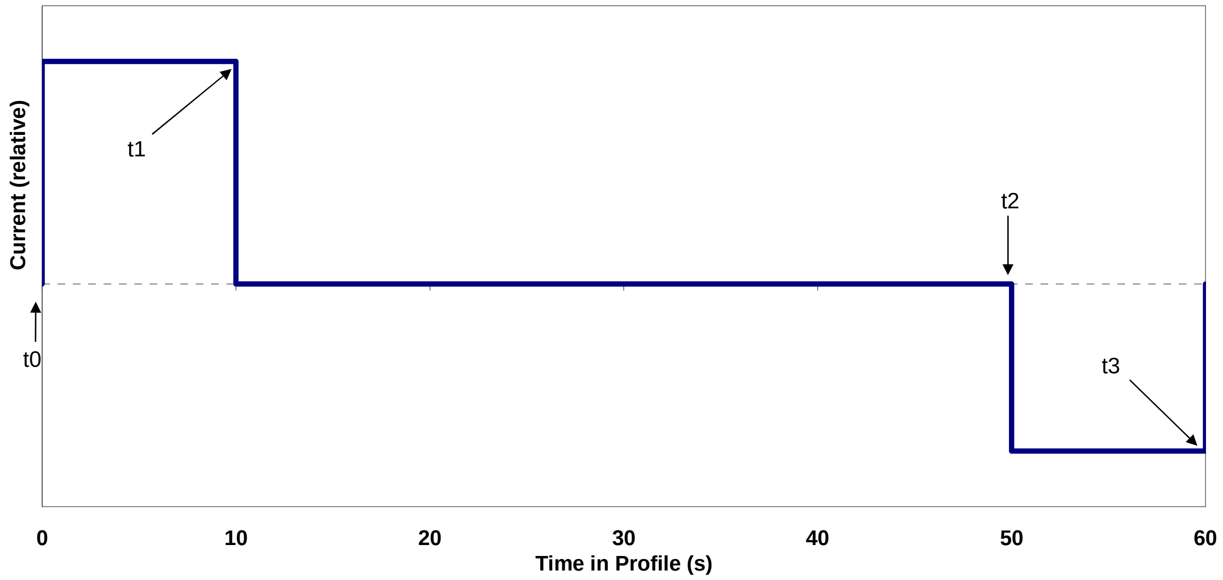

Figure 8. Resistance calculation time points.

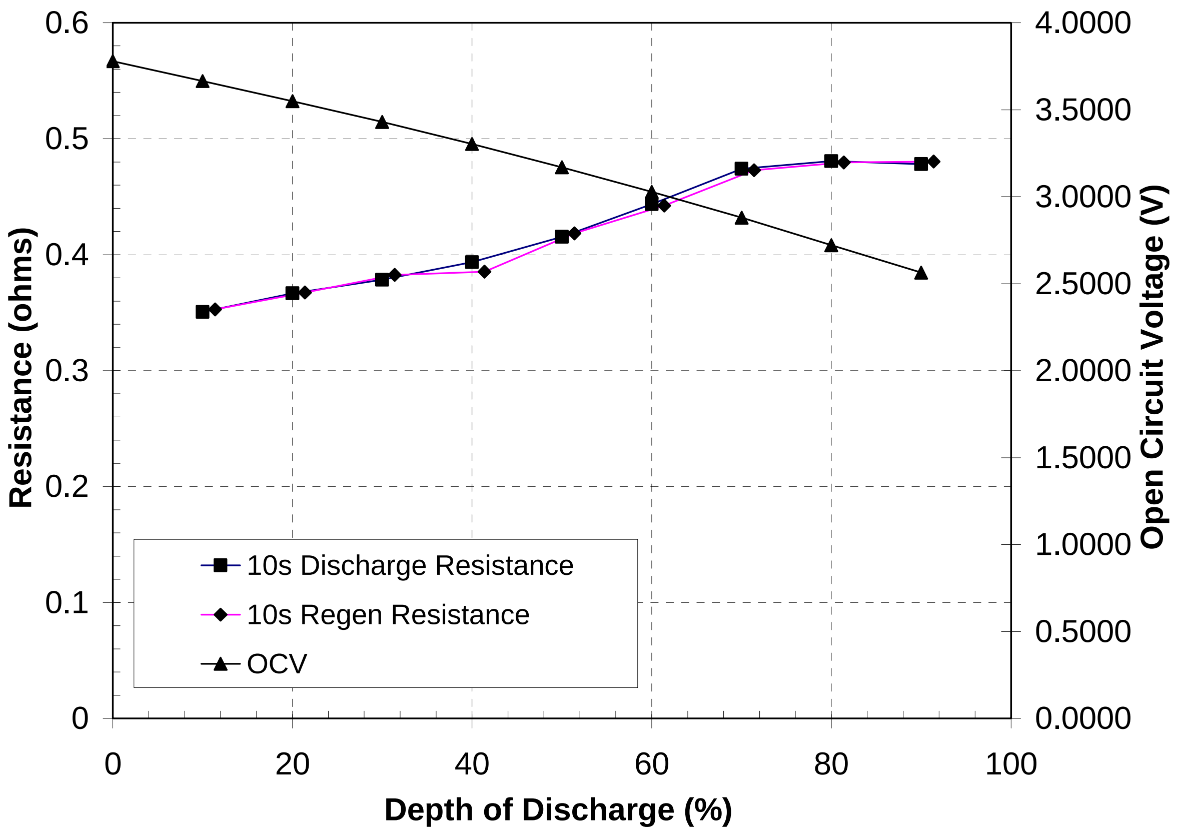

Figure 9. Open-circuit voltage and pulse resistances versus depth of discharge.

4.3.3 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. (See footnote [E] in Section 3.3 regarding allowable values for V_{MAX} and V_{MIN}.)

Discharge and regen pulse power capability is calculated at each available DOD increment from the open-circuit voltage and resistance determined for that DOD (as shown in Figure 9), using Equations (4) and (5).

$$\text{Discharge Pulse Power Capability} = V_{MIN} \bullet (OCV_{dis} - V_{MIN}) \div R_{discharge} \tag{4}$$

$$\text{Regen Pulse Power Capability} = V_{MAX} \bullet (V_{MAX} - OCV_{regen}) \div R_{regen}\ ^{Y} \tag{5}$$

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

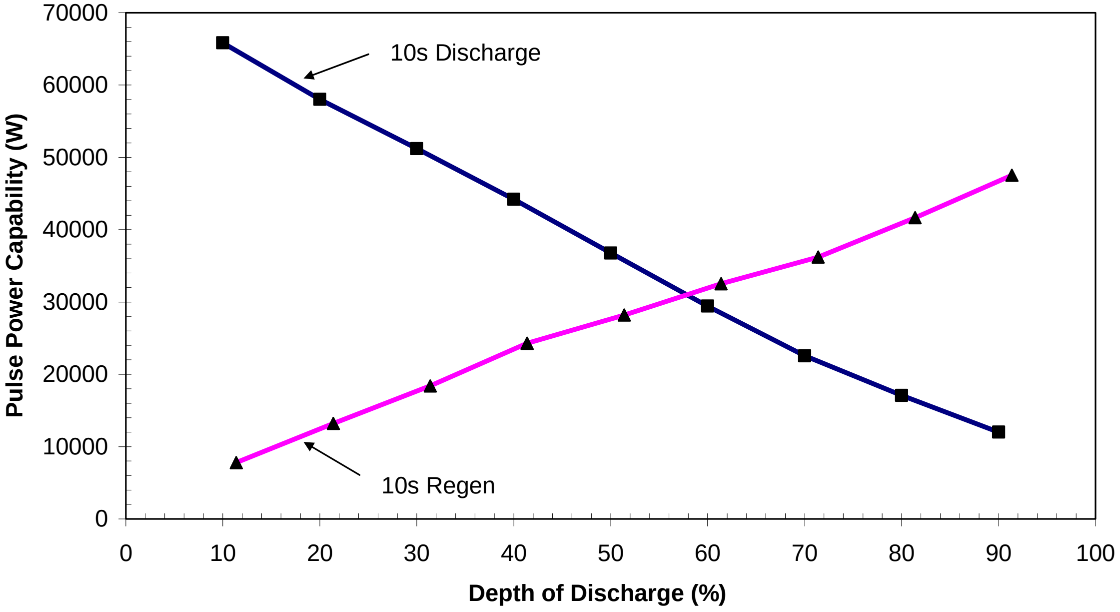

Figure 10. Pulse power capability vs. depth of discharge.

[Y]. 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.

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

Pulse power capability can also be calculated from the maximum current, as shown using Equations (6) and (7).

$$Discharge\ Pulse\ Power\ Capability = I_{MAX}^{2} \div R_{discharge} \qquad (6)$$

$$Regen\ Pulse\ Power\ Capability = I_{MAX}^{2} \div R_{regen} \qquad (7)$$

4.3.4 Available Energy

Available Energy (also known as the Energy over which both requirements are met) is defined as the energy removed during a $C_1/1$ discharge over the DOD range for which the discharge and regen pulse power targets for a given mode are precisely met. Determining available energy consists of the following steps:

1. Establish the relationship between HPPC power and $C_1/1$ energy as a function of DOD.
2. Scale both the energy and power results using the Battery Size Factor.
3. Determine the minimum and maximum DOD values over which the LEESS power targets can be met.
4. Calculate the available ($C_1/1$) energy over the discharge region where the targets are precisely met.

This is also shown in Figure 17 and Section 4.3.7

HPPC power capability and $C_1/1$ energy values are related by assuming that the corresponding measured DOD values in a pair of such tests are equivalent.[AA] 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 $C_1/1$ test.

[AA]. 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.

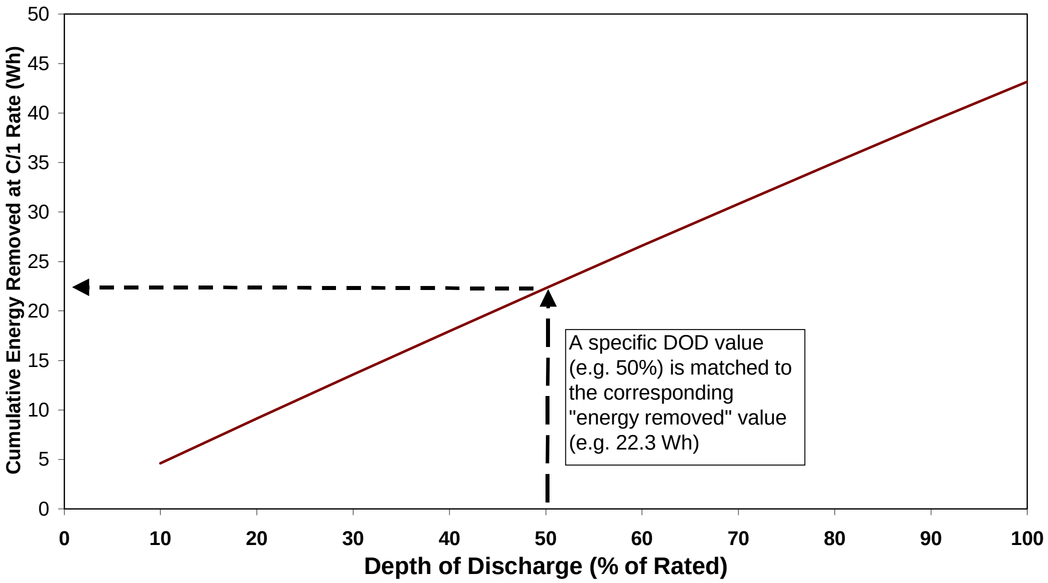

Figure 11. Relationship between energy and DOD in a C1/1 discharge.

Figure 11 shows the example $C_1/1$ equivalence, and Figure 12 illustrates the resulting HPPC power versus $C_1/1$ energy plot for cell-level data.[BB] (Power and energy values are illustrative only.)

By definition, if the Discharge and Regen Energy Requirements for LEESS PA HEV of 56 and 83 Wh, respectively then are met as long as the Available Energy is greater than 0, since a 20 kW discharge pulse for 10 seconds would be ~ 56 Wh (55.56) and a 30 kW regen pulse for 10 seconds would be ~83 Wh (83.33). Thus, the energy window for vehicle use is also met if the Available Energy is greater than 26 Wh, (56 + 83 + 26 = 165). Evaluation of these targets is built into the test.

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

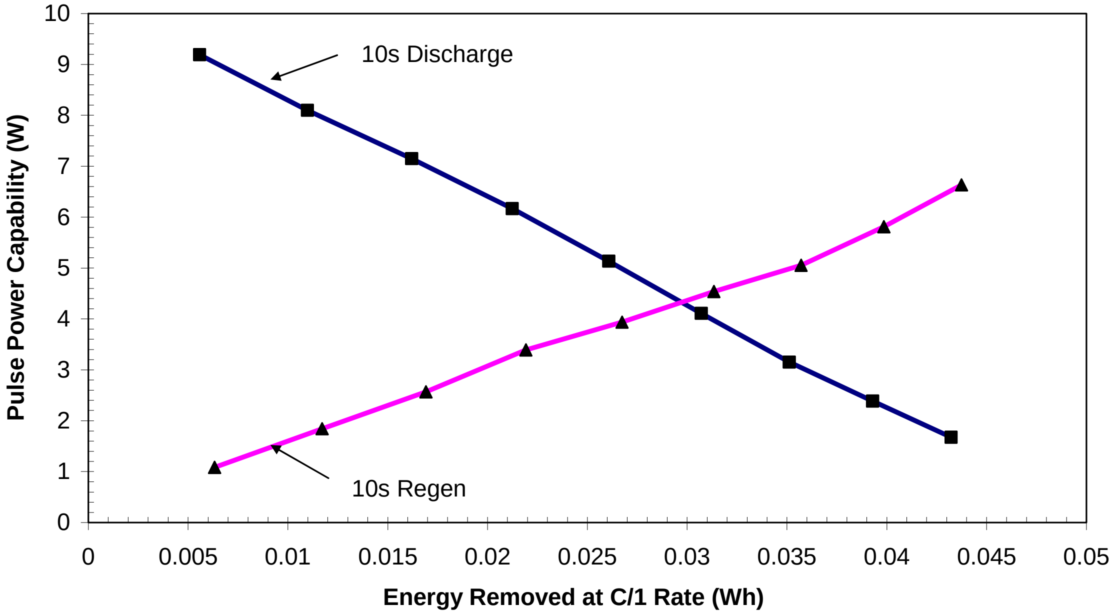

Figure 12. Unscaled HPPC cell power capability versus C1/1 energy removed.

This power-versus-energy data plot can now be scaled by the Battery Size Factor for comparison with the LEESS Power-Assist 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 plotted on a second axis scaled by the ratio of required regen to discharge power, e.g., 30-kW regen and 20-kW discharge for the LEESS Power-Assist targets. Figure 13 illustrates the result of this scaling applied to Figure 12, for a Battery Size Factor of 6500.

Note that the crossover point of the two power capability curves shifts 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 (4) and (5), 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 usable energy range can be varied if desired by altering the operating voltage range (within the allowable LEESS voltage limits.)

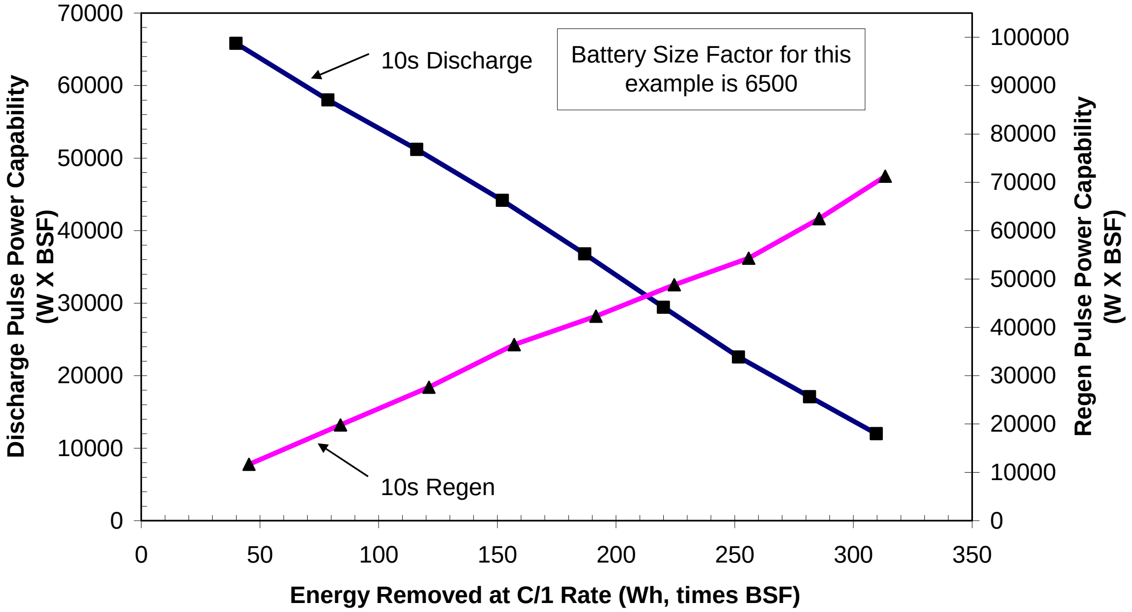

Figure 13. HPPC power versus C1/1 energy scaled by the Battery Size Factor.

The comparison of these results to the Targets can be performed graphically by adding a horizontal line representing the power targets and determining the available energy based on the intersection of this target line and the discharge and regen power capability curves, as shown in Figure 14. (This horizontal line represents both the discharge and regen targets because the two vertical axes are scaled in proportion to these targets.) For this example, with the values shown it can be seen that the available energy is approximately equal to the difference between 265.7 Wh and 130.9 Wh, or 134.8 Wh.[CC]

In the example, this result would indicate an energy *margin* of 108.8 Wh over the Power-Assist target of 26 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 LEESS power and energy targets are required to be met at end of life, the point where this energy margin decreases to zero is necessarily *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 variation of energy margin over life is illustrated in Figure 15 (which is derived from a different data set than other illustrations in this section.) This figure shows the energy margin and power margin at beginning of life, and it illustrates how these margins are zero (by definition) at end of life.[DD]

[CC]. These data values are illustrative only. In practice, a value of available energy that equaled almost 5 times the applicable target (as here) might indicate that the Battery Size Factor had been improperly determined.

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

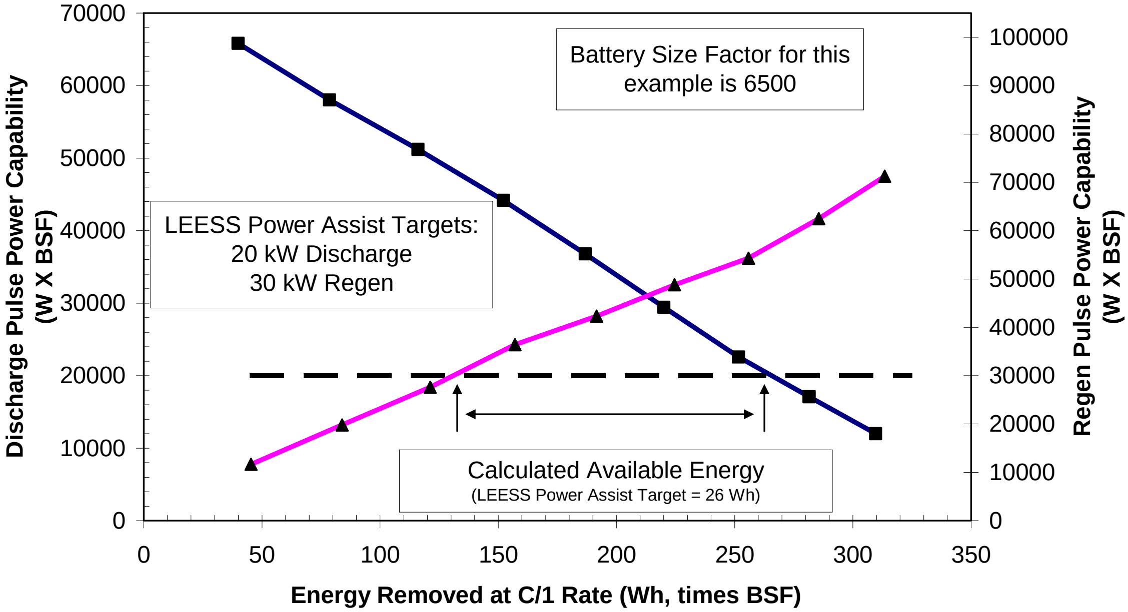

Figure 14. Available Energy determination.

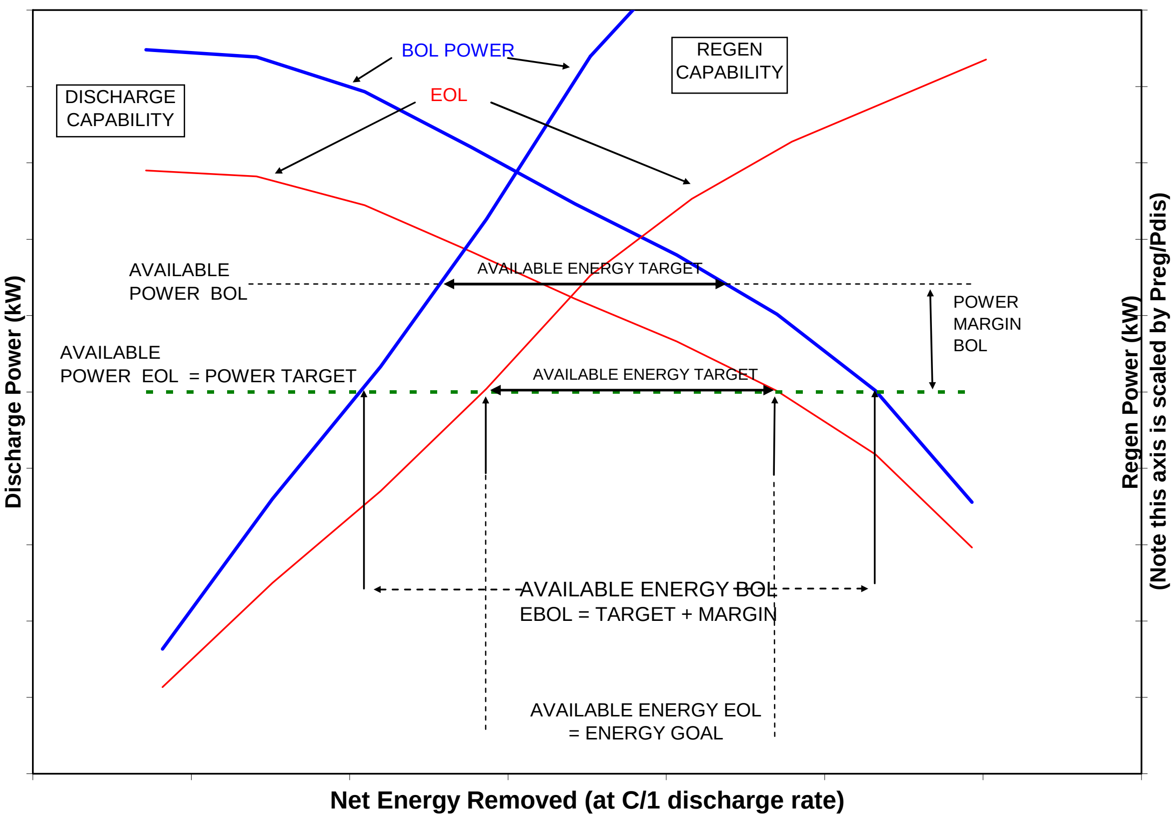

Figure 15. Available Energy and Available Power margins over life.

4.3.5 Available Power

Available Power is the discharge power capability at which usable energy is equal to the Available Energy target for a given mode. In effect it is the maximum discharge power capability at which the Available Energy target 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. This parameter is defined primarily for reporting battery degradation over life. Available Power and Available Energy in fact represent two complementary aspects in the performance of a battery at any point in time.

A more complete representation of the energy and power behavior is represented by the example Usable Energy versus Power curve illustrated in Figure 16. The usable energy is calculated as the energy between the discharge and regen power capability curves at various values of discharge pulse power. In this context, Figure 14 illustrates one such specific energy value (Available Energy) which happens to be calculated at a power equal to the discharge pulse power target.

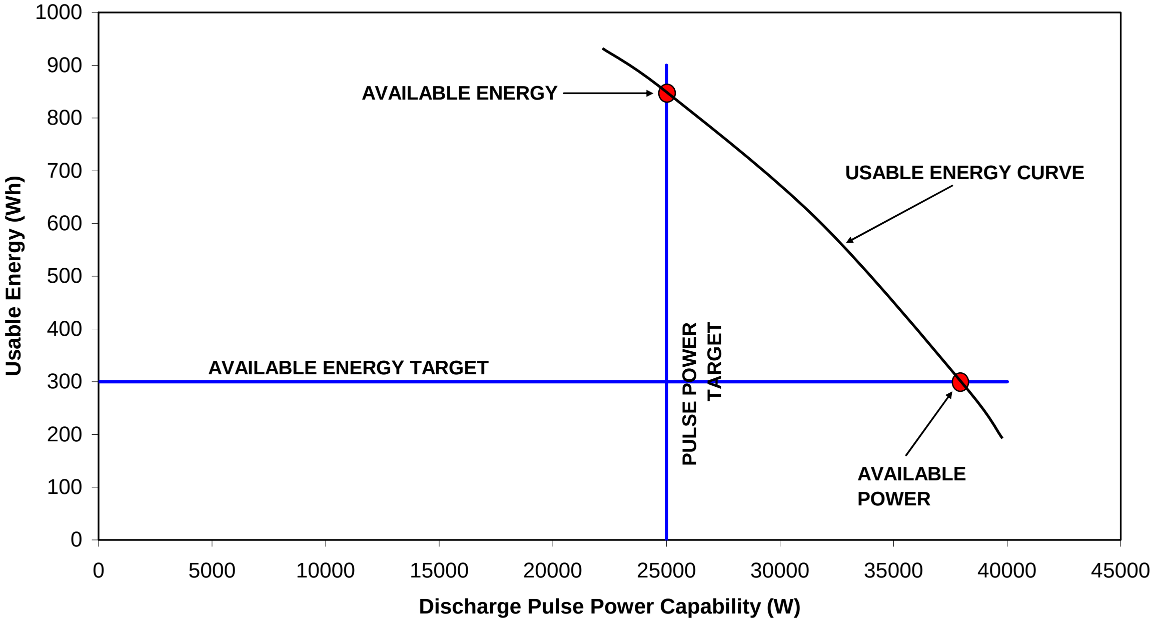

Figure 16. Scaled Usable energy versus power curve.

4.3.6 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, Energy Fade Capacity Fade, and Resistance Fade, both expressed as percentages of the original (BOL) values as shown in Equations (6), (7), (8), and (9).

$$Power\ Fade\,(\%) = 100 \times \left(1 - \frac{Available\ Power_{t1}}{Available\ Power_{t0}}\right) \qquad (6)$$

$$\mathit{Energy\ Fade}\,(\%) = 100 \times \left(1 - \frac{\mathit{Available\ Energy}_{t1}}{\mathit{Available\ Energy}_{t0}}\right) \tag{7}$$

$$\mathit{Capacity\ Fade}\,(\%) = 100 \times \left(1 - \frac{\mathit{Capacity}_{t1}}{\mathit{Capacity}_{t0}}\right) \tag{8}$$

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

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.

4.3.7 Minimum and Maximum DOD Values

Minimum and maximum DOD values where the LEESS 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 14, but plotted against the original DOD values from the HPPC test (i.e., DOD values are not converted to the equivalent $C_1/1$ energy values.) Figure 17 shows the results of this scaling applied to the same example data as previously. This graph shows that the minimum and maximum DOD values where the Power-Assist targets, 20 kW of discharge power and 30 kW of regen power can be met are approximately 35 and 74%, respectively. The value where the 26 Wh is met at 28,823 W is the Available Power, which represents a 44% power margin.

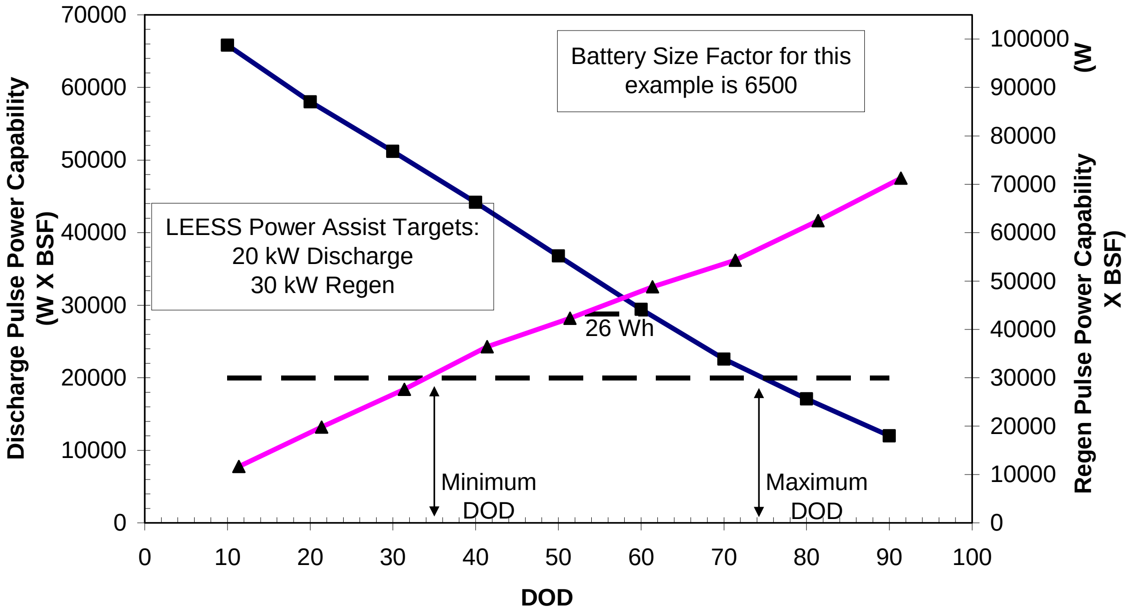

Figure 17. Minimum and maximum DOD values where Targets are met.

4.3.8 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.

4.3.9 Other Laboratory Cell Performance Characteristics

Other laboratory cell performance characteristics can be calculated from the HPPC data to permit scale-up calculations to full-size cells. 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

Cell capacity and energy in area-specific, volumetric, and gravimetric 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 Power-Assist applications.

A recommended practice would be to acquire the cell temperature data during testing.

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 Self-Discharge Test

Self-discharge rate is determined over a fixed period (nominally 30 days) at one or more intermediate DOD conditions (nominally 30% DOD). The difference between the energy (watt-hours) capacities 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 for the applicable mode, as shown in Equation (10).

$$Self\ Discharge = \frac{Wh_{C/1\,before\,test} - (Wh_{part\ 1} + Wh_{part\ 2})}{Stand\ Time\ in\ Days} \times BSF \tag{10}$$

The result of this calculation is not reported but to be used for comparison with the other technologies.

4.5 Cold Cranking Test

The fundamental result of the Cold Cranking Test is the power capability at the end of the third 2-s pulse at -30°C, which is to be multiplied by the Battery Size Factor and compared to the LEESS target of 5 kW. The actual power achieved does not necessarily represent the maximum power capability; it merely shows whether the device was able to meet the target. (Some batteries may be capable of higher power than this.) The maximum power capability may be calculated in a manner analogous to the normal pulse-power capability results, as follows:

1. Calculate discharge pulse resistance values using the voltage and current values at three pairs of time points [(t0, t1), (t2, t3), and (t4, t5), illustrated in Figure 18, using the same $\Delta V/\Delta I$ calculation (Equation [2]) used for discharge resistance in Section 4.3.2.

2. Calculate the discharge pulse power capability for each of the Cold Cranking Test pulses using Equation (4) as in Section 4.3.3. 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 three pulse power capability values by the Battery Size Factor and report the resulting power values for comparison with the LEESS target of 5 kW.

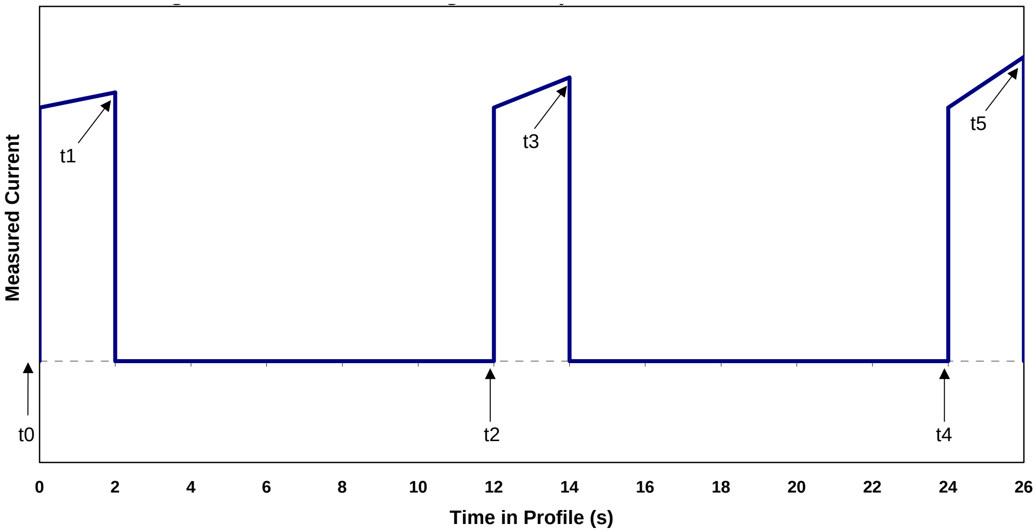

Figure 18. Cold Cranking Test resistance calculation points.

4.6 Thermal Performance Tests

Measured capacity at the $C_1/1$ rate is reported over the range of temperatures at which the Static Capacity Test is performed. Results of HPPC testing at temperatures other than nominal are reported in the same formats defined in Section 4.3, except that the test temperature must accompany all data and graphs.

4.7 Energy Efficiency Test

Round trip energy efficiency is calculated from 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, 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 the profiles, expressed in percent as shown in Equation (11).

$$Round\text{ - }trip\ efficiency = \frac{watt \cdot hours\ (discharge)}{watt \cdot hours\ (regen)} \times 100\ \ (\%) \tag{11}$$

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.[EE]

4.8 Operating Set Point Stability Test

No results are reported specifically from this test. The current, voltage, and residual capacity data are reviewed to 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 treated as part of cycle life testing.

4.9 Cycle Life Tests

For the selected life test profile, the cumulative number of test profiles executed prior to the most recent Reference Performance Tests is reported, along with any performance changes measured by these Reference Performance Tests. If testing is terminated due to the inability of the cell to perform the programmed test profile within the voltage limits or some other end-of-test condition, this is reported. However, the number of profiles performed is not necessarily the cycle life and should not be reported as such. Detailed results of the reference tests are reported over life as described under these specific tests, including the magnitude of adjustments made (if any) due to the measured temperatures being above or below the nominal temperature. In addition, degradation of capacity, pulse power capability, Available Energy, and Cold Cranking Power capability as a function of life (i.e., number of test profiles performed) should be reported graphically.

[EE]. The Power-Assist Efficiency Test and Cycle life Test profiles are identical, so Power-Assist Life Test data are directly usable for efficiency calculations if cycling is done at a constant SOC.

The value of cycle life to be reported for a device subjected to cycle life testing is defined as the number of test profiles performed before end of life is reached. In general an end of life condition is reached when the device is no longer able to meet the LEESS 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 LEES 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. [FF] If the cycle life based on power and energy performance is very near the target, the end of life point may need to be interpolated based on the change in HPPC performance from the previous reference test.

4.10 Calendar Life Test

Summary-reported results of this test include (a) calendar life in months versus storage temperature, (b) capacity versus calendar time and temperature as measured by the periodic $C_1/1$ discharge tests, and (c) cell discharge (10-s) and regen (10-s) resistance versus calendar time and temperature as measured by the periodic HPPC tests. The corresponding values of pulse power capability and Available Energy and Cold Cranking Power capability (all scaled by the Battery Size Factor) are also reported versus calendar time and temperature.

4.11 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.

4.12 System-Level Testing

In general, the analysis and reporting of test results for complete battery systems is conducted similarly to comparable cell tests. Additional reporting requirements (e.g., detailed cell or module performance) should be specified in a battery-specific test plan that accounts for the specific design features of such a system.

Test procedures and the associated reporting requirements are not defined in this manual for system-level thermal management load testing.

5. REFERENCES

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

[FF]. 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.

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

6. APPENDIX A

Gap Analysis

End of Life Characteristics	Unit	Target	BOL	Present
2s / 10s Discharge Pulse Power	kW	55/20		
2s / 10s Regen Pulse Power	kW	40/30		
Maximum current	A	300		
Available Energy (@ C1/1 rate)	Wh	26		
Energy Efficiency	%	95		
Maximum allowable self-discharge rate	Wh/day	5		
Cycle-life	Cycles	300,000 (HEV)		
Cold-Cranking Power at -30ºC (after 30 day stand at 30 °C)	kW	5		
Calendar Life	Years	15		
Maximum System Weight	kg	20		
Maximum System Volume	Liter	16		
Maximum Operating Voltage	Vdc	≤400		
Minimum Operating Voltage	Vdc	≥0.55V_{max}		
Unassisted Operating Temperature Range	ºC	-30 to +52		
30 ° -52°C	%	100		
0°C (% of Available Power)	%	50		
-10°C (% of Available Power)	%	30		
-20°C (% of Available Power)	%	15		
-30°C (% of Available Power)	%	10		
Survival Temperature Range	ºC	-46 to +66		
Selling Price/System @ 100k/yr)	$	400		

7. APPENDIX B

State-of-Charge Control for Life Testing

Background

Life testing in the context of this appendix includes both continuous cycle life testing and calendar life testing. Cycle life test procedures in this manual are intended for cycling at fixed values of state-of-charge (SOC), defined on the basis of a fractional depth-of-discharge (DOD, i.e., percent of rated capacity in Ah) from a fully charged state. All life test profiles are approximately charge-neutral, and control of SOC required during such cycling is done by slightly altering the length of one of the profile steps under program control to force the average SOC to the desired value. Additionally, calendar life testing is done at fixed (or approximately fixed) SOC values.

Under some conditions it is desirable to define the target SOC in terms of open-circuit voltage rather than fractional discharge, since this may represent the electrochemical state of the cell or battery more accurately than % DOD, as battery capacity declines over life. The state-of-charge of a battery as measured by its OCV is generally equal to (100% - DOD) at reference conditions when the battery is new. (This is more or less by definition, since the OCV versus SOC curve is commonly measured by a reference discharge.) This correspondence changes as the battery ages and its capacity decreases, with the result that % SOC < (100 - % DOD). Consequently, the rest of this appendix will distinguish between SOC (referenced to OCV) and DOD (referenced to fractional discharge) for purposes of test control, though the differences may not be significant during any given testing period.

Calendar Life Testing at Fixed SOC

Because devices subjected to calendar life testing are not being continuously cycled, SOC control is done by bringing the device to the target state and allowing it to stand at open-circuit voltage condition during a testing period that is typically several weeks in duration. The target state is determined and reached in one of two ways, depending on whether testing is done based on % DOD or on OCV. (Either approach is permissible in the procedure in Section 3.10.) The DOD method simply discharges the device to the target % DOD at a $C_1/1$ constant current rate. The OCV method clamps the device to the target voltage (while limiting the current to a $C_1/1$ rate) until the device SOC stabilizes. In both cases, some correction may be needed for any change that results from bringing the device to its test temperature, though this is frequently ignored. Once the target voltage is reached, there is no practical difference between the two cases, though the target value for the DOD case may need to be re-determined at the beginning of each continuous cycling period.

Continuous Life Cycling at a Fixed Target SOC/DOD Value[GG]

The Operating Set Point Stability Test (OSPS, Section 3.8) is defined for use in verifying that the target cycle life conditions are reached and that stable cycling can be conducted at a fixed SOC or DOD. Conduct of the OSPS is identical to the planned cycle life test regime, except that the test profile is only executed for a short number of iterations (typically 100). Cycling is then suspended,

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[GG] Cycle life testing over a variable SOC/DOD range is not treated in this manual and is not used for LEESS testing.

the device is returned to 30°C if necessary, and the device SOC/DOD is determined by the appropriate methods (examination of the equilibrium OCV and discharge of the residual capacity.) If the target SOC/DOD has been achieved after this limited number of profiles and cycling is stable, life cycling continues; otherwise, some adjustment of the SOC control scheme is necessary, and the process iterates. A detailed description of this control scheme follows.

Use of Control Voltage Limiting for State-of-Charge Control

Establishing and controlling state-of-charge conditions for fixed SOC life cycling is accomplished through the following steps:

1. Determine the cycle life profile to be used (including profile power scaling) and the target SOC/DOD at which cycling is to be performed.

2. From HPPC Low-Current test data, calculate or estimate the control voltage required to maintain the target state during cycling with the selected cycle life test profile.

3. Using this control voltage, perform a fixed number of iterations of the selected cycle life test profile and verify that (a) a stable cycling condition is reached, and (b) this stable condition is sufficiently close to the target state. (This step is the OSPS test.)

4. If condition (3b) is not satisfied, determine a modified control voltage and repeat the OSPS test.

5. Begin continuous life cycling using the control voltage determined in previous steps. At the end of each continuous life cycling period, verify that the target state has been maintained.

6. If the condition of the device changes (e.g., due to aging) such that the maintained SOC/DOD is not sufficiently close to the target, repeat Steps 2 through 5 starting with recent HPPC data.

The following description deals primarily with steps 2 and 3 above.

Assumptions

1. Cycle life testing generally controls SOC by varying the initial discharge step in the test profile. It is also possible to control SOC by varying the final regen or recharge step. The process is conceptually identical (or at least symmetrical), and the following description deals only with the discharge step control. Use of charge step control is accomplished by varying (e.g., shortening) the charge step when a predetermined maximum voltage is reached. The major difference between the two approaches is that the discharge step method forces the SOC down to the target value, while the charge step method forces the SOC up to the target value.[HH]

[HH] *A third method removes (or adds) the additional charge needed to balance the test profile by applying a clamp voltage during a nominal rest interval in the test profile. This approach requires the current to be limited during this 'rest' interval (which is now really a low-value discharge or charge step) to minimize perturbation of the profile shape. This is only one of many possible variations of the control strategy discussed in this section, some of which have not been verified by test.*

2. The method described for calculating the control voltage is not intended for use with cycle life profiles whose discharge steps are more than 10 s in length because this is the length of the HPPC discharge pulse. Extrapolation of the device resistance will be required if this assumption is not satisfied.

3. The selected cycle life test profile is assumed to be slightly charge-positive, i.e., its regen steps return slightly more capacity to the device than is removed in the discharge step(s). Only slight modification should be required to satisfy this condition in any case.

4. This process normally uses HPPC data acquired at the same temperature at which cycle life testing is to be performed. If this assumption is not satisfied, additional OSPS iterations may be required due to the change in device resistance over temperature.

Determination of the Control Voltage (Trial Value)

During continuous cycling, the *control voltage* is the voltage that the device achieves (under load) at the end of the discharge pulse when the state of charge is at the target value. Calculating the initial value of this control voltage for use in the OSPS test is as follows:

1. Determine the device discharge resistance expected at the end of the cycle life profile discharge pulse, at or near the target SOC/DOD. This is done using HPPC data for the discharge pulse nearest the target SOC. For example, if the target SOC for life cycling is 70%, the 30% DOD HPPC discharge pulse data can be used. The effective resistance is calculated as dV/dI over the planned duration of the cycle life discharge pulse. For example, if the cycle life discharge pulse is 5 s in duration, dV/dI is calculated using the last rest data point before the HPPC pulse starts and the data point 5 s into the pulse.[II]

2. Calculate the voltage drop expected under load at the end of the cycle life discharge pulse as [device resistance] times [pulse current ≈ pulse power/end-of-pulse voltage]. For example, if the pulse current is to be 10 A for 5 s and the 5-s device resistance is 30 milliohms; the expected voltage drop at the end of the discharge pulse is 0.3V.[JJ]

3. Determine the device OCV corresponding to the target state-of-charge for cycling. This can be done from the HPPC OCV data or from a reference OCV-versus-SOC curve.

4. The control voltage for the OSPS test is the OCV from Step 3 minus the voltage drop from Step 2. For example, if the OCV at the target SOC is 3.7 V and the voltage drop is calculated at 0.3 V as above, the control voltage is 3.4 V. *This represents the voltage that would be expected to be reached at the end of the discharge pulse if the device were at the target SOC when the discharge pulse begins.*

[II] *If life cycling is to be done at an SOC value that does not correspond exactly to one of the HPPC data points, the resistance could be interpolated between two HPPC data points. However, this degree of precision is generally not warranted because the process is iterative.*

[JJ] *Because cycle life profiles are defined strictly in terms of power (not current) steps, this is apparently an iterative calculation, i.e., it uses the end-of-pulse voltage to calculate the voltage drop, which is in turn used to calculate end-of-pulse voltage. In practice steps 2, 3 and 4 are combined, and the end-of-pulse voltage is calculated (as the solution of a quadratic equation) to be* $V_{control} = 0.5 \cdot \{OCV + (OCV^2 - 4 \cdot R_{discharge} \cdot Power_{step})^{1/2}\}$

Overall SOC Control Approach and Use of the Control Voltage

The target state of charge is maintained during cycle life testing by varying the length of the test profile discharge step (the first discharge step only, if there is more than one). Cycle life profiles are normally slightly charge-positive at their nominal values. For control purposes, the maximum duration of the discharge step is increased enough to make the profile charge-negative by a similar amount. (Obviously this logic can be reversed if the nominal profile is charge-negative.) The time duration required to do this depends on the magnitude of the discharge step. For example, if the discharge step is 10 W for 10 s, and the test profile is charge-positive by 5 W-s, the maximum duration of the discharge step is increased by one second.[KK] The discharge step is thus allowed to vary between 10 and 11 s duration, with a charge-neutral condition expected to occur at about 10.5 s.

To ensure that the discharge pulse is not shorter than the nominal time and not longer than the maximum (extended) time, it is commonly programmed as a sequence of two contiguous pulses with the same magnitude. The first pulse has a fixed length equal to the nominal time (e.g., 10 s), and the second pulse has a maximum length equal to the time *increase* (e.g., 1 s). The first step in the sequence is terminated only on time (e.g., is always the same length), while the second step is terminated either by its programmed duration or by device voltage reaching the control voltage. When this modified test profile is executed repetitively, it will force the device state-of-charge to the target SOC value in the following manner.

(a) If device conditions are such that the control voltage is not reached during this extended discharge step (e.g., state-of-charge is higher than the target value), it will terminate at its maximum duration. Since this duration has been chosen such that it makes the profile charge-negative, the SOC will decrease during each profile execution until the target SOC is reached.

(b) If the device state-of-charge is significantly lower than the target value, the voltage at the beginning of the second (extended) discharge step will be less than or equal to the control voltage. This extended step will terminate immediately, forcing the overall test profile to be charge-positive. Successive executions of the test profile in this condition will drive the SOC upward toward the target value.

Verification of Target SOC and Adjustment of Control Voltage

This process will eventually reach a stable cycling condition. If the starting SOC is near the target value, it normally stabilizes in less than the number of profiles executed by the OSPS test. However, this stable condition is generally not at exactly the target SOC, due largely to internal heating that occurs within the device while cycling. Hence, the OSPS is terminated after a fixed number of profile executions, so that the actual SOC at the cycling condition can be determined. This is done by returning the device to 30°C and then observing the OCV, removing the residual capacity, or both.[LL]

[KK] *The extra discharge increment needed is actually based on charge, not energy. The charge balance of a power step profile is dependent on the efficiency of the device under test, so this adjustment will need to be determined by inspecting the actual profile charge balance from test data rather than from the nominal profile values.*

[LL] For some battery technologies (e.g. NiMH) residual capacity is the only reliable indicator of final SOC.

If the achieved SOC is acceptably close to the target value for life cycling, the OSPS is complete, and continuous life cycling can begin. If it deviates by an unacceptable amount (which is test plan-specific, though 5% SOC has been commonly used), the control voltage must be adjusted and the OSPS repeated. The simplest way to modify the control voltage is to add or subtract the difference between the OCV at the target SOC and the OCV corresponding to the measured SOC at the end of the OSPS. For example, if the OCV at the SOC where the OSPS completes is 50 mV higher than the OCV for the target SOC, the control voltage can be reduced by 50 mV.

Note that the SOC during cycling may drift away from the target value if the device resistance changes over life. This may require the control voltage to be adjusted periodically to maintain SOC within an acceptable range. The achieved SOC is easily verified at the end of every cycling period by observing the OCV and/or residual capacity when cycling stops and new HPPC data will typically be available for recalculating the control voltage at these points. If the resistance changes drastically during a given cycling interval, the SOC at the end of the interval may vary significantly from the target value. A more common problem late in life is that the device resistance growth forces cycling to be terminated due to maximum or minimum voltage limits being reached (i.e., it is no longer possible to perform the test profile within these limits at the target SOC.) In general, testing must terminate when the target SOC cannot be maintained, unless the device-specific test plan specifically allows revising the target SOC.

Additional Considerations

It is strongly recommended that the control approach(es) selected to implement a cycle life regime should be verified by test before long-term cycling begins. The OSPS is intended to accomplish this, and it can be repeated as needed (as often as the beginning of every cycling interval) without excessive effort.

If life cycling is done at other than 30°C, the aspects of this process that depend on battery resistance and open-circuit voltage should be reviewed with special care.