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PNGV Battery Test Manual

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FOREWORD

This manual was prepared by and for the Partnership for a New Generation of Vehicles (PNGV) Program Electrochemical Energy Storage Team. It is based on the goals established for PNGV energy storage development, testing done for Phases I and II of the PNGV energy storage program, and earlier hybrid test procedures work sponsored by the U.S. Department of Energy, particularly at the Idaho National Engineering and Environmental Laboratory. The specific procedures were developed primarily to characterize the performance of a particular device relative to the PNGV requirements. However, it is anticipated that these procedures will have some utility for characterizing hybrid energy storage device behavior in general.

A continuing need to improve these procedures is expected. This fourth published version of the manual continues to emphasize testing of laboratory cells and full-size cells and modules, with some additional features to support testing of full-size energy storage systems. Suggestions or comments should be directed to the author, Gary Hunt, at the INEEL, by email to glh@datawav.net or to Chet Motloch at motlcg@inel.gov.

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ACRONYMS

ASI	area-specific impedance
BSF	Battery Size Factor
DOD	depth of discharge
DST	Dynamic Stress Test
EMI	electromagnetic interference
EV	electric vehicle
HEV	hybrid/electric vehicle
HPPC	hybrid pulse power characterization
MWh	million watt-hours (megawatt-hours)
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 – a value calculated from HPPC test results that represents the discharge energy available over the DOD range where the PNGV power goals can be met. This energy is measured using a C/1 constant current discharge rate for Power Assist operation and using a 6 kW constant power discharge rate for Dual Mode operation.

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 PNGV performance and life goals. 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 PNGV energy goals with a 30% power margin at beginning of life. Battery Size Factor is determined separately for Power Assist and Dual Mode applications.

Battery Parameter Estimator (BPE) [b] – an analysis tool that applies linear regression techniques to HPPC raw data to estimate the component values for a five-component lumped parameter battery model.

Charge – any condition in which energy is supplied to the device rather than removed from the device. Charge includes both recharge and regen conditions.

Cycle Life Efficiency Model (CLEM) – an analysis tool that uses BPE results and system requirements to estimate efficiency, operating voltages and other parameters for a continuously applied charge-neutral pulse profile.

Depth of Discharge (DOD) – the percentage of a device's rated capacity removed by discharge from 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 – a condition reached when the device under test is no longer capable of meeting the PNGV goals. This is normally determined from HPPC test results scaled using the Battery Size Factor, and it may not coincide exactly with the ability to perform the life test profile (especially if cycling is done at elevated temperatures.) The number of test profiles executed at end of test is not necessarily equal to the cycle-life per the PNGV goals.

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 goal for a given application, expressed as a percent of the energy goal.

Extended Simplified Model (ESM) – an analysis tool that uses HPPC cell data to estimate the cell capacity and number of cells required to satisfy the PNGV power and energy goals.

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

[b] Underlined terms are specific to Appendix D and may not appear elsewhere in this manual.

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 PNGV operating conditions.

Maximum Rated Current (Imax) – the maximum discharge current that a manufacturer will permit to be sustained by a device for 18s at some DOD.

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

Profile – a connected sequence of pulses used as the basic 'building block' of many PNGV 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.

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 PNGV power goals. Available Energy is the value of Usable Energy at the actual PNGV power goal values. (Usable Energy is frequently but inaccurately called Available Energy.)

ERRATA SHEET

Revision 3b
February 2002

Note: Revision 3b supersedes all previous Errata Sheets, including Rev 3a. In general these changes are due to minor errors in the original issue of Revision 3 of this manual. However, the various changes involving the 217A current limit are due to the later elimination of this restriction by the PNGV Electrochemical Energy Storage Technical Team.

Pg. X. Add the following to the Glossary:

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

Pg. 2. delete the 217A limit from Table 1.:

~~(Note: Maximum current is limited to 217 A at any power level)~~

Pg. 7. delete references to 217A limit in the text and the associated footnote [k], and delete all of footnote [l]:

~~For properly scaled full-size devices, this peak discharge current must not exceed 75% of 217 A (i.e., 163 A), because 217 A is the maximum current permitted by the PNGV goals, as specified in Table 1.[l],~~

[k]: ~~(The 217-A limit still applies.)~~

~~[l]. If the rated capacity of a device is larger than desired (as determined using the Extended Simplified Model as described in Appendix D), the manufacturer's rated I_{max} should be scaled by the ratio of the desired to rated capacities before it is compared to 217A. For example., if I_{max} is 300A for a cell rated at 11 Ah, and the ESM indicates the desired capacity is only 8 Ah, the ratio 8/11 times 300A is 218A. The 300A I_{max} would need to be scaled to 298A so that the implied current for the 8 Ah cell would be less than 217A. In such cases it is possible for I_{max} to exceed 217A because the cell size has not yet been optimized for the PNGV requirements.~~

Pg. 19. Change the second line in the first paragraph of Section 3.10.3.3 as follows:

. . . profile defined in Section ~~3.8.1~~ 3.8.1.2 . . .

Pg. 19. Add the following to the end of the first paragraph in Section 3.10.3.3:

Note: especially for NiMH, the target SOC must always be approached from the discharge direction due to the inherent hysteresis.

Pg. 19. Revise Section 3.10.3.3, Item 2 as follows:

~~(in watts)~~ (in W-s)

Pg. 23. Revise Table 10 in Section 3.12 as follows:

Table 10. Reference Performance Test intervals for life testing.

Life Test Profile Used	Number of Continuous Repetitions between Reference Tests
25-Wh Life Cycle Test Profile (Power Assist)	~~20,000~~ 30,000
1500-Wh Life Test Profile (Dual Mode)	~~250~~ 375
Other cycle-life profiles TBD	5 to 10% of expected cycle-life
Calendar-Life Test	Approximately ~~3 weeks~~ 25 days (~~500~~ 600 hours)

Pg. 28. Change Section 4.3.3 as follows:

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

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

Pg. 28. delete footnote [gg]:

~~[gg]. For properly scaled full-size devices, if the power capability calculated by either equation, when scaled by the Battery Size Factor, corresponds to a current greater than the PNGV limit of 217 A, the value must be reduced to stay within this current limit. This generally means that the result of each equation, divided by [V_{MAX} or V_{MIN} times the Battery Size Factor], must be less than 217 A. Additionally, if cell V_{MAX} times the Battery Size Factor exceeds 440 V, then at least two strings of cells would be required, and the individual cell current must not exceed one-half of 217 A. For devices whose capacity is larger than optimal, this limit may not apply directly; see note on Section 3.3.2.~~

PNGV Battery Test Manual

1. PURPOSE AND APPLICABILITY

This manual defines a series of tests to characterize aspects of the performance or life cycle behavior of batteries for hybrid electric vehicle applications. Tests are defined based on the Partnership for a New Generation of Vehicles (PNGV) program goals, though it is anticipated these tests may be generally useful for testing energy storage devices for hybrid electric vehicles. In the past, separate test regimes were defined for laboratory cells, battery modules or full-size cells, and complete battery systems. This distinction has largely been removed by the revised test procedures in this manual. Most tests are now common to all three test regimes, while others are not normally applicable to some regimes.

1.1 Laboratory Cell Testing

Laboratory cell testing is intended primarily for early assessment of electrochemical systems to assess their potential, identify design tradeoffs, establish a data base to project battery pack performance, and provide feedback to the development process.

The objective is to define electrochemical system performance on a unit cell (1-cm^2) basis, excluding considerations for final packaging, external current collection, or other items outside the active cell area. Performance data can be normalized to a /cm^2 basis to allow relative performance comparison of different cell configurations and to permit first-order estimates of battery pack performance. Weight and volume of the normalized active cell area can be estimated by summing the weight or volume of all elements required for the cell to operate, such as electrodes, separator, cell current collectors, and electrolyte.

1.2 Full-Size Cell or Module Testing

Full-size cell or module testing is intended to verify that the selected design will satisfy the PNGV program performance criteria and provide a data base for subsequent development of related battery management systems. Modules typically are an assemblage of full-size cells and may include integral electronics for balancing and otherwise monitoring and regulating cell behavior. They may also include thermal management features. Objectives are first to verify that scale-up to the full-size cell or module was successful and subsequently to evaluate full-size cell/module performance.

1.3 Battery System Testing

Battery system testing is intended to predict or to verify overall battery pack performance required to ensure acceptable in-vehicle performance. A pack typically is a collection of modules and may include additional electronic and thermal control systems.

1.4 PNGV Energy Storage Goals

PNGV Energy Storage Goals are the primary driving force for the test procedures and methods defined in this manual. These goals are outlined in Table 1 for both the Power Assist and Dual Mode vehicles whose characteristics are specified for the PNGV Program. In general, the Dual Mode concept assumes that the battery supplies a larger fraction of the overall hybrid/electric vehicle (HEV) power and energy needs than for the Power Assist concept. Hence, the Dual Mode power and energy goals are considerably higher than the Power Assist goals. Note that this table of PNGV goals is presented as the primary basis for this test manual. Establishing or verifying battery performance in comparison to these goals is a principal objective of the test procedures defined in this document.

Table 1. PNGV Energy Storage System performance goals (revised 2000 and February 2001).

Characteristics	Units	Power Assist	Dual Mode
Pulse discharge power	kW	25 (18 s)	45 (12 s)
Peak regenerative pulse power	kW	30 (2 s) (min 50 Wh over 10 s regen total)	35 (10 s) (97 Wh pulse)
Total available energy (over DOD range where power goals are met)	kWh	0.3 (at C/1 rate)	1.5 (at 6-kW constant power)
Minimum round-trip energy efficiency	%	90	88
Cold cranking power at -30ºC (three 2-s pulses, 10-s rests between)	kW	5	5
Cycle-life, for specified SOC increments	cycles	300,000 Power Assist cycles (7.5 MWh)	3750 Dual Mode cycles (22.5 MWh)
Calendar life	years	15	15
Maximum weight	kg	40	100
Maximum volume	l	32	75 (at 165-mm max height)
Operating voltage limits (Note: Maximum current is limited to 217 A at any power level)	Vdc	max $\leq$440 min $\geq$(0.55 × Vmax)	max $\leq$440 min $\geq$(0.5 × Vmax)
Maximum allowable self-discharge Rate	Wh/ day	50	50
Temperature range:			
Equipment operation	°C	-30 to +52	-30 to +52
Equipment survival		-46 to +66	-46 to +66

Note: Calendar Life and Cycle-Life goals were revised February 2001 to facilitate eventual compliance with California "Partial Credit for Zero Emissions Vehicles" (PZEV) requirements; minimum operating temperature was also revised from –40 to –30°C at this time.

2. TEST PROFILES DERIVED FROM PNGV GOALS

The test procedures described in this manual are intended for use over a broad range of devices at various stages of developmental maturity. Application of the procedures is further complicated by the existence of two different sets of vehicle performance goals. 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 then be used in various combinations, and with the appropriate scaling factors, to define specific performance or life cycle tests for the three levels of testing: laboratory cell, full-size cell/module, and battery system. The test profiles in this version of the manual supercede all previous versions defined in earlier editions. Because there is essentially a one-to-one relationship between test profiles and test procedures in this version of the manual, each profile is now defined within the respective procedure described.

3. TEST PROCEDURES

3.1 General Test Conditions and Scaling

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

3.1.1 Temperature Control

Unless otherwise specified in a device-specific test plan, the ambient temperature for all tests shall be controlled at a default nominal temperature of 30ºC. 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 Life Cycle Test Profiles

With the exception of the Hybrid Pulse Power Characterization Test (HPPC) and Calendar-Life Test, all performance and life cycle test profiles are defined in terms of required power levels at the system (i.e., full-size vehicle battery) level. Testing any device smaller than a full-size system requires a method for scaling these test profiles to a level appropriate to the size of the device (cell, module, or sub-battery) under test. This is done by using a *battery size factor*. For purposes of this manual, the Battery Size Factor is defined as the minimum number of units (cells, modules or sub-batteries) of a given design required for a device to meet all PNGV goals, 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 HPPC test results. From the low-current HPPC results for a given device (or identical group of devices), determine the minimum number of such devices required to provide 130% of the PNGV power goal concurrent with 100% of the PNGV available energy goal for the applicable operating mode (Power Assist or Dual Mode).[d] The arbitrary power margin of 30% is to allow for degradation resulting from cycle-life and calendar-life effects.

Once the Battery Size Factor is determined, it becomes a constant (i.e., fixed over life) scaling factor for all subsequent performance and life cycle tests. Any test profile (except HPPC or calendar life)

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c. 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 constant-current discharge rate.) Also, the term "fully charged" means "charged in accordance with the manufacturer's recommended procedure".

d. In some cases, this value and/or the associated voltage limits may require modification to ensure that the PNGV round-trip efficiency goals are also met. The analysis process needed to calculate this value is described in Section 4.3.8 and Appendix D.

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. Note that the Battery Size Factor is different for Power Assist and Dual Mode operation.

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 capacity in ampere-hours (e.g., if the rated 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, 50% 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 PNGV 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.[e]

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} cell discharge power capability at the end of an 18-s (12-s Dual Mode) discharge current pulse and (b) the V_{MAX} cell regen power capability over the first 2 s (10 s Dual Mode) of a regen current pulse.[f] Secondary objectives are to derive from the 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 Pulse Power Characterization Profile.

The objective of this profile is to demonstrate the discharge pulse and regen pulse power capabilities at various states of charge (SOC) for both the Power Assist goals (18-s discharge, 2-s regen) and Dual Mode goals (12-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. The characterization profile is shown in Table 2 and Figure 1.

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[e] 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 PNGV program management before testing continues. Use of a reasonably representative capacity value is important for high quality HPPC test results.

[f] V_{MIN} and V_{MAX} refer to the cell minimum and maximum voltages that correspond to the PNGV 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 Table 1 limits for Power Assist or Dual Mode operation as appropriate.

Table 2. Pulse Power Characterization profile.

Time Increment (s)	Cumulative Time (s)	Relative Currents
18	18	1.00
32	50	0
10	60	-0.75

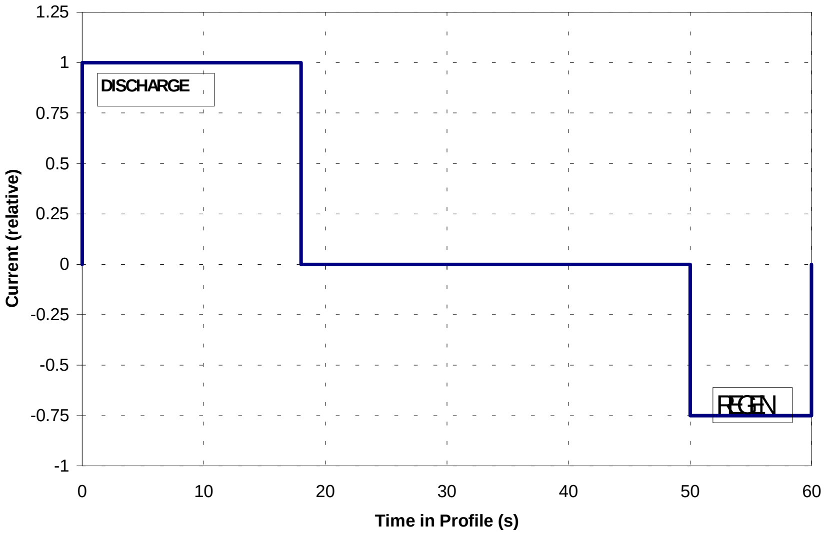

Figure 1. Pulse Power Characterization Profile

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. (The opposite convention is used in the USABC Electric Vehicle testing manual.[Reference 1])

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 discharge segments,[g] each followed by a 1-hr rest period to allow the cell to return to a charge 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 rate to 100% DOD, and a final 1-

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[g] 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 available 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.

hr rest.[h] 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 discharge segments is illustrated in Figures 2 and 3. Figure 2 also illustrates a recommended C/1 discharge to be executed just prior to each HPPC test.[i]

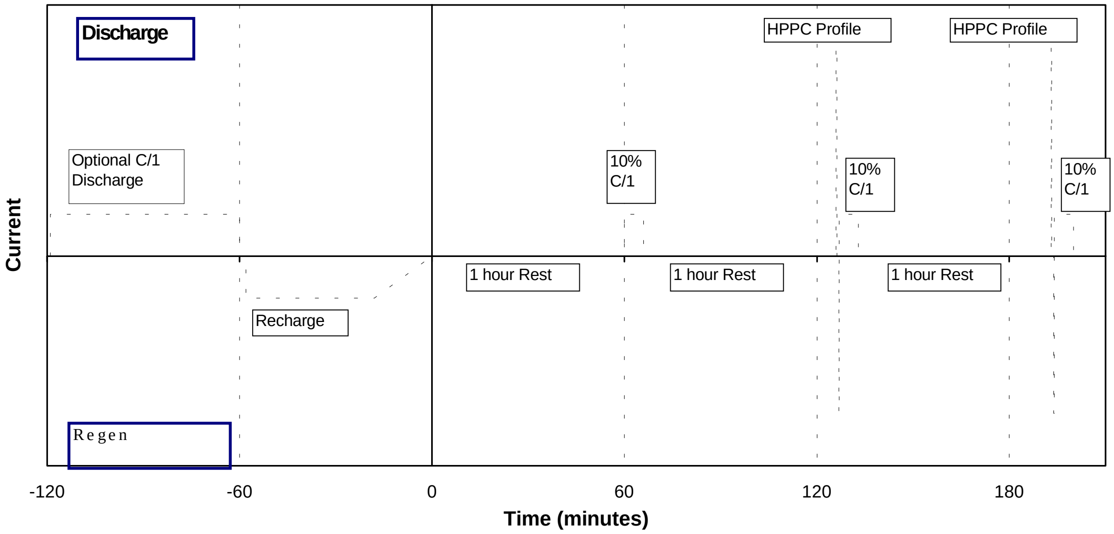

Figure 2. Hybrid pulse power characterization test (start of test sequence, including C/1).

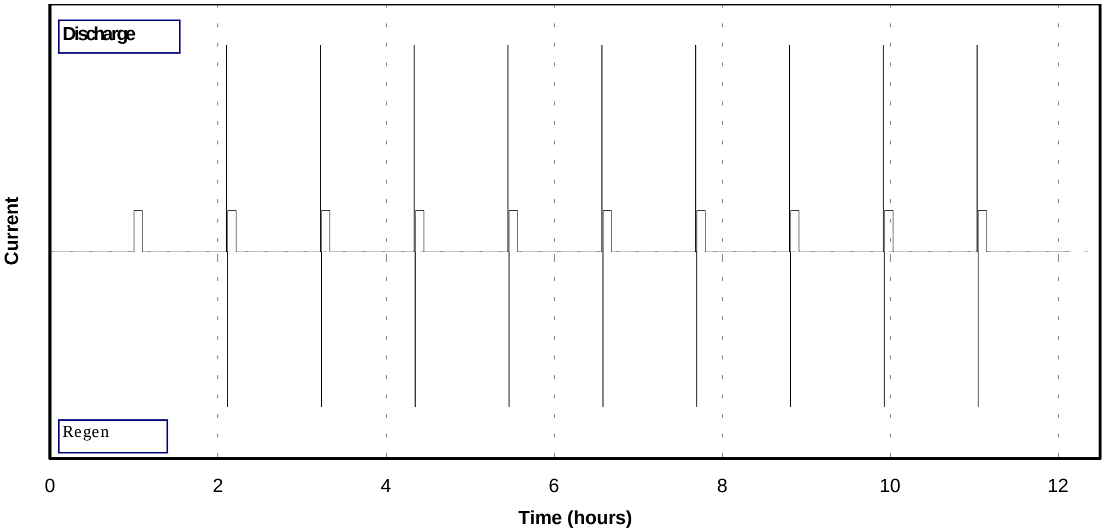

Figure 3. Hybrid pulse power characterization test (complete HPPC sequence).

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[h] 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 discharge rate can be sustained.

[i] This C/1 discharge is recommended because the HPPC results for Power Assist devices will eventually be reported as power capability versus energy removed at a C/1 rate. The availability of linked C/1 data (or 6-kW discharge data for Dual Mode) will facilitate this analysis and reporting; see Section 4.3.

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

LOW CURRENT LEVEL TEST—The peak profile discharge current is 25% of I_{max}, where I_{max} is the manufacturer's absolute maximum allowable pulse discharge current for 18 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.[j]

HIGH CURRENT LEVEL TEST—The peak profile discharge current is selected as 75% of I_{max} (as defined previously).[k] For properly scaled full-size devices, this peak discharge current must not exceed 75% of 217 A (i.e., 163 A), because 217 A is the maximum current permitted by the PNGV goals, as specified in Table 1.[l, m]

3.4 Available Energy Test (Dual Mode Constant Power)

Available Energy for Power Assist operation is calculated from the HPPC and C/1 test results as described in Section 4.3. No special testing is required for this determination. However, the Dual Mode available energy goal is specified at a 6-kW constant power discharge rate, and a special test is defined to allow available energy to be measured under this condition. The test consists of a complete 6-kW constant power discharge.[n] Note that this test only applies to devices intended for Dual Mode operation.

The procedure for this test is as follows:

1. Determine the test power level as 6 kW divided by the Battery Size Factor determined as in Section 3.1.2, i.e., if the Battery Size Factor for a given device is 40, the test power is 6000 / 40 = 150 W.

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

[k] 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}. (The 217-A limit still applies.)

[l] If the rated capacity of a device is larger than desired (as determined using the Extended Simplified Model as described in Appendix D), the manufacturer's rated I_{max} should be scaled by the ratio of the desired to rated capacities before it is compared to 217A. For example., if I_{max} is 300A for a cell rated at 11 Ah, and the ESM indicates the desired capacity is only 8 Ah, the ratio 8/11 times 300A is 218A. The 300A I_{max} would need to be scaled to 298A so that the implied current for the 8 Ah cell would be less than 217A. In such cases it is possible for I_{max} to exceed 217A because the cell size has not yet been optimized for the PNGV requirements.

[m] For procedural reasons, the peak discharge current may not exceed a value that would allow the nominal pulse profile to remove more than 10% of the device's rated capacity; however, this is not expected to occur because such a current would exceed a 34C rate.

[n] The energy results from this 6-kW discharge are later combined with HPPC power data to calculate available energy in a manner similar to the Power Assist available energy calculation. The analysis process used to do this is described in Section 4.3.5.

2. Discharge the fully charged device at this power level to the discharge voltage limit.

3.5 Self-Discharge Test

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

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 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 rate, and allow it to stand for a nominal interval of 7 days (1 week). (The actual stand period should be selected based on the expected stand loss rate, with the value chosen to yield an expected capacity loss between 5% and 25% 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 discharge rate.

4. Recharge the cell and fully discharge it again at a C/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.

3.6 Cold Cranking Test

The Cold Cranking test is intended to measure 2-s power capability at low temperature (normally -30ºC) for comparison with the PNGV Cold Cranking Power goal in Table 1. The test is conducted at the maximum DOD (minimum state of charge) where the PNGV Available Energy goal is just met, based on present HPPC data.[o] The test consists of the following sequence of activities:

1. At normal ambient temperature, discharge the fully charged device at a C/1 constant current discharge rate to the maximum DOD value (minimum state of charge) determined as above.

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 3.6.1. The pulse power level to be used is 5 kW divided by the Battery Size Factor as determined in Section 3.1.2; e.g., if the Battery Size Factor is 40 for a given device, the pulse power to be used for the test is 5000/40 = 125 W. 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 PNGV 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

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[o] The analysis procedure to determine this DOD range is described in Section 4.3.6.

stay within the minimum discharge voltage) to permit the later calculation of Cold Cranking power capability.

3.6.1 Cold Cranking Test Profile.

The Cold Cranking Test profile is a literal implementation of the Cold Cranking Power goal, which requires the ability to provide 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.

Table 3. Cold Cranking Test profile.

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

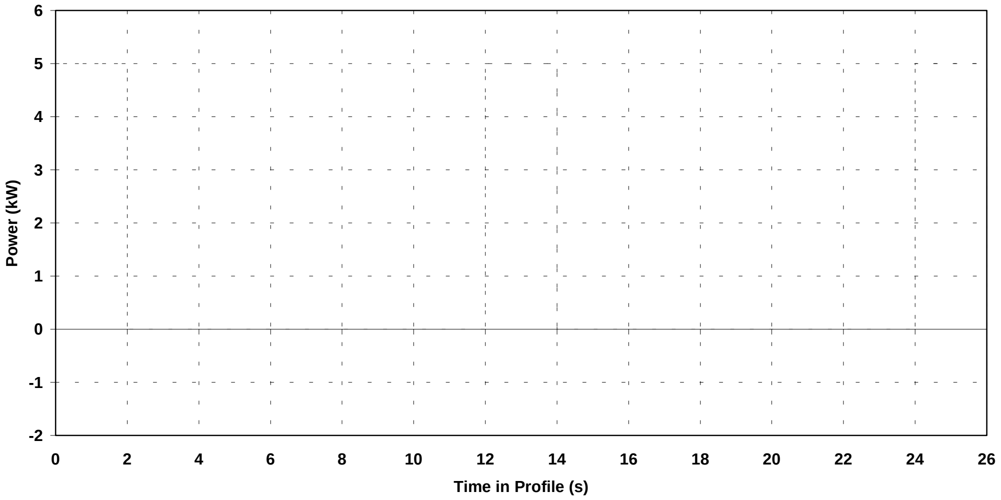

Figure 4. Cold Cranking Test profile.

3.7 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 PNGV operating temperature goal range (-30 to +52ºC). At the laboratory cell level, such testing has two goals: 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.

3.8 Energy Efficiency Test

Round-trip efficiency is determined at the cell level by calculation from a charge-balanced pulse profile. Separate efficiency test profiles are defined for Power Assist and Dual Mode use in Section 3.8.1. (These profiles have been constructed for use in both efficiency and life cycle testing.) This test is performed similarly to the OSPS, as follows:

1. Bring the cell to a specified target state of charge value and operating temperature.

2. Perform 100 efficiency test profiles (Power Assist or Dual Mode as appropriate) while controlling state of charge as described in Appendix C 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.

3.8.1 Efficiency Test Profiles.

3.8.1.1 Power Assist Efficiency Test Profile.

The Power Assist Efficiency Test Profile is a 72-s, nominally charge-neutral pulse profile (also used as the Power Assist 25-Wh Life Cycle Test profile) that is scaled to a level appropriate to verify the Power Assist round trip energy efficiency goal of 90%.[p] This test profile is defined in Table 4 and illustrated in Figure 5.

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[p] This profile is calculated to be charge-neutral for a device that exactly meets the 90% efficiency goal. Appendix C explains in detail how to adjust it to a charge balanced state in the case where the efficiency is higher than the goal. Efficiency lower than the goal is not anticipated, but the Appendix C procedure is easily modified to accommodate this as well. Note that because the

Table 4. Power Assist Efficiency and Life Cycle Test profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
9	9	10	25	25
27	36	0	0	25
2	38	-16	-8.9	16.1
4	42	-11	-12.2	3.9
4	46	-6	-6.7	-2.8
26	72	0	0	-2.8

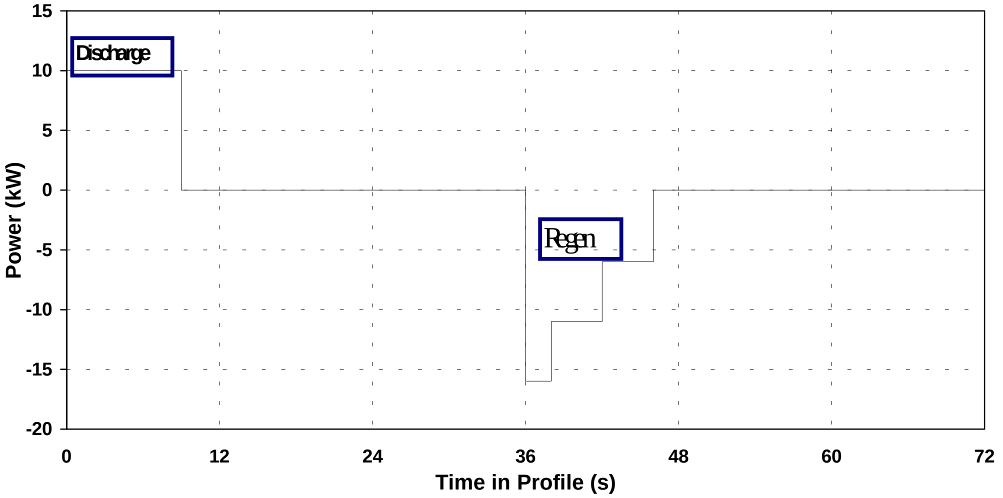

Figure 5. Power Assist Efficiency and Life Cycle Test profile.

3.8.1.2 Dual Mode Efficiency Test Profile.

The Dual Mode Efficiency Test profile is a 96-s, nominally charge-neutral pulse profile (similar to the Dual Mode Life Cycle Test recharge profile) scaled to a level appropriate to verify the Dual Mode round trip energy efficiency goal of 88%.[q] This test profile is defined in Table 5 and illustrated in Figure 6.

Power Assist Efficiency Test and Life Cycle Test profiles are identical, the Efficiency Test may also serve as the OSPS Test if the same SOC value is appropriate.

[q] This profile is calculated to be charge-neutral for a device that exactly meets the 88% efficiency goal. Appendix C explains in detail how to adjust it to a charge balanced state in the case where the efficiency is higher than the goal. Efficiency lower than the goal is not anticipated, but the Appendix C procedure is easily modified to accommodate this as well.

Table 5. Dual Mode Efficiency Test profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
12	12	30	100	100
38	50	0	0	100
2	52	-30	-16.7	83.3
4	56	-25	-27.8	55.5
4	60	-20	-22.2	33.3
36	96	-4.7	-47	-13.7

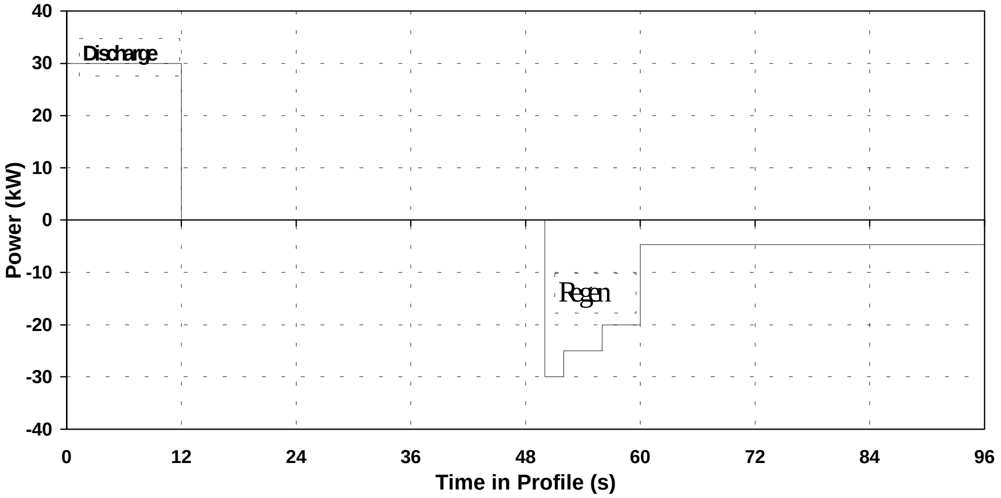

Figure 6. Dual Mode Efficiency Test profile.

3.9 Operating Set Point Stability Test

This test is a special case of the life cycle testing regime to be applied to a given cell or battery. Since life cycle 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 life cycle test(s) defined in 3.10 is normally specified in a device-specific test plan based on projected use of the device.[r] This test is normally performed immediately before the beginning of life cycle testing.

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[r] 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 life cycle testing.

With the cell at the selected state-of-charge value and all other conditions (e.g., operating temperature) as required for life cycling, apply the selected Life Cycle Test profile for a period long enough to reach thermal equilibrium and to return to the target SOC.[s, t] 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 constant-current rate to verify the depth of discharge at the end of the cycling interval.

3.9.1 Adjusting the Operating Set Point.

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

3.9.2 Controlling the State of Charge During the OSPS Test.

The preferred approach to maintaining a target state of charge during the OSPS test and later life cycle testing depends on the test profile used and on test equipment capabilities. Guidelines for accomplishing this are provided in Appendix C, and the specific method to be used can be called out in a device-specific test plan. For the Dual Mode Life Cycle Test profile, alteration of the recharge offset built into the recharge pulse profile may also be needed. (See Section 3.10.3 for a description of this.)

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 10.

3.10 Cycle-Life Tests

Cycle-life testing is performed using one of the Hybrid Life Cycle Test profiles defined in Section 3.10.3 for Power Assist or Dual Mode operation. Life cycle testing is performed in one of two ways: (1) the test profile is repeated at a fixed state of charge (i.e., the profile is charge-neutral), or (2) the cell state of charge is varied over a target range while cycling is in progress (i.e., either the profile is not charge-neutral, or SOC is varied in some controllable fashion between profiles.)[u] The overall life testing

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[s] s. For Power Assist life cycle testing, this means approximately 100 complete pulse profiles. For Dual Mode life cycle testing, this means at least one of the complete "major cycle" sequences (without the 10-minute clamp voltage interval at the end of the sequence) requiring about 90 minutes each. The clamp voltage interval must be omitted to allow the actual profile SOC variance to be measured.

[t] t. Where a non-charge-neutral test profile is used and the SOC is deliberately varied over an extended period, there is not a single "target SOC" to be maintained, and thermal equilibrium cannot be determined by stable voltage values from profile to profile. However, the results of such cycling should still be reviewed over the initial testing period to see that (a) the desired rate and magnitude of change in SOC is being accomplished and (b) the target SOC value is returned to at the appropriate time.

[u] u. Power Assist life cycle testing can be performed either way by suitable adjustments to the test profile, though the first case is typical. Dual Mode life cycle testing is necessarily the second case, because it combines two noncharge-neutral profiles in a sequence that varies SOC over much of the device's usable energy range.

process is the same for both approaches. Control of the state of charge is addressed in detail in Appendix C.

3.10.1 Controlling and Maintaining State of Charge during Cycling.

The preferred approach to controlling state of charge during life cycle testing depends on (a) whether SOC is fixed or varied over a range during cycling, (b) the specific test profile used, and (c) test equipment capabilities. Methods and guidelines for accomplishing this control are described in Appendix C.

3.10.2 Cycle-Life Test Procedure Outline.

The cycle-life testing process consists of the following steps:

1. Scale the selected test profile by dividing the nominal profile power values by the Battery Size Factor as defined 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.[v]

   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.[w]

   End of test may also be chosen to occur when cycle-life meeting the PNGV goals has been substantiated (i.e., when the number of properly scaled test cycles exceeds the applicable PNGV goal.) Note that *end of test* and *end of life* are not the same, and they may not even be related.[x]

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

4. Repeat the selected test profile a number of times, depending on the profile, as specified in Table 10 or a device-specific test plan. If SOC is varied during life cycling, the SOC variation generally takes place over a defined interval (e.g., 24 hr), and profiles will be performed for some integer multiple of these intervals.

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v. At this point, the cell has insufficient available energy and capacity at the test conditions to execute the test, i.e. its ‘sweet spot’ capacity (SOC range where the power goals are met) is less than the state-of-charge swing required by the test profile. If the device-specific test plan permits cycling over a range of SOC values, the target SOC and operating set point values may need to be adjusted (as in Section 3.10.1) over life to keep the profile SOC excursion within a useable range as cell performance shifts.

w. 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.

x. *End of Test* is simply the point where life testing is halted, either because criteria specified in the test plan are reached, or because it is not possible to continue testing. *End of life* is a condition reached when the device under test is no longer capable of meeting the PNGV goals. See the Glossary for more information on this distinction. The determination of End of Life is discussed in Section 4.10.1 .

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 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 specified in Table 10, though these may be adjusted somewhat if required for time synchronization of cells being tested under different test regimes.

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

3.10.3 Hybrid Life Cycle Test Profiles.

The objective of these test profiles is to demonstrate device life when subjected to different energy use levels and patterns appropriate to the PNGV goals. Separate profiles are defined for such use based on the PNGV Power Assist and Dual Mode goals.

The Power Assist profile is a 72-s pulse profile intended to demonstrate the ability to meet the PNGV cycle-life goal of 300,000 cycles with a 25-Wh swing. The Dual Mode profile removes approximately 1500 Wh during an 18-minute interval, and then returns to the initial SOC in an additional 82 minutes, for use in verifying the PNGV Dual Mode life cycle goal. The Power Assist profile transfers about 7.5-million watt-hours (MWh) in and out of the device over 300,000 cycles. The Dual Mode profile transfers about 22.5-million watt-hours in and out of the device over 3750 complete cycles.

These test profiles are all defined at the battery pack level. They are 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.

3.10.3.1 25-Wh Power Assist Life Cycle Test Profile

The Power Assist Life Cycle Test profile removes 25 Wh on discharge and is nominally charge-balanced (for a device that just satisfies the Power Assist 90% efficiency goal.) The profile is identical to the Power Assist Efficiency Test profile defined in Section 3.8.1. It is repeated here for easy reference as Table 6 and is illustrated in Figure 5.

Table 6. 25-Wh Power Assist Life Cycle and Efficiency Test profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
9	9	10	25	25
27	36	0	0	25
2	38	-16	-8.9	16.1
4	42	-11	-12.2	3.9
4	46	-6	-6.7	-2.8
26	72	0	0	-2.8

3.10.3.2 1500-Wh Dual Mode Life Cycle Test Profile

The 1500-Wh Dual Mode Life Cycle Test profile includes a sequence of three Dynamic Stress Test (DST) pulse profiles scaled to 36 kW and performed consecutively.[y] The gross discharge during this 18-minute sequence of DST profiles is approximately 1500 Wh. The device under test is then returned to its initial charge condition using a sequence of 45 conventional pulse profiles (Dual Mode Life Cycle Recharge pulse profiles) over 72 minutes, for a total duration of 1.5 hr. This is followed by a 10-minute clamp voltage interval (with current limited to a C/1 rate) to ensure that the device has returned to the target state of charge. Table 7 shows the resulting test profile . The DST sequence is illustrated in Figure 7, the recharge pulse profile in Figure 8, and the combined profile sequence in Figure 9.

Table 7. 1500-Wh Dual Mode Life Cycle Test profile.

Time Increment (s)	Cumulative Profile Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
		DST Pulse Profile (1 of 3)		
16	16	0	0	0
28	44	4.5	35	35
12	56	9.0	30	65
8	64	-4.5	-10	55
16	80	0	0	55
24	104	4.5	30	85
12	116	9.0	30	115
8	124	-4.5	-10	105
16	140	0	0	105
24	164	4.5	30	135
12	176	9.0	30	165
8	184	-4.5	-10	155
16	200	0	0	155
36	236	4.5	45	200
8	244	36.0	80	280
24	268	22.5	150	430
8	276	-9.0	-20	410
32	308	9.0	80	490

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[y] The DST profile is defined in the *USABC Electric Vehicle Battery Test Procedures Manual*, DOE/ID-10479. Only the profile shape is used here; the test procedure defined here is not the DST.

Table 7. (continued).

Time Increment (s)	Cumulative Profile Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
8	316	-18	-40	450
44	360	0	0	450
Repeat DST sequence above 2 times (total of 3 iterations for 1080 s)				
Recharge Pulse Profile (1 of 45)				
12	12	29.2	97.33	97.33
38	50	-0.8	-8.44	88.89
2	52	-30.8	-17.11	71.78
4	56	-25.8	-28.67	43.11
4	60	-20.8	-23.11	20.0
36	96	-5.5	-55.0	-35.0
Repeat Recharge Pulse Profile above 44 times (total of 45 iterations for 4320s)				
Voltage Clamp Interval (at target SOC voltage)				
600	600 (6000s total at completion)	(voltage clamp with C/1 current limit)	(as required)	N/A

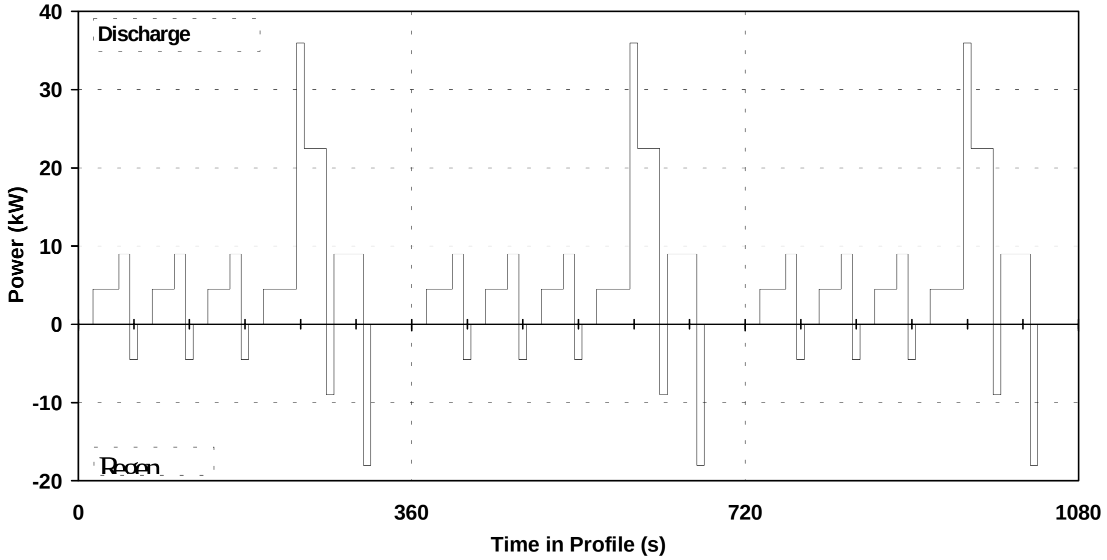

Figure 7. Dual Mode Life Cycle Test profile (DST portion).

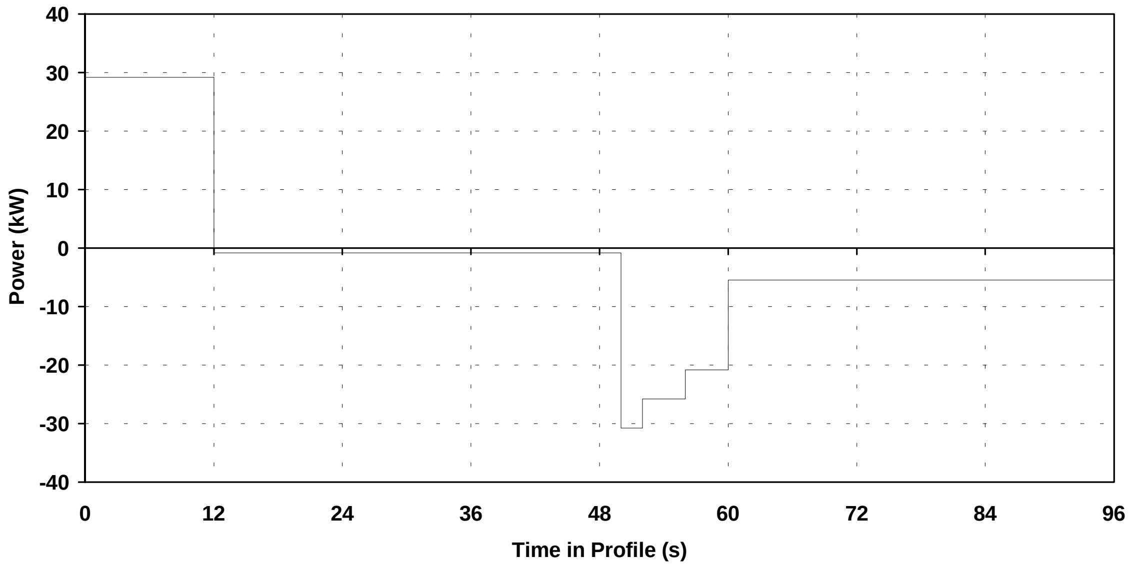

Figure 8. Dual Mode Life Cycle Recharge pulse profile.

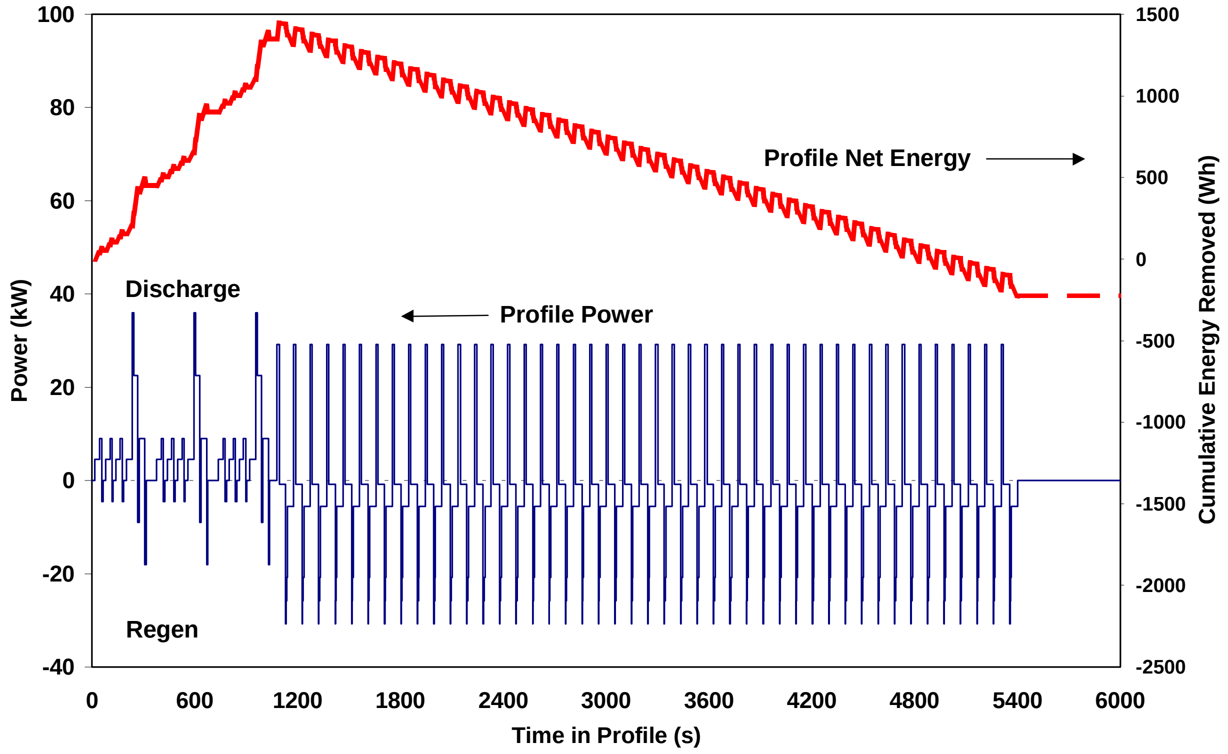

Figure 9. Dual Mode Life Cycle Total Test profile.

3.10.3.3 Correcting A Dual Mode Life Cycle Profile Charge Imbalance

The recharge pulse profile is identical to the (nominally charge-neutral) Dual Mode Efficiency Test profile defined in Section 3.8.1, except that all its power levels (including rest intervals) have been shifted downward to add a recharge offset of -800W to the entire profile. This provides the additional charge energy needed to return to the original SOC after 45 profiles, based on a device that just meets the 88% efficiency goal. A device whose efficiency differs from this may reach a SOC (after the recharge profiles) that is significantly different than the target value. The final clamp voltage interval is only 10-minutes long, so it is not possible to make major adjustments to the ending state of charge during this period. Such an imbalance must be detected and corrected (generally during the OSPS test) by altering the recharge offset in the recharge pulse profile, i.e., by shifting all profile power levels up or down so that the target SOC is reached at the end of the entire profile sequence. This new offset can be calculated as follows:

1. Determine the difference between the target SOC and the actual SOC reached at the completion of the 45 recharge pulse profiles (before the 10-minute clamp voltage interval.)

2. Determine the energy (in watts) corresponding to this SOC difference. (This should normally be done using HPPC data rather than C/1 data.)

3. Divide this energy by the measured device efficiency to estimate the extra recharge energy needed to correct the SOC difference.

4. Divide the result of Step 3 by 4320 s to find the alteration needed in the profile recharge power offset (in watts).

5. If the actual SOC is lower than the target SOC, subtract the result of Step 4 from each Recharge Pulse Profile step power in Table 7.[z] (This increases the average recharge rate.) If the actual SOC is higher than the target, add the result of Step 4 to the recharge pulse profile step powers to decrease the average recharge rate.

6. The revised Recharge Pulse Profile power levels should be close enough to the ideal values that any remaining SOC offset can be corrected by the 10-minute clamp voltage interval.[aa]

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[z] These calculations can be performed either before or after the Battery Size Factor is applied to the test data, i.e., either the actual device energy can be used to calculate the actual new device power levels, or the scaled energy values can be used to calculate new system-level powers to which the Battery Size Factor can be applied.

[aa] But note that these revised values must be applied with high precision. At the system level, an error in the recharge offset power of only 360 W (i.e., 1% of the peak Dual Mode life cycle power of 36 kW) will result in a SOC error of 432 Wh after the 45 recharge pulse profiles. This would require an average power of ~2.5 kW over the 10-minute clamp voltage interval to correct; if possible, the average power during the 10-minute clamp period should not exceed the recharge power offset (i.e., 800 W nominal at the system level.)

3.11 Calendar Life Test

This test is designed to permit the evaluation of cell degradation as a result of the passage of time with minimal usage. It is not a pure shelf life test, because the cells under test are 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. 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 life cycle test matrix where calendar life testing is considered a limiting life cycle test, i.e., one in which the state-of-charge swing during cycling is zero. The design of experiments for such a 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. At least three different test temperatures are recommended, and groups containing more than one cell should be subjected to each temperature where possible. Three cells per group is the suggested minimum number for test repeatability.

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. This is also important for testing at elevated temperatures in order to minimize the fraction of time not spent at target temperature. This may not be practical at very high temperatures due to the rapid degradation that takes place; in this case, reference tests should be performed at an integer submultiple (e.g., half) of the interval used for other cells.

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 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 rate. 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 3.11.1. 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 larger.)

4. Bring the cell to the target temperature. When the ambient temperature and the cell open-circuit voltage have stabilized, clamp the cell at this voltage.[bb]

5. When the cell temperature and voltage are stable (i.e., no significant current[cc] is required to sustain the voltage clamp), apply a single iteration of the Calendar Life Test profile defined in Section 3.11.1 at the same current level defined in Step 3. The clamp voltage is then restored, and the cell continues at the target conditions.

6. Once every 24 hr, repeat Step 5. Note that data acquisition requirements during this pulse profile execution will be similar to those for HPPC tests, even though data may be required only infrequently during the voltage clamp intervals.[dd]

7. At intervals as specified in Table 10 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 rate. Conduct one full C/1 discharge and one HPPC (Low-Current) discharge at 30ºC, along with any other required periodic Reference Performance Tests, and return the cells to their test temperatures.

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

3.11.1 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 rate and extent 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 8 and illustrated in Figure 10.

Table 8. Calendar Life Test profile.

Step Time (s)	Cumulative Time (s)	Current (Ratio)	Cumulative 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

[bb] For cells with a high self-discharge rate, care should be taken to ensure that delays do not cause a significant capacity loss (SOC shift) before the cell voltage is clamped. Also, in some particular cases the cell may be tested at open-circuit conditions, with SOC allowed to vary to some extent over time, rather than at a fixed clamp voltage.

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

[dd] While the cell is stored at the target temperature with its voltage clamped, the current required to maintain it at this voltage (*leakage current*) can also be monitored if the test channels in use have sufficiently low current resolution.

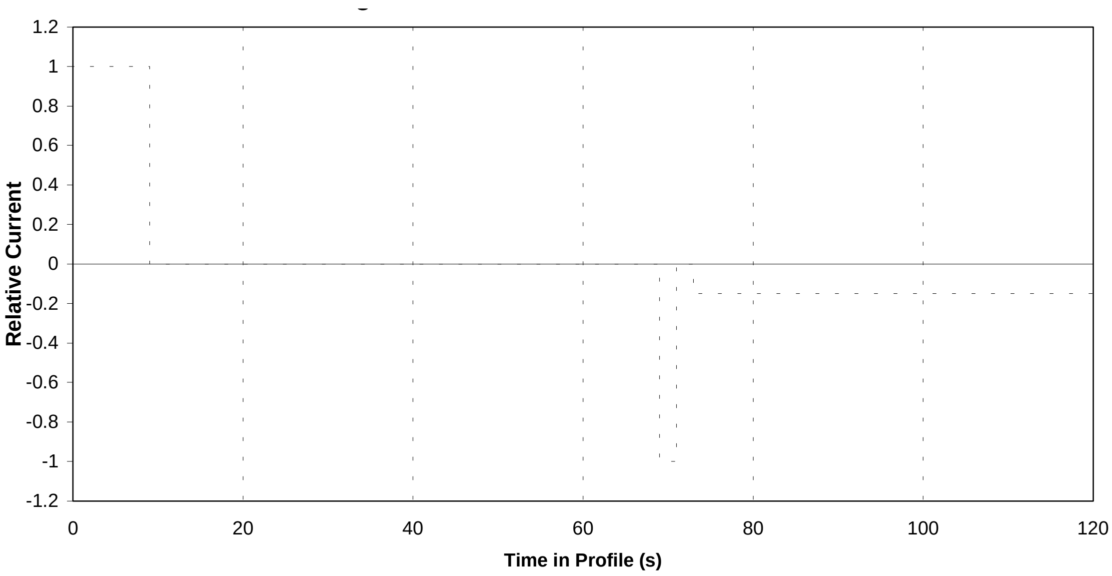

Figure 10. Calendar Life Test profile.

3.12 Reference Performance Tests

Reference Performance Tests 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 life cycle testing or calendar-life testing.

A Reference Performance Test iteration consists of one repetition of each test listed in Table 9. It is recommended that these tests be performed in the order listed.[ee]

Table 9. Reference Performance Tests for life testing.

Power Assist Devices	Dual Mode Devices
C/1 Constant-Current Discharge Test	C/1 Constant-Current Discharge Test
Low-Current HPPC Test	6 kW Constant Power Available Energy Test
	Low-Current HPPC Test

[ee] The Cold Cranking Test is not included in the list of Reference Performance Tests, because it will not routinely be performed at the intervals specified in Table 10. However, it should typically be performed along with the Reference Performance Tests at each of three times over the life of a device: (1) as part of initial characterization testing, (2) about halfway through the projected life, and (3) at the end of life testing.

Table 10 lists typical intervals for reference tests during life cycle 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.

Table 10. Reference Performance Test intervals for life testing.

Life Test Profile Used	Number of Continuous Repetitions between Reference Tests
25-Wh Life Cycle Test Profile (Power Assist)	20,000
1500-Wh Life Test Profile (Dual Mode)	250
Other cycle-life profiles TBD	5 to 10% of expected cycle-life
Calendar-Life Test	Approximately 3 weeks (500 hours)

3.13 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. No standard test procedures are defined for this use. However, the following measurement practice is recommended, especially for cells that are to be life-tested:

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

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

A list of specific issues to be considered for such testing, along with some suggested default values for test conditions, has been added to the guidance in Appendix A.

3.14 Module Controls Verification Tests (Module-Level Testing)

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

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

3.15 Thermal Management Load (System-Level Testing)

Verification of overall thermal behavior is necessarily done at the system level due to the broad operating temperature range (-30ºC to +52ºC) specified by the PNGV goals. 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 PNGV operating temperature range in a manner that is influenced by the statistics of annual climatic (i.e., in-vehicle) conditions in various geographic locations.

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

4. ANALYSIS AND REPORTING OF TEST RESULTS

4.1 General

4.1.1 Laboratory Cell Performance Test Results

A series of performance tests are defined in Section 3 and its subsections. At the cell level, the objective of these tests is to characterize the performance of candidate electrochemical couples to evaluate their suitability for PNGV energy storage system use. The characterization can be performed on a per cm^2 basis by considering only the active cell area and removing all burden considerations associated with current collection, packaging, thermal management, or any other items external to the active cell area. The normalized performance data will allow relative performance comparison of different electrochemical couples and will permit first-order estimates of full-size cell, module, and/or battery pack performance. In general, certain information must be supplied by the manufacturer of a laboratory cell to permit this normalized characterization:

• Active cell area	cm^2
• Active cell area weight	grams
• Active cell area volume	liters

Where this information is not available, results will be reported based on overall cell performance (over life where applicable) and total cell weight and volume at beginning of life. Based on the particular tests performed, the following information is to be determined (measured or calculated from test data) for each laboratory cell tested.

4.1.2 Minimum Test Reporting Requirements

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 PNGV testing and is tabulated in Appendix B. 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 PNGV operating conditions, and thus it does not reflect conformance to the PNGV Available Energy goal. 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.

4.3 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 PNGV goals. Since the PNGV goals 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 3.3.) The Battery Size Factor for a cell is necessarily specific to either the Power Assist or Dual Mode goals, and technologies that are targeted to both sets of goals will require two separate evaluations.

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 12. From these data, OCV at other DOD values can be estimated by straight-line interpolation, or, more accurately, by fitting a curve (such as a fourth-order polynomial) 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 18 s (Power Assist) or 12 s (Dual Mode) after start of discharge pulse
2. Regen resistance 2 s (Power Assist) or 10 s (Dual Mode) after start of regen pulse.

Discharge and regen resistances are determined using a ΔV/ΔI calculation for each iteration of the test profile, according to the following equations and Figure 11. Resistances are normally only calculated for test profile pulses where the selected test current is maintained between the calculation times.[ff]

$$Discharge\ Resistance = \frac{\Delta V}{\Delta I} = \frac{V_{t0} - V_{t1}}{I_{t0} - I_{t1}}$$

$$Regen\ Resistance = \frac{V_{t2} - V_{t3}}{I_{t2} - I_{t3}}$$

These discharge and regen resistances are plotted as a function of depth of discharge, as shown in Figure 12. Note that only one set of goals (Dual Mode or Power Assist) may be applicable to a given device under test.

[ff] 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 INEEL 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 PNGV goals.

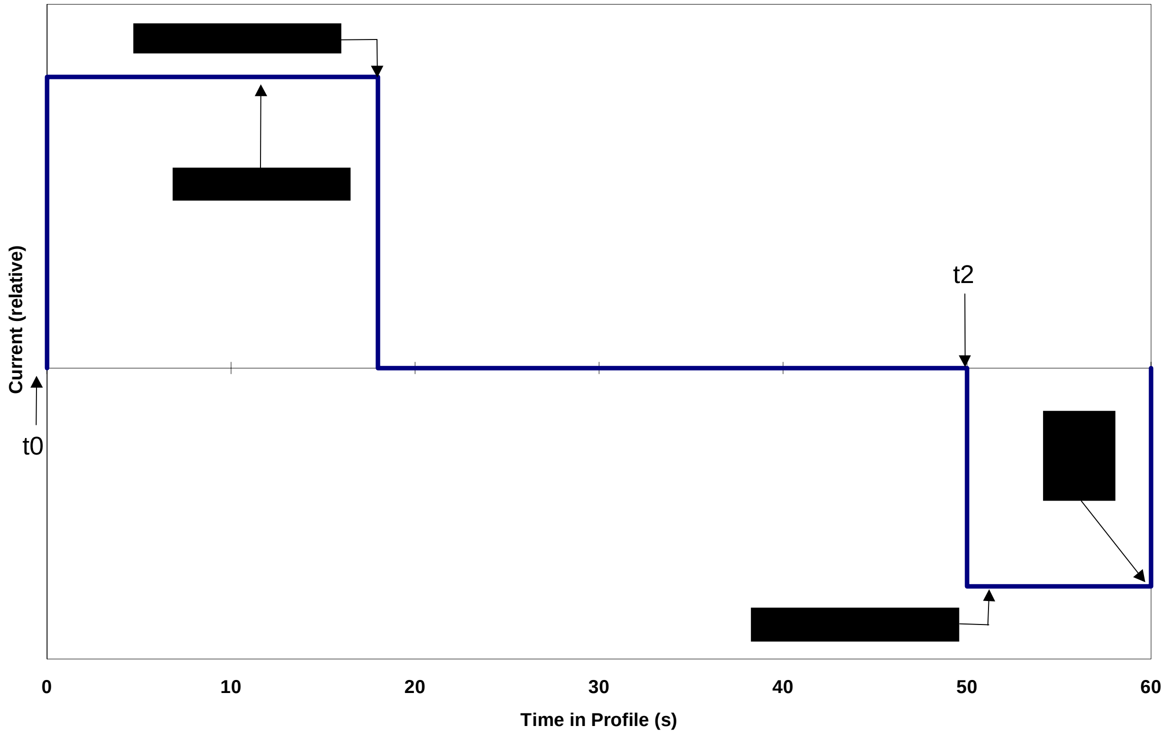

Figure 11. Resistance calculation time points.

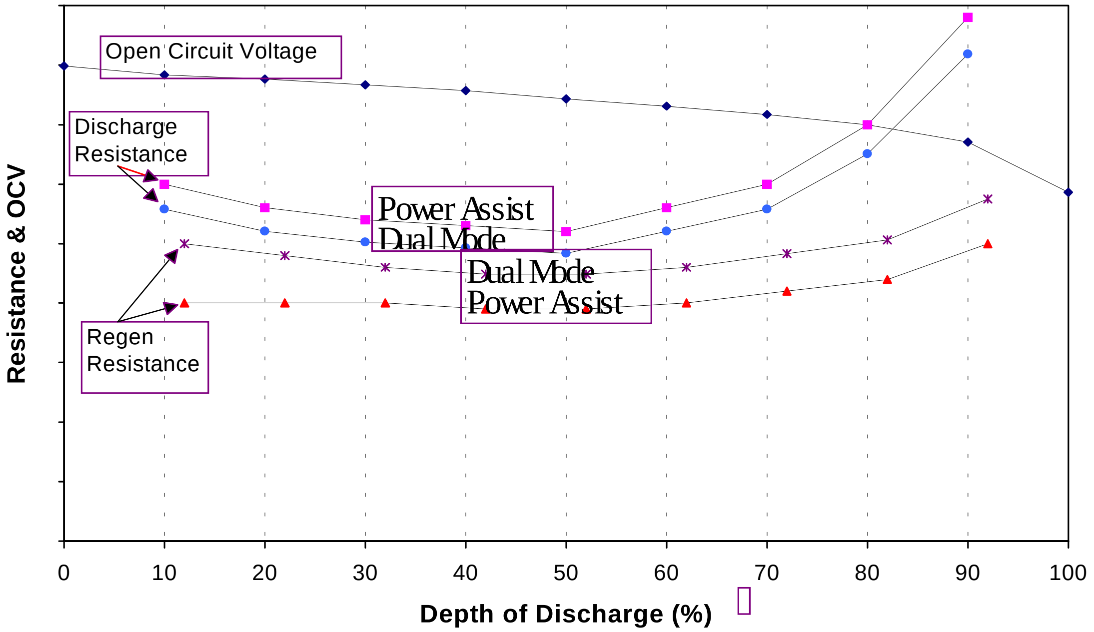

Figure 12. Open-circuit voltage and pulse resistances versus depth of discharge.

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 [d] 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 12), using the same equations as in the USABC Peak Power Test.[Ref. 1] Because pulse power capability is usually voltage-limited,[gg] the applicable equation is typically

$$\text{Discharge Pulse Power Capability} = V_{MIN} \bullet (OCV - V_{MIN}) \div R_{discharge}$$

or

$$\text{Regen Pulse Power Capability} = V_{MAX} \bullet (V_{MAX} - OCV_{regen}) \div R_{regen}$$ [hh]

These power capability values are used to determine the total available state of charge and energy swing that can be used (within the PNGV operating voltage limits) for specified discharge and regen power levels. Note that profile charge removal has to be accounted for in determining DOD, i.e., the DOD values plotted represent the actual net ampere-hours removed (as a fraction of rated capacity) from the cell from top-of-charge down to the point at which the specific discharge or regen pulse occurs, including any previous pulse profiles performed.[ii] An example of the power capability versus DOD plot is shown in Figure 13. (Power values shown are for illustration only, and results for both Power Assist and Dual Mode calculations are shown, though these would typically be plotted separately.)

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gg . For properly scaled full-size devices, if the power capability calculated by either equation, when scaled by the Battery Size Factor, corresponds to a current greater than the PNGV limit of 217 A, the value must be reduced to stay within this current limit. This generally means that the result of each equation, divided by [V_{MAX} or V_{MIN} times the Battery Size Factor], must be less than 217 A. Additionally, if cell V_{MAX} times the Battery Size Factor exceeds 440 V, then at least two strings of cells would be required, and the individual cell current must not exceed one-half of 217 A. For devices whose capacity is larger than optimal, this limit may not apply directly; see note on Section 3.3.2.

hh. 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 at 10% DOD removes 3% of the device capacity, the subsequent regen pulse OCV is interpolated at 13% DOD.

ii. In this manual, plotted DOD values always represent the beginnings of their respective discharge or regen pulses; this is different from the USABC Peak Power Test [Reference 1], where values are plotted at the DOD achieved at the end of the pulse.

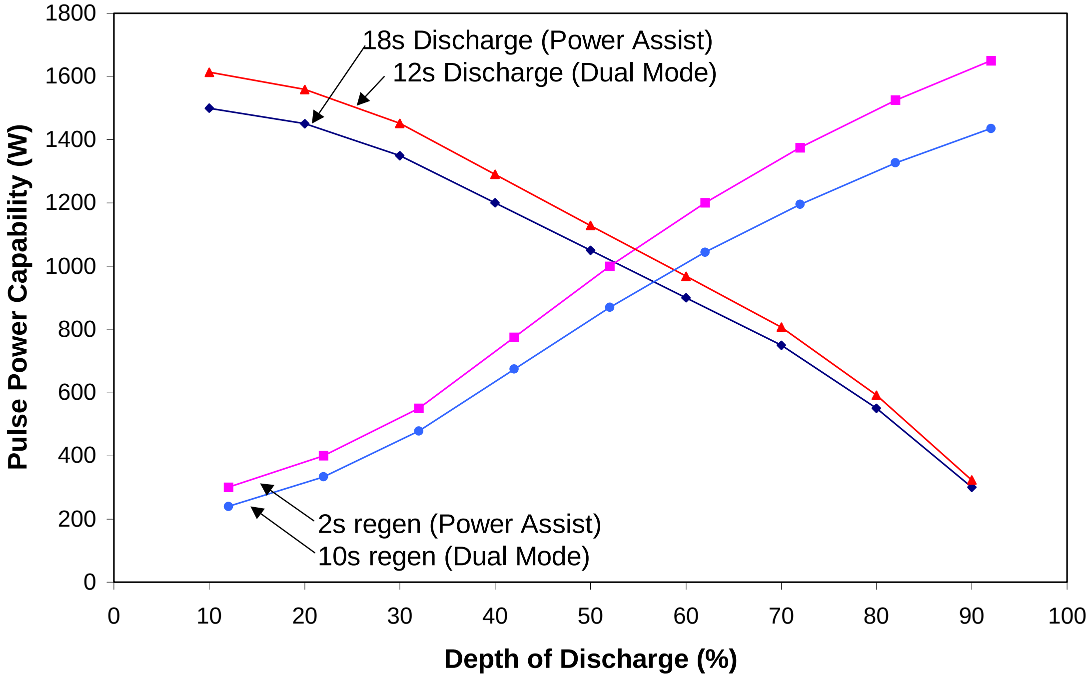

Figure 13. Pulse Power Capability vs Depth-of-Discharge

4.3.4 Available Energy for Power Assist.

Available energy for Power Assist operation is defined as the energy removed during a C/1 discharge over the DOD range for which the PNGV power goals can be met.[jj] Determining available energy consists of the following steps:

1. Establish the relationship between HPPC power and C/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 PNGV power goals can be met.
4. Calculate the available (C/1) energy over the discharge region where the goals can be met.

HPPC power capability and C/1 energy values are related by assuming that the corresponding measured DOD values in a pair of such tests are equivalent.[kk] With this assumption, Figure 13 can be

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jj. Available Energy for Dual Mode operation is calculated similarly from the results of HPPC testing and a special 6-kW Constant Power Test defined in Section 3.4. See Section 4.3.5 for more information.

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 test. Figure 14 shows an example C/1 equivalence, and Figure 15 illustrates the resulting HPPC power versus C/1 energy plot for cell-level data.[ll] (Power and energy values are illustrative only.)

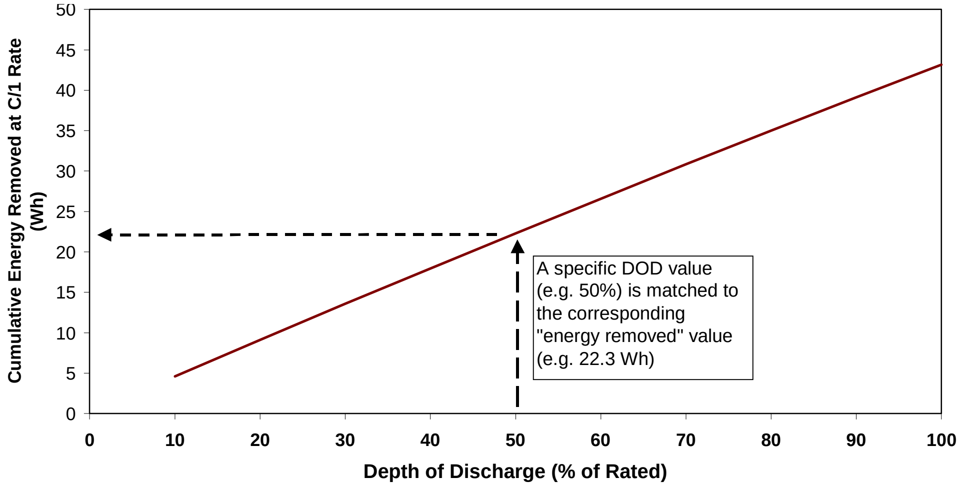

Figure 14. Relationship between energy and DOD in a C/1 discharge.

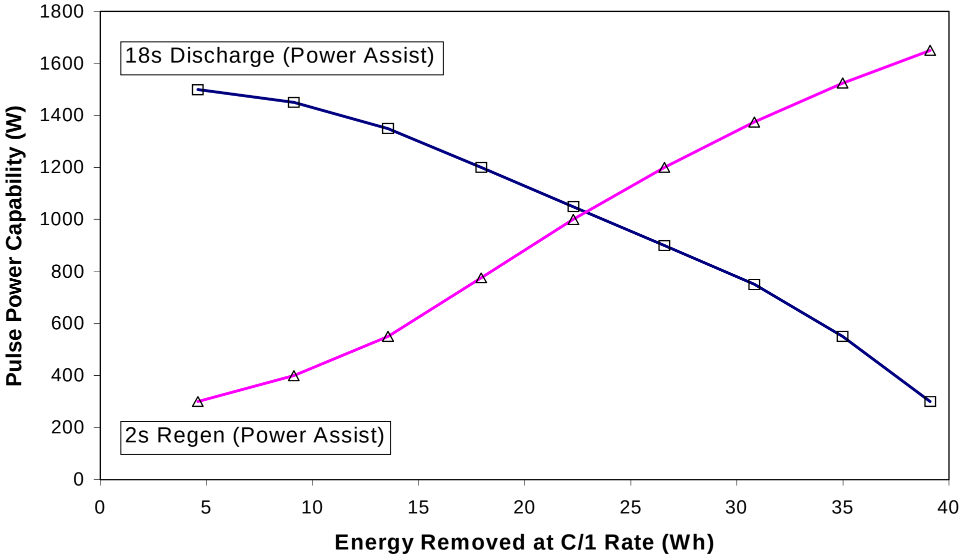

Figure 15. HPPC cell power capability versus C/1 energy removed.

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kk. 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 nearly the same state of charge in both tests.

ll. In Figure 15 and the following figures, the data markers continue to correspond to data taken at 10% DOD intervals.

This power-versus-energy data plot can now be scaled by the Battery Size Factor for comparison with the PNGV goals. This is performed by multiplying all cell-level power and energy values by the Battery Size Factor (for Power Assist, in this case). To simplify the goals comparison, the regen power results are plotted on a second axis scaled by the ratio of required regen to discharge power, i.e., 30-kW regen and 25-kW discharge for the Power Assist goals. Figure 16 illustrates the result of this scaling applied to Figure 15, for a Battery Size Factor of 40.

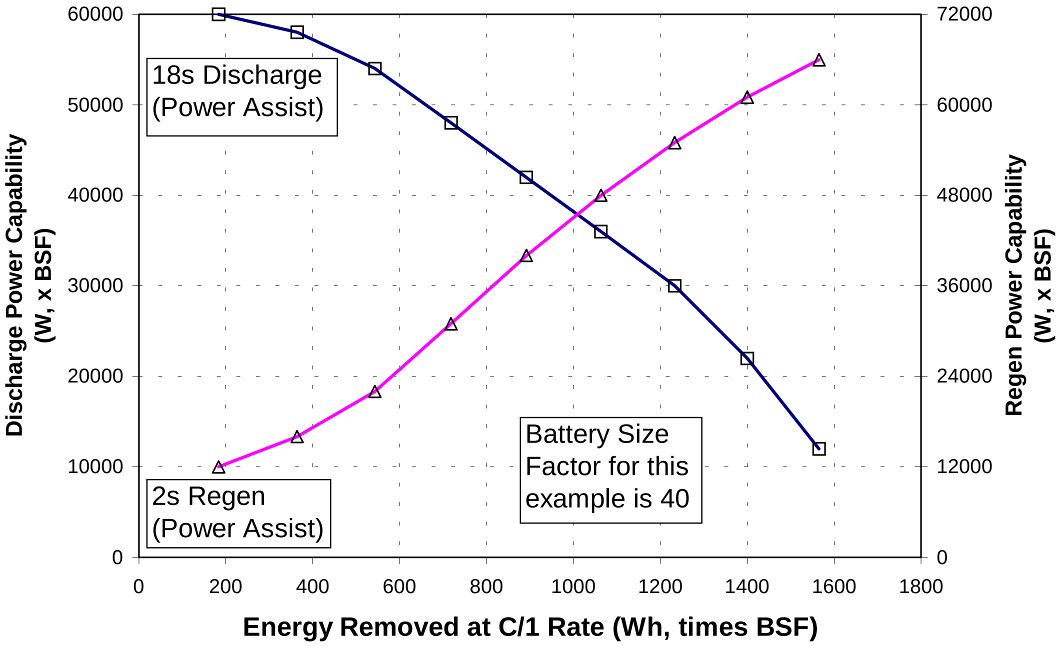

Figure 16. HPPC power versus C/1 energy scaled by the Battery Size Factor.

The comparison of these results to the PNGV goals can be performed graphically by adding a horizontal line representing the power goals and determining the available energy based on the intersection of this goal line and the discharge and regen power capability curves, as shown in Figure 17. (This horizontal line represents both the discharge and regen goals because the two vertical axes are scaled in proportion to these goals.) For this example, with the values shown it can be seen that the available energy is approximately equal to the difference between 1320 Wh and 700 Wh, or 620 Wh.[mm]

In the example, this result would indicate an energy *margin* of 320 Wh over the Power Assist goal. 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 PNGV power and energy goals are required to be met at end of life, the point in life where this energy margin decreases to zero is necessarily *end of life*, unless some other goal 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

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mm. These data values are illustrative only. In practice, a value of available energy that equaled more than twice the applicable goal (as here) might indicate that the Battery Size Factor had been improperly determined. More information on the calculation of available energy is included in Appendix E.

illustrated in Figure 18 (which is derived from a slightly different data set than other illustrations in this section.)

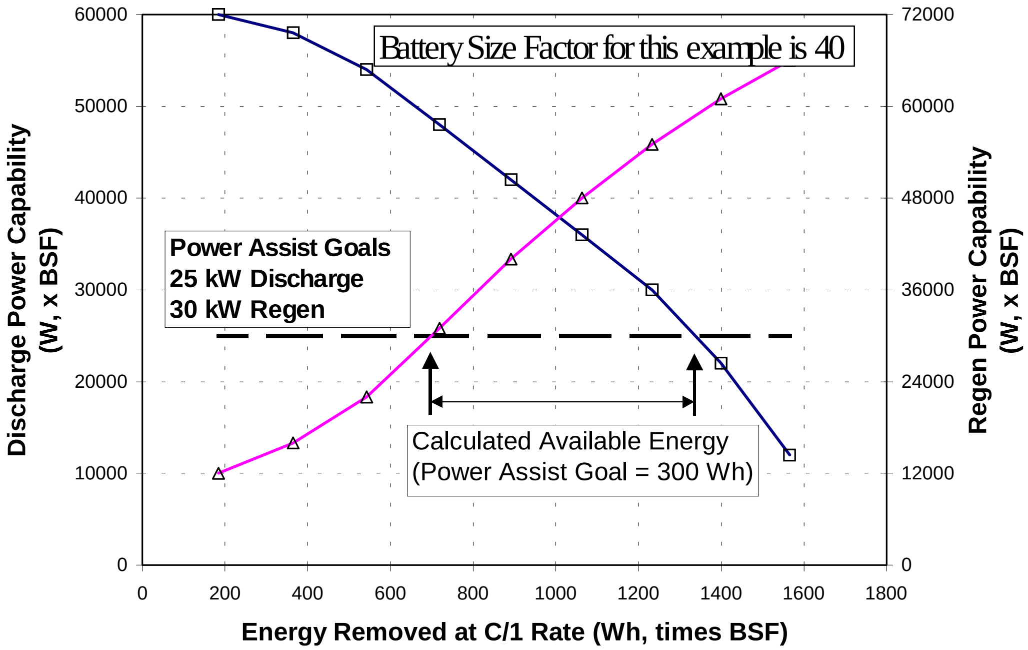

Figure 17. Available Energy determination.

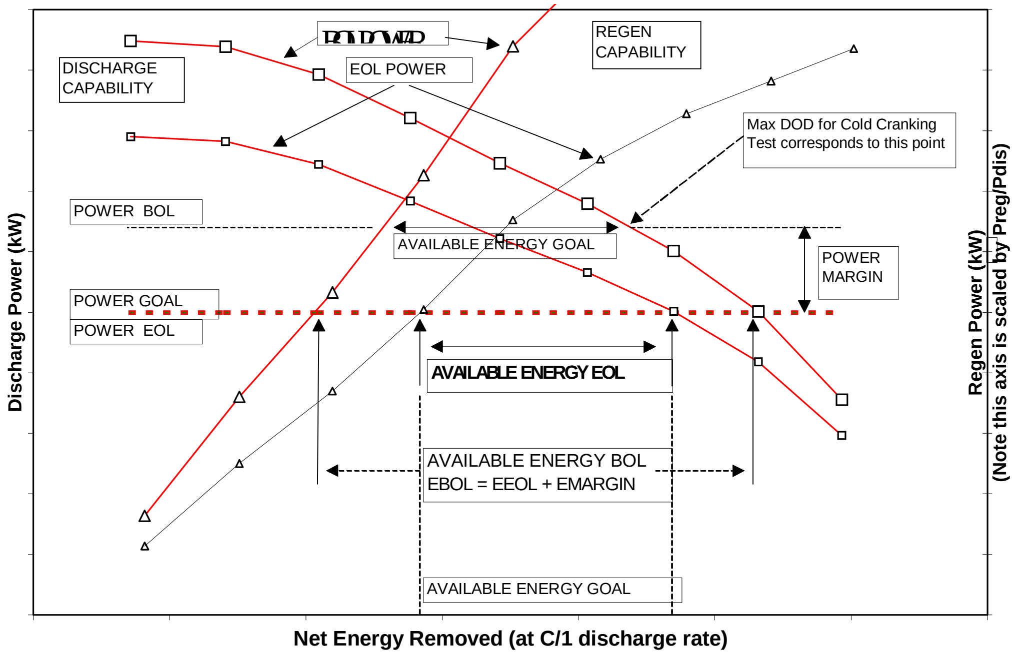

Figure 18. Available Energy and Power margins over life.

4.3.5 Available Energy for Dual Mode.

Available Energy for Dual Mode operation is defined as the energy removed during a 6-kW discharge over the DOD range for which the PNGV power goals can be met. This is calculated by a process that is identical to that used for Power Assist devices in Section 4.3.4, except that the energy from a 6-kW discharge is used rather than the energy from a C/1 discharge. The steps of this process are as follows:

1. Establish the relationship between HPPC power and 6-kW 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 PNGV power goals can be met.

4. Calculate the available (6 kW) energy over the discharge region where the goals can be met.

The only unusual aspect of this process is that a 6 kW data set is not available for use with the initial HPPC test data if the manufacturer has been unable to provide the Battery Size Factor. In this case the Dual Mode available energy must be estimated using HPPC energy data so that the Battery Size Factor can be calculated. (The Battery Size Factor is required for scaling the 6-kW test.) This is not an issue for subsequent tests once the Battery Size Factor is established.

4.3.6 Minimum and Maximum DOD Values.

Minimum and maximum DOD values where the PNGV power goals 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 17, but plotted against the original DOD values from the HPPC test (i.e., DOD values are not converted to the equivalent C/1 energy values.) Figure 19 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 goals can be met are approximately 41 and 76%, respectively. Figure 19 also shows that the maximum DOD value where the Available Energy goal is just met is about 67% for this data set; this is the DOD value where the Cold Cranking test is performed. This point is determined by finding the highest power at which the Available Energy goal is met (i.e. corresponding to the upper arrow labeled "Available Energy Goal" in Figure 18) and transferring this power value to the discharge power vs DOD curve.

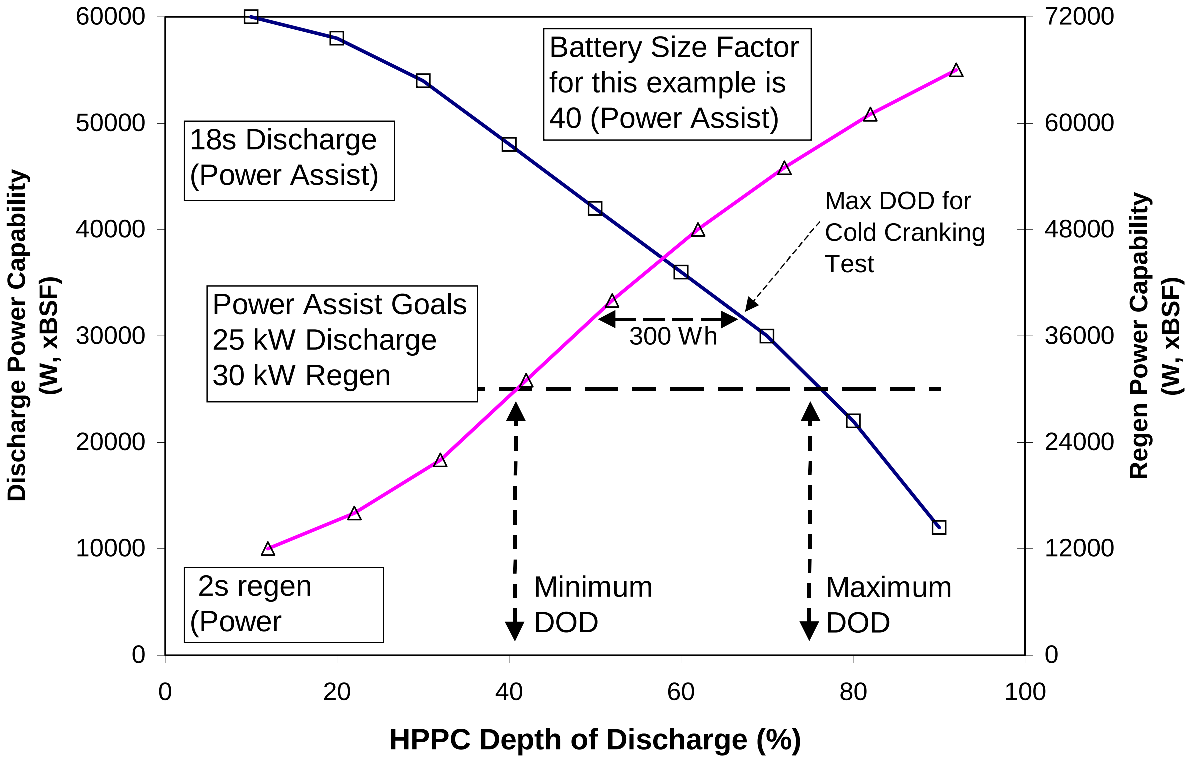

Figure 19. Minimum and Maximum DOD values where PNGV goals are met.

4.3.7 Pulse Power Characterization Profile Voltage Response.

Voltage response to the associated current stimulus is shown by graphing the measured voltage as a function of time during one or more executions of the HPPC pulse profile.

4.3.8 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 Pulse Power Profile 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 pulse current at t = 0 s and t = 18 s, and for regen pulse current at t = 0 s and t = 2 s profile points for Power Assist application. The corresponding profile times for Dual Mode use are t = 0 s and t = 12 s for discharge pulses and t = 0 s and t = 10 s for regen pulses.

The data acquired from HPPC testing are ultimately used for modeling cell characteristics and for the selection and design of full-size module and battery pack characteristics. Additional information regarding the use of HPPC test data for estimating battery performance parameters is contained in Appendix D. This appendix describes a spreadsheet-based approach to such parameter estimation, generally based on a five-component equivalent circuit for the device that accounts for state of charge and polarization effects.

4.3.9 Determining Battery Size Factor When Not Supplied By Manufacturer.

Section 3.1.2 discusses the special case where the device manufacturer is unable to supply a Battery Size Factor in advance of testing. In this case, the minimum Battery Size Factor is calculated directly from the initial HPPC test results. The method for doing this is effectively an inversion of the available energy calculation process described in Section 4.3.4 or 4.3.5, with steps as follows:

1. Establish the relationship between HPPC power and either C/1 energy (for Power Assist) or HPPC energy (for Dual Mode) as a function of DOD.[nn]

2. Determine a multiplier to be applied to the power and energy results which gives an available energy exactly equal to the goal at power values equal to 130% of the applicable goals.[oo] (This is an iterative process that is best done using an automated analysis tool. However, it can be estimated graphically as a check on the calculation.) Round this value to the next larger integer.

3. Verify that this Battery Size Factor is expected to give round-trip efficiency values within the PNGV goals at end of life. This is most easily done by actually executing the Efficiency Test at a power level scaled at 130% of the value indicated by this factor (i.e., test power = full system power divided by Battery Size Factor multiplied by 1.3.) However, the efficiency can also be estimated using the analytical process described in Appendix D. If the applicable efficiency goal(s) are not met using this scaling factor, the multiplier must be increased appropriately.

4. The Battery Size Factor resulting from this process is used for all future testing. (A single typical or average value can be used for testing a group of identical devices.)

4.4 Available Energy Test (Dual Mode Constant Power)

The energy removed between the minimum and maximum DOD values calculated in Section 4.3.6 is the Dual Mode available energy per cell. If this value is multiplied by the Battery Size Factor, it can be

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[nn] For the Dual Mode case, the relationship between HPPC power and 6-kW (constant power) discharge energy is actually needed instead. However, this requires scaled 6-kW discharge data that cannot be obtained until after the Battery Size Factor is defined. To avoid this circular condition, HPPC discharge energy is used for the Dual Mode case as an approximation to the 6-kW energy versus DOD relationship. The process is otherwise the same for Power Assist or Dual Mode.

[oo] Note that this 30% increase will not increase the available energy margin at beginning of life by 30%, due to the accompanying increase in power capability of the larger size device. The power-to-energy (P/E) ratios corresponding to exactly meeting the goals are fixed (83.3 for Power Assist, 30.0 for Dual Mode), but the P/E function for a given device is highly nonlinear. Thus, the effect of this 30% margin may be a change of much more or much less than 30% in available energy, depending on where the resulting device powers fall on the P/E curves.

compared with the PNGV goal of 1500 Wh. (The analysis process described in Section 4.3.6 actually calculates this value from the scaled power and energy values, which already include the Battery Size Factor, but in principle it does not matter whether the Battery Size Factor scaling is done before or after the usable discharge region is determined.)

4.5 Self-Discharge Test

Self-discharge rate is determined over a fixed period (nominally 7 days) at one or more intermediate DOD conditions (nominally 30% DOD). The difference between the energy (watt-hours) capacity measured before and during (i.e., over) the stand period is considered to be the energy loss reflecting self-discharge. This energy loss is computed as the difference between the pretest C/1 energy and the sum of the energies in the partial C/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 Power Assist or Dual Mode, or both).

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

The result of this calculation is reported for comparison with the PNGV goal of no more than 50 Wh per day.

4.6 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 PNGV goal of 5 kW. However, because the test is run at a (scaled) power level equal to 5 kW, the actual power achieved does not necessarily represent this power capability. (Some batteries may be capable of higher power than this.) The power capability is 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 20], using the same $\Delta V/\Delta I$ calculation 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 the same equation defined 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 PNGV goal of 5 kW.

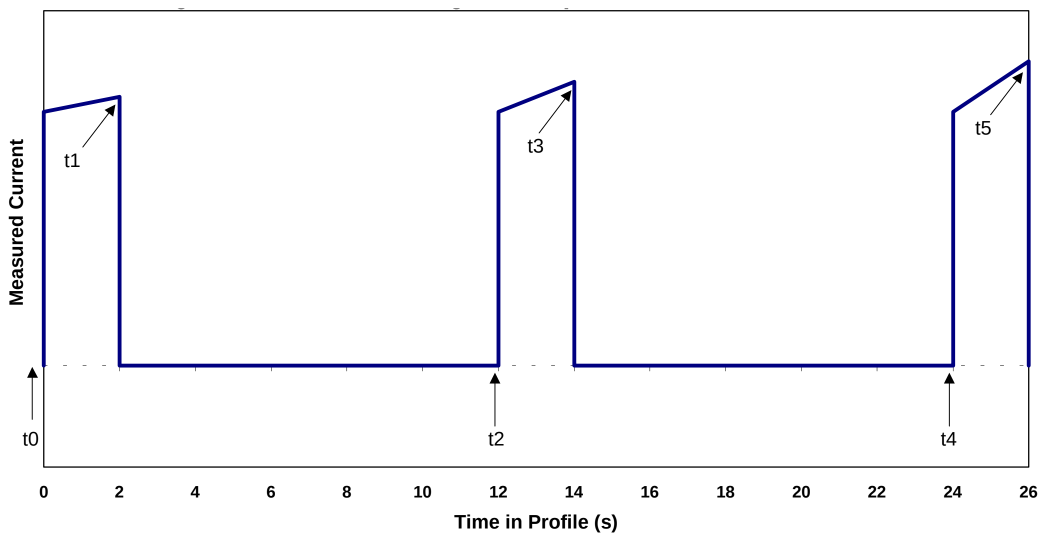

Figure 20. Cold Cranking Test resistance calculation points.

4.7 Thermal Performance Tests

Measured capacity at the C/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 is reported in the same formats defined in Section 4.3, except that the test temperature must accompany all data and graphs.

4.8 Energy Efficiency Test

Round trip energy efficiency is calculated from an integral number of test profiles of the Efficiency Test. The preferred approach is to use a group of 10 or more consecutive test profiles, 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-hr and the regen ampere-hr 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:

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

Round-trip efficiency may also be calculated if desired over a longer period of time (e.g., during life cycling) using any 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. However, the value of efficiency calculated using Dual Mode life test data cannot be compared directly to the PNGV goals.[pp]

4.9 Operating Set Point Stability Test

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

4.10 Cycle-Life Tests

For the selected life test profile, the 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. 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.

4.10.1 Determining Cycle Life and the End-of-Life Condition

The value of Cycle Life to be reported for a device subjected to life cycle 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 PNGV goals. The ability to meet the goals 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 goal value at the goal power), the device has reached end-of-life. In addition, the inability to meet any of the other PNGV technical goals (e.g., the cold cranking power, efficiency or self-discharge goal) also constitutes end-of-life. However, these 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 be determined with high accuracy. The basis for the reported cycle life value (i.e., the limiting goal condition) should also be reported. If the cycle life based on power and energy performance is very near the goal, the end-of-life

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[pp] For Dual Mode life cycling, the calculation would have to be done over some integral number of the overall 100-minute test profiles, which would not be expected to give the same result as using the Dual Mode Efficiency Test profile alone. The Power Assist Efficiency Test and Life Cycle Test profiles are identical, so Power Assist Life Test data are directly usable for efficiency calculations if cycling is done at a constant SOC.

point may need to be interpolated based on the change in HPPC performance from the previous reference test.

4.11 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 discharge tests, and (c) cell discharge (18-s) and regen (2-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.

Analytical methods for predicting calendar life as a function of temperature, state of charge, or other factors are still under development for the PNGV program. When these are defined, projected calendar life at the nominal in-vehicle storage (i.e., non-driving) temperature of a device (defined by the manufacturer) should be reported based on each testing interval and the associated Reference Performance Test results.

4.12 Module Controls Verification Tests

Because standard tests have not yet been defined for module control behavior, analysis and reporting requirements for such tests must be detailed in device-specific test plans, as needed.

4.13 System-Level Testing

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

Test procedures and the associated reporting requirements are not yet defined for thermal management load testing.

5. REFERENCES

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

Appendix A

Generic Test Plan Outline for PNGV Testing

Appendix A

Generic Test Plan Outline for PNGV Testing

Information in italics is generally intended as guidance for the user of this appendix and should be deleted or replaced by appropriate information in an actual device-specific test plan.

1.0 Purpose and Applicability

This section should describe the intent of the testing and the general nature and type of the devices to be tested.

2.0 References

2.1 *PNGV Battery Test Manual,* Revision 3, DOE/ID-10597, published 2000

2.2 *Other references may be included as appropriate*

3.0 Equipment

3.1 *General description of any specific requirements or limitations that the test equipment used for this test plan must satisfy*

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

4.0 Prerequisites and Pretest Preparation

4.1 A notebook for the devices should be started, and both the manufacturer and laboratory identification numbers should be recorded.

4.2 Actual weights and open-circuit voltages of the cells as delivered should be recorded. Also a 1-kHz ac impedance measurement should be made on each device at the 'as-received' state of charge to verify device condition.

4.3 Prior to start of testing, a test readiness review should be conducted.

4.4 *Any other conditions necessary for the start of testing should be described.*

5.0 Ratings, Test Limitations, and Other Test Information

Items in bold print are required for the test laboratory to establish test conditions for certain tests. These should be obtained from the manufacturer whenever possible. Other items (not in bold print) can be provided by the manufacturer for the protection of the device(s) under test as necessary.

5.1 Ratings

Cell Rated Capacity: ____ Ah (C_1/1 rate)

Cell Operating Temperature Range: ____ ºC to ____ ºC discharge/charge

____ ºC to ____ ºC storage

Cell Intended Application: Power Assist (Yes/No)
Dual Mode (Yes/No)

Battery-Size Factor __

5.2 Nominal Values (Information Only)

Cell Nominal Capacity: ____ Ah
Cell Nominal Weight: ____ kg (analysis use only)
Cell Nominal Volume: ___ L (analysis use only)

5.3 Discharge Limits

Minimum Discharge Voltage for 18 s: ____ V

Discharge Voltage Limit (V_{DVL}) for continuous discharge: ____ V

Minimum Discharge Voltage for Cold Cranking (2s at -30ºC): ____ V

Maximum Discharge Current for 18 s (I_{max}): ____ A

5.4 Regen Limits

Maximum Regen Voltage for 10 s: ____ V

Maximum Regen Current for 10 s: ____ A

5.5 Charge Limits and Procedure

Maximum Charge Voltage ___ V

Maximum Continuous Charge Current: ___ A

Recharge Procedure: ____________________________________
____
____

5.6 End-of-Test Criteria for Life Testing:

1. Completion of a number of properly scaled life-cycle test profiles adequate to meet the PNGV life-cycle goal (power assist or dual mode as appropriate for the technology);
or

2. Inability to perform the life cycle test profile at the programmed values at the required DOD without exceeding the voltage limits;
or
3. Inability to give valid data from the HPPC Reference Performance Test at three or more DOD values (for both discharge and regen);
or
4. When directed by the PNGV Program Manager.

6.0 Safety and Health

6.1 Hazard Identification

The checklist below provides a listing of potential hazards that may be encountered during the normal conduct of the tests. Exclusive of unanticipated upset conditions but including handling of batteries, construction of test setup, and use of peripheral supporting equipment (e.g. cooling systems), check any hazards to which personnel may be exposed or hazardous activities anticipated.

Table 6.1. Checklist of potential hazards to be considered

Check if applicable to planned tests	**Hazard**
	Flammable materials (flash point < 100°F or 38°C)
	Combustible materials (flash point < 200°F or 93°C)
	Handling of corrosives (pH<2 or pH>12)
	Toxic materials (Used as a pure substance or >1% in mixture)
	Carcinogenic materials (Used as a pure substance or >.1% in mixture)
	Pyrophoric or reactive materials
	Cryogenic materials
	Compressed gasses
	Rotating equipment (exclusive of hand tools)
	Welding, soldering, brazing
	Irritants or sensitizers
	Dust, mists, aerosols, ashes
	Use of fume hood, elephant trunk, glove box
	Pressurized system of components (>30 psi)
	High Temperature sources or surfaces (>125°F or 52°C)
	Low Temperature sources or surfaces (< 32°F or 0°C)
	Exposed electrical contacts (≥ 50 V)
	High currents (>50 mA DC or 10ma AC)
	Heavy Lifting (>50 lbs)
	Stored energy devices other than test items (batteries, capacitors, springs, hydraulic accumulators)
	Other hazards. Please specify:

Although not a specific hazard, the following items may present hazards that need to be considered in the execution of the planned testing activities. Check all that apply.

Table 6.2. Other activities of potential concern

Check if applicable to planned tests	**Testing Activity includes:**
	Disposal of hazardous waste
	Working alone
	Unattended operation or testing
	Purchasing, use, or storage of chemicals
	Other activities

6.2 Hazard Mitigation

For each checked item above, describe the nature and magnitude of the hazard, exposure or activity. If unknown, so state. Describe any extraordinary recommended actions (e.g. safe handling precautions, personal protective equipment required and when it should be worn)

Describe any other recommended precautions that should be taken during the conduct of this testing (such as storage conditions, or other manufacturer recommendations)

6.3 Lessons Learned

Describe or reference any known failures and/or upset conditions experienced with this type of battery. The cause, consequences and lessons learned resulting from the failure should be described. All test personnel prior to commencement of testing activities must review reference material.

6.4 Emergency Response

Describe any initial actions or actions in addition to laboratory standard operating procedures that are to be taken in the event of a credible failure of the test item and/or supporting system. This should include known failure mechanisms resulting from unintended abuse of the test item.

7.0 Tests to be Performed Under this Test Plan

The devices to be tested under this test plan will be subjected to the characterization test sequence in Table 7.1. Life cycle and calendar life testing will be conducted in accordance with the test sequences in Tables 7.2 and 7.3 respectively. Unless otherwise specified, the ambient device temperature for all tests shall be 30 ± 3 ºC. Depth of Discharge (DOD) will be determined by removing a percentage of the rated capacity from a fully charged cell at a $C_1/1$ rate. The devices will be tested in temperature chambers unless this becomes unfeasible, in which case the responsible program or project engineer should be notified before testing continues.

This section should identify the number of groups of devices, and the number of devices in each group, to be tested under this test plan. It should also identify which devices are to be tested against Power Assist or Dual Mode requirements (or both.) The list of tests in Tables 7.1, 7.2 and 7.3 is intended to be comprehensive; all tests may not be required for any given device. Also, the specific information in these tables regarding particular tests is illustrative only.

If only some devices are to be subjected to a given test, criteria must be provided for choosing the specific devices (either here or in the specific table entries.)

Note that all section references in Tables 7.1, 7.2 and 7.3 (shown in italics) refer to the PNGV Testing Manual, Reference 2.1 in this test plan.

Table 7.1. Characterization test sequence.

Item	**Sequence of Initial Characterization Tests for All Cells**	No. Iterations
1	**Static Capacity Test** *(Section 3.2)* Conduct this test on all devices. This test consists of multiple constant current $C_1/1$ discharges based on the rated capacity. All tests are to be terminated at the minimum discharge voltage of 2.5 V. * Repeat discharge until measured capacity is stable within 2% for three successive discharges (maximum 10 discharges)	*
2	**Hybrid Pulse Power Characterization Test** *(Section 3.3)* Perform this test on all devices at two current levels. The Low-Current Test is performed at a peak discharge current of ____A (based on 25% of the maximum current I_{max} of ___ A or a 5 C rate, whichever is larger). The High-Current Test is performed at a peak discharge current of ____A (75% of I_{max}, which is _____A.) Pulse Power Capability will be computed initially for all cells using V_{MIN} to V_{MAX} voltage ranges of [_____V to _____V for Power Assist] and/or [____V to _____V for Dual Mode]	2
3	**Available Energy Test (Dual-Mode Constant Power)** *(Section 3.4)* The Battery-Size Factor to be used for scaling the 6-kW discharge is ______. [*Alternative where the manufacturer does not provide BSF: …will be determined by analysis of the initial HPPC Low Current test results from No. 2.*]	1
4	**Self Discharge Test** *(Section 3.5)* Conduct this test on all ____ of the devices for a ____-day stand interval at 30% DOD. Note: If the final measured $C_1/1$ is significantly less than the pretest	1

.

Item	**Sequence of Initial Characterization Tests for All Cells**	No. Iterations
	value, contact the Program Engineer prior to beginning life testing.	
5	**Cold Cranking Test** *(Section 3.6)* Conduct this test on _____ devices at -30 °C at the maximum DOD value where the PNGV goals can be met. For this test plan, the cold soak time at -30 °C prior to pulse testing shall be _____ hours. The Battery-Size Factor to be used for scaling the nominal 5-kW pulse power is _____. [*Alternative if manufacturer does not provide BSF: …will be determined by analysis of the initial Low Current HPPC Test results from No. 2.*] The maximum DOD value where the test will be conducted will be determined from Low-Current HPPC results. Power Assist goals will be used for ____ devices, and Dual-Mode goals for _____ devices.	1
6	**Thermal Performance Tests** *(Section 3.7)* *Define any planned thermal performance testing here.*	As Req'd
7	**Efficiency Test** *(Section 3.8)* Perform this test on ____ devices using the scaled Efficiency Test profile, with each cell at the target DOD value specified: *Specify target DOD values here for each device* The Battery-Size Factor to be used for scaling the test profile is _____. *[Alternative where manufacturer does not provide BSF: …will be determined by analysis of the initial Low Current HPPC test results from No. 2.]* _____ devices will be scaled based on Power Assist goals, and _____ devices will be scaled based on Dual Mode goals.	1
8	**Impedance Spectrum Tests** Impedance Spectrum measurements will be made on devices at both 100% and 0% state of charge as part of initial characterization and again at end-of-testing. Special considerations for this testing are listed in Section 7.1	2

Table 7.2. Life-cycle test sequence.

Item	**Sequence of Life-Cycle Tests for All Cells**	No. Iterations
1	**Reference Performance Tests** *(Section 3.12)* Perform the Reference Performance Tests required by *Reference 2.1 Table 9* prior to the start of life cycle testing. During life cycle testing, repeat the required Reference Performance Tests at the intervals required by *Reference 2.1 Table10.* The required tests for Power Assist in *Table 9* should be performed on _____ devices, and/or the required tests for Dual Mode should be done on _____ devices. For Power Assist devices, the RPT C/1 discharge data should be included in the same data file with the HPPC results. For Dual-Mode devices, the RPT Dual-Mode Available Energy (constant power) data should be included in the same data file with the HPPC results. At completion of life cycle testing, perform the required Reference Performance Tests as above. Also repeat the Impedance Spectrum measurements performed in Table 7.1 No.8 as part of characterization testing.	Periodic
2	**Operating Set Point Stability Test**. *(Reference 2.1 Section 3.9*) Conduct this test on _____ devices at the target DOD listed, using the Life Cycle test profile specified in No. 3: *List devices and target DOD values here.* This test is conducted at the beginning of life cycle testing using the same test profile(s) and conditions required for life cycle testing. *If any tests are to be conducted at a DOD value determined from earlier testing (e.g., minimum DOD where goals can be met), describe the source of these DOD values.)*	1
3	**Life Cycle Testing** *(Section 3.10)* Subject ____ devices to the appropriate Life-Cycle Test Profile *(Reference 2.1 Section 3.10.3)* at the same target DOD values used for the OSPS test in *No.* 2. Perform the number of test profiles specified in Table 10, after which the Reference Performance Tests of No.1 are repeated.	Per Table 3.10

Item	**Sequence of Life-Cycle Tests for All Cells**	No. Iterations
	Life Cycle Conditions Device # Life-Cycle Profile Target DOD value *List devices, life cycle profiles and target DOD values here.*	

Table 7.3. Calendar-Life Test Sequence

Item	**Sequence of Calendar-Life Tests for All Cells**	No. Iterations
1	**Reference Performance Tests** *(Section 3.12)* Perform the Reference Performance Tests required by *Reference 2.1 Table 9* prior to the start of calendar life testing. During calendar life testing, repeat the required Reference Performance Tests at the intervals required by *Reference 2.1 Table 10.* The required tests for Power Assist in *Table 9* should be performed on _____ devices, and/or the required tests for Dual Mode should be done on _____ devices. For Power Assist devices, the RPT C/1 discharge data should be included in the same data file with the HPPC results. For Dual-Mode devices, the RPT Dual-Mode Available Energy (constant power) data should be included in the same data file with the HPPC results. At the completion of calendar life testing, perform the required Reference Performance Tests as above. Also, repeat the Impedance Spectrum measurements performed in Table 7.1 No. 8 as part of characterization testing.	Periodic
2	**Calendar Life Tests** *(Section 3.11)* *Identify required calendar-life test conditions and associated devices here.*	N/A

7.1 Impedance Spectrum Testing Considerations

The following conditions should be defined and controlled when performing Electrochemical Impedance Spectroscopy (EIS) measurements to assure consistent results. (Suggested default conditions are listed in brackets.)

a. Location of measurements, i.e., in situ or in a special controlled environment such as a Faraday cage. [Except in unusual circumstances, this testing is recommended to be done in situ in the normal test setup.]

b. State-of-charge [100% and 0%]
c. Temperature [30°C or nominal device operating temperature]
d. Recovery/soak time after SOC and temperature conditions are established [1 hour minimum, 8 hour maximum]
e. EIS amplitude [as low as possible with acceptable signal-to-noise ratio]
f. EIS frequency range [nominally 0.1 Hz to 10 kHz, 1 kHz value must be included for comparison with initial check]
g. Impedance of test leads must be minimized and controlled

8.0 Measurement and Reporting Requirements

8.1 Measurements

For each group of devices subjected to a common test regime at a given temperature, the ambient temperature for this device group should also be measured and included in the data for the first (lowest numbered) device in that group. For data consistency, this should normally be the last recorded variable for that particular device. This ambient temperature measurement is in addition to the measured temperature of the device itself.

Detailed data acquisition and reporting requirements for the characterization and life-cycle tests are as required for the applicable test procedures in Reference 2.1. For measurements made near the start of discharge or regen pulses, current and voltage measurements must be made near-simultaneously. Measurements at other times during pulse steps should have channel-to-channel latency between current and voltage measurements of less than 100 milliseconds. The response of Maccor cell test channels is considered adequate to meet this requirement, provided that a data point is acquired near the beginning of each pulse-type step; the response of other data acquisition systems may need to be reviewed further.

8.2 Data Recording Intervals

During all pulse profiles for HPPC, Cold Cranking and Efficiency tests, and once-per-day Calendar-Life pulse profiles, data should be acquired at a periodic rate of once per second during discharge pulses, regen pulses and the rest intervals between them. This rate may be decreased to once per 2 seconds for pulses or rest intervals that are longer than 30 seconds. Voltage and current data should also be acquired at the beginning and end of each discharge and initial regen pulse.

During the 1-hour HPPC rest intervals, C_1/1 discharge periods, Dual-Mode Constant Power discharge periods, and battery charge periods, data may be acquired once per minute; a data point is also required at the termination of all these periods. For rest intervals greater than 1 hour (e.g., calendar life periods), the data may be acquired once per half hour. In general, specified rest periods should be treated as part of the associated test with respect to data acquisition and archiving; voltage and temperature data should be acquired during these periods.

Data should be acquired at one-second intervals for Operating Set Point Stability (OSPS) tests. Data should also be acquired at one-second intervals during Life-Cycle testing for test profiles recorded; however, not all profiles need to be recorded. For Power Assist Life-Cycle testing, the first and last 100 profiles of each test interval are required to be recorded, along with at least one complete profile of every 100. For Dual-Mode Life-Cycle testing, the first and last two profiles of each test interval are required to be recorded, along with at least one complete profile of every 50. (A Dual-Mode "profile" consists of the complete test sequence defined in Reference 2.1 Table 7.)

8.3 Data Access *(typical for test laboratory)*

Describe requirements for data protection or archiving here.

All data should be treated as CRADA Protected and marked as "Protected Battery Information." *[Applies to government test labs only.]* Access to these data will be restricted to program personnel and to the manufacturer and PNGV representatives listed in Section 11, unless written authorization for other persons is provided by the responsible Program Engineer or Department Manager.

8.4 Data Files *(typical for test laboratory)*

Individual HPPC tests should be archived as a single data file. It is recommended that this HPPC file should also include the associated $C_1/1$ discharge (for Power Assist devices) or Dual-Mode Available Energy (Constant Power) discharge.[1] (For devices being tested against both sets of goals, both the $C_1/1$ and Constant Power data may be included in the HPPC data file.) This file may or may not include the charge prior to the start of the test. For Stand Tests, the initial partial discharge, stand period, and final partial discharge after stand should be included in a single data file where possible. Life-Cycle Test data should be separated into no more than three data files for each testing interval: the initial profiles required to be recorded, the final profiles required to be recorded, and all other data acquired between these two groups of profiles. At the completion of testing, the characterization and RPT results should be transcribed to a compact disk or other storage medium and sent to the PNGV Technical Contact.

9.0 Anticipated Results

Briefly summarize general or specific results that are desired or expected from testing.

9.1 Testing Deliverables

Describe required periodic or final reporting along with any data deliverables due to PNGV technical team or program management.

10.0 Post-Test Examination and Analysis

Describe any required post-test examination or analysis here.

---

[1] *Combining these files is done to facilitate automated analysis of the results. The revised PNGV goals require that Available Energy is calculated from both the HPPC power results and the $C_1/1$ energy (for Power Assist) or 6-kW power (for Dual-Mode) results simultaneously.*

11.0 Contact Persons *(typical for government test labs only)*

Laboratory Program Manager:
Name: ______________
Phone: ______________
Fax: ______________
Email: ______________

Laboratory Program Engineer:
Name: ______________
Phone: ______________
Fax: ______________
Email: ______________

Laboratory Project Engineer:
Name: ______________
Phone: ______________
Fax: ______________
Email: ______________

Manufacturer Technical Contact:
Name: ______________
Phone: ______________
Fax: ______________
Email: ______________

USABC/PNGV Program Manager:
Name: ______________
Phone: ______________
Fax: ______________
Email: ______________

DOE/USABC Test Manager:
Name: ______________
Phone: ______________
Fax: ______________
Email: ______________

DOE Program Manager
Name: ______________
Phone: ______________
Fax: ______________
Email: ______________

Appendix B

Minimum Test Reporting for PNGV Testing

Appendix B

Minimum Test Reporting for PNGV Testing

The following information should be reported for each device tested, for each of the following tests when conducted. (This list does not imply that all tests listed will or should be performed.) Test conditions are tabulated first, followed by test results.

General

Manufacturer Serial Number __________________ Test Lab Reference Number _____________
Device Weight ___________ (g) Device volume _____________ (l)
Device Electrode Area (if known) __________ (cm^2)
Rated Capacity ___________ (W-h) (reference for DOD/SOC values)
Maximum Current for 18-s ________ (A) (reference for HPPC test currents)
Discharge Voltage Limit (for continuous discharge) __________ (V)
Cold Cranking Voltage Limit (for 2-s at -30°C) __________ (V)
Minimum Pulse Discharge Voltage for 18-s _________ (V)
Maximum Pulse Regen Voltage for 10-s __________ (V)
Manufacturer-specified recharge algorithm (describe)

Static Capacity (C/1) Test (at 30°C nominal)
Manufacturer-specified Discharge Voltage Limit _________ (V)
Measured Capacity ____________ (A-h) Delivered Energy ___________ (W-h)
(Both to manufacturer-specified discharge voltage limit at C/1 rate)
Discharge/Recharge Efficiency ____________ (%, coulometric) ____________(%, energy)
(Using manufacturer-specified recharge algorithm)

Hybrid Pulse Power Characterization Test (at 30 °C nominal)
Peak Discharge Test Current (Low) ______________ (A)
Peak Discharge Test Current (High) ______________ (A)

Open-Circuit Voltage versus DOD (V versus %) *(plot)*
For Power Assist devices (as applicable):
    18-s Discharge Resistance versus DOD (W versus %) *(plot)*
    2-s Regen Resistance versus DOD (W versus %) *(plot)*
For Dual-Mode devices (as applicable):
    12-s Discharge Resistance versus DOD (W versus %) *(plot)*
    10-s Regen Resistance versus DOD (W versus %) *(plot)*
(Note: for modeling purposes, actual voltage and current values versus time and DOD may be required for each HPPC test profile at one or more test current levels)

Discharge and Regen Pulse Power Capability versus Energy (W versus Wh with DOD points marked)
    (*plot* simultaneously, for Power Assist and/or Dual Mode as applicable)
Minimum PNGV Discharge Voltage used for calculating PPC _____________ (V_{MIN})
Maximum PNGV Regen Voltage used for calculating PPC ______________ (V_{MAX})
(Note: these will normally be the manufacturer-supplied limits unless these must be restricted to stay within PNGV voltage or efficiency limits)

Battery-Scaling Factor _________________ (Power Assist)
Battery-Scaling Factor _________________ (Dual Mode, as applicable)

Source of BSF Values Manufacturer-supplied ___ Calculated from HPPC ___

Available DOD range at Goal Power Levels (using BSF)
- Based on Low-Current HPPC and C/1 (Power Assist) _____ _____ (upper & lower, %)
- Based on Low-Current HPPC and 6-kW (Dual Mode) _____ _____ (upper & lower, %)

Available Energy at Goal Power Levels (using BSF)
- Based on Low-Current HPPC and C/1 (Power Assist) __________ (Wh)
- Based on Low-Current HPPC and 6-kW (Dual Mode) __________ (Wh)

Self Discharge Test
Stand DOD ________ (%) (nominal 30%)
Stand Time ________ (days or hours) Stand Temperature ______ (nominal 30°C)
Total Energy Loss _______ (W-h) Stand Loss __________ (Wh/day)

Cold Cranking Test
Test Temperature ______ (°C) (nominal –30°C) Test DOD ______ (%)
Minimum Cold Cranking Voltage ______ (V)
Pulse Power Level Used ______ (W) (should be 5-kW divided by BSF.)
Pulse Power Capability Pulse 1 _____ Pulse 2 ______ Pulse 3 ______ (W)

Thermal Performance Tests
Test Temperature ______ (°C) Measured Capacity ________ (A-h)
(At C/1 constant current discharge rate to manufacturer-specified minimum discharge voltage)

HPPC tests at temperature, same reporting requirements as at nominal 30°C testing above

Efficiency Test
Power Assist Round Trip Efficiency ______ (%) [if applicable]
Power Assist Efficiency Test Power Level ______ (W) (should be nominal divided by applicable BSF)

Dual Mode Round Trip Efficiency ______ (%) [if applicable]
Dual Mode Efficiency Test Power Level ______ (W) (should be nominal divided by applicable BSF)

Operating Set Point Stability Test
No reporting requirements

Calendar Life Test
Storage Temperatures ____, ____, ____ (°C)
Total Time at Temperature (to date) ________ (at each test temperature)
Estimated Calendar Life at 30°C ______ (years, if available)

Results of periodic reference tests, same reporting requirements as above
Static Capacity versus time (A-h versus months, at each test temperature) *(plot)*
Discharge and Regen Impedance versus time (ohms versus months, at each test temperature) *(plot)*
Pulse Power Capability versus time (W versus months, at each test temperature) *(plot)*
Periodic Executions of Life-Cycle Test Profile, samples of actual voltage and current data

Cycle-Life Tests
Test Profile Used _____________________ (25-Wh Power Assist, 1500-Wh Dual Mode)
Nominal Depth-of-Discharge Used _______ (%)

Nominal State-of-Charge Swing _______ (%) [for variable SOC cycling]
Peak Discharge Power ________ (W) (should be nominal divided by BSF)

Total Profiles Tested ________ (Number of test profiles achieved)
End-of-Test Condition ________________ (Inability to perform profile, etc.)
Estimated Cycle-Life ________ (profiles, based on ability to meet goals)
End-of-Life Condition _________________ (goal limit reached at cycle life)

Periodic C/1 and HPPC tests, same reporting requirements as above
Static Capacity versus Life (A-h versus cycles) *(plot)*
Discharge and Regen Resistance versus Life (ohms versus cycles) *(plot)*
Discharge and Regen Power Capability at Nominal DOD versus Life (W versus cycles) *(plot)*

Impedance Spectrum Measurements
Value As Received _______ (ohms) (1-kHz only)
Beginning of Life *(Plot of complex impedance)*
End of Testing *(Plot of complex impedance)*

Appendix C

State-of-Charge Control for Life Testing

Appendix C

State-of-Charge Control for Life Testing

BACKGROUND

Life testing in the context of this appendix includes both continuous life-cycle testing and calendar-life testing. PNGV life-cycle test procedures through Revision 1 of this manual were 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 was done by slightly altering the length of one of the profile steps under program control to force the average SOC to the desired value.

Starting with Revision 2 of this manual, continuous life cycling at variable SOC conditions is also included in the PNGV testing regime. The approach adopted for such cycling is to define both a target SOC (as in previous testing) and a range of SOC variation from this target value, normally in the direction of reduced SOC. Thus, there are now three types of PNGV life testing for which SOC control is required:

a. Calendar life testing at a fixed SOC value

b. Continuous life cycling at a fixed target SOC or DOD value

c. Continuous life cycling over a range of SOC/DOD values starting at a fixed SOC/DOD target

Additionally, 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 continuous cycling period.

CALENDAR LIFE TESTING AT FIXED SOC

Because devices subjected to calendar life testing are not being continuously cycled, SOC control is done by clamping the cell voltage at a target value and maintaining this voltage during a testing period that is typically several weeks in duration. The target voltage is determined and reached in one of two ways, depending on whether testing is done based on % DOD or on OCV. (Both methods are included in the procedure in Section 3.11.) The DOD method discharges the device to the target % DOD, measures the corresponding OCV, and maintains this voltage. The OCV method clamps the device to the target voltage (while limiting the current to a C/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

The Operating Set Point Stability Test (OSPS, Section 3.9) is defined for use in verifying that the target life-cycle 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 life cycle test regime, except that the test profile is only executed for a short number of iterations (typically 100 for Power Assist or one for Dual Mode.) Cycling is then suspended, the device is returned to 30°C if necessary, and the device SOC/OCV is determined by the appropriate method (examination of the equilibrium OCV or discharge of the residual capacity.) If the target SOC/OCV 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 life cycle profile to be used (including profile power scaling) and the target state-of-charge at which cycling is to be performed.

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

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

6. If the condition of the cell changes (e.g., due to aging) such that the maintained state of charge 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. Most PNGV testing through Revision 1 of this manual controlled life-cycle SOC by varying the initial discharge step in the test profile. It is also possible to control SOC by varying the final regen step. The process is conceptually identical (or at least symmetrical), and the following description deals only with the discharge step control. Use of regen step control is accomplished by varying (e.g., shortening) the regen 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 regen step method forces the SOC up to the target value.[1]

2. The method described for calculating the control voltage is not intended for use with life-cycle profiles whose discharge steps are more than 18 s in length; extrapolation of the cell resistance will be required if this assumption is not satisfied.

3. The selected life-cycle test profile is assumed to be slightly charge-positive, i.e., its regen steps return slightly more capacity to the cell than is removed in the discharge step(s). This is generally true of PNGV life test profiles, but 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 life-cycle testing is to be performed. If this assumption is not satisfied, additional OSPS iterations may be required due to the change in cell 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 life-cycle 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 life-cycle discharge pulse. For example, if the life cycle discharge pulse is 10 s in duration, dV/dI is calculated using the last rest data point before the HPPC pulse starts and the data point 10 s into the pulse.[2]

2. Calculate the voltage drop expected under load at the end of the life-cycle discharge pulse as [device resistance] times [pulse current $\simeq$ pulse power/end-of-pulse voltage].[3] For example, if the pulse current is to be 10 A for 10 s and the 10-s device resistance is 30 milliohms, the expected voltage drop at the end of the discharge pulse is 0.3V.

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.

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[1] *A third method removes (or adds) the additional charge needed to balance the test profile by applying a clamp voltage during one of the nominal rest intervals 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 as yet been verified by test.*

[2] *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.*

[3] *Because life cycle profiles are now 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* $V_{control} = 0.5 \cdot \{OCV + (OCV^2 - 4 \cdot R_{discharge} \cdot Power_{step})^{1/2}\}$

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.*

Overall SOC Control Approach and Use of the Control Voltage

The target state of charge is maintained during life-cycle testing by varying the length of the test profile discharge step (the first discharge step only, if there is more than one). PNGV life-cycle 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. 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 nominal test profile is charge-positive by 5 W-s, the maximum duration of the discharge step is increased by one second.[4] 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 by either its programmed duration or 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

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[4] *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.*

executions, so that the actual SOC at the cycling condition can be determined. This is done by returning the device to 30°C and observing the OCV, removing the residual capacity, or both.

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 for PNGV testing), 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 actual OCV at the end of the OSPS. For example, if the OCV measured at the completion of the OSPS 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 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 cell 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.) For previous PNGV testing, the control voltage (and thus the cycling SOC) has been adjusted up or down as required to stay within max/min voltage limits. Some test plans do not permit this alteration, and testing must terminate when the target SOC cannot be maintained.

CONTINUOUS LIFE CYCLING OVER A SOC/DOD RANGE [5]

The PNGV cycle life goals are dependent on the magnitude of the energy swing applied to the battery, e.g., the Power Assist cycle life goal is 300,000 repetitions of a charge/discharge behavior which removes and returns 25 Wh (or about 8%) for a minimum size battery. The various test profiles have been constructed to remove different amounts of energy corresponding to the various life goals. However, PNGV life testing done prior to Revision 2 of this manual was all done at a fixed (average) SOC which varied only as a result of the profile steps. Successive profiles were all intended to start (and end) at the same SOC. The effects of overall SOC were evaluated by testing different devices at different average SOC values.

Starting with Revision 2, life testing is permitted using test sequences where the average SOC is varied between a target maximum and minimum value, typically over a period of hours or a few days. Test timing is typically based on a “major interval,” e.g., 24 hours, during which time the SOC would be reduced (“ramped down”) from a maximum to a minimum value (requiring most of the interval)[6] and then held at the minimum for the remainder of the interval before being restored to the maximum value. SOC control for this test involves four sequential tasks:

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[5] *Note that the new 1500 Wh Dual Mode Life Cycle test profile (defined in Revision 3) is necessarily an instance of this cycling mode, because it uses a combination of charge-negative and charge-positive pulse profiles to cycle the device over much of its available DOD range. However, as presently defined, most of the SOC variation is done using fixed profile values, and the return to the starting (target) SOC/DOD is accommodated during a final clamp voltage interval. The preferred control strategy for doing this is described in Section 3.10.3 of the manual. This section of this appendix applies only to Power Assist life cycling.*

[6] *Typically, the “ramp down” portion of this procedure should be designed to require more than 50% of the major interval, but no more than 90%, depending on the precision of the test channel used. The intent of this guideline is to ensure that the full SOC swing will be experienced during every major interval, while also assuring that the device SOC is being varied during most of the interval. This means it should reach the minimum SOC every time but should not spend most of the test time at that state.*

1. Establishing the initial (maximum) target SOC
2. Decreasing the SOC in a controlled fashion to the minimum target value
3. Maintaining the SOC at the minimum target value for a period of time
4. Returning the SOC to the maximum target value

(a) For practical purposes, establishing the initial maximum target SOC is done in the same way as for fixed SOC life cycling, and the OSPS test can be used to verify that this is done within acceptable tolerances.

(b) Decreasing the SOC to the minimum target value is done by altering the discharge step of the test profile (by increasing either its magnitude or its duration) such that the overall profile is charge-negative. (Changing the magnitude has the advantage of maintaining the overall profile length, which simplifies timing calculations.) The amount of charge decrease per profile is calculated as follows:

Δ charge = (total charge swing needed) $\div$ [(time required) $*$ (no. profiles per unit time)] .

For example, if the target charge swing is 20% DOD[7] *for a 300-Wh battery ~~ 60 Wh = 216,000 W-s, the time interval is 10 hours, and the 25-Wh Power Assist life-cycle test profile (length 72-s) is used,*

Δ charge = 216,000 W-s $\div$ (10 hr $*$ 50 profiles/hr) = 432 W-s per profile

If this profile is being used at the full-scale Power Assist values (see Table 6), the discharge step is nominally 10 kW for 9 s. In this example, the value will need to be reduced to 9.952 kW for the net charge balance of each profile to be decreased by 432 W-s.

As described, this is an open-loop process. The SOC reached at the end of the predetermined time interval may vary slightly from the target value, depending on the accuracy and precision of the test channel used and the relative times involved. Longer time intervals or smaller SOC swings will increase the required accuracy. Improved accuracy can be reached by implementing a lower limit (based on voltage conditions) at the minimum target SOC. (See item c following.)

(c) Maintaining the SOC at the minimum target value is done by reverting to charge-neutral cycling at this point. The most reliable way to accomplish this is to know (on the basis of a previously performed OSPS at the minimum SOC) what control voltage is needed to accomplish this using the same scheme as for fixed SOC cycling. If this approach is used, tasks (b) and (c) can possibly be accomplished by a single profile, i.e., the nominal profile is charge-negative by the appropriate amount for the “ramp down” (Step b), and the profile discharge step is terminated early by a control voltage to restore charge-neutral behavior when the minimum SOC is reached.

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[7] *The calculation shown assumes that DOD and energy removed are related linearly. In general this is not exactly true, but it is likely to be adequately accurate for the intended purpose. A more exact calculation would use ampere-hours but would then have to take into account the voltage variation over the DOD range; in practice this adjustment is likely to be iterative in any event.*

(d) If the number of profiles to be performed before step (d) is small (i.e., the "ramp down" time consumes almost all the time interval), a simpler alternative is to switch to a profile that is nominally charge-neutral at this point. Because of charge/discharge inefficiencies, the SOC will drift somewhat over time. However, step (d) will return the SOC to a known value, so the error experienced here is not cumulative and it may be small.

(e) Returning the SOC to the maximum target value is done by charging the device at a C/1 constant current rate (or a corresponding constant power rate) until the device voltage reaches the (value of) OCV for the target SOC. The voltage is then clamped at the target value, with charge current limited to a C/1 rate, until the current tapers to a low value. At this point, the "ramp down" cycling process can resume, and the entire process is repeated for the requisite cycling interval, e.g., 28 days. Note that the time required to perform this step is not fixed but should be relatively constant over life. It may be acceptable to omit the current taper period and simply resume cycling when a target voltage is reached at the C/1 rate, though the SOC reached will suffer some variability as the battery resistance increases over life. (This can be minimized by periodically adjusting the target voltage.)

ADDITIONAL CONSIDERATIONS

It is strongly recommended that the control approach(es) selected to implement a life-cycle regime should be verified by test before long-term cycling begins. The OSPS is intended to accomplish this for fixed SOC cycling, and it can be repeated as needed (as often as the beginning of every cycling interval) without excessive effort. Variable SOC cycling is necessarily more complex, and more dependent on the precision and accuracy of test channels; so experimental verification is critical to obtaining and maintaining the desired SOC accuracy.

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.

Appendix D

HPPC Data Analysis Procedure

Appendix D Contents

1. INTRODUCTION

The Hybrid Pulse Power Characterization (HPPC) Procedure provides the basis for almost all PNGV power and energy related test results. The Test Procedures section of the PNGV Battery Test Manual describes how to conduct the HPPC test, and the Analysis and Reporting section describes how to perform the calculations that yield the commonly reported results. The purposes of this appendix are (a) to summarize the normal analytical process applied to HPPC test data, and (b) to describe the use of several analytical tools that have been developed to assist this process as well as for other analysis purposes. A theoretical derivation for each of these analytical tools was done, and these are provided as separate reports (not part of this appendix.) All these tools were originally developed by Harold Haskins of the Ford Motor Company, and some have uses for PNGV analysis which extend beyond the scope of this document.

2. HPPC DATA ANALYSIS PROCESS

An understanding of the overall HPPC data analysis process is needed to place the various analysis tools in context. The following outline describes the typical analysis efforts that are applied to HPPC test data; it is not all-inclusive, because HPPC data can be applied for a wide variety of purposes which are not directly the subject of this manual. A generic flow chart of this data analysis process is illustrated as Figure D-1. (Refer to the Glossary in the manual for more explanation of some terms and acronyms used here.)

a. The analysis process begins with the raw data recorded from an HPPC test, which consists of time records of voltage, current , accumulated ampere-hours, and accumulated energy. (Other parameters are typically included in this data, but these are not used specifically in the analysis described here.) For a “normal” test, this data is recorded on a second-by-second basis for each of nine pulse profiles at 10% DOD intervals, starting at 10% DOD. A data file also includes data during the rest intervals and the constant current discharge intervals, although these may be at longer time intervals.

b. For each of the 9 pulse profiles (i.e. at each of the 9 DOD values from 10 to 90%), the open circuit voltage (OCV) is measured as the rest voltage immediately before the start of the pulse profile. The pulse resistances for both discharge and regen conditions are calculated using the equations in Section 4.3.2; and the corresponding pulse power capabilities are calculated as in Section 4.3.3 of the test manual. Plots of these calculated values versus DOD are the most basic results generated from HPPC data. Note that all calculations are performed separately for Power Assist operation or Dual Mode operation, i.e., a device which is targeted for both modes requires this process to be performed twice using the same data set.

c. The data from a corresponding C/1 constant current discharge (for Power Assist) or a 6 kW constant power discharge (for Dual Mode) is used to establish the relationship between battery DOD and discharge energy removed during a test.

d. From the results of (b) and (c), the relationship between HPPC power capability and discharge energy (during the applicable energy test) is established by equating the corresponding DOD values during the 2 tests. This relationship will allow both energy and power capability to be compared to the PNGV goals for the applicable operating mode.

e. If this is the initial Low Current HPPC data set for a given device under test, a number of one-time calculations are required to verify or establish various conditions required for further testing. *If not, skip to step [h].*

f. *(Initial Low Current HPPC Test Only)* The HPPC test is conducted at a specified fraction of the manufacturer's Maximum Rated Current I_{max}. If this rating is not available, the first HPPC test will have been performed at an arbitrary constant current, and the value of Imax to be used for all further testing will be calculated as required in Section 3.3.2. If the rating is supplied by the manufacturer, this calculation will still be performed so that the result can be compared for 'reasonableness' to the manufacturer's rating. In either case, I_{max} must be compared to the PNGV maximum allowable current of 217A. This comparison will be done by applying the Extended Simplified Model (ESM) as described in Section 5 of this appendix to estimate the desired cell capacity, and then by scaling I_{max} by the ratio of the desired and rated capacities.[1]

g. *(Initial Low Current HPPC Test Only)* The Battery Size Factor (BSF) for a device is provided by the manufacturer for scaling all PNGV test results. If it is not provided, it is calculated from the initial HPPC test results as described in Section 4.3.9. In either case, the resulting BSF value must be verified as acceptable with respect to efficiency and operating voltage swing. This can be done by actual test, but it can also be done analytically from these initial results. The analytical approach is a two-step process:

Step 1: The Battery Parameter Estimator (BPE) described in Section 3 of this document is used to calculate the best estimate values for a five-component lumped parameter model, where the value of each component is treated as a function of DOD.

Step 2: The BPE component values are provided as inputs to the Cycle Life Efficiency Model (CLEM) described in Section 5 of this document, along with certain device characteristics and system power requirements. The Battery Size Factor is used along with the applicable Efficiency Test Profile (for either Power Assist or Dual Mode operation) to estimate round trip efficiency and the minimum-to-maximum voltage ratio. For the BSF calculated from data, this is done by removing the beginning-of-life 30% power margin prior to calculating efficiency. For a manufacturer-supplied BSF, it is done by determining (with the CLEM) the minimum number of cells (or modules) that yields projected efficiencies and voltage ratios within the PNGV targets, and then calculating the implied power and energy margins included in the manufacturer-supplied BSF. If these margins are very small, the supplied BSF may need to be increased.

h. The power and energy capabilities determined in [d] are scaled by the BSF, and values are determined for Available Energy, power margin and energy margin according to Sections 4.3.4 and 4.3.5.

i. If a Cold Cranking Test is required to be performed following the HPPC test, the DOD where the test is to be done is calculated from the results of [b] and [d] as described in Section 4.3.6.

This analysis process allows the results of a given HPPC test to be compared to the PNGV goals for energy and power. It also allows beginning-of-life results to be used for verifying the reasonableness of the established maximum rated current and Battery Size Factor.

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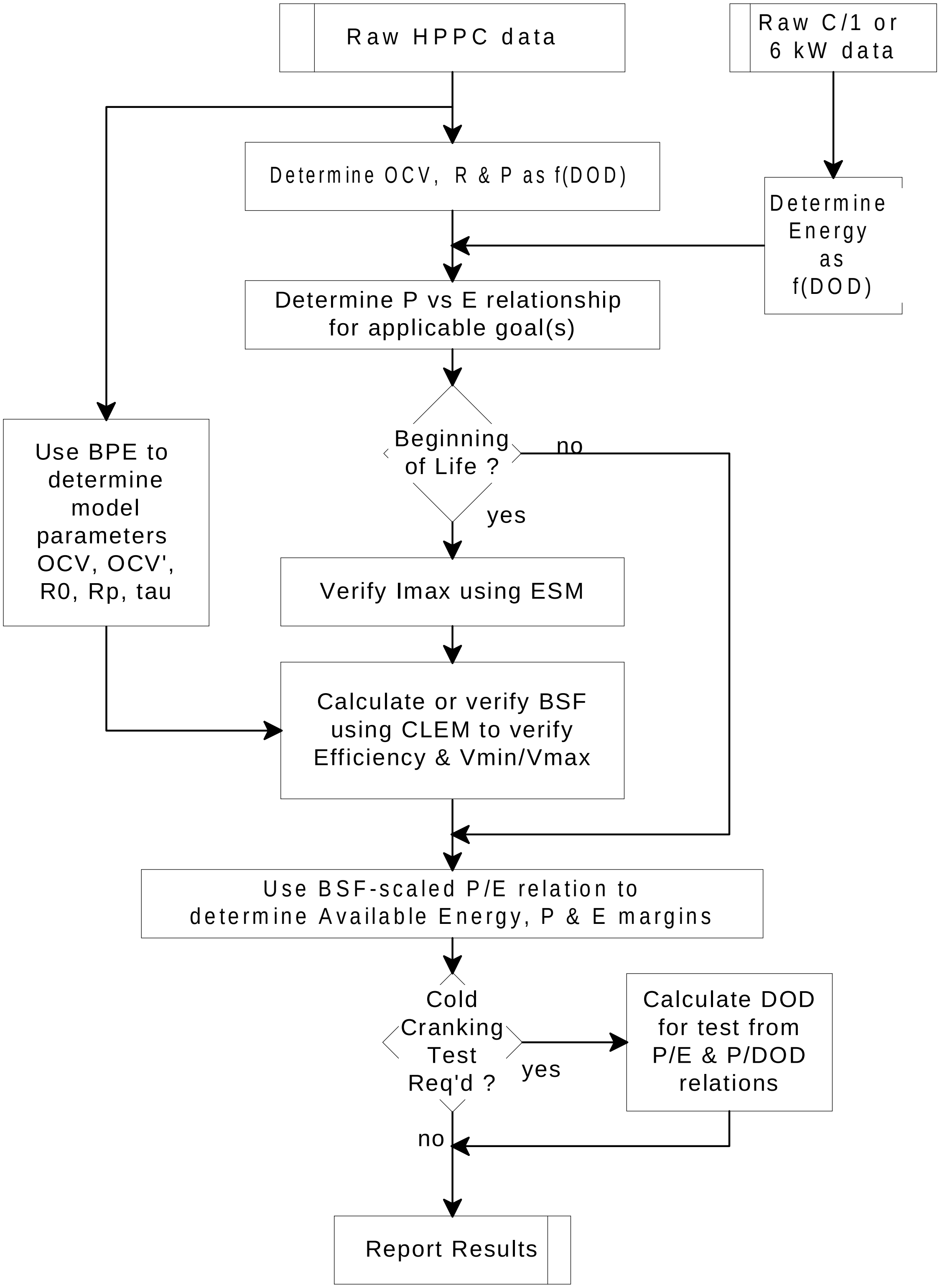
[1] See the note at the end of Section 3.3.2 of the manual for further information.

Figure D-1. HPPC Data Analysis Process



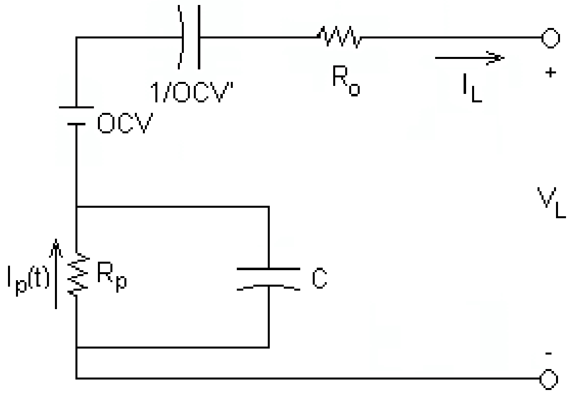
3. BATTERY PARAMETER ESTIMATOR

3.1 Lumped Parameter Battery Model

This section describes the simple PNGV linear battery model and describes the use of an EXCEL-based parameter estimation procedure based on HPPC data. The parameter values calculated for this simple model predict the battery terminal voltage under pulse conditions and can be used for battery system modeling or other analytical purposes. In this testing manual, only the use of these parameters as inputs to the Cycle Life Efficiency Model is further discussed. The analytical basis for the procedure is described in the report[2] accompanying this testing manual.

A battery is a complex non-linear electrochemical energy storage device. A model that attempts to describe all facets of its performance over its entire life and over any energy storage cycle will contain parameters that are difficult or impossible to estimate from available test data. The approach taken with the PNGV simple model is to linearize battery behavior at a given point in life based on a repeatable test cycle, in this case the Hybrid Pulse Power Characterization test. The characteristics determined for this model are not expected to be constant over life or with all possible energy storage cycles. The PNGV lumped parameter model is shown in figure D-2.

Figure D-2. PNGV linearized battery model



The parameters of the model are:

OCV	An ideal voltage source that represents "open circuit" battery voltage
R_O	Battery internal "ohmic" resistance
R_P	Battery internal "polarization" resistance (e.g., due to concentration gradients)
C	Shunt capacitance around R_P
τ	Polarization time constant, $\tau = R_P C$
I_L	Battery load current
I_P	Current through polarization resistance
V_L	Battery terminal voltage

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[2] See file "Battery Model Parameter Estimation From HPPC Tests.PDF"

$\frac{1}{OCV'}$ A capacitance that accounts for the variation in open circuit voltage with the time integral of load current I_L . OCV' is not usually equal to the slope of V_L measured open circuit vs. battery state of charge.

The model is a linear lumped parameter equivalent circuit that attempts to predict the battery terminal voltage V_L for HPPC pulse load conditions. The following circuit equation describes the relation for V_L .[3]

$$V_L = OCV - OCV'[\int I_L dt] - R_O[I_L] - R_P[I_P] \tag{1}$$

3.2 Use of the Battery Parameter Estimator Spreadsheet

3.2.1 Background

The intent of this procedure is to estimate values for the lumped parameter battery model components $\mathbf{OCV_0}$, **OCV'**, $\mathbf{R_o}$, $\mathbf{R_p}$ and $\boldsymbol{\tau}$ using a HPPC data file. This is done by performing a multiple linear regression on test data to obtain these parameters in Equation (1), assuming that the parameters are constant (or nearly so) at a given state of charge. Since the HPPC test repeats a pulse profile at several fixed depth-of-discharge values, where each profile is preceded by a one-hour rest, each pulse profile is used as an independent data set to estimate the parameters at that DOD value.[4] The regression process is most conveniently done using an Excel spreadsheet. A working example of this spreadsheet[5] is provided with this manual, and an accompanying PowerPoint presentation[6] gives a step-by-step illustration of its use.

The spreadsheet uses Excel's LINEST function to perform the regression on the data sets. LINEST is an array function which assumes a relationship of the form $y = m_1 x_1 + m_2 x_2 + m_3 x_3 + \ldots b$, where x_1, x_2, $x_3\ldots$ are linear arrays. In this case there are three independent variables: the load current $\mathbf{I_L}$, the time integral of this current $\boldsymbol{\Sigma (I_L \Delta t)}$, and the polarization current $\mathbf{I_p}$. The resulting load voltage $\mathbf{V_L}$ is the dependent variable.

The file of measured data will provide the load current and corresponding load voltage at discrete points in time throughout the load profile.[7] A typical test data file will also contain columns for a

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[3] Note that the sign associated with *OCV'* in equation (1) is negative, in keeping with its identification as a physical capacitance. The corresponding equation in the next section uses a (+) sign instead, because the original spreadsheet was written this way; it thus calculates a negative value for *OCV'*.

[4] See Section 3.3.2 for a detailed description of the HPPC test sequence and pulse profile.

[5] See file "BatteryParameterEstimatorSpreadsheet.XLS"

[6] See file "How_To_Use_The_BPE_Spreadsheet.PPT"

[7] For this analysis to be successful, there must be a negligible time lag between corresponding measurements of current and voltage. This is most important for data obtained during rapid changes in the load, e.g., at step transitions from one power level to the next level. If it appears that the time lag is not negligible for any particular current-voltage pair, it will be necessary to edit out those data from the file used for the regression. The approach used to do this will be described later.

number of other variables, including the type of operation (e,g,, C=charge, D= discharge, R=rest) for the present test step. These data may generally be ignored in performing the regression analysis. The one exception is when the load current is unsigned; then the operation code must be used to establish the sign of the load current (positive for discharge, negative for recharge).

The polarization current is not directly measured and will be calculated using a series approximation derived from Equation (2).[8] This calculation will be dependent on τ, the RC time constant of the equivalent polarization circuit, which is also not known. The regression procedure uses manual iteration with assumed values for τ in order to determine a best estimate for its value.

3.2.2 Spreadsheet parameters and relationships

The following parameters are used in edited data columns in the order shown. (The numbers shown for these parameters are relative column values used in this appendix for reference, not the actual spreadsheet data column numbers.)

1. Time, $\mathbf{t_i}$, in seconds from the start of the profile under analysis (e.g., from the start of a 60-second HPPC profile)

2. Current, $\mathbf{I_{L,i}}$, in amperes, transferred from the tabulated test data, but with the sign convention of positive on discharge and negative on charge.

3. Polarization current, $\mathbf{I_p}$, in amperes, calculated using the following formula:

$$\begin{aligned} \mathbf{I_{p,i}} &= \{ 1 - [1 - \exp(-\Delta t/\tau)] / (\Delta t/\tau) \} \times \mathbf{I_{L,i}} \\ &\quad + \{ [1 - \exp(-\Delta t/\tau)] / (\Delta t/\tau) - \exp(-\Delta t/\tau) \} \times \mathbf{I_{L,i-1}} \\ &\quad + \{ \exp(-\Delta t/\tau) \} \times \mathbf{I_{p,i-1}} \end{aligned} \tag{2}$$

   where the time increment between data points is: $\Delta t = t_i - t_{i-1}$
   and where the polarization time-constant, τ, has been entered in a cell as specified below. Note that the polarization current should be set to an initial condition corresponding to time = zero. This initial value should be zero for the first profile in the overall discharge cycle (assuming a reasonable rest interval prior to the start of discharge). Thereafter, the value should be set to the value obtained at the end of the previous profile, including the final rest period.[9]

4. Integral of the current with respect to time, $(\Sigma I_L \Delta t)_i$ in amp-seconds, set equal to zero at time = zero. The following formula is recommended:

$$(\Sigma I_L \Delta t)_i = (\Sigma I_L \Delta t)_{i-1} + (I_{L,i} + I_{L,i-1}) \times (t_i - t_{i-1}) / 2 \tag{3}$$

5. Voltage, $\mathbf{V_{L,i}}$ in volts, transferred from the tabulated test data.

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[8] Equation (2) is a recursive approximation derived from the differential equation describing the polarization current behavior, $dI_p/dt = (I_L - I_p) / \tau$. The derivation of this approximation is provided in the report "Battery Model Parameter Estimation From HPPC Tests"accompanying this testing manual.

[9] In practice this value is assumed to be zero because of the one-hour rest period before each of the pulse profiles, which is very long compared to battery time constants of interest.

6. Estimated voltage, $\underline{\mathbf{V}}_{L,i}$ calculated using the coefficients from the linear regression function, LINEST, as noted below:

$$\underline{\mathbf{V}}_{L,i} = \mathbf{OCV_0} + \mathbf{OCV'} \times (\Sigma I_L \Delta t)_i - I_{L,i} \times R_o - I_{p,i} \times R_p \qquad (4)$$

7. Voltage error, ΔV, calculated using the following formula:

$$\Delta V = \underline{\mathbf{V}}_{L,i} - V_{L,i} \qquad (5)$$ [10]

3.2.3 Spreadsheet Procedure

Using the example spreadsheet provided with this manual (or a similar one built using the information in the previous section), the following procedure should be followed to calculate values for the model components at each DOD value:

a. Paste the measured data values for time, current and voltage into the appropriate columns

b. Verify that the LINEST array is defined to calculate using data columns 2 through 5 in the preceding section (2 through 4 for X values, 5 for the Y value) for the entire duration of the HPPC pulse profile, and that LINEST logical variables CONST and STATS are set to TRUE.[11]

c. Enter an estimate of the time constant **τ** (this is typically in the range of a few seconds)

d. Review the LINEST results, which are shown in an array as illustrated in Figure D-3.

Figure D-3. Format of LINEST results

Column 9	Column 10	Column 11	Column 12
OCV'	$\mathbf{R_p}$	$\mathbf{R_o}$	$\mathbf{OCV_0}$
Estimated standard errors in the above four parameters			
$\mathbf{r^2}$	Standard error in $\mathbf{V_L}$	(Not used)	(Not used)
F-statistic	Number of degrees of freedom	(Not used)	(Not used)
Sum-of-squares for the regression	Sum-of-squares for the residual	(Not used)	(Not used)

e. Optimize the linear regression of the data to get the best estimates of $\mathbf{OCV_0}$, $\mathbf{R_o}$, $\mathbf{R_p}$ and **OCV'** by varying the value of the time constant **τ** and noting the response in either the $\mathbf{r^2}$ cell or

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[10] It may be more convenient to multiply this formula by a factor of 1000 to express the voltage error in millivolts.

[11] Note that array functions in EXCEL are entered by simultaneously pressing the *Ctrl*, *Shift*, and *Enter* keys, with the full results array selected (highlighted).

the residual sum-of-squares cell. The desired value of $\boldsymbol{\tau}$ is that which maximizes $\mathbf{r^2}$ and minimizes the residual sum-of-squares (the two criteria are equivalent).

f. If a value of $\mathbf{r^2}$ >0.995 cannot be achieved by varying the time constant, check the column containing the voltage errors to see if the lack of agreement is due to just a few “noisy” data.[12] If necessary, edit out these “noisy” data from the regression by replacing their measured values (in column 5) with a reference to the corresponding estimated value (in column 6). Since this will introduce circular references into the spreadsheet, EXCEL must be in the "Iterative" mode of calculation, selected from the menu using "Tools/Options/Calculation". The residual voltage error is thus forced to zero, and the datum has no impact on the regression.

g. Note the improvement in $\mathbf{r^2}$ after the editing in step (f) is completed, and continue editing until the $\mathbf{r^2}$ criteria is met, or until the remaining data all exhibit the same magnitude of error.

h. Record the values of $\mathbf{OCV_0}$, **OCV’**, $\mathbf{R_o}$, $\mathbf{R_p}$ and $\boldsymbol{\tau}$ and the corresponding DOD value, by transferring them to a tabular array using the "Copy/Paste Special/Values" sequence.

i. Repeat steps (a) through (h) for additional pulse profiles at other DOD values as required. Data for the next DOD can be overlaid into the raw data columns without the need for setting up another regression file. (Both the LINEST array and the voltage comparison chart bounds will need to be re-defined if a new data set contains a different number of data points.)

The final result of the regression procedure is a table of regression coefficients with DOD (or SOC) as the independent variable.

4. CYCLE LIFE EFFICIENCY CALCULATION

4.1 Background

The PNGV program defines a number of goals for battery performance over life. (See Table 1 in the body of this manual.) Power and energy capability are evaluated using the HPPC test, while round-trip efficiency and cycle life are evaluated using special pulse profile tests for either Power Assist or Dual Mode operation. Limits are also placed on the allowable voltages during pulse conditions. The inter-relation of these goals and limits and the corresponding test conditions used for their evaluation is complex and does not lend itself to a simple step-by-step calculation procedure. A Cycle Life Efficiency Model (CLEM) spreadsheet has been developed for certain elements of this evaluation, and a working sample[13] of this spreadsheet is included with this manual. The derivation of the model is also described in the reports[14] accompanying this testing manual. In general it uses the same lumped parameter circuit model previously described, although for some calculations this is simplified.

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[12] This can be done by visual inspection of the calculated voltage error values, but it is more convenient to use charts showing (a) the voltage error vs time, and (b) the measured voltages (as discrete points in time) and the estimated voltages (as a continuous trace in time) to visually check the agreement between the two.

[13] See file “CycleLifeEfficiencyModelSpreadsheet.XLS”.

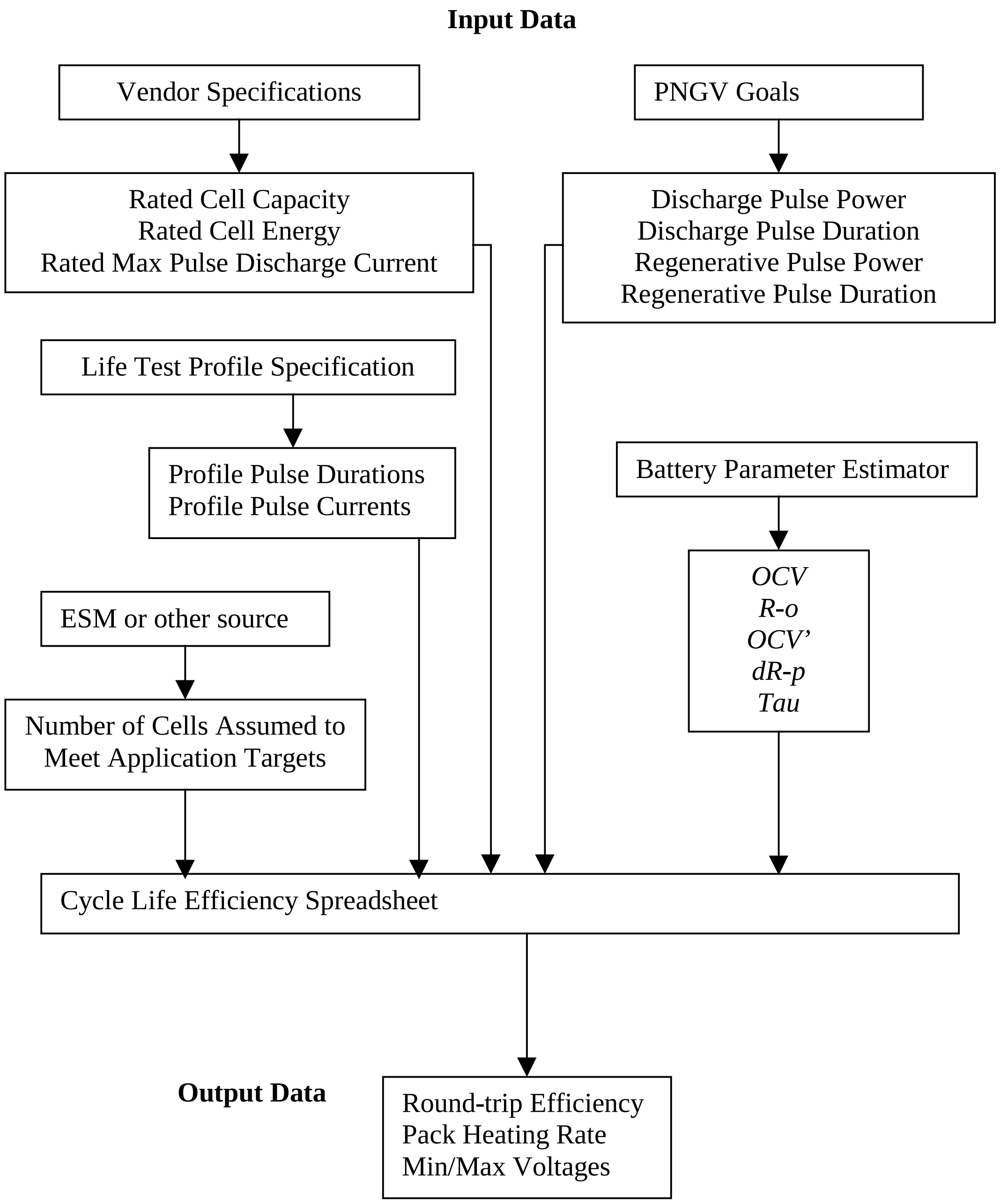
[14] See the files “Basis_For_Cycle_Life_Efficiency_Model.PDF” and “AverageHeatingRateForSteadyStatePulseProfile.PDF”

The fundamental purpose of this spreadsheet is to calculate round-trip efficiency and some related values for a continuously-executed pulse profile (life cycle/efficiency test) based on certain vendor specifications, PNGV goals and HPPC test results. For purposes of this testing manual, it is used to determine the reasonableness of the Battery Size Factor (BSF) for a device under test, by calculating round-trip efficiency for a given life-cycle/efficiency test profile and target SOC. Some other uses for the model/spreadsheet are discussed briefly in a later section.

4.2 Use of the CLEM Spreadsheet

Figure D-4 gives a visual representation of the input and output variables for the spreadsheet.

Figure D-4: Inputs and Output for CLEM Spreadsheet



4.2.1 Spreadsheet Variables

The labels used in the Excel spreadsheet often differ from the terminology and variable names used in the later equations, so their correspondences (in the order that the variables are used) are given below. For a more in-depth description of these variables and the derivations of their equations see the report referenced in Section 4.1 of this appendix. Figure D-5 illustrates the efficiency spreadsheet with some example values. Highlighted and lettered blocks organize the cells so that they are easier to describe.

Figure D-5. Cycle Life Efficiency Calculation Spreadsheet

CALCULATION OF CYCLE-LIFE PROFILE EFFICIENCY vs. V-min/V-max VOLTAGE RATIO

Reference hardware test for basic data: Generic cell data

A	Rated cell capacity (Ah, at C/1):	6.25
	Rated cell energy (Wh, at C/1):	21.9
	Rated max pulse discharge current (A):	125

	Application data:	PNGV Pwr Asst
C	Discharge pulse power (kW, at EOL) =	25
	Discharge pulse durations (sec) =	18
	Regenerative pulse power (kW, at EOL) =	30
	Regenerative pulse duration (sec) =	10

	Cell basic data:	@SOC-max	@SOC-cycle	@SOC-min
B	SOC = State-of-charge (%)	80	55	30
	OCV = Open-circuit voltage (V)	3.78	3.78	3.78
	R-o = Ohmic resistance (mohm)	4	4	4
	OCV' = dOCV/dAH (mohm/sec)	-0.032	-0.032	-0.032
	dR-p = Pol. resistance increment (mohm)	3.20	3.20	3.20
	Tau = Pol. time constant (sec)	10	10	10

D	# of cells assumed to meet appl. targets =	72
	Discharge pulse resistance (mohm) =	7.25
	Regenerative pulse resistance (mohm) =	6.34
	Minimum operating voltage (V) =	2.918
	Maximum operating voltage (V) =	4.383
G	V-min/V-max ratio =	0.666

Cycle-Life Profile Data (Const. Curr.) 25-Wh Efficiency & Cycle Life Profile

	Pulse type:	Discharge	Rest	Regen-1	Regen-2	Regen-3	Rechg
E	Pulse duration (sec):	9	27	2	4	4	26
	Pulse discharge current (A)	38.75	0	-55.3	-38.4	-21.2	0.01
	(	31%	of max rated)				
I	Cumulative duration (sec):	9	36	38	42	46	72
	Cumulative discharge (A-sec):	348.75	348.75	238.15	84.55	-0.25	0
	Pol. curr. @ start of pulse (A):	-1.4	22.4	1.5	-8.8	-18.6	-19.4
	App. OCV @ start of pulse (V):	272.5	267.0	271.8	274.2	276.4	276.6
	R @ start of pulse (mohm):	288	288	288	288	288	288
	Voltage @ start of pulse (V):	261.3	267.0	287.7	285.2	282.5	276.6
	Average voltage over pulse (V):	257.8	270.4	289.1	286.6	282.7	273.7
	Voltage @ end of pulse (V):	255.0	271.8	290.4	287.8	282.9	272.5
F	Average dischg pulse power (kW):	10.0	0.0	-16.0	-11.0	-6.0	0.0
	Pulse dischg energy (kW-sec):	89.9	0.0	-32.0	-44.0	-24.0	0.1
	Pulse dischg energy (Wh):	25.0	0.0	-8.9	-12.2	-6.7	0.0

Profile summary data:							
	dSOC (%) =	1.55	P-dis/P-goal =	0.40	**H**	Round-trip Eff. (%) =	90.0
	P-r/P-d =	1.60	Pack heating rate (W) =	139		Est. D/T eff. (%) =	105.5

4.2.1.1 Inputs

Vendor Specifications (Block A):

C_{RATED} = Rated cell capacity (C/1 capacity for a single cell, Ah)

E_{RATED} = Rated cell energy (C/1 energy for a single cell, Wh)

$I_{MAX,RATED}$ = Rated max pulse discharge current (maximum allowable current, A)

Battery HPPC Performance Data from Appendix D (Block B):

OCV = OCV (open circuit voltage, volts per cell)

R_O = R-o (ohmic resistance, mohms per cell)

OCV' = OCV’ (variation in OCV due to changing current, mohms/sec per cell)

R_P = dR-p (incremental change in polarization resistance, mohms per cell)

τ = Tau (time constant, sec)

PNGV Application Requirements (Block C):

P_{LDis} = Discharge Pulse Power (total battery discharge power, kW)

t_{Dis} = Discharge Pulse Duration (time elapsed during the discharge pulse, sec)

$P_{L\,\mathrm{Re}\,gen}$ = Regenerative Pulse Power (total battery regenerative power, kW)

$t_{\mathrm{Re}\,gen}$ = Regenerative Pulse Duration (time elapsed during the three regen pulses, sec)

PNGV Life Cycle Application Specification (Block E):

Δt_i = Pulse duration (time elapsed during each step, sec)

Note: Δt_1 corresponds to the discharge step, Δt_2 to the rest, etc.

I_i = Pulse discharge current (required current for each step, A)

Block D (ESM or other source):

N = # of cells assumed to meet application targets

4.2.1.2 Calculated Values and Outputs

Block G:

R_{LDis} = Discharge Pulse Resistance (cell resistance seen by load during discharge, mohm)

$R_{L\,\mathrm{Re}\,gen}$ = Regenerative Pulse Resistance (cell resistance seen by load during recharge, mohm)

V_{LDis} = Minimum operating voltage (V)

$V_{L\,\mathrm{Re}\,gen}$ = Maximum operating voltage (V)

$V_{\min}/V_{\max}$ = Vmin / Vmax ratio

Block I:

T_i = Cumulative Duration of Pulse (running total of time elapsed during pulse, sec)

T = Total Duration of Pulse (time elapsed during entire pulse, sec)

$A\text{-}s_i$ = Cumulative Discharge (running total of amp-seconds discharged, A-sec)

I_{P0} = Polarization Current @ start of pulse (polarization current at beginning of discharge step, A)

I_{Pi} = Polarization Current @ start of pulse (polarization at the beginning of each step after discharge, A)

OCV_{APP} = App. OCV @ start of pulse (OCV less voltage across R_p, V)

R_i = R @ start of pulse (total battery ohmic resistance, milliohms)

V_i = Voltage @ start of pulse (voltage at the beginning of each step, V)

$\overline{V_i}$ = Average voltage over pulse (average voltage over each step, V)

$V_i\left(t = \Delta t_i^-\right)$ = Voltage @ end of pulse (voltage at the end of each step, V)

Block F:

$\overline{P_i}$ = Average discharge pulse power (average power over each step, kW)

E_i = Pulse discharge energy (energy consumed or released during each step, kW-sec)

Block H:

$dSOC$ = dSOC (change in SOC during discharge pulse, %)

P_r / P_d = P-r/P-d (pulse power of first regen step over pulse power of discharge step)

P_{dis} / P_{goal} = P-dis/P-goal (pulse power of discharge pulse over PNGV discharge power)

$\dot{Q}_{AVG}$ = Pack Heating Rate (W)

η_{RT} = Round trip efficiency

4.2.2 Entering Information into the Spreadsheet

Labels on the items that follow correspond to the marked regions in Figure D-5.

A. The manufacturer's rated cell capacity (C_{RATED}), energy (E_{RATED}) and maximum pulse discharge current ($I_{MAX,RATED}$) are entered as inputs in area A.

B. The five output parameters from the linear regression procedure (**OCV_0, R_o, R_p, OCV'** and **τ**) are entered as inputs in this area for three different states-of-charge: the target SOC for life cycling, and the minimum and maximum SOC values of interest for life cycling.

Selection of the SOC values to be used involves some judgment, because the choices interact with the assumed number of cells and the resulting calculated efficiency and other values. In general the largest acceptable min/max SOC values are the range over which the pulse power capability goal is met for a given operating mode, because operating outside this range would imply a power deficiency. This range may need to be reduced to maintain the min/max voltage ratio within the PNGV limits. The smallest acceptable min/max range is that over which the available energy goal is just met; if voltage limits cannot be met over this range, the number of cells (item D) must necessarily be increased. Note that the min/max values chosen affect only the calculated results for pulse resistance and min/max operating voltage.

C. The system-level power-time requirements for the appropriate set of PNGV goals (P_{LDis}, t_{Dis}, P_{LRegen}, t_{Regen}) are entered as inputs in this area. Figure D-5 uses the Power Assist goal values.

D. The assumed number of cells in a full-size battery (N) is entered as an input in this area. This value may be the Battery Size Factor assigned to a battery, or it may be calculated from the Extended Simplified Model or some other source. This value can be varied to explore the effects of various Battery Size Factors on efficiency and operating voltage ratios. See Section 4.2.4 for an illustration of how this is used.

E. Step durations (Δt_i) and current values (I_i) are entered in this area for the desired pulse profile, which is assumed to consist of a single discharge pulse followed by a rest interval, a three-step regen pulse sequence, and a final recharge step to charge-balance the profile. Note that the calculation process assumes the profile steps have fixed current levels; however, the current values can be manipulated iteratively to produce a desired discharge power or energy level. (The example in Figure D-5 actually illustrates the derivation of the Power Assist 25 Wh Efficiency and Life Cycle Test Profile.)

4.2.3 Results From the Spreadsheet

The other areas highlighted in Figure D-5 are results calculated from the inputs as follows:

F. The calculated average power ($\overline{P_i}$) and energy values (E_i) for each pulse step in the test profile are shown here. As noted under (E) above, specific desired results can be produced by varying the current and/or time values for the profile steps.

G. The calculated minimum discharge voltage (V_{LDis}), maximum regen voltage (V_{LRegen}), and the corresponding voltage ratio (V_{min}/V_{max}) required for execution of the pulse profile under the conditions input are displayed in this area. This can be compared to the maximum allowable PNGV voltage ratios (e.g. 0.55x for Power Assist operation.)

H. The calculated round trip energy efficiency (η_{RT})is displayed here. This can be compared to the appropriate PNGV efficiency goal (e.g. 90% for Power Assist.)

I. Various intermediate results (not described here) are calculated in this section.

4.2.4 Evaluating Battery Size Factor Using the Spreadsheet

Section 4.3.9 of the manual describes the process for calculating a Battery Size Factor when a suitable value is not supplied by the manufacturer. It also notes that the calculated BSF should be verified to be compatible with the PNGV efficiency goals.[15] The spreadsheet and its variables described in the preceding section can be used for this purpose as follows:

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[15] This verification may also be appropriate for Battery Size Factors that are supplied by a manufacturer, as a check on the reasonableness of the supplied value. However, this will require using calculated values as described here and then comparing the results to the manufacturer-supplied value (which includes a probably unknown margin for degradation over life.)

1. Enter the cell ratings in area (A), linear regression results from HPPC data in area (B), and system-level power requirements in area (C). These values will not change during this evaluation, except that the minimum and maximum SOC values should be chosen to agree as closely as practical with the minimum and maximum DOD values (from Section 4.3.6 of the manual) corresponding to the number of cells to be used in (2).

2. From the HPPC data, determine the minimum number of devices that are required to just meet the appropriate PNGV power and energy goals. (This is the value that would be calculated in Section 4.3.9 if the 130% power factor was *not* used.)[16] Enter this value (not the larger Battery Size Factor) as the number of cells in (D).

3. Enter the appropriate system-level Efficiency Test Profile durations and magnitudes in (E). The system voltage will vary with the BSF., so iteration of the current values will be required to yield the appropriate discharge pulse energy and the correspondingly scaled regen energy values. Since the profile is required to be charge-neutral, and the relative regen power and energy levels will vary with battery efficiency, the resulting regen power levels may not be exactly the same as those in the nominal profile.

4. Compare the calculated round-trip efficiency in (H) and min/max voltage ratio in (G) to the appropriate PNGV goals and limits as describe above. If the calculated values are outside the goal values, the BSF. must be increased. A revised multiplier for the Battery Size Factor can be found by increasing the number of cells in (D) until the efficiency and voltage ratio are within the limits. The original BSF. must then be increased by the ratio of this new number of cells to the original number in (2).[17]

4.2.5 Equations Used for CLEM Spreadsheet Calculations

The following description of the equations used in the CLEM spreadsheet is provided for the user who desires to understand specifically what is being calculated. The derivation of these relationships is provided in the reports referenced in Section 4.1 of this appendix. As in previous sections, equations are grouped according to the labeled areas in Figure D-5.

Block G:

With all the data entered, the Excel spreadsheet will automatically find round trip efficiency, but it starts by finding the ratio of Vmin to Vmax. Beginning with Equations 1 and 2, Discharge and Regenerative Pulse Resistance are found for Block G. R_{LDis} will use data corresponding to SOC min data and R_{LRegen} will use SOC max data.

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[16] This reduced number of devices must be used because the PNGV goals (including efficiency) are required to be met at *end-of-life*. The 130% power factor is included in the BSF. to allow for degradation over life, so this factor must be removed for this evaluation done at beginning-of-life.

[17] This rather complicated scaling approach is necessary because the 130% factor built into the BSF. calculation is a multiplier on the minimum power requirements, not on the minimum number of cells. The conceptually simpler method of increasing the system-level power demands by 30% and using the calculated BSF. would also work, but it would require the profile power and energy levels to be increased correspondingly.

$$R_{LDis} = R_0 + OCV' \cdot t_{Dis} + R_P \left(1 - e^{-t_{Dis}/\tau} \right) \tag{1}$$

$$R_{L\,\mathrm{Re}\,gen} = R_0 + OCV' \cdot t_{\mathrm{Re}\,gen} + R_P \left(1 - e^{-t_{\mathrm{Re}\,gen}/\tau} \right) \tag{2}$$

Next, Minimum and Maximum Operating Voltage are calculated with Equations 3 and 4. This time, V_{LDis} uses SOC-min data and V_{LRegen} uses SOC-max data.

$$V_{LDis} = \left[OCV + \left(OCV^2 - \left(4 P_{LDis} R_{LDis} \right) / N \right)^{1/2} \right] / 2 \tag{3}$$

$$V_{LRregen} = \left[OCV + \left(OCV^2 - \left(4 P_{L\,\mathrm{Re}\,gen} R_{L\,\mathrm{Re}\,gen} \right) / N \right)^{1/2} \right] / 2 \tag{4}$$

The final part of Block G calculates the Vmin/Vmax ratio. This is accomplished by simply dividing Minimum by Maximum Operating Voltage as in Equation 5; this ratio is used for comparison with the PNGV operating limits of 0.55x for Power Assist and 0.5x for Dual Mode.

$$V_{\min} / V_{\max} = V_{LDis} / V_{L\,\mathrm{Re}\,gen} \tag{5}$$

Block E:

Block E consists of rows of data corresponding to test profile steps. Pulse Duration and Pulse Discharge Current are constants that correspond to the Cycle-Life profile. Below that is the Cumulative Duration row; it is simply a running total of the pulse durations. Then Cumulative Discharge is a running total of Amp-seconds discharged; they are calculated using Equations 6.

$$\begin{aligned} T_i &= T_{i-1} + \Delta t_i \\ A - s_i &= I_i \cdot \Delta t_i + A - s_{i-1} \end{aligned} \tag{6}$$

Block I:

Block I contains intermediate results calculated for each of the test profile steps that describe the voltage behavior over each step. For Polarization Current there are two equations used; Equation 7 is used to find the current at the beginning of the first step (discharge pulse) of the typical waveform of the periodic test sequence (i.e. when steady-state cycling conditions are reached.)

$$I_{P0} = \left[I_1\left(1-e^{-\Delta t_1/\tau}\right)e^{-(\Delta t_2+\Delta t_3+\Delta t_4+\Delta t_5+\Delta t_6)/\tau} + I_2\left(1-e^{-\Delta t_2/\tau}\right)e^{-(\Delta t_3+\Delta t_4+\Delta t_5+\Delta t_6)/\tau} + I_3\left(1-e^{-\Delta t_3/\tau}\right)e^{-(\Delta t_4+\Delta t_5+\Delta t_6)/\tau} + I_4\left(1-e^{-\Delta t_4/\tau}\right)e^{-(\Delta t_5+\Delta t_6)/\tau} + I_5\left(1-e^{-\Delta t_5/\tau}\right)e^{-(\Delta t_6)/\tau} + I_6\left(1-e^{-\Delta t_6/\tau}\right)\right] \Big/ \left[1-e^{-T/\tau}\right] \qquad (7)$$

Then Equation 8 is used to for the rest and recharge steps, i.e., the remaining pulses of a typical periodic waveform.

$$I_{Pi} = I_i\left(1-e^{-\Delta t_i/\tau}\right) + I_{P0}e^{-\Delta t_i/\tau} \qquad (8)$$

The next row calculates App. OCV (open circuit voltage minus polarization voltage) at the start of each pulse; it is based on Equation 9. For this, values of OCV and dR-p are found under SOC-cycle. (The factor of 1000 in the following equations is because dR-p is expressed in millohoms.)

$$OCV_{APP} = \left(OCV - \left(R_P I_{Pi}\right)/1000\right)\cdot N \qquad (9)$$

Resistance at start of each pulse is calculated by multiplying Ohmic Resistance by Number of Cells; it remains constant across the row.

$$R = R_o \cdot N \qquad (10)$$

Voltage at the start of a pulse is calculated by Equation 11.

$$V_i = OCV_{APP} - \left(I_i \cdot R\right)/1000 \qquad (11)$$

Average voltage over a pulse is calculated by Equation 12.

$$\overline{V_i} =$$

$$\big[OCV - I_{Pi}R_P\frac{\tau}{\Delta t_i}\left(1-e^{-\Delta t_i/\tau}\right) - I_i OCV'\frac{\Delta t_i}{2} - I_i\left(R_0+R_P\right) + R_P I_i\frac{\tau}{\Delta t_i}\left(1-e^{-\Delta t_i/\tau}\right) \qquad (12)$$

Voltage at the end of a pulse is calculated by Equation 13. (Again, the factor of 1000 is necessary because resistance is expressed in milliohms.)

$$V_i\left(t=\Delta t_i^-\right)=$$

$$\left[OCV-\frac{R_o I_i + OCV' I_i \Delta t_i + R_P\left[I_{Pi}e^{-\Delta t_i/\tau}+I_i\left(1-e^{-\Delta t_i/\tau}\right)\right]}{1000}\right]\cdot N \tag{13}$$

Block F:

Block F calculates Average discharge pulse power (14) and Pulse discharge energy (15) for each step in the test profile.

$$\overline{P_i}=\overline{V_i}\cdot I_i \tag{14}$$

$$E_i=\overline{P_i}\cdot\Delta t_i \tag{15}$$

Final Outputs:

dSOC is calculated by Equation 16, Pr/Pd by Equation 17, P-dis/P-goal by Equation 18, Round Trip Efficiency by Equation 19, and finally Pack Heating Rate by Equation 20. (Note that *dSOC* and efficiency η_{RT} are multiplied by 100 to convert the results to percent, and Pack Heating Rate is multiplied by 1000 because $E_{discharge}$ is expressed in kilowatt-seconds.)

$$dSOC=\frac{A-s_i}{C_{RATED}}\cdot 100 \tag{16}$$

$$P_r/P_d=\frac{\overline{P_{Regen1}}}{\overline{P_{Discharge}}} \tag{17}$$

$$P_{dis}/P_{goal}=\frac{\overline{P_{Discharge}}}{P_{LDis}} \tag{18}$$

$$\eta_{RT}=-\frac{E_{Discharge}}{E_{Regen1}+E_{Regen2}+E_{Regen3}+E_{Rechg}}\cdot 100 \tag{19}$$

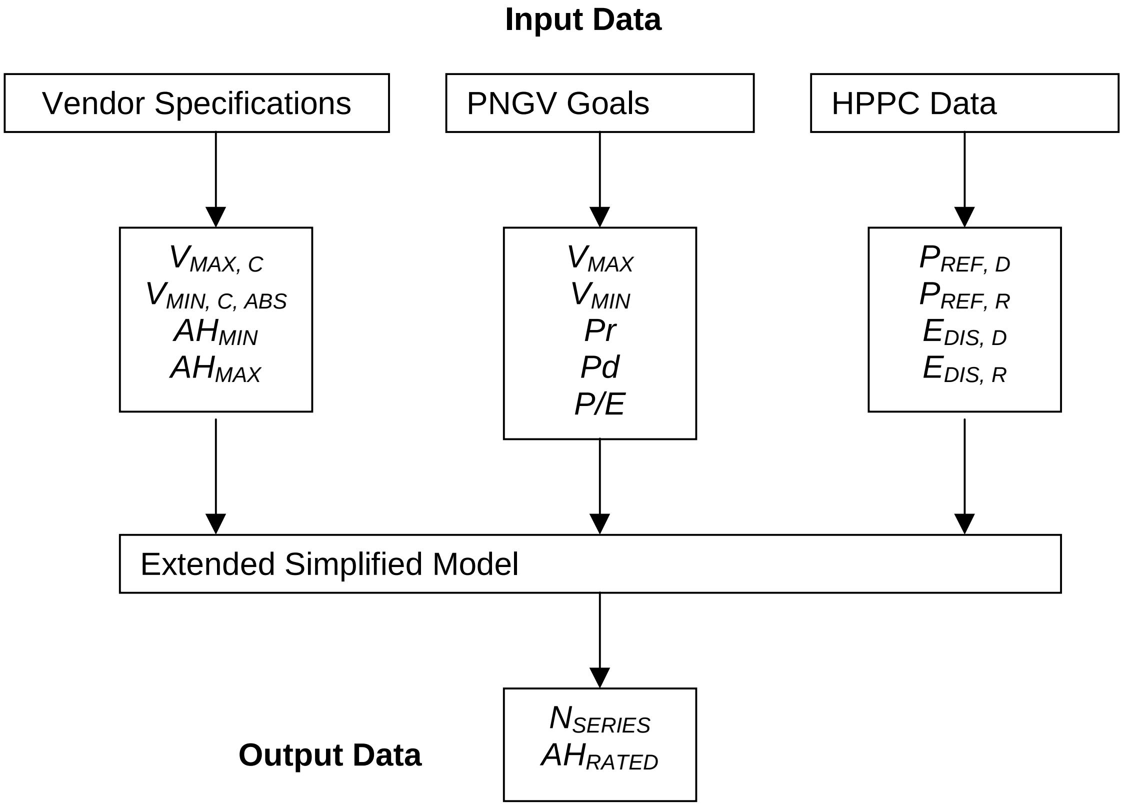
$$\dot{Q}_{AVG}=\frac{E_{Discharge}}{T}\cdot\frac{100-\eta_{RT}}{\eta_{RT}}\cdot 1000 \tag{20}$$

5. EXTENDED SIMPLIFIED MODEL

5.1 Use of the ESM Spreadsheet

A detailed discussion of the basis for the Extended Simplified Model (ESM) is given in a report accompanying this manual.[18] This appendix includes only a description of how to use the ESM and what calculations are performed by the ESM spreadsheet supplied with this testing manual.[19] The user begins by carrying in data from the vendor's specifications, PNGV goals, and HPPC data. Next, the data will be submitted to an Excel spreadsheet to get results. Figure D-6 illustrates what is carried in and out of the ESM spreadsheet.

Figure D-6. Inputs and Outputs for the ESM Spreadsheet



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[18] See file "Extended_Simplified_Model_Explanation.PDF" accompanying this manual.

[19] See file "ESM_Example_Spreadsheet.XLS" provided with this manual. This example spreadsheet has not been organized and labeled as thoroughly as the other examples provided for this manual; some user modification is likely to be required before it can be used as described. In particular, available energy is presently a user-supplied value requiring manual iteration, rather than a directly-calculated result, although the equations necessary to calculate it are present in the spreadsheet.

5.1.1 Input Variables

The Excel implementation is fully automated; all the user has to do is paste in the appropriate data from outside sources:

Vendor Specifications:

$V_{MAX,\,C}$ = maximum allowable cell voltage

$V_{MIN,\,C,\,ABS}$ = absolute minimum allowable cell voltage

AH_{MIN} = rated minimum cell capacity

AH_{MAX} = rated maximum cell capacity

PNGV Specifications:

V_{MAX} = maximum allowable battery voltage

V_{MIN} = minimum allowable battery voltage

Pr = maximum regenerative pulse power

Pd = maximum discharge pulse power

P/E = nominal power/energy ratio required by PNGV

HPPC Data:

$P_{REF,\,D}$ = discharge pulse power data set (same as DPPC)

$P_{REF,\,R}$ = recharge pulse power data set (same as RPPC)

$E_{DIS,\,D}$ = energy discharged from any SOC (measurements taken during HPPC discharge pulses)

$E_{DIS,\,R}$ = energy discharged from any SOC (measurements taken during HPPC recharge pulses)

5.1.2 Values Derived and Variables Used:

$V_{MIN,\,C} = V_{MAX,\,C} \times (V_{MIN}/V_{MAX})$ (minimum allowable cell voltage relative to PNGV requirements)

E = “usable” energy (i.e. energy within the SOC region where a given power can be sustained)

P = independent variable for power

$A_D, B_D, C_D, A_R, B_R, C_R, A_A, B_A, C_A$ =
coefficients from LINEST linear regressions done to obtain a quadratic fit

NC/E = battery sizing parameter (Ah/Wh)

N_{SERIES} = required number of cells in series for a battery

AH_{RATED} = battery rated capacity

5.1.3 Procedure and Equations

The analysis begins by plotting energy with respect to power for both discharge and recharge data. Then the LINEST function is used to assign second order polynomial fits to the data; Equations 1 and 2 represent these quadratic fits.[20]

$$E_{DIS,D} = A_D + B_D \cdot P_{REF,D} + C_D \cdot P_{REF,D}{}^2 \tag{1}$$

$$E_{DIS,R} = A_R + B_R \cdot P_{REF,R} + C_R \cdot P_{REF,R}{}^2 \tag{2}$$

A_D, B_D, C_D, A_R, B_R, and C_R are coefficients of the quadratic equations that LINEST creates.

Using the coefficients for $E_{DIS,\,D}$ and $E_{DIS,\,R}$, Equations 1 and 2 are combined to create an equation for "usable" energy that depends on power:

$$E = A_A + B_A \cdot P + C_A \cdot P^2 \tag{3}$$

A_A = $A_D - A_R$

B_A = $B_D - B_R \times (Pr/Pd)$

C_A = $C_D - C_R \times (Pr/Pd)^2$

By suitable transformations, Equation 3 can be solved for E, divided by cell capacity AH_{REF}, and inverted to give Equation 4, which defines a "normalized battery sizing parameter" NC/E.

---

[20] Note that a second-order polynomial will not necessarily give a high-quality fit to the data. If the "goodness-of-fit" coefficient $\mathbf{r^2}$ for either energy equation (1) or (2) is less than 0.99, the original power and energy data pairs should be reviewed to determine whether values outside the region of interest can be deleted from the curve fit. In particular, values corresponding to powers much beyond the Pulse Power Limit can be ignored, because this region has no usable energy.

$$\frac{NC}{E} = \frac{-2 \cdot C_A \cdot (P/E)^2 \cdot AH_{REF}}{\sqrt{1 - 2 \cdot B_A \cdot (P/E) + \left(B_A{}^2 - 4 \cdot A_A \cdot C_A\right) \cdot (P/E)^2} - \left(1 - B_A \cdot (P/E)\right)} \qquad (4)$$

Comparing $V_{MIN,\,C}$ and $V_{MIN,\,C,\,ABS}$, the spreadsheet uses the more restrictive of the two (i.e., keeps whichever is greater) and calls it $V_{MIN,\,C}$.

Next, an estimate for the number of cells required N_{SERIES} is made using Equation 5; the integer operator is used to force the result to the next larger whole number:

$$N_{SERIES} = INTEGER\{V_{MIN} / V_{MIN,C}\} + 1 \qquad (5)$$

The battery sizing parameter and N_{SERIES} are used to calculate AH_{RATED}:

$$AH_{RATED} = 1000 \cdot (NC/E) \cdot (E_{AVAIL} / N_{SERIES}) \qquad (6)$$

AH_{RATED} is checked to be sure that it falls within the allowable range of capacity values in Equation 7:

$$AH_{MIN} \le AH_{RATED} \le AH_{MAX} \qquad (7)$$

If AH_{RATED} goes out of bounds, it will be set equal to whichever boundary was violated. Now N_{SERIES} can be re-estimated using Equation 8:

$$N_{SERIES} = INTEGER\{1000 \cdot (NC/E) \cdot (E_{AVAIL} / AH_{RATED})\} \qquad (8)$$

If AH_{RATED} was equal to AH_{MAX} , the original N_{SERIES} was too small and it is incremented by 1. As the final step, Equation 6 is repeated to find a new AH_{RATED} using the last estimate for N_{SERIES}:

$$AH_{RATED} = 1000 \cdot (NC/E) \cdot (E_{AVAIL} / N_{SERIES})$$

5.1.4 Output Variables

The results of these calculations are “optimized” values for the number of cells and the needed cell capacity:

N_{SERIES} = required number of cells in series for a battery

AH_{RATED} = battery rated capacity

The present version of this spreadsheet requires available energy E_{AVAIL} to be provided as an input. However, Equation (3) is a direct calculation of “usable” energy as a function of discharge power, and its coefficients are contained on the second sheet of the spreadsheet. If this equation is evaluated at the appropriate PNGV power goal, and the result is scaled by the Battery Size Factor used for testing, the result is in fact Available Energy.

Appendix E

Calculation of Available Energy From HPPC Test Results

Calculation of Available Energy From HPPC Test Results

Section 4.3.5 of this manual describes a means of graphically determining the available energy for a cell or battery using data from an HPPC test. This appendix describes a somewhat more analytical method of making this determination, based on the same results. It should be noted that energy can still be calculated as a function of power for a battery that is not capable of meeting the PNGV goals. However, care should be used in presenting the results of such calculations to avoid misleading interpretations.

The process begins with a validated HPPC data set, from which the standard Pulse Power Capability vs Net Energy Removed plot (Figure 15 in the manual) can be produced.[1] This data is then scaled by the Battery Size Factor to yield results scaled for a full size system as in Figure 16 in the manual. An example of such a plot is reproduced here as Figure E-1.[2]

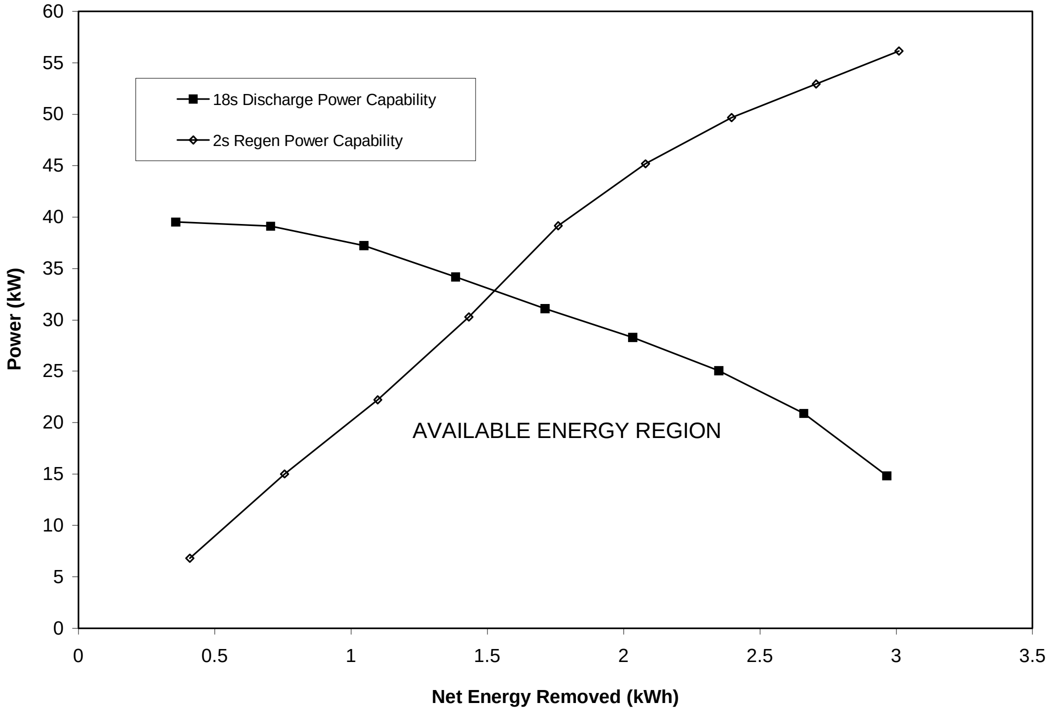

Figure E- 1. Pulse Power Capability Example Results

Since the PNGV discharge and regen pulse power requirements are different, the determination of available energy must account for the ratio of regen to discharge power demand. The graphical method in

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[1] For purposes of this appendix, Power Assist goals will be used, so the "net energy removed" is actually energy from a C/1 discharge. However, the process is exactly the same when Dual Mode goals are used, except that the energy is derived from 6 kW constant power discharge and the Dual Mode power goals are used. Hence the graphs in this appendix are not labeled as to the specific source of the energy data.

[2] This example data is actually derived from a Low Current HPPC test of a small cell, with the results multiplied by 1000 so that graphs can be labeled as kW instead of W and kWh instead of Wh. (This corresponds to using a Battery Size Factor of 1000 on the original cell data.)

the manual does this by using different axis scales to plot the discharge and regen power data. For calculation purposes, this is better done by actually re-scaling the regen power curve in proportion to this ratio. This example is based on the Power Assist minimum pulse power requirements of 25 kW discharge (18s) and 30 kW regen (2s). Figure E-2 illustrates this same data with the regen power re-scaled by dividing by this 30/25 ratio. Note that the effect of this scaling is to reduce the area of the "available energy region", due to the higher regen requirement. Energy values associated with the scaled regen curve and the discharge curve can now be compared at the same power values, since they are both based on the comparable *discharge* power values.

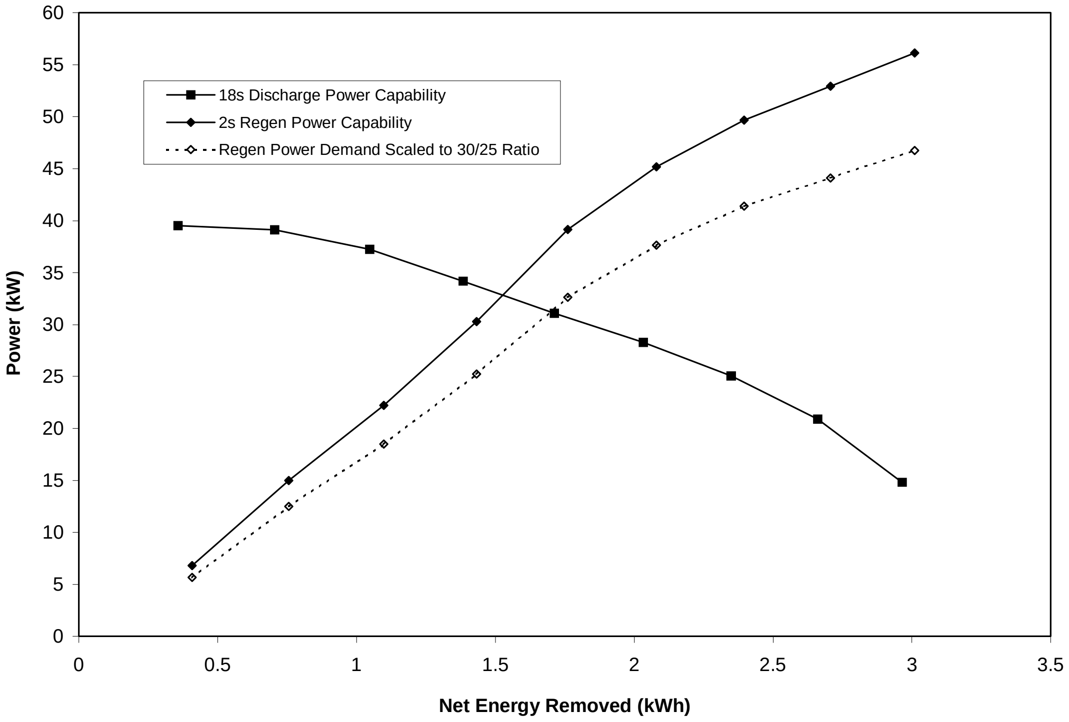

Figure E- 2. Pulse Power Capability Scaled for Regen/Discharge Power Ratio

From this point on, the available energy calculation process uses only the re-scaled regen power values, i.e. all power values are based on *discharge* power. It is possible to fit a curve through these data and use the fitted curves for calculating power vs energy over the range of interest. Figure E-3 shows such a set of curve-fit results.[3]

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[3] The Extended Simplified Model described in Appendix D performs this operation in a different order, by first performing the curve-fits to the original data and then substituting the re-scaled power values in the regen energy calculation. This gives a different result because the resulting scaled/curve-fitted regen curves are not exactly the same. Both results are approximations, and the quality of the curve-fits may have a greater effect on the result than the order of the calculations.

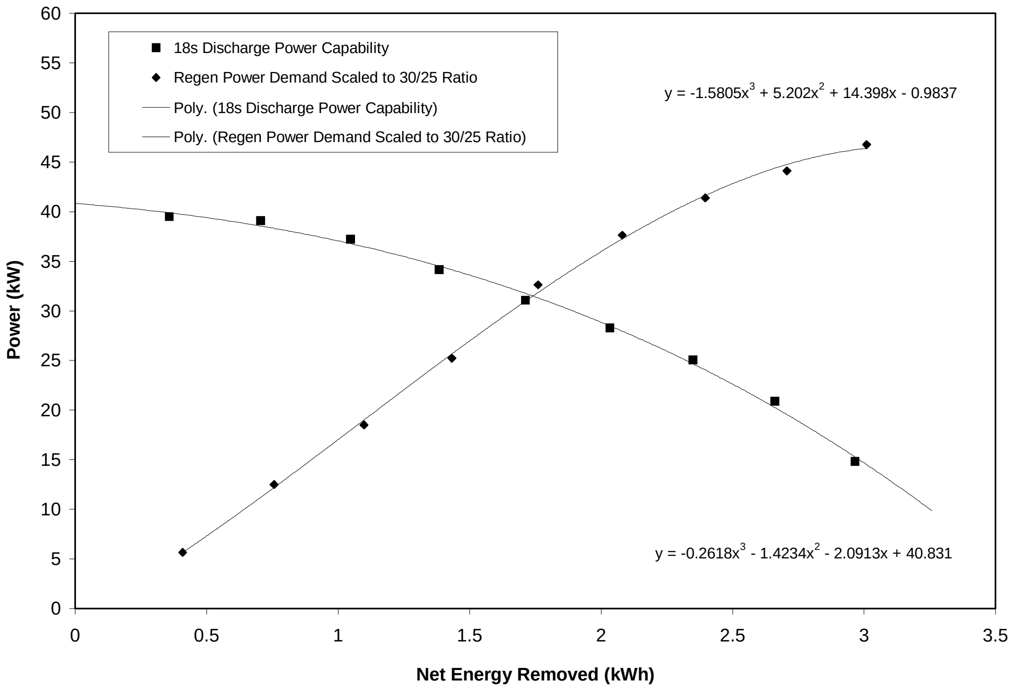

Figure E-3. Power Capability vs Energy from HPPC Test Results

These equations, however, are not well suited to available energy calculations, because they express power as a function of energy, rather than energy as a function of power. Using them to calculate available energy requires that they be solved simultaneously for energy at the same power value. It is much simpler to invert the presentation of the power capability results, as shown in Figure E-4 following.

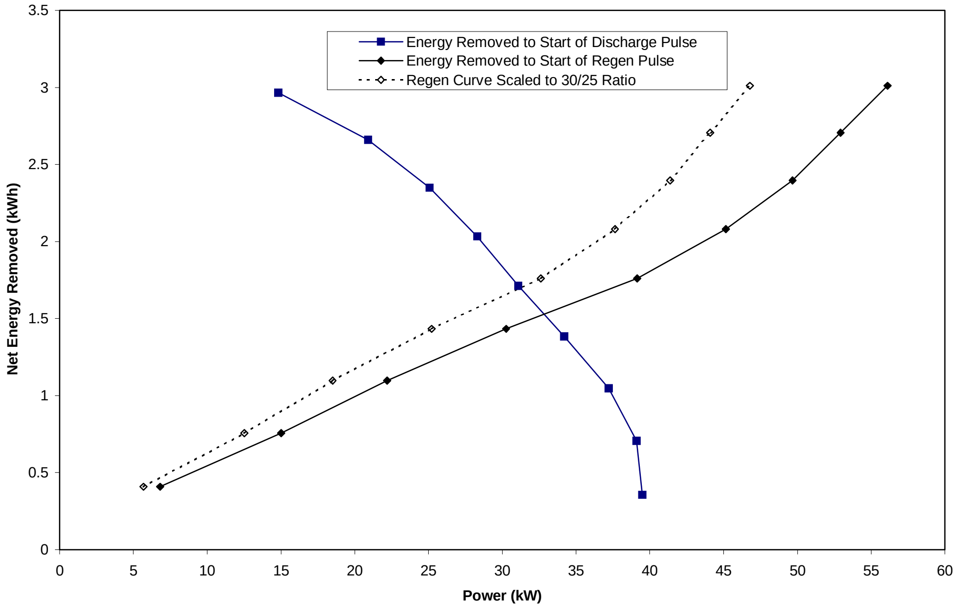

Figure E- 4. Energy vs Power Capability from HPPC Test Results

Curve fitting the discharge and scaled regen curves in this form provides two equations that allow the corresponding discharge and regen energy values to be calculated directly from any desired power demand. Figure E-5 illustrates the results of such curve-fitting.

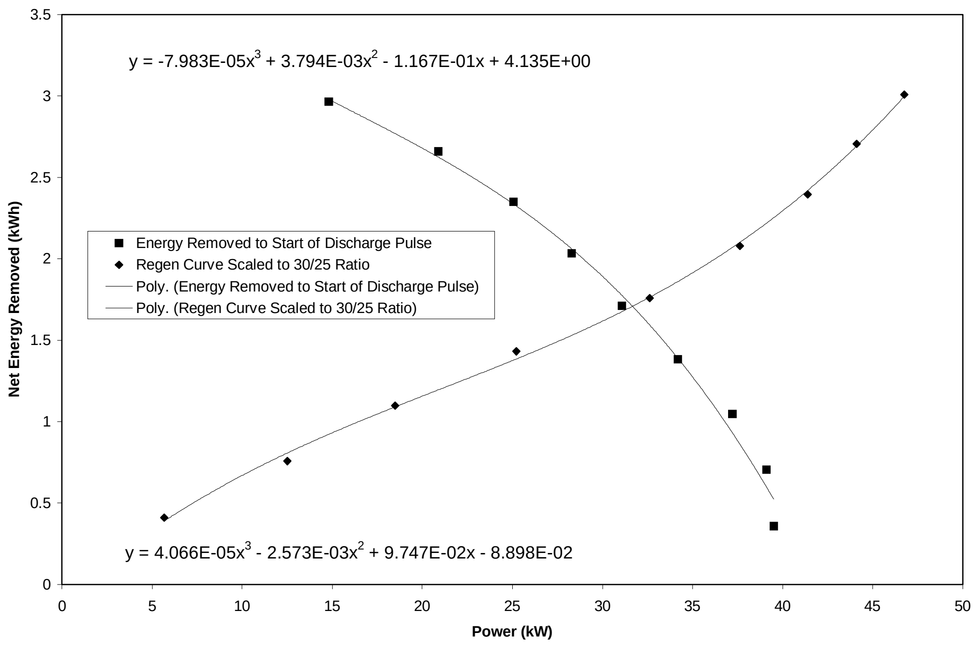

Figure E-5. Curve-Fitting to Scaled Energy vs Power Results

Note that the calculation of energy values from these equations should probably be confined to the limits of the HPPC data; extrapolation of polynomial curve fits can result in non-sensible results. It should also be noted that the use of third-order polynomials gives useable but not perfect correspondence with the actual data points. Higher-order polynomials may give a better fit; however, there is inevitably some scatter in the test results, so it is not clear that a more precise curve-fit will always agree better with the underlying behavior. Third-order polynomials are used here for illustrative purposes. In actual practice, equivalent accuracy could probably be obtained by using linear interpolation between pairs of actual data points, and this method would be simpler to automate.

The equations in Figure E-5 can be used to generate a plot of “Usable” Energy vs Power, where “Usable” Energy is represented by the difference between the 2 curves at a given power value, i.e., it represents the energy available over the operating region where a specified power demand can be met. For modeling purposes it may also be helpful to express these results in terms of power-to-energy (P/E) ratio, which is simply the quotient of a given power and its associated energy value. Both these quantities are plotted in Figure E-6 (which also includes the power capability data points for reference). Note that the P/E ratio is unbounded at the points where the discharge and regen power curves cross. Neither the energy nor the P/E ratio is calculated for powers exceeding this limit. Such a calculation would give negative usable energy, which is likely to be confusing although it is some indication of how large the energy “shortfall” is at a given power value.

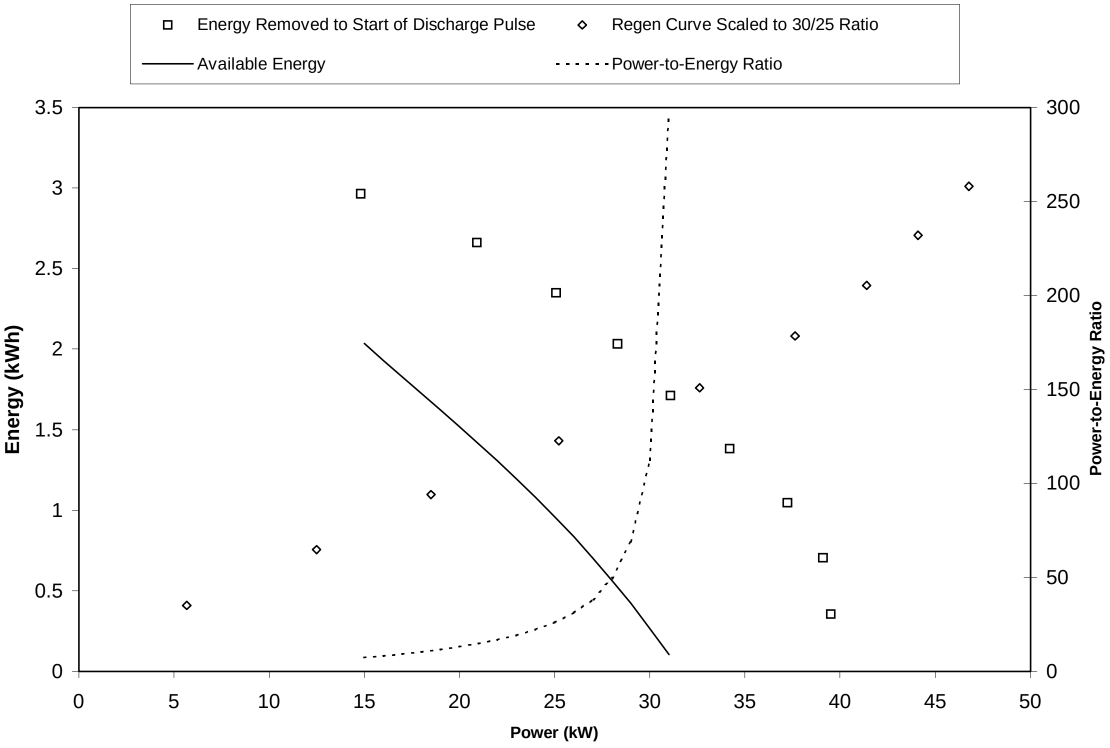

Figure E-6. Usable Energy and Power/Energy Ratio as a Function of Power Required

The actual calculation of Available Energy for comparison with the PNGV goal does not require use of this graph. For this Power Assist example, Available Energy is simply the difference in the two energy vs power equations in Figure E-5 evaluated at the goal power of 25 kW (discharge power), or 0.96 kWh. This value is shown graphically (for illustrative purposes only) in Figure E-7.

This energy is more than three times the goal value, which might seem to suggest that the Battery Scaling Factor is not properly chosen. However, if the original data represents beginning-of-life performance, Figure E-2 shows that the power where usable energy would be zero is about 31 kW, which is only about 24% higher than the power goal. Hence the margin for power degradation over life is actually fairly modest. The large available energy resulting from this margin is due to the steep slope of the P/E curve for this cell at the target power level, where the desired P/E ratio is 25 kW / 0.3 kWh = 83.3.

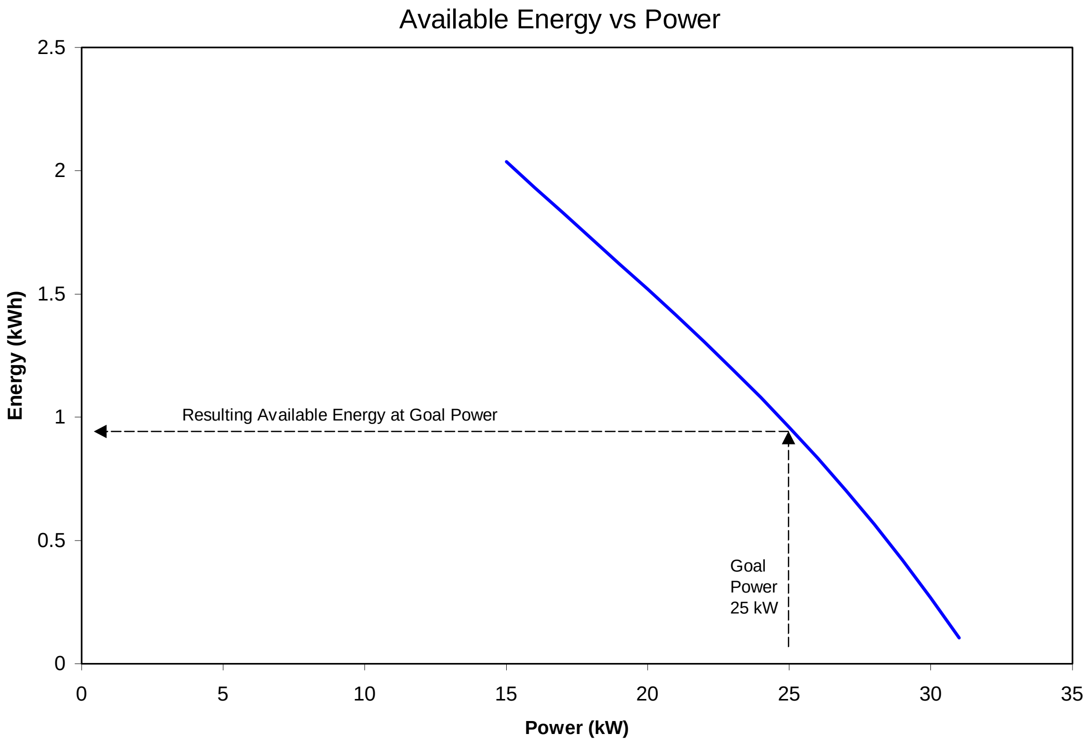

Figure E-7. Available Energy as a Function of Power Required (Evaluated at Power Assist Goal Requirements)

Appendix F

Procedure for Estimation of Thermal Management Energy Consumption

Appendix F

Procedure for Estimation of Thermal Management Energy Consumption

BACKGROUND

Battery system thermal management is generally required to meet battery performance and life goals while operating over a wide range of ambient temperature (Table 1 in Section 1.4). Battery thermal management will include three principal features – active cooling, active heating, and thermal insulation within the battery enclosure. Active cooling is expected to use a mechanical refrigeration unit, probably as an adjunct to the vehicle air conditioning system. Active heating might involve only transfer of waste heat from the engine or fuel cell to the battery. Alternatively, when the vehicle is parked with the engine off, it may be desirable to use self-powered battery heaters to maintain the battery's temperature for starting the vehicle. Given the need for active cooling and heating, thermal insulation of the battery is desirable to minimize the energy consumed to keep the battery within its best temperature range.

This appendix provides a procedure for estimating the energy consumption of the battery thermal management over a semi-annual variation in ambient temperatures. The assumptions, input parameters, and equations for the procedure are given in the following. Also, an Excel spreadsheet program implementing the procedure is provided with this Revision 3 of the PNGV Battery Test Manual as file "Assessment_of_Thermal_Mgmt_Losses.XLS".

ASSUMPTIONS

The procedure is based on the following assumptions regarding battery thermal management design and operation, vehicle usage, and ambient temperature variation.

Thermal Management Design and Operation.

The battery thermal management is designed to keep the battery at its specified nominal operating temperature. Battery cooling uses an air conditioning unit with a given coefficient-of-performance (COP) that determines the amount of heat removed from the battery per unit of energy consumed by the air conditioner. Battery heating uses waste heat from the engine or fuel cell, transported to the battery by fans or pumps with an overall COP that determines the amount of heat supplied to the battery per unit of energy consumed by the fans or pumps. When the vehicle is parked with the engine off, the battery is allowed to reject or accept heat from ambient through its insulated enclosure. If the ambient temperature is below a specified minimum battery operating temperature, the battery is used to power internal heaters that can hold the battery at its minimum temperature until the vehicle is restarted. The COP for this battery self-heating is unity. If the battery is not at its nominal operating temperature when the vehicle is restarted, heat is removed or added (if retention of internal waste heat is not sufficient) during driving to bring the battery to its desired temperature by the end of each driving period.

Vehicle Usage

A weekly vehicle usage profile has been developed for use in estimating the battery thermal management energy consumption (Table F-1). Monday through Friday the vehicle is driven to work for 30 minutes, parked for the morning, driven 15 minutes each way from work to lunch and back to work, parked for the afternoon, and driven home for 30 minutes. On weekends the vehicle is only driven for 30 minutes total to run errands on Saturday. This profile is repeated for 50 weeks per year. Over the 15-year battery life, the vehicle is operated for a total of 6000 hours at an average speed of 25 mph for 150,000 miles. For any extended periods of vehicle parking (*e.g.*, two weeks of vacation per year), it is assumed that the battery is allowed to track the ambient temperature without trying to hold at the minimum operating temperature. Thus, the energy consumption during such periods is zero.

During periods of vehicle operation the battery is assumed to be generating waste heat at an average rate determined by: (1) its throughput over the 6000 hours of operating life; and (2) its round-trip electrical efficiency. The battery system throughput is specified as the total electrical energy delivered on discharge (*e.g.*, 7.5 MWh for the power assist application). The battery's round-trip electrical energy efficiency is assumed to meet the specified PNGV target (e.g., 90% for the power assist application).

Ambient Temperature Variation

Two statistical distributions of ambient temperature *vs*. time-above-temperature were developed for use in testing electric vehicle (EV) batteries (Ref: USABC Electric Vehicle Battery Test Procedures Manual, Revision 2, January 1996, Procedure #14B, page 38). They correspond to Buffalo, NY and Palm Springs, CA. These statistical distributions have been used to provide week-by-week average ambient temperatures for the purposes of this estimation procedure (Table F-2).[1] Although considered appropriate at the time for EV battery use, it is recognized that these distributions are not necessarily the most severe for the range of markets applicable for hybrid vehicles. Other distributions may be specified in the future, either generically for PNGV use or by each automobile manufacturer as part of a product development program.

INPUT PARAMETERS

Developers must specify the following list of input parameters for their particular battery system technology. Otherwise, the default values given will be used.

Symbol	Definition	Default Value
T_{NOM}	Nominal battery operating temperature	30°C
$T_{MIN,OP}$	Minimum battery operating temperature	-30°C
$C_{SP,BAT}$	Battery specific heat capacity	0.25 Wh/kg/°C
M_{BAT}	Battery mass	40 kg
G_{TH}	Battery thermal conductance to ambient	1.0 W/°C
COP_{HOLD}	Coefficient-of-performance for self-heating	1.0

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[1] *The supplied temperature profiles are semi-annual, i.e., they include only 6 months of values. Annual temperature behavior is assumed to be symmetrical, so that semi-annual results can simply be multiplied by 2.*

COP_{HEAT}	Coefficient-of-performance for heating	10.0
COP_{COOL}	Coefficient-of-performance for cooling	2.0
$E_{DIS,TOTAL}$	Total battery throughput energy	7.5 MWh
η_{RT}	Battery round-trip energy efficiency	90%

Table F-1. Weekly Vehicle Utilization Profile

Day of the week	Operation	Start time	Duration
Monday - Friday	Drive from home to work	7:30 am	0.5 hr
	Park at work for morning	8:00	3.5 hr
	Drive to lunch	11:30	0.25 hr
	Park for lunch	11:45	1.0 hr
	Drive back to work	12:45 pm	0.25 hr
	Park at work for afternoon	1:00	4.5 hr
	Drive home from work	5:30	0.5 hr
	Park overnight at home	6:00	13.5 hr
Saturday	Continue to park at home	7:30 am	7.5 hr
	Run errands and return home	3:00 pm	0.5 hr
	Park at home	3:30	16.0 hr
Sunday	Park at home	7:30 am	24.0 hr

Total duration of driving = 8.0 hr per week

Table F-2. Semi-annual Ambient Temperature Profiles

Buffalo, NY	Week #	Temp.(C)	Week #	Temp.(C)	Week #	Temp.(C)
	1	-20^o	10	5^o	19	18^o
	2	-11^o	11	7^o	20	19^o
	3	-8^o	12	8^o	21	21^o
	4	-6^o	13	10^o	22	23^o
	5	-4^o	14	11^o	23	24^o
	6	-2^o	15	12^o	24	26^o
	7	1^o	16	14^o	25	28^o
	8	2^o	17	15^o		
	9	4^o	18	17^o		

Palm Springs, CA	Week #	Temp.(C)	Week #	Temp.(C)	Week #	Temp.(C)
	1	0^{o}	10	18^{o}	19	30^{o}
	2	5^{o}	11	19^{o}	20	31^{o}
	3	7^{o}	12	21^{o}	21	33^{o}
	4	10^{o}	13	22^{o}	22	35^{o}
	5	11^{o}	14	23^{o}	23	37^{o}
	6	12^{o}	15	24^{o}	24	39^{o}
	7	14^{o}	16	26^{o}	25	45^{o}
	8	16^{o}	17	27^{o}		
	9	17^{o}	18	28^{o}		

EQUATIONS

Battery thermal characteristics

Battery heat capacity = $C_{TH} = M_{BAT} \times C_{SP,BAT}$ ~ Wh/^{o}C

Battery thermal time-constant = $\tau_{TH} = C_{TH} / G_{TH}$ ~ h

Battery average heat generation rate = $Q_{GEN} = E_{DIS,TOTAL} \times (1 - \eta_{RT}) / \eta_{RT} / 6000$ ~ W

Battery temperatures at the start of each driving period

Duration of parking up to the start of driving = Δt_{PARK} ~ h (from Table F-1)

Ambient temperature during parked period = T_{AMB} ~ ^{o}C (from Table F-2)

Temperature at start of driving = T_{START} ~ ^{o}C

T_{START} = Maximum of $\{T_{MIN,OP}\}$ or $\{T_{NOM} - (T_{NOM} - T_{AMB}) \times [1 - \exp(-\Delta t_{PARK} / \tau_{TH})]\}$

Duration of battery hold at minimum operating temperature

Duration of hold at $T_{MIN,OP}$ = Δt_{HOLD} = zero for $T_{AMB} \geq T_{MIN,OP}$

Otherwise $\Delta t_{HOLD} = \Delta t_{PARK} - \tau_{RT} \times \log_e[(T_{NOM} - T_{AMB}) / (T_{MIN,OP} - T_{AMB})]$ ~ h

Net heat input to the battery required during driving periods

Heat to bring battery to T_{NOM} = $\Delta Q_{START} = C_{TH} \times (T_{NOM} - T_{START})$ ~ Wh

Heat to balance loss to ambient = $\Delta Q_{LOSS} = G_{TH} \times [(T_{START} + T_{NOM})/2 - T_{AMB}]$ ~ Wh

Duration of driving = Δt_{DRIVE} ~ h (from Table F-1)

Heat generated by battery operation = $\Delta Q_{HEAT} = Q_{GEN} \times \Delta t_{DRIVE}$ ~ Wh

Battery net heat input = $\Delta Q_{NET} = \Delta Q_{START} + \Delta Q_{LOSS} - \Delta Q_{HEAT}$ ~ Wh

Energy consumed attributable to each driving period

Heat to hold at $T_{MIN,OP}$ prior to start = $\Delta Q_{HOLD} = G_{TH} \times (T_{MIN,OP} - T_{AMB}) \times \Delta t_{HOLD}$ ~ Wh

Energy required to hold at $T_{MIN,OP}$ = $\Delta E_{HOLD} = \Delta Q_{HOLD} / COP_{HOLD}$ ~ Wh

Energy required for net heat input = $\Delta E_{NET} = \{\Delta Q_{NET} / COP_{HEAT}\}$ ~ Wh for $\Delta Q_{NET} >$ zero

or $\Delta E_{NET} = \{- \Delta Q_{NET} / COP_{COOL}\}$ ~ Wh for $\Delta Q_{NET} <$ zero

Increment of energy consumed = $\Delta E_C = \Delta E_{HOLD} + \Delta E_{NET}$ ~ Wh

Total energy consumption and average per day

Daily energy consumption = ΔE_D = Sum of ΔE_C from each driving period ~ Wh

Weekly energy consumption = $\Delta E_W = \Delta E_{D,MON} + 4 \times \Delta E_{D,T\text{-}F} + \Delta E_{D,SAT} + \Delta E_{D,SUN}$ ~ Wh

Annual energy consumption = ΔE_Y = 2 x Sum of ΔE_W for 25 weeks of operation ~ Wh

Total lifetime energy consumption = $E_{TOTAL} = 15 \times \Delta E_Y$ ~ Wh

Average energy consumption per day = $E_{AVG} = E_{TOTAL} / 5475$ ~ Wh/day

PROCEDURE SUMMARY

This interim procedure applies the equations in the preceding section to the input parameters described previously. This is done by using the Buffalo and Palm Springs temperature profiles separately, i.e., energy consumption is calculated for each of these profiles independently. The results are then reported for both profiles, and the lifetime and daily energy consumptions can be compared, for example, to the overall throughput and the PNGV self-discharge goal as an indication of relative energy losses. Figure F-1 illustrates the results of a sample calculation for the Palm Springs profile, using the spreadsheet supplied with this manual. (Only the first of 25 weeks is shown in the figure. See the spreadsheet for example results for the entire profile) It results in a lifetime energy consumption of 274.6 kWh, which is 3.7% of the total 7.5 MWh throughput required for a Power Assist battery. The average energy consumed per day is 50.2 Wh, which is essentially the same as the PNGV self discharge goal. There is no goal specifically for thermal management energy losses, so these results are used for comparison of different technologies.

Figure F-1. Example calculation of thermal management losses

PROGRAM FOR ESTIMATION OF ENERGY CONSUMED BY BATTERY THERMAL MANAGEMENT HJH 10/17/00
(Revised February 2001 for new PNGV 15-year life and -30C min temperature goals) Rev 2/2/2001 glh

Battery thermal management design parameters:

T-nom =	30	C	= Nominal battery operating temperature
T-min =	-30	C	= Minimum battery operating temperature
C-sp,bat =	0.25	Wh/kg/C	= battery specific heat capacity
M-bat =	40	kg	= battery mass
G-th =	1	W/C	= battery thermal conductance to ambient

implies:	C-th =	10	Wh/C	= M-bat x C-sp,bat	= battery heat capacity
	Tau-th =	10	h	= C-th / G-th	= battery thermal time constant

COP-holding =	1.0	W-th/W-heater	= coefficient of performance for battery heating	(internal battery-powered heaters)
COP-heating =	10.0	W-th/W-heater	= coefficient of performance for battery heating	(Fans only, to circulate engine waste heat)
COP-cooling =	2.0	W-th/W-comp,fan	= coefficient of performance for battery cooling	(A/C compressor & fans)

Battery heat generation parameters:

Total energy throughput =	7.5	MWh
Round-trip efficiency =	90	%
Implies:		
Average heating rate =	139	W

Weekly vehicle usage profile (h): (repeated for 50 weeks per year, for a total of 15 years life)

Mon. - Fri.:	7:30 am	0.50	drive to work
	8:00 am	3.50	park for morning
	11:30 am	0.25	drive to lunch
	11:45 am	1.00	park for lunch
	12:45 pm	0.25	return to work
	1:00 pm	4.50	park for afternoon
	5:30 pm	0.50	drive home from work
	6:00 pm	13.50	park overnight
Sat.:	7:30 am	7.50	continue parking
	3:00 pm	0.50	run errands and return home
	3:30 pm	16.00	park for balance of weekend
Sun:	7:30 am	24.00	park for balance of weekend

Results:			
	Total driving time =	8	hr per week
		400	hr per year
		6000	hr per 15-year life
	Average driving speed =	25	mph for 150,000 miles
	Energy consumed per year =	18.31	kWh
	Total 15-yr energy consumed =	274.6	kWh
	Energy consumed per day =	50.2	Wh/day (average)
		177.9	Wh/day (worst week)
		13.5	Wh/day (best week)

Semi-annual climatic variation in ambient temperature & implied thermal energy losses: Palm Springs, CA

Week #	**1**	T-start,1	dQ-1	dE-1	T-start,2	dQ-2	dE-2	T-start,3	dQ-3	dE-3	T-start,4	dQ-4	dE-4	E/day
T-amb =	**0.0**													
Mon		0.5	232.7	23.3	21.1	60.3	6.0	27.1	1.0	0.1	19.1	51.5	5.2	34.5
Tue-Fri		7.8	162.2	16.2	21.1	60.3	6.0	27.1	1.0	0.1	19.1	51.5	5.2	27.5
Sat-Sun		3.7	202.2	20.2							Total energy loss per week			164.8