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FreedomCAR Battery Test Manual
For Power-Assist Hybrid Electric Vehicles

FreedomCAR

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FreedomCAR Battery Test Manual For Power-Assist Hybrid Electric Vehicles

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FOREWORD

This manual was prepared by and for the FreedomCAR Program Electrochemical Energy Storage Team. It is based on the goals established for FreedomCAR energy storage development and is similar (with some important changes) to an earlier manual for the former Partnership for a New Generation of Vehicles (PNGV) program. The specific procedures were developed primarily to characterize the performance of energy storage devices relative to the FreedomCAR 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 first published version of this manual defines testing methods for full-size energy storage systems, along with provisions for scaling these tests for cells, modules or other subscale devices. Suggestions or comments should be directed to 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

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

GLOSSARY[a]

Available Energy –the discharge energy available over the DOD range where both the FreedomCAR discharge and regen pulse power goals for a given mode (Minimum or Maximum Power-Assist) are precisely met. This energy is measured using a $C_1/1$ constant current discharge rate, and the limiting power conditions are calculated using a procedure defined in this manual.

Available Power –the discharge pulse power at which the usable energy is equal to the Available Energy goal for a given mode (Minimum or Maximum Power-Assist).

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 FreedomCAR 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 FreedomCAR energy goals with a 30% power margin at beginning of life. Battery Size Factor is determined separately for each mode.

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.

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

$C_1/1$ Rate – a current corresponding to the manufacturer's rated capacity (in ampere-hours) for a one-hour discharge. For example, if the battery's rated one-hour capacity is 10Ah, then $C_1/1$ is 10A.

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

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 relative to a fully charged condition, normally referenced to a constant current discharge at the $C_1/1$ rate.

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

End of Life (EOL) – a condition reached when the device under test is no longer capable of meeting the FreedomCAR goals. This is normally determined from HPPC test results scaled using the

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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.

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 FreedomCAR 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.

Extended Simplified Model (ESM) – an analysis tool that uses HPPC cell data to estimate the appropriate cell capacity for a cell design to satisfy the FreedomCAR power and energy goals.

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 FreedomCAR operating conditions.

Maximum Rated Current (Imax) – the maximum discharge current that a manufacturer will permit to be sustained by a device for 10s. (This value need not be achievable at all DOD values.)

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

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

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

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

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

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

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

FreedomCAR Battery Test Manual
For Power-Assist Hybrid Electric Vehicles

1. PURPOSE AND APPLICABILITY

This manual defines a series of tests to characterize aspects of the performance or cycle life behavior of batteries for hybrid electric vehicle applications. Tests are defined based on the FreedomCAR program goals for power-assist hybrid electric vehicles, though it is anticipated these tests may be generally useful for testing energy storage devices for hybrid vehicles. The test procedures in this manual are directly applicable to complete battery systems. However, most can also be applied with appropriate scaling to the testing of cells, modules or less-than-full-size batteries. Much of the rationale for the test procedures and analytical methodologies utilized in this manual evolved from the former PNGV Battery Test Manual (Reference 2).

1.1 FreedomCAR Energy Storage Goals For Power-Assist Hybrid Electric Vehicles

FreedomCAR 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 minimum and maximum levels of Power-Assist performance specified for the FreedomCAR Program. Note that this table of FreedomCAR 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. FreedomCAR Energy Storage System Performance Goals for Power-Assist Hybrid Electric Vehicles (November 2002).

Characteristics	Units	Power-Assist (Minimum)	Power-Assist (Maximum)
Pulse discharge power (10s)	kW	25	40
Peak regenerative pulse power (10s)	kW	20 (55-Wh pulse)	35 (97-Wh pulse)
Total available energy (over DOD range where power goals are met)	kWh	0.3 (at C_1/1 rate)	0.5 (at C_1/1 rate)
Minimum round-trip energy efficiency	%	90 (25-Wh cycle)	90 (50-Wh cycle)
Cold cranking power at -30ºC (three 2-s pulses, 10-s rests between)	kW	5	7
Cycle Life, for specified SOC increments	cycles	300,000 25-Wh cycles (7.5 MWh)	300,000 50-Wh cycles (15 MWh)
Calendar Life	years	15	15
Maximum weight	kg	40	60
Maximum volume	l	32	45
Operating voltage limits	Vdc	max $\leq$400 min $\geq$(0.55 × Vmax)	max $\leq$400 min $\geq$(0.55 × Vmax)
Maximum allowable self-discharge rate	Wh/day	50	50

Temperature range: Equipment operation Equipment survival	°C	-30 to +52 -46 to +66	-30 to +52 -46 to +66
Production Price @ 100,000 units/year	$	500	800

2. TEST PROFILES DERIVED FROM FREEDOMCAR 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 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 be used in various combinations, with the appropriate scaling factors, to define specific performance or cycle life tests for cells, modules or battery systems. The test profiles in this manual supercede all previous versions defined for the earlier PNGV program. Because there is essentially a one-to-one relationship between test profiles and test procedures, each profile is defined within the respective procedure described.

3. TEST PROCEDURES

3.1 General Test Conditions and Scaling

In general, FreedomCAR testing is divided into three broad phases, i.e., characterization, life, and reference performance testing. Characterization testing establishes the baseline performance and includes static capacity, hybrid pulse power characterization, self-discharge, cold cranking, thermal performance, and efficiency tests.[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 FreedomCAR 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.

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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 $C_1/1$ constant-current discharge rate.) Also, the term “fully charged” means “charged in accordance with the manufacturer’s recommended procedure”.

3.1.2 Scaling of Performance and Cycle Life Test Profiles

With the exception of the Hybrid Pulse Power Characterization Test (HPPC) and Calendar Life Test, all performance and cycle life test profiles are defined in terms of required power levels at the system (i.e., full-size vehicle battery) level. Testing any device smaller than a full-size system requires a method for scaling these test profiles to a level appropriate to the size of the device (cell, module, or sub-battery) under test. This is done by using a *battery size factor*. For purposes of this manual, the Battery Size Factor (BSF) is defined as the minimum number of units (cells, modules or sub-batteries) of a given design required for a device to meet all FreedomCAR 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 Low Current HPPC test results by applying a nominal power margin of 30% to allow for degradation resulting from cycle life and calendar life effects. See Section 4.3.10 for details of this determination. [d]

Once the Battery Size Factor is determined, it becomes a constant (i.e., fixed over life) scaling factor for all subsequent performance and cycle life tests. Any test profile (except HPPC or calendar life) is then scaled by dividing the nominal profile power levels by the Battery Size Factor. For example, if the Battery Size Factor is 40 for a particular cell design, the 5-kW (Minimum Power-Assist) Cold Cranking test would then be performed at a pulse power level of 5000/40 = 125 W for such cells. Note that there is a separate mode-specific Battery Size Factor for Minimum and Maximum Power-Assist 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 C_1 capacity in ampere-hours (e.g., if the rated one-hour discharge capacity is 10 Ah, the discharge rate is 10 A.) Discharge is terminated on a manufacturer-specified discharge voltage limit. If the manufacturer does not provide a discharge voltage limit, or if the provided limit is unrealistically low, either an appropriate value is determined from the literature or 55% of the maximum charge voltage is used. (This will automatically become the lowest possible value for full-size battery tests in any event because of the FreedomCAR 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

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

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

discharge, (a) the V_{MIN} discharge power capability at the end of a 10-s discharge current pulse and (b) the V_{MAX} regen power capability at the end of a 10-s regen current pulse.[f] These power capabilities are then used to derive other performance characteristics such as Available Energy and Available Power. Secondary objectives when used for cell testing are to derive from the voltage response curves the fixed (ohmic) cell resistance and cell polarization resistance as a function of state of charge with sufficient resolution to reliably establish cell voltage response time constants during discharge, rest, and regen operating regimes. The resistance measurements will be used to evaluate resistance degradation during subsequent life testing and to develop hybrid battery performance models for vehicle systems analysis.

3.3.1 Hybrid Pulse Power Characterization Test Profile

The objective of this profile is to demonstrate the discharge pulse and regen pulse power capabilities at various depth of discharge (DOD) values for both the Minimum and Maximum Power-Assist goals (10-s discharge, 10-s regen). The normal test protocol uses constant current (not constant power) at levels derived from the manufacturer's maximum rated discharge current. The characterization profile is shown in Table 2 and Figure 1.

Table 2. Hybrid Pulse Power Characterization Test profile.

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

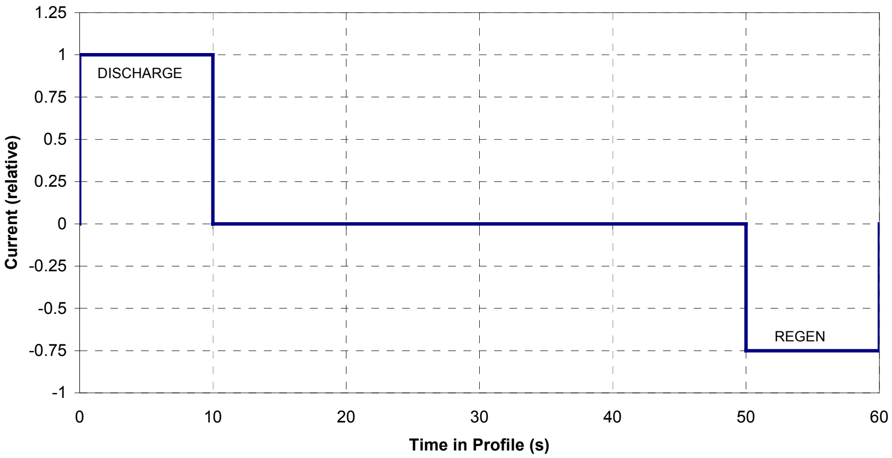

Figure 1. Hybrid Pulse Power Characterization Test profile.

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

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

3.3.2 Test Procedure Description

The HPPC test incorporates the pulse power characterization profile as defined in Section 3.3.1. Constant current steps are used in the ratios listed in Table 2. The test is made up of single repetitions of this profile, separated by 10% DOD (depth of discharge) constant current $C_1/1$ discharge segments,[g] each followed by a 1-hr rest period to allow the cell to return to an electrochemical and thermal equilibrium condition before applying the next profile. The test begins with a fully charged device after a 1-hr rest and terminates after completing the final profile at 90% DOD, discharge of the cell at a $C_1/1$ rate to 100% DOD, and a final 1-hr rest.[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 $C_1/1$ discharge segments is illustrated in Figures 2 and 3. These figures also illustrate a $C_1/1$ discharge to be executed just prior to each HPPC test.[i]

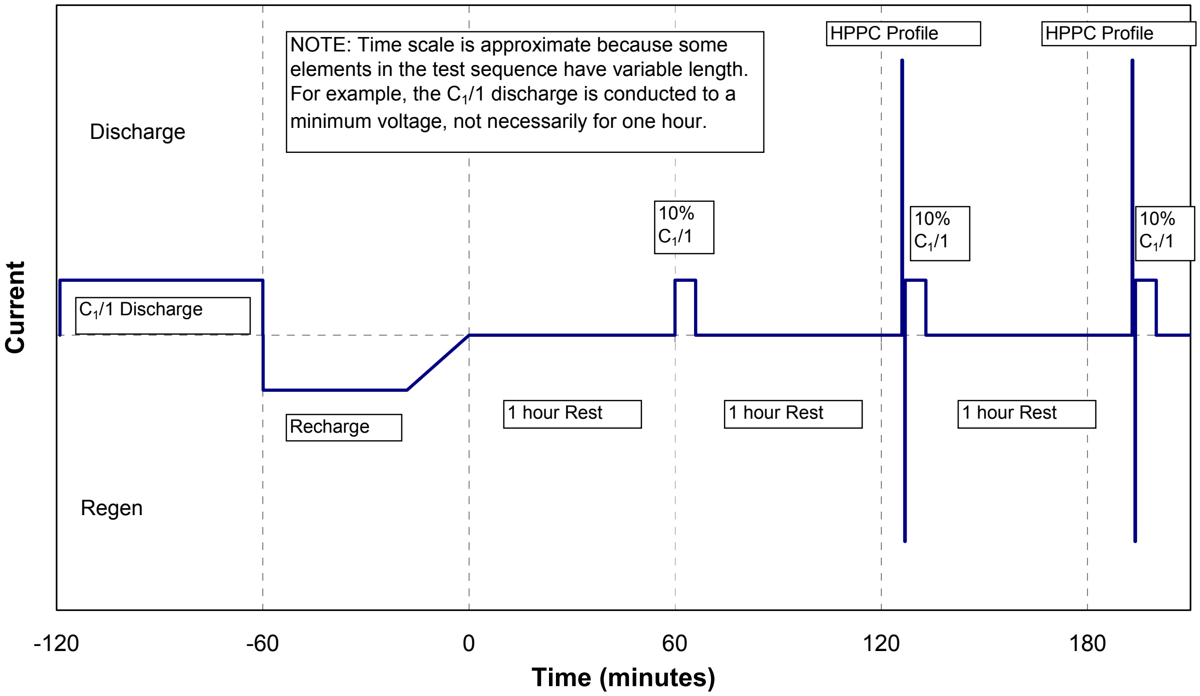

Figure 2. Hybrid Pulse Power Characterization Test (start of test sequence).

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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 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.

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

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

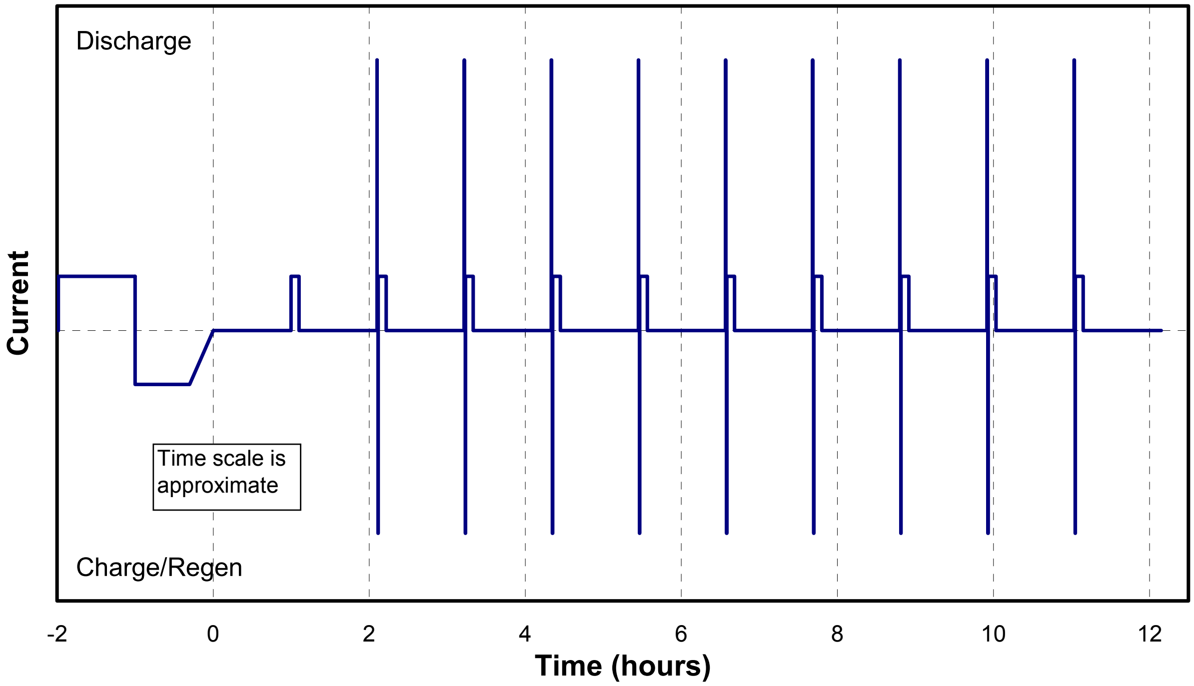

Figure 3. Hybrid Pulse Power Characterization Test (complete HPPC sequence).

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

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

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

3.3.3 Special HPPC Verification Test

In general the HPPC test produces slightly conservative results, because it is normally performed at power levels that are less than the goal values. (At higher test currents, internal heating lowers the battery

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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}.

resistance and gives higher power capability.) In some cases (e.g. when a new technology, a new cell design or a full-size battery design is tested for the first time), it may be desirable to verify the extent of this conservatism by performing a test at the actual goal values. This is done using a special test sequence as follows:

1. From HPPC test results, calculate (a) the minimum DOD value DOD_{MIN} at which the regen pulse power goal can be met, (b) the maximum DOD value DOD_{MAX} at which the discharge pulse power goal can be met, and (c) the Available Energy, which is the energy discharged at a $C_1/1$ rate between DOD_{MIN} and DOD_{MAX}. These values are calculated using Section 4.3.4 and 4.3.7 of this manual.

2. Starting with a fully-charged battery, discharge to DOD_{MIN} at a $C_1/1$ constant current rate, and then rest for one hour at open-circuit conditions.

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

4. Recharge the battery.

5. Discharge to DOD_{MAX} at a $C_1/1$ constant current rate, and then rest for one hour at open-circuit conditions.

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

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

3.4 Self-Discharge Test

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

The test consists of the following sequence of activities:

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

2. Discharge the cell for 30% of the rated capacity at a $C_1/1$ rate, and allow it to stand in an open-circuit condition for a nominal interval of 7 days (1 week).[1] (The actual stand period should be selected based on the expected stand loss rate, with the value chosen to yield an expected capacity loss of 5% or more over the interval.) All measurement equipment may need to be disconnected from the cell during this period to reduce parasitic losses.

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

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

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

3.5 Cold Cranking Test

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

1. At normal ambient temperature, discharge the fully charged device at a $C_1/1$ 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 3.5.1. The pulse power level to be used is 5 kW (Minimum Power-Assist) or 7 kW (Maximum Power-Assist) divided by the Battery Size Factor as determined in Sections 3.1.2 and 4.3.10. Note that the manufacturer may specify a different minimum discharge voltage for cold cranking testing. This voltage, if specified, will be used for both test control and the subsequent calculation of cold cranking power capability; but it may not exceed the FreedomCAR voltage ratio limits in Table 1. Note also that the profile pulses must be performed for the full 2-s duration (even if the test power has to be limited to stay within the minimum discharge voltage) to permit the later calculation of Cold Cranking power capability.

3.5.1 Cold Cranking Test Profile

The Cold Cranking Test profile is a literal implementation of the Cold Cranking Power goals, which require the ability to provide either 5 kW or 7 kW of discharge power for three 2-s pulses at 12-s intervals (i.e., 10 s between pulses.) The profile is defined in Table 3 and illustrated in Figure 4 for both the Minimum and Maximum Power-Assist goals.

Table 3. Cold Cranking Test profiles for Minimum and Maximum Power-Assist goals.

Time Increment (s)	Cumulative Time (s)	System Power (kW) Minimum Power-Assist	System Power (kW) Maximum Power-Assist
2	2	5	7
10	12	0	0
2	14	5	7
10	24	0	0
2	26	5	7

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[m] The analysis procedure to determine this DOD value is described in Section 4.3.7.

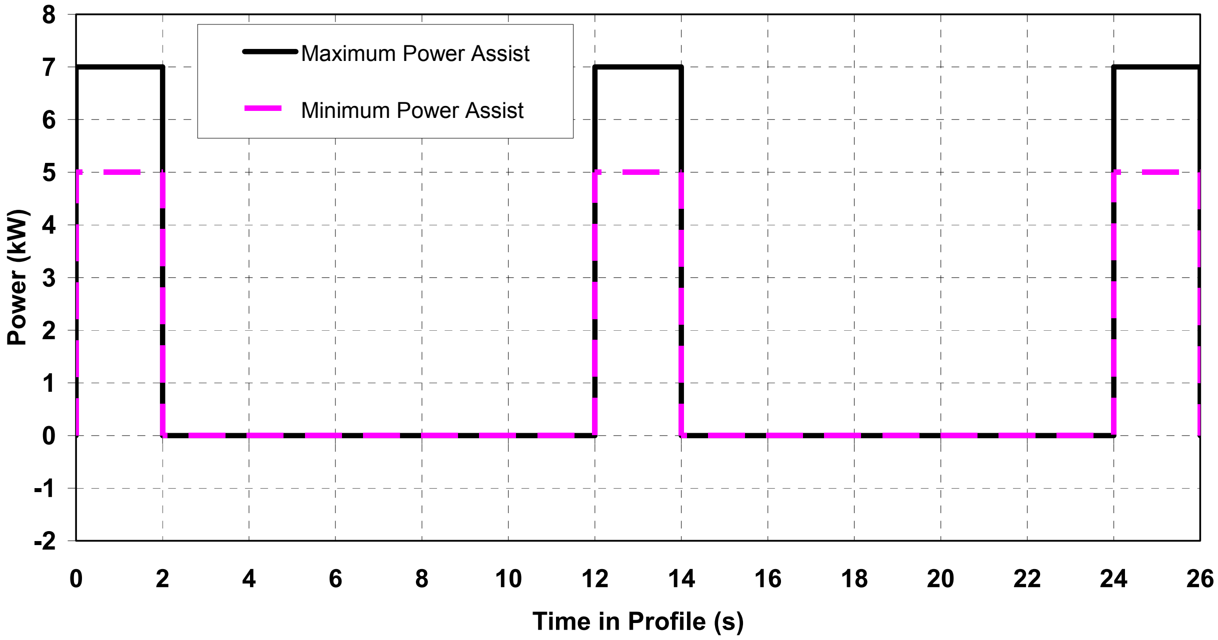

Figure 4. Cold Cranking Test profiles.

3.6 Thermal Performance Test

The effects of environment (ambient temperature) on device performance will be measured as required by performing the Static Capacity Test, Low-Current Hybrid Pulse Power Characterization Test, and/or Cold Cranking Test at various temperatures within the FreedomCAR 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.

3.7 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 Minimum (25 Wh) and Maximum (50 Wh)

Power-Assist mode use in Sections 3.7.1 and 3.7.2 respectively. These profiles have been constructed for use in both efficiency and cycle life testing. This test is performed similarly to the Operating Set Point Stability (OSPS) Test, as follows:

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

2. Perform 100 efficiency test profiles (Minimum or Maximum Power-Assist 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.

3.7.1 Minimum Power-Assist (25 Wh) Efficiency Test Profile

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

Table 4. Minimum Power-Assist (25 Wh) Efficiency and Baseline Cycle Life Test profile.

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

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

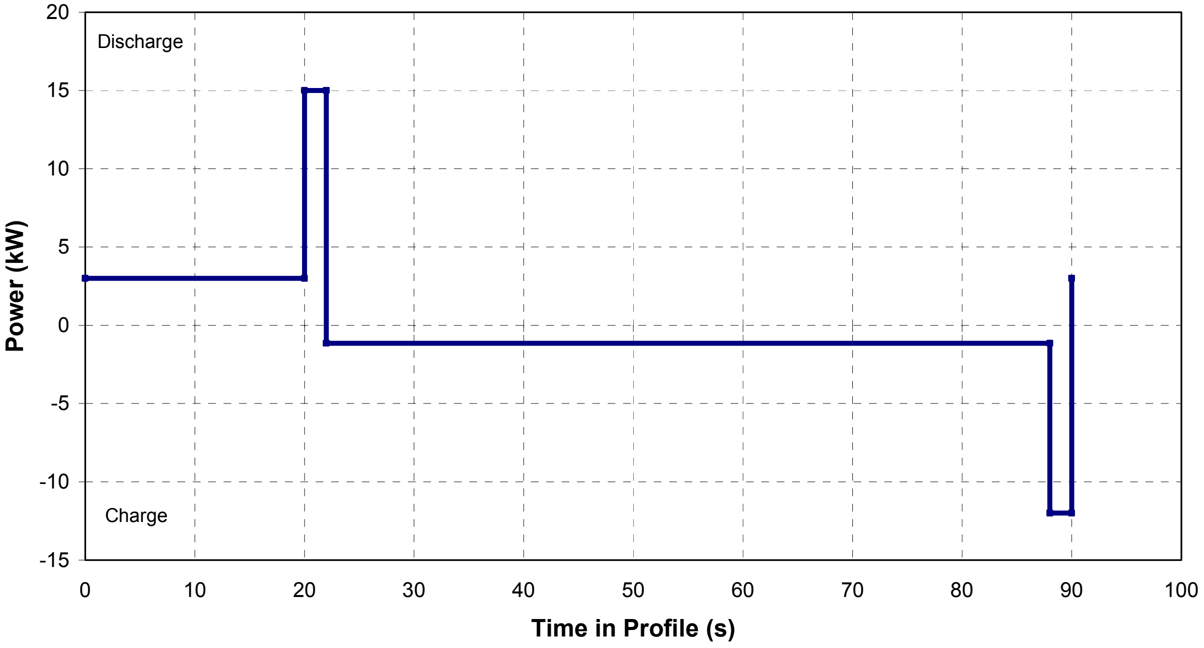

Figure 5. Minimum Power-Assist (25 Wh) Efficiency and Baseline Cycle Life Test profile.

3.7.2 Maximum Power-Assist (50 Wh) Efficiency Test Profile

The Maximum Power-Assist Efficiency Test profile is a 90-s, nominally charge-neutral pulse profile scaled to a level appropriate to verify the Maximum Power-Assist round trip energy efficiency goal of 90% with a 50-Wh energy swing.[o] This test profile is defined in Table 5 and illustrated in Figure 6.

Table 5. Maximum Power-Assist (50 Wh) Efficiency and Baseline Cycle Life Test profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)
36	36	3.00	30.00	30.00
3	36	24.00	20.00	50.00
49	88	-3.22	-43.89	6.11
2	90	-21.00	-11.67	-5.56

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[o] This profile is calculated to be charge-neutral for a device that exactly meets the 90% efficiency goal. See the note on the previous section regarding profile changes if the efficiency differs from 90%.

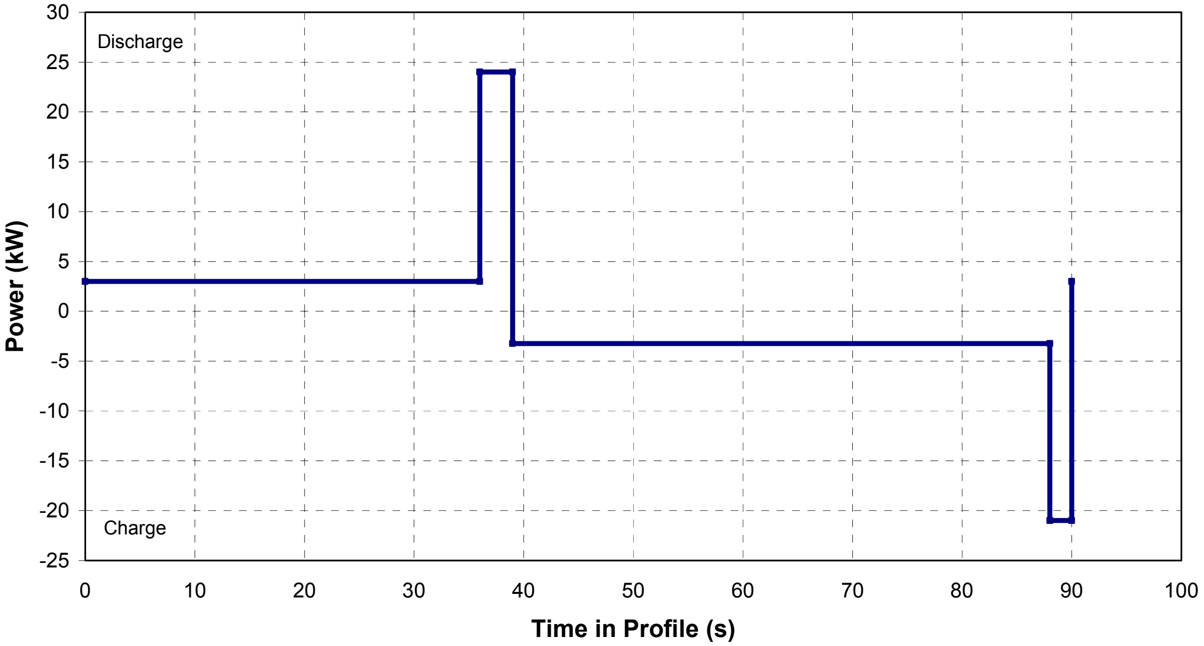

Figure 6. Maximum Power-Assist (50 Wh) Efficiency and Baseline Cycle Life Test profile.

3.8 Operating Set Point Stability Test

This test is a special case of the cycle life testing regime to be applied to a given cell or battery. Since cycle life testing is normally done at an intermediate state of charge, it is necessary to determine that stable cycling will occur at the target SOC, and to adjust test conditions if necessary to ensure that this will be the case. The target state of charge for the cycle life test(s) defined in 3.9 is normally specified in a device-specific test plan based on projected use of the device.[p] This test should be performed immediately before the beginning of cycle life testing.

With the cell at the selected state-of-charge value and all other conditions (e.g., operating temperature) as required for life cycling, apply the selected Cycle Life Test profile for a period long enough to reach thermal equilibrium and to return to the target SOC.[q] Determine the change (if any) in the state of charge before and after the cycling interval. Allow a 1-hr rest before and after this cycling is performed to determine any change in open-circuit voltage. The residual capacity can also be removed at a $C_1/1$ constant-current rate to verify the depth of discharge at the end of the cycling interval.

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[p] There is no "default nominal" state of charge for life cycling. However, if the appropriate value is not known in advance of the start of testing, the range of usable target SOC values can be determined from the HPPC test results (see Section 4.3) based on the peak discharge and regen powers planned for cycle life testing.

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

3.8.1 Adjusting the Operating Set Point

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

3.8.2 Controlling the State of Charge during the OSPS Test

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

Note that achieving the target SOC and a stable cycling condition are related but separate constraints. The maximum and minimum pulse voltages from profile to profile are usually the most sensitive indicators of stable cycling (unless the device resistance is changing during the cycling period), while the SOC during cycling must actually be measured after cycling stops. The intent of this test is to establish control parameter values, and if necessary to fine-tune the test profile, such that life cycling can be performed continuously over the intervals between reference tests specified in Table 9.

3.9 Cycle Life Tests

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

The cycle-life testing approach adopted for this manual makes use of a family of three test profiles for each set of Power Assist goals. The Baseline profile in each family is a relatively low-stress profile designed for verification of the round-trip efficiency goal and is considered to represent an 80th percentile driving demand. A higher stress profile is designated as the 95th percentile load demand, and the highest stress profile is designated the 99th percentile load demand. In keeping with these designations, a complete cycle life test regime is performed using combinations of all three profiles, with the Baseline profile used for 80% of the total life testing, the 95th percentile profile used for an additional 15%, and the 99th percentile profile used for the remaining profiles. All the profiles have the same duration, so the time required to perform a given number of profiles is not affected by which profile is used.

3.9.1 Cycle Life Test Procedure Outline

The cycle life testing process consists of the following steps:

1. Scale the selected family of test profiles by dividing the nominal profile power values by the Battery Size Factor as described in Section 3.1.2.
2. Determine end-of-test criteria for cycle life testing. These are normally specified in a device-specific test plan. A default (and generally mandatory) end-of-test condition is

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

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.[s]

End of test is normally chosen to occur when one of the following conditions exists: (a) cycle life meeting the FreedomCAR goals has been attained (i.e., the number of properly scaled test cycles exceeds the applicable FreedomCAR goal); or (b) Available Energy drops below the goal value. In case (a) the battery may not have reached end of life when testing stops, but further testing is not usually considered cost-effective. In case (b), end of life has occurred at some prior time.[t]

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

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

5. After the specified number of repetitions, suspend cycling. If cycling is being done at other than 30ºC, return the cell to 30ºC. Observe the open-circuit voltage after a 1-hr rest. Remove the residual capacity at a $C_1/1$ constant-current rate to verify the cycling depth of discharge, and perform one or more Reference Performance Tests to determine the extent of degradation in capacity and/or power capability. The reference tests are listed in Table 9. The intervals between repetitions of these reference tests are also specified in Table 9, though these may be adjusted somewhat if required for time synchronization of cells being tested under different test regimes.

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

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

3.9.2 Hybrid Cycle Life 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 FreedomCAR goals. Two separate families of profiles are defined for such use based on the FreedomCAR Minimum and Maximum Power-Assist goals.

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

[s] 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.

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

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

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

The Minimum Power-Assist profiles are a set of 90-s pulse profiles intended to demonstrate the ability to meet the FreedomCAR cycle life goal of 300,000 cycles with a 25-Wh swing. The Maximum Power-Assist profiles are a set of 90-s pulse profile intended to demonstrate the ability to meet the FreedomCAR cycle life goal of 300,000 cycles with a 50-Wh swing. The Minimum and Maximum Power-Assist profile families transfer about 7.5-million and 15-million watt-hours (MWh) respectively in and out of the device over 300,000 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.

3.9.2.1 Minimum Power-Assist (25 Wh) Cycle Life Test Profiles

Each of the Minimum Power-Assist (25 Wh) Cycle Life Test profiles remove 25 Wh on discharge and is nominally charge-balanced for a device that just satisfies the 90% efficiency goal using the Baseline profile. The Baseline profile is identical to the Minimum Power-Assist Efficiency Test profile defined in Section 3.7.1. The family of Minimum Power Assist profiles is listed here as Table 6 and is illustrated in Figure 7.

Table 6. Minimum Power-Assist (25 Wh) Cycle Life Test profiles.

APPLICATION	TEST PROFILE	PULSE CHARACTERISTICS					PROFILE CHARACTERISTICS	
			ENG-OFF	LAUNCH	CRUISE	REGEN		
25-kW Power Assist	Baseline	Power(kW) =	3.00	15.00	-1.15	-12.00	Discharge Energy(Wh) =	25.00
		Duration(s) =	20.00	2.00	66.00	2.00	Round-trip Efficiency =	90.0%
		Energy(Wh) =	16.67	8.33	-21.11	-6.67	Avg. Heating Rate (W) =	111
		Stress Factors:					Weighting Factor =	80%
		Power(%) =	100	60		60	Throughput (MWh) =	6.00
		Energy(%) =	5.6	12		12	Test Cycles =	240,000
	95th Percentile	Power(kW) =	3.00	20.00	-1.07	-16.00	Discharge Energy(Wh) =	25.00
		Duration(s) =	10.00	3.00	75.00	2.00	Round-trip Efficiency =	80.2%
		Energy(Wh) =	8.33	16.67	-22.29	-8.89	Avg. Heating Rate (W) =	247
		Stress Factors:					Weighting Factor =	15%
		Power(%) =	100	80		80	Throughput (MWh) =	1.13
		Energy(%) =	2.8	24		16	Test Cycles =	45,000
	99th Percentile	Power(kW) =	3.00	24.00	-1.11	-19.00	Discharge Energy(Wh) =	25.00
		Duration(s) =	6.00	3.00	79.00	2.00	Round-trip Efficiency =	71.6%
		Energy(Wh) =	5.00	20.00	-24.38	-10.56	Avg. Heating Rate (W) =	397
		Stress Factors:					Weighting Factor =	5%
		Power(%) =	100	96		95	Throughput (MWh) =	0.38
		Energy(%) =	1.7	29		19	Test Cycles =	15,000

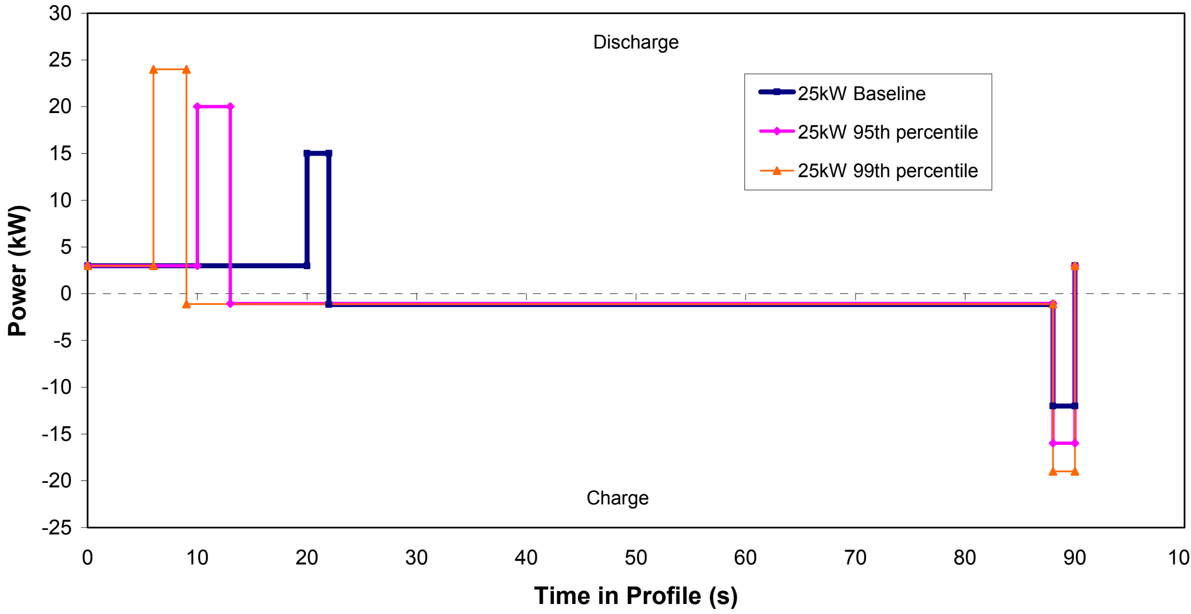

Figure 7. Minimum Power-Assist (25Wh) Cycle Life Test Profiles

3.9.2.2 Maximum Power-Assist (50 Wh) Cycle Life Test Profile

Each of the Maximum Power-Assist (50 Wh) Cycle Life Test profiles removes 50 Wh on discharge and is nominally charge-balanced for a device that just satisfies the 90% efficiency goal using the Baseline profile. The profile is defined here as Table 7 and is illustrated in Figure 8.

Table 7. Maximum Power-Assist (50 Wh) Cycle Life Test Profiles.

APPLICATION	TEST PROFILE	PULSE CHARACTERISTICS					PROFILE CHARACTERISTICS	
			ENG-OFF	LAUNCH	CRUISE	REGEN		
40-kW Power Assist	Baseline	Power(kW) =	3.00	24.00	-3.22	-21.00	Discharge Energy(Wh) =	50.00
		Duration(s) =	36.00	3.00	49.00	2.00	Round-trip Efficiency =	90.0%
		Energy(Wh) =	30.00	20.00	-43.89	-11.67	Avg. Heating Rate (W) =	222
		Stress Factors:					Weighting Factor =	80%
		Power(%) =	100	60		60	Throughput (MWh) =	12.00
		Energy(%) =	6	18		12	Test Cycles =	240,000
	95th Percentile	Power(kW) =	3.00	32.00	-2.78	-28.00	Discharge Energy(Wh) =	50.00
		Duration(s) =	28.00	3.00	57.00	2.00	Round-trip Efficiency =	84.0%
		Energy(Wh) =	23.33	26.67	-43.99	-15.56	Avg. Heating Rate (W) =	382
		Stress Factors:					Weighting Factor =	15%
		Power(%) =	100	80		80	Throughput (MWh) =	2.25
		Energy(%) =	4.7	24		16	Test Cycles =	45,000
	99th Percentile	Power(kW) =	3.00	38.00	-2.63	-33.00	Discharge Energy(Wh) =	50.00
		Duration(s) =	22.00	3.00	63.00	2.00	Round-trip Efficiency =	77.7%
		Energy(Wh) =	18.33	31.67	-45.99	-18.33	Avg. Heating Rate (W) =	573
		Stress Factors:					Weighting Factor =	5%
		Power(%) =	100	95		94.3	Throughput (MWh) =	0.75
		Energy(%) =	3.7	28.5		18.9	Test Cycles =	15,000

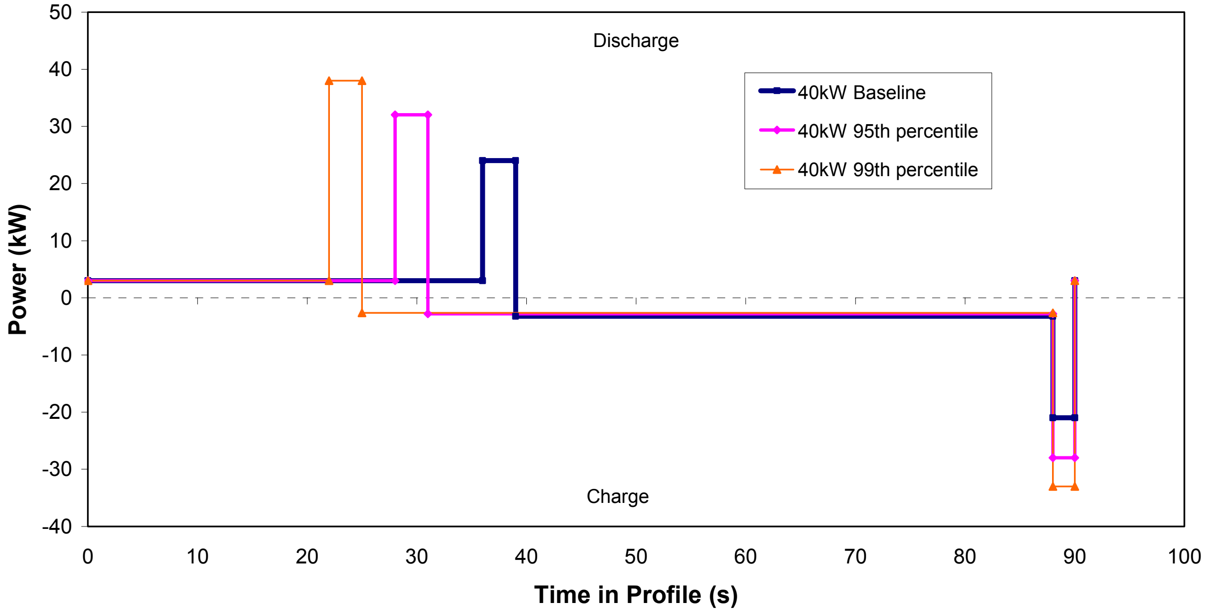

Figure 8. Maximum Power-Assist (50 Wh) Cycle Life Test profiles

3.10 Calendar Life Test

This test is designed to permit the evaluation of cell or battery degradation as a result of the passage of time with minimal usage. It is not a pure shelf life test, because the devices under test are maintained at or near a target state-of-charge during the test. They must also be periodically subjected to reference discharges to determine the changes (if any) in their performance characteristics.

In general, calendar life testing is performed using multiple cells over a range of test conditions.[w] It is commonly done at elevated temperatures in order to shorten the time required for obtaining useful results. Cells to be tested may be included in a matrix of test variables such as temperature and state of charge. This matrix may in turn be part of a larger cycle life test matrix where calendar life testing is considered a limiting cycle life test, i.e., one in which the state-of-charge swing during cycling is zero. The design of experiments for such a larger test matrix is not described in this manual. The calendar life test procedure assumes that the target test conditions for each cell or group of cells have been defined, typically in a device-specific test plan.

3.10.1 Calendar Life Test Planning

Careful planning and analysis of calendar life tests are critical to estimation of battery life with high confidence. Accurate life estimates are, in turn, essential for assessing battery warranty risks and costs.

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

The following recommended approach for calendar life testing is based on Monte Carlo simulations using the EXCEL spreadsheet described in Appendix G.

Calendar life estimates are necessarily based on accelerated test methods. The general approach is to store cells or batteries under open-circuit conditions at elevated temperatures to artificially increase their rates of performance deterioration. The key tradeoff in the selection of storage temperatures is to avoid introducing irrelevant failure modes at too high a temperature, while achieving high rates of deterioration to minimize test time and cost.

Five to seven elevated temperatures should be selected. The lowest temperature should result in approximately half of the target life of 15 years, while the highest temperature should result in an end of life condition at the desired test duration (e.g., two years). Other temperatures should be equally spaced between these extremes. At least three cells should be tested at each elevated temperature.

The cells under test should be stored in an open-circuit condition, but with voltage monitoring using sensing circuits that present negligible loads to the devices under test. Periodically, based on criteria for acceptable decay in open-circuit voltages (and the corresponding SOE), the cells should be brought back to nominal operating temperature (i.e., 30° C) and their performance measured. Such performance tests should be done at least monthly on each cell.

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

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

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

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

3.10.2 Calendar Life Test Procedure

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

1. Characterize the cell using the Static Capacity Test (Section 3.2) and Hybrid Pulse Power Characterization Test (Section 3.3) and other reference tests as appropriate.

2. Discharge the fully charged cell to the target DOD/SOC value at 30ºC. This can be done in one of two ways: (1) [default] remove the appropriate fraction of the cell's rated capacity at a $C_1/1$ rate, or (b) if the open-circuit voltage corresponding to the target DOD/SOC is

known, clamp the cell at this voltage while limiting discharge current to a $C_1/1$ rate and then wait for the voltage and current to stabilize.[x] Note that the default method will typically reach the target DOD more quickly. However, in some cases it may be desirable to use voltage (rather than fractional discharge) as the measure of SOC.

3. Apply a single iteration of the Calendar Life Test Profile defined in Section 3.10.1. 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 at open-circuit condition and wait for the ambient temperature and voltage to stabilize.

5. Apply a single iteration of the Calendar Life Test profile defined in Section 3.10.1 at the same current level defined in Step 3. The device is then placed in an open-circuit state and the test continues at the target conditions.

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

7. At intervals as specified in Table 9 or a device-specific test plan, return the cell to nominal temperature (e.g., 30ºC), observe its open-circuit voltage after a 1-hr rest, and apply a single iteration of the Calendar Life Test profile before discharging its remaining capacity at the $C_1/1$ rate. Conduct a single iteration of the required periodic Reference Performance Tests, and then return the cells to their test temperatures.

8. Repeat this test sequence until the cell reaches an end-of-test condition. Default end-of-test conditions are generally analogous to those for cycle life testing in Section 3.9.1: (a) the Calendar Life Test profile cannot be performed within the voltage limits; (b) the HPPC reference test yields insufficient information to show further degradation; (c) calculated Available Energy is less than the goal; or (d) sufficient data is acquired to project calendar life at 30ºC with a predetermined degree of confidence. Note that condition (d) may take precedence over condition (c) in some cases.

3.10.3 Calendar Life Test Profile

This test profile is intended for once-per-day execution during calendar life testing at the target temperature and state of charge. The data provide daily information regarding the extent and rate of cell degradation during the intervals between periodic reference tests. This test profile differs from Cycle Life Test profiles in that it is not intended for continuous execution; instead, it is executed once during each 24-hr period while the cell under test is maintained at a given temperature and state of charge. The pulse profile is shown in Table 8 and illustrated in Figure 9.

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

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

Table 8. Calendar Life Test profile.

Step Time (s)	Cumulative Time (s)	Relative Current (Ratio)	Relative Net Charge (A-s/A)
9	9	1.0	9.0
60	69	0	9.0
2	71	-1.0	7.0
2	73	0	7.0
47	120	-0.149	0

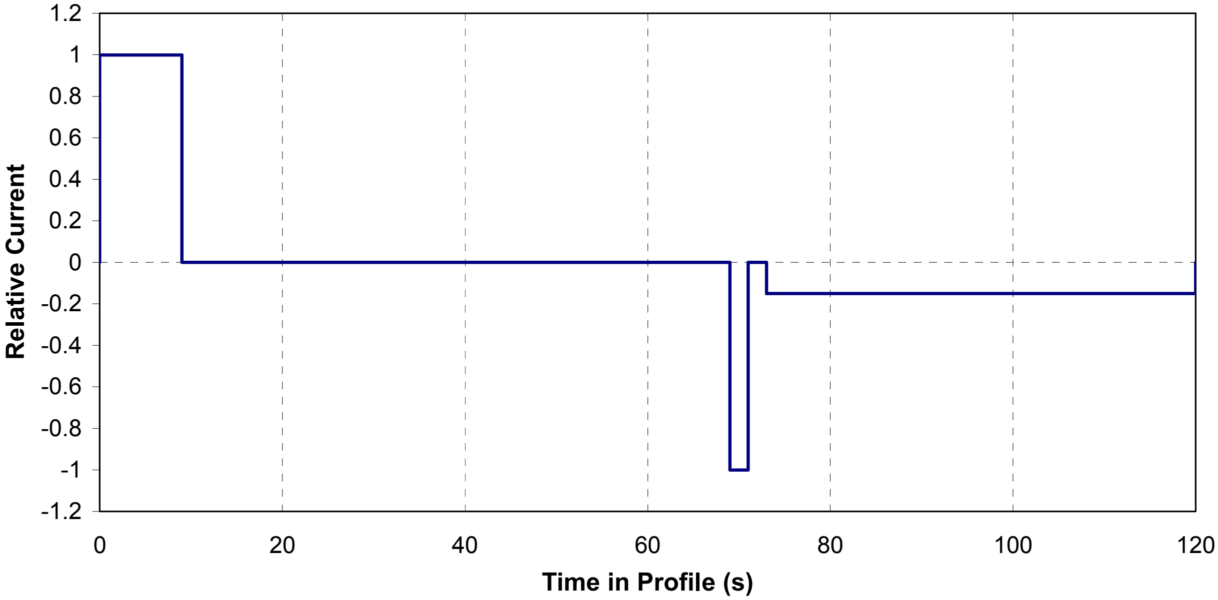

Figure 9. Calendar Life Test profile.

3.10.4 Alternative Calendar Life Test

In some cases calendar life testing may be conducted without using the once-per-24 hr Calendar Life Test profile. The most likely reason for this is a shortage of continuously available test channels for the number of devices to be tested. (If the 24-hr pulse profile is not performed, a test channel is required only for the periodic Reference Performance Tests and possibly for occasional charge increments.) The earlier procedure can be used in this fashion by omitting the daily performance of the test profile specified in Step 4. If testing is performed in this fashion, the device open-circuit voltage should be checked every 24 to 48 hours to verify that the state of charge remains in an acceptable region.

3.11 Reference Performance Tests

Reference Performance Tests (RPTs) are a set of tests performed at periodic intervals during life testing to establish the condition and rate of performance degradation of devices under test. Except as modified by a device-specific test plan, these tests should be performed (a) prior to the start of life testing;

(b) at defined periodic intervals; and (c) at end of testing, for all devices undergoing either cycle life testing or calendar life testing. [z]

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.[aa] These tests are performed for all HEV testing modes.

Table 9. Reference Performance Tests and Test Intervals for Life testing.

Type of Life Testing	Interval Between RPTs	Reference Performance Tests
Cycle Life Testing	30,000 cycle life profiles (25 Wh or 50 Wh profiles as appropriate)	C_1/1 Constant-Current Discharge Test Low-Current HPPC Test
Calendar Life Testing	Approximately 25 days (600 hours)	
Other Life Tests TBD	10% of expected life	

Table 9 also lists typical intervals for reference tests during cycle life and calendar life testing. In practice, these intervals may have to be adjusted somewhat to synchronize reference testing for groups of multiple cells, especially where calendar life and cycle life cells are being tested in the same temperature chamber.

3.12 Impedance Spectrum Measurements

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

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

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[z] For battery chemistries that have a strong dependence of performance on temperature, it may be desirable to measure accurately the actual (ambient) temperature of the test article during the RPTs and adjust the performance results using the data from the Thermal Performance Tests (Section 3.6) to estimate the present performance at the nominal 30°C temperature. Performing such an adjustment is necessarily limited to those cases where the following conditions are satisfied: temperature data is available with accuracy better than the variations to be corrected (2°C or less); Thermal Performance Test data is available "near" the normal testing range, e.g., within ±5°C on either side of the nominal temperature; and the test whose data is to be adjusted is conducted within this limited range "near" the nominal temperature.

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

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

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

3.13 Module Controls Verification Tests (Module-Level Testing)

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

Electrical Behavior - Power and energy required for module controls
- Electromagnetic interference (EMI) generation and susceptibility
- Cell balancing behavior and energy use

Thermal Behavior - Effectiveness of thermal control (cooling and/or heating) with ambient temperature variation
- Energy required for thermal control (cooling and/or heating) with ambient temperature variation

3.14 Thermal Management Load (System-Level Testing)

Verification of overall thermal behavior is necessarily done at the system level due to the broad operating temperature range (-30ºC to +52ºC) specified by the FreedomCAR 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 FreedomCAR 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.

3.15 System-Level Combined Life Verification Test

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

In principle such a test regime consists of a calendar life test performed as in Section 3.10, interspersed with periodic (typically daily) intervals of life cycling. The number of life cycles to be performed each day is determined by dividing the total cycle life goal by the predicted calendar life (in days) at the test temperature. For example, if the projected calendar life of a battery at 50°C is 300 days, the 300,000-cycle life goal could be demonstrated by performing 1000 cycle life test profiles each day.

In practice there are other issues to be considered. The 300,000-cycle life goal is considered to apply at the battery’s nominal operating temperature (30°C by default), while calendar life testing is normally done at significantly elevated temperatures to accelerate the testing. Thus the effects of cycling at elevated temperatures cannot be assumed to be the same as at normal temperature. The preferred way to address this problem is to have an “equivalent” cycle life at the calendar life test temperature, based on cycle life testing previously performed at the same temperature. This temperature-equivalent number of cycles is then distributed over the calendar life testing. Under such conditions, this combined life test can be expected to show whether and to what extent there is a deleterious interaction between calendar life and cycle life performance.

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

4. ANALYSIS AND REPORTING OF TEST RESULTS

4.1 General

For purposes of test reporting consistency (particularly between multiple testing organizations), a required minimum subset of information, based on the procedures in this manual, has been compiled for FreedomCAR 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 FreedomCAR operating conditions, and thus it does not reflect conformance to the FreedomCAR 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.

4.2.1 Capacity Fade

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

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

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

4.3 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 FreedomCAR goals. Since the FreedomCAR 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 3.1.2.) The Battery Size Factor for a cell is necessarily specific to either the Minimum or Maximum Power-Assist 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 11. From these data, OCV at other DOD values can be estimated by straight-line interpolation or by fitting a curve through the measured data.

4.3.2 Calculated Resistance Characteristics as a Function of Depth of Discharge

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

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

Discharge and regen resistances are determined using a ΔV/ΔI calculation for each iteration of the test profile, in accordance with Equations (2) and (3) and Figure 10. Resistances are normally only calculated for completely unabated test profile pulses, i.e., those with full duration and amplitude.[bb]

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

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

The signs of all terms in these equations have been chosen to agree with the manual convention that discharge current is positive and regen current is negative, thus assuring that the calculated resistance is always a positive quantity. These discharge and regen resistances are plotted as a function of depth of discharge, as shown in Figure 11. Also it may be informative to plot open-circuit voltage on this same figure as shown here. Note that only one set of goals (Minimum or Maximum Power-Assist) may be applicable to a given device under test.

[bb] 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 FreedomCAR goals.

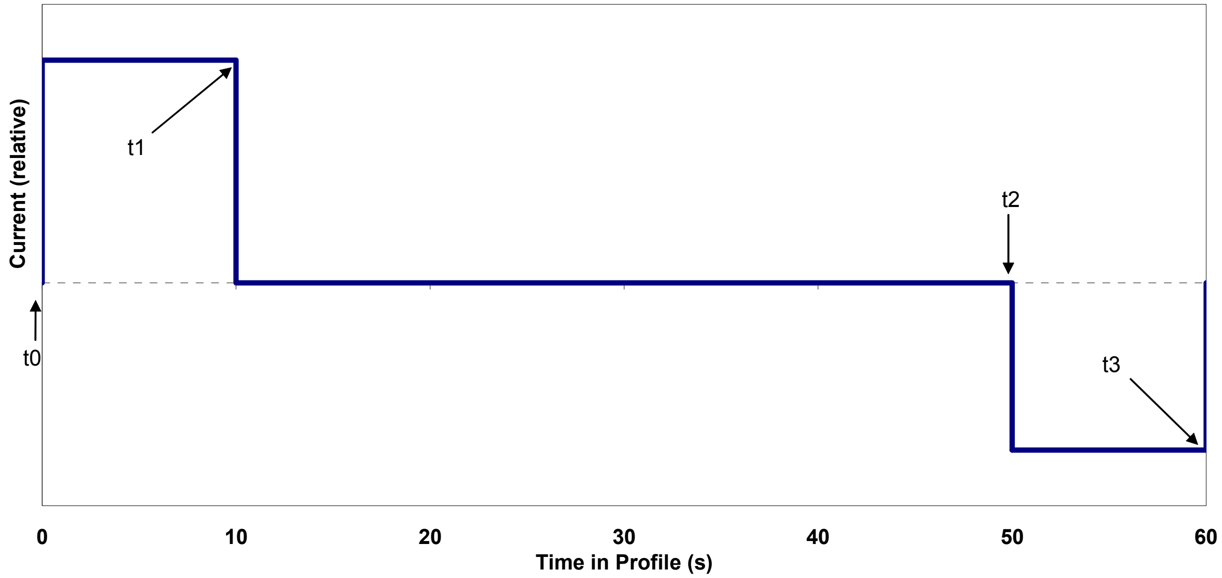

Figure 10. Resistance calculation time points.

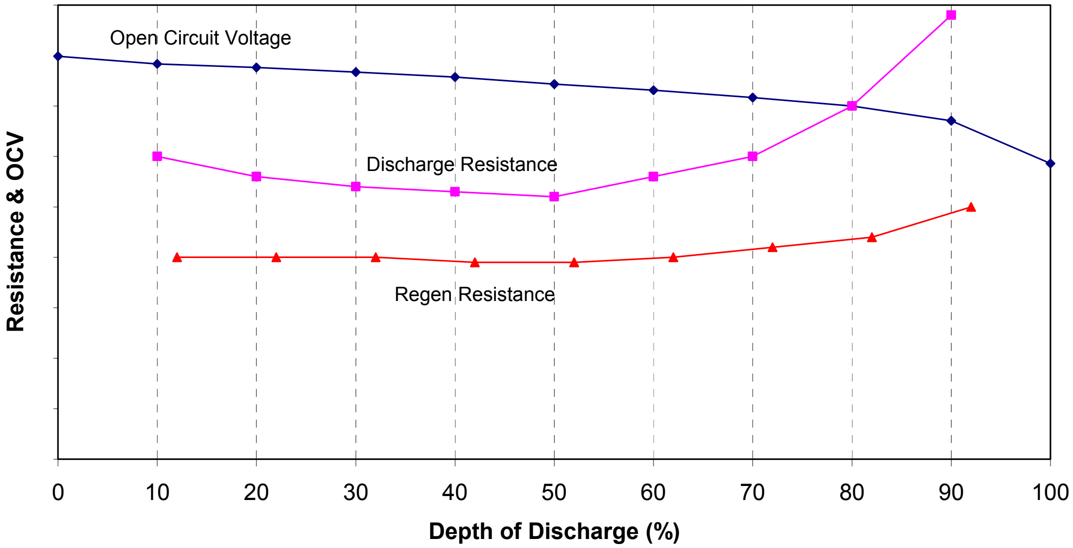

Figure 11. Open-circuit voltage and pulse resistances versus depth of discharge.

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 [f] 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 11), using Equations (4) and (5).

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

and

$$\textit{Regen Pulse Power Capability} = V_{MAX} \bullet (V_{MAX} - OCV_{regen}) \div R_{regen}\text{[cc]} \quad (5)$$

These power capability values are used to determine the total available depth of discharge and energy swing that can be used (within the FreedomCAR operating voltage limits) for specified discharge and regen power levels. Note that profile charge removal has to be accounted for in determining DOD.[dd] An example of the power capability versus DOD plot is shown in Figure 12. (Power values shown are for illustration only.)

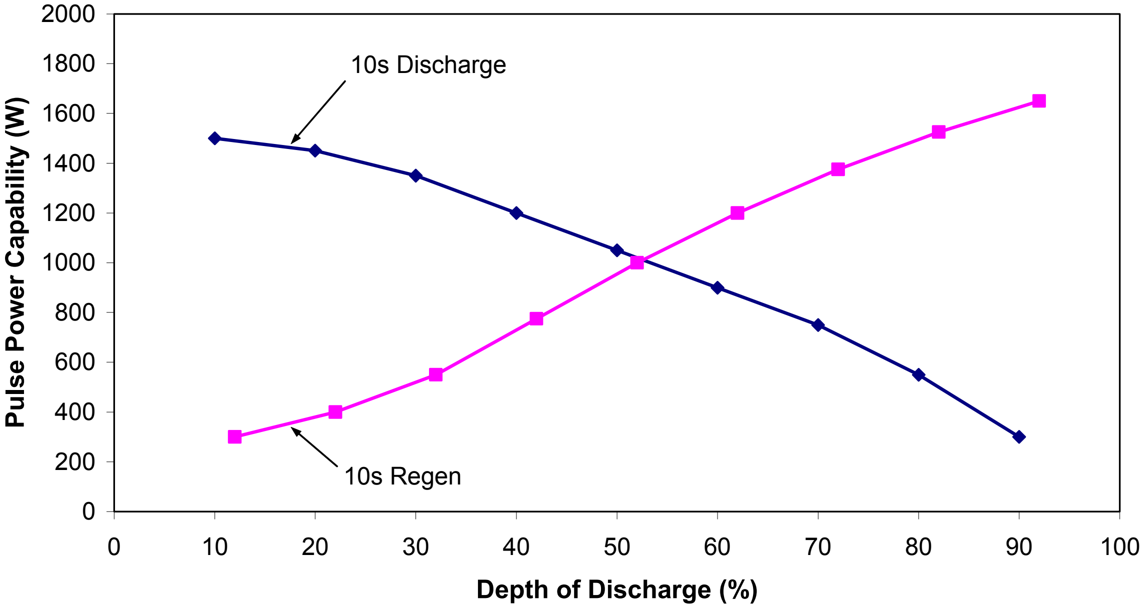

Figure 12. Pulse power capability vs depth of discharge.

4.3.4 Available Energy

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

1. Establish the relationship between HPPC power and $C_1/1$ energy as a function of DOD.

2. Scale both the energy and power results using the Battery Size Factor.

[cc] Note that OCV at the start of each regen pulse must be interpolated from the OCV curve derived from the rest periods before each discharge pulse, accounting for the percent DOD removed by the discharge pulse (i.e., this is not the same OCV used for discharge calculations.) For example, if the discharge pulse starting at 10% DOD removes 3% of the device capacity, the subsequent regen pulse OCV is interpolated starting at 13% DOD.

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

3. Determine the minimum and maximum DOD values over which the FreedomCAR power goals can be met.

4. Calculate the available ($C_1/1$) energy over the discharge region where the goals are precisely met.

HPPC power capability and $C_1/1$ energy values are related by assuming that the corresponding measured DOD values in a pair of such tests are equivalent.[ee] With this assumption, Figure 12 can be transformed to a power-versus-energy plot by replacing each DOD value from the HPPC data with the energy value at that DOD from a corresponding $C_1/1$ test. Figure 13 shows an example $C_1/1$ equivalence, and Figure 14 illustrates the resulting HPPC power versus $C_1/1$ energy plot for cell-level data.[ff] (Power and energy values are illustrative only.)

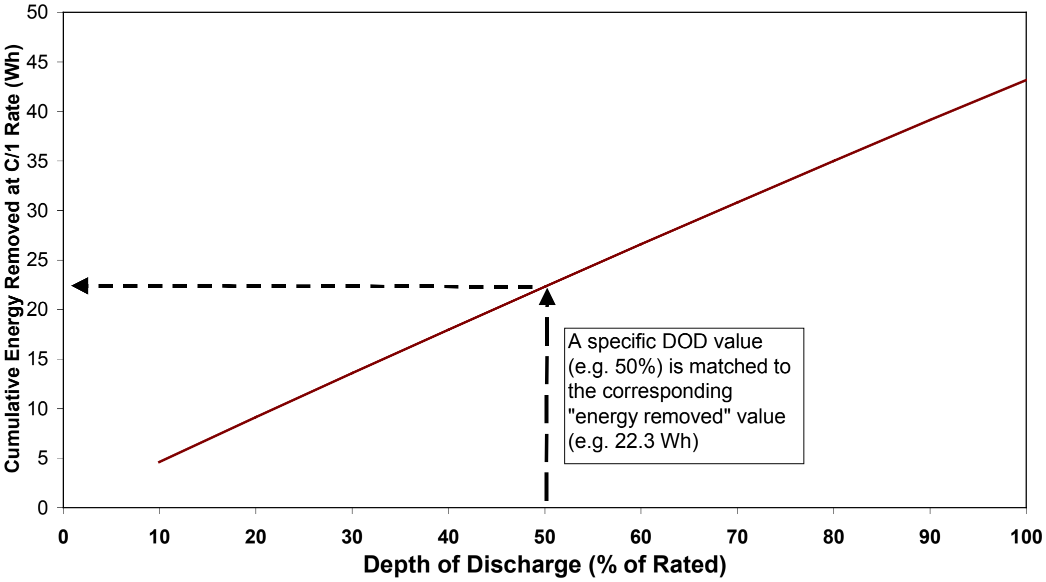

Figure 13. Relationship between energy and DOD in a $C_1/1$ discharge.

[ee] This equivalence is not exact, because part of each 10% capacity increment removed in the HPPC test is due to the pulse profile. However, for high-power batteries the corresponding DOD values are assumed to represent the same state of charge in both tests.

[ff] In Figure 16 and the following figures, the data markers continue to correspond to data taken at 10% DOD intervals.

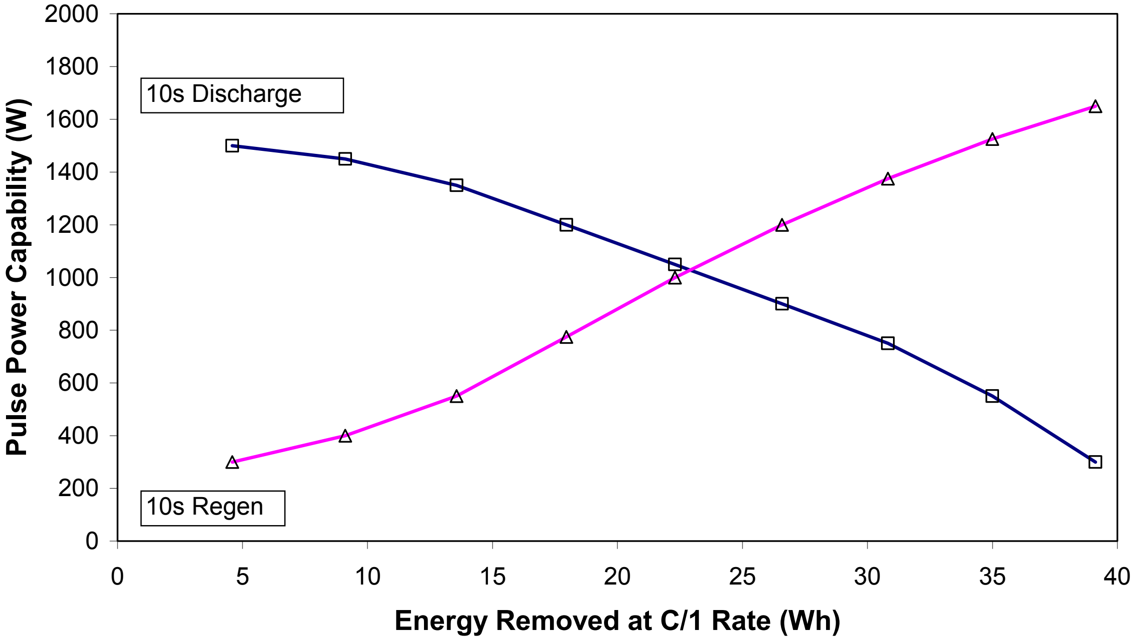

Figure 14. Unscaled HPPC cell power capability versus $C_1/1$ energy removed.

This power-versus-energy data plot can now be scaled by the Battery Size Factor for comparison with the FreedomCAR goals. This is performed by multiplying all cell-level power and energy values by the Battery Size Factor (for Minimum or Maximum Power-Assist as applicable). 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, e.g., 20-kW regen and 25-kW discharge for the Minimum Power-Assist goals. Figure 15 illustrates the result of this scaling applied to Figure 14, for a Battery Size Factor of 40.

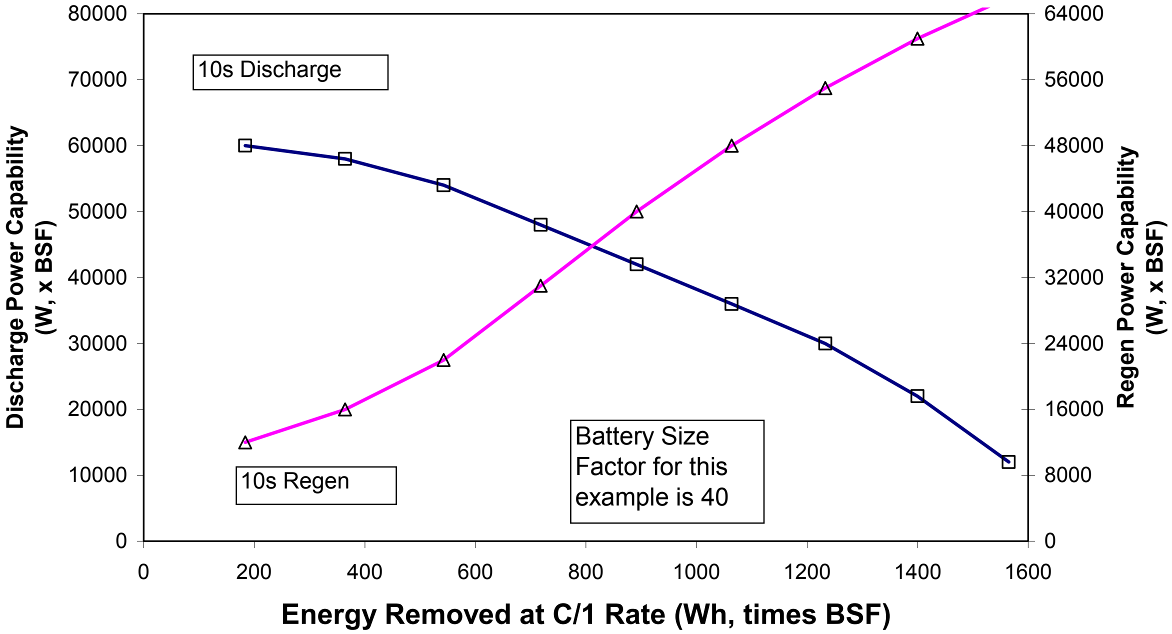

Figure 15. HPPC power versus $C_1/1$ energy scaled by the Battery Size Factor.

Note that the crossover point of the two power capability curves shifts when the axes are scaled in proportion to the discharge and regen pulse power goals. Because of the way these pulse power values are calculated in Equations (4) and (5), changing the operating voltage limits V_{MAX} and/or V_{MIN} will also cause the curves to shift relative to each other. Thus the location of the usable energy range can be varied if desired by altering the operating voltage range (within the allowable FreedomCAR voltage limits.)

The comparison of these results to the FreedomCAR 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 16. (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 1330 Wh and 480 Wh, or 850 Wh.[gg]

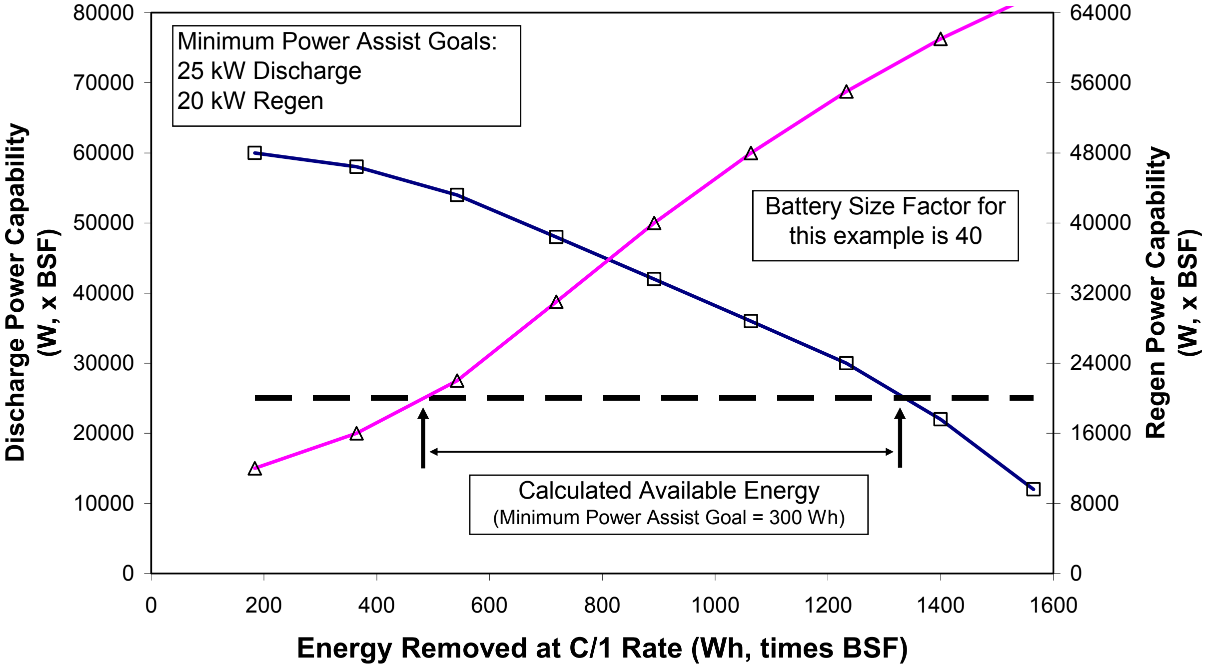

Figure 16. Available Energy determination.

In the example, this result would indicate an energy *margin* of 550Wh over the Minimum Power-Assist goal of 300 Wh. Some margin is necessary at beginning of life to allow for the degradation of power capability and available energy that occurs over both life cycling and calendar life. Because the FreedomCAR 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 illustrated in Figure 17 (which is derived from a different data set than other

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[gg] These data values are illustrative only. In practice, a value of available energy that equaled almost 3 times 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.

illustrations in this section.) This figure shows the energy margin and power margin at beginning of life, and it illustrates how these margins are zero (by definition) at end of life.[hh]

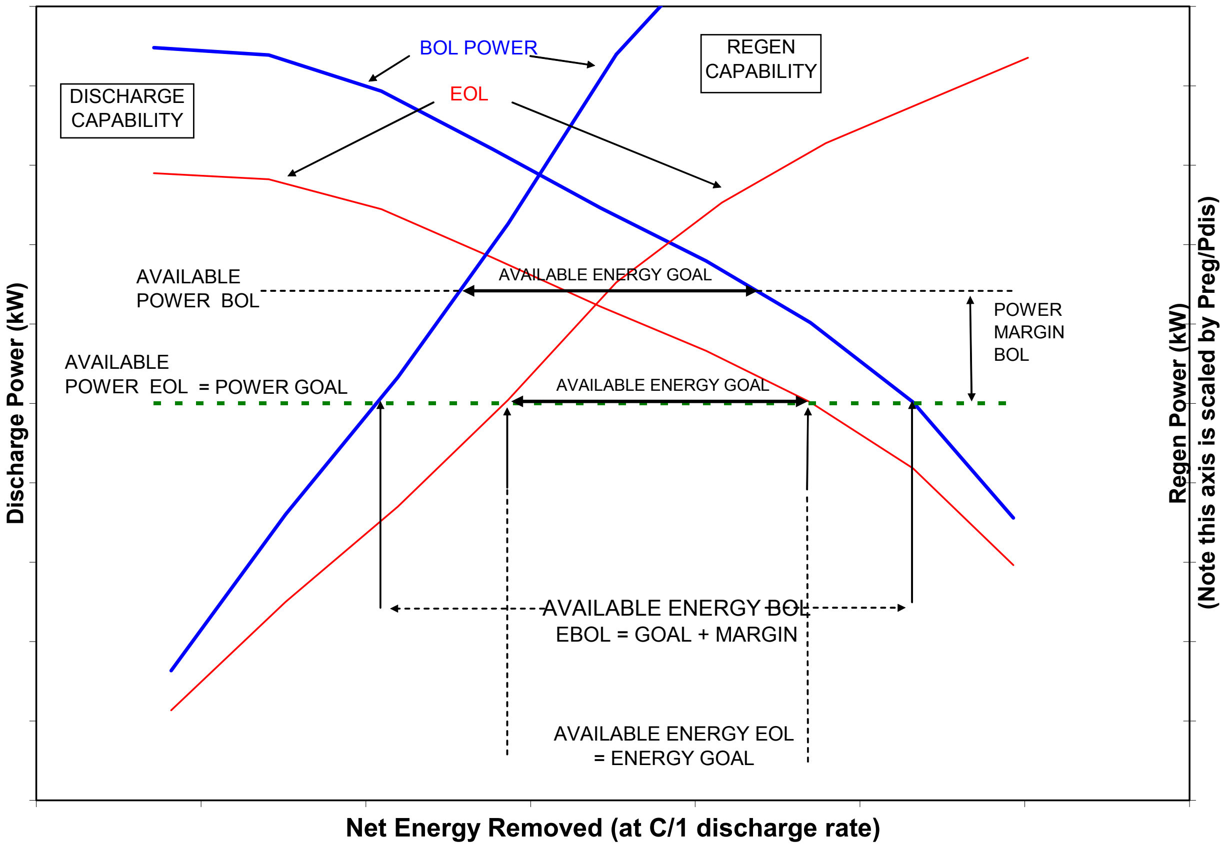

Figure 17. Available Energy and Available Power margins over life.

4.3.5 Available Power

Available Power is the discharge power capability at which usable energy is equal to the Available Energy goal for a given mode. In effect it is the maximum discharge power capability at which the Available Energy goal is precisely met. Available Power is illustrated at both beginning-of-life (BOL) and end of life (EOL) conditions in Figure 17. Available Power at EOL is precisely equal to the discharge goal power. This parameter is defined primarily for reporting battery degradation over life. Available Power and Available Energy in fact represent two complementary aspects in the performance of a battery at any point in time.

A more complete representation of the energy and power behavior is represented by the example Usable Energy versus Power curve illustrated in Figure 18. The usable energy is calculated as the energy between the discharge and regen power capability curves at various values of discharge pulse power. In this context, Figure 16 illustrates one such specific energy value (Available Energy) which happens to be

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

calculated at a power equal to the discharge pulse power goal. More information about computing this curve and finding Available Energy and Available Power is found in Appendix E.

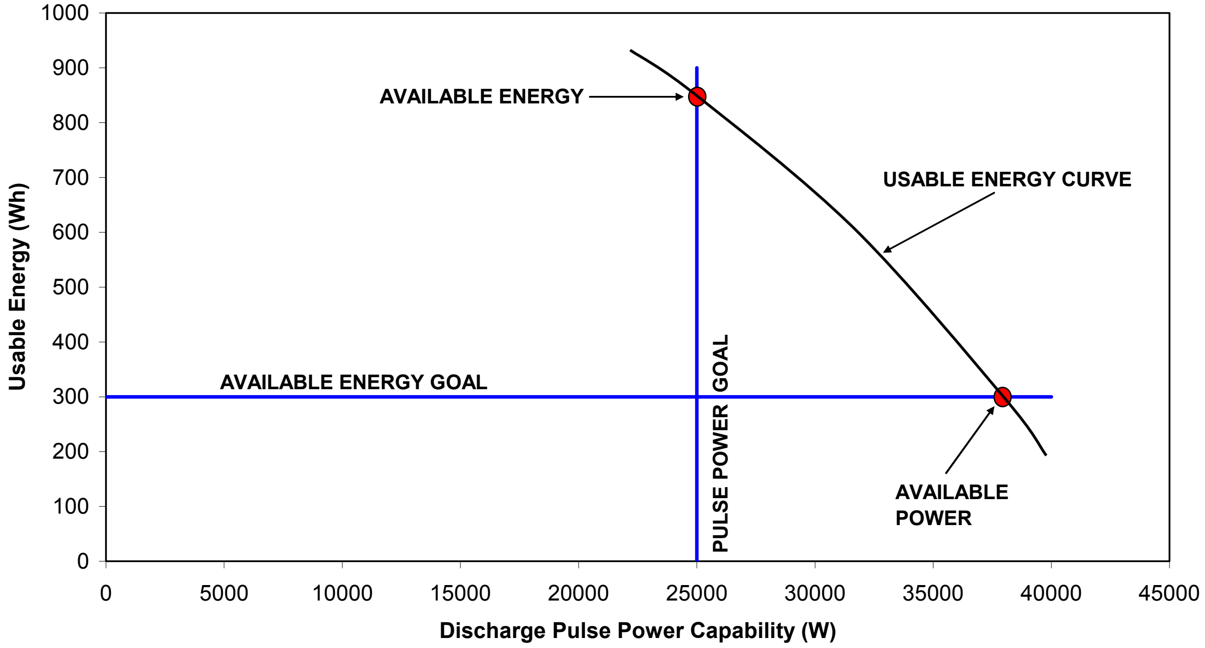

Figure 18. Usable energy versus power curve.

4.3.6 Power and Energy Fade

For devices subjected to life testing, the change in Available Power and Available Energy from the beginning-of-life values (measured just prior to the start of life testing) to some later point in time are to be reported periodically as Power Fade and Energy Fade, both expressed as percentages of the original (BOL) values as shown in Equations (6) and (7).

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

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

In both cases *t0* refers to the time of the initial (BOL) RPT and *t1* refers to the time of the later RPT where power and energy fade are to be determined.

4.3.7 Minimum and Maximum DOD Values

Minimum and maximum DOD values where the FreedomCAR 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 16, but plotted against the original DOD values from the HPPC test (i.e., DOD values are not converted to the equivalent $C_1/1$ energy values.) Figure 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 28 and 76%, respectively. Figure 19 also shows that the maximum DOD value where the Available Energy goal is just met is about 57% 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 17) and transferring this power value to the discharge power vs DOD curve.

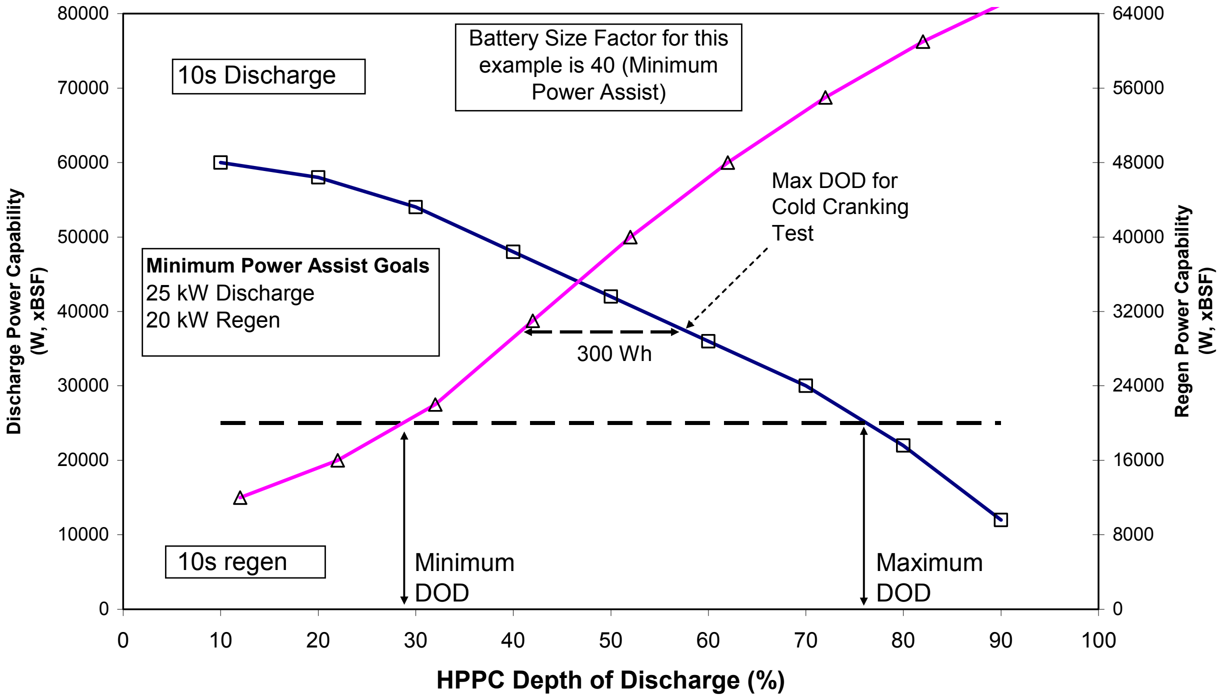

Figure 19. Minimum and maximum DOD values where FreedomCAR goals are met.

4.3.8 Pulse Power Characterization Profile Voltage Response

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

4.3.9 Other Laboratory Cell Performance Characteristics

Other laboratory cell performance characteristics can be calculated from the HPPC data to permit scale-up calculations to full-size cells. These include some or all of the following:

- Voltage response time constant estimates for discharge, regen, and rest periods derived from the current-driven HPPC test data
- Cell capacity and energy in area-specific, volumetric, and gravimetric units (mAh/cm^2, mWh/cm^2, Ah/kg, Wh/kg, Ah/liter, Wh/liter)
- Cell area-specific impedance (ASI) in ohms-cm^2 for discharge and for regen from HPPC data for Power-Assist applications.

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

4.3.10 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 Low Current HPPC test results. The method for doing this is effectively an inversion of the available energy calculation process described in Section 4.3.4, with steps as follows:[ii]

1. Establish the relationship between HPPC power and C_1/1 discharge energy, both as functions of DOD, and plot this relationship as shown in Figure 14.

2. Rescale the regen power by the ratio of the regen power and discharge power goals and re-plot the results as in Figure 16, but without a Battery Size Factor applied.

3. Develop the Usable Energy versus discharge pulse power capability using the method described in Section 4.3.5 and depicted in Figure 18, again without applying a Battery Size Factor multiplier to the results. Figure 20 illustrates such a graph along with the results of the following steps.

4. On the Usable Energy graph, draw a line from the origin having a slope equal to the ratio of the energy goal to the discharge power goal with a 30% power margin. For Minimum Power-Assist, this slope would be 300 Wh ÷ [25 kW x 1.3].[jj]

5. Determine the value of energy at the point where this line intersects the Usable Energy curve.

6. Divide this energy value into the energy goal. The result (normally rounded to the next larger integer) is the Battery Size Factor. For the graph shown in Figure 20, the resulting BSF would be about 35 cells, rather than the previously-shown arbitrary value of 40.

7. Verify that this Battery Size Factor is still expected to give round-trip efficiency values within the FreedomCAR goals at end of life. This can be done by executing the Efficiency Test at a power level scaled at 130% of the normal value (i.e., test power = full system power divided by Battery Size Factor and multiplied by 1.3.) [kk] However, the efficiency can

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

[jj] Note that this 30% power margin will not necessarily 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 Minimum Power-Assist, 80 for Maximum Power-Assist), but the P/E function for a given device is highly nonlinear. Thus, the effect of this 30% power 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.

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

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.

8. 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.)

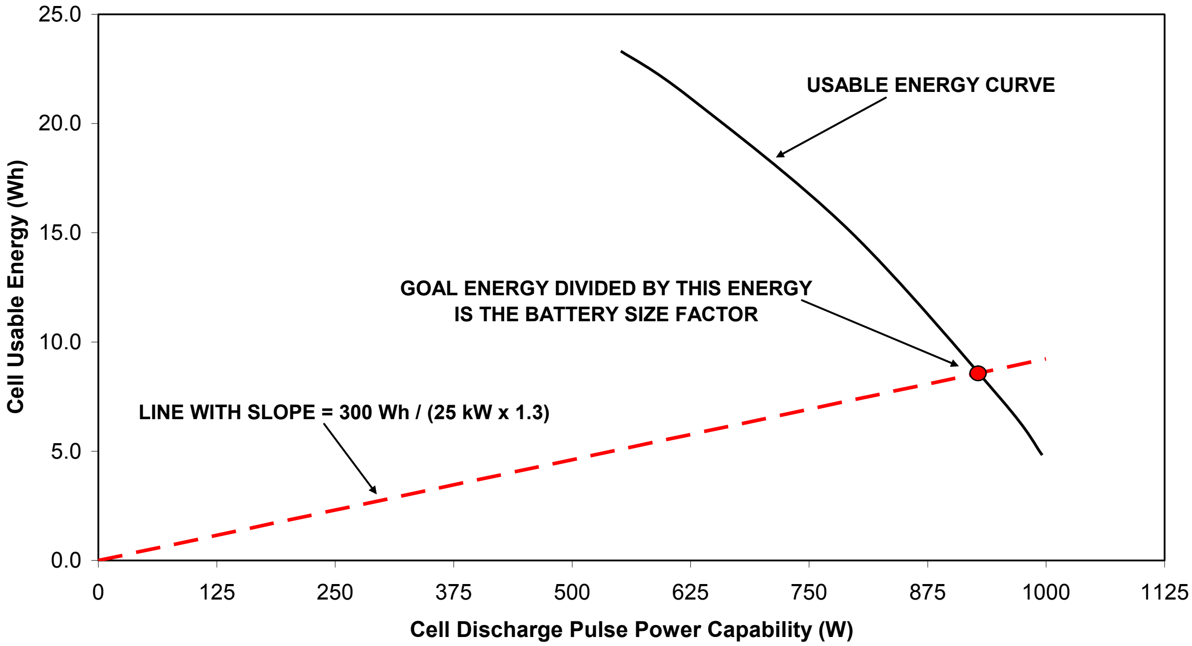

Figure 20. Finding a Battery Size Factor Using Device-Level Results.

4.4 Self-Discharge Test

Self-discharge rate is determined over a fixed period (nominally 7 days) at one or more intermediate DOD conditions (nominally 30% DOD). The difference between the energy (watt-hours) capacities measured prior to the test and during the test is considered to be the energy loss reflecting self-discharge during the stand period. This energy loss is computed as the difference between the pretest $C_1/1$ energy and the sum of the energies in the partial $C_1/1$ discharges before and after the stand period. This value is then divided by the length of the stand period in days and multiplied by the appropriate Battery Size Factor for the applicable mode, as shown in Equation (8).

$$Self\ Discharge = \frac{Wh_{C/1\,before\ test} - (Wh_{part\ 1} + Wh_{part\ 2})}{Stand\ Time\ in\ Days} \times BSF \qquad (8)$$

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

4.5 Cold Cranking Test

The fundamental result of the Cold Cranking Test is the power capability at the end of the third 2-s pulse at -30°C, which is to be multiplied by the Battery Size Factor and compared to the FreedomCAR goal of 5 or 7 kW depending on mode. The actual power achieved does not necessarily represent the maximum power capability; it merely shows whether the device was able to meet the goal. (Some batteries may be capable of higher power than this.) The maximum power capability may be calculated in a manner analogous to the normal pulse-power capability results, as follows:

1. Calculate discharge pulse resistance values using the voltage and current values at three pairs of time points [(t0, t1), (t2, t3), and (t4, t5), illustrated in Figure 21, using the same ΔV/ΔI calculation (Equation [2]) used for discharge resistance in Section 4.3.2.
2. Calculate the discharge pulse power capability for each of the Cold Cranking Test pulses using Equation (4) as in Section 4.3.3. The current limitations described in the footnote to this section must also be observed here. If the manufacturer specifies a minimum discharge voltage specifically for cold cranking, this voltage must be used for the calculation in place of the normal Minimum Discharge Voltage.
3. Multiply each of these three pulse power capability values by the Battery Size Factor and report the resulting power values for comparison with the FreedomCAR goal of 5 or 7 kW.

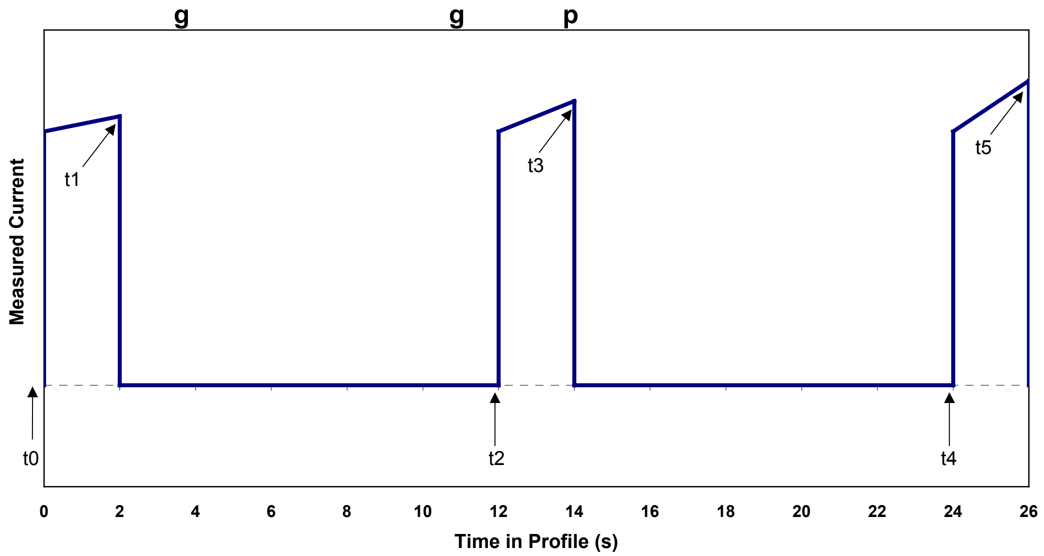

Figure 21. Cold Cranking Test resistance calculation points.

4.6 Thermal Performance Tests

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

4.7 Energy Efficiency Test

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

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

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

3. Calculate round-trip efficiency as the ratio of discharge energy removed to regen energy returned during the profiles, expressed in percent as shown in Equation (9).

$$Round\text{ - }trip\ efficiency = \frac{watt \cdot hours\ (discharge)}{watt \cdot hours\ (regen)} \times 100\ \ (\%) \tag{9}$$

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

4.8 Operating Set Point Stability Test

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

4.9 Cycle Life Tests

For the selected life test profile, the cumulative number of test profiles executed prior to the most recent Reference Performance Tests is reported, along with any performance changes measured by these Reference Performance Tests. If testing is terminated due to the inability of the cell to perform the programmed test profile within the voltage limits or some other end-of-test condition, this is reported.

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

However, the number of profiles performed is not necessarily the cycle life and should not be reported as such. Detailed results of the reference tests are reported over life as described under these specific tests, including the magnitude of adjustments made (if any) due to the measured temperatures being above or below the nominal temperature. In addition, degradation of capacity, pulse power capability, Available Energy, and Cold Cranking Power capability as a function of life (i.e., number of test profiles performed) should be reported graphically.

The value of cycle life to be reported for a device subjected to cycle life testing is defined as the number of test profiles performed before end of life is reached. In general an end of life condition is reached when the device is no longer able to meet the FreedomCAR goals (regardless of when testing is actually terminated). 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 FreedomCAR technical goals (e.g., the cold cranking power, efficiency or self-discharge goal) also constitutes end of life. The basis for the reported cycle life value (i.e., the limiting goal condition) should also be reported. [mm] If the cycle life based on power and energy performance is very near the goal, the end of life point may need to be interpolated based on the change in HPPC performance from the previous reference test.

4.10 Calendar Life Test

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

The data analysis procedure consists of the following general steps:

1. Curve-fit the performance data (P) vs. time-at-temperature (t) for each battery at each temperature (T) in °C using a polynomial method.[nn] The degree of the polynomial (n) used should be the same for all the curve-fits, and should be at least two (quadratic fit), but no higher than necessary to obtain an $R^2 > 0.99$ for each polynomial.

2. Correlate each coefficient (C_i) in the polynomials vs. temperature using the Arrhenius method:

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

[nn] This outline is not intended to imply that polynomials are the best form to represent life degradation behavior. However, the example spreadsheet in Appendix G is based on such functions and it has not yet been generalized to work with other models of calendar life behavior.

$$\ln(C_i) = A_i + B_i\,[1/(T + 273.16)]$$

3. Calculate the average value for each coefficient using the following integral:

$$C_{i,AVG} = \int \exp\,[\,A_i+B_i(1/\text{absolute } T\{t'\})\,]\,dt' \quad \text{over the interval } t'=0 \text{ to } 1$$

   Where T{t'} is the specified cumulative battery temperature distribution, and t' is the fraction of time the battery temperature is below T{t'}.

4. Use the average coefficients to obtain the following equation for calendar life (CL):

$$P_{EOL} = P_{BOL} + C_{1,AVG}\,(CL) + C_{2,AVG}\,(CL)^2 + C_{3,AVG}\,(CL)^3 + \ldots + C_{n,AVG}\,(CL)^n$$

   Where P_{BOL} is the average beginning-of-life value of P for all the batteries tested, and P_{EOL} is the corresponding end of life criterion for P.

5. Solve the resulting equation for CL, using numerical methods if necessary.

This procedure should be used for each performance parameter (P) that is a candidate for limiting battery calendar life, including at least the available energy (or energy margin) and cold-start minimum voltage or voltage margin.

An example of this procedure is provided in Appendix G using a simulation of battery calendar life test results for available energy. The simulation is based on a hypothetical quadratic function for the "actual" battery life as a function of temperature, and a hypothetical cumulative temperature distribution. The measured available energy values for each battery at each temperature may be "corrupted" by a user-selected combination of manufacturing variability and measurement-to-measurement variability. These variabilities may be set to zero or to target values based on estimates from the manufacturing and measurement processes. Multiple trials (e.g., 100 cases) can be used to estimate the confidence intervals for battery calendar life at the assumed levels of manufacturing and measurement variability. The analysis of actual calendar life test data can be supported by such simulations by matching observed variabilities with the inputs to the simulation, and running multiple trials at those levels to find, for example, life estimates for an 80% confidence interval.

In addition to the projected calendar life and confidence interval for the analysis procedure described above (at a given point during testing), reported results for this testing should include supporting graphs of the performance parameters versus time. These include (a) capacity versus calendar time and temperature as measured by the periodic $C_1/1$ discharge tests, and (b) cell discharge (10-s) and regen (10-s) resistance versus calendar time and temperature as measured by the periodic HPPC tests. The corresponding values of pulse power capability and Available Energy and Cold Cranking Power capability (all scaled by the Battery Size Factor) are also reported versus calendar time and temperature.

All reported reference test results should include the magnitude of adjustments made (if any) due to the measured temperatures being above or below the nominal temperature.

4.11 Reference Performance Tests

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

4.12 Module Controls Verification Tests

Standard tests are not defined in this manual for module control behavior, so analysis and reporting requirements for such tests must be detailed in device-specific test plans, as needed.

4.13 System-Level Testing

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

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

5. REFERENCES

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

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

Appendix A

Generic Test Plan Outline for FreedomCAR Testing

Appendix A

Generic Test Plan Outline for FreedomCAR 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 *FreedomCAR Battery Test Manual,* Revision TBD, DOE/ID-TBD, published 2003

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 ±3ºC.

3.3 *Requirements for cooling systems or other ancillary equipment required for proper operation of the specific devices to be tested should be included here.*

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 devices as delivered should be recorded.

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

4.4 AC impedance measurements at 1 kHz should be made prior to the start of testing with the devices fully discharged and again with them fully charged. These measurements may be repeated as needed during the testing program.

4.5 *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

Rated Capacity: ____ Ah (C_1/1 rate)

Intended Application: Minimum Power Assist (Yes/No)
Maximum Power Assist (Yes/No)

Battery-Size Factor ____ (state source)

Operating Temperature Range: ____ ºC to ____ ºC discharge
____ ºC to ____ ºC charge
____ ºC to ____ ºC storage
____ ºC to ____ ºC extended storage

5.2 Nominal Values (Information Only)

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

5.3 Discharge Limits

Minimum Discharge Voltage for 10 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 10 s (I_{max}): ____ A
Maximum Continuous Discharge Current: ____ 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 Life Test Conditions

Nominal DOD value for life testing: ____ %
Any special constraints on the control of SOC or DOD should be described here.

5.7 End-of-Test Criteria for Life Testing

1. (Cycle Life testing only) Completion of a number of properly scaled cycle life test profiles adequate to meet the FreedomCAR cycle life goal for the mode tested; or
2. (Calendar Life testing only) acquisition of calendar life data which is adequate to predict the device calendar life at 30 ºC with the desired confidence level; or
3. inability to perform the cycle life test profile or the calendar life test profile at the programmed values at the required DOD without exceeding the voltage limits; or
4. inability to give valid data from the HPPC Reference Performance Test at three or more DOD values (for both discharge and regen); or
5. inability to meet the FreedomCAR power and energy goals based on the BSF; or
6. when directed by the FreedomCAR Program Manager.

6.0 Safety and Health (requirements may be test laboratory-specific)

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.

6.5 Device-Specific Handling Precautions

Any potential safety concerns due to the specific characteristics of the device(s) to be tested should be included here, including cautions provided by the manufacturer. These may include but are not limited to: preferred DOD conditions for handling, use of personal protective equipment, precautions against shorting or overtightening terminals, potentially abusive conditions, storage during non-test intervals and at the end of testing, and disposal or return to the manufacturer after the completion of testing.

6.6 Monitoring and Shutdown System

The temperature of each device shall be monitored by the test equipment, which shall be programmed to terminate testing upon exceeding an allowable operating temperature range, which will be determined by the test engineer.

Specify any requirements for the use of an independent monitoring and shutdown system here, including any alarm and shutdown temperatures or other monitored conditions to be used.

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. Cycle life and calendar life testing (if performed) 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 device at a $C_1/1$ rate. *In general devices should be tested in temperature chambers; exceptions should be specifically spelled out in the test plan.*

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. If devices are to be tested against both Minimum and Maximum Power Assist requirements, the devices to be tested for each mode and any mode-specific constraints should be identified here. 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 FreedomCAR Testing Manual, Reference 2.1 in this test plan.

Table 7.1. Characterization test sequence.

Item	**Sequence of Initial Characterization Tests for All Devices**	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 manufacturer's discharge voltage limit. * Repeat discharge until measured capacity is stable within 2% for three	*

Item	**Sequence of Initial Characterization Tests for All Devices**	No. Iterations
	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 $I_{\mathbf{max}}$ 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 $I_{\mathbf{max}}$, which is _____A.) Pulse Power Capability will be computed initially for all devices using $V_{\mathbf{MIN}}$ to $V_{\mathbf{MAX}}$ voltage ranges of _____V to _____V	2
3	**Self Discharge Test** *(Section 3.4)* *C*onduct this test on all / ____ of the devices for a ____-day stand interval at 30% DOD. *Provide an estimate of expected capacity loss if available.* Note: If the final measured $C_1/1$ is significantly less than the pretest value, contact the Program Engineer prior to beginning life testing.	1
4	**Cold Cranking Test** *(Section 3.5)* Conduct this test at the appropriate BSF-scaled power on _____ devices at -30 °C at the maximum DOD value where the FreedomCAR goals can be met (determined from Low Current HPPC results.) For this test plan, the cold soak time at -30 °C prior to pulse testing shall be _____ hours.	1
5	**Thermal Performance Tests** *(Section 3.6)* *Define any planned thermal performance testing here.*	As Req'd
6	**Efficiency Test** *(Section 3.7)* Perform this test on ____ devices using the BSF-scaled Efficiency Test profile, with each device at the target DOD value specified: *Specify target DOD values here for each device.*	1
7	**Impedance Spectrum Tests** *(Section 3.12)* 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. Cycle Life Test Sequence.

Item	**Sequence of Cycle Life Tests for All Devices**	No. Iterations
1	**Reference Performance Tests** *(Section 3.11)* Perform the Reference Performance Tests required by *Reference 2.1 Table 9* prior to the start of cycle life testing. During cycle life testing, repeat the required Reference Performance Tests at the intervals required by *Reference 2.1 Table 9.* The RPT C/1 discharge data should be included in the same data file with the HPPC results. At completion of cycle life testing, perform the required Reference Performance Tests as above. Also repeat the Impedance Spectrum measurements performed in Table 7.1 No.7 as part of characterization testing.	Periodic
2	**Operating Set Point Stability Test**. *(Section 3.8*) Conduct this test on _____ devices at the target DOD listed, using the cycle life test profile specified in No. 3: *List devices and target DOD values here.* This test is conducted at the beginning of cycle life testing using the same test profile(s) and conditions required for cycle life 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	**Cycle Life Testing** *(Section 3.9)* Subject ____ devices to the appropriate Cycle Life 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. Cycle Life Conditions Device # Cycle Life Profile Target DOD value *List devices, cycle life profiles and target DOD values here.*	Per Table 3.9

Table 7.3. Calendar Life Test Sequence

Item	Sequence of Calendar Life Tests for All Devices	No. Iterations
1	**Reference Performance Tests** *(Section 3.11)* 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 9.* The RPT C/1 discharge 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 3.10)* *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 [nominally 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 cycle life 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 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 regen pulse. Data should be acquired at 10 samples per second during Cold Cranking pulses.

During the 1-hour HPPC rest intervals, $C_1/1$ 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 Cycle Life testing for test profiles recorded; however, not all profiles need to be recorded. 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.

8.3 Data Access *(typical for test laboratory)*

Describe requirements for data protection or archiving here.

All data will be archived. 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 FreedomCAR 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. This HPPC file should also include the associated $C_1/1$ discharge. (Combining these files is done to facilitate automated analysis of the results. The FreedomCAR goals require that Available Energy be calculated from both the HPPC power results and the $C_1/1$ energy.) This file may or may not include the charge prior to the start of the test.

For Self-Discharge Tests, the initial partial discharge, stand period, and final partial discharge after stand should be included in a single data file where possible. This file may also include the initial $C_1/1$ full discharge and any other $C_1/1$ discharge(s) performed immediately after the test if desired.

Cycle Life 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 FreedomCAR 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 FreedomCAR technical team or program management.

10.0 Post-Test Examination and Analysis

Describe any required post-test examination or analysis here.

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/FreedomCAR Program Manager:
Name: ______________
Phone: ______________
Fax: ______________
Email: ______________

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

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

Appendix B

Minimum Test Reporting for FreedomCAR Testing

Appendix B

Minimum Test Reporting for FreedomCAR 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 be performed.) Test conditions are tabulated first, followed by test results.

General Conditions and Limits

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 10-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)
Energy versus DOD (Wh vs %) *(plot)*

Hybrid Pulse Power Characterization Test (at 30 °C nominal)

Peak Discharge Test Current (Low) _____________ (A)
Peak Discharge Test Current (High) _____________ (A)
Battery Size Factor ________________ (Minimum or Maximum Power Assist as applicable)
Source of BSF Values Manufacturer-supplied ___ Calculated from HPPC ___
Minimum FreedomCAR Discharge Voltage used for calculations ____________ (V_{MIN})
Maximum FreedomCAR Regen Voltage used for calculations ____________ (V_{MAX})
(Note: these will normally be the manufacturer-supplied limits unless these must be restricted to stay within FreedomCAR voltage or efficiency limits)

Unscaled results:
Open-Circuit Voltage versus DOD (V versus %) *(plot)*
For Minimum or Maximum Power Assist devices as applicable:
    10-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)

BSF-scaled results:

Discharge and Regen Pulse Power Capability versus Energy (W versus Wh with DOD points marked)
(*plot* simultaneously, for Minimum or Maximum Power Assist as applicable)
Minimum and Maximum DOD values where FreedomCAR power goals are just met
Minimum ______ (%) Maximum ______ (%)
Available Energy at Goal Power Levels (using BSF) ______ (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 ______ (%) (Based on maximum DOD where Available Energy goal is precisely met)
Pulse Power Level Used ______ (W) (should be 5-kW divided by BSF.)
Minimum Allowed Cold Cranking Voltage ______ (V)

Minimum Measured Cold Cranking Voltage ______ (V)
Pulse Power Capability Pulse 1 _____ Pulse 2 ______ Pulse 3 ______ (W) (scaled by BSF)

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

Efficiency Test Profile Used ______________________ (Minimum or Maximum Power Assist)
Efficiency Test Power Level ______ (W) (should be nominal divided by applicable BSF)

Round Trip Energy Efficiency ______ (%)

Operating Set Point Stability Test

No reporting requirements

Cycle-Life Tests

Test Profile Used _____________________ (Minimum or Maximum Power Assist)
Nominal Depth-of-Discharge Used _______ (%)
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)

Results of periodic C/1 and HPPC tests, same reporting requirements as above
Energy Fade and Power Fade versus Life (% vs cycles) *(plot)*
Static Capacity and Capacity Fade versus Life (A-h & % versus cycles) *(plot)*
Usable Energy vs Power over Life (Wh vs W at RPT intervals) *(plot)*
Discharge and Regen Resistance versus Life (ohms versus cycles) *(plot)*

Calendar Life Test

Storage Temperatures (tabulate device ID vs °C)
Total Time at Temperature (to date) ________ (at each test temperature)

Projected Calendar Life at 30°C ______ (years, if available)

Results of periodic reference tests, same reporting requirements as above
Energy Fade and Power Fade versus Life (% vs months) *(plot)*
Static Capacity and Capacity Fade versus Life (A-h & % versus months, at each test temperature) *(plot)*
Usable Energy vs Power over Life (Wh vs W at RPT intervals) *(plot)*
Discharge and Regen Resistance versus time (ohms versus months, at each test temperature) *(plot)*

Impedance Spectrum Measurements

Value As Received _______ (ohms) (1-kHz only)
1-kHz values at other times if measured

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

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

CALENDAR LIFE TESTING AT FIXED SOC

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

CONTINUOUS LIFE CYCLING AT A FIXED TARGET SOC/DOD VALUE[2]

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

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[1] Calendar life testing for the previous PNGV program was often done with the device voltage clamped at a fixed value during the test interval. This approach is not used for FreedomCAR testing.

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

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

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

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

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

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

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

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

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

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

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

Assumptions

1. Cycle life testing generally controls SOC by varying the initial discharge step in the test profile. It is also possible to control SOC by varying the final regen or recharge step. The process is conceptually identical (or at least symmetrical), and the following description deals only with the discharge step control. Use of charge step control is accomplished by varying (e.g., shortening) the charge step when a predetermined maximum voltage is reached. The major difference between the two approaches is that the discharge step method forces the SOC down to the target value, while the charge step method forces the SOC up to the target value.[3]

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

2. The method described for calculating the control voltage is not intended for use with cycle life profiles whose discharge steps are more than10 s in length because this is the length of the HPPC discharge pulse. Extrapolation of the device resistance will be required if this assumption is not satisfied.

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

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

Determination of the Control Voltage (Trial Value)

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

1. Determine the device discharge resistance expected at the end of the cycle life profile discharge pulse, at or near the target SOC/DOD. This is done using HPPC data for the discharge pulse nearest the target SOC. For example, if the target SOC for life cycling is 70%, the 30% DOD HPPC discharge pulse data can be used. The effective resistance is calculated as dV/dI over the planned duration of the cycle life discharge pulse. For example, if the cycle life discharge pulse is 5 s in duration, dV/dI is calculated using the last rest data point before the HPPC pulse starts and the data point 5 s into the pulse.[4]

2. Calculate the voltage drop expected under load at the end of the cycle life discharge pulse as [device resistance] times [pulse current ≈ pulse power/end-of-pulse voltage]. For example, if the pulse current is to be 10 A for5 s and the 5-s device resistance is 30 milliohms, the expected voltage drop at the end of the discharge pulse is 0.3V.[5]

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

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

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[4] *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.*

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

Overall SOC Control Approach and Use of the Control Voltage

The target state of charge is maintained during cycle life testing by varying the length of the test profile discharge step (the first discharge step only, if there is more than one). FreedomCAR cycle life profiles are normally slightly charge-positive at their nominal values. For control purposes, the maximum duration of the discharge step is increased enough to make the profile charge-negative by a similar amount. (Obviously this logic can be reversed if the nominal profile is charge-negative.) The time duration required to do this depends on the magnitude of the discharge step. For example, if the discharge step is 10 W for 10 s, and the test profile is charge-positive by 5 W-s, the maximum duration of the discharge step is increased by one second.[6] The discharge step is thus allowed to vary between 10 and 11 s duration, with a charge-neutral condition expected to occur at about 10.5 s.

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

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

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

Verification of Target SOC and Adjustment of Control Voltage

This process will eventually reach a stable cycling condition. If the starting SOC is near the target value, it normally stabilizes in less than the number of profiles executed by the OSPS test. However, this stable condition is generally not at exactly the target SOC, due largely to internal heating that occurs within the device while cycling. Hence, the OSPS is terminated after a fixed number of profile executions, so that the actual SOC at the cycling condition can be determined. This is done by returning the device to 30°C and then observing the OCV, removing the residual capacity, or both.[7]

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-

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[6] *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.*

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

specific, though 5% SOC has been commonly used), the control voltage must be adjusted and the OSPS repeated. The simplest way to modify the control voltage is to add or subtract the difference between the OCV at the target SOC and the OCV corresponding to the measured SOC at the end of the OSPS. For example, if the OCV at the SOC where the OSPS completes is 50 mV higher than the OCV for the target SOC, the control voltage can be reduced by 50 mV.

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

ADDITIONAL CONSIDERATIONS

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

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

Appendix D

HPPC Data Analysis Procedure

October 2003

Appendix D Contents

1. INTRODUCTION

The Hybrid Pulse Power Characterization (HPPC) Procedure provides the basis for almost all FreedomCAR power and energy related test results. The Test Procedures section of the FreedomCAR 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 were provided as separate reports accompanying Reference 2. These derivations are not part of this appendix. All these tools were originally developed by Harold Haskins of the Ford Motor Company, and some have uses for FreedomCAR analysis that 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 that 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 Minimum and Maximum Power Assist 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 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 FreedomCAR 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.

g. *(Initial Low Current HPPC Test Only)* The Battery Size Factor (BSF) for a device is provided by the manufacturer for scaling all FreedomCAR test results. If it is not provided, it is calculated from the initial HPPC test results as described in Section 4.3.10. In either case, the resulting BSF value must be verified as acceptable with respect to efficiency and operating voltage swing.[1] 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 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 FreedomCAR 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, Available Power, 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 4.3.7.

This analysis process allows the results of a given HPPC test to be compared to the FreedomCAR 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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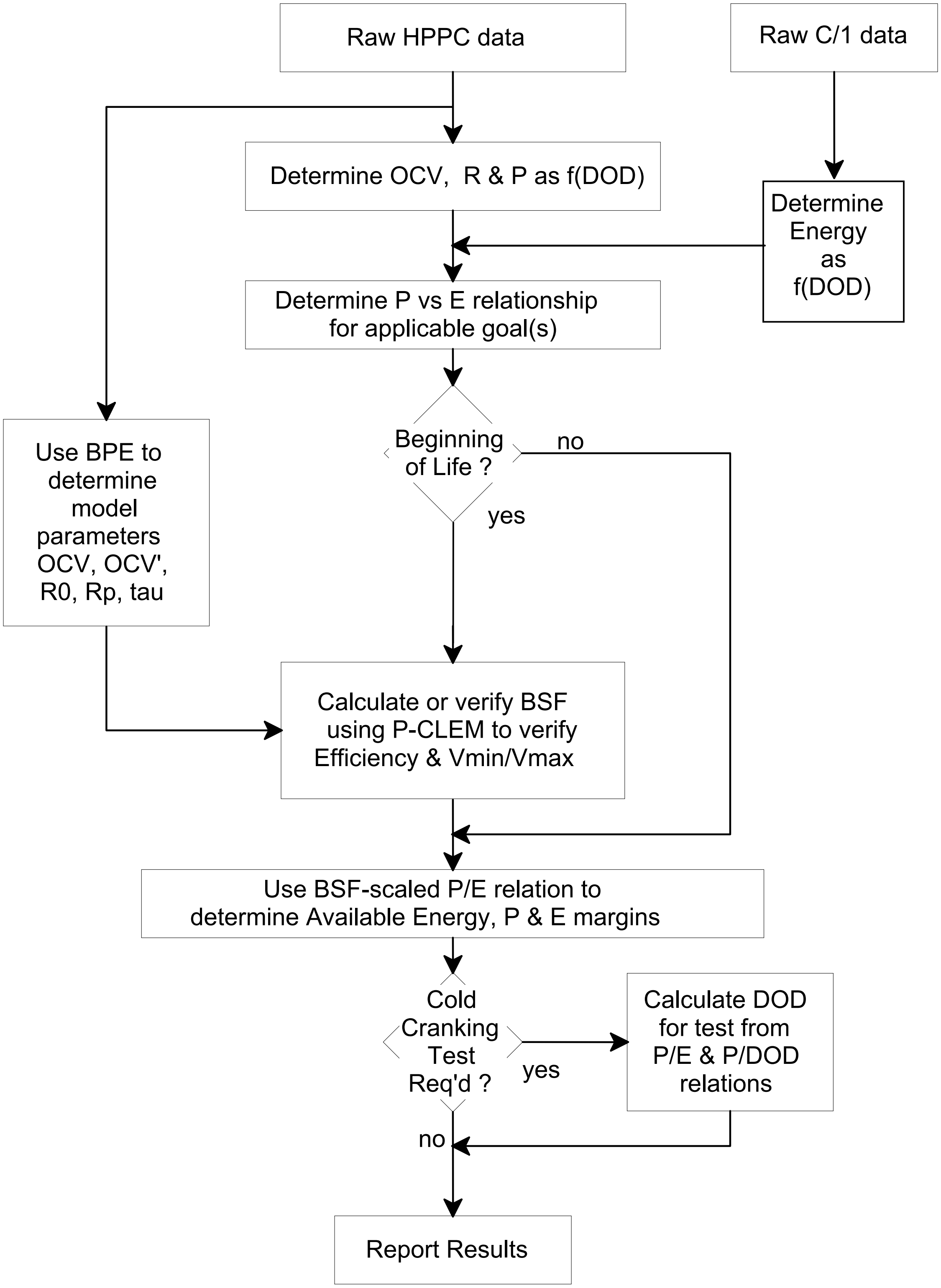
[1] Strictly speaking, the BSF is likely to be affected by the Cold Cranking requirement as well. This manual does not yet provide a means to account for this effect, which may be substantial in some cases.

Figure D-1. HPPC Data Analysis Process



3. BATTERY PARAMETER ESTIMATOR

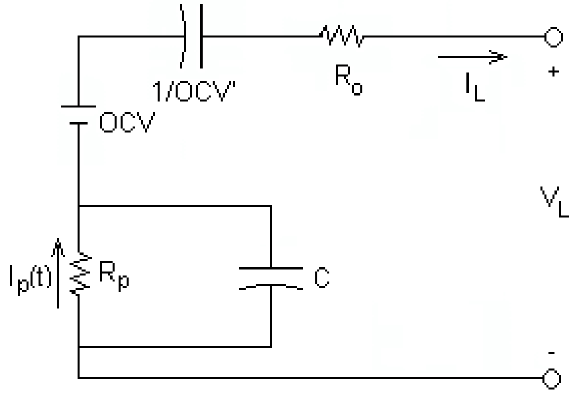
3.1 Lumped Parameter Battery Model

This section describes the simple FreedomCAR 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 a report which accompanied Reference 2.

Note that the Lumped Parameter Model could also be used with battery test data to model a battery system's response to dynamic loading conditions, as might be encountered in vehicle driving cycle simulations. Direct application of the battery HPPC data in these highly dynamic simulations may not provide the desired accuracy in predicting the battery system response. Improved accuracy can be obtained in these cases by applying the correlation method described in this section to test data obtained under continuous pulse profile replications, as would be encountered in the Energy Efficiency Test, Operating Set Point Stability Test or Cycle Life Test defined in sections 3.7 through 3.9 of this manual. Due to different physical responses of the battery cells between the HPPC procedure (with a one-hour rest prior to each pulse profile) and continuous profiles (which reach a stable steady-state response), the correlation coefficients from this method are expected to be different, particularly the "polarization time-constant." Correlation coefficients based on HPPC data are recommended for use in establishing the Battery Size Factor and the energy and pulse power performance margins.

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 FreedomCAR 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 FreedomCAR lumped parameter model is shown in figure D-2.

Figure D-2. FreedomCAR 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
$\frac{1}{OCV'}$	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 .[2]

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

where the polarization current I_p is the solution of the differential equation $\frac{dI_P}{dt} = \frac{(I_L - I_P)}{\tau}$ with a specified initial condition, e.g., $I_p = 0$ at $t = 0$.

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 **OCV$_0$**, **OCV’**, **R$_o$** , **R$_p$** and τ 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.[3] The regression process is most conveniently done using an Excel spreadsheet.

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[2] 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’*.

[3] See Section 3.3 for a detailed description of the HPPC test sequence and pulse profile.

A working example of this spreadsheet[4] is provided with this manual, and an accompanying PowerPoint presentation[5] 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 $\mathbf{\Sigma (I_L \Delta t)}$, 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.[6] A typical test data file will also contain columns for a 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).[7] 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:

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[4] See file "BatteryParameterEstimatorSpreadsheet.XLS"

[5] See file "How_To_Use_The_BPE_Spreadsheet.PPT"

[6] 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.

[7] Equation (2) assumes a linear variation in the load current $\mathbf{I_L}$ over the time interval $\mathbf{\Delta t}$, for integration of the differential equation describing the polarization current behavior in Equation (1). Additional information on the derivation of this relationship is found in Harold Haskins' technical note "Derivation of the Lumped Parameter Battery Model Paragraphs 3.1 and 3.2 of Appendix D of the Test Manual, Rev. 3" included with the CD version of Reference 2.

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

where the time increment between data points is: $\mathbf{\Delta t = t_i - t_{i-1}}$ 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.[8]

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

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

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

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

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

7. Voltage error, $\mathbf{\Delta V}$, calculated using the following formula:

$$\mathbf{\Delta V} = \underline{\mathbf{V}}_{\mathbf{L,\,i}} - \mathbf{V_{L,\,i}}\ ^{\mathbf{9}} \qquad (5)$$

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.[10]

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.

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[8] 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.

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

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

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 the residual sum-of-squares cell. The desired value of τ 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.[11] 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 τ 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.)

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[11] 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.

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 FreedomCAR 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 Minimum Power Assist or Maximum Power Assist 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 Power-based Cycle Life Efficiency Model (P-CLEM) spreadsheet has been developed for certain elements of this evaluation, and a working sample[12] of this spreadsheet is included with this manual. This spreadsheet is similar in principle to an earlier CLEM spreadsheet included with Reference 2. The present version is based on cycle-life test profiles composed of constant-power steps rather than the constant-current steps used in some testing for the earlier PNGV Program. It also incorporates a number of changes to make it significantly easier to use than the previous version. The derivation of the model is described in reports that accompanied Reference 2. In general it uses the same lumped parameter circuit model previously described, although for some calculations this is simplified.

The P-CLEM spreadsheet is used to calculate battery round-trip efficiency for a specific battery design and a power-based cycle-life test profile. The battery design is generated using actual test data for cells, modules, or a complete system. The test results are scaled up to a full battery system using an input battery size factor (BSF). The test profile is assumed to be the general four-pulse type of profile specified in this manual. The profile is forced to be charge-neutral or, if desired for use with subprofiles that are not charge neutral, with a specified residual charge surplus/deficit. If subprofiles are combined, they should be charge-neutral in total to obtain a valid round-trip efficiency.

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, FreedomCAR 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 P-CLEM Spreadsheet

Figure D-4 gives a visual representation of the input and output variables for the spreadsheet. One major difference between the old and new CLEM spreadsheets is that the new version uses the actual cycle-life test profile(s) as inputs, where these profiles are assumed to be defined elsewhere. (The old version used the goal powers instead and required multiple manual iterations to define a set of profile steps that gave the needed efficiency.)

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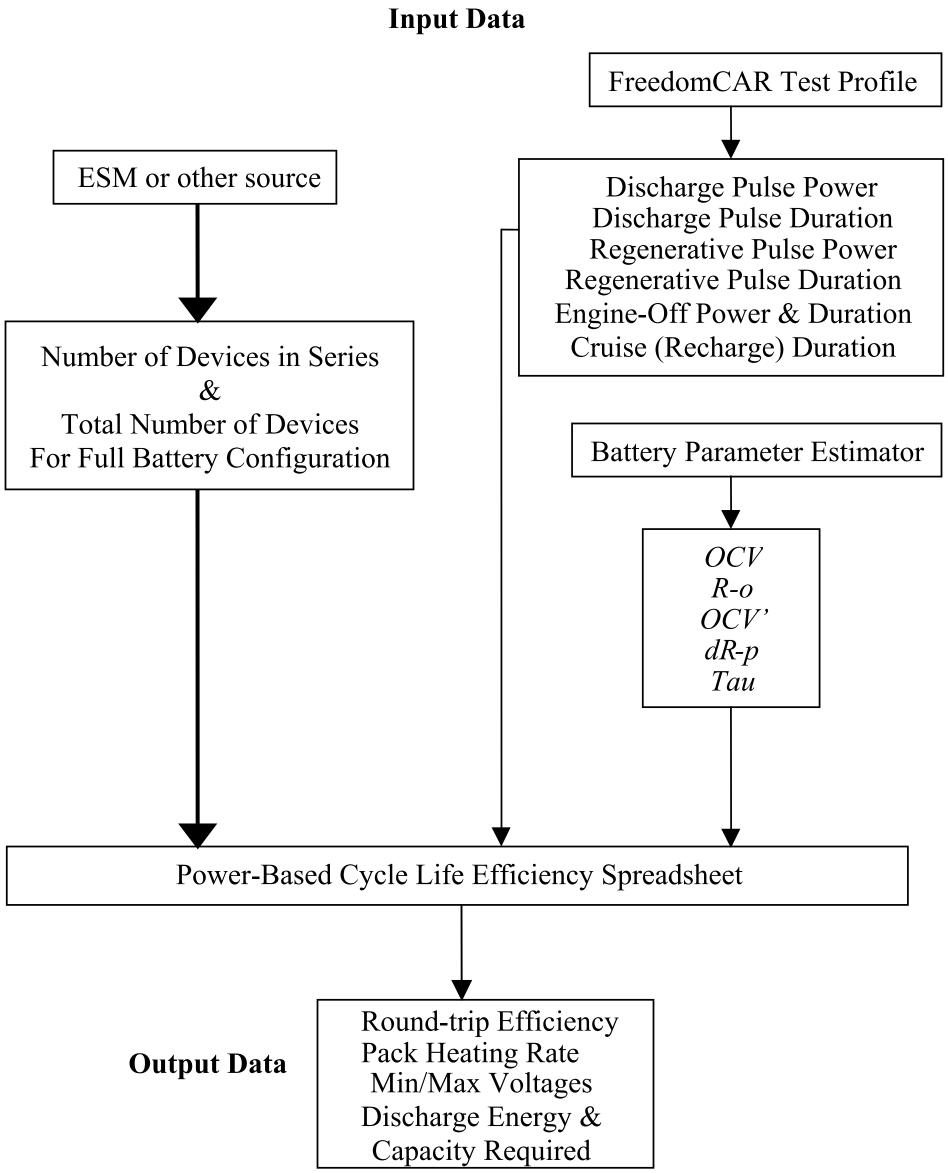
[12] See file "Power-basedCycleLifeEfficiencyModelSpreadsheet.XLS".

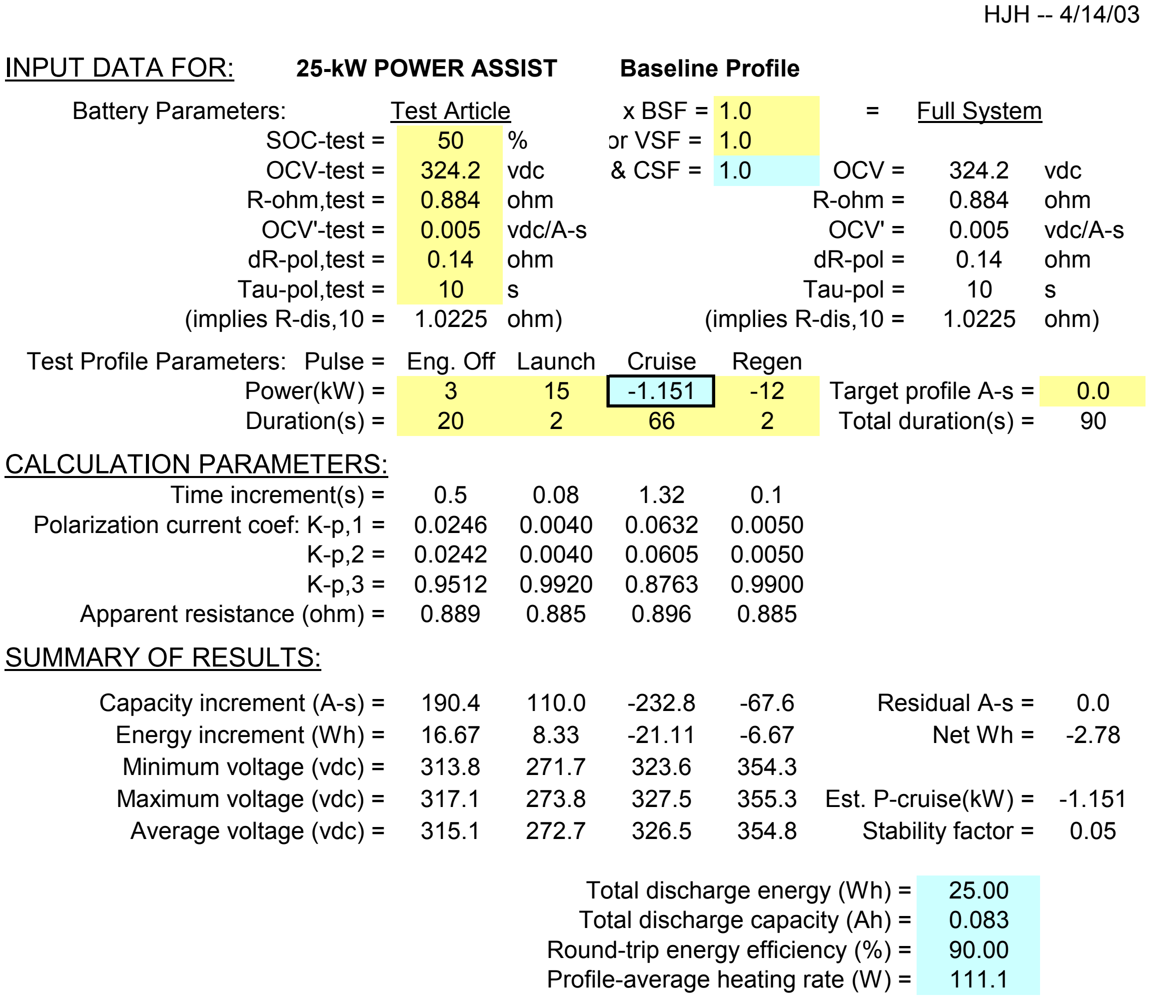
Figure D-4: Inputs and Output for P-CLEM Spreadsheet



4.2.1 Spreadsheet Variables

The labels used in the Excel spreadsheet sometimes differ from the terminology and variable names used elsewhere, so the inputs and outputs are identified below. Figure D-5 illustrates the efficiency spreadsheet with some example values.

Figure D-5. Power-Based Cycle Life Efficiency Calculation Spreadsheet



HJH -- 4/14/03

INPUT DATA FOR: **25-kW POWER ASSIST** **Baseline Profile**

Battery Parameters:	Test Article		x BSF =	1.0	=	Full System		
SOC-test =	50	%	or VSF =	1.0				
OCV-test =	324.2	vdc	& CSF =	1.0	OCV =	324.2	vdc	
R-ohm,test =	0.884	ohm			R-ohm =	0.884	ohm	
OCV'-test =	0.005	vdc/A-s			OCV' =	0.005	vdc/A-s	
dR-pol,test =	0.14	ohm			dR-pol =	0.14	ohm	
Tau-pol,test =	10	s			Tau-pol =	10	s	
(implies R-dis,10 =	1.0225	ohm)			(implies R-dis,10 =	1.0225	ohm)	

Test Profile Parameters: Pulse =	Eng. Off	Launch	Cruise	Regen		
Power(kW) =	3	15	-1.151	-12	Target profile A-s =	0.0
Duration(s) =	20	2	66	2	Total duration(s) =	90

CALCULATION PARAMETERS:

Time increment(s) =	0.5	0.08	1.32	0.1
Polarization current coef: K-p,1 =	0.0246	0.0040	0.0632	0.0050
K-p,2 =	0.0242	0.0040	0.0605	0.0050
K-p,3 =	0.9512	0.9920	0.8763	0.9900
Apparent resistance (ohm) =	0.889	0.885	0.896	0.885

SUMMARY OF RESULTS:

Capacity increment (A-s) =	190.4	110.0	-232.8	-67.6	Residual A-s =	0.0
Energy increment (Wh) =	16.67	8.33	-21.11	-6.67	Net Wh =	-2.78
Minimum voltage (vdc) =	313.8	271.7	323.6	354.3		
Maximum voltage (vdc) =	317.1	273.8	327.5	355.3	Est. P-cruise(kW) =	-1.151
Average voltage (vdc) =	315.1	272.7	326.5	354.8	Stability factor =	0.05

Total discharge energy (Wh) =	25.00
Total discharge capacity (Ah) =	0.083
Round-trip energy efficiency (%) =	90.00
Profile-average heating rate (W) =	111.1

4.2.1.1 Inputs (in yellow)

Battery HPPC Performance Data, e.g., from Appendix D:

SOC-test = state-of-charge corresponding to test data used (%)
OCV-test = open circuit voltage (volts per cell)
R-ohm,test = ohmic resistance (ohms per cell)
OCV'-test = variation in OCV due to changing current (V/A-s per cell)
dR-pol,test = incremental change in polarization resistance (ohms per cell)
Tau-pol,test = time constant (s)

FreedomCAR Life-Cycle Test Profile Parameters:

Engine Off (Accessory Load) Power (kW) and Duration (s)
Launch (Discharge Pulse) Power (kW) and Duration (s)
Cruise (Recharge) Duration (s)
Stop (Regen Pulse) Power (kW) and Duration (s)
Target Profile A-s (used only for non-charge-neutral sub-profiles, normally set to zero)

Battery Scaling Parameters (to convert cell data to equivalent full-size battery results):

BSF = total number of devices (cells) required to meet power & energy
VSF = Voltage Scaling Factor (number of devices in series)

4.2.1.2 Calculated Values and Outputs (in blue)

CSF = Capacity Scaling Factor (system capacity required relative to test device)
Cruise Power = Cruise (Recharge) Power required to charge-balance profile (kW)

Total discharge Energy required to perform the test profile (Wh)
Total discharge Capacity required to perform the test profile (Ah)
Round-trip energy efficiency calculated for the test profile (%)
Profile-average heating rate due to losses during the test profile (W)

A number of other intermediate results are calculated and displayed for information in the spreadsheet, such as the energy, capacity and minimum and maximum voltages for each step of the test profile.

4.2.2 Entering Information into the Spreadsheet

The items that follow correspond to the yellow input cells in Figure D-5.

A. The five output parameters from the linear regression procedure (**OCV_0, R_o, R_p, OCV'** and τ) are entered as inputs for the desired state-of-charge, which could be the target SOC for life cycling.

B. The system-level power-time requirements for the appropriate cycle-life test profile are entered as inputs in this area. This profile is assumed to have four steps: An Engine-Off (accessory load) step, a Launch (engine start/accelerate) pulse, a Cruise (recharge) step, and a Stop (regen) pulse. Figure D-5 uses a 25 Wh Power Assist profile as an example. Note that the magnitude of the cruise power step is not an input; the spreadsheet calculates this value as required to charge-balance the profile.

C. The total number of devices (cells) required to meet power and energy goals (BSF) and the number of devices in series needed to provide the required voltage (VSF) in a full-size battery are entered as inputs BSF and VSF. These values may be determined by the Battery Size Factor assigned to a battery, or they may be calculated from the Extended Simplified Model or some other source. These values 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.

D. Because life-cycle test profiles are normally charge-balanced to allow repetitive cycling, the "Target Profile A-s" input cell is left at zero. In the event the spreadsheet is being used for calculations with a more complex test profile consisting of multiple subprofiles, each of which may not be charge-balanced, this input can be set to the degree of charge imbalance required for such a subprofile.

4.2.3 Results From the Spreadsheet

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

E. The relative capacity required for the full-size battery is calculated as the Capacity Size Factor (CSF). This value represents the cell (or module) capacity needed at the system level compared to the test article. Conceptually it can be regarded as the number of cell strings (of length VSF) in parallel required to give the appropriate power capability. (Note that it need not be an integer result for the purposes of the calculations.)

F. The Cruise (recharge) power required to achieve a charge-balanced test profile for the specified battery performance is calculated.

G. The summary results calculated by the spreadsheet are total discharge energy (Wh) and total discharge capacity (Ah) for the profile, round trip energy efficiency (%) and the average heating rate (W) for the profile. The efficiency can be compared to the appropriate FreedomCAR efficiency goal, and the other results indicate the energy and heat removal requirements resulting from the test profile.

Various intermediate results (not described here) are also calculated and shown in the non-highlighted parts of the spreadsheet.

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 FreedomCAR efficiency goals.[13] The spreadsheet and its variables described in the preceding section can be used for this purpose as follows:

1. Enter the cell linear regression results from HPPC data. These values will not change during this evaluation, except that the SOC value used should be chosen to agree as closely as practical with the minimum DOD value likely to be encountered during cycle-life testing with 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 FreedomCAR 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.)[14] Enter this value (not the larger Battery Size Factor) as the number of devices in input cell BSF. If the resulting maximum and minimum system-level voltages are too large, this value may be divided by an appropriate value which is used in input cell VSF. The relative Capacity Size Factor (ratio of BSF to VSF) is then calculated as CSF. The subsequent calculations are performed for a hypothetical battery with BSF total cells, of capacity CSF times the test article, in a string of length VSF cells.

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[13] 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.)

[14] This reduced number of devices must be used because the FreedomCAR 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.

3. Enter the appropriate system-level Efficiency Test Profile durations and magnitudes in the appropriate input cells, except for the Cruise (recharge) power level, which is calculated automatically from the other values.

4. Compare the calculated round-trip efficiency and minimum and maximum voltages to the appropriate FreedomCAR goals and limits as describe above. If the calculated values are outside the goal values, the BSF must be increased.[15] A revised multiplier for the Battery Size Factor can be found by increasing the total number of cells 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).**[16]**

4.2.5 Equations Used for P-CLEM Spreadsheet Calculations

The spreadsheet calculations are based on the following general voltage and current equations:

$P_i = V_i \times I_i$ = specfied battery power at time = t_i (positive on discharge)

where: V_i = battery voltage at time = t_i

$$= OCV - I_i \times Ro - OCV' \times [\int I\,dt]_i - Ip_i \times \Delta Rp$$

I_i = battery current at time = t_i

and where: $[\,dIp/dt\,]_i = (Ip_i - I_i) / \tau p$ = rate of change in polarization current, Ip, at time = t_i

$[\int I\,dt]_i$ = cumulative discharge capacity (A-s) at time = t_i

The five response coefficients/time-constant for the full battery system are:

OCV = battery open-circuit voltage (vdc)

Ro = battery “ohmic” resistance (ohm)

OCV’ = rate of change in battery OCV with respect to cumulative discharge capacity (vdc/A-s)

ΔRp = increment of battery resistance due to concentration polarization (ohm)

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[15] It is technically possible for the results to indicate that the BSF should be decreased. In practice this is not expected to occur because the efficiency test profiles typically involve reduced power and energy levels compared to the performance goals.

[16] 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.

τp = time-constant for buildup of concentration polarization (s)

These are obtained from cell, module, or full-battery test data using the following scaling laws:

OCV = VSF x OCV-test

Ro = (VSF / CSF) x Ro-test

OCV' = (VSF / CSF) x OCV'-test

ΔRp = (VSF / CSF) x ΔRp-test

τp = τp-test

where: VSF = voltage scaling factor (= number of test articles in series)

CSF = capacity scaling factor (= number of test articles in parallel)

and where: BSF = VSF x CSF = battery size factor

Note that these scaling laws imply that battery power = BSF x test article power, as expected.

The battery response coefficients/time-constant will generally vary with battery SOC. For the P-CLEM spreadsheet it is assumed that this variation is negligible, due to the relatively small swings in battery SOC over the profiles of interest. For profiles with large swings in SOC, such as extended-duration drive cycle profiles, this variation would have to be included in the calculations of battery response.

The approach taken to solve these battery voltage and current response equations is to divide the constant-power pulse durations into a number of small time steps:

$$t_i = t_{i-1} + \Delta t$$

Then, for sufficiently small time steps, the battery current can be assumed to be approximately linear.

$$I = I_{i-1} + (I_i - I_{i-1}) \times (t - t_{i-1}) / \Delta t$$

This allows the following solution for the polarization current to be used:

$$Ip_i = Kp{,}1 \times I_i + Kp{,}2 \times I_{i-1} + Kp{,}3 \times Ip_{i-1}$$

where: $Kp{,}1 = 1 - [\,1 - \exp(-\Delta t / \tau p)\,] / (\Delta t / \tau p)$

$Kp{,}2 = [\,1 - \exp(-\Delta t / \tau p)\,] / (\Delta t / \tau p) - \exp(-\Delta t / \tau p)$

$$Kp,3 = \exp(-\Delta t / \tau p)$$

And at time = t_i the cumulative discharge capacity is:

$$[\int I\,dt]_i = [\int I\,dt]_{i-1} + (I_{i-1} + I_i) \times \Delta t / 2$$

These results lead to the following expression for the battery power at time = t_i:

$$P_i = (\text{OCV-app}_i - I_i \times \text{R-app}_i) \times I_i$$

where: OCV-app_i = the battery's apparent OCV at time = t_i

$$= \text{OCV} - \text{OCV}' \times \{ [\int I\,dt]_{i-1} + I_{i-1} \times \Delta t / 2 \} - \Delta Rp \times [Kp,2 \times I_{i-1} + Kp,3 \times Ip_{i-1}]$$

R-app_i = the battery's apparent resistance at time = t_i

$$= Ro + \text{OCV}' \times \Delta t / 2 + Kp,1 \times \Delta Rp$$

Note that the battery's apparent resistance is constant if the time step is constant, as is the case over a given pulse in the profile. Given the battery power at each point in time, the battery current at
time = t_i can be calculated from the results up to time = t_{i-1} using the quadratic solution:

$$I_i = \{ \text{OCV-app}_i - [(\text{OCV-app}_i)^2 - 4 \times \text{R-app}_i \times P_i]^{1/2} \} / (2 \times \text{R-app}_i)$$

This result then allows the entire solution to be updated to the point time = t_i:

$$[\int I\,dt]_i = [\int I\,dt]_{i-1} + (I_{i-1} + I_i) \times \Delta t / 2$$

and $Ip_i = Kp,1 \times I_i + Kp,2 \times I_{i-1} + Kp,3 \times Ip_{i-1}$

The initial conditions at time = 0 are:

$[\int I\,dt]_0 = 0$ or the residual cumulative discharge capacity from the previous subprofile.

Ip_0 = final polarization current at the end of the last pulse in the profile.

At the transition between pulses, the values for the cumulative discharge capacity and polarization current for the start of the next pulse are equal to the values from the end of the previous pulse.

The P-CLEM spreadsheet must be run in Excel's iterative calculation mode. (It is also recommended that the manual calculation mode be used to allow several inputs to be changed at one time, before recalculating the sheet.) Two parts of the solution must be iterated to achieve convergence in the results. The first iterative part is to force the initial polarization current to be equal to the final polarization current. Excel provides this convergence with no appearance of instability.

The second iterative part is to force the final cumulative discharge capacity to equal the desired value that is specified as an input. This is done by iteratively adjusting the power level for the "cruise" pulse. Excel cannot provide convergence for this part in a direct iterative manner. The calculation is intrinsically unstable. Instead, a workaround has been implemented as follows:

$$\text{P-cruise, new} = \text{F-stability} \times \text{P-cruise,est} + (1 - \text{F-stability}) \times \text{P-cruise,old}$$

where:

$$\begin{aligned}\text{P-cruise,est} = {} & \text{P-cruise,old} \times \left\{ 1 - (\Delta\text{AH-res} - \Delta\text{AH-tgt}) / \left[\textstyle\int I\,dt\right]\text{-cruise} \right\} \\ & + \left\{ \text{R-app,cruise} \times (\Delta\text{AH-res} - \Delta\text{AH-tgt}) / (\text{t-cruise})^2 \right\} \\ & \times \left\{ \left[\textstyle\int I\,dt\right]\text{-cruise} - (\Delta\text{AH-res} - \Delta\text{AH-tgt}) \right\}\end{aligned}$$

and where: P-cruise,new = the new value of curise pulse power to be used in the next iteration

P-cruise,old = the value of cruise pulse power used in the previous iteration

F-stability = the weighting factor for the estimated cruise pulse power in determing the new cruise pulse power for the next iteration

ΔAH-res = the residual cumulative discharge capacity at the end of the profile from the previous iteration

ΔAH-tgt = the target value for the residual cumulative discharge capacity at the end of the profile from the previous iteration

$[\int I\,dt]$-cruise = cumulative discharge capacity for the cruise pulse

R-app,cruise = battery apparent resistance for the cruise pulse

t-cruise = total duration of the cruise pulse

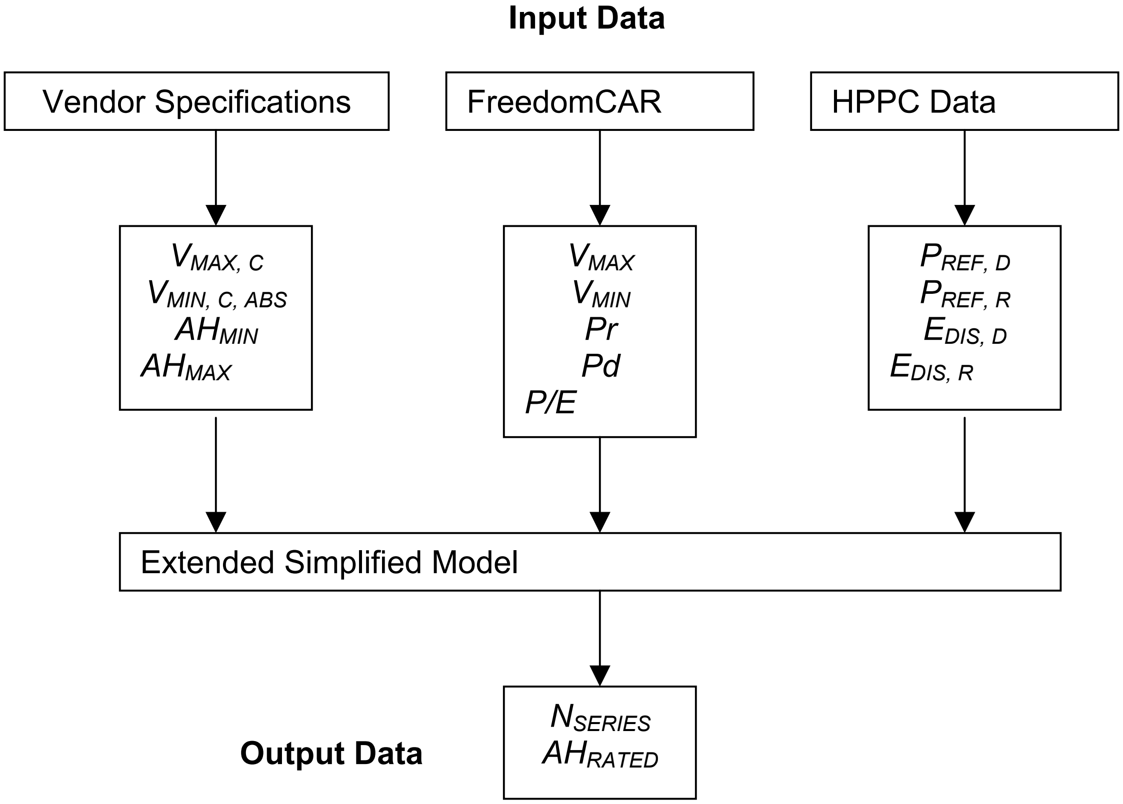
Note that in the spreadsheet the new value of P-cruise replaces the old value in the same cell. The calculated value of P-cruise,est (the estimated value of P-cruise that will drive the residual cumulative discharge capacity to its target value) is contained in a separate spreadsheet cell. This conditionally stable iterative scheme converges well for F-stability = 0.05, but diverges for F-stability ≥ 0.5

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 Reference 2. 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.[17] The user begins by carrying in data from the vendor's specifications, FreedomCAR 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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[17] 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

FreedomCAR 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 FreedomCAR

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:

$V_{MIN, C}$ = $V_{MAX, C}$ x (V_{MIN} / V_{MAX}) (minimum allowable cell voltage relative to FreedomCAR 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.[18]

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

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

$A_D, B_D, C_D, A_R, B_R,$ 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:

$$E = A_A + B_A \cdot P + C_A \cdot P^2 \qquad (3)$$

$A_A = A_D - A_R$

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

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

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.

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[18] 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 crossover of the pulse power capability curves can be ignored, because this region has no usable energy.

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

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:

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

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

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

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

$$AH_{MIN}\le AH_{RATED}\le AH_{MAX} \tag{7}$$

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:

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

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 FreedomCAR 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

Sections 4.3.4 and 4.3.5 of this manual describe a means of graphically determining the available energy and available power 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 FreedomCAR 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. 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]

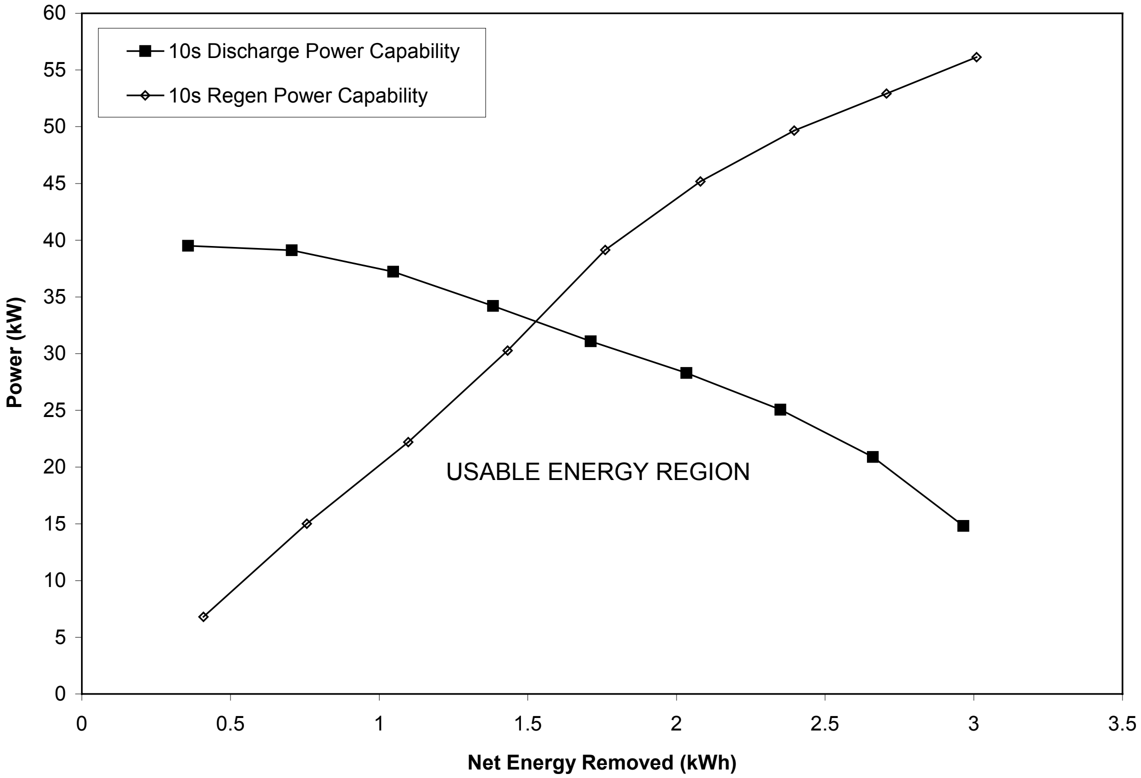

Figure E- 1. Pulse Power Capability Example Results

Since the FreedomCAR 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 the manual does this by using different axis scales to plot the discharge and regen power data. For

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[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.)

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 Minimum Power Assist pulse power requirements of 25 kW discharge (10s) and 20 kW regen (10s). Figure E-2 illustrates this same data with the regen power re-scaled by dividing by this 20/25 ratio. Note that the effect of this scaling is to increase the area of the "usable energy region", due to the lower regen requirement.[3] 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.

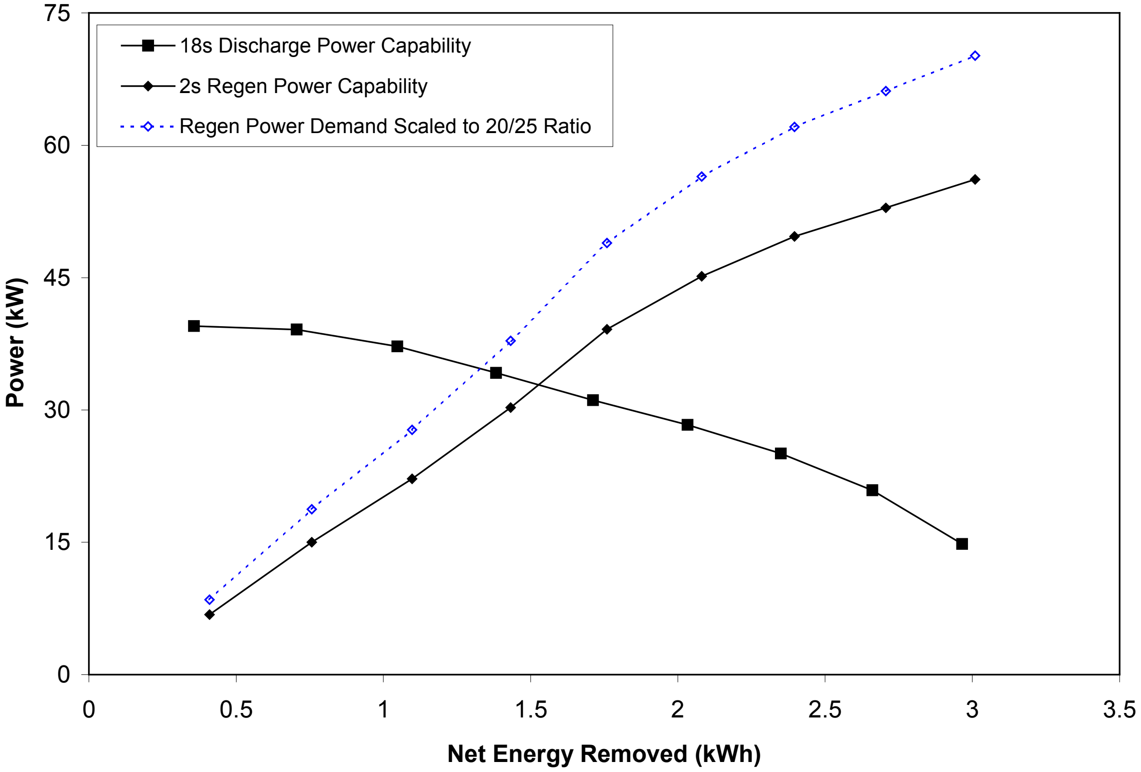

Figure E- 2. Pulse Power Capability Scaled for Regen/Discharge Power Ratio

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.[4]

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[3] Another effect of this scaling is to shift the usable energy region toward the lower discharge (left) end of the plot. This may be important for battery life but it is generally irrelevant to the calculation process described here.

[4] 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.

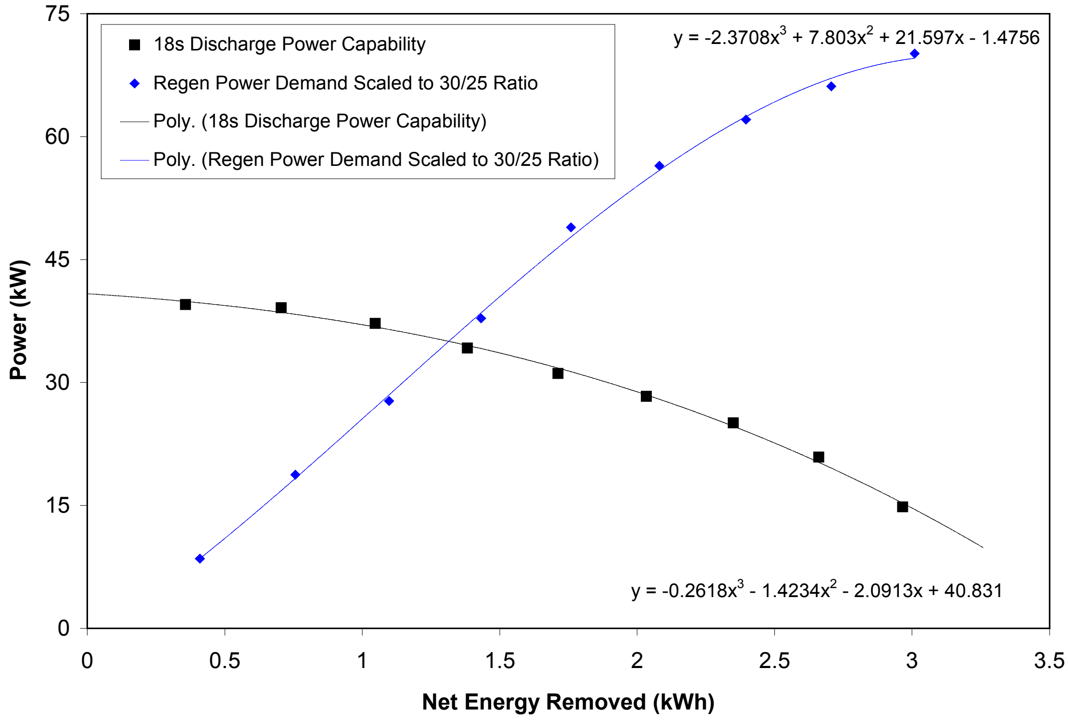


Figure E-3. Power Capability vs Energy from HPPC Test Results

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.

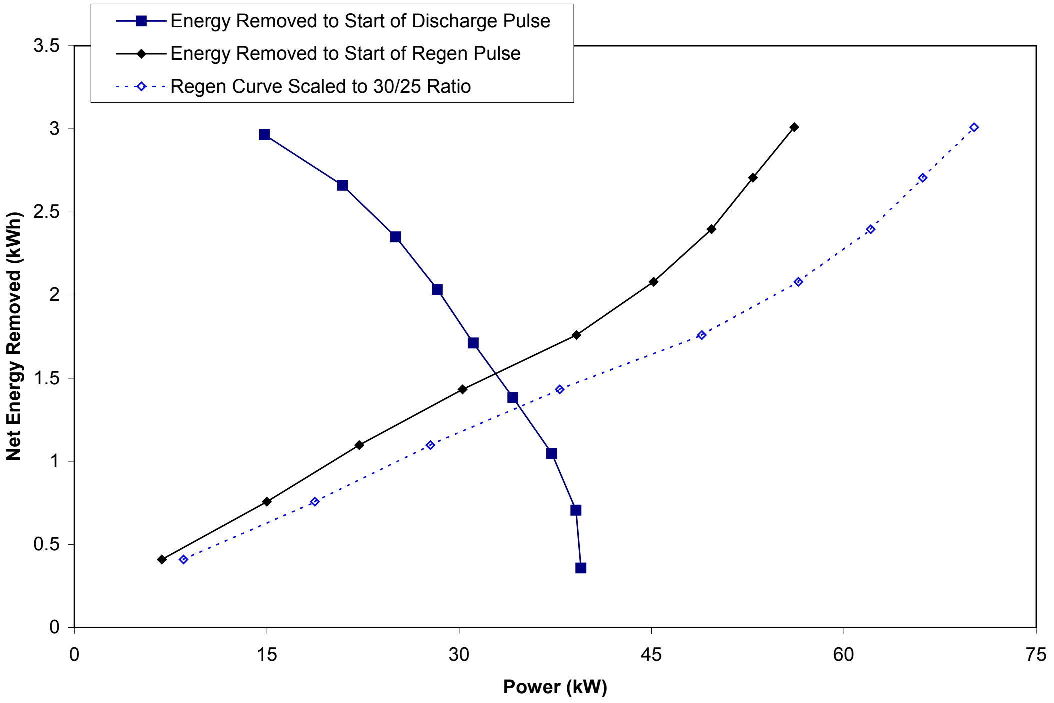


Figure E- 4. Energy versus Power Capability from HPPC Test Results

Curve fitting the discharge and scaled regen data 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.

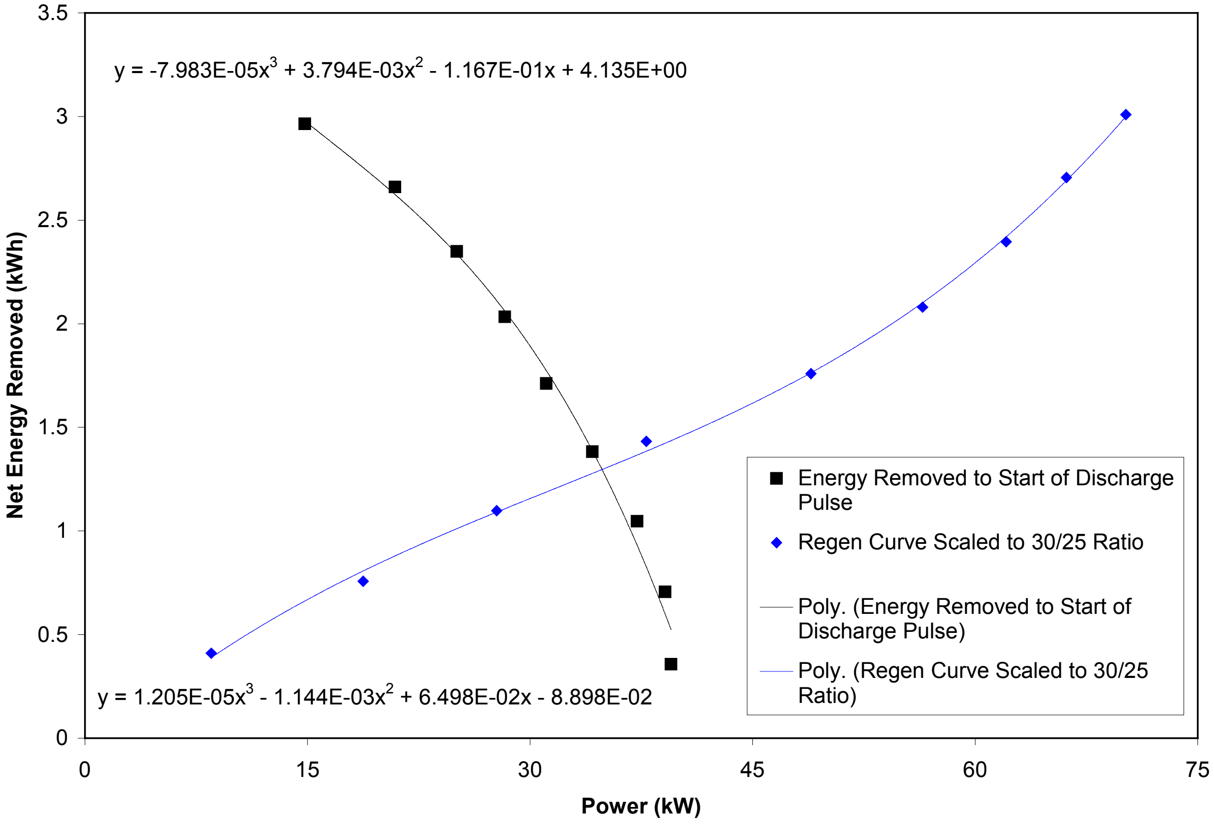


Figure E-5. Curve-Fitting to Scaled Energy vs Power Results

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, and 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.

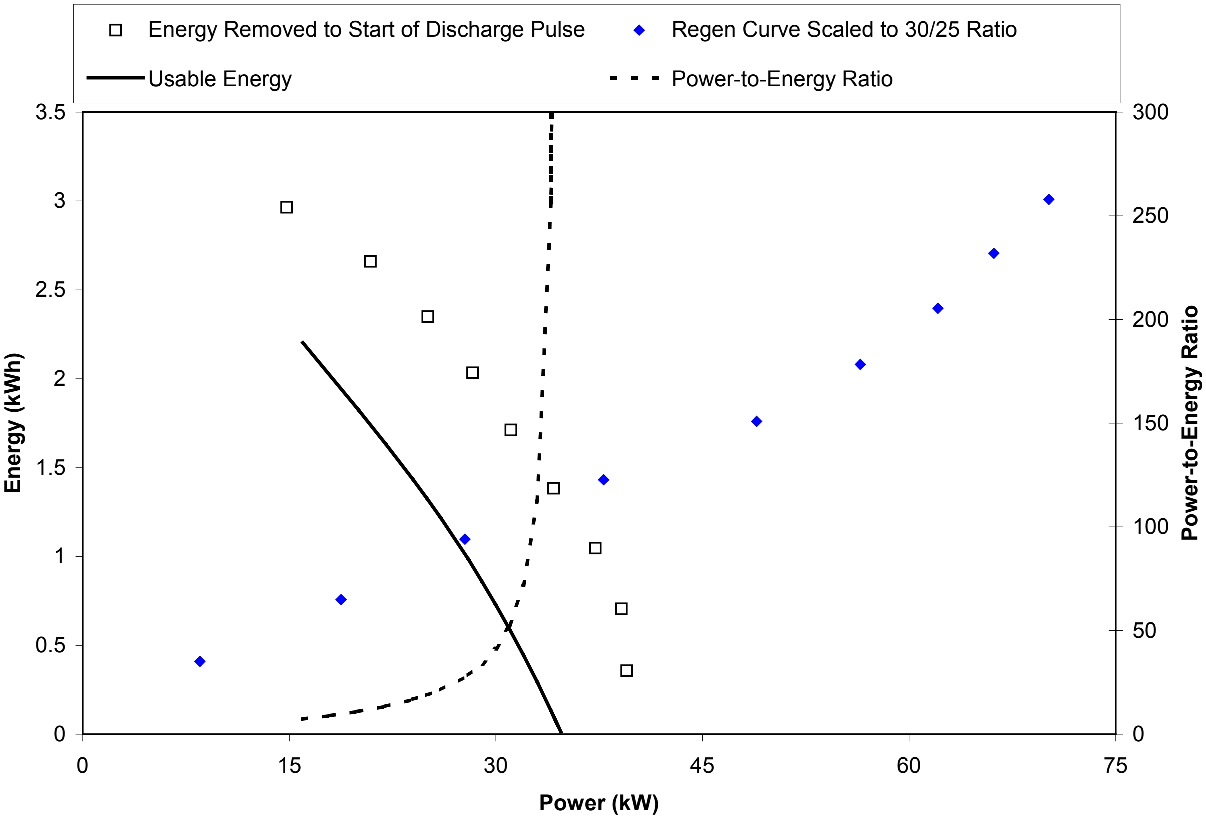


Figure E-6. Usable Energy and Power/Energy Ratio as a Function of Power Required

The actual calculation of Available Energy for comparison with the FreedomCAR 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 1.33 kWh. This value is shown graphically (for illustrative purposes only) in Figure E-7.

This energy is four 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-7 also shows that the Available Power (i.e. the discharge pulse power capability corresponding to the 0.3 kWh [300 Wh] Minimum Power Assist energy goal) is 32.95 kW, which is only about 32% higher than the power goal. This 32% margin for power degradation over life is actually fairly typical. The large available energy resulting from this margin is due to the high value of the P/E ratio for this cell at this scaling factor (P/E is approximately 105 at the 300 Wh energy goal.)

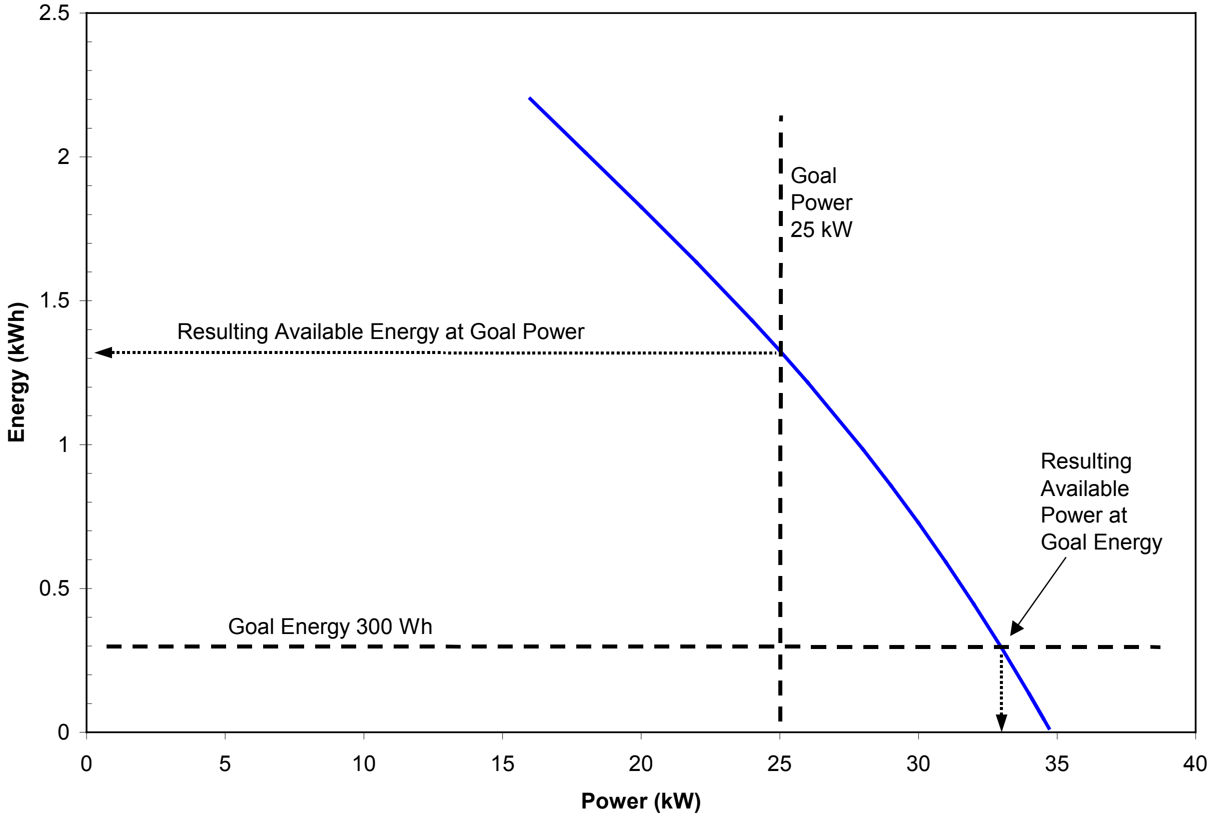


Figure E-7. Available Energy and Available Power determined from the Usable Energy curve

The Available Power value of 32.95 kW was actually obtained by iterating the Available Energy calculation until the desired value of 300 Wh was produced, rather than by finding it from the graph. It is possible to calculate Available Power directly by subtracting the two equations shown in Figure E-3 and evaluating the result at 0.3 kWh. If this is done using the coefficients shown, the resulting value of Available Power is about 34.43 kW, which is 4½ % higher than the previous result. This rather large difference is due to the scatter in the original data and the fact that a polynomial curve fit only approximates the data. In addition, even though the exact same data points are represented in Figures E-3 and E-5, the resulting curve fits are not perfectly reciprocal. In general it is recommended that curve fitting be done only on the energy vs power form of the data to avoid this inconsistency.

As a practical approach, the simplest way to calculate either Available Energy or Available Power is to use piecewise linear interpolation on the data (i.e. using only the data points immediately on either side of the desired result.) This introduces some error in that the relationships are clearly not linear overall; however, there is no clear indication that this error exceeds that due to polynomial curve fitting. Interpolation using cubic splines might mitigate the errors due to either of these approaches, but this more complex computational approach has not been shown to result in large practical benefits. A measurement uncertainty study in progress at INEEL is reviewing this issue, although it should be noted that a totally conclusive answer is unlikely because the analytical form of the underlying power curves is not known.

October 2003

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 1.1). 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 FreedomCAR testing manual as file "Assessment_of_Thermal_Mgmt_Losses_revised2002.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 within a specified operating temperature range. 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 within its nominal operating temperature range while the vehicle is operating, heat is removed or added (if retention of internal waste heat is not sufficient) during driving to bring the battery within the range.

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, for a total of four driving periods each weekday. 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 FreedomCAR Minimum Power Assist application). The battery's round-trip electrical energy efficiency is assumed to meet the specified FreedomCAR target of 90% for power assist applications.

Ambient Temperature Variation

Two statistical distributions of ambient temperature *vs*. time-above-temperature were developed for use in testing electric vehicle (EV) batteries (Reference 1: 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 FreedomCAR 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_{MAX}	Maximum battery operating temperature	30°C
T_{MIN}	Minimum battery operating temperature	10°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

---

[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_{HOLD}	Coefficient-of-performance for self-heating	1.0
COP_{HEAT}	Coefficient-of-performance for using waste heat	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 AND CALCULATION PROCESS

Battery thermal characteristics

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

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

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

Battery temperatures at the start of each driving period

Duration of parking up to the start of driving $= \Delta t_{PARK}$ (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)

For the start of driving on Monday morning,

$$T_{START,1} = maximum\ \{T_{MIN},\ [T_{AMB} + (T_{END,PREV} - T_{AMB})\ exp(-\Delta t_{PARK} / \tau_{TH})]\ \}$$

where $T_{END,PREV}$ is the battery temperature at the end of the Saturday driving from the previous week. For the first week, the end-of-week #1 temperature is used, based on the symmetry of the ambient temperature profile. Thereafter, the end-of-week temperature for each week is used for calculating the start temperature for the following week.[2]

Duration of battery hold at minimum operating temperature

Duration of hold at $T_{MIN} = \Delta t_{HOLD} = 0$ for all vehicle parked periods where $T_{AMB} \geq T_{MIN}$

---

[2] *In general variables whose subscripts end in ",1" (such as* $T_{START,1}$ *) represent the value of a parameter at the first driving period of the first weekly cycle, i.e., Monday morning after being parked for the weekend. These calculations are subsequently repeated for each driving period during a week and then for each week during the semiannual cycle..*

At the start of driving on Monday morning,

$\Delta t_{HOLD,1} = minimum \{(\Delta t_{PARK} - \tau_{TH} \log_e[(T_{END,PREV} - T_{AMB}) / (T_{MIN} - T_{AMB})]) , 0\}$ (h)

Net heat generation in the battery during driving periods

Battery net heat generation $= \Delta Q_{NET,1} = \{Q_{GEN} - G_{TH}[(T_{START,1} + T_{END,1})/2 - T_{AMB}]\} \Delta t_{DRIVE,1}$ (Wh)

This represents the waste heat generated within the battery during operation, minus the heat lost (or gained) to (or from) ambient through the battery thermal insulation during driving. The average battery temperature during driving is used to calculate the ambient heat exchange.

Energy consumed attributable to each driving period

The amount of heat that must be removed from the battery by an active cooling system to keep the battery temperature at or below the specified maximum is calculated:

$$\Delta Q_{COOL,1} = minimum \{[\Delta Q_{NET,1} - C_{TH}(T_{MAX} - T_{START,1})] , 0\}$$

where the sensible thermal energy of the battery has been included.

Instead of battery cooling, supplemental battery heating may be needed (for elevated-temperature batteries) under cold ambient conditions, when the net heat generated is less than zero. The heat required to keep the battery at or above T_{MIN} during driving is calculated as:

$$\Delta Q_{HEAT,1} = minimum \{[- \Delta Q_{NET,1} - C_{TH}(T_{START,1} - T_{MIN})] , 0\}$$

Then, a heat balance for the battery gives the following result for the temperature at the end of the driving period:

$$T_{END,1} = T_{START,1} + (\Delta Q_{NET,1} - \Delta Q_{COOL,1} + \Delta Q_{HEAT,1})/C_{TH}$$

This procedure will automatically keep $T_{END,1}$ within the specified operating temperature window.

Note that this system of equations is implicit in the variable $T_{END,1}$, and therefore the Excel program must be in the "Iterative Mode" under the Options for Calculation.

Finally, the energy loss is calculated for the first driving period as:

$$\Delta E_1 = \Delta Q_{COOL,1}/COP_{COOL} + \Delta Q_{HEAT,1}/COP_{HEAT} + G_{TH}(T_{MIN} - T_{AMB})\Delta t_{HOLD,1}/COP_{HOLD}$$

Total energy consumption and average per day

This calculation is repeated for all driving periods in the three weekly categories, and the energy losses are then summed for each week, annually, and over the 15-year battery life as in the present procedure. The Excel spreadsheet now also includes a chart of the weekly energy losses resulting from one or more sets of input conditions.

Daily energy consumption $= \Delta E_D =$ Sum of ΔE_i from each driving period, $i = 1 \ldots \#$ *driving periods* (Wh)

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

Annual energy consumption $= \Delta E_Y =$ 2 x Sum of ΔE_W for 25 weeks of operation (Wh)

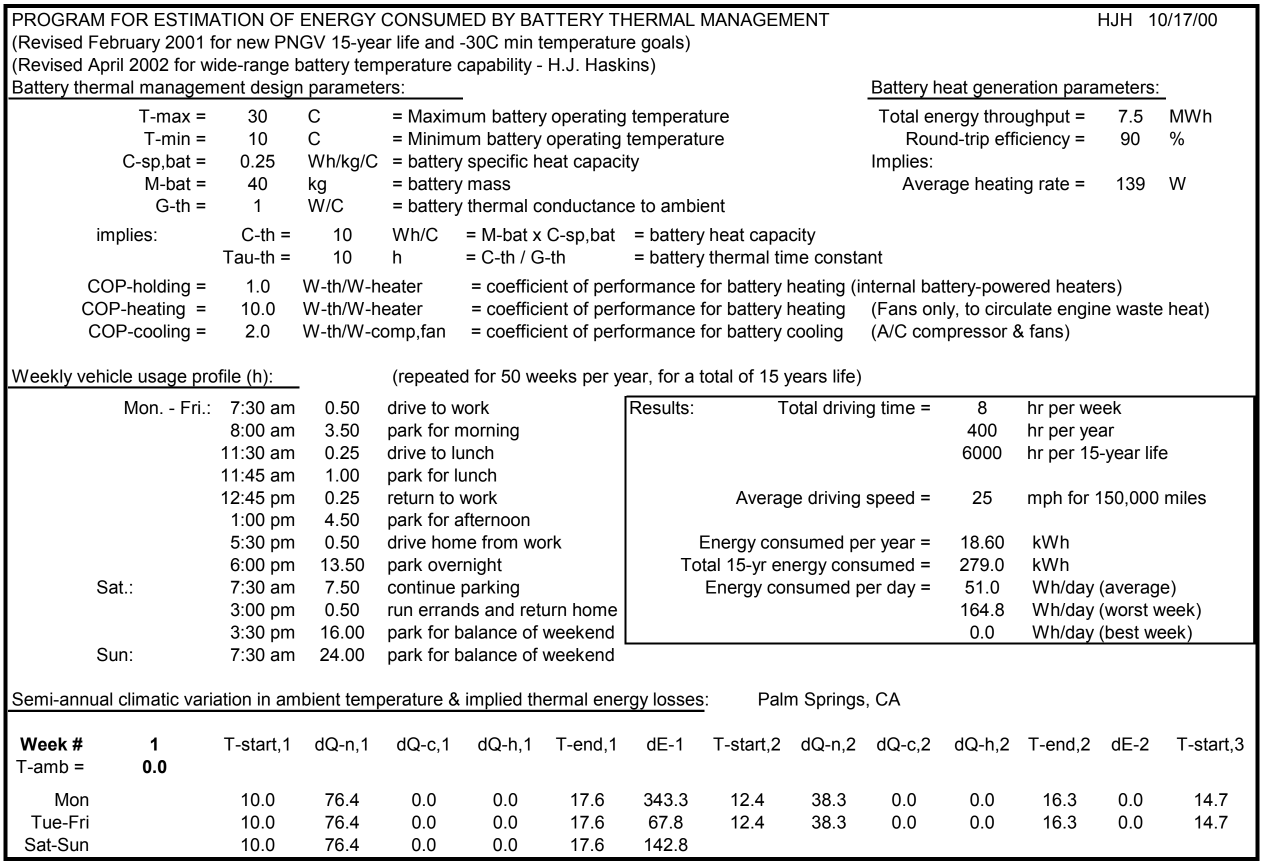
Total lifetime energy consumption $= E_{TOTAL} = 15\ \Delta E_Y$ (Wh)

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

PROCEDURE SUMMARY

This 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 FreedomCAR 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 part of 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 279.0 kWh, which is 3.7% of the total 7.5 MWh throughput required for a Minimum Power Assist battery. The average energy consumed per day is 51 Wh, which is essentially the same as the FreedomCAR 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)
(Revised April 2002 for wide-range battery temperature capability - H.J. Haskins)

Battery thermal management design parameters:

T-max = 30 C = Maximum battery operating temperature
T-min = 10 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 = 18.60 kWh
Total 15-yr energy consumed = 279.0 kWh
Energy consumed per day = 51.0 Wh/day (average)
164.8 Wh/day (worst week)
0.0 Wh/day (best week)

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

Week #	**1**	T-start,1	dQ-n,1	dQ-c,1	dQ-h,1	T-end,1	dE-1	T-start,2	dQ-n,2	dQ-c,2	dQ-h,2	T-end,2	dE-2	T-start,3
T-amb =	**0.0**													
Mon		10.0	76.4	0.0	0.0	17.6	343.3	12.4	38.3	0.0	0.0	16.3	0.0	14.7
Tue-Fri		10.0	76.4	0.0	0.0	17.6	67.8	12.4	38.3	0.0	0.0	16.3	0.0	14.7
Sat-Sun		10.0	76.4	0.0	0.0	17.6	142.8							

APPENDIX G

Calendar Life Test Simulation and Analysis Tool

Appendix G

Calendar Life Test Simulation and Analysis Tool

An EXCEL spreadsheet analysis tool has been developed to support calendar life test planning and data analysis. The objectives are to: (1) design a calendar life test that maximizes the confidence level for subsequent estimations of battery life; and (2) provide a range of life estimates for any desired confidence level. The EXCEL file is called "*CL Test Simulation.xls*," and instructions for its use are presented below, starting with the analysis methodology. A listing of the inputs and results for an example set of calculations are shown at the end of this appendix.

Analysis Methodology

The spreadsheet analysis is based on the general method for analysis of calendar life test data presented in Section 3.3.3 of this manual. The general flow of the spreadsheet is as follows:

1. The battery design is specified, including the goal or target energy for the intended application, the expected Available Energy (AE), expected calendar life at two temperatures, an "accelerating decay factor" to account for faster-than-linear decay in performance over time, and the manufacturing variability (σ) in battery AE, as a percentage of the application's target energy.

2. The variability (σ) of the test measurement process is specified for the performance parameter of interest, here assumed to be the battery's AE.

3. The cumulative temperature distribution over the life of the battery is specified using a simple linear-plus-extremes profile.

4. A matrix of test temperatures, intended or actual, is specified. The "actual" lifetimes of the battery design are then calculated at each temperature, including the effect of manufacturing variability on AE at beginning-of-life (BOL).

5. A matrix of simulated test data is then calculated, using the specified test measurement variability to "corrupt" the actual AE values for the battery(s) at each test temperature.

6. Data from the matrix are correlated assuming a quadratic fit of AE vs. time-at-temperature, corresponding to the form of the function used to generate actual battery life. [The end of life (EOL) condition is when each battery's AE has decayed to just the target energy, i.e., the performance margin is zero.]

7. The final data correlation is the fit of the coefficients of the performance decay function vs. test temperature. An Arrhenius form is assumed for these correlations.

8. The specified cumulative temperature distribution is used to calculate average values for the coefficients of the performance decay function. This is done by numerical integration over the percentage of time the battery is below any given temperature, from zero at the lowest extreme temperature to unity at the highest extreme temperature.

9. The estimated battery life is calculated using the averaged coefficients and the EOL performance criterion for the life-limiting performance parameter (assumed to be the AE in the present analysis).

Each time the spreadsheet is recalculated, a new set of random numbers is generated for simulation of the test data. Each recalculation is termed a "trial," and the number of trials used in the simulation is under user control. (See instructions below.) The present spreadsheet has been set up for calculating 100 trials at a time. Multiples of 100 trials can be easily accommodated, as noted below.

Spreadsheet Instructions

The following specific steps should be implemented when using the spreadsheet for either test planning or analysis of actual test data.

EXCEL Calculation Settings

The spreadsheet must be run in Manual mode, Iteration enabled, with one (1) iteration per calculation. Before setting up a simulation, check the EXCEL Preferences to be sure that these settings are being used by EXCEL.

Modifying the assumed form of the performance decay function

Separate analysis of the actual calendar life data must be performed first to establish the form of the performance decay function. The present model assumes a linear-plus-quadratic decay in performance vs. time-at-temperature. It is quite likely that such a simple function will not be applicable to a given battery technology. The function selected should maximize the coefficient of determination (R^2) for the test data matrix. The same function must be used for all test temperature, but not all temperatures need to be included in the analysis. (Low temperatures may have a very poor signal-to-noise ratio, and high temperatures may have induced irrelevant battery decay modes. Such conditions may not be evident until the data have been analyzed.)

Initializing the Current Trial Number

To begin a set of 100 trials, set the "Current Trial No." to zero in EXCEL cell K3. Then enter the following formula in cell K3:

= K3 + 1

Generating a set of 100 trials

Command EXCEL to perform a recalculation. This will increment the Current Trial No. by one, and generate a new value of "Estimated Calendar Life" for the current trial, in the "RESULTS" section of the spreadsheet. Note also that the column of "Est. CL" is updated at Trial No. 1 (EXCEL cell P5). Continue commanding EXCEL to recalculate until the Current Trial No. reaches a value of 101. Examine the results of the trials by scrolling through EXCEL column P. In some cases, the results will not be valid, due to excessive noise in a particular trial that created a logic error in the spreadsheet calculations. (This will appear as "#VALUE!" in the Est. CL column for that particular trial.) To replace an invalid result, enter the trial number + 1 in cell K3 and recalculate until a valid result appears in the Estimated Calendar Life for the current trial. Repeat this process until valid results are obtained for all 100 trials. (If an excessive number of invalid results are obtained, it is an indication that the signal-to-noise ratio is too low for at least one of the low temperatures in the test matrix. Change the range used in the data correlations to eliminate one or more of the low temperature results.)

Recording and sorting the results of each set of 100 trials

Transfer the results for Est. CL for the 100 trials by selecting EXCEL cells P5 through P104, choosing Copy, selecting cell Q5, choosing Paste Special/Values, and choosing Sort Ascending from the control panel. The estimated lives for the set of 100 trials will be stored in cells Q5 through Q104 in ascending order. The Statistics of Estimated Calendar Life portion of the RESULTS section of the spreadsheet will contain the median life and the ranges of life corresponding to 50%, 80%, and 90% confidence intervals. (Note that the higher the confidence levels, the wider the range in estimated life.)

Multiple sets of 100 trials can be accommodated by repeating the above process, with the sorted results stored in adjacent cells R5 through R104, cells S5 through S104, etc. The statistics for each set can similarly be recorded adjacent to the "Current" values (EXCEL cells K14 through K20).

Interpreting the results of the simulation

The two principal uses of the simulation – test planning to meet a target confidence level for life estimation, and estimating the confidence level for a given set of actual test data – require different approaches for interpreting the results.

First, for test planning purposes, it is desired to determine the number of test temperatures, their target values, the target duration of the test, the number of batteries at each test temperature, and the target variability in the performance parameter measurement process. Overall, it is desired to have a narrow range of estimated calendar life at the highest confidence level (e.g., 90%) within the shortest possible test duration and using the fewest batteries, given realistic levels of variability in battery manufacturing and performance parameter measurement. Simulations can be run at various levels for these inputs to determine the optimum test matrix. Obviously, the more information about the battery's life characteristics available prior to test, the better will be the test design.

Second, it is desired to quantify the range of estimated battery life corresponding to any given confidence level for a matrix of actual test results. This requires curve fitting the actual data to select the best form for the performance decay function. Once the statistical coefficient of determination (R^2) has been maximized, the spreadsheet will need to be modified to incorporate the best decay function. The so-called actual values for the battery life that are input to the spreadsheet will be the best fits of the data using the selected decay function. Next, the manufacturing and test measurement variabilities are adjusted to provide agreement between the values of R^2 obtained in the best fits with those calculated in the spreadsheet. The resulting values for the various confidence intervals are then the best estimates that can be inferred from the test data. (Note that one-sided confidence intervals – "the estimated life of the battery is at least X years, with a confidence of Y%" – can also be calculated.) The total number of spreadsheet trials necessary to reach a valid conclusion is probably less than 1000. This should be verified by showing that the desired confidence interval is approaching limits as the number of trials is increased.

Example Spreadsheet Calculation

The following listing is taken directly from the spreadsheet “CL Test Simulation.xls” which is provided with this manual. It shows the results generated from a synthetic set of input values based on an artificially constructed set of calendar life test data. Note that the distribution of results is produced using randomly generated variations in certain parameters; thus it may not be repeated exactly even if the calculations are re-run using the same inputs.

July 2002

Calendar Life Test Simulation

H. J. Haskins

INPUT: No. of Trials = 1		
Battery Design:		
Target Rated Energy (Wh) =	250	
Available Energy at BOL (Wh) =	500	
Expected Calendar Life (y) =	15	at 30 deg C
	2	at 60 deg C
Accelerating Decay Factor =	25%	
Manufacturing Variability (% of R.E.) =	5.00%	1-sigma
Performance Test Variability (% of R.E.	0.50%	1-sigma
Cumulative Temperature Distribution:		
Normal Cold Temperature (C.) =	10	
Normal Hot Temperature (C.) =	35	
Delta Extreme Temperature (C.) =	10	
Distribution Characteristic =	0.15	

RESULTS: Current Trial No. =	0				
Expected Energy Margin at BOL =	100%				
Estimated Energy Margin at BOL =	102.3%				
Expected Calendar Life (y) =	17.68				
Estimated Calendar Life (y) =	17.74	for current trial			
Estimated Calendar Life (y) =	17.69	average for all trials			
Statistics of Estimated Calendar Life:					
	Current	Set #1	Set #2	Set #3	
Median Calendar Life (y) =	17.65				
50% Confidence Int. (y): Min =	16.66				
Max =	18.54				
80% Confidence Int. (y): Min =	15.69				
Max =	19.99				
90% Confidence Int. (y): Min =	15.39				
Max =	20.52				

TEST TEMPERATURE MATRIX:

							LN(Y) vs. 1000/T CORR. PARAMETERS		
Test Temperature (C.) =	30	40	45	50	55	60			
1000/Abs. Test Temp. (1/K) =	3.2986	3.193	3.143	3.094	3.047	3.0016	A	B	R^2
Expected Life at Test Temp. (y) =	15	7.34	5.22	3.76	2.73	2	-19.668	6.784	1
Actual Coeff. Of Linear Decay (1/y) =	13.33	27.24	38.29	53.26	73.33	100.00	24.966	-6.784	1.0000
ct. Coeff. Of Quadratic Decay (1/y^2) =	0.2222	0.9277	1.8328	3.5452	6.7212	12.5000	43.248	-13.567	1.0000
Actual A.E. at BOL (Wh) =	513.2	502.5	509.8	506.1	490.4	512.4	505.7	(Average Act. AE-bol)	
Actual Cal. Life (y) at Test Temp. =	15.65	7.40	5.39	3.83	2.64	2.08	-19.923	6.871	0.9987

TEST DATA CORRELATION SUMMARY:

Test Temperature (C.) =	30	40	45	50	55	60	A	B	R^2
Estimated A.E. at BOL (Wh) =	512.9	502.1	509.1	506.3	490.6	512.9	505.7	(Average Est. AE-bol)	
Est. Coeff. Of Linear Decay (1/y) =	12.98	27.39	34.92	53.78	73.84	100.34	25.557	-6.979	0.9939
st. Coeff. Of Quadratic Decay (1/y^2) =	0.4113	0.7442	3.8123	3.4109	6.4956	12.4118	41.250	-12.894	0.8761
Estimated Cal. Life (y) at Test Temp. =	14.02	7.62	4.85	3.83	2.64	2.08	-19.378	6.690	0.9906
Coefficient of Determination (R^2) =	0.9703	0.9941	0.9977	0.9988	0.9997	0.9999			

TEST DATA CORRELATION DETAILS:

est Temperature (C.) = 30	-0.4112728	-12.9841	512.9321
	0.9613631	1.990625	0.8596
	0.9702536	1.548805	#N/A
	358.79294	22	#N/A
	1721.3434	52.77355	#N/A
est Temperature (C.) = 40	-0.7442353	-27.3934	502.138
	0.8849767	1.832457	0.791299
	0.9940977	1.425743	#N/A
	1852.6847	22	#N/A
	7532.0624	44.72034	#N/A
est Temperature (C.) = 45	-3.812301	-34.9203	509.1258
	0.8074919	1.672015	0.722016
	0.9977319	1.300911	#N/A
	4838.9677	22	#N/A
	16378.639	37.23212	#N/A
est Temperature (C.) = 50	-3.4108816	-53.782	506.3239
	0.828753	1.716039	0.741027
	0.9988197	1.335164	#N/A
	9308.4225	22	#N/A
	33187.538	39.21856	#N/A
est Temperature (C.) = 55	-6.4956331	-73.8375	490.5575
	0.5615398	1.16274	0.502099
	0.999736	0.904669	#N/A
	41648.185	22	#N/A
	68171.981	18.00539	#N/A
est Temperature (C.) = 60	-12.411826	-100.342	512.9372
	0.55679	1.152905	0.497852
	0.9998752	0.897017	#N/A
	88134.912	22	#N/A
	141833.72	17.70208	#N/A

Act. Coeff. Of Linear Decay (1/y):	-6.78356	24.96644
	5.83E-13	1.83E-12
	1	1.39E-13
	1.35E+26	4
	2.631919	7.78E-26
Act. Coeff. Of Quadratic Decay (1/y^2):	-13.5671	43.24826
	1.43E-12	4.48E-12
	1	3.42E-13
	9.01E+25	4
	10.52768	4.67E-25
Actual Cal. Life (y) at Test Temp.:	6.870833	-19.9229
	0.124033	0.388375
	0.998698	0.029663
	3068.624	4
	2.700076	0.00352
Est. Coeff. Of Linear Decay (1/y):	-6.97873	25.55738
	0.316898	0.981327
	0.993852	0.048026
	484.9694	3
	1.118601	0.00692
Est. Coeff. Of Quadratic Decay (1/y^2):	-12.8937	41.24985
	2.799271	8.66841
	0.876115	0.424235
	21.21609	3
	3.818368	0.539925
Estimated Cal. Life (y) at Test Temp.:	6.689565	-19.3783
	0.37644	1.16571
	0.99059	0.05705
	315.7937	3
	1.027823	0.009764

Matrix of LN(CL) for T = 30, 40, 45, 50, 55, 60 deg C

Act. AE':	2.590	3.305	3.645	3.975	4.295	4.605
Act. AE":	-1.504	-0.075	0.606	1.266	1.905	2.526
Act. CL:	2.751	2.002	1.685	1.343	0.971	0.733
Est. AE':	2.564	3.310	3.553	3.985	4.302	4.609
Est. AE":	-0.888	-0.295	1.338	1.227	1.871	2.519
Est. CL:	2.641	2.031	1.579	1.344	0.972	0.734

SUMMARY OF TRIAL RESULTS:

Trial No.	Est. C.L.	Sorted C.L.
1	15.83	13.79
2	17.65	14.63
3	16.02	14.65
4	18.43	15.14
5	14.63	15.15
6	19.36	15.39
7	17.69	15.48
8	17.36	15.59
9	18.44	15.63
10	17.61	15.64
11	14.65	15.69
12	17.38	15.80
13	17.61	15.82
14	18.93	15.83
15	17.70	15.94
16	17.90	15.99
17	16.10	16.02
18	18.52	16.10
19	16.89	16.14
20	17.98	16.23
21	18.96	16.34
22	15.63	16.40
23	20.72	16.51
24	20.09	16.52
25	19.15	16.63
26	20.34	16.66
27	17.94	16.75
28	17.97	16.77
29	21.06	16.81
30	16.84	16.84
31	17.71	16.89
32	16.77	16.90
33	16.34	17.02
34	17.04	17.03
35	15.39	17.04
36	13.79	17.06
37	18.97	17.16
38	17.06	17.21
39	16.14	17.25
40	18.02	17.26
41	19.93	17.28
42	17.75	17.36
43	17.95	17.38
44	15.94	17.38
45	17.21	17.39
46	17.28	17.47
47	18.90	17.51
48	16.66	17.61
49	15.80	17.61
50	18.09	17.65
51	17.51	17.66
52	17.38	17.69
53	16.81	17.70
54	18.18	17.71
55	17.75	17.74
56	19.30	17.75
57	15.59	17.75
58	17.26	17.80
59	19.48	17.90
60	17.47	17.94
61	16.23	17.95
62	17.99	17.97
63	20.51	17.98
64	16.75	17.99
65	15.64	17.99
66	16.63	18.02
67	18.30	18.09
68	19.90	18.09
69	17.02	18.18
70	20.71	18.30
71	17.39	18.43
72	19.10	18.44
73	20.48	18.46
74	17.80	18.52

MEASURED CALENDAR LIFE TEST DATA:

	T =	30		40		45		50		55		60	
Time	t^ 2	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated
0	0	513.2	512.9	502.5	502.1	509.8	509.1	506.1	506.3	490.4	490.6	512.4	512.9
0.08	0.01	514.7	511.8	498.8	499.9	505.8	506.2	503.3	501.8	484.6	484.4	505.5	504.5
0.17	0.03	510.4	510.7	496.0	497.6	504.4	503.2	498.9	497.3	478.0	478.1	495.9	495.9
0.25	0.06	507.9	509.6	493.8	495.2	499.9	500.2	491.3	492.7	471.1	471.7	486.0	487.1
0.33	0.11	506.0	508.5	495.7	492.9	496.0	497.1	487.3	488.0	465.2	465.2	477.1	478.1
0.42	0.17	509.3	507.4	491.8	490.6	495.1	493.9	482.4	483.3	459.0	458.7	470.5	469.0
0.50	0.25	503.9	506.3	490.1	488.3	489.2	490.7	478.6	478.6	453.0	452.0	460.4	459.7
0.58	0.34	504.1	505.2	484.7	485.9	484.1	487.5	473.9	473.8	445.9	445.3	451.1	450.2
0.67	0.44	505.9	504.0	483.8	483.5	484.0	484.2	468.8	469.0	439.0	438.4	440.3	440.5
0.75	0.56	504.4	502.9	480.9	481.2	482.4	480.8	463.5	464.1	430.9	431.5	428.7	430.7
0.83	0.69	502.1	501.8	477.9	478.8	477.6	477.4	459.6	459.1	421.9	424.5	421.4	420.7
0.92	0.84	499.3	500.6	479.7	476.4	476.0	473.9	454.2	454.2	417.0	417.4	410.2	410.5
1.00	1.00	499.6	499.5	472.8	474.0	471.7	470.4	447.3	449.1	411.2	410.2	400.8	400.2
1.08	1.17	500.3	498.3	470.3	471.6	466.3	466.8	442.8	444.1	403.2	402.9	389.7	389.7
1.17	1.36	497.1	497.1	469.7	469.2	464.8	463.2	439.7	438.9	395.3	395.6	379.8	379.0
1.25	1.56	496.9	496.0	466.1	466.7	458.6	459.5	433.3	433.8	387.8	388.1	367.3	368.1
1.33	1.78	493.9	494.8	463.9	464.3	455.2	455.8	429.0	428.6	381.1	380.6	356.1	357.1
1.42	2.01	492.3	493.6	461.0	461.8	451.1	452.0	426.5	423.3	371.8	372.9	345.0	345.9
1.50	2.25	493.0	492.4	458.9	459.4	447.3	448.2	417.4	418.0	365.7	365.2	334.5	334.5
1.58	2.51	490.3	491.2	456.8	456.9	445.5	444.3	414.5	412.6	358.9	357.4	323.8	322.9
1.67	2.78	490.8	490.0	456.0	454.4	440.1	440.3	408.2	407.2	348.4	349.5	312.0	311.2
1.75	3.06	489.6	488.8	449.7	451.9	434.8	436.3	399.6	401.8	342.7	341.4	299.9	299.3
1.83	3.36	489.5	487.6	449.7	449.4	432.8	432.3	397.5	396.3	333.5	333.4	287.8	287.3
1.92	3.67	487.1	486.4	448.0	446.9	428.9	428.2	389.6	390.7	324.9	325.2	274.5	275.0
2.00	4.00	483.1	487.0	444.7	444.4	424.0	424.0	384.1	385.1	316.2	316.9	262.1	262.6

75	16.40	18.54
76	17.03	18.72
77	15.82	18.86
78	20.62	18.90
79	19.34	18.93
80	16.90	18.96
81	18.86	18.97
82	17.16	19.10
83	15.14	19.15
84	15.99	19.30
85	18.46	19.34
86	18.54	19.36
87	17.25	19.48
88	17.66	19.90
89	15.15	19.93
90	16.52	19.99
91	18.09	20.09
92	15.48	20.34
93	20.52	20.48
94	17.99	20.51
95	17.74	20.52
96	16.51	20.62
97	19.99	20.71
98	15.69	20.72
99	# VALUE!	21.06
100	21.63	21.63

CUMULATIVE BATTERY TEMPERATURE DISTRIBUTION & CALCULATION OF TEMPERATURE-WEIGHTED COEFFICIENTS

					AE'	Integrals	of AE'		AE"	Integrals	of AE"
F	T (deg C)	T (deg F)	1000/T	Expected	Estimated	Expected	Estimated	Expected	Estimated	Expected	Estimated
0.00	0.0	32.0	3.661	1.1420	1.0093	0.0000	0.0000	0.0016	0.0026	0.0000	0.0000
0.02	1.8	35.2	3.638	1.3378	1.1877	0.0248	0.0220	0.0022	0.0035	3.87E-05	6.11E-05
0.04	3.3	38.0	3.617	1.5426	1.3751	0.0536	0.0476	0.0030	0.0046	9.08E-05	1.42E-04
0.06	4.8	40.7	3.598	1.7547	1.5700	0.0866	0.0770	0.0038	0.0059	1.59E-04	2.47E-04
0.08	6.1	43.1	3.580	1.9727	1.7710	0.1238	0.1105	0.0049	0.0073	2.46E-04	3.79E-04
0.10	7.4	45.3	3.565	2.1955	1.9772	0.1655	0.1479	0.0060	0.0090	3.55E-04	5.43E-04
0.12	8.5	47.4	3.550	2.4223	2.1876	0.2117	0.1896	0.0073	0.0109	4.89E-04	7.42E-04
0.14	9.6	49.3	3.537	2.6525	2.4017	0.2625	0.2355	0.0088	0.0129	6.50E-04	9.79E-04
0.16	10.6	51.1	3.524	2.8855	2.6191	0.3178	0.2857	0.0104	0.0151	8.42E-04	1.26E-03
0.18	11.5	52.7	3.513	3.1213	2.8395	0.3779	0.3403	0.0122	0.0176	1.07E-03	1.59E-03
0.20	12.4	54.3	3.502	3.3599	3.0630	0.4427	0.3993	0.0141	0.0202	1.33E-03	1.96E-03
0.22	13.2	55.8	3.492	3.6012	3.2896	0.5123	0.4628	0.0162	0.0231	1.63E-03	2.40E-03
0.24	14.0	57.3	3.482	3.8456	3.5195	0.5868	0.5309	0.0185	0.0261	1.98E-03	2.89E-03
0.26	14.8	58.6	3.473	4.0934	3.7530	0.6662	0.6036	0.0209	0.0294	2.38E-03	3.45E-03
0.28	15.5	60.0	3.464	4.3450	3.9906	0.7506	0.6811	0.0236	0.0330	2.82E-03	4.07E-03
0.30	16.2	61.2	3.455	4.6010	4.2326	0.8400	0.7633	0.0265	0.0368	3.32E-03	4.77E-03
0.32	16.9	62.5	3.447	4.8619	4.4797	0.9347	0.8504	0.0295	0.0408	3.88E-03	5.54E-03
0.34	17.6	63.7	3.439	5.1284	4.7325	1.0346	0.9426	0.0329	0.0452	4.51E-03	6.40E-03
0.36	18.2	64.8	3.432	5.4011	4.9916	1.1399	1.0398	0.0365	0.0498	5.20E-03	7.35E-03
0.38	18.9	66.0	3.424	5.6808	5.2578	1.2507	1.1423	0.0403	0.0549	5.97E-03	8.40E-03
0.40	19.5	67.1	3.417	5.9684	5.5318	1.3672	1.2502	0.0445	0.0603	6.82E-03	9.55E-03
0.42	20.1	68.2	3.410	6.2647	5.8145	1.4895	1.3637	0.0491	0.0661	7.75E-03	1.08E-02
0.44	20.7	69.3	3.403	6.5707	6.1069	1.6179	1.4829	0.0540	0.0724	8.78E-03	1.22E-02
0.46	21.3	70.4	3.396	6.8875	6.4100	1.7524	1.6080	0.0593	0.0791	9.91E-03	1.37E-02
0.48	21.9	71.4	3.389	7.2163	6.7250	1.8935	1.7394	0.0651	0.0865	1.12E-02	1.54E-02
0.50	22.5	72.5	3.382	7.5583	7.0532	2.0412	1.8772	0.0714	0.0944	1.25E-02	1.72E-02
0.52	23.1	73.6	3.375	7.9151	7.3959	2.1960	2.0217	0.0783	0.1031	1.40E-02	1.92E-02
0.54	23.7	74.6	3.369	8.2883	7.7548	2.3580	2.1732	0.0859	0.1125	1.57E-02	2.13E-02
0.56	24.3	75.7	3.362	8.6797	8.1319	2.5277	2.3320	0.0942	0.1228	1.75E-02	2.37E-02
0.58	24.9	76.8	3.355	9.0915	8.5291	2.7054	2.4986	0.1033	0.1341	1.94E-02	2.62E-02
0.60	25.5	77.9	3.348	9.5263	8.9490	2.8916	2.6734	0.1134	0.1466	2.16E-02	2.90E-02
0.62	26.1	79.0	3.341	9.9868	9.3943	3.0867	2.8569	0.1247	0.1603	2.40E-02	3.21E-02
0.64	26.8	80.2	3.334	10.4765	9.8685	3.2913	3.0495	0.1372	0.1756	2.66E-02	3.55E-02
0.66	27.4	81.3	3.327	10.9992	10.3755	3.5061	3.2519	0.1512	0.1926	2.95E-02	3.91E-02
0.68	28.1	82.5	3.320	11.5597	10.9197	3.7317	3.4649	0.1670	0.2117	3.27E-02	4.32E-02
0.70	28.8	83.8	3.312	12.1635	11.5069	3.9689	3.6891	0.1849	0.2332	3.62E-02	4.76E-02

0.78	31.8	89.2	3.280	15.1656	14.4384	5.0553	4.7202	0.2875	0.3547	5.47E-02	7.07E-02
0.80	32.6	90.7	3.271	16.1172	15.3712	5.3681	5.0183	0.3247	0.3982	6.08E-02	7.83E-02
0.82	33.5	92.3	3.261	17.1799	16.4149	5.7011	5.3361	0.3689	0.4496	6.78E-02	8.67E-02
0.84	34.4	93.9	3.251	18.3756	17.5913	6.0566	5.6762	0.4221	0.5109	7.57E-02	9.63E-02
0.86	35.4	95.7	3.241	19.7316	18.9282	6.4377	6.0414	0.4867	0.5850	8.48E-02	1.07E-01
0.88	36.5	97.6	3.230	21.2825	20.4604	6.8478	6.4353	0.5662	0.6755	9.53E-02	1.20E-01
0.90	37.6	99.7	3.218	23.0720	22.2324	7.2914	6.8622	0.6654	0.7875	1.08E-01	1.35E-01
0.92	38.9	101.9	3.205	25.1563	24.3013	7.7737	7.3276	0.7911	0.9282	1.22E-01	1.52E-01
0.94	40.2	104.3	3.191	27.6084	26.7414	8.3013	7.8380	0.9528	1.1077	1.40E-01	1.72E-01
0.96	41.7	107.0	3.176	30.5234	29.6505	8.8826	8.4019	1.1646	1.3405	1.61E-01	1.97E-01
0.98	43.2	109.8	3.160	34.0278	33.1582	9.5281	9.0300	1.4474	1.6482	1.87E-01	2.26E-01
1.00	45.0	113.0	3.143	38.2910	37.4394	10.2513	9.7360	1.8328	2.0627	2.20E-01	2.64E-01