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FreedomCAR 42V Battery Test Manual

Idaho National Engineering & Environmental Laboratory
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FOREWORD

This manual was prepared by and for the FreedomCAR Program Electrochemical Energy Storage Team. It is based on goals established by this technical team for 42V energy storage systems and to some extent derives from earlier hybrid test procedures used by the Partnership for a New Generation of Vehicles (PNGV) program (now FreedomCAR) sponsored by the U.S. Department of Energy along with Daimler Chrysler, Ford and General Motors.

The Idaho National Engineering and Environmental Laboratory maintains and updates this manual as needed. This first version of the manual emphasizes testing of full-size 42V energy storage systems rather than cells or sub-units of such systems. Suggestions or comments should be directed to the author, Gary Hunt, at the INEEL, by email to glh@datawav.net or to Chet Motloch at motlcg@inel.gov.

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ACRONYMS

AE	available energy
BCOSOE	best case operating state-of-energy
BOL	beginning of life
BSF	Battery Size Factor
CL	calendar life
EOL	end of life
EOT	end-of-test
EV	electric vehicle
FPA	full power-assist
FUDS	Federal Urban Driving Schedule
HEV	hybrid electric vehicle
HRC	heat rejection coefficient
M-HEV	mild hybrid electric vehicle (mode)
OCV	open-circuit voltage
OSPS	operating set point stability
PEDV	power and energy design verification
P-HEV	power-assist hybrid electric vehicle (mode)
PNGV	Partnership for a New Generation of Vehicles
PPA	partial power-assist
RPT	reference performance test
SEC	static energy capability
SOE	state-of-energy
S-S	start-stop (mode)
TBD	to be determined
USABC	United States Advanced Battery Consortium
ZPA	zero power-assist

GLOSSARY[a]

Available Energy (AE) – for a given test data set, a value that represents the 3 kW constant power discharge energy (in watt-hours) available over the energy range where the 42V power goals are concurrently met, i.e., between *SOEmax* and *SOEmin*. (See the diagram following the glossary.)

Best Case Operating State-of-Energy (*BCOSOE*) – the highest energy state/condition above which the pulse power and available energy goals can all be satisfied within the operating voltage limits. This is the SOE point at which the Self-Discharge and Cold Cranking Tests are performed. (See the diagram following the glossary.)

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

Depth of Discharge – this term is generally not used in this manual because of the potential for confusion with other testing protocols. All references to charging and discharging for 42V systems apply to energy, not to ampere-hour capacity..

End of Life (EOL) – a condition reached at the point where the device under test is no longer capable of meeting any one of the 42V goals. This is normally determined from reference test results, 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 goals.

End of Test (EOT) – 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 the test.

Energy Margin – for a given test data set, the difference between the Available Energy and the energy goal for a given application, expressed either in watt-hours or as a percent of the energy goal. (See the diagram following the glossary.)

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.

Fully Discharged – The condition reached by a device when it has been discharged to the minimum allowable discharge voltage (normally referenced to a constant power discharge at the 3 kW rate.) (This minimum allowable voltage is the Minimum Operating Voltage V_{min} in Table 1 unless the manufacturer's minimum discharge voltage is higher than V_{min}.)

Maximum State-of-Energy (SOEmax) – the highest SOE value at which the regen pulse power goal can be met for a given operating mode. (See the diagram following the glossary.)

Minimum State-of-Energy (SOEmin) – the lowest SOE value at which the discharge pulse power goal can be met for a given operating mode. (See the diagram following the glossary.)

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[a] Only selected terms specific to this manual or those potentially 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 2 and the Handbook of Batteries, Reference 3.

Profile – a connected sequence of steps used as the basic 'building block' of many test procedures. A test profile may include discharge, rest and/or charge steps in a specific order, and each step is typically defined as having a particular (fixed) value of 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-Energy (SOE) – the percentage of a device's usable energy that could be removed at a fixed discharge rate (normally a 3 kW constant-power rate) from the present condition to the fully discharged state. Also used generically to refer to the *amount* of energy available at this rate from the present condition to the fully discharged state.

Usable Energy – a value that represents the 3 kW discharge energy available over a defined energy range for a given operating mode. The usable energy range for each mode is bounded by (a) *SOEupper*, the highest SOE achievable at the mode-specific Recharge Rate without exceeding the Maximum Operating Voltage V_{max} and (b) *SOElower*, the lowest SOE value achievable at 3 kW discharge without exceeding the Minimum Operating Voltage V_{min}, defined as zero SOE for this manual. (See the diagram following.)

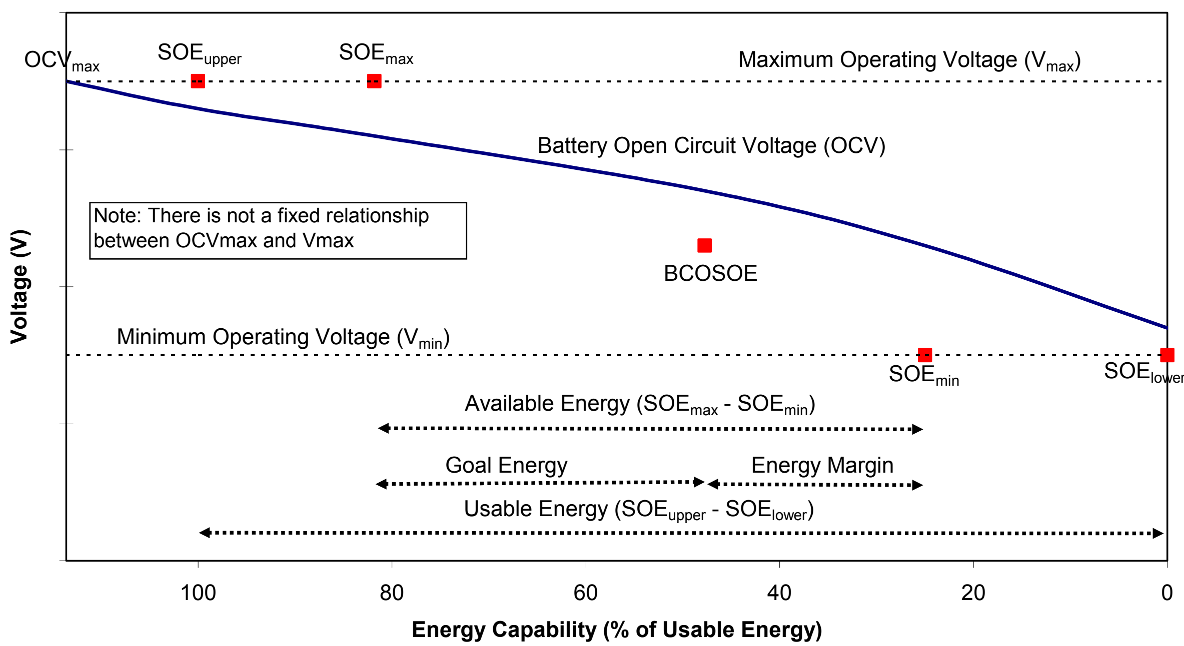

Figure 1. Relationships between energy terms and voltage conditions

FreedomCAR 42V Battery Test Manual

1. PURPOSE, APPLICABILITY AND GOALS

This manual defines a series of tests to characterize aspects of the performance and life behavior of batteries for 42V automotive applications. Tests are defined based on the FreedomCAR program 42V goals, though it is anticipated these tests may be generally useful for other similar applications. The test procedures in this manual are defined for complete 42V energy storage systems; application of the procedures to cells, modules or sub-units of such 42V systems is not discussed in detail. [b]

1.1 42V Energy Storage Goals

Performance and life goals are outlined in Table 1 for three 42V vehicle-operating modes specified for the FreedomCAR Program. These are identified as Start-Stop, Mild HEV (M-HEV) and Power-Assist HEV (P-HEV). The Start-Stop concept assumes that the battery supplies power for engine start (only) and energy for engine-off accessory loads, with no requirement to accept regenerative energy from braking. The M-HEV concept assumes that power is also supplied for an initial 2s power-assist (acceleration boost), while the P-HEV concept provides power-assist for a full 10s acceleration period. Regeneration energy is accepted for 2s for both the M-HEV and P-HEV concepts. This table of 42V 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 42V Energy Storage System End of life Performance Goals (August 2002).

42V Targets Rev. August 2002	Start-Stop	M-HEV	P-HEV
Discharge Pulse Power (kW)	6 (for 2 s)	13 (for 2 s)	18 (for 10 s)
Regenerative Pulse Power (kW)	N/A	8 (for 2 s)	18 (for 2 s)
Engine-Off Accessory Load (kW)	3 (for 5 min)		
Available Energy (Wh @3 kW)	250	300	700
Recharge Rate (kW)	2.4 kW	2.6 kW	4.5 kW
Energy Efficiency on Load Profile (%)	90		
Cycle Life, Miles & Profiles (Engine Starts)	150k (450k)		
Cycle Life and Efficiency Load Profile	Zero Power-Assist (ZPA)	Partial Power-Assist (PPA)	Full Power-Assist (FPA)
Cold Cranking Power @ -30°C on Cold-Start Profile (kW)	8 (21V min.)		
Calendar Life (Yrs)	15		
Maximum System Weight (kg)	10	25	35
Maximum System Volume (Liters)	9	20	28
Selling Price ($/system @ 100k/yr)	150	260	360
Maximum Operating Voltage V_{max} (Vdc)	To be specified by battery supplier		
Maximum Open Circuit Voltage (Vdc)	48 (after 1 second)		

[b] The term "42V" does not refer to an actual (measured) voltage level in this manual. It is a label used to refer to systems with operating characteristics as described in Table 1.

Minimum Operating Voltage V_{min} (Vdc)	27	
Self-Discharge (Wh/day)	<20	
Heat Rejection Coefficient (W/°C)	N/A	>30
Maximum Cell-to-Cell Temperature Difference (°C)	N/A	<4
Operating Temperature Range (°C)	-30 to +52	
Warmup Time from –30 °C Cold Start Condition (minutes)	TBD (at TBD W input power)	
Survival Temperature Range (°C)	-46 to +66	

1.2 Test Profiles Derived from 42V Goals

The approach taken for the test procedures described in this manual is to define a small set of load profiles based on the overall vehicle characteristics. These profiles are specified in terms of vehicle power demand versus time. They can then be used in various combinations as needed to define specific performance or cycle life tests for battery system testing. Each profile is defined within its associated procedure.

2. TEST PROCEDURES

2.1 General Test Conditions

In general, the FreedomCAR 42V testing process is divided into three broad phases, i.e., characterization, life, and reference performance testing. Characterization testing establishes the baseline performance and includes static energy capability, power and energy design verification, self-discharge, cold cranking, thermal performance, and efficiency tests. Life testing establishes behavior over time at various temperatures, states of energy or charge or other stress conditions of interest and includes both cycle life and calendar life testing. Reference Performance Tests are used to establish changes in the baseline performance and to determine when end of life is reached. They are performed periodically during life testing, as well as at the start and end of life testing. A list of information required for the conduct of these tests is contained in the checklist in Appendix A. Note that a number of specific state-of-energy conditions are used or found in various tests; the Glossary and its associated diagram should be consulted for a definition of each of these states.

2.1.1 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. As a general practice, a rest of 60 minutes (or more if required to reach a stable condition) shall be performed after each complete charge and each complete discharge (i.e. to V_{min}) prior to proceeding with further testing, to allow devices to reach stable voltage and temperature conditions. "Stable temperature" means a starting device temperature of 30 ± 3 °C or within ±3°C of the target temperature for thermal performance tests or life tests at other temperatures.

2.1.2 Scaling of Performance and Cycle Life Test Profiles

The performance and cycle life test profiles in this manual 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 tests to a level appropriate to the size of the device under test. Such scaling is not defined in detail in this manual, because it is anticipated that full-size battery systems will be provided for test. If such scaling is determined to be necessary for a manufacturer's internal use, the Battery Size Factor approach described in Reference 1 can be used for this purpose.[c]

2.2 Characterization Test Procedures

The exact number and type of characterization tests to be performed on a battery prior to life testing are variable and will generally be specified in a device-specific test plan. In the absence of such a plan, the following default sequence can be used. Note that the test profiles to be used for (b), (e), (f) and (g) are specific to the operating mode (Start-Stop, M-HEV or P-HEV) for which the battery is designed.

a. One Static Energy Capability (SEC) test (Section 2.2.1) to verify stable battery condition. ("Stable" is defined to mean that the measured discharge energy capability (in Wh) is consistent within 4% for three consecutive tests and there is no indication of a consistent cycle-to-cycle trend in this capability.) [d]
b. One 42V Power & Energy Design Verification (PEDV) test (Section 2.2.2) to verify that the power and energy goals are met at beginning of life
c. One self-discharge test (Section 2.2.3) to verify the self-discharge goal is met
d. One cold-cranking test (Section 2.2.4) to verify the cold cranking goal is met
e. (Optional) Thermal performance tests at cold temperatures. (Section 2.2.5.1 or 2.2.5.2)
f. (P-HEV mode only) Heat Rejection Test (Section 2.2.5.4)
g. Two efficiency tests (Section 2.2.6) to verify that the efficiency goal is met within the operating SOE range, to be conducted immediately prior to start of life testing

2.2.1 Static Energy Capability Test

This test measures device energy capability in watt-hours at a 3 kW constant power discharge rate. Discharge is terminated on a manufacturer-specified discharge voltage limit. If the manufacturer does not provide a discharge voltage limit, then the Table 1 minimum operating voltage of 27 V (at the system level) is used.[e] In addition to characterizing the gross energy capability of a battery, this test is used as the reference for state-of-energy (SOE) for other tests in this manual. All 42V energy goals are defined in terms of a 3 kW constant power discharge rate. However, the energy measured in this test *cannot* be compared directly to the Available Energy goal, because the goal is based on an operating SOE range over which the pulse power goals can also be satisfied.

This test is performed in two parts:

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[c] The Battery Size Factor (BSF) used in Reference 1 is a manufacturer-assigned multiplier representing the number of units of the device under test (cells, modules etc.) that would be required to construct a system satisfying all the program performance goals over the required life of the system. Note that the BSF is a constant over life for all devices of a given design, so it necessarily includes some margin (especially for power and energy) at beginning of life. See Reference 1 for more information. Also note that 42V scaling will be influenced by both charge and discharge behavior due to the high mode-specific recharge rates required by the 42V goals.

[d] This 4% criterion is broader than the 2% variability in constant-current ampere-hour capacity allowed at the start of Reference 1 characterization testing. This is due to the lower voltage vs energy slope that occurs at the 3 kW testing level.

[e] For devices which are not full-size 42V systems, 56% of the fully charged open-circuit voltage is the default value due to Table 1 constraints, although a more restrictive value may be chosen from the literature.

(A) a 3 kW constant power discharge to V_{min} from full charge (using the manufacturer's recommended charge procedure), typically repeated 5 times; and

(B) a 3 kW constant power discharge to V_{min} from *SOEupper* (reached by charging at the mode-specific Recharge Rate in Table 1, using Vmax as the charge cutoff criterion), typically repeated 5 times.

2.2.2 Power and Energy Design Verification (PEDV) Test

The Power and Energy Design Verification (PEDV) test is designed to demonstrate a battery's ability to meet the pulse power and available energy goals by direct application of the goal power and discharge energy values in a combined test sequence.

2.2.2.1 Power and Energy Design Verification Load Profiles

Three different versions of the load profile are defined, corresponding to the Start-Stop, M-HEV and P-HEV goals shown in Table 1. These load profiles are based on the following steps:

(a) *Vehicle Stop*. A regen pulse at the regen power goal values (zero for Start-Stop, 8 kW for 2s for M-HEV or 18 kW for 2s for P-HEV).

(b) *Engine-Off Accessory Load*. A 3 kW constant power discharge that removes the available energy.

(c) *Engine Start/Acceleration*. A discharge pulse at the discharge pulse power goal values (6 kW for 2s for Start-Stop, 13 kW for 2s for M-HEV or 18 kW for 10s for P-HEV).

(d) *Charge (while driving)*. A constant power charge step at the mode-specific Recharge Rate to a fixed termination condition.

This load profile (Stop, Engine-Off, Start/Acceleration, Drive/Charge) can be regarded as a segment of continuous driving operation, where this segment repeats (loops) during driving. These load profiles are defined in Table 2 and illustrated in Figures 2, 3 and 4 following.

Table 2. 42V Power and Energy Design Verification Load Profiles

Step	Start-Stop			M-HEV			P-HEV		
	Time (s)	Power (kW)	Energy (Wh)	Time (s)	Power (kW)	Energy (Wh)	Time (s)	Power (kW)	Energy (Wh)
Regen Pulse	0	None	0	2	-8	-4.4	2	-18	-10
Accessory Load	*Note*	3	Calculated Available Energy	*Note*	3	Calculated Available Energy	*Note*	3	Calculated Available Energy
Discharge Pulse	2	6	3.3	2	13	7.2	10	18	50
Charge	To V_{max}	-2.4	*Note*	To V_{max}	-2.6	*Note*	To V_{max}	-4.5	*Note*

Note: times and/or energy amounts for these steps are as required to reach the specified conditions.

Note that this manual represents discharge parameters (power, energy, current etc.) as positive values, while regen and charge values are represented as negative. Note also that the durations of the accessory load and recharge steps are not defined in Table 2, because they are not fixed in advance: rather they are determined during the test itself. *Thus the durations of these steps shown in Figures 2, 3 and 4 are for illustration only.*[f]

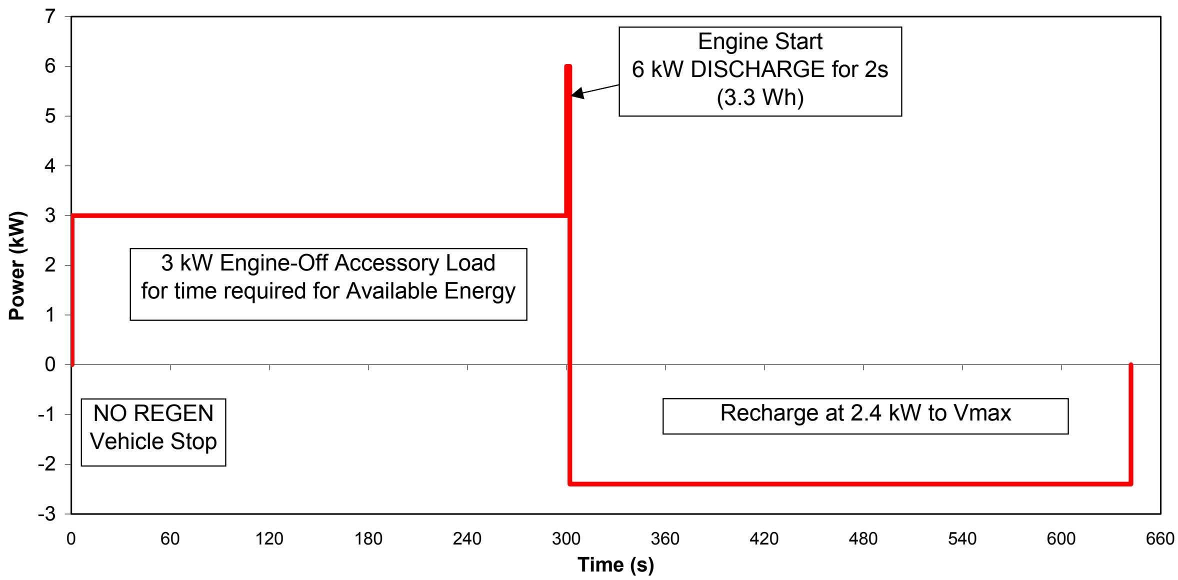

Figure 2. Start-Stop Power & Energy Verification Design Load Profile

[f] Strictly speaking, Table 1 only requires the 3 kW discharge to be available for 5 minutes continuously, and the maximum time required for the mode-specific recharge power is not specified. The PEDV procedure performs both the 3 kW discharge and the mode-specific recharge continuously over the full battery operating voltage range. Preliminary testing prior to the release of this manual indicates that this does not result in unreasonable thermal behavior, and it simplifies a procedure which is already quite complex.

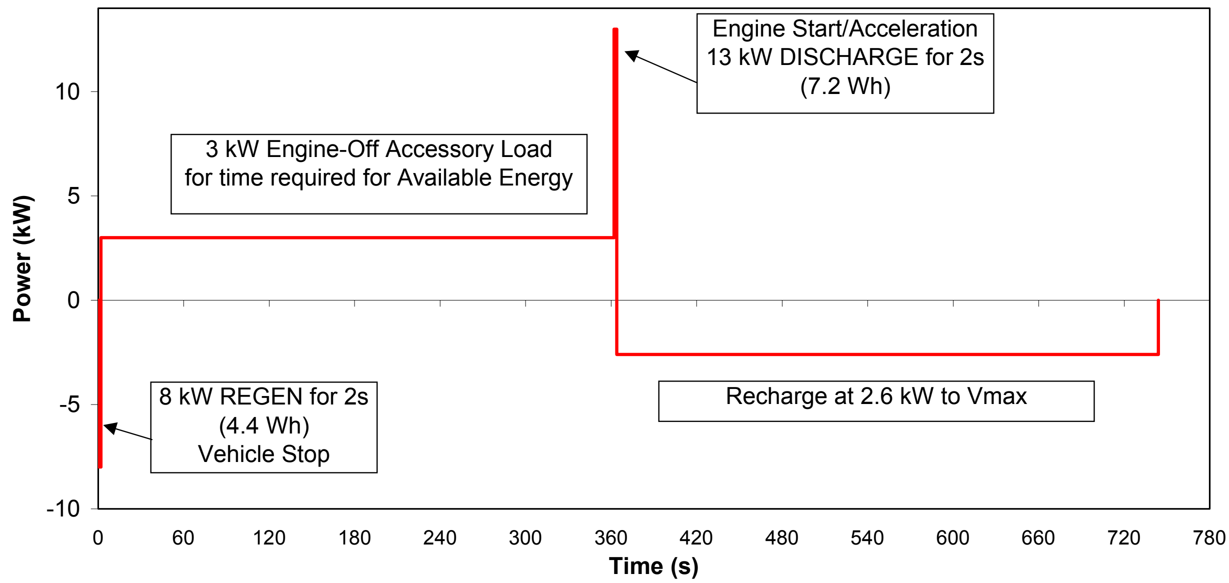

Figure 3. M-HEV Power & Energy Design Verification Load Profile

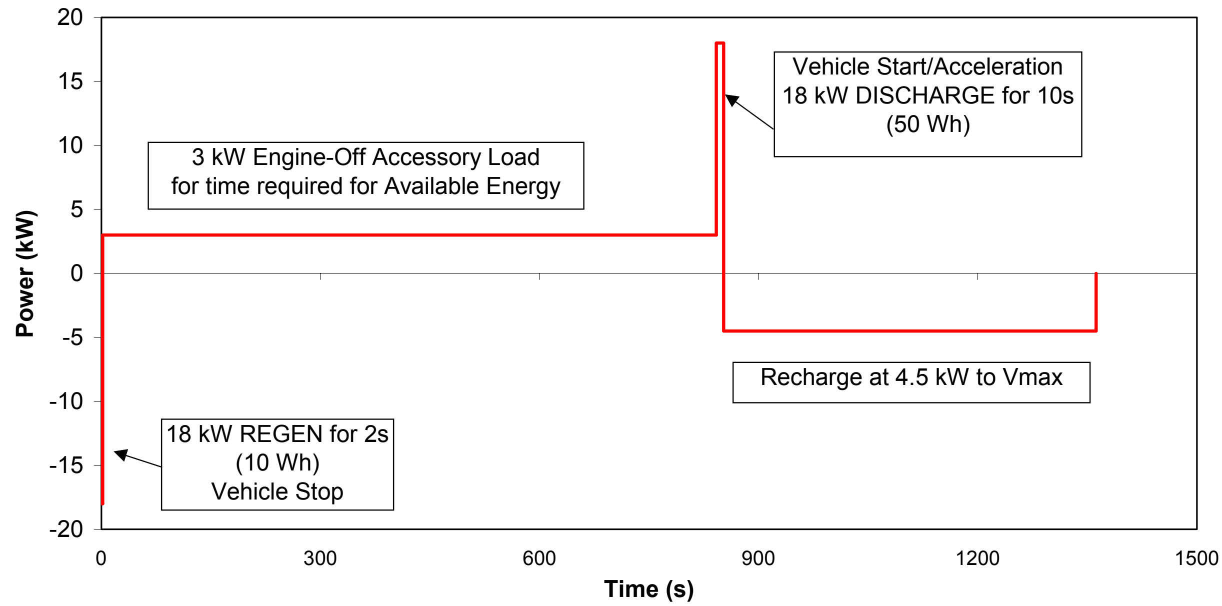

Figure 4. P-HEV Power & Energy Design Verification Load Profile

2.2.2.2 Test Procedure Description

The 42V Power and Energy Design Verification (PEDV) Test is conducted in accordance with the following sequence of steps, which are generally illustrated through the example voltage plot in Figure 5 up to the point where Available Energy can be calculated.[g]

This procedure uses maximum and minimum operating voltages (V_{max} and V_{min}), to be specified by the manufacturer. These may be used for both continuous and pulse operation. For testing purposes only, the manufacturer is strongly encouraged to specify less restrictive voltage limits for pulse conditions, denoted by $V_{maxPULSE}$ and $V_{minPULSE}$. If defined, these broader values will be used for pulse limiting during the test, although pulse values outside the range V_{min} to V_{max} will not count toward the pulse power goals.[h]

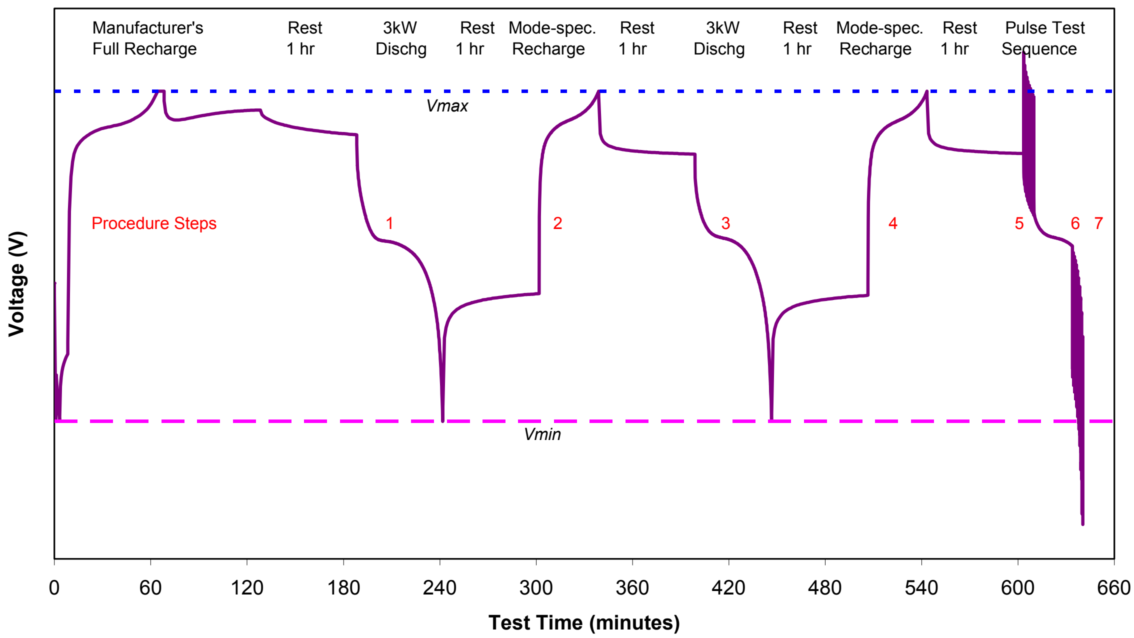

Figure 5. PEDV test sequence and voltage behavior through Step 7.

1. Discharge at a 3 kW constant power rate from full charge to the minimum operating (discharge) voltage V_{min} (e.g. 27V). [This is equivalent to Part (A) of the Static Energy Capability test from 2.2.1 above.] Then rest 1 hour at open-circuit conditions.

2. Recharge at the mode-specific Recharge Rate in Table 1 to the maximum operating (charge) voltage V_{max} specified by the manufacturer. [This establishes the upper bound of the usable energy range *SOEupper* for power tests. For Start-Stop tests, this is also the actual SOE limit *SOEmax*.] Then rest 1 hour.

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[g] This test can be scaled by the Battery Size Factor if the test article is not a full-size 42V device. Scaling can be done using a methodology similar to that described in the PNGV Battery Test Manual, Revision 3, February 2001, but using 42V goals in place of the PNGV goals. Note that this scaling approach may not be accurate for some 42V goals such as cold cranking; some experimentation may be necessary in such cases.

[h] These relaxed limits make it possible to obtain pulse voltage data points below V_{min} and above V_{max}, which generally improves the accuracy of determining *SOEmax* and *SOEmin*.

3. Discharge at a 3 kW constant power rate from this upper SOE value to V_{min}. [This is equivalent to Part (B) of the Static Energy Capability Test from 2.2.1. It establishes the maximum 3 kW energy available within voltage limits, without considering pulse power limits. This value is called the "Usable Energy".] Then rest 1 hour.

4. Recharge at the mode-specific Recharge Rate to V_{max}. [This is the same as Step 2; it verifies *SOEupper* and the charge energy required to reach it, as well as the discharge/charge efficiency over this SOE region.] Then rest 1 hour.

5. The following steps utilize the discharge static energy capability from either Part (B) of a previously performed Static Energy Capability Test (SEC-B) or from the equivalent Step 3 of this test.

   Start-Stop Mode:
   Discharge at a 3kW constant power rate for 50% or more of the SEC-B energy.[i] Then go to Step 6.

   M-HEV and P-HEV Modes:
   a. Perform the mode specific regen pulse from Table 1. Use $V_{maxPULSE}$ as the upper voltage limit if available; otherwise limit the pulse on V_{max}.[j]
   b. Discharge at a 3kW rate for a 1% net SEC increment (including the regen pulse).[k]
   c. Repeat steps 5a and 5b until the end-of-pulse voltage is less than V_{max}, and then repeat two additional times.[l]
   d. Discharge at a 3 kW rate until the net discharge energy is 50% or more of the SEC-B energy; then go to Step 6.[m]

6. The following steps also utilize the previously obtained discharge static energy capability (SEC-B or the result of the equivalent Step 3 of this test). In all cases use $V_{minPULSE}$ as the lower pulse voltage limit if available; otherwise limit the pulse at V_{min}.

   a. Perform the mode specific discharge pulse from Table 1.

   b. Perform the appropriate action depending on the end-of-pulse voltage in Step 6a:
      - If the end-of-pulse voltage is $\leq V_{min}$, go to Step 7.[n]

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[i] The intent of the 50% constraint here and in step (5d) is to avoid unnecessary pulses in the middle of the SOE range, where they do not contribute to finding the SOE corresponding to the pulse voltage limits. The optimum SOE amount to be removed before discharge pulsing begins may be technology specific and can be estimated from previous test data.

[j] If previous testing indicates that *SOEupper* is a much higher value than *SOEmax*, an appropriate energy increment can be removed at a 3 kW constant power rate before the first regen pulse to avoid unnecessary pulse iterations. However, the first pulse should still occur above *SOEmax* for best results.

[k] The length of this step can be controlled based on either a fixed step energy or a fixed time that will produce this energy at 3 kW. A simple spreadsheet called “PEDV_Planning_Worksheet.xls” is provided with this manual to convert various step energy values in Steps 5 and 6 to the appropriate step times.

[l] If V_{max} is set too low relative to the pulse resistance, this loop may never terminate. To account for this possibility, the loop may need to be limited to a number of executions that will not allow it to continue below approximately 50% SOE. This can be done by calculating the net energy in each execution of Steps 5a and 5b.

[m] This can be done in one of two ways: (1) if the tester is accumulating net energy for the entire test, the 50% point is directly available; (2) otherwise the 3 kW discharge voltage at 50% SOE can be found from the SEC-B data.

- If the end-of-pulse voltage is ≥110% of V_{min}, discharge at a 3kW rate for a net 5% SEC increment (including the discharge pulse) with a minimum 1% SEC increment to be performed at 3 kW.[o] If V_{min} is reached during this discharge, go to Step 7. Otherwise go to Step 6a and repeat.
- If the end-of-pulse voltage is between V_{min} and 110% of V_{min}, discharge at a 3 kW rate for a 1% SEC increment (not including the discharge pulse.) If V_{min} is reached during this discharge, go to Step 7. Otherwise go to Step 6a and repeat.

7. Rest for a maximum of 10s to allow the voltage to recover above V_{min}. Then discharge at a 3kW constant power rate to V_{min}.[q]

8. Calculate Available Energy, *SOEmax* and *SOEmin* as described in Section 3.2.2.1.

9. To verify the Available Energy result, perform the following sequence of steps.

   a. Recharge at the mode-specific Recharge Rate (Table 1) to V_{max} (i.e. to *SOEupper*). [r]

   b. Discharge at a 3 kW constant power rate to the *SOEmax* value found in Section 3.2.2.1 by removing an amount of energy equal to (*SOEupper – SOEmax)*, where *SOEupper* is found in Step 3. [Not applicable to Start-Stop.]

   c. Perform the mode specific PEDV load profile from Table 2.

      (c1) Perform a regen pulse at the goal power and duration. Verify the peak pulse voltage is less than or equal to V_{max}. [Not applicable to Start-Stop.]

      (c2) Discharge at 3 kW for the Available Energy calculated in Section 3.2.2.1.

      (c3) Perform the mode-specific discharge pulse at the goal power and duration. Verify the minimum pulse voltage is greater than or equal to V_{min}.

      (c4) Recharge at the mode-specific Recharge Rate to V_{max}.

Both the calculated results of Step 8 and direct observation of the results of Step 9 provide verification that the power and energy goals are met. If all the parts of Step 9 are performed at the target

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[n] Note that if the manufacturer's minimum pulse voltage is equal to V_{min}, it will not be possible to complete a discharge pulse at a voltage less than V_{min}. Thus the last pulse data point may not be valid, and the value of *SOEmin* will need to be extrapolated (rather than interpolated) from the data points above V_{min}.

[o] The intent of the 1% constraint is to assure that some minimum amount of 3kW discharge always occurs, to allow the load voltage to recover to the 3kW discharge curve. The change from 5% to 1% increments need not be at exactly 110% of V_{min}. It can be selected to occur at any value that results in an appropriate number of pulses (e.g. 2 or 3) at 1% increments above V_{min}.

[q] The energy removed by this final discharge step is critical to the calculations in Step 8. The rest period is intended to avoid premature termination of this step due to voltage depression during the last discharge pulse.

[r] In exceptional cases (e.g. lead-acid batteries) it may be necessary to precede this step with a full recharge and a 3 kW discharge to V_{min} to assure that the SOE at the end of this step is the same *SOEupper* reached at the end of Step 2.

power values, and none of the battery operating voltages is violated, this demonstrates compliance with the goals.[s, t]

2.2.3 Self-Discharge Test

This test is intended to determine the temporary energy capability loss that results from a battery standing (at rest) for a predetermined period of time. This energy loss is measured at a fixed point within the operating SOE range that corresponds to removing exactly the goal energy (i.e., this point is just above any energy margin.)

The test consists of the following steps:

1. Discharge the fully charged battery to the minimum discharge voltage V_{min} at a 3 kW constant power rate.
2. Recharge the battery at the Table 1 mode-specific Recharge Rate to *SOEupper* (i.e. to V_{max}).
3. Discharge the battery to the minimum discharge voltage V_{min} at a 3 kW constant power rate. (This provides the reference energy capability for this test.)
4. Recharge the discharged battery at the Table 1 mode-specific Recharge Rate to *SOEupper* (i.e. to V_{max}). Then discharge at a 3 kW constant power rate to *SOEmax* by removing an amount of energy equal to (*SOEupper – SOEmax*).[u]
5. Discharge the battery at 3 kW for an amount of energy equal to the goal energy. The resulting SOE point is called the Best Case Operating SOE (*BCOSOE*).
6. Allow the battery to stand for a nominal interval of 7 days (1 week). (For improved measurement uncertainty, the actual stand period should be selected based on the expected stand loss rate, with the value chosen to yield an expected energy capability loss between 5% and 25% over the interval.) Disconnect test or measurement equipment from the battery during this period only if necessary to limit parasitic losses to those intrinsic to the battery.
7. Measure the battery open circuit voltage at the end of the stand period, and discharge the battery for its remaining (residual) energy at a 3 kW constant power discharge rate to V_{min}.

After the test is completed, the battery should be recharged using the manufacturer's recommended charge algorithm and then fully discharged at a 3 kW rate. If a loss of energy capability is observed compared to step (1), a number of additional full recharge/discharge cycles (from three to a maximum of ten) can be performed to try to return the battery to its nominal energy capability.

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[s] See Section 3.2.2.1 for the required agreement between the results of Steps 8 and 9.

[t] In principle, verification Step 9 is sufficient to verify the goals and establish the energy margin. In principle it might be possible to estimate *SOEmax* and *SOEmin* from other performance information (e.g. cycle life test profile performance) and perform Step 9 without performing the rest of the PEDV test sequence. In practice this is likely to lead to repeated tests which will not reduce the total time required.

[u] In exceptional cases (e.g. some lead-acid batteries) there may be a cycle-to-cycle variation in measured energy due to the mode-specific recharge, which includes no overcharge. In such cases it may be necessary to insert a full manufacturer's recharge and full 3 kW discharge between Steps 3 and 4 to prevent this variability from perturbing the test results.

2.2.4 Cold Cranking Test

The Cold Cranking test is intended to measure 2-s power capability at low temperature (normally -30ºC) for comparison with the Cold Cranking Power goal in Table 1. The test is conducted at the same Best Case Operating SOE value defined previously in Section 2.2.3. The test consists of the following sequence of activities:

1. At 30ºC, establish the battery at the Best Case Operating SOE (*BCOSOE*) value as in Section 2.2.3 Steps (4) and (5).

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 hours minimum). Battery thermal management controls should be deactivated during this step and the following one.

3. Perform the Cold Cranking test profile defined in the following section. The pulse power level to be used is 8 kW. Note that the goals in Table 1 allow a different minimum discharge voltage for cold cranking tests. This voltage will be used for both test control and the subsequent calculation of cold cranking power capability. Note also that the profile pulses must be performed for the full 2-s duration (even if the power has to be limited to stay within the minimum discharge voltage) to permit the later calculation of Cold Cranking power capability.

2.2.4.1 Cold Cranking Test Profile.

The Cold Cranking Test profile is a direct implementation of the Cold Cranking Power goal, which requires the ability to provide 8 kW of discharge power for three 2-second pulses without exceeding (i.e., dropping below) the minimum cold-cranking voltage (21V). The 2-s pulses are performed at 12-s intervals (i.e., 10 s between pulses.) The test profile is defined in Table 3 and illustrated in Figure 6.

Table 3. Cold Cranking Test Profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)
2	2	8
10	12	0
2	14	8
10	24	0
2	26	8

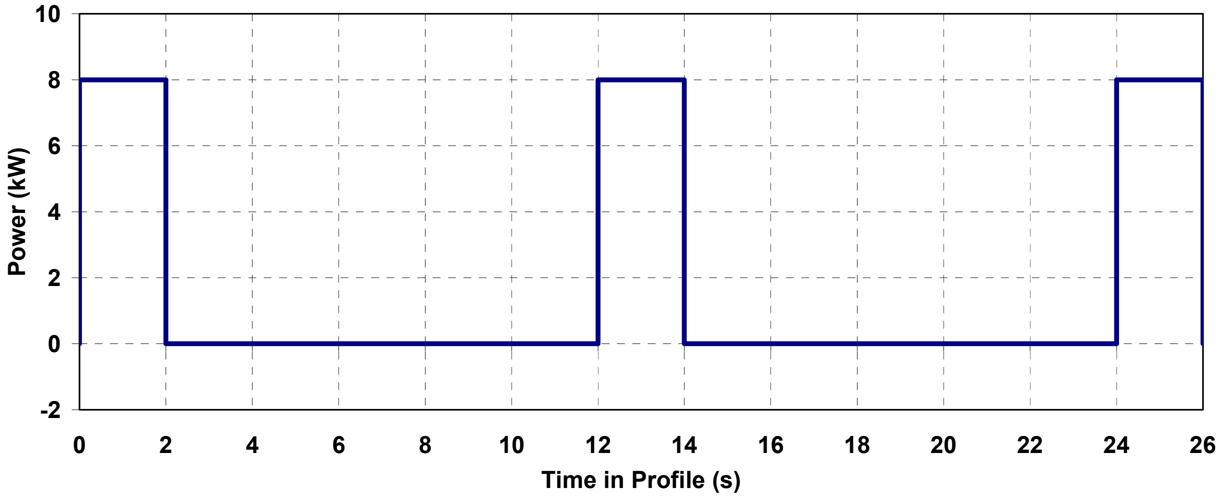

Figure 6. Cold Cranking Test Profile

2.2.5 Thermal Performance Tests

Unless otherwise specified, initial charging should be performed at 30ºC during thermal performance tests. This implies a test sequence as follows: (1) fully charge the battery at a starting temperature of 30±3ºC; (2) lower the battery ambient temperature to the target value; (3) wait a suitable soak period for thermal equalization, typically 3 hr or more; and (4) execute the desired performance test. If self-discharge is a major concern during the soak period, the battery can be voltage-clamped during this period; however, this requires attention to the OCV-versus-temperature behavior to ensure that the SOE is not changed inadvertently.

2.2.5.1 Standard Thermal Performance Tests

The effects of environment (ambient temperature) on battery performance will be measured as required by performing the Power and Energy Design Verification (PEDV) Test (which also includes the Static Energy Capability Test) and/or the Cold Cranking Test at various temperatures within the operating temperature goal range. A primary intent of such tests should be to determine the battery temperature at which the energy margin or the cold cranking power margin reaches zero. This can be done systematically by performing the PEDV test at fixed temperature increments below 30°C and stopping when the energy goal is not met (e.g. nominally at 20, 10, 0, -10, -20 and -30°C). Alternatively, the results of the characterization PEDV test and the Cold Cranking test can be used to estimate the test temperatures.

It may be necessary to adjust the rest intervals during the Power and Energy Design Verification test to ensure that battery temperature remains within the tolerances defined in Section 2.1.1. In some cases it may be necessary to delay the start of regen or discharge pulses until battery temperature is within tolerances, or to limit the 3 kW discharge steps to 5 minutes of continuous discharge followed by 5 minutes of rest, in order to avoid non-representative results at very low temperatures. The cold temperature version of the PEDV test can be done in two different ways depending on recharge strategy:

1. Return to 30°C for all recharge (not regen) steps, i.e., Steps 2, 4, 9a and 9(c4) in Section 2.2.2.2. This amounts to testing the device's low temperature discharge, regen and 3 kW energy performance over what would be the normal 30°C operating SOE range of the battery.

2. Perform the entire test sequence of Section 2.2.2.2 at the test temperature, including recharge steps. This will limit testing to the SOE region that can be reached at the test temperature without exceeding charge voltage limits.

In general the first version of this test is preferred, because it covers the SOE region where the battery is most likely to be left when the vehicle is parked. The second version is of interest primarily to evaluate recharge limitations at cold temperatures. In either case the PEDV steps will need to be referenced to the cold-temperature SEC-B energy discharge capability rather than to the 30°C results.

It is recommended that these tests be done only at temperatures below 30°C, since performance will normally improve (at the expense of life) above this test temperature. Even if the battery electrochemistry is operated at higher temperatures internally, in general there is no reason to do characterization tests above an ambient temperature of 30°C.

2.2.5.2 Alternative System-Level Thermal Performance Test

The system-level thermal performance test is intended to determine the time required for battery thermal controls to raise the battery to the temperature T_{min} where the energy margin is zero. This test is based on two prerequisites: (1) A system specification is defined for the amount of power available (when the engine is started) to do battery warm-up while also returning charge to the battery. (2) The temperature T_{min} is known either as the result of the standard tests defined in Section 2.2.5.1 or from other information. [v]

This test can be done as an addendum to the Cold Cranking test as follows:

(a) After the cold cranking profile is executed (while the battery is still at -30°C), battery thermal controls are activated.

(b) Power is applied to the battery terminals at the specification level, to be used by the system for warm-up or recharge in accordance with the battery system design.

(c) Battery temperature is then monitored until the temperature reaches T_{min}, at which point the warm-up/recharge is stopped and the required time and energy to reach this point are known.

The battery is then returned to 30°C and the residual energy is discharged at 3 kW to determine the final state-of-energy produced.

In addition to determining the warm-up time, the power and energy performance at T_{min} should be verified by performing the PEDV test at this temperature (in addition to or in lieu of the standard thermal performance tests.)

2.2.5.3 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 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

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[v] Note that this test is not very useful unless the battery system controls have actually been designed to do such warm-up (as opposed to just using the supplied power for charging).

operating and storage temperatures selected for various battery technologies (for performance and life reasons) will interact with the 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 energy losses due to temperature management) has been defined and is described in Appendix F of Reference 1. This process is analytical in nature, but its use requires information 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.) Much of the required performance and life data can be gathered using the tests in this manual, particularly the thermal tests defined in 2.2.5.1, 2.2.5.2 and 2.2.5.4. These can also determine basic energy costs for system/module control and conditioning. To be useful for this purpose, the tests must be instrumented such that separate monitoring of power and energy supplied to system thermal controls is provided, and additional temperature sensors may be needed. Experimental verification of thermal behavior (including control effectiveness) at the system level is highly desirable, but conduct of such tests will generally require system-specific information. Consequently such tests are not defined in detail in this manual other than as needed to verify specific goals.

2.2.5.4 Heat Rejection Test (P-HEV Mode Only)

Table 1 defines additional goals for the thermal management performance of P-HEV mode batteries. These goals include the Heat Rejection Coefficient (HRC), which is a measure of a battery's ability to dispose of heat generated by losses within the battery; and Maximum Cell-to-Cell Temperature Difference, which is a measure of the uniformity of temperatures within the battery under high load conditions. These parameters are measured using a test profile scaled to produce a sufficiently high level of battery heat generation. (This profile scaling is done primarily to obtain an acceptable accuracy of the result; in principle the HRC can be evaluated using any profile that produces adequate steady-state internal heating.)

The Heat Rejection test profile is scaled to result in 300W losses for a battery whose efficiency is 90% on the Full Power-Assist profile (Section 2.2.6.3). The test profile is constructed by using the accessory load power and P-HEV pulse power goal values, with the accessory load (stop) interval shortened to raise the average power. A corresponding recharge interval (at the level used in the FPA profile) is selected to charge-balance the profile. The resulting profile is defined in Table 4 and illustrated in Figure 7.

Table 4. Heat Rejection Test Profile

Time (s)	Cumulative Time (s)	Power (kW)	Energy (Wh)	Thermal Loss (Wh) [w]
18	18	3	15	0.28
10	28	18	50	6.89
79	107	-2.925	-64.19	1.07
2	109	-18	-10	.88

[w] For a theoretical battery with an open-circuit voltage of 42.0 V and a fixed internal resistance yielding 90% efficiency on the FPA test profile, with all losses assumed to go to battery heating.

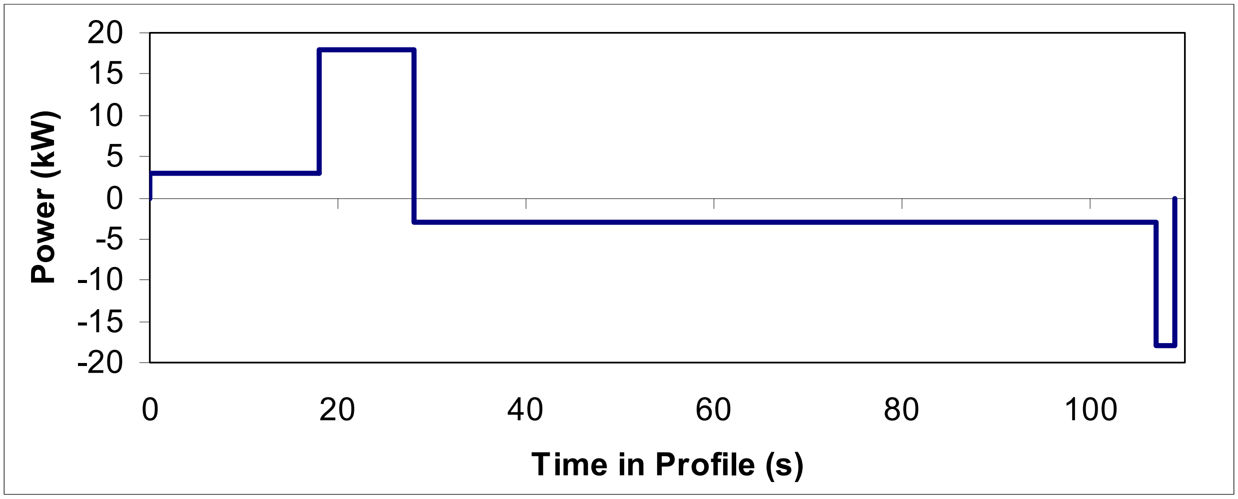

Figure 7. Heat Rejection Test Profile

This test is conducted similarly to the Energy Efficiency test defined inthe following section, by executing the test profile a sufficient number of times (e.g. 100) to reach a stable cycling state and to achieve thermal equilibrium conditions in the battery. The battery inlet and outlet temperatures are measured at this condition, and battery thermal losses are calculated based on the energy efficiency achieved for this profile at stable cycling conditions.[x] The Heat Rejection Coefficient is then calculated as described in Section 3.2.6. This test can also be used to find the Maximum Cell-to-Cell Temperature Difference reached under these test conditions if the battery is instrumented with temperature sensors in appropriate locations. The results will not be representative of a real operating state because of the unrealistically high internal heat generation, but the higher temperature differences (when scaled to normal operating levels) should give more accurate results. [y]

2.2.6 Energy Efficiency Test

2.2.6.1 Background

Compliance with the round-trip energy efficiency goal is determined using the charge-neutral load profile for the specified application (zero power-assist or ZPA profile for Stop-Start, partial power-assist or PPA profile for M-HEV, and full power-assist or FPA profile for P-HEV). The three load profiles, which are also used for cycle life verification, have been developed using the following ground rules:

1. Overall round-trip energy efficiency of 90%
2. 90th percentile customer usage
3. Three stop-starts per mile, average
4. Goal-level pulse power capability for Stop-Start and M-HEV applications

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[x] Note that the HRC goal applies to a fully engineered battery system with thermal management included. This test is not useful at lower levels of system integration.

[y] There are a number of battery-specific considerations in measuring the Maximum Cell-to-Cell Temperature Difference that are not treated here, such as the number, location and type of temperature sensors to be provided with the battery.

5. De-rated pulse power capability for P-HEV applications
6. Distribution of engine-off times based on Federal Urban Driving Schedule (FUDS)
7. Average vehicle speed during driving (engine-on) of 1.25 x FUDS
8. Full cycle life demonstration within one year of testing (~7200 hours of cycling)

Each profile consists of three engine-off/start/recharge/stop sequences. The engine-off durations are 42, 16, and 5 seconds, corresponding approximately to the 95th, 50th, and 5th percentile vehicle-stopped durations in the FUDS. The engine-start pulses are at the rated power levels for the ZPA and PPA profiles, since those levels will normally be used in those applications. For the FPA profile, normal usage will not be at the full goal-level pulse power ratings. For that application, the derating factors used in Reference 1 for the 25-Wh load profile, relative to the Power-Assist performance targets, were assumed.[z]

Not including stopped/engine-off times, the average vehicle speed on the FUDS is about 25 mph. For the 90th percentile customer, a factor of 1.25 was used to obtain a more representative average speed of 31.5 mph (about 23 mph including stopped times). This assumption results in a profile duration of 177 seconds for all three profiles. Demonstration of the 150,000-cycle life goal will therefore require about 7,375 hours (307 days or 44 weeks) of continuous cycling, plus time for Reference Performance Tests.

The recharge power was adjusted for each profile to achieve the desired 90% energy efficiency goal. At the beginning of life, batteries are likely to have higher energy efficiency than this goal. To maintain charge neutrality, as is required to achieve continuous unattended cycling, it will be necessary to occasionally adjust the recharge power, generally by increasing the recharge power level as cycle life accumulates. The recharge power levels specified in the three profiles should be only required at the end of battery life. The following Energy Efficiency Test will establish the recharge power level needed to maintain charge-neutrality at any point in the battery's life.

2.2.6.2 Energy Efficiency Test Procedure

The Energy Efficiency Test is performed as follows:

1. Bring the battery to a specified target state-of-energy value and operating temperature. For Characterization testing purposes, it is recommended that the test be performed twice, at both the maximum and minimum operating SOE values *SOEmax* and *SOEmin* found from the PEDV results. (See Section 2.2.2.2).[aa]

2. Perform 100 efficiency test profiles (ZPA, PPA or FPA as appropriate) while controlling the state-of-energy at the value intended for life cycling.

3. Determine the change (if any) in the state-of-energy before and after the 100 profiles, generally by removing the residual energy and/or observing the open circuit voltage. Allow a 1-hr rest period before and after the 100 profiles are performed to determine any change in open circuit voltage.

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[z] The full discharge pulse power requirement of 18 kW for 10s is not appropriate for a continuous cycle life test profile based on 90th percentile customer usage at 3 stops/starts per mile.

[aa] The states of charge to be used for efficiency and/or cycle life testing should be specified in a battery-specific test plan, because they depend on the usable operating range. Note that efficiency can be checked at the cycle life testing SOE at any later time by performing the efficiency calculation on a block of cycle life test profiles.

4. Verify that stable cycling is achieved by the completion of 100 profiles and that the final SOE is within 5% of the target value. "Stable cycling" generally means that the peak pulse voltages (discharge and regen) are not changing from profile to profile and that battery temperature has reached a stable value.

   a. If cycling converges to a stable condition but the final SOE is not the target value, the SOE control point should be adjusted. The recommended control method for this test is to vary the length of the third recharge step slightly (up to 10%) depending on the final voltage achieved. [bb]

   b. If cycling appears to be converging but a stable condition is not reached by 100 profiles, repeat the test with a larger number of profiles.

   c. If cycling is not converging to a stable condition, the recharge level in the test profile must be adjusted to a charge balanced condition. This is done by dividing the difference between the initial and final SOE values by the number of profiles, and then altering the recharge value (power, not time) in the profile to add or subtract this amount of energy. (Example: if the final SOE value is 100 Wh lower than the initial value after 100 profiles, the recharge power in the profile must be raised by an amount sufficient to give an additional 1 Wh of charge energy per profile. For the ZPA profile, this is 33 W over 108s of recharge, which would raise the recharge power level to –1.700 kW.) [cc]

2.2.6.3 Zero Power-Assist (ZPA) Efficiency and Life Test Profile.

The Zero Power-Assist (ZPA) Test Profile is a 177-s, nominally SOE-neutral pulse profile that is used to verify the Start-Stop goal of 90% for round trip energy efficiency using the discharge pulse power capability requirement of 6 kW for 2s. This test profile is defined in Table 5 and illustrated in Figure 8.

[bb] Dynamic control of SOE during cycling is discussed in detail in Appendix C of Reference 1. (Reference 1 actually deals with state-of-charge control, but the approaches described are directly applicable here.)

[cc] This example does not mean that 4-digit precision is required in the test profile. The normal control methods (see previous note) have enough tolerance to account for some variation from the target values due to tester limitations.

Table 5. Zero Power-Assist (ZPA) Efficiency and Life Test Profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh) [dd]
42	42	2	23.33	23.33
2	44	6	3.33	26.66
36	80	-1.667	-16.67	11.66
16	96	2	8.89	20.55
2	98	6	3.33	23.88
36	134	-1.667	-16.67	8.88
5	139	2	2.78	11.66
2	141	6	3.33	14.99
36	177	-1.667	-16.67	0

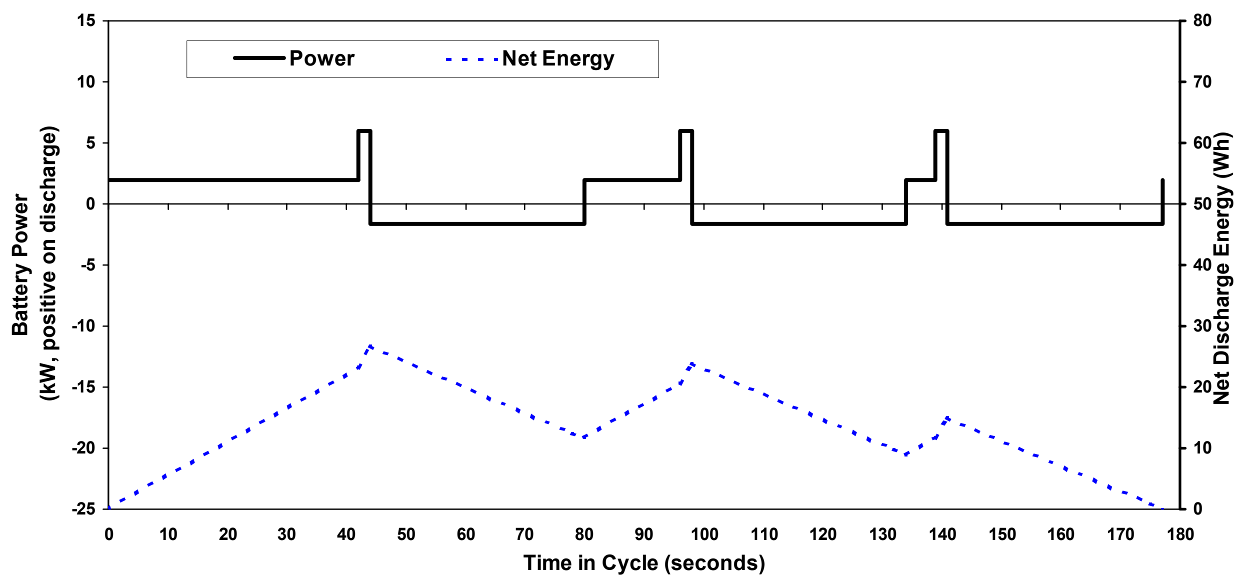


Figure 8. Zero Power-Assist (ZPA) Efficiency and Life Test Profile

2.2.6.4 Partial Power-Assist (PPA) Efficiency and Life Test Profile.

The Partial Power-Assist (PPA) Test profile is a 177-s, nominally SOE-neutral pulse profile that is used to verify the Start-Stop goal of 90% for round trip energy efficiency using the required pulse power capabilities of 13 kW discharge and 8 kW regen for 2s. This test profile is defined in Table 6 and illustrated in Figure 9.

[dd] Battery net energy, based on an assumed discharge/charge efficiency of 90% (i.e., this profile is calculated to be charge-neutral for a device that exactly meets the 90% efficiency goal. If actual battery efficiency is different than the goal, it may be necessary to adjust the recharge power level as discussed in the text.

Table 6. Partial Power-Assist (PPA) Efficiency and Life Test Profile.

Time Step (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh) [ee]
42	42	2	23.33	23.33
2	44	13	7.22	30.55
34	78	-1.752	-16.55	15.66
2	80	-8	-4.44	11.66
16	96	2	8.89	20.55
2	98	13	7.22	27.77
34	132	-1.752	-16.55	12.88
2	134	-8	-4.44	8.88
5	139	2	2.78	11.66
2	141	13	7.22	18.88
34	175	-1.752	-16.55	3.99
2	177	-8	-4.44	0

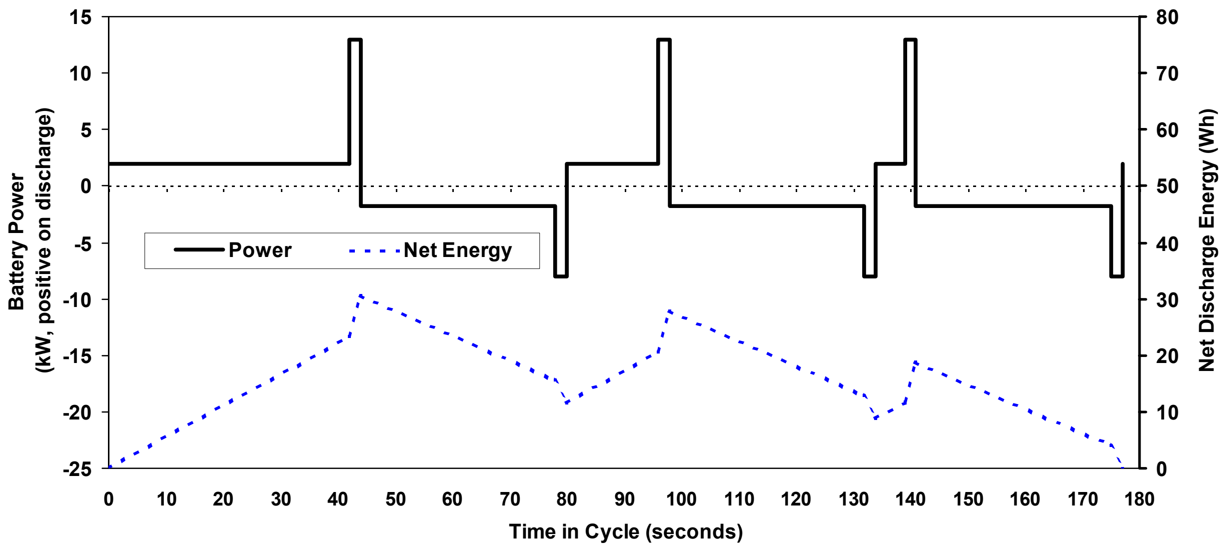


Figure 9. Partial Power-Assist (PPA) Efficiency and Life Test Profile

2.2.6.5 Full Power-Assist (FPA) Efficiency and Life Test Profile

The Full Power-Assist (FPA) Test profile is a 177-s, nominally SOE-neutral pulse profile that is used to verify the P-HEV goal of 90% for round trip energy efficiency. This profile uses the regen pulse power capability goal of 18 kW for 2s along with a 20 Wh discharge pulse (14.4 kW for 5s). This test profile is defined in Table 7 and illustrated in Figure 10.

[ee] See note on Table 5 regarding the assumed discharge/charge efficiency of 90%.

Table 7. Full Power-Assist (FPA) Efficiency and Life Test Profile.

Time Increment (s)	Cumulative Time (s)	System Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh) [ff]
42	42	2	23.33	23.33
5	47	14.4	20	43.33
31	78	-2.93	-25.23	20.62
2	80	-18	-10	11.62
16	96	2	8.89	20.51
5	101	14.4	20	40.51
31	132	-2.93	-25.23	17.80
2	134	-18	-10	8.80
5	139	2	2.78	11.58
5	144	14.4	20	31.58
31	175	-2.93	-25.23	8.87
2	177	-18	-10	0

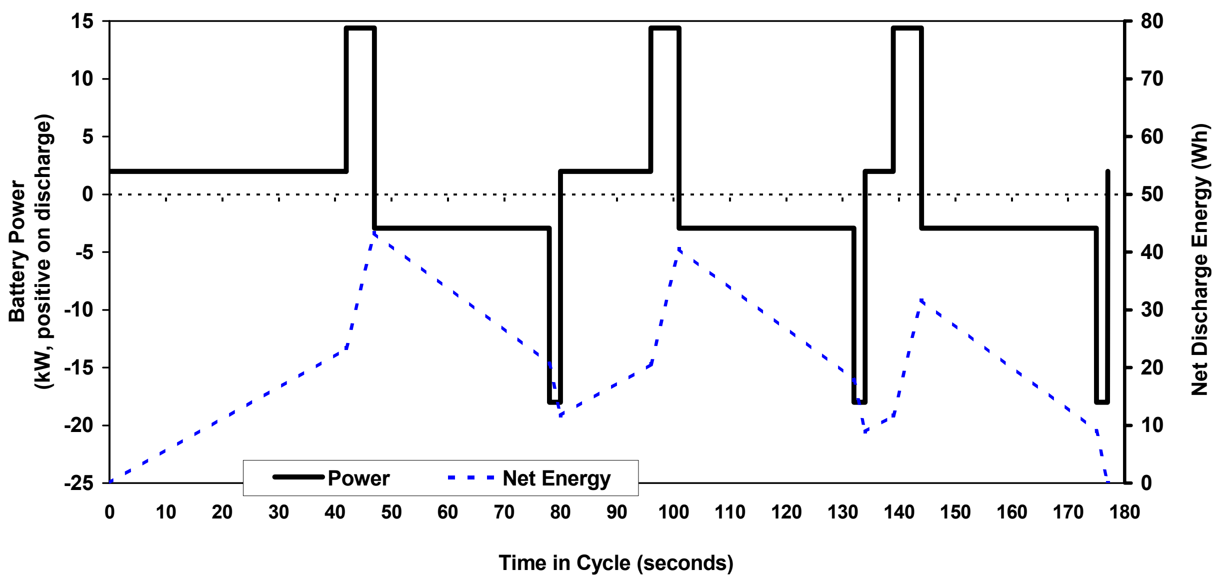


Figure 10. Full Power-Assist (FPA) Efficiency and Life Test Profile

2.3 Life Test Procedures

2.3.1 Operating Set Point Stability Test

This test actually constitutes the beginning of cycle life testing. Since cycle life testing is done at an intermediate state-of-energy, it is necessary to determine that stable cycling will occur at the target SOE, and to adjust test conditions if necessary to ensure that this will be the case. The target state-of-

[ff] See note on Table 5 regarding the assumed discharge/charge efficiency of 90%.

energy for cycle life test(s) is normally specified in a battery-specific test plan based on projected use of the device. (See Section 2.3.2.3 for further discussion.) The OSPS test is functionally identical to the efficiency test defined in Section 2.2.6, and the same profiles are used for both. In practice they can be the same test if efficiency tests are done immediately prior to the start of cycle life testing and the same SOE value is suitable. Note that any adjustments required to the test profile for the efficiency test may also be needed for cycle life testing.

2.3.2 Cycle Life Tests

Cycle life testing is performed using one of the Efficiency and Cycle Life Test profiles previously defined in Section 2.2.6. Cycle life testing is performed by repeating the test profile continuously at a fixed state-of-energy (i.e., the states at the beginning and ending of the profile are the same) for a defined number of times (typically several thousand at a time). This test procedure assumes that any required characterization tests have already been performed, along with the initial iteration of the required Reference Performance Tests (RPTs) defined in Section 2.4.

2.3.2.1 Cycle Life Test Profiles.

The test profiles used for cycle life testing are identical to those previously defined for efficiency tests in Section 2.2.6.

2.3.2.2 Cycle Life Test Procedure Outline.

The cycle life testing process consists of the following steps:

1. Determine end-of-test criteria for cycle life testing. These are normally specified in a device-specific test plan. A default (generally mandatory) end-of-test condition is reached when the test profile cannot be executed within the discharge and regen voltage limits.

   Another default end-of-test condition occurs if performance degrades to a point that the Power and Energy Design Verification reference test yields insufficient information to show further degradation.[gg]

   End-of-test is normally chosen to occur when one of the following conditions exists: (a) cycle life meeting the goals has been attained (i.e., the number of properly scaled test cycles exceeds the applicable 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.[hh]

2. Select the desired operating state-of-energy for cycle life testing and perform the Operating Set Point Stability Test to verify stable operation at the selected SOE point. (See Section 2.3.2.3 for further discussion of SOE considerations.) Make any needed adjustments to the test profile or test operating conditions.[ii]

[gg] In practice, this is not likely to occur while the cycle life profile can still be executed.

[hh] A failure to meet the power or energy goals during reference tests is always an end of life condition but not necessarily end-of-test; in some cases (e.g. calendar life), testing to failure may be desirable. See the Glossary for more information on the distinction between *end of test* and *end of life* conditions.

[ii] More discussion of state-of-energy (charge) control during life testing is contained in Appendix C of Reference 1.

3. Repeat the selected test profile a number of times as specified in Table 9 or a device-specific test plan.

4. After the specified number of repetitions, suspend cycling. If cycling is being done at other than 30ºC, return the battery to 30ºC. Observe the open-circuit voltage after a 1-hr rest. Remove the residual energy at a 3 kW constant-power rate to verify the cycling state-of-energy, and perform one or more Reference Performance Tests to determine the extent of degradation in energy capability and/or power capability. The reference tests are listed in Table 8. The intervals between repetitions of these reference tests are specified in Table 9, though these may be adjusted somewhat if required for time synchronization of batteries being tested under different test regimes.

5. Repeat Steps 3 and 4 until an end-of-test condition is reached. Note that the OSPS may need to be re-performed to find new SOE control conditions that maintain the target SOE as the battery resistance increases over life. (Deliberately varying the target SOE over life to enable a test to continue is not permitted unless authorized by a battery-specific test plan.)

2.3.2.3 State-of-Energy Considerations for Cycle life Testing

There is no “default nominal” state-of-energy for cycle life testing. If the appropriate value is not known in advance of the start of testing, the range of usable target SOE values can be determined from the PEDV test results based on the peak discharge and regen powers in the applicable cycle life test profile. Note that allowances will need to be made for the decrease in operating range as the battery degrades over life. This generally means that the target SOE should be selected somewhere in the middle of the beginning-of-life operating range, so that the cycle life profile falls within the operating SOE range at end of life. If this target SOE is not selected properly, cycling may terminate (due to inability to perform the test profile within voltage limits) before end of life is reached.

The default recommended SOE control method for this test is the same as that defined for the efficiency test in Section 2.2.6 (4a). It should be noted that the objective of SOE control for cycle life testing is to permit cycling to occur uninterrupted for the interval specified in Table 9, which is about a month. This is a much longer interval than is required for the efficiency test, and some form of automated SOE control is generally required.

Where available, a simulation of the SOE management strategy intended for in-vehicle battery use can be applied. This may require a special interface to the tester, or in some cases it may be possible for the test station itself to mimic this strategy.

2.3.3 Calendar Life Test

This test is designed to permit the evaluation of 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-energy during the test. They must also be periodically subjected to reference discharges to determine the changes (if any) in their performance characteristics.

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

2.3.3.1 Calendar Life Test Planning

Calendar life estimates are necessarily based on accelerated test methods. The general approach is to store 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 two batteries should be tested at each elevated temperature.

The batteries under test should be stored in an open-circuit condition, but with voltage monitoring using sensing circuits that present negligible loads to the batteries. Periodically, based on criteria for acceptable decay in open-circuit voltages (and the corresponding SOE), the batteries 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 battery.

Two parameters should be monitored by the periodic performance tests: available energy and minimum voltage (or voltage margin) in theCold Cranking test procedure. The corresponding end of life criteria for these parameters are: (1) available energy < goal energy; and (2) a minimum cold-start voltage < goal value (21 V). The test-to-test repeatability of these parameters should be no worse than one percent of the goal values (to one standard deviation).

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

1. Discharge the fully charged battery to the target SOE value at 30ºC, by either (a) removing the appropriate fraction of the battery's energy at a 3 kW constant-power rate, or (b) if the open circuit voltage corresponding to the target SOE is known, clamp the battery at this voltage while limiting discharge current to a 3 kW rate.

2. Place the battery in an open-circuit condition and bring it to the target temperature.

3. Monitor the battery open-circuit voltage. When this voltage indicates that battery state-of-energy has decreased by a pre-determined amount (nominally 10 to 20% of the goal energy), either (a) return this amount of energy to the battery at a 3 kW constant-power rate (accounting for losses due to charge/discharge efficiency), or (b) if an appropriate interval has elapsed, proceed to Step 4.[jj]

4. At intervals as specified in Table 9 or a device-specific test plan, return the battery to nominal temperature (e.g., 30ºC), observe its open-circuit voltage after a 1-hr rest, and discharge its remaining energy at a 3 kW constant power rate.

[jj] For nickel-based batteries, voltage hysteresis effects will cause the OCV after this "boost" charge to be significantly higher than it was at the beginning of Step 3. To minimize this effect, the charge added should be at least 10% SOE more than needed, and this additional amount should then be removed at a 3 kW constant power discharge rate. The intent is to return to the initial SOE value of Step 2 at the end of a substantial amount of discharge to permit a meaningful interpretation of the OCV.

5. Conduct the required periodic Reference Performance Tests defined in Section 2.4, and return the battery to its test conditions by repeating steps 1 and 2. Repeat this test sequence until the battery reaches an end-of-test condition.

It is anticipated that a future version of this manual will define a combined calendar life/cycle life test regime to verify that both life goals can be met concurrently. This test would serve as a final design verification test after the calendar life and cycle life are independently determined.

2.4 Reference Performance Tests

Reference Performance Tests are a set of tests performed at periodic intervals during life testing to establish the initial 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 the end of testing, for all devices undergoing either cycle life testing or calendar life testing.

A Reference Performance Test iteration consists of one repetition of each test listed in Table 8. It is recommended that these tests be performed in the order listed.

Table 8. Reference Performance Tests for life testing.

RPT Sequence
Power & Energy Design Verification (PEDV) Test (Note: PEDV test actually includes SEC verification)
Cold Cranking Test

Table 9 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 tests for groups of devices, especially if calendar life and cycle life devices are being tested at the same time.

Table 9. Reference Performance Test intervals for life testing.

Life Test Profile Used	Number of Continuous Repetitions or Time Interval Between Reference Tests
ZPA, PPA or FPA Cycle life Test Profile	15,000
Other cycle life profiles TBD	5 to 10% of expected cycle life
Calendar life Test	Approximately 31 days or 738 hours (Same as cycle life test interval)

3. ANALYSIS AND REPORTING OF TEST RESULTS

3.1 General

3.1.1 Minimum Test Reporting Requirements

For purposes of test reporting consistency (particularly between multiple testing organizations), a required minimum subset of information, based on the procedures in this manual, has been compiled for 42V tests and is included as 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 always reported in a consistent fashion.

3.2 Characterization Test Results

3.2.1 Static Energy Capability Test

Capacities are reported in watt-hours (and ampere-hours, for information only) at the 3 kW constant power discharge rate, based on both the manufacturer-specified charge algorithm and on recharge to the maximum operating voltage at the Table 1 Recharge Rate. These are reported based on discharge to the minimum operating voltage. Note that all of this capability will not be useable within 42V operating conditions, and thus it does not directly reflect conformance to the Available Energy goal.

Watt-hours and ampere-hours returned (and the corresponding overall charge/discharge efficiencies) are also reported for both the manufacturer-specified charge algorithm and for recharge to the maximum operating voltage at the Table 1 Recharge Rate.

3.2.2 Power and Energy Design Verification Test

The fundamental result of the PEDV test is the confirmation or failure of the battery to comply with the power and energy goals in Table 1. Both the calculated and the experimentally verified results of the PEDV test are based on the use of actual goal power values, and the available energy and energy margin are directly verified. Thus the rather complex process of calculating battery resistances and pulse power capabilities as described in Reference 1 is not required in this manual.

3.2.2.1 Determination of Available Energy

Calculating Available Energy is done using the data from the Power and Energy Design Verification test (defined in Section 2.2.2) in the following sequence of steps. A spreadsheet which has been devised to assist with the calculation process is described in Appendix D and is included with this manual.

1. Determine the discharge energy for Step 3 as $E_{3kW,dis}$.

2. Accumulate the net discharge energy for the total of Steps 5, 6 and 7 as $E_{PEDV,dis}$.

3. Determine a correction factor K_{eff} to be applied to $E_{PEDV,dis}$ that will best match the voltage response (as a function of energy removed) during the 3kW discharge segments of Steps 5, 6 and 7 to the voltage response during Step 3.[kk]

4. For both discharge and regen pulses (separately), plot the end-of-pulse voltages versus the corrected SOE (in watt-hours). Fit a curve through each of these voltage plots. From these curves, interpolate [or extrapolate if necessary] (a) the state-of-energy *SOEmax* at which the end-of-pulse regen voltage is equal to the maximum operating voltage V_{max}, and (b) the state-of-energy *SOEmin* at which the end-of-pulse discharge voltage is equal to the minimum operating voltage V_{min}.

5. Calculate *Available Energy (AE)* in watt-hours as *SOEmax – SOEmin*.

6. If Available Energy exceeds the applicable goal, calculate *Energy Margin = AE -* E_{goal}

Results to be reported include the values of Available Energy (in Wh), Energy Margin (in Wh and as a percentage of the energy goal), the minimum and maximum operating SOE values *SOEmin* and *SOEmax*, the correction factor used for Steps 3 and 4, and the curves of voltage versus net energy removed (or SOE) from the discharge segments of the PEDV test (procedure steps 3, 5/6/7 and 9). If the verification test results from 2.2.2.2(9) are not substantially equal to the values calculated here (i.e. if the difference in Available Energy exceeds ~2%), the values of *SOEmax*, *SOEmin* and Available Energy verified by test must also be reported. [ll]

3.2.3 Self-Discharge Test

Self-discharge rate is determined over a fixed period (nominally 7 days) at an intermediate energy state (normally the *BCOSOE* value defined in Section 2.2.3.) The difference between the usable energy (watt-hours) capability measured before and during (i.e., over) the stand period is considered to be the energy loss reflecting self-discharge. This energy loss is computed as the difference between the pretest 3 kW usable energy and the sum of the energies in the partial 3 kW discharges before and after the stand period. This value is then divided by the length of the stand period.[mm]

$$\text{Self - Discharge} = \frac{Wh_{3kW \text{ before test}} - (Wh_{\text{part 1}} + Wh_{\text{part 2}})}{\text{Stand Time in Days}}$$

The result of this calculation (in Wh per day) is reported for comparison with the Table 1 goal of no more than 20 Wh per day.

[kk] Ideally no correction will be necessary, if the shape of the voltage curve does not change during the pulse portion of the test. In some cases *Keff* can be simply defined as the ratio of $E_{3kW,dis}$ to $E_{PEDV,dis}$. In other cases it may be necessary to choose *Keff* to match the voltage vs energy curves in the SOE region of interest rather than over the entire discharge, or even to use a nonlinear correction factor.

[ll] The most likely cause for such a discrepancy is a difference between the 3 kW and pulse discharge curves leading to errors in predicting *SOEmax* and *SOEmin*. If either measured end-of-pulse voltage in 2.2.2.2(9) differs from its respective voltage limit (V_{max} or V_{min}) by an amount corresponding to more than 2.5% of the calculated Available energy, or if the calculated and measured Available Energy values differ by more than 5%, the verification step 2.2.2.2(9) should be repeated using empirically-adjusted values for *SOEmax* and *SOEmin*.

[mm] A stand time of 7 days is normally used to decrease the uncertainty of the test results. Stand loss in batteries with low self-discharge cannot be reliably measured over short periods of time due to measurement uncertainties.

3.2.4 Cold Cranking Test

The fundamental result of the Cold Cranking Test is the power capability at the end of the third 2s pulse at -30°C, which is to be compared to the Table 1 goal of 8 kW. No analysis is required to determine whether or not the goal is met; this can be seen by inspection of the test results. However, because the test is run at a power level equal to the goal, the actual power achieved does not necessarily represent the power capability. (Some batteries may be capable of higher power than this, and batteries that fail to meet the goal still have some power capability.) The actual power capability can be calculated if desired as described in Reference 1 Section 4.6. [nn]

Items to be reported include the voltage margin at the end of each Cold Cranking pulse (i.e., the difference between the end-of-pulse voltage and the Cold Cranking Minimum Voltage from Table 1) and the actual power delivered at the end of each pulse (which is normally 8 kW unless the pulse is reaches the minimum voltage.) A graph of voltage versus time during the test profile may also be informative.

3.2.5 Thermal Performance Tests

3.2.5.1 Standard Thermal Performance Tests

Measured energy capability at the 3 kW rate is reported over the range of temperatures at which the Static Energy Capability Test is performed. Results of PEDV at temperatures other than nominal is reported in the same fashion as for the normal (ambient temperature) versions of these tests, except that the test temperature must accompany all data and graphs.

3.2.5.2 Alternative System-Level Thermal Performance Test

The fundamental result of this test is the time required for the battery to heat from –30°C to the temperature T_{min} at which the energy margin is zero (i.e. the lowest temperature at which the power and energy goals can be met for some SOE value.) Results to be reported include the time required to reach T_{min}, the power and energy applied to the battery during this test interval, and the SOE reached at the end of the test (based on residual energy measured after the battery is returned to 30°C.)

3.2.5.3 Thermal Management Load Test (System-Level Testing)

Specific reporting requirements are not defined for thermal management load testing.

3.2.5.4 Heat Rejection Test (P-HEV Mode Only)

Results to be reported for this test include the steady state heat loss (in watts, as estimated from battery efficiency calculations on the test profile)[oo], the battery inlet and outlet temperatures (in °C) at equilibrium cycling conditions, battery thermal management power (watts versus time during the test) and energy used (Wh) during the test. The battery Heat Transfer Coefficient (HRC) should be reported (in W/°C) as

---

[nn] Note that the Battery Size Factor (BSF) used for a 42V battery system would be unity (1) for any of the calculations to be performed using Reference 1 methods.

[oo] All the losses computed from this efficiency calculation are assumed to result in battery heating.

$$HRC = \frac{Heat\ Loss}{T_{outlet} - T_{inlet}}$$

If the battery contains internal temperature sensors on multiple cells, the peak temperatures reached during the test should also be reported.

3.2.6 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 average SOE (as implied by temperature and peak voltage behavior) is stable, normally at the end of the cycling period. The amount of time to reach this condition varies but will commonly be an hour or more after the start of cycling.

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

3. Calculate round-trip efficiency as the ratio of discharge energy removed to regen energy returned during the profiles, expressed in percent:

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

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

Values to be reported for this test include the test profile (mode) used, the total discharge and recharge energies and capacities during the test profiles used for calculation, the average SOE value(s) at which the test was conducted, and the resulting round-trip energy efficiency result(s).

[pp] Such a result should be comparable to the 42V efficiency test results provided the SOE and temperature for life cycling are the same as those used for the efficiency test.

3.3 Life Testing Results

3.3.1 Operating Set Point Stability Test

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

3.3.2 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 a test is terminated due to the inability of the battery to perform the programmed test profile within the voltage limits or some other end-of-test condition, this is reported. However, the number of profiles performed is not necessarily the cycle life and should not be reported as such.

The final 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 goals. The ability to meet the goals is evaluated based on the periodic Reference Performance Tests. When the power and energy performance of the device degrades to the point that there is no energy margin, the device has reached end of life. In addition, the inability to meet any of the other technical goals (e.g., the cold cranking power, efficiency or self-discharge goal) also constitutes end of life. However, these are not necessarily all measured at regular intervals during life testing, so the point during life cycling where such an end of life condition is reached cannot be determined with high accuracy. The basis for the reported cycle life value (i.e., the limiting goal condition) should also be reported. If the cycle life based on power and energy performance is very near the goal, the end of life point may need to be interpolated based on the change in performance from the previous reference test.

Detailed results of the reference tests are reported over life as described under these specific tests. In addition, degradation of available energy and cold cranking power capability as a function of life (i.e., number of test profiles or Reference Performance Tests performed) should be reported graphically based on periodic Reference Performance Test results. For consistency with calendar life test analysis, available energy fade and cold cranking voltage margin fade should also be reported as a percentage over time. The term “fade” as applied to a performance parameter means the reduction in this parameter compared to its value at the beginning of life testing as shown in the following generic equation.

$$Fade = 1 - \frac{Parameter\ Value_{RECENT}}{Parameter\ Value_{INITIAL}} \quad \text{or} \quad Fade(\%) = 100 \times \left(1 - \frac{Parameter\ Value_{RECENT}}{Parameter\ Value_{INITIAL}}\right)$$

3.3.3 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. 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:

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

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

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

4. REFERENCES

1. *PNGV Battery Test Manual*, DOE/ID-10597, Revision 3, published February 2001. (It is intended that the most recent version of this manual should be used for reference.)

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

3. *Handbook of Batteries*, Third Edition, David Linden and Thomas B. Reddy, editors, McGraw-Hill, 2001.

APPENDIX A

Required Manufacturer-Specified Battery Information for 42V Testing

Required Manufacturer-Specified Battery Information for 42V Testing

(***Items in bold text are required for the applicable modes***. *Others are optional or as needed)*

Start-Stop Mode:
Maximum Operating Voltage ___________ V dc (for continuous charging at 2.4 kW)
Minimum Operating Voltage ___________ V dc (Must be ≥27V for normal operation)
Minimum pulse (discharge) voltage ___________ V dc (at 6 kW for 2s)

M-HEV Mode:
Maximum Operating Voltage ___________ V dc (for continuous charging at 2.6 kW)
Minimum Operating Voltage ___________ V dc (Must be >27V for normal operation)
Maximum pulse (regen) voltage ___________ V dc (at 8 kW for 2s)
Minimum pulse (discharge) voltage ___________ V dc (at 13 kW for 2 s)

P-HEV Mode:
Maximum Operating Voltage ___________ V dc (for continuous charging at 4.5 kW)
Minimum Operating Voltage ___________ V dc (Must be >27V for normal operation)
Maximum pulse (regen) voltage ___________ V dc (at 18 kW for 2s)
Minimum pulse (discharge) voltage ___________ V dc (at 18 kW for 10s)

Minimum Cold Cranking Voltage ___________ V dc (Must be ≥21V for cold crank at –30°C)

Recommended charge algorithm (for full recharge) at 30°C ambient:
____
____
____

Estimated self-discharge in 7 days ___________ Wh (used only to set duration of Self-Discharge test)

Temperature T_{min} where Available Energy = 0 ___________ °C (if known, at beginning of life)

Description of battery SOE management strategy for in-vehicle use (if available):
____
____
____
(For possible use in cycle life test control)

Battery System Weight ______________ kg Basis________________________________
Battery System Volume ______________ liters Basis________________________________

APPENDIX B

Minimum Test Reporting for 42V Testing

Minimum Test Reporting for 42V Testing

In general these reporting requirements apply to each device tested if the test is performed. Exceptions should be noted in a device-specific test plan.

A. Characterization Tests (beginning of life)

Static Energy Capability Test

Energy & Capacity (full discharge, to V_{min}) __________ Wh __________ Ah
Energy & Capacity (discharge from *SOEupper* to V_{min}) __________ Wh __________ Ah

Recharge Energy & Capacity required (full charge) __________ Wh __________ Ah
Charge/Discharge Efficiency __________ %
Recharge Energy & Capacity (to *SOEupper*) __________ Wh __________ Ah
Charge/Discharge Efficiency __________ %

Power and Energy Design Verification (PEDV) Test

SOEmax __________ Wh (beginning of life)
SOEmin __________ Wh (beginning of liferemaining energy)
Available Energy __________ Wh (beginning of life) __________% of goal
Energy Margin __________ Wh (AE – goal energy, beginning of life) __________ % of goal
Charge/Discharge Efficiency Factor used to calculate Available Energy __________ %
(Curves of Voltage versus SOE (or energy removed) determined from PEDV test)
Best Case Operating SOE condition used forSelf-Discharge and Cold Cranking tests:
__________ Wh (beginning of life)

Self-Discharge Test

Stand Loss __________ Wh over __________ days __________ Wh/day

Cold Cranking Test

Voltage margin (V) __________ (1st pulse) __________ (2nd pulse) __________ (3rd pulse)
End-of-Pulse Power (kW) __________(1st pulse) __________ (2nd pulse) __________ (3rd pulse)
Power Capability (kW) (opt.) __________(1st pulse) __________ (2nd pulse) __________ (3rd pulse)
Graphs of Voltage versus Time during test profile (optional)

Standard Thermal Performance Test(s)

The results to be reported from these tests are identical to those required for the same tests at 30°C, except that the actual test temperature must be reported and shown on all graphs

System-Level Thermal Performance Test

Time required to reach T_{min} __________ minutes

Energy applied during heatup __________ Wh at average power level ___________ W
SOE at end of test (residual energy, at 30°C) __________ Wh

Heat Rejection Test

Steady-state heat loss due to test profile __________ W (estimated from efficiency)
Battery inlet temperature __________ °C (at equilibrium cycling condition)
Battery outlet temperature __________ °C (at equilibrium cycling condition)
Heat Transfer Coefficient __________ W/°C
Thermal Management Energy __________ Wh and Average Power __________ W during test
(Plot of thermal management power vs time if available)
Maximum cell/module temperature during test __________ °C
Maximum cell-to-cell temperature difference __________ °C (if battery is instrumented for this purpose)

Energy Efficiency Test

Test Profile Used: ZPA ____ PPA ____ FPA ____

For the consecutive group of test profiles used for calculation:
Average SOE value for profiles used for computation ____________ Wh
Total Discharge __________ Wh __________ Ah
Total Recharge __________ Wh __________ Ah
Round-Trip Energy Efficiency __________ %
Note: if test is performed at both *SOEmax* and *SOEmin* as recommended, both sets of values are reported.

B. Cycle life Tests (periodically reported as performed)

Test Profile Used: ZPA ____ PPA ____ FPA ____

Number of test profiles performed __________ (through most recent RPTs)
Testing Finished ____ Yes ____ No
Reason for Cycle life test termination (if applicable):
____
____
Final Cycle Life ___________ profiles (determined using Section 3.3.2)

C. Calendar Life Tests (periodically reported as performed)

Test Conditions: Temperature __________ °C SOE __________ Wh (residual)
Other_______________________________________
Time at temperature (to most recent RPTs) __________ weeks
Projected Calendar Life _________ years at ________ % confidence interval

D. Reference Performance Tests (periodically reported as performed)

PEDV Test

Results to be reported from periodic PEDV tests are the same as those for the characterization PEDV test. In addition, Available Energy, Energy Margin, *SOEmax* and *SOEmin* should be plotted over time to show battery degradation, and the percent fade of Available Energy should be reported over time.

Cold Cranking Test

Results to be reported from periodic cold cranking test are identical to those for the characterization test. In addition, all reported values should be plotted over time to show battery degradation, and the percent fade of Cold Cranking voltage margin should be reported over time.

APPENDIX C

Calendar Life Test Simulation and Analysis Tool

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, 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 No. 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 unaltered 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:

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
Expected Life at Test Temp. (y) =	15	7.34	5.22	3.76	2.73	2
Actual Coeff. Of Linear Decay (1/y) =	13.33	27.24	38.29	53.26	73.33	100.00
ct. Coeff. Of Quadratic Decay (1/y^2) =	0.2222	0.9277	1.8328	3.5452	6.7212	12.5000
Actual A.E. at BOL (Wh) =	513.2	502.5	509.8	506.1	490.4	512.4
Actual Cal. Life (y) at Test Temp. =	15.65	7.40	5.39	3.83	2.64	2.08

LN(Y) vs. 1000/T CORR. PARAMETERS

A	B	R^2
-19.668	6.784	1
24.966	-6.784	1.0000
43.248	-13.567	1.0000
505.7	(Average Act. AE-bol)	
-19.923	6.871	0.9987

TEST DATA CORRELATION SUMMARY:

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

A	B	R^2
505.7	(Average Est. AE-bol)	
25.557	-6.979	0.9939
41.250	-12.894	0.8761
-19.378	6.690	0.9906

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:

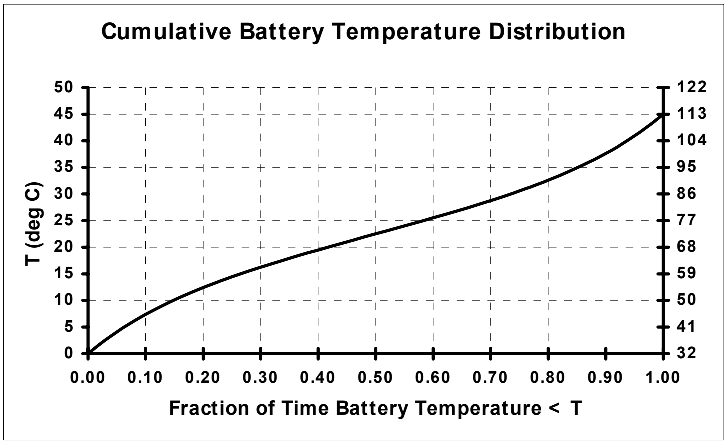
	T =	30		40		45		50		55		60	
Time	t^2	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated	Actual	Estimated
0	0	513.2	512.9	502.5	502.1	509.8	509.1	506.1	506.3	490.4	490.6	512.4	512.9
0.08	0.01	514.7	511.8	498.8	499.9	505.8	506.2	503.3	501.8	484.6	484.4	505.5	504.5
0.17	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



Appendix D

Calculating Available Energy from PEDV Test Results

Calculating Available Energy from PEDV Test Results

Section 3.2.2.1 of this manual defines in general terms the process to be used for calculating Available Energy along with *SOEmax* and *SOEmin*. These values are the primary results of the first part of the PEDV test, and they are needed for the performance of the final verification portion of the procedure in Step 9. Because the PEDV test procedure is relatively new, an automated process for performing these calculations is not yet practical. A Microsoft Excel spreadsheet has been devised that can assist with these calculations, although it still requires considerable manual manipulation of the test data. A copy of this tool with the file name "*AvailableEnergyCalculationSpreadsheet.xls*" accompanies this manual. Instructions for using the spreadsheet are contained in the actual file, but a brief explanation of its use will be given here.

The spreadsheet consists of four worksheets named as follows:

1. Instructions
2. Pulse Voltages & Results
3. ExampleData
4. V vs Wh Graph

The "*Instructions*" worksheet contains a numbered series of step-by-step instructions for using the spreadsheet.

The "*ExampleData*" worksheet is a sample data file (generated by a Maccor tester) which was imported directly into Excel. It serves to illustrate how the spreadsheet works, but in actual use it is replaced by an actual PEDV data file and plays no role in the calculation process. All the links to data on this *ExampleData* worksheet are re-defined by the user to point to the corresponding data on the actual PEDV data file.

The "*V vs Wh Graph*" spreadsheet is a plot of battery (cell in this case) voltage as a function of the net energy removed from the device during two stages of the PEDV test: (1) the 3 kW constant power discharge from *SOEupper* to V_{min} in Step 3 of the procedure; and (2) the pulse discharge portion of the test in Steps 5, 6 and 7 of the procedure. It also shows the minimum and maximum operating voltage limits V_{min} and V_{max}. This graph, shown as Figure D-1, is generated to assist the user in deciding how best to match the two voltage curves. It originally points to data on the *ExampleData* worksheet, and its two test data series must be re-defined by the user to point to the appropriate data in the actual PEDV data file.

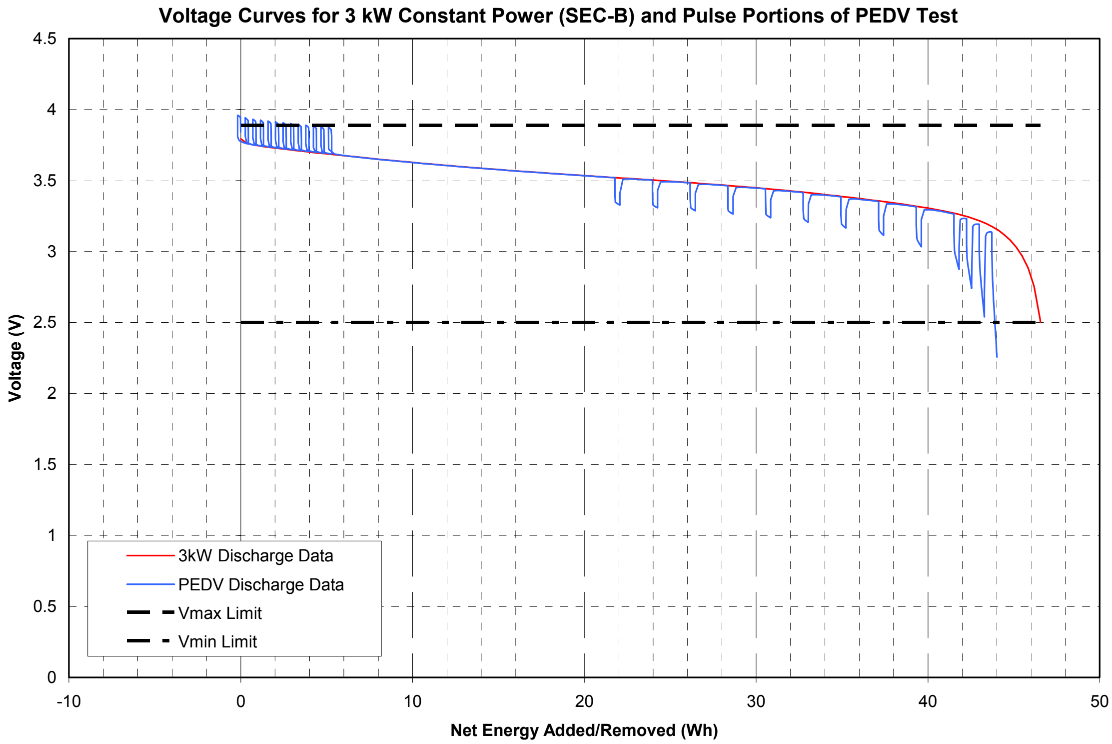


Figure D-1. Example V vs Wh Graph

The "*Pulse Voltages & Results*" worksheet includes all the inputs and outputs for the calculation process, along with some additional instructions for its use. It performs all the actual calculations and displays the results. This worksheet is illustrated in Figure D-2. The example data values and results shown are derived from the *ExampleData* worksheet.

The process of copying various data values from the actual PEDV data file to the input cells is mechanical and straightforward, provided that the data file includes cumulative energy values for the two discharge segments of interest. In practice these must sometimes be generated by the user for the pulse portion of the test through the use of Excel formulas, because of programming limitations for various types of battery test stations. User judgment is required in two areas: (1) choosing how to match the two voltage curves as a function of energy; and (2) determining whether the pulse voltage data must be extrapolated or interpolated to find V_{max} and/or V_{min}.

The *Pulse Voltages & Results* worksheet provides three relatively simplistic options for matching the voltage curves: (a) no scaling, which means the energy scales are treated as equivalent for the 3 kW constant power and the pulse portions of the test; (b) linear scaling, which scales the pulse discharge energy by a linear multiplier to make it equal to the 3 kW energy; and (c) no scaling up to some energy value, followed by linear scaling from that point. In practice option (c) is the most likely choice, and it works acceptably if the two voltage curves match until late in the discharge. In the example shown above, none of the choices would work well because the final increment of 3 kW discharge energy was not removed during the pulse portion of the test due to a test programming glitch. In such a case the user is forced to guess at what the final energy in the pulse portion of the test should have been, which necessarily leads to much greater uncertainty in the calculated results.

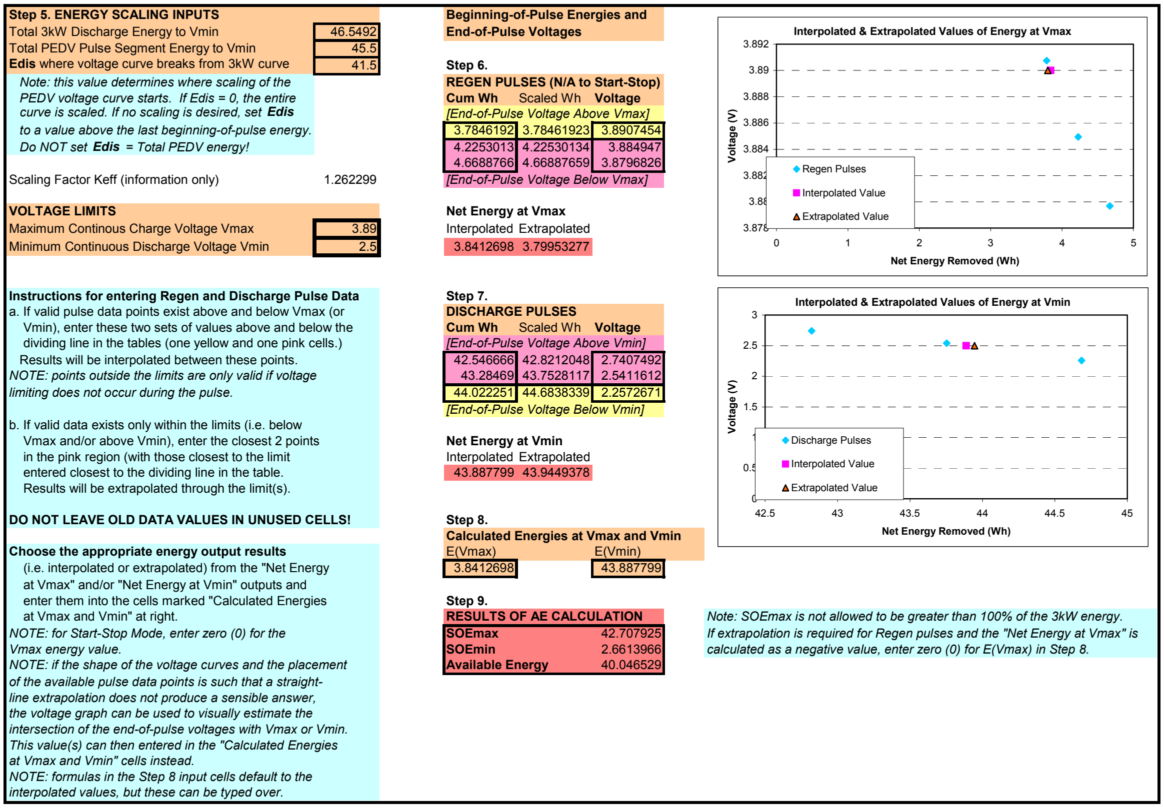


Figure D-2. Pulse Voltages & Results Worksheet

The worksheet will calculate both interpolated and extrapolated V_{max} and V_{min} results (using only the two nearest data points in each case) if suitable data is available, but the user is responsible for deciding which results are appropriate and entering them in the appropriate worksheet cells.

The output of this worksheet is a set of values for Available Energy, *SOEmax* and *SOEmin* which are used in turn for the conduct of the PEDV verification step.