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PNGV Battery Test Manual
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PNGV Battery Test Manual
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Foreword

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

A continuing need to improve these procedures is expected. This first published version of this manual emphasizes the testing of laboratory cells; it does not yet fully define certain procedures for full size energy storage systems. Suggestions or comments should be directed to the author, Gary Hunt, INEL, telephone (208) 526-1095 or by email to GLH@INEL.GOV.

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1.0 **Purpose and Applicability**

This manual defines a series of tests to characterize aspects of the performance or life cycle behavior of batteries for hybrid electric vehicle applications. Tests are defined based on the Partnership for New Generation Vehicles (PNGV) program goals, although it is anticipated these tests may be generally useful for testing energy storage devices for hybrid electric vehicles. Separate test regimes are defined for laboratory cells, battery modules or full size cells, and complete battery systems. Some tests are common to all three test regimes, while others are not normally applicable to some regimes. The test regimes are treated separately because their corresponding development goals are somewhat different.

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

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

1.2 **Module or full size cell testing** is intended to verify that the selected full size cell or module design will satisfy the PNGV program performance criteria and provide a data base for subsequent development of related battery management systems. The objective is to initially verify that scale-up to the full size cell or module level was successful and subsequently to evaluate overall full size cell/module performance.

1.3 **Battery systems testing** is intended to predict or to verify overall battery pack performance as required to insure acceptable in-vehicle performance.

1.4 **PNGV Energy Storage Goals** are the primary driving force for the test procedures and methods defined in this manual. These goals are outlined in Table 1.4 for both the "fast response" and "slow response" engine vehicles whose characteristics are specified for the PNGV Program. In most cases the test procedures are based on the "Minimum" goals; extension of these procedures to the "Desired" goals will be treated at a future date. It should be noted that this table of PNGV goals is provided as the primary basis for this test plan. Establishing or verifying battery performance in comparison to these goals is a principal objective of the test procedures defined in this plan.

Table 1.4 PNGV Energy Storage System Performance Goals

Characteristics	Units	Fast Response Engine		Slow Response Engine	
		Minimum	Desired	Minimum	Desired
Pulse Discharge Power (constant for 18s)	kW	25	40	65	80
Peak Regenerative Pulse Power (trapezoidal pulse for 10s for the specified pulse energy)	kW	30 (for 50 Wh pulse)	60 to 110 (for 150 Wh pulse)	70 (for 150 Wh pulse)	150 (for 150 Wh pulse)
Total Available Energy (discharge plus regenerative)	kWh	0.3	0.5 to 0.75	3	3 to 8
Minimum Round-trip Efficiency on FUDS/ HWFET cycle	%	90	90	95	95
Cycle Life, for specified SOC Increments	cycles	200 K for 25 Wh 50 K for 100 Wh	300 K for 35 Wh 100 K for 100 Wh	120 K for 100 Wh 20 K for 600 Wh	300 K for 200 Wh 100 K for 600 Wh
Maximum Weight (plus marginal increase/kWh for E>3 kWh)	kg	40	35	65 (+10 kg/kWh over 3 kWh)	50 (+10 kg/kWh over 3 kWh)
Maximum Volume (plus marginal increase/kWh for E>3 kWh)	l	32	25	40 (+8 l/kWh over 3 kWh)	40 (+8 l/kWh over 3 kWh)
Operating Voltage Limits	vdc	300 min 400 max	300 min 400 max	300 min 400 max	300 min 400 max
Maximum Allowable Self-discharge Rate	Wh/ day	50	50	50	50
Temperature Range: Equipment Operation Equipment Survival	°C	-40 to +52 -46 to +66	-40 to +52 -46 to +66	-40 to +52 -46 to +66	-40 to +52 -46 to +66

2.0 Test Profiles Derived from PNGV Goals

The test procedures to be defined in this manual are intended to be used over a broad range of devices at various stages of development maturity. The application of the procedures is further complicated by the existence of two different sets of vehicle performance goals, each of which has both a minimum and a desired set of energy storage performance targets. The approach taken for these procedures is to define a small set of driving profiles based on the overall vehicle characteristics, i.e. independent of the size or capability of the device to be tested. These profiles are specified in terms of vehicle power demand. They can then be used in various combinations, and with the appropriate scaling factors, to define specific performance or life cycle tests for the 3 levels of testing: laboratory cell, full size cell/module, and battery system. At this time the following test profiles are defined.

2.1 Pulse Power Characterization Profiles

The objective of these profiles is to demonstrate the 18 second discharge pulse and 10 second regen pulse power capabilities at various states of charge (SOC). Test protocols may use either constant current or constant power. Generally, constant current will be used for laboratory cells to provide performance model coefficients for vehicle systems modeling and analysis, and constant power will be used for subsequent full size cell, module or battery pack performance verification. Specific test plans will specify the desired protocol. For a given vehicle power demand, equivalent worst case currents can be derived based on the PNGV operating voltage range limitations (300V minimum discharge voltage and 400V maximum regen voltage.)

2.1.1 Pulse Power Characterization Profile (Slow Response Engine)

The characterization profile at the battery pack level is shown in Table 2.1 and illustrated in Figure 1, reflecting the minimum discharge and regen power requirements for the slow response engine. To simplify test procedures, a continously decreasing regen pulse (which would occur in a vehicle) is simulated by a series of steps approximating the area of the specified sloping regen power profile. A two second step followed by 2 - four second steps at lower power levels are used to simulate the 'trapezoidal' regen pulse.

Table 2.1. Pulse Power Characterization Profile (Slow Response Engine)

Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
18	18	65	325	325	216	3888
32	50	0	0	325	0	3888
2	52	-70	-38.8	286.2	-175	3538
4	56	-55	-61.1	225.1	-137.5	2988
4	60	-47.5	-52.8	172.3	-118.8	2513

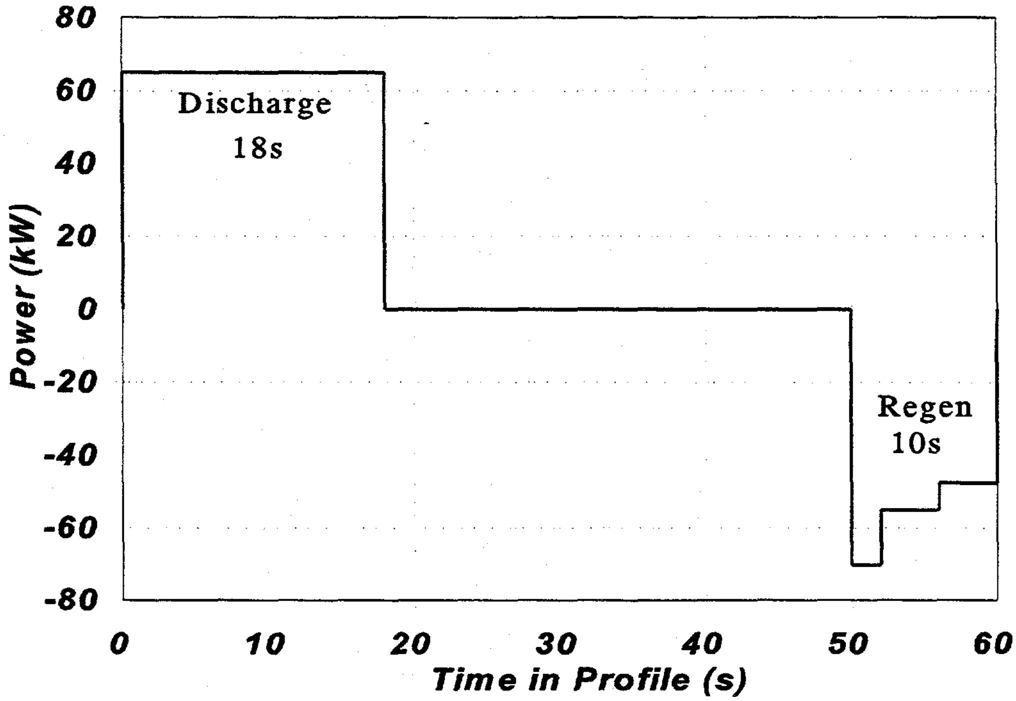

Figure 1. Pulse Power Characterization Profile

2.1.2 Pulse Power Characterization Profile (Fast Response Engine)

A similar characterization test profile is defined for the minimum Fast Response Engine performance goals in Table 1.4, with values as shown in Table 2.2. Incorporation of this profile into a test procedure, with associated rest periods and other procedural requirements, is treated in Section 3.2.2.2.

Table 2.2. Pulse Power Characterization Profile (Fast Response Engine)

Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
18	18	25	125	125	83.3	1500
32	50	0	0	125	0	1500
2	52	-30	-16.7	108.3	-75	1350
4	56	-20	-22.2	86.1	-50	1150
4	60	-10	-11.1	75	-25	1050

2.2 Hybrid Life Cycle Test Profiles (Slow Response Engine)

The objective of these test profiles is to demonstrate battery life when subjected to different energy utilization levels. Three profiles are defined for such use based on the PNGV Slow Response Engine goals. Two additional profiles are defined in Section 2.3 based on the PNGV Fast Response Engine goals.

The first Slow Response profile is a 60 second test profile intended to demonstrate the ability to meet the PNGV cycle life minimum goal of 120,000 cycles with a 100 Wh energy swing. The second profile, which is derived from the the first by simply doubling its step times, achieves a 200 Wh energy swing; it is primarily intended for verifying sensitivity of battery life to the magnitude of the energy swing. The third profile provides approximately a 600 Wh swing over a 360s interval, for use in verifying the PNGV Slow Response Engine goal of 20,000 cycles for such an energy swing increment. Each of these profiles would result in the transfer in and out of a battery of about 12 million watt-hours (12 MWh) of energy over the target number of cycles.

These test profiles are all defined at the battery pack level. Where applicable, current or power levels to be used for testing laboratory cells, full size cells and module designs are scaled to reflect the device performance required to provide the level of battery pack performance implied by the PNGV goals.

2.2.1 100 Wh (120K) Life Cycle Test Profile

The 100 Wh Life Cycle Test Profile includes a 9 second discharge pulse, followed by an 18s rest period and a 10s trapezoidal regen pulse. A subsequent makeup charge for 23 seconds is provided to achieve a very net slight charge condition. The resulting pulse profile for a 100 Wh swing in SOC is shown in Table 2.2.1 and illustrated in Figure 2.

Table 2.2.1. 100 Wh Life Cycle Test Profile

Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
9	9	40	100	100	122	1098
18	27	0	0	100	0	1098
2	29	-42	-23.3	76.7	-112.7	872
4	33	-27	-30	46.7	-74.1	576
4	37	-12	-13.3	33.3	-33.7	441
23	60	-6.8	-43.4	-10.1	-19.3	-2

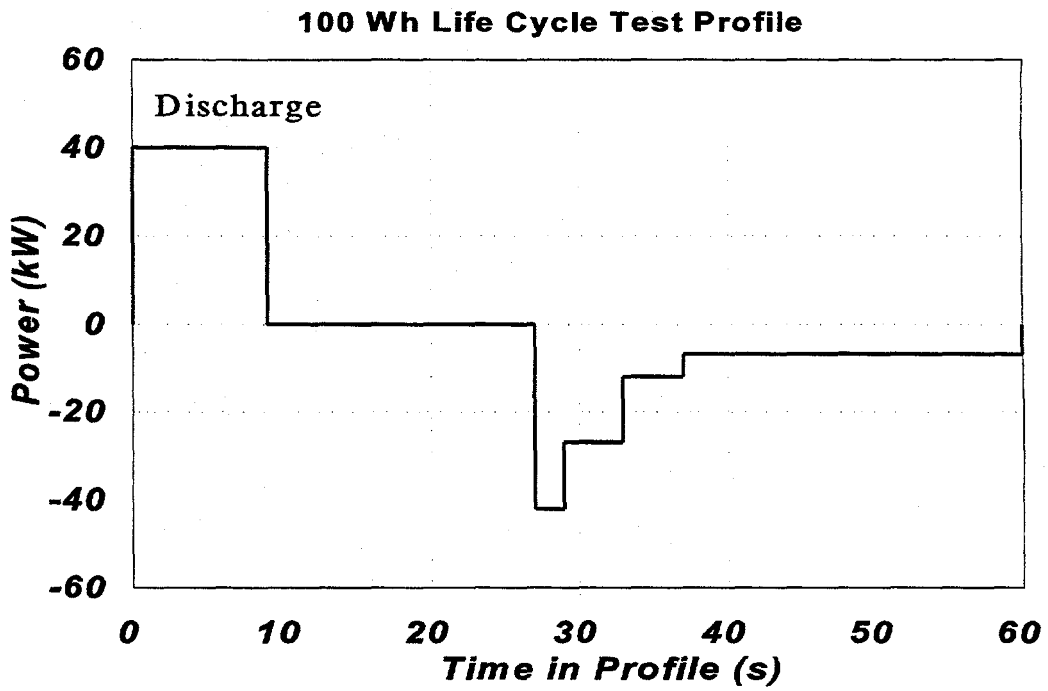

Figure 2. 100 Wh Life Cycle Test Profile

2.2.2 200 Wh Life Cycle Test Profile

The 200 Wh Life Cycle Test Profile includes an 18 second discharge pulse, followed by a 36s rest period and a 20s trapezoidal regen pulse. A subsequent makeup charge for 46 seconds is provided to achieve a very slight net charge condition. The resulting pulse profile for a 200 Wh swing in SOC is shown in Table 2.2.2 and illustrated in Figure 3. Note that the power (or current) levels for this profile are identical to the 100 Wh profile; only the step times are changed.

Table 2.2.2. 200 Wh Life Cycle Test Profile

Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
18	18	40	200	200	122	2196
36	54	0	0	200	0	2196
4	58	-42	-46.7	153.3	-112.7	1745
8	66	-27	-60	93.3	-74.1	1152
8	74	-12	-26.7	66.7	-33.7	883
46	120	-6.8	-86.9	-20.2	-19.3	-3

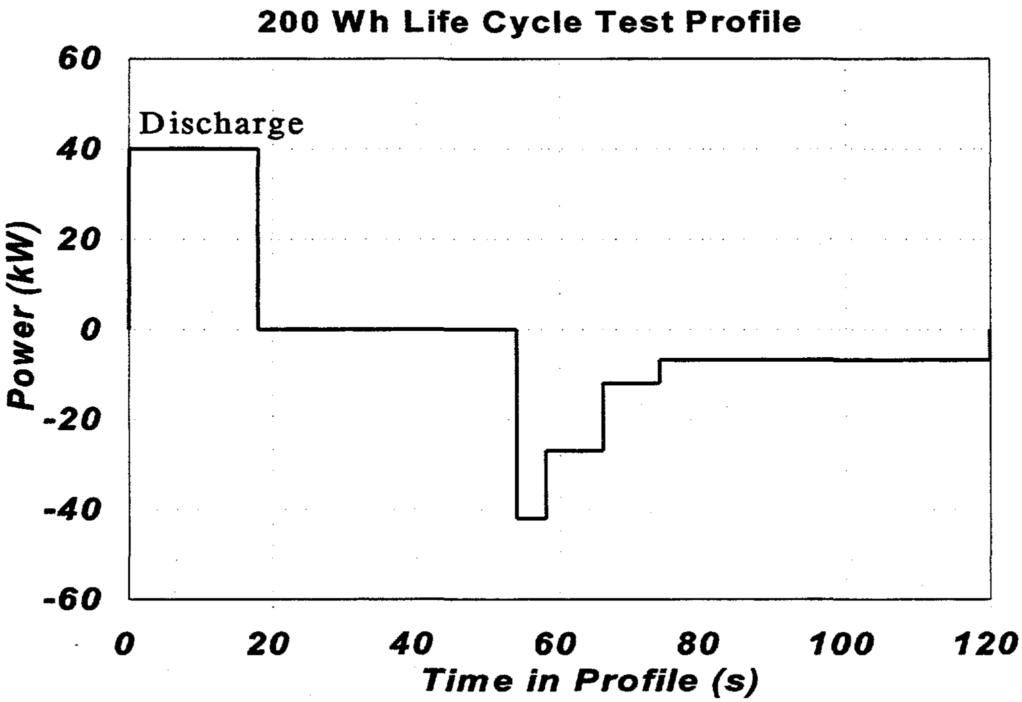

Figure 3. 200 Wh Life Cycle Test Profile

2.2.3 600 Wh (20K) Life Cycle Test Profile

The 600 Wh Life Cycle Test Profile consists of three consecutive "Net-discharge Subprofiles", each 60s long and providing a 200 Wh net decrease in energy, followed by three consecutive "Net-recharge Subprofiles", each of which returns somewhat more than 200 Wh of energy to the battery. Each subprofile contains a 9 second discharge pulse and a 10 second trapezoidal regen pulse. The two subprofiles are derived from the 100 Wh profile by scaling the power levels in either the discharge or regen direction to yield approximately double the energy swing. The accumulated recharge is such that the overall profile has a very slight net charge. The resulting pulse profile for a 600 Wh energy swing is shown in Table 2.2.3 and illustrated in Figure 4.

Table 2.2.3. 600 Wh Life Cycle Test Profile (sub-elements only)

'NET DISCHARGE' Subprofile						
Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
9	9	52	130	130	161.6	1454
18	27	14	70	200	41.1	2195
2	29	-30	-16.7	183.3	-81.9	2031

'NET DISCHARGE' Subprofile						
Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
4	33	-15	-16.7	166.7	-41.9	1863
4	37	0	0	166.7	0	1863
23	60	5	31.9	198.6	14.5	2197
'NET RECHARGE' Subprofile						
Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
9	9	26.4	66	66	78.9	710
18	27	-11.6	-58	8	-32.6	124
2	29	-55.6	-30.9	-22.9	-146.5	-169
4	33	-40.6	-45.1	-68	-109.2	-606
4	37	-25.6	-28.4	-96.4	-70.4	-888
23	60	-20.6	-131.6	-228.1	-57.1	-2200

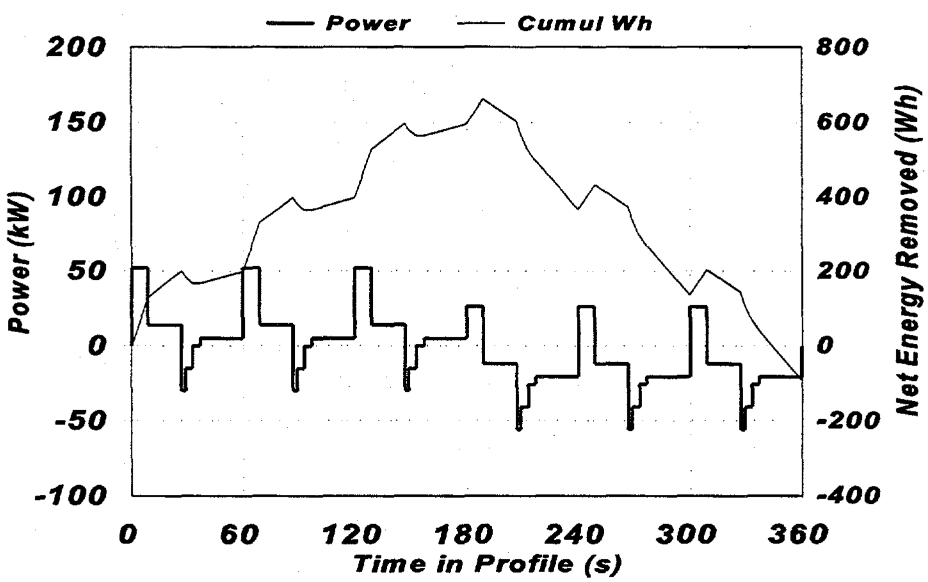

Figure 4. 600 Wh Life Cycle Test Profile (overall)

2.3 Hybrid Life Cycle Test Profiles (Fast Response Engine)

The Fast Response test profiles are (a) a 60 second profile which is intended to demonstrate the ability to meet the PNGV cycle life minimum goal of 200,000 cycles with a 25 Wh energy swing, and (b) a 100 Wh swing test profile derived from the 25 Wh version by simply doubling both the durations and the power levels for each step.

2.3.1 25 Wh (200k) Life Cycle Test Profile

The 25 Wh Life Cycle Test Profile includes a 9 second discharge pulse, followed by a 19s rest period and a 6s trapezoidal regen pulse. A subsequent makeup charge for 26 seconds is provided to achieve a projected charge-neutral condition, based on an assumed 90% energy efficiency. (The actual power levels are adjusted if necessary to achieve a true charge-neutral condition in the test procedure itself.) The resulting pulse profile for a 25 Wh swing in energy is shown in Table 2.3.1 and illustrated in Figure 5.

Table 2.3.1. 25 Wh Life Cycle Test Profile

Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
9	9	10	25	25	TBD	TBD
19	28	0	0	25	TBD	TBD
2	30	-12	-6.67	18.33	TBD	TBD
4	34	-6	-6.67	11.66	TBD	TBD
26	60	-2	-14.44	-2.78	TBD	TBD

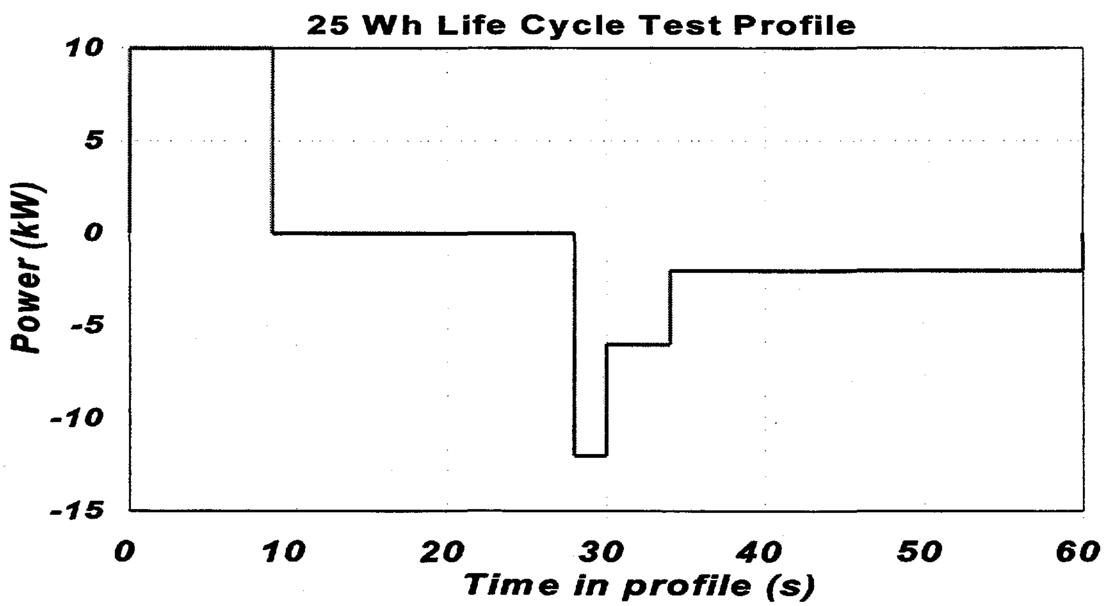

Figure 5. 25 Wh Fast Response Engine Life Cycle Test Profile

2.3.2 **100 Wh (50k) Life Cycle Test Profile**

The 100 Wh (Fast Response Engine) Life Cycle Test Profile is derived directly from the 25 Wh profile by doubling all the step times and the step power levels. The resulting pulse profile for a 100 Wh swing in energy is shown in Table 2.3.2 and illustrated in Figure 6.

Table 2.3.2. 100 Wh Life Cycle Test Profile

Time Increment (s)	Cumulative Time (s)	Power (kW)	Energy Increment (Wh)	Cumulative Energy (Wh)	Equiv. Current (A)	Capacity Removed (A-s)
18	18	20	100	100	TBD	TBD
38	56	0	0	100	TBD	TBD
4	60	-24	-26.67	73.33	TBD	TBD
8	68	-12	-26.67	46.66	TBD	TBD
52	120	-4	-57.78	-11.12	TBD	TBD

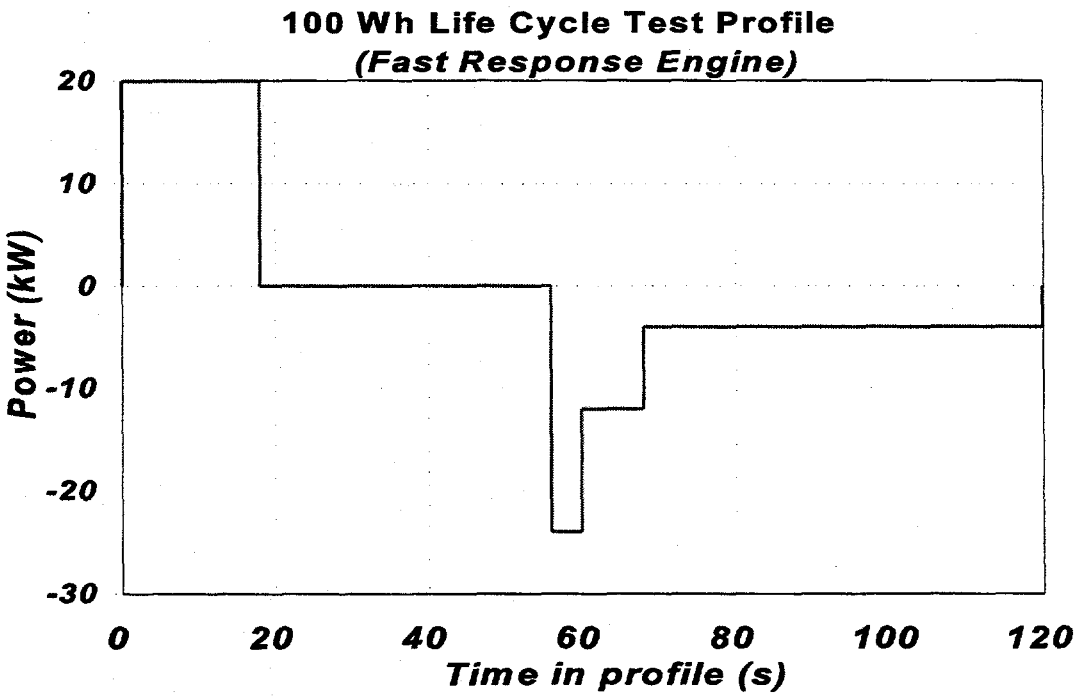

Figure 6. 100 Wh Fast Response Engine Life Cycle Test Profile

3.0 **Test Procedures**

3.1 **Laboratory Cell Tests**

The tests defined in this section are intended primarily to characterize the performance of battery technologies in a developmental stage, where the ability of a technology to meet the PNGV goals has not yet been established. The results of these tests will commonly be reported on a 'unit cell' basis for use in battery modeling, as well as to simplify their use in performance projection and design tradeoffs. The use of these tests is generally not appropriate for full-size cells, modules or battery systems because results are not easily compared to the PNGV goals.

3.1.1 **Static Capacity Test**

This test measures the battery capacity in ampere-hours as a function of constant current discharge rate. Discharge is terminated on a manufacturer-specified discharge voltage limit. If the manufacturer does not provide a discharge voltage limit, or if the provided limit is unrealistically low, 3/4 of the maximum charge voltage will be used. (This will automatically become the discharge voltage limit for full size battery tests in any event because of the 300 to 400V PNGV operating voltage range.) The one hour rate ($C_1/1$) is used as the reference for static capacity and energy measurement and as a 'standard' rate for module and system-level testing. The slower rates more commonly used for EV batteries are unrealistically low for hybrid applications.

3.1.2 **Hybrid Pulse Power Characterization Test**

The Hybrid Pulse Power Characterization (HPPC) Test is intended to determine dynamic power capability over the battery's useable charge and voltage range using a test profile which incorporates both discharge and regen pulses. The primary objective of this test is to establish, as a function of SOC, (1) the $\mathbf{V_{MIN}}$ cell discharge power capability at the end of an 18 second discharge current pulse and (2) the $\mathbf{V_{MAX}}$ cell regen power capability over the first 2 seconds of a trapezoidal regen current pulse.[1] Secondary objectives are to derive from the voltage response curves the fixed cell impedance and cell polarization impedance as a function of time with sufficient resolution to reliably establish cell voltage response time constants during discharge, rest and regen operating regimes. The impedance measurements will be used to evaluate impedance degradation during subsequent life testing and to develop hybrid battery performance models for vehicle systems analysis.

The HPPC test incorporates the Pulse Power Characterization Profile as defined in

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[1] $\mathbf{V_{MIN}}$ and $\mathbf{V_{MAX}}$ refer to the cell minimum and maximum voltages which correspond to the PNGV operating voltage range of 300 to 400 VDC. For cells, the specific voltages can be any values appropriate to the technology as long as they are in a 3:4 ratio (or less).

Section 2.1. Only constant current steps, in the same ratio as the current values in Table 2.1, are used at the laboratory cell level. The test is made up of single repetitions of this profile, separated by approximately 10% DOD constant current C/1 discharge segments,[2] each followed by a 1 hour rest period to allow the cell to return to a charge equilibrium condition before applying the next profile. The test begins with a fully charged battery after a 1 hour rest period and terminates after

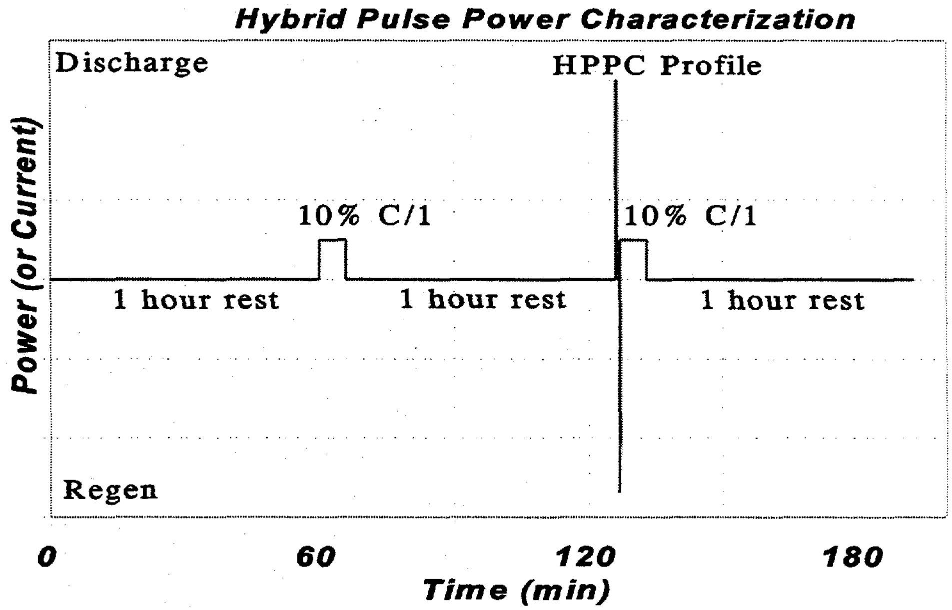

Figure 7. Beginning of HPPC Test Sequence

completing the final profile at 90% DOD, discharge of the cell at a C/1 rate to 100% DOD, and a final 1 hour rest period. The voltages during each rest period are recorded to establish the cell's OCV behavior. The sequence of rest periods, pulse profiles and C/1 discharge segments is illustrated in Figures 7 and 8.

Where applicable, current/power levels to be used for testing laboratory cells should be scaled to reflect the cell performance required to accommodate the battery pack power levels shown in Figure 1. However, it is expected that the cell discharge and regen power capabilities will vary significantly as a function of SOC and may not be known in the developmental stage. Consequently the HPPC test sequence is performed using peak currents scaled to at least 3 different levels, with the complete test performed at each level. Scaling of the levels is determined by the following criteria.

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2 Note that the energy of the pulse profile must be accounted for in determining the actual state of charge at which the profile was performed, e.g., the profile in Table 2.1 removes almost 2% of the available energy from a minimum-size Slow Response Engine device.

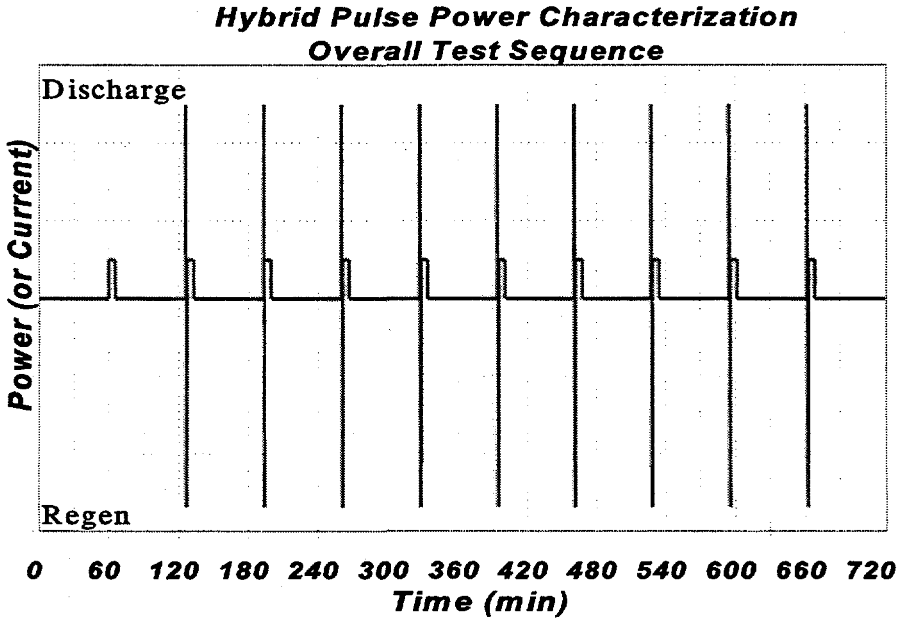

Figure 8. Complete HPPC Test Sequence

LOWEST CURRENT LEVEL - A peak profile current should be selected to enable the 18s discharge pulse to be done at low SOC (10%) and the 10s regen pulse to be done at high SOC (90%) without violating the manufacturer's V_{min} or V_{max} voltage limits.[3] [4] This current may be specified by the manufacturer (if known), or it may be determined experimentally by choosing an arbitrary low current for the test (e.g. using 2X or 3X the $C_1/1$ rate for the discharge current pulse value.) The regen impedance at 10% DOD and the discharge impedance at 90% DOD can be estimated from these results (see 4.1.2) From these impedances the maximum possible profile currents (without violating voltage limits) can be estimated at 10% and 90% SOC.

If the results indicate that the peak profile current used was not at least 75% of the maximum value which could have been used without violating voltage limits, then the discharge should be re-run using a peak current at least 75% of the maximum. Note: when a value is chosen for the discharge current step, all other step currents are ratioed to this value in accordance with Table 3.1.2.

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[3] These limits may or may not be equal to the PNGV limits, i.e. the test may be done using manufacturer-specified limits, although the results will be reported with respect to the PNGV voltage limits.

[4] Note that the first 2s regen step of the profile is generally limiting for V_{max}.

Table 3.1.2. Test Current Ratios for HPPC Test Pulse Profile

Step Number	Step Length (s)	Cumul Time (s)	Relative Current Ratio
1	18	18	1.0
2	32	50	0
3	2	52	-0.81
4	4	56	-0.63
5	4	60	-0.55

INTERMEDIATE CURRENT LEVEL - A peak profile current should be selected to enable both the 18s discharge pulse and the 10s regen pulse to be done over a SOC range of 30% to 70%. The pulses will still be executed outside this SOC range, but it is anticipated that current limiting may take place to enforce the manufacturer's V_{min} and V_{max} voltage limits. The peak current to be used for this iteration of the test should be calculated from the resistance values determined from the Lowest Current Level test (see 4.1.2). The value used should be about 90% of the calculated maximum value which will allow the pulses to be performed at 30% and 70% SOC without exceeding voltage limits. Note that the intent is that no current limiting should occur in the data for states-of-charge between 30% and 70%.

HIGHEST CURRENT LEVEL - A peak profile current should be selected to enable both the 18s discharge pulse and the 10s regen pulse to be done over a SOC range of 40% to 60%. All other constraints are the same as for the previous iteration, i.e., the results of the Intermediate Current Level test should be used to determine the peak test current, which should be about 90% of the maximum value which will allow the pulses to be performed at 40% to 60% SOC without violating voltage limits.

Control of cell temperature is important for this series of tests to avoid test artifacts due to internal heating as a result of the high currents employed. For laboratory cells this may require the use of a temperature bath.

Analysis and reporting of the results from this series of tests is described in Section 4.1.2.

3.1.3 Operating Set Point Stability test

This test is a special case of the life cycle testing regime to be applied to a given cell or battery. Since life cycle testing is normally done at an intermediate state-of-charge, it is necessary to determine that cycling will result in a stable condition with respect to SOC, and to adjust test conditions if necessary to assure that this will be the case. The target state-of-charge for the life cycle test(s) defined in 3.1.5 is normally determined from the HPPC test results (see 4.1.2) based on the peak discharge and regen powers planned for life cycle testing.

With the cell at the selected state-of-charge value derived from the HPPC test results, apply 100 of the selected life cycle test profiles and determine the change (if any) in the state-of-charge before and after the 100 profiles. Allow a 1 hour rest period before and after the 100 profiles are performed to determine any change in open circuit voltage.

3.1.3.1 Adjusting the Operating Set Point

If the cell conditions do not reach a voltage and temperature equilibrium during the first 100 test profiles, upper or lower voltage constraints or other limits may be adjusted (within manufacturer limits) to provide stable cycling conditions, and this test may be repeated or extended if necessary.

For ease of analysis of test results, it is desirable that current limiting is not encountered during the profile steps. The means for doing this is dependent on the type of tester used. For testers which are capable of terminating a specific step based on criteria other than time, the following arrangement is acceptable: (1) from the HPPC results, establish a minimum (termination) voltage for the discharge step which the cell is just capable of sustaining for the defined length of the step at the target state-of-charge. (This value will be greater than V_{min}.) (2) Extend the programmed length of the step slightly so that the overall profile has a slight net discharge, e.g. for the 100 Wh profile, the discharge step can be extended from 9 to 10s. (It may be desirable to do this by simply adding an additional 1s discharge step to the profile.) When this modified profile is executed repeatedly, the length of the discharge portion of the profile will vary dynamically to (a) hold the state-of-charge near the target value while (b) sustaining the discharge current at the programmed value for at least the defined discharge time. For testers which do not allow premature step termination, current limiting on an extended discharge step can be used to produce an equivalent result provided that it takes place after the 'defined' length of the step, e.g. after 9s for the 100 Wh profile.

A complementary approach based on regen voltage limiting could also be used; however, it is not desirable to vary the length of the initial regen step (which is the largest in all defined profiles), because of its short duration, or to allow current limiting during this step. Execution of this approach would thus require adjusting the length or magnitude of a later regen step based on the voltage encountered during the initial regen step; this approach is generally not directly supported by cell test hardware.

3.1.4 Self Discharge Test

This test is intended to determine the temporary capacity loss which results from a cell or battery standing (i.e. at rest) for a predetermined period of time. It is conducted similarly to the USABC Stand Test, except that the device under test is at an intermediate state-of-charge during the rest period.

The test consists of the following sequence of activities:
(1) measure the actual cell capacity using a C/1 constant current discharge rate, and recharge it using the manufacturer's recommended charge algorithm.
(2) discharge the cell for one-half (1/2) the measured capacity, and allow it to stand for an interval between 48 hours and 1 week. (The stand period should be selected based on the expected stand loss rate, with the value chosen to yield an expected capacity loss between 5% and 25% over the interval.) All measurement equipment may need to be disconnected from the cell during this period to reduce parasitic losses.
(3) discharge the cell for its remaining capacity.
(4) recharge the cell, and discharge it again at a C/1 rate. If a loss of capacity is observed between (1) and (4), additional discharges may be done to return the cell to its nominal capacity.

3.1.5 Cycle Life Tests

Cycle life testing is done using one of the Hybrid Life Cycle Test Profiles defined in Section 2.2 or 2.3. For laboratory cells the 100 Wh (Slow Response Engine) profile is considered a baseline test. However, any of the defined profiles may be specified in a test plan for the particular device(s) to be tested. The cycle life testing process consists of the following steps:

(1) Determine the peak discharge power or current value to be used for the selected test profile. (All other test power or current values are set relative to this peak discharge value, in proportion to the values in Tables 2.2.1, 2.2.2, 2.2.3, 2.3.1 or 2.3.2 as appropriate.) In general this peak value should correspond to the demands that the PNGV requirements would make on the battery if it were scaled to vehicle size. For laboratory cells, this correspondence is not generally known. Consequently one of three scaling methods is used for laboratory cell testing:

(A) WEIGHT SCALING - Select a scaling factor based on the ratio of actual cell weight (adjusted as necessary to account for projected system packaging burden) to the PNGV weight goals, and multiply the peak 'system power' value of the selected test profile by this factor to determine the peak discharge test power P_{max}.

Using the Hybrid Pulse Power Characterization (HPPC) Test results for the cell, calculate the discharge pulse current which should result in a power equal to P_{max} at the end of an 18s discharge pulse at the nominal DOD specified for the life cycle test. Use this current for the discharge pulse value; current values for other profile steps are then assigned in ratios defined for each test profile.

(B) CELL AREA SCALING - Project the cell performance measured by the HPPC Test to a full size battery system, and determine the areal current density required to achieve the peak 'system current' required by the selected test profile. The peak discharge test current is then selected as the product of the test cell electrode area and this peak current density. Current values for other profile steps are then assigned in ratios defined for each test profile.

(C) ARBITRARY SCALING - The peak discharge test current is specified by the test sponsor/project manager based on the capabilities of the test cell. This can be done based on some fraction of the measured HPPC 'sweet spot' capability (see 4.1.2), or on the results of previous life testing of similar cells, or some other criterion. Current values for other profile steps are then assigned in ratios defined for each test profile.

(2) Determine the End-of-Life and End-of-Test criteria for cycle life testing. In general, both End-of-Life and End-of-Test are necessarily reached when the test profile cannot be executed within the discharge and regen voltage limits, for any value of state-of-charge[5]. At this point the cell has insufficient capacity available at the test conditions to execute the test, i.e. its 'sweet spot' capacity is less than the state-of-charge swing required by the test profile. However, the number of test profiles executed at this point WILL NOT BE equal to the cycle life per the PNGV goals, unless the following conditions have been met: (a) the regen and discharge voltage limits used are in a 4:3 ratio or less; and the test currents used give actual test powers proportional to the PNGV goals. To minimize the amount of extrapolation required to predict performance against the PNGV goals, it is desirable that the test conditions (especially voltage limits) should be as close as practical to the PNGV operating conditions.

(3) Select the desired operating state-of-charge for cycle life testing based on the HPPC results, and perform the Operating Set Point Stability Test (3.1.3) to verify stable operation at the selected SOC point. Make any adjustments to the test profile or test operating conditions required as described in 3.1.3.1.

(4) Repeat the selected test profile a number of times dependent on the profile, as specified in Table 3.1.5.

(5) After the specified number of repetitions, suspend cycling and perform one or more reference performance tests to determine the extent of degradation in capacity and/or power capability. The intervals between these reference tests are specified in Table 3.1.5.

(6) Repeat steps (4) and (5) until an end-of-test condition is reached.

---

5 Note that the target state-of-charge and operating set point may need to be adjusted (as in Section 3.1.3.1) to keep the profile SOC excursion within a useable range as the cell characteristics shift over life.

Table 3.1.5. Reference Performance Test Intervals for Cycle Life Testing

Life Cycle Test Profile Used	Number of Continuous Repetitions Between Reference Tests	Frequency of Reference Tests
25 Wh Cycle Life Test Profile	20,000	C/1 every 20,000; HPPC every 50,000
100 Wh Cycle Life Test Profile (Slow Response)	10,000	C/1 every 10,000; HPPC every 30,000
100 Wh Cycle Life Test Profile (Fast Response)	4,000	C/1 every 4000; HPPC every 12,000
200 Wh Cycle Life Test Profile	5,000	C/1 every 5000; HPPC every 15,000
600 Wh Cycle Life Test Profile	2,000	C/1 every 2000; HPPC every 6000
Other profiles TBD	Approximately 10% of expected cycle life	C/1 ~ every 10% of expected life; HPPC every 3rd time the C/1 is done

3.1.6 Efficiency Testing

The PNGV goals are specified in terms of round-trip energy efficiency on a FUDS/HWFET cycle. (These cycles are used for emissions compliance testing; they are not included in the first version of this manual but may be treated later.) For laboratory cells, where the intent is to determine technology capability rather than to verify program goals, such a cycle is unnecessarily complex. The simplest way to determine a measure of round-trip efficiency is by calculation from one or more of the life cycle tests defined in Section 3.1.5. Because the repetitive cycling in these tests is done on a charge-neutral basis, energy efficiency can be determined from the data for a single test profile (using energy removed vs energy returned) as described in Section 4.1.6.

3.1.7 Thermal Performance Test

A separate test profile for temperature performance is not defined. The effects of battery environment (ambient temperature) on battery performance should be measured by performing the Static Capacity Test and/or Hybrid Pulse Power Characterization Test at various temperatures up to the PNGV operating temperature goals (-40 to +52°C). At the laboratory cell level, such testing has two goals: to characterize the performance of the technology as a function of temperature, and to bound the likely constraints on thermal management of full size cells or batteries.

It may be necessary to adjust the rest intervals in the HPPC Test to assure that thermal stability as well as voltage equilibrium is reached before each repetition of the Pulse Power Characterization Profile.

3.2 General Module/Cell Tests

3.2.1 Static Capacity Test

This test is identical to the comparable test for laboratory cells in 3.1.1, except possibly for termination conditions. It measures the battery capacity in ampere-hours and watt-hours using a one hour rate ($C_1/1$) constant current discharge. Discharge is terminated on a manufacturer-specified discharge voltage limit, which however cannot be less than 3/4 of the maximum charge voltage. (This will automatically become the discharge voltage limit for full size battery tests in any event because of the 300 to 400V PNGV operating voltage range.)

3.2.2 Hybrid Pulse Power Characterization Test

This test is intended to be performed on full-size cells or modules which have been sized appropriately for the PNGV performance goals. If the correspondence between cells or modules to be tested and the appropriate PNGV targets for capacity, weight etc. is not known, the laboratory cell test in 3.1.2 should be used instead. For full-size cells or modules, this test differs from the laboratory cell test in 3.1.2 in several respects, depending on whether the devices to be tested are intended for use in Slow Response or Fast Response Engine vehicle designs.

3.2.2.1 Hybrid Pulse Power Characterization (Slow Response Engine)

This test is conducted identically to the laboratory cell version in Section 3.1.2 except as noted in the following:

The test is performed using the power (rather than current) values from Table 2.1. The power levels for the test are determined by dividing the power values in the table by the number of modules or cells required to provide the PNGV operating voltage range of 300 to 400V.[6] For comparison with earlier device testing, the current-based version of the profile may be performed also (using the actual current values defined in Table 2.1), but the power-based profile should be considered the primary

---

6 Note that selecting this number of cells/modules is necessarily part of the propulsion system design optimization process, i.e. it cannot be done arbitrarily based on battery considerations only.

test. Note that the 10% capacity increments are still removed using a C/1 constant current discharge rate; only the Pulse Power Characterization Profile Steps are based on power.

If the cell or module performance is such that power limiting is not observed (i.e. the programmed power is delivered within the voltage limits for both discharge and regen steps) over at least the 40% to 60% SOC range, only a single repetition of the test is required. (However, this may not provide an accurate determination of available energy.) If this condition is not met, the test should be repeated at a lower power level which satisfies the 40 to 60% SOC criterion.

3.2.2.2 Hybrid Pulse Power Characterization (Fast Response Engine)

This version of the test, designated as HPPC(F) to distinguish it from the Slow Response Engine version, is performed using the profile from Table 2.2. The power levels to be used for the test are determined by dividing the values in Table 2.2 by the number of modules or cells required to provide the PNGV operating voltage range of 300 to 400V.[6] Because a single execution of this test profile removes a significant fraction (up to 25%) of the energy from a Fast Response Engine-type device, the HPPC test sequence from 3.1.2 cannot be used. The intent of the test is still to establish the open circuit voltage and pulse power capabilities from approximately 10% to 90% DOD in 10% increments. However, the cell or module must be recharged after each pulse profile and then discharged to each approximate starting DOD at a C/1 rate.

Consequently the test consists of a series of partial (but increasing) C/1 discharges, each of which is followed by a pulse profile and a recharge. The beginning of this sequence is illustrated in Figure 9, and the complete sequence is shown in Figure 10. Note that this sequence will usually terminate before completion, because a battery will generally be unable to perform the test profile at a DOD value approaching 90%.

If the cell or module performance is such that power limiting is not observed (i.e. the programmed power is actually delivered within the voltage limits for both discharge and regen steps) over at least the 40% to 60% SOC range, only a single repetition of the test is required. If this condition is not met, the test should be repeated at a lower power level which will permit this condition to be satisfied. This is necessary so that data showing the useable (i.e. non-limited) behavior of the device is obtained for at least the midrange SOC values.

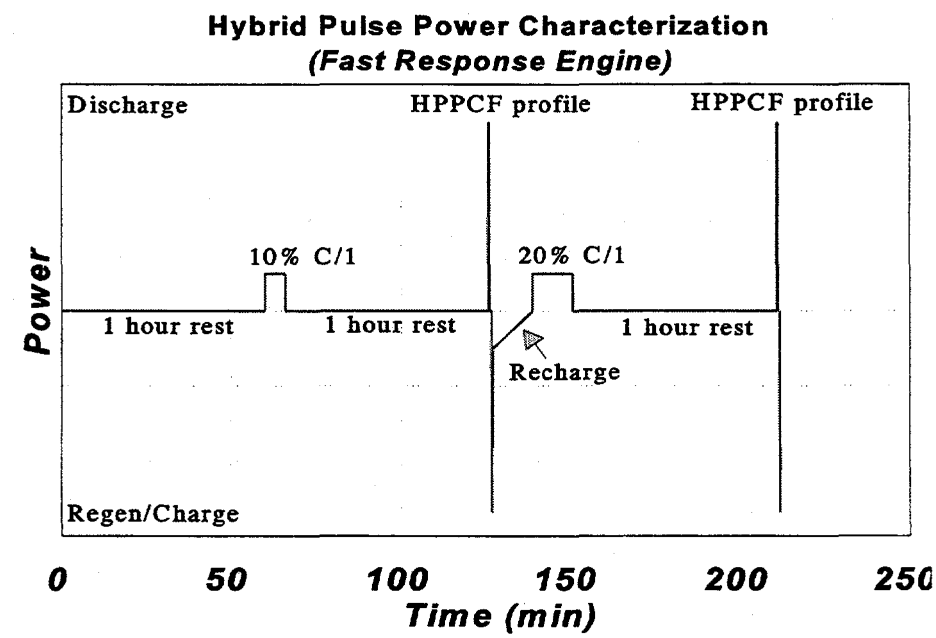

Figure 9. Beginning of HPPC(F) Test Sequence

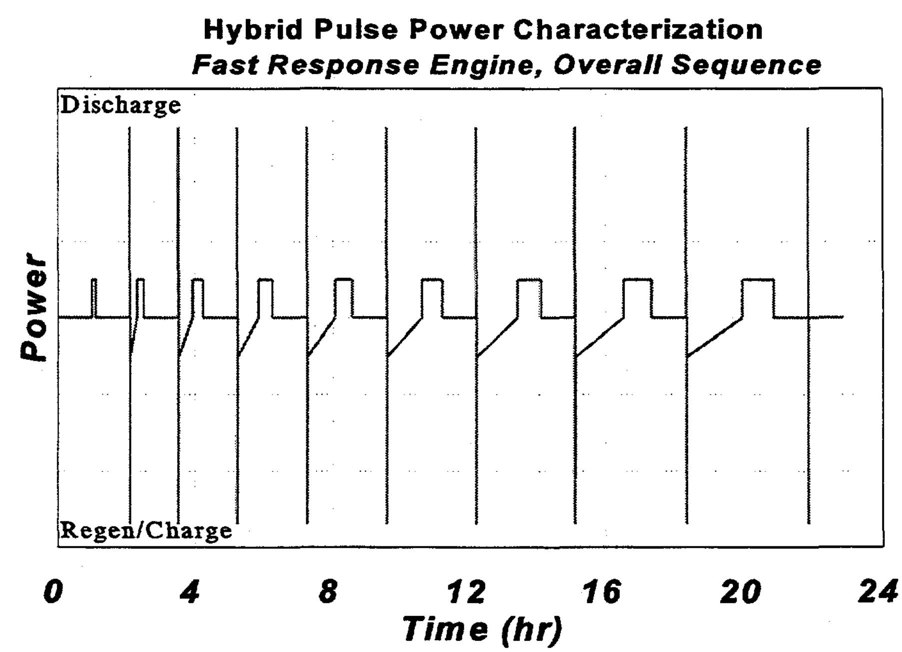

Figure 10. Complete HPPC(F) Test Sequence

3.2.2.3 Alternative HPPC Test (Fast Response Engine)

If the general behavior of a device is well understood, it may be desirable to abbreviate the Fast Response Engine version of the HPPC test, particularly for reference iterations during life cycle testing. Instead of performing the pulse profile at 10% DOD increments, these may be performed at 20% increments instead, or at the 40% and 60% DOD points only. This will shorten the duration of the test by several hours while still providing key reference data to determine power capability degradation over life.

3.2.3 Self Discharge Test

This test is identical to the corresponding laboratory cell test in Section 3.1.4, except that the stand period is fixed at 48 hours. (For a battery whose self-discharge rate exactly met the PNGV goals in Table 1.4, the resulting stand losses over a 48 hour period would be between 1.3 and 33% depending on battery size.)

3.2.4 Slow Response Engine Life Cycle Test

For a slow response engine design, the battery is required to provide the total vehicle power under some conditions, which means that the vehicle will have some all-electric range. Thus a meaningful life cycle test must include both this condition, when the battery state-of-charge is decreasing, and the condition where an auxiliary power unit is operating to provide the base operating power and/or to recharge the battery. The outline for this life cycle test procedure is a sequence of steps as follows:

1. Charge the battery fully, and if necessary, remove energy using a C/1 discharge until a maximum operational state-of-charge is reached, i.e., the highest SOC at which it is possible to perform the PPC profile in step 2 without exceeding regen voltage limits.

2. Subject the battery to the Pulse Power Characterization Profile of Section 2.1.1 until it reaches a minimum operational state-of-charge, i.e., the lowest SOC at which it is possible to perform the PPC profile without exceeding discharge voltage limits. (Each execution of this profile will remove about 6% of the battery capacity for a minimum-size slow response engine storage device.) The profile should be scaled as in Section 3.2.2.1, by dividing the profile power values by the number of modules or cells required to provide the PNGV operating voltage range.

3. Subject the battery to a dynamic test profile (one of the defined life cycle test profiles from 2.2) adjusted for a slight net discharge and scaled as above for a 1 hour period, with voltage constraints imposed to prevent the state-of-charge from dropping below the minimum operational value.

4. Recharge the battery at constant power at the scaled equivalent of 25 kW (at the vehicle level) until it reaches the maximum operational state-of-charge. (This is the functional equivalent of stopping the vehicle with the auxiliary power unit running.)

5. Subject the battery to the same test profile as in (2) for 1 hour.

6. Repeat (2) through (5) continuously for a total test time of approximately 1 week. A single iteration of this profile will generally look as shown in Figure 11.

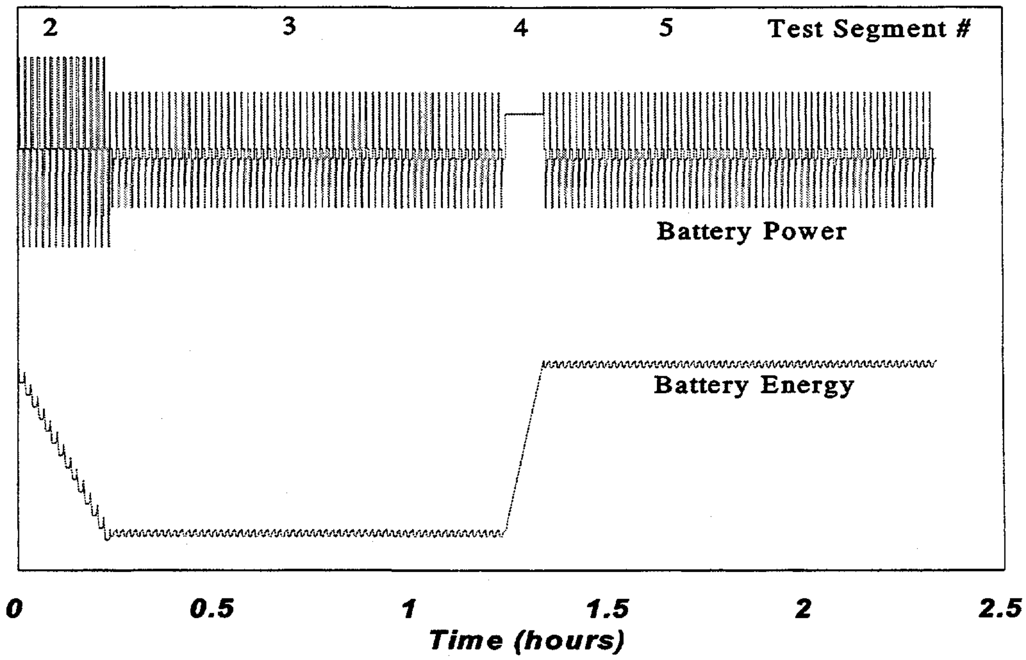

Figure 11. Typical Slow Response Engine Life Test Profile

7. Recharge the battery fully, and perform a Static Capacity Test. A Hybrid Pulse Power Characterization Test should also be performed every third time this point is reached, i.e. after about every 3 weeks of cycling.

8. Repeat steps (1) through (7) until an end-of-test condition defined for the battery is reached. This condition will generally occur when either (a) the Pulse Power Characterization Profile cannot be performed within the voltage limits, or (b) the charge-neutral dynamic test profile cannot be executed at any depth-of-discharge.

3.2.5 Fast Response Engine Life Cycle Test

This test is conducted identically to the laboratory cell cycle life test in Section 3.1.5 except that either the 25 Wh (2.3.1) or 100 Wh (2.3.2) profile is used. The number of profiles performed continuously between reference tests is in accordance with Table 3.1.5.

3.2.6 Thermal Performance Test

Thermal performance is characterized for full size cells or modules by performing the Static Capacity Test and the appropriate Hybrid Pulse Power Characterization Test over the PNGV operating temperature range of -40 to +52°C. Most battery technologies will not be capable of performing the HPPC over this temperature range without thermal management, so such testing will necessarily interact with the development of system level thermal models and/or control systems.

3.3 Battery System Tests

3.3.1 Static Capacity Test

This test is performed identically to the comparable test for full-size modules/cells (Section 3.2.1) except that the maximum charge voltage and minimum discharge voltage must be within the PNGV operating voltage range.

3.3.2 Hybrid Pulse Power Characterization Test

This test is performed identically to the corresponding Slow Response or Fast Response Engine HPPC Test in Section 3.2.2.1 or 3.2.2.2, except that the maximum regen voltage and minimum discharge voltage must be within the PNGV operating voltage range.

3.3.3 Self Discharge/Stand Loss Test

TBD

3.3.4 Life Cycle Tests

TBD

3.3.5 System Efficiency Test

TBD

3.3.6 Operating Temperature Range Test

TBD

4.0 Analysis and Reporting of Test Results

4.1 **Laboratory cell performance test results** (from tests defined in Section 3.1)

A series of laboratory cell performance tests are defined in Section 3.1 and its subsections. The objective of these tests is to characterize the performance of candidate electrochemical couples at a cell level to evaluate their suitability for PNGV Energy Storage System use. The characterization can be done on a per cm^2 basis by considering only the active cell area and removing all burden considerations which are associated with current collection, packaging, thermal management, or any other items external to the active cell area. This normalized performance data will allow relative performance comparison of different electrochemical couples and will permit first order estimates of full size cell, module and/or battery pack performance. In general, certain information must be supplied by the manufacturer of a laboratory cell to permit this normalized characterization:

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

Based on the particular tests performed, the following information is to be determined (measured or calculated from test data) for each laboratory cell tested.

4.1.1 Static Capacity Test

- Capacity in ampere-hours and watt-hours at the specified discharge rate, based on manufacturer-specified discharge termination conditions. (Note that all of this capacity will not generally be useable within PNGV operating conditions, and thus it does not reflect conformance to the PNGV Available Energy goal. However, it is still considered a useful measure of capacity at the laboratory cell stage.)
- Ampere-hours and watt-hours returned (and the corresponding overall charge/discharge efficiencies) for the manufacturer-specified charge algorithm

4.1.2 Hybrid Pulse Power Characterization Test

- Actual cell power and calculated impedance characteristics, as a function of DOD, derived from the pulse profile test data:
  1. Discharge power and impedance at start of each discharge pulse (<100 ms)
  2. Discharge power and impedance 18 seconds after start of discharge pulse
  3. Regen power and impedance at start of each regen pulse segment (<100 ms from beginning of pulse)
  4. Regen power and impedance 2s after start of regen pulse

- Open circuit voltage is measured and plotted as a function of DOD at the end of each HPPC rest period, as shown in Figure 13. From this data, OCV at other DOD values can be estimated by straight-line interpolation, or more accurately by fitting a curve through the measured data.

- Discharge and regen impedances (items 2 and 4 above) are determined using a $\Delta V/\Delta I$ calculation for each iteration of the test profile according to the following equations and Figure 12, where V_{ocv2} is the open circuit voltage (NOT the actual measured voltage) at the depth-of-discharge corresponding to the start of the regen pulse (time t2). V_{ocv2} is interpolated as noted above from the OCV plot.

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

$$\textit{Regen Impedance} = \frac{V_{ocv2} - V_{t3}}{I_{t2} - I_{t3}}$$

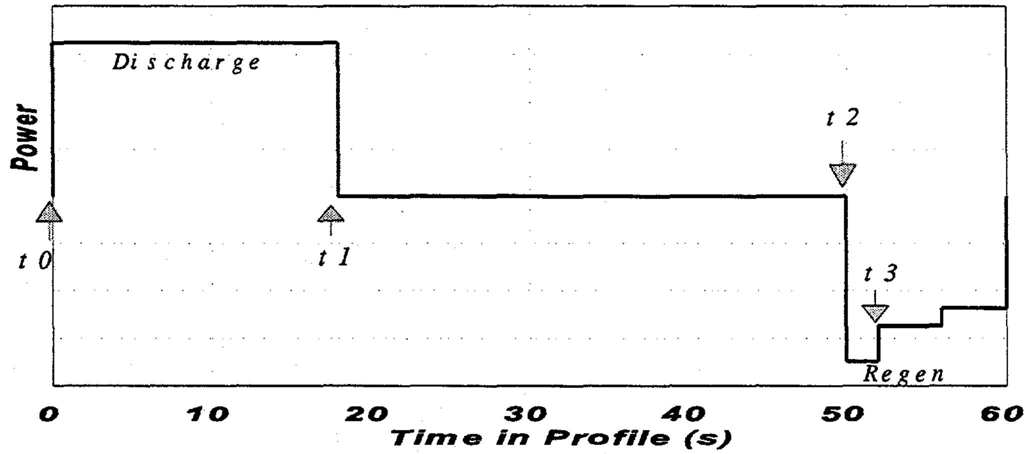

Figure 12. Impedance Calculation Time Points

These discharge and regen impedances are also plotted as a function of depth of discharge as shown in Figure 13.

- Pulse power capability is plotted from the power and impedance characteristics, showing the 18s V_{MIN} discharge capability and 2s V_{MAX} regen capability at each DOD tested. (See Footnote 1 regarding allowable values for V_{MAX} and V_{MIN}.) These values are derived using data from the highest current discharge or regen pulse test data which does not violate the manufacturer's V_{min} or V_{max} voltage limit criteria, i.e. data from different HPPC test runs may be used at different DODs. Discharge and regen pulse power capability is calculated at each 10% DOD increment from the open circuit voltage and resistance determined for that DOD (as shown in Figure 13), using the same equations as in the USABC Peak Power Test (Reference 5.1). Because pulse power capability is usually voltage limited, the applicable equation is typically

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

or

$$\text{Regen Pulse Power Capability} = V_{MAX} \bullet (V_{MAX} - OCV) \div R_{regen}$$

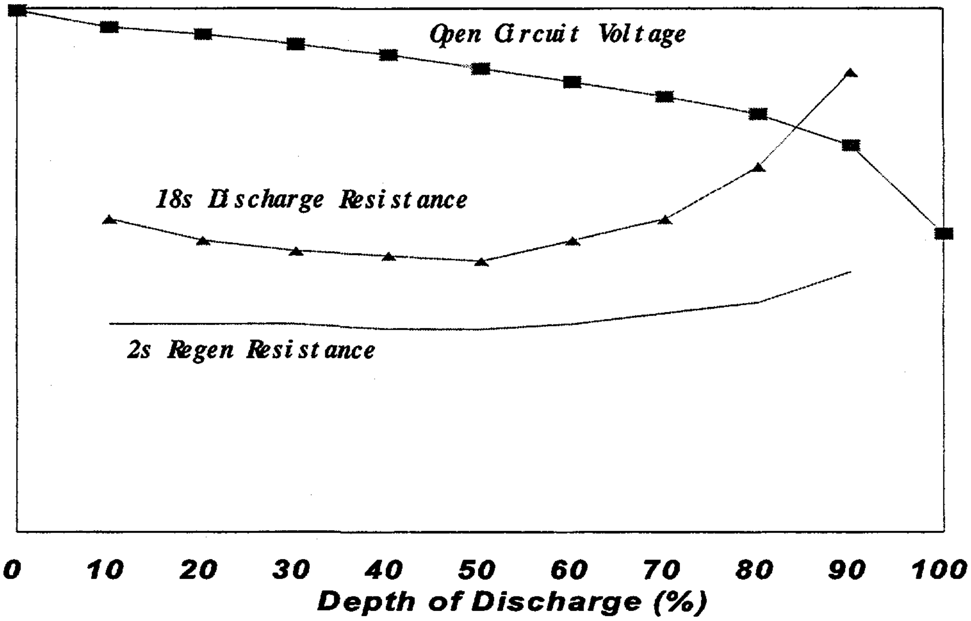

Figure 13. Open Circuit Voltage and Pulse Resistance vs DOD

This plot is used to determine the total available state-of-charge and energy swing that can be utilized (within the PNGV operating voltage limits) for specified discharge and regen power levels. Note that profile charge removal has to be accounted for in determining DOD, i.e. the DOD values plotted represent the actual net ampere-hours removed from the cell from top-of-charge down to the point at which the specific discharge or regen pulse occurs, including any previous pulse profiles performed. An example of this plot is shown as Figure 14.

As noted on the plot, the common means of interpreting this plot is a 3-step process: (1) determine the peak discharge power required; and (2) determine the corresponding peak regen power. The DOD range over which these pulse power levels can be achieved is then shown as (3) on Figure 14. Note that the plotted DOD values represent the ***beginnings*** of their respective discharge or regen pulses; this is different from the USABC peak power test, where values are plotted at the DOD achieved at the ***end*** of the pulse.

- Pulse power characterization profile voltage response is shown by graphing the measured current and voltage as a function of time during one or more executions of the HPPC pulse profile.

- Overall charge/discharge efficiency can be calculated as a function of fractional charge removal and return as derived from HPPC profile test data.

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

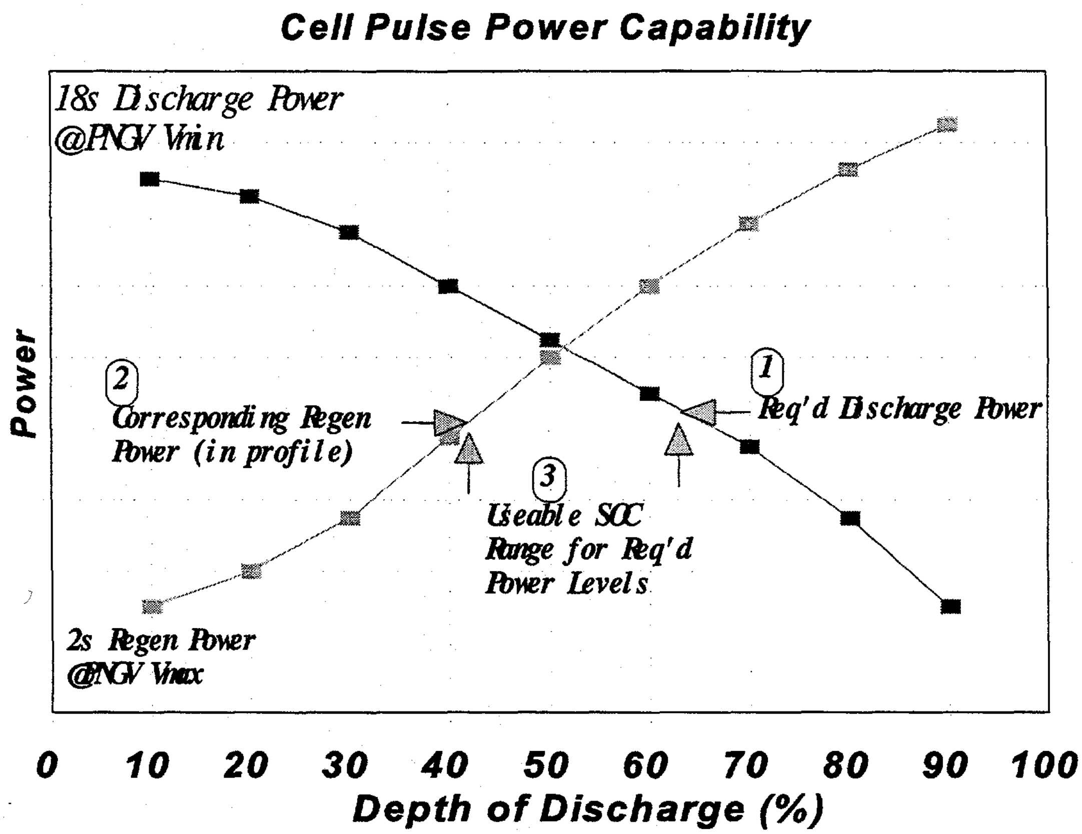

Figure 14. Pulse Power Capability ("Sweet Spot") Plot

- Voltage response time constant estimates for discharge, regen and rest periods, derived from the current driven pulse power profile test data

- Cell capacity in areal, volumetric and gravimetric units (milli-amphrs/cm^2, amphrs/kg, amphrs/liter, milli-watthrs/cm^2, watthrs/kg, watthrs/liter)

- Cell discharge power capability at t = 18 seconds derived for an equivalent battery pack minimum voltage (V_{MIN}) of 300 volts (milli-watts/cm^2, watts/kg, watts/liter)

- Cell regen power capability at t = 0 and t = 2 seconds derived for an equivalent battery pack maximum voltage (V_{MAX}) of 400 volts (milli-watts/cm^2, watts/kg, watts/liter)

- Cell Area Specific Impedance (ASI) for discharge pulse current at t = 0 and t =18s and for regen pulse current at t = 0 and t = 2s profile points (ohms-cm^2)

4.1.3 Operating Set Point Stability Test

No results are reported from this test. The current and voltage data are reviewed to determine that state-of-charge and other conditions are stable for continuous life cycle testing, but otherwise this test is treated as part of life cycle testing.

4.1.4 Self Discharge Test

Self discharge rate is determined over a fixed period (nominally 48 hours or 1 week as appropriate for the technology) at both full charge conditions (equivalent to the USABC stand test) and one or more intermediate DOD conditions. The result is reported as a percentage capacity loss, i.e. the difference between the ampere-hour capacity measured with and without the stand period.

4.1.5 Cycle Life

For the selected life test profile, cycle life is determined and reported as the number of profiles which can be executed before the cell is unable to perform the test profile (at any DOD) within the voltage limits without encountering current limiting.

4.1.6 Energy Efficiency Determination from Life Cycle Test Data

Round trip energy efficiency is calculated from a single test profile of any of the life cycle tests as follows:

a. From an examination of the data for a period of repetitive cycling, choose a test profile where the cell conditions (e.g. temperature and voltage behavior) are stable. The amount of time to reach this condition varies but will typically be 1 to 2 hours after the start of cycling; thus profile 100 of a group might be a suitable choice.

b. Integrate both the current and power for the discharge and regen intervals of the profile(separately.) Verify that the discharge ampere-hours and the regen ampere-hours are equal (within 1% or less); if not, this profile is not sufficiently charge-neutral (or the data rate is insufficient) and a different one should be selected.

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

$$\textit{Round-trip Efficiency} = \frac{\textit{Watt-hours (discharge)}}{\textit{Watt-hours(regen)}}$$

Round trip efficiency may also be calculated if desired over a longer period of time using any number of repeated test profiles for which the state-of-charge is stable, e.g. an entire block of several thousand profiles may be used instead of a single profile.

4.1.7 Thermal Performance Tests

Measured capacity at the C/1 rate is reported over the range of temperatures at which the Static Capacity Test is performed. Results of HPPC testing at temperatures other than nominal is reported in the same formats defined in Section 4.1.2, except that the test temperature must accompany all data and graphs.

4.2 General Cell/Module Performance Test Results (from tests defined in Section 3.2)

TBD

4.3 Battery System Performance Test Results (from tests defined in Section 3.3)

TBD

5.0 References

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

5.2 PNGV Energy Storage Program Goals (performance and life values are repeataed in Section 1.4 for reference)

Appendix A

Generic Test Plan Outline for PNGV Testing

3.0 Equipment

Special attention must be given to the power, current and voltage capabilities required to perform the tests defined in this plan. The regen power levels, battery power-to-energy ratios, and peak-to-average power requirements of the dynamic tests are much more demanding than those for comparable electric vehicle tests. Some notable test equipment considerations include: (1) peak regen power values that equal or in some cases exceed the peak discharge powers required; (2) the ability to perform 'triangular' (i.e. linearly decreasing) rather than 'rectangular' (i.e. constant power) regeneration power steps; and (3) for life cycle testing, the ability to perform tests (and acquire test data) which may last for days without interruption due to operation at intermediate charge states.

4.0 Prerequisites and Pre-Test Preparation

In addition to any prerequisites defined in individual test procedures, the following actions will be performed by the testing organization prior to testing a battery under control of this test plan:

4.1 An identification number for the battery will be determined and affixed to the battery (if this has not been done by the manufacturer.) (See TBD for numbering system.)

4.2 The battery or battery modules will be examined to determine that damage has not occurred during shipping or handling, and that the type and configuration (e.g. number and interconnection of modules) are correct and agree with the assigned identification number.

4.3 The battery's physical dimensions and weight will be measured. For battery packs containing multiple subunits (modules or cells) interconnected by lab personnel after receipt, the modules will be weighed individually; in other cases, the entire battery may be weighed as a unit to avoid disassembling it (see TBD Worksheet).

4.4 Actual current (A) or power levels (kW) and capacities (in kW·h or A·h) must be established for those planned tests specified in Section 7.0 where the procedures do not specify these levels. These values should be derived from the ratings specified in Section 5.0 of this plan, based on the manufacturer's worksheet (Appendix TBD) and the measured weight or other characteristics of the battery. If these are based on values other than manufacturer's ratings or a fixed percentage of the PNGV goals, the basis will be noted in the test plan and the battery log and subsequently reported.

5.0 Ratings, Test Limitations and Other Test Information TO BE PROVIDED

Battery ID Number ______________________________

NOTE: If more than one battery is covered by this test plan, provide a table of ID numbers. If a group of otherwise identical batteries is to be subjected to different sets of performance tests, multiple copies of Tables 7.x may be used.

5.1 RATINGS (DISCHARGE)

NOTE: All ratings are at Beginning of Life. A worksheet summarizing information to be supplied by the manufacturer for each battery is included as Appendix TBD.

Rated Capacity _______________ **(Ah)**

Note: For PNGV testing, Rated Capacity is defined as capacity at the 1-hour C/1 constant current discharge rate. All references to state-of-charge (SOC) or depth-of-discharge (DOD) are with respect to this value. For laboratory cell testing this value may be either supplied by the manufacturer or set equal to the actual measured capacity at the 1-hour rate. For all other types of testing the value should be supplied by the manufacturer. This capacity may be rated with respect to the manufacturer's minimum discharge voltage, which need not be identical to the PNGV 4:3 ratio of operating voltage swing. However, the determination of battery performance will be based on the PNGV voltage range.

Rated Energy Capacity ________ (kWh at 1-hour C/1 rate)

Test Unit Peak Power (rating at 2/3 OCV and 80% DOD at beginning of life, Reference 2.1 Procedure 3) ________________ (W or kW) (Nominal)

Peak Discharge Power to be applied on dynamic testing
__________________ (W or kW)

Maximum Allowable (Peak) Currents to be applied during dynamic tests:
Discharge __________________ (Amperes)
Regen __________________ (Amperes)

5.2 TEST LIMITS AND TERMINATION CONDITIONS (as applicable to planned tests)

Note that a condition such as a minimum discharge voltage may be either a test limitation (to be enforced by restricting power or current as necessary) or a test termination condition (i.e. end-of-test) depending on the specific procedure in use. In no case should such a limit be exceeded; however, the action to be taken when a limit is reached depends on the procedure.

DISCHARGE LIMITATIONS	VALUE	UNITS
Discharge Voltage Limit		V/cell etc. *
Discharge Temperature Limit(s)		°C
Other (e.g. Max Current etc.)		

* Specify load conditions if rate-sensitive

END OF LIFE TEST CONDITION(S): ____
____
____

5.3 OPERATING TEMPERATURE (Initial and limits for testing)

____
____
____

5.4 CHARGING AND REGEN

Normal Recharge Procedure: ____
____
____
____

CHARGE/REGEN LIMITATIONS	VALUE	UNITS/DEFAULT
Maximum Voltage		V/cell and/or battery
Maximum Temperature		°C
Maximum Charge Rate		Amperes, watts, time
Other limitations		

5.5 OTHER INFORMATION (Attachments can be referenced here)

Test laboratory Readiness Review requirements: _________________________

Thermal enclosure or other battery management system handling instructions (if applicable): ____

Commissioning Instructions: ____

Battery Configuration Description: ______________________________________
____
____
____

6.0 Safety Concerns and Precautions

Battery-specific information, TBD

7.0 Types of Tests to be Performed Under this Test Plan

7.1 ACCEPTANCE/PRECONDITIONING/TEST CONTINUATION CRITERIA

Any ratings or required test results that constitute acceptance for testing (i.e. further testing should not be performed unless these criteria are met) should be identified here or noted in the tables. Normally, the capacity of the unit must be within the rated C/1 constant current discharge and pulse power capabilities specified by the supplier. The results of these tests will be used as a basis for comparison with various reference tests specified throughout this test plan.

Table 7.3.1 - Laboratory Cell Performance Tests

TEST PROCEDURE	MINIMUM NO. REQ'D	DESCRIPTION
Cell formation and/or pre-conditioning	none	Manufacturer specific tests (if any) required prior to the start of normal performance testing
7.3.1 Static Capacity Test	3 at each rate used	Determination of basic energy capacity as a function of (constant) discharge current

TEST PROCEDURE	MINIMUM NO. REQ'D	DESCRIPTION
7.3.2 Pulse Power Characterization Test)	3	Determination of dynamic power capability (discharge and regen) as a function of SOC Determination of impedance and discharge power capability over an 18s discharge interval as a function of state of charge Determination of impedance and regen power acceptance capability over a 10s regen interval as a function of SOC. Determination of overall charge/ discharge efficiency as a function of fractional charge removal. Determination of OCV as a function of $C_1/1$ rate.
7.3.3 Operating Set Point Stability Test	2	Determination of whether or not a change occurs in the set point after 100 HPAT cycles.
7.3.4 Self Discharge Test	2	Determination of self discharge over a 48 hour period
7.3.5 Cycle Life Tests	3	Determination of capacity and power degradation as a function of cycles.
7.3.6 Thermal Performance Test(s)	TBD	Determination of the effects of temperature on above cell performance parameters

7.3 GENERAL MODULE/CELL PERFORMANCE TESTS

TEST PROCEDURE	DESCRIPTION
7.3.1 Static Capacity Test	Determination of basic energy capacity using a single constant discharge current ($C_1/1$)
7.3.2 Dynamic Capacity Test	Determination of useable energy capacity using a complex discharge/regen power profile (scaled DST)
7.3.3 Pulse Power Characterization Test	Same as 7.2.4?

TEST PROCEDURE	DESCRIPTION
7.3.4 Thermal Performance Test(s)	Determination of the acceptable range of thermal operation, to establish requirements for thermal management. (Same as 7.2.6 except that base test profile should be 7.3.1, 7.3.2 or 7.3.3.)
7.3.5 Stand Loss Test	Determination of energy and capacity losses during battery rest intervals, as a function of elapsed time (Same as USABC Test 7 except for time interval)
7.3.6 Vibration Test	Determination of the effects of a representative vibration profile on battery performance and/or life (Same as USABC Test 10?)

7.4 BATTERY SYSTEM PERFORMANCE TESTS

TEST PROCEDURE	DESCRIPTION
7.4.1 Static Capacity Test	Same as 7.3.1
7.4.2 Dynamic Capacity Test	Same as 7.3.2
7.4.3 Pulse Power Characterization Test	Same as 7.3.3?
7.4.4 System Efficiency Test	Determination of overall battery system energy efficiency, including charge/discharge and environmental losses, in a representative operating regime TBD
7.4.5 Stand Loss Test	Same as 7.3.5, except that all system operating losses should be measured as a function of ambient temperature, including energy required to maintain battery environmental conditions

7.5 LIFE CYCLE TESTING REGIMES

TEST PROCEDURE	DESCRIPTION
Laboratory Cells:	
7.5.1 Fast Response Engine (Power Assist)	Determination of expected life (cycles) for a test regime involving continuous operation at high power levels and intermediate states of charge (i.e. charge-neutral test profile)
7.5.2 Slow Response Engine (Dual Mode)	Determination of expected life (cycles) for a test regime involving charge/discharge operation over a significant fraction of the battery capacity

TEST PROCEDURE	DESCRIPTION
7.5.3 Modules/Cells:	TBD
7.5.4 Battery Systems:	TBD

8.0 Special Measurement Requirements

Requirements for measurement accuracy, dynamic response, sampling intervals, amount of data to be retained for analysis etc. are TBD. In general these will be procedure dependent because of the varied nature of the tests.

9.0 Post-Test Examination and Analysis

Battery-specific information, TBD