High Power Battery Test Methods for Hybrid Vehicle Applications

Gary L. Hunt
Idaho National Engineering & Environmental Laboratory
P. O. Box 1625
Idaho Falls, ID 83402-3830
E-mail: glh@inel.gov

Harold Haskins, Ford Motor Company
Bernie Heinrich, Chrysler Corporation
Raymond Sutula, U.S. Department of Energy

Abstract

Commonly used EV battery tests are not very suitable for testing hybrid vehicle batteries, which may be primarily intended to supply vehicle acceleration power. The capacity of hybrid vehicle batteries will be relatively small, they will typically operate over a restricted range of states-of-charge, and they may seldom if ever be fully recharged. Further, hybrid propulsion system designs will commonly impose a higher regeneration content than is typical for electric vehicles. New test methods have been developed for use in characterizing battery performance and life for hybrid vehicle use. The procedures described in this paper were developed from the requirements of the government-industry cooperative Partnership for A New Generation of Vehicles (PNGV) program; however, they are expected to have broad application to the testing of energy storage devices for hybrid vehicles.

The most important performance measure for a high power battery is its pulse power capability as a function of state-of-charge for both discharge and regeneration pulses. It is also important to characterize cycle life, although the ‘cycles’ involved are quite different from the conventional full-discharge, full-recharge cycle commonly used for EV batteries. This paper illustrates in detail several test profiles which have been selected for PNGV battery testing, along with some sample results and lessons learned to date from the use of these test profiles. The relationship between the PNGV energy storage requirements and these tests is described so that application of the test methods can be made to other hybrid vehicle performance requirements as well. The resulting test procedures can be used to characterize the pulse power capability of high power energy storage devices including batteries and ultracapacitors, as well as the life expectancy of such devices, for either power assist or dual mode hybrid propulsion system designs.

Background
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Testing the performance and life behavior of batteries for electric transportation has historically been done using methods and procedures which are based on the requirements of pure electric vehicles, i.e., those which are powered solely by stored energy from batteries. In the United States, such test procedures were evolved by entities of the Federal government, which sponsored much of the electric vehicle research and development in this country through the 1980s. Beginning in 1991, much of this Federal responsibility was transitioned to the United States Advanced Battery Consortium (USABC), a cooperative effort of the U.S. auto manufacturers, the Department of Energy (DOE) and the U.S. electric utility industry. This resulted in the formal definition and publication of a body of procedures for testing advanced technology electric vehicle batteries which has become widely used; many of these procedures subsequently have been adopted by the Society of Automotive Engineers (SAE) for testing near-term electric vehicle batteries as well. The perceived importance of this effort from the standpoint of this paper is that it established a precedent for an integrated set of test procedures designed to monitor and verify progress toward a set of application-specific battery program development goals.

By 1994 the DOE was well along toward establishing performance goals for hybrid energy storage devices in preparation for an emerging succession of cooperative development efforts with U.S. auto manufacturers. It was evident that the established testing methods for electric vehicle batteries could not provide high quality feedback on the performance of hybrid vehicle batteries. The demands on batteries for the two types of applications are simply too different to permit a common set of test methods. Consequently DOE commissioned an effort to develop test procedures appropriate for hybrid energy storage devices. This investigation focused on the needs of two types of hybrid drivetrains which were considered most likely to be used, called ‘dual mode’ and ‘power assist mode’. Candidate test cycles were proposed based on preliminary energy storage specifications, and some exploratory testing was performed using these candidate test cycles. This early effort identified a number of testing concerns and tradeoffs which must be considered in developing a coherent approach to hybrid battery testing. Oversight of this effort was subsequently transferred to the Electrochemical Energy Storage Team of the government-industry cooperative Partnership for A New Generation of Vehicles (PNGV) Program, and it is this latter effort which is the subject of this paper.

PNGV Program Goals

The PNGV Program goals were established in top-down fashion, in that a set of vehicle performance targets were defined at the beginning of the program. Goals for the energy storage components of the PNGV vehicle were then derived from these overall vehicle targets. A subset of those PNGV energy storage goals relevant to this paper is given in Table 1. This table shows only the minimum performance targets; a more aggressive set of ‘desired’ performance targets also exists but are not shown here.

Performance goals are shown for both “fast response engine” and “slow response engine” propulsion system designs. In PNGV terminology, a fast response engine design corresponds to what has been called a ‘power assist’ hybrid vehicle, one in which the energy storage device serves only to provide added acceleration power. Slow response engine designs are those for which the energy storage device will be the sole source of power in some operating conditions. These correspond to so-called ‘dual mode’ hybrid vehicles,
which will have some significant all-electric range. It can be seen from Table 1 that batteries for a slow response engine design are expected to accommodate higher power densities and higher absolute powers for both discharge and regenerative braking. However, the smaller fast response engine devices will require much higher power-to-energy ratios. Other types of energy storage devices than batteries might be candidates for either of these applications; however, this paper will refer only to batteries for convenience. Other significant PNGV energy storage constraints include a strong emphasis on round-trip energy efficiency and a much narrower operating voltage range than is typical for pure electric vehicles.

Table 1.4 PNGV Energy Storage System Performance Goals

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Units</th>
<th>Fast Response Engine Minimum Values</th>
<th>Slow Response Engine Minimum Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Discharge Power (constant for 18s)</td>
<td>kW</td>
<td>25</td>
<td>65</td>
</tr>
<tr>
<td>Peak Regenerative Pulse Power (trapezoidal pulse for 10s for the specified pulse energy)</td>
<td>kW (for 50 Wh pulse)</td>
<td>30 (for 150 Wh pulse)</td>
<td></td>
</tr>
<tr>
<td>Total Available Energy (discharge plus regenerative)</td>
<td>kWh</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>Minimum Round-trip Efficiency</td>
<td>%</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>Cycle Life, for specified SOC Increments</td>
<td>cycles</td>
<td>200 K for 25 Wh 50 K for 100 Wh</td>
<td>120 K for 100 Wh 20 K for 600 Wh</td>
</tr>
<tr>
<td>Maximum Weight (plus marginal increase per unit of energy&gt;3 kWh)</td>
<td>kg</td>
<td>40</td>
<td>65 (+10 kg/kWh over 3 kWh)</td>
</tr>
<tr>
<td>Maximum Volume (plus marginal increase per unit of energy&gt;3 kWh)</td>
<td>l</td>
<td>32</td>
<td>40 (+8 l/kWh over 3 kWh)</td>
</tr>
<tr>
<td>Operating Voltage Limits</td>
<td>vdc</td>
<td>300 min 400 max</td>
<td>300 min 400 max</td>
</tr>
</tbody>
</table>

Testing Considerations for Hybrid Vehicle Batteries

The technical performance concerns for hybrid batteries still emphasize energy, power and life just as for electric vehicle batteries; however, there are significant shifts in emphasis which affect testing such batteries. Capacity, and thus energy density, are still important, but the much smaller size of hybrid batteries means that power capability is the dominant performance consideration. The enormous power densities required to meet both acceleration and braking demands (1000 W/kg or more for both discharge output and regenerative braking input) mean that pulse power capability is more critical than sustained power. These demands are mitigated somewhat by the expectation that hybrid vehicle
batteries will normally be operated at intermediate states-of-charge, where the batteries’ discharge and charge/regen capabilities are typically somewhat balanced.

Hybrid vehicle operation is expected to subject batteries over their life to a very large number of shallow discharge/charge cycles as acceleration energy is removed and braking energy is returned to the battery. The PNGV goals account for this behavior and allow for the fact that the cycle life of a battery is a strong function of the fractional energy removed in each ‘cycle’. Because the PNGV Program is fundamentally aimed at developing vehicles with very high fuel economy, this cycling behavior also means that high round-trip efficiency is necessary to minimize the losses from continually shuttling energy in and out of the battery.

**Approach to PNGV Battery Testing**

The evolution of testing procedures for PNGV hybrid vehicle battery testing has been done by constructing test profiles which are tied to the PNGV power requirements, and then integrating these test profiles into sequences which can be used to determine whether a battery is capable of meeting the PNGV power, capacity and life goals. During the early stages of this process, attempts were made to use existing EV battery test profiles, such as the USABC Dynamic Stress Test, by suitably scaling or offsetting the profile power levels. This approach was judged unsatisfactory because the results did not lend themselves to easy comparison to the program goals or to modeling the performance of the batteries.

A fundamental distinction was also made by the PNGV energy storage team between the various stages of battery development. The goal of testing batteries during their development phase is commonly to determine what their performance and life potential is, so that judgments can be made about the desirability of continuing the development of particular technologies or designs. As these battery designs mature, testing emphasis then shifts toward measuring their approach to meeting the program goals. This means, for example, that developmental batteries are characterized in terms of ‘unit cell’ behavior for comparison with other technologies and for modeling purposes; while full-size batteries are properly tested against the actual PNGV performance requirements. The same test profiles are used in either case; this distinction primarily affects how the profiles are scaled in power and how tests are terminated.

A useful approach to hybrid battery testing must trade off the desire for a small number of understandable test procedures against the multiplicity of potential hybrid vehicle operating modes. The PNGV approach is to use a single, simple dynamic test profile for all aspects of power and life testing, and to modify either the fine details of this profile or its concatenation into a complete test sequence to evaluate performance against the various goals. It should be noted that this approach greatly downplays the importance of capacity testing; the baseline PNGV capacity test is a simple constant current discharge at a one-hour rate.

**Test Profiles**
The fundamental test profile selected for PNGV battery testing derives directly from the Slow Response Engine pulse power goals in Table 1. It consists of (a) an 18s discharge pulse at 65 kW, (b) a regenerative charge pulse beginning at 70 kW and decreasing over 10s, and (c) a 32s rest period separating the discharge and charge segments, which brings the total profile length to 60s. This profile is illustrated in Figure 1 and is used, either exactly as shown or suitably scaled, for characterizing pulse power capability.

For batteries intended for Fast Response Engine designs, this identical test profile is used for pulse power characterization, except that it is scaled to the corresponding power levels of 25 kW discharge and 30 kW regen. It should be noted that the linear decrease in regeneration power implied by the PNGV requirements is approximated as a series of steps in this profile. This is done for programming simplicity, as many battery testers are unable to perform linearly-varying power steps.

For life cycle testing, two additional constraints are imposed on the test profile: (1) each of the PNGV life cycle goals is predicated on the transfer of a given increment of energy from/to the battery, and (2) life cycle behavior is of interest primarily at intermediate states-of-charge. For example, the Slow Response Engine goal of 120,000 cycles is based on removing and returning 100 Wh of energy to a full size battery. This is only about 3.3% of the minimum capacity required for such a battery. The other life cycle goals in Table 1 are based on the removal and return of energy increments between 8 and 33% of the corresponding minimum capacities. The likely operating strategies for such hybrid vehicles will maintain the batteries in the middle of their useable capacity range, so that they are capable both of delivering high acceleration power and accepting high regeneration power when required. A useful life cycle test profile must remove and return about the same fixed amount of energy and thus be approximately state-of-charge neutral to permit continuous cycling for such large numbers of cycles.

The basic PNGV 100 Wh life cycle test profile is very similar to the pulse power characterization profile, except that the discharge pulse is adjusted downward in both power and duration so that it only removes 100 Wh of discharge energy. The regen segment is also adjusted downward in power, and a recharge...
segment is added at the end of the profile, to return slightly more than 100 Wh of energy and to make the resulting profile charge-neutral. The 100 Wh baseline life cycle test profile is shown in Figure 2.

Life cycle test profiles for the other PNGV life goals have been derived in a similar fashion. For example, the 600 Wh test profile is constructed as a sequence of three 200 Wh “net discharge” sub-profiles followed by three 200 Wh “net charge” sub-profiles. These sub-profiles in turn are derived by sliding the basic 100 Wh profile up or down while retaining its essential shape. The resulting power profile, and the corresponding net energy removed, are shown in Figure 3.

An entire family of these similar and logically related test profiles has been constructed to allow batteries to be evaluated against all the PNGV goals for both Fast Response and Slow Response Engine designs. These test profiles along with the related test procedure definitions are incorporated in a manual which is now publicly available

**Test Procedures**

The family of test profiles described above is used to define a set of test procedures which can determine the extent to which a given battery can meet the program goals. Examples of these procedures will be described for three of the Slow Response Engine PNGV goals: pulse power capability, cycle life, and round trip energy efficiency, as applied to developmental cells.

**Pulse Power Capability**

Determining the pulse power capability of a battery during the developmental phase is the most complex testing problem encountered in the PNGV Program to date. This is largely due to the following considerations:

- Extrapolation of laboratory cell behavior to full-size battery systems is difficult, because cell designs are typically non-optimized and scaling methods are not defined.
- The fraction of cell capacity, and thus the state-of-charge range, that will be needed to satisfy the requirements cannot yet be determined at this stage.
- The correspondence between manufacturer-determined cell operating voltage limits and the PNGV system operating voltage range is not fixed. As a minimum it depends on the number of cells used in the final system design, which is influenced by factors other than voltage requirements.
- The correspondence between

![Figure 3. 600 Wh Life Cycle Test Profile](image)
PNGV system power and current levels and the values to be used for testing laboratory cells is not fixed, because of all these scaling uncertainties involving capacities and voltages.

Because of these uncertainties, the PNGV Hybrid Pulse Power Characterization (HPPC) Test has been designed to determine, as a function of depth-of-discharge, what the power capabilities of a developmental battery are when subjected to the test profile shape in Figure 1. The test is analogous to the USABC Peak Power Test in that the battery is subjected to a pulse profile one time at each of various depths-of-discharge, with energy being removed at a constant current between these pulse profile executions. Each pulse profile is preceded with a rest period (nominally 1 hour) which is long enough to allow the battery to return to its open circuit value. The resulting test sequence is illustrated by the current trace in Figure 4, where each rectangular pulse represents the removal of 10% of the battery’s ampere-hour capacity, including the preceding pulse profile execution. An example of actual voltage response data from the performance of this test on a Sony lithium ion camcorder battery cell is also shown in Figure 4.

The results of this test do not, of course, directly measure the cell’s pulse power capability. Rather this is determined from the test data through the following sequence of calculations, performed at each depth-of-discharge (DOD) where the HPPC pulse profile is executed:

- Determine the Open Circuit Voltage $OCV_1$ at the start of the pulse profile.
- Interpolate $OCV_2$ at the DOD corresponding to beginning of the regen portion of the pulse profile, based on charge removed in the discharge pulse.
- Calculate the implied cell resistance over the 18s discharge pulse using Equation 1, where $V_1$ and $I_1$ are the voltage and current at the end of the pulse.

$$18s\text{ Discharge resistance} = \frac{OCV_1 - V_1}{I_1}$$

- Calculate the implied cell resistance over the 2s regen pulse using Equation 2, where $V_2$ and $I_2$ are the voltage, and current at the end of the pulse.

**Figure 4.** HPPC Test Profile and Example Voltage Response Data
A sample plot of these open circuit voltage and resistance values, derived from the data in Figure 4, is shown as Figure 5. Note that the regen resistance rises sharply at low depths of discharge. In fact this cell was unable to accept the programmed regen current for 2 seconds at 10% DOD within the manufacturer-specified operating voltage limits.

From the OCV and resistance behavior, the maximum power capability of a cell can be calculated at each depth-of-discharge. This is done for both discharge and regen power, relative to cell minimum and maximum voltages which are constrained to be within the PNGV operating voltage ratio of 300 to 400VDC. Note that the HPPC test is performed based on manufacturer-specified voltage limits, but the results are reported relative to this (possibly narrower) set of program voltage constraints. The resulting values for this particular set of test data are shown in Figure 6.

\[
2s \text{ Regen Resistance} = \frac{OCV_2 - V_2}{-I_s}
\]
This “Pulse Power Capability” plot characterizes the dynamic power behavior of a cell or battery, such that the usable depth-of-discharge range can be determined for the PNGV pulse power profile executed at any desired power level. Where a full size battery is to be tested, this procedure is applied by simply performing the test profile at the actual target power levels; no scaling of the test profile is required.

**Cycle Life**

![Sample Pulse Power Capability from HPPC Test Results](image)

**Figure 6.** Sample Pulse Power Capability from HPPC Test Results

The PNGV cycle life test procedure performs one of the defined life cycle test profiles, such as those shown in Figures 2 or 3, continuously for several thousand repetitions. In order for this to be done automatically, provision must be made to keep the test profile charge neutral as the cell or battery characteristics change gradually due to temperature variations, aging or other causes. The battery must also be maintained at the desired depth-of-discharge under these conditions. The means adopted to do this is to vary the length of the profile discharge step slightly, based on an artificial minimum discharge voltage constraint which can barely be satisfied at the target discharge time. For example, the 100 Wh life cycle profile has a 9s discharge step. This step is artificially extended in the test program to 10s, and is then terminated (or current is limited) between 9s and 10s when the voltage constraint is reached.

The practical effect of this is that the test profile is charge-neutral, and the battery state-of-charge is automatically maintained over thousands of test profiles. If the battery under test is adequately cooled, equilibrium conditions are typically reached after 15 minutes of cycling or less. Figure 7 demonstrates the quickly stabilized voltage and current behavior for the first 30 life cycle test profiles (30 minutes) of the same Sony lithium ion cell used to
illustrate HPPC behavior.

**Round Trip Energy Efficiency**

The system PNGV goals for round-trip energy efficiency are officially specified in terms of performance on a Federal Urban Driving Schedule (FUDS) or similar test. However, a much simpler testing approach has been devised for evaluation of developmental batteries. Because PNGV life cycling as in Figure 7 is done under charge-neutral conditions, round trip energy efficiency can be measured directly from the resulting data. When stable cycling conditions exist, this efficiency is simply the ratio of the energy removed in the discharge portion of the test profile to the energy returned in the regen portion. Thus a special efficiency test is not needed to determine this value.

**Summary**

An integrated set of test profiles and test procedures for hybrid vehicle batteries has been developed for the PNGV energy storage development program. Specific test profiles are defined from the PNGV energy storage performance goals, derived in turn from vehicle performance requirements. The test procedures themselves are believed to be adaptable to a broad range of hybrid energy storage evaluations. In particular, the approaches devised for pulse power capability and cycle life determination are considered appropriate for characterizing the dynamic behavior of energy storage devices for most hybrid vehicles, provided that suitable test profiles can be inferred from the vehicle requirements.

**References**


