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USABC and PNGV test procedures

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1. Introduction

A number of unique test procedures have been devised to consistently evaluate the performance and abuse tolerance of advanced batteries for electric and hybrid vehicles. These procedures were developed by a team of engineers and scientists at the U.S. Department of Energy's national laboratories and the three U.S. car companies: GM, Ford and Daimler Chrysler. The procedures are the results of many years of experience in testing rechargeable batteries for propulsion applications.

The procedures have been used extensively to evaluate contract deliverables, which were developed under the U.S. Advanced Battery Consortium (USABC) and the Partnership for a New Generation of Vehicles (PNGV) Programs, and to benchmark foreign battery technologies. These procedures are neutral to the battery technology being tested. They can be used to evaluate any battery technology. As such, they provide an unbiased measure of the performance of different batteries based on the goals of the USABC and PNGV. The testing and post-mortem results obtained during the evaluation process provide invaluable insights to guide the battery developers to improve their designs and to provide basic data for battery modeling which, in turn, can then be used to predict the performance of vehicles with a given battery technology.

These procedures are described in detail in the following published documents:

–USABC Electric Vehicles Battery Test Procedures, Revision 2 [1]
–PNGV Test Manual, Revision 2 [2]
–USABC Electrochemical Energy Storage Abuse Test Procedures [3]

They have been recognized internationally as the standard in the industry, and many of them have been adopted by the Society of Automotive Engineers as Recommended Practice.

2. USABC electric vehicles battery test procedures

The USABC Electric Vehicles Battery Test Procedures Manual defines procedures to evaluate the performance of high-energy batteries against the USABC requirements. These specific tests are used to characterize the core performance: self-discharge loss, power capability, cycle life and calendar life. The two key test procedures are the Peak Power Test and the Life Cycle Test.

The USABC definition of peak power is the maximum discharge power that a battery can produce into a load for 30 s at a given depth-of-discharge (DOD) without allowing the voltage to drop below two-thirds of its open circuit value. [1] The voltage under load is limited because of issues of efficiency and propulsion system design. Three peak powers at 80% DOD are calculated using the USABC battery test equations:

$$2/3V_{oc}:\quad V_{load} = 2/3 \times V_{oc}$$
$$\text{Current}_{load} = -1/3 \times V_{oc}/R$$
$$\text{Peak power capability} = -2/9 \times V_{oc}^2/R$$
$$V_{lim}:\quad V_{load} = \text{Discharge voltage limit}$$
$$\text{Current}_{load} = -(V_{oc} - V_{load})/R$$
$$\text{Peak power capability} = -V_{load} \times (V_{oc} - V_{load})/R$$
$$I_{max}:\quad \text{Peak power capability} = I_{max} \times (V_{oc} + R \times I_{max}),$$

where V_{load} is voltage across the load, V_{oc} is the iR-free voltage ($V_{oc} = V_{load} - iR$), R is battery resistance, the discharge voltage limit is the higher of (a) two-thirds of the

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[1] USABC Battery Test Procedures, DOE/ID-10479, Rev. 2, January 1996, pp. I-3 to I-4.

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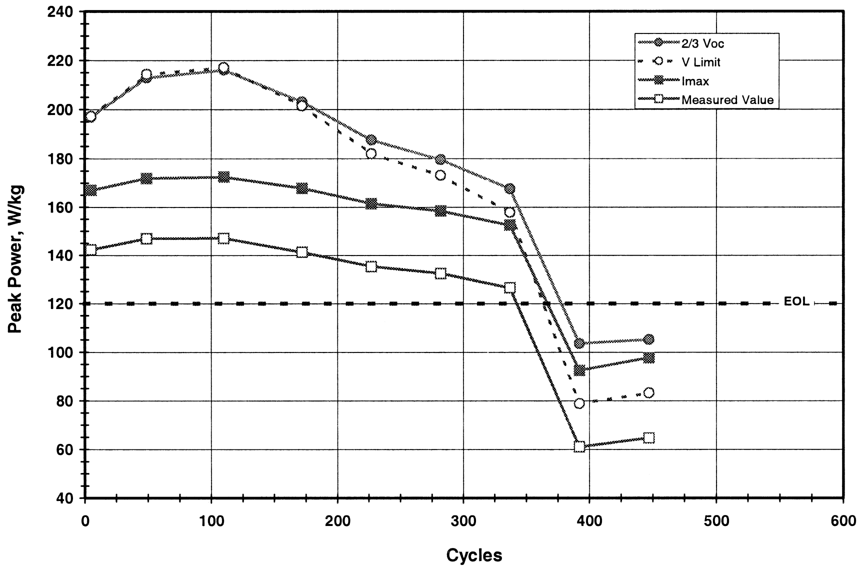

Fig. 1. Peak power test results — peak power vs. cycle number for a battery under test at 25°C.

open circuit voltage at 80% DOD at the beginning of life or (b) the manufacturer-specified minimum discharge voltage, and I_{max} is the manufacturer's maximum rated current for the battery. The peak power should not depress the voltage below the manufacturer's defined voltage limit (V_{lim}), or cause the current to surge above the manufacturer's defined maximum current (I_{max}). As a result, the lowest value calculated using the $2/3V_{oc}$, V_{lim} and I_{max} equations is reported as the peak power value. If conditions cause the current to be limited, then the measured value actually achieved under test is reported. The peak power value that is calculated at 80% DOD is critical because it serves as the basis of comparison between derived power and power goal for the given battery technology. A battery is at power end-of-life (EOL) if its peak power is less than 80% of the rated value.

The peak power test is one of the reference tests that are performed periodically to gauge how the performance of the battery changes with cycle count. Fig. 1 illustrates the peak power vs. cycle number test results and shows how the values from the methods of calculating peak power at 80% DOD differ from the measured values.

In this example, the measured values are always lower than that calculated. In addition, a decrease in available peak power is seen as the battery under test is cycled. For the bulk of the testing interval, the value from the I_{max} equation is reported since it is the lowest. At some time prior to cycle number 390, the peak power falls below 120 W/kg and the battery has reached power EOL.

The Life Cycle Test is used to determine the electrical performance of a battery under charge and discharge cycling. There are many different types of life cycle profiles, depending on the application. For electric vehicle applications, the Federal Urban Driving Schedule (FUDS) is a commonly used simulation available to represent the power demands of an actual vehicle. A simplified version of the FUDS (SFUDS) profile was developed by the DOE Battery Test Task Force in 1988 for specific vehicles. In turn, the USABC modified and generalized the SFUDS profile. The new variable-power profile is called the Dynamic Stress Test (DST). The profile is scaled to a percentage of the USABC power goal (normally 80%) and requires higher relative regeneration levels than the SFUDS profile. The DST profile effectively simulates dynamic charging and discharging by means of many 360-s-long test profiles. End-of-discharge is defined when the net capacity removed (in ampere-hours) is 80% of the rated capacity. A given discharge is terminated if the power value for any step of the test profile cannot be performed within the battery's specified limits. Fig. 2 illustrates the DST life cycle profile (negative values represent discharge conditions).

During the course of life cycle testing, reference tests are performed periodically to assess capacity changes in the battery. Typically, the capacity reference tests consist

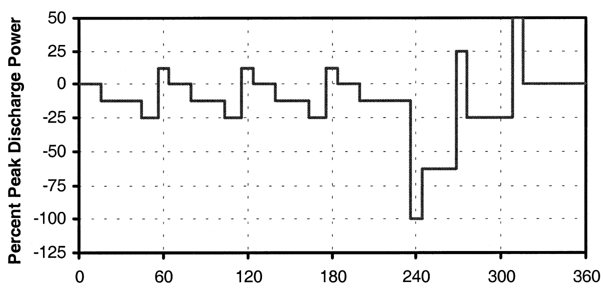

Fig. 2. DST life cycle profile.

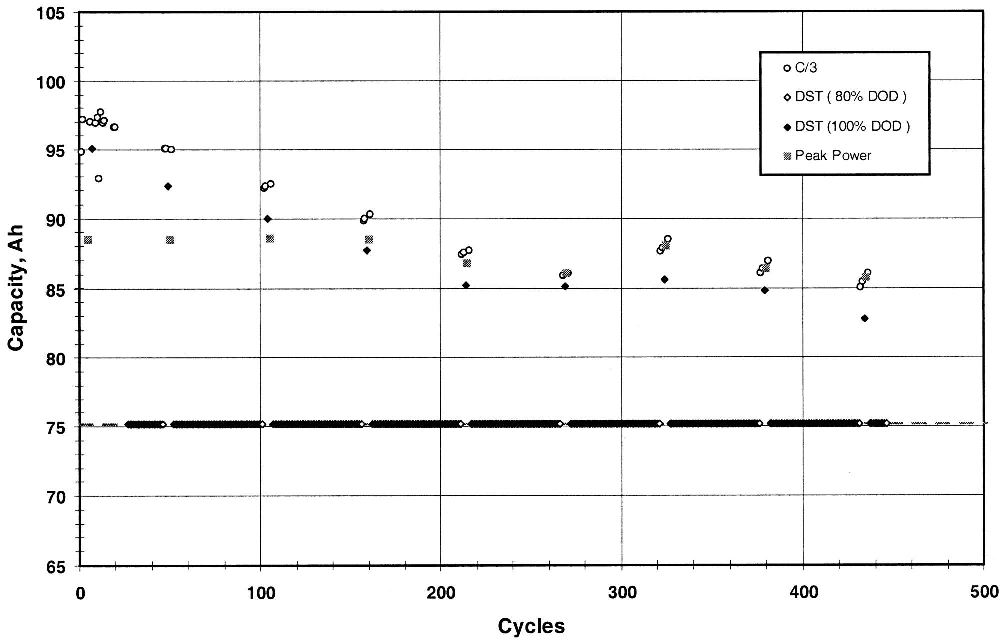

Fig. 3. Results from 80% DOD DST life cycling. The 100% DST, C/3 and peak power capacities are results from the reference tests.

of the 3-h constant current (C/3) discharge capacity, measured capacity during the peak power test, and the 100% DOD DST capacity. These capacity measurements are performed in addition to the power capability characterization (see above). Ideally, there should be no change in any of these values during testing.

The results from an actual life cycle test are given in Fig. 3. The figure shows the measured 80% DOD DST capacities and the capacities measured during the various reference tests. The figure shows that there is a decline in the 100% DST and C/3 capacities, but no decline in the peak power capacity.

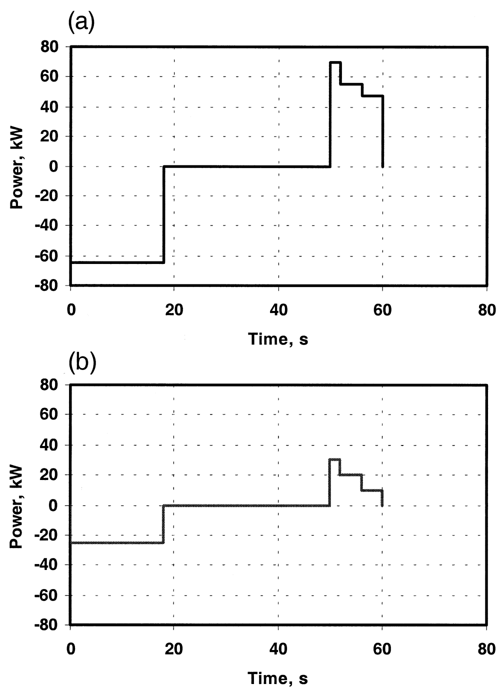

Fig. 4. HPPC pulse profiles for (a) slow- and (b) fast-response engines.

3. PNGV high power battery test procedures

The PNGV Test Manual defines procedures to evaluate the performance of high-power batteries against the PNGV requirements. In some cases, two sets of test profiles are defined to address two different sets of requirements: one for the fast response engine (dual mode of operation) and one for the slow response engine (range extender mode). Specific tests include: Static Capacity, Hybrid Pulse Power Characterization, Self Discharge, Life Cycling, Thermal Performance, Energy Efficiency and Calendar Life.

A key procedure in this manual is the Hybrid Pulse Power Characterization Test (HPPC). The primary objec-

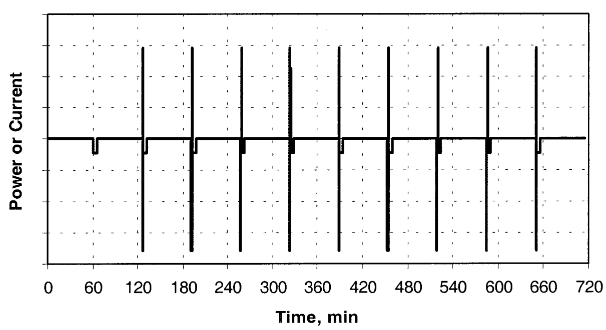

Fig. 5. Complete HPPC test profile (slow response engine).

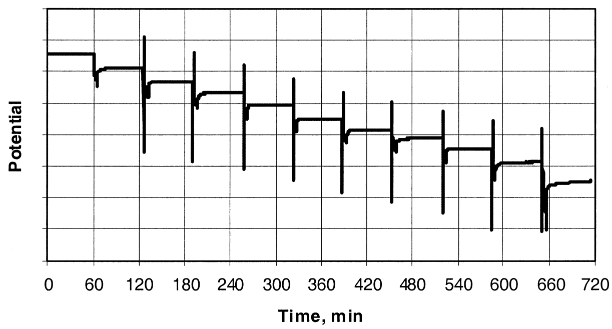

Fig. 6. Battery potential vs. time trace for a typical complete HPPC test.

tive of this test is to determine a battery's dynamic power capability over its useable state-of-charge (SOC) range. This is accomplished by establishing, as a function of SOC, (1) the V_{MIN} battery discharge power capability at the end of an 18-s discharge current pulse and (2) the V_{MAX} battery regen power capability over the first 2 s of a trapezoidal regen current pulse. V_{MIN} and V_{MAX} refer to the battery minimum and maximum voltages that correspond to the PNGV operating voltage ratio of V_{MIN}:V_{MAX} equal to 3:4.

The HPPC test, whether for the fast or slow response engine models, incorporates a sequence of constant-current discharge steps (10% of rated capacity or greater) and pulse-power characterization profiles. Here, the difference between the two engine models is the amount of power needed and the amount of battery capacity withdrawn per step. These pulse power profiles for the two engine models are given in Fig. 4. The complete pulse power profile for a typical HPPC test (slow response engine model) is given in Fig. 5.

In Fig. 5, discharge is indicated as negative or in the downward direction. Each discharge step (combined with its associated pulse profile) removes 10% of the C/1 capacity and is followed by a 1-h rest period for cell thermal and chemical equilibration. The HPPC pulse profile (shown as spikes in the figure) immediately precedes the C/1 discharge. The corresponding battery potential vs. time trace is given in Fig. 6.

Important battery characteristics, such as changes in battery impedance and the available power vs. percent state-of-charge (%SOC), are calculated. These are illustrated in Figs. 7 and 8, respectively.

Fig. 7 shows that the impedance of the battery varies with the duration and type of the pulse and with %SOC. The difference in impedance values with pulse width and type indicates the influence of diffusion-related phenomena in the electrolyte and within the electrodes. The change in impedance with %SOC is due to changes in the electrode materials as the battery is discharged.

The pulse-power performance over a certain range of SOC for battery and application is very important for PNGV goals. Usually the SOC range of interest is approximately between 30% and 70%. The performance of an example battery is given in Fig. 8 and shows that the discharge and regeneration power varies with SOC.

4. USABC electrochemical energy storage abuse test procedures

A comprehensive series of tests has been developed to characterize the abuse tolerance of advanced batteries developed under the USABC and PNGV Programs. Understanding the abuse tolerance characteristics of these batteries is vital to the successful integration of such batteries into electric vehicles. The results provide vehicle manufac-

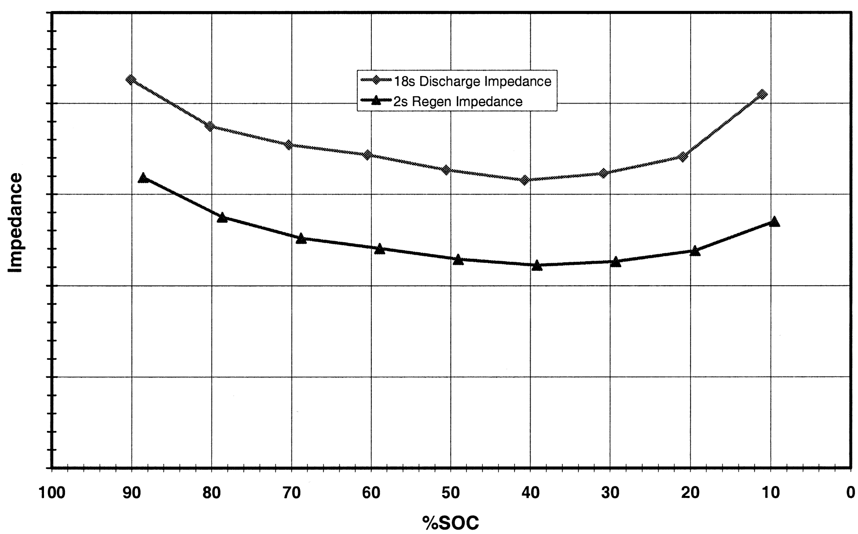

Fig. 7. Battery impedance vs. %SOC calculated from HPPC results.

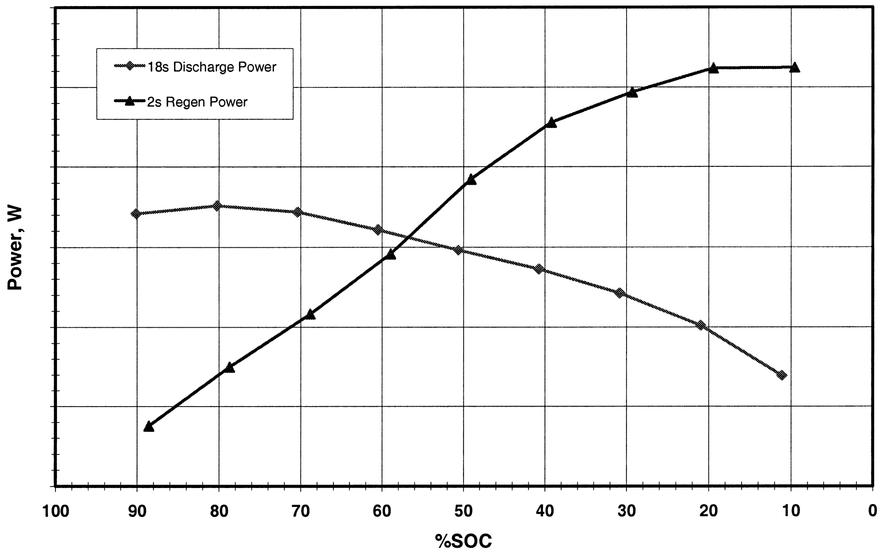

Fig. 8. Power vs. %SOC calculated from HPPC results.

turers with the necessary tools to make sound engineering decisions. These include the suitability of a particular battery technology for use in a specific application; the need for protective packaging, either mechanical or thermal; and the controls required for a reliable energy storage system integration. Listed below are the four principal test categories and their specific procedures.

4.1. Mechanical abuse tests

Mechanical abuse tests include mechanical shock, drop, penetration, rollover, immersion, and crush tests. The outcome of these tests may dictate the type of packaging and preferred orientation of the cells or modules in an electric vehicle.

4.2. Thermal abuse tests

Thermal abuse tests include radiant heat, thermal stability, compromise of thermal insulation, overheat, thermal shock cycling, elevated temperature storage, and extreme cold temperature test. These tests are designed to determine how a battery technology responds to a wide range of temperature variations and other thermal conditions that may occur in electric vehicle applications. They may determine the need for thermal controls or other special design features.

4.3. Electrical abuse tests

Electrical abuse tests include short circuit, partial short circuit, overcharge, overdischarge, and AC current exposure tests. Overcharge is one of the more important abuse tests in the recommended test sequence since failure in any of a number of systems can result in excessive overcharge.

4.4. Vibration tests

Vibration tests include cyclical tests of varying magnitudes, which simulate the exposure that components experience in automotive applications. These tests characterize the effect of long term, road induced, vibration and shock on the performance and service life of battery technologies.

References

[1] USABC Electric Vehicle Battery Test Procedures Manual, Revision 2
[2] PNGV Battery Test Manual, Revision 2
[3] USABC Electrochemical Storage System Abuse Test Procedure Manual, Revision 1