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Journal of Power Sources 158 (2006) 760–764
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Performance and cycle life test results of a PEVE first-generation prismatic nickel/metal-hydride battery pack

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Received 28 July 2005; received in revised form 17 August 2005; accepted 31 August 2005
Available online 18 November 2005

Abstract

A first-generation, prismatic, nickel/metal-hydride battery pack from Panasonic EV Energy Company Ltd. (PEVE) was characterized following the standard PNGV test procedures and then cycle life tested at 25 °C. The pack met, or exceeded, PNGV power and energy goals at the beginning of life. After more than 500,000 cycles, the data for capacity and discharge pulse power capability showed no measurable fade; similarly, discharge pulse resistance at 60% DOD also showed no measurable change. After the same pack was tested with two size factors, it still met or exceeded the PNGV goals.

Keywords: Battery; Nickel/metal-hydride; Cycle life

1. Introduction

An important part of the U.S. Department of Energy's (DOE's) battery testing program is the benchmarking of foreign battery technologies. As a part of this program, Argonne National Laboratory (ANL) acquired and tested a first-generation, prismatic, nickel/metal-hydride battery pack from PEVE. The pack was designed for hybrid electric vehicle applications, but it was not designed with the goals of the Partnership for a New Generation of Vehicles (PNGV[1]) in mind. Some of the pack's performance characteristics have been reported elsewhere; the prismatic design was reported to have twice the power of the cylindrical design [1].

The pack acquired by ANL was evaluated using the goals stated in Revision 3 of the *PNGV Battery Test Procedures Manual* [2]. The PNGV end-of-life goals require that a full-scale battery technology have, in part, a 25 kW pulse discharge power for an 18 s discharge, a 30 kW pulse regenerative power for a 2 s regenerative pulse, a total available energy of 300 Wh over the state-of-charge range where the power goals are met, and a cycle life of 300,000 power assist cycles [2]. In our work, we used two battery size factors, 2 and 3 (2 being the more severe case). We found that the pack met or exceeded the PNGV cycle life goals regardless of which scaling factor was used.

2. Experimental procedure

The single pack that was available for testing consisted of 20 series-connected modules; each module contained six cells, also in series. Adjacent modules were separated by air gaps for cooling. Blowers and an air manifold were provided by ANL to meet cooling conditions, a minimum 80 m^3/h airflow at the air outlet (at the top of the modules) during charge and discharge.

The pack was designed for hybrid electric vehicle (HEV) propulsion applications. The rated performance and operating limits of the pack, as provided by PEVE, are given in Table 1. Fig. 1 shows a photograph of the pack.

The pack was tested according to standard PNGV characterization and cycle life test protocols. First, characterization tests were conducted on the pack at ∼25 °C; the pack was then cycle life tested at ∼25 °C. Since the test was not conducted in an environmental chamber, some temperature fluctuations are expected.

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[1] Initiated in 1993, PNGV became the FreedomCAR Partnership in 2002.

0378-7753/$ – see front matter
doi:10.1016/j.jpowsour.2005.08.053

Table 1
Pack ratings

Test pack nominal voltage (V)	144.0
Test pack nominal capacity (Ah)	6.5
Energy density (Wh kg)	37.2
Power density (W kg)	729
Test pack operating temperature (°C)	−30–+50
Test pack weight (kg)	25.2
Test pack internal resistance (mΩ)	289.5

Based on the data, the temperature varied between about 20 and 26 °C.

The PNGV characterization tests are conducted to verify rated performance and to provide a baseline for comparison with life-cycle test results. Also, a battery size factor (BSF) is calculated from the characterization results. The BSF is used to scale the test results for comparison with PNGV full-scale goals and to scale the life-cycle profile to power levels appropriate for a given test article. The following three tests were performed on the PEVE prismatic pack at ∼25 °C for characterization [2]:

1. Static capacity test;
2. Hybrid pulse power characterization (HPPC) test at the 5 C current rate;
3. Self-discharge test.

The HPPC test measured the impedance and power capability of the pack. The raw data were reduced to produce discharge and recharge (“regen”) impedance and power calculations for each iteration of the test profile according to the following equations:

$$\text{discharge resistance} = \frac{\Delta V}{\Delta I} = \frac{(V_{t0} - V_{t1})}{(I_{t0} - I_{t1})}$$

$$\text{regen resistance} = \frac{(V_{t3} - V_{t4})}{(I_{t3} - I_{t4})}$$

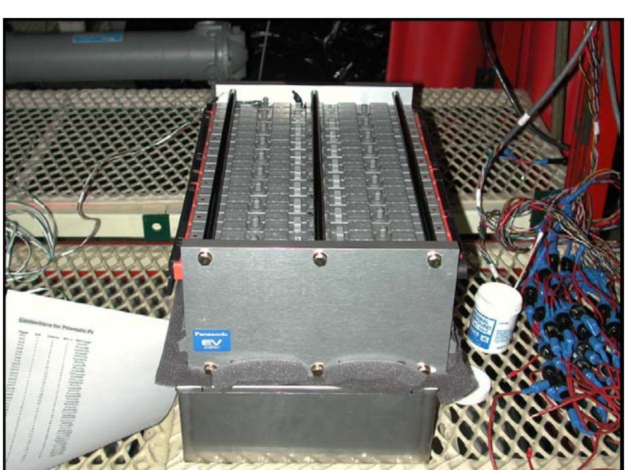

Fig. 1. PEVE prismatic pack.

$$P_{\text{discharge}} = 108\frac{\text{OCV} - 108}{R_{\text{discharge}}}$$

$$P_{\text{regen}} = 178.5\frac{(178.5 - \text{OCV}_{\text{regen}})}{R_{\text{regen}}}$$

where $t_0 = 0$ s, $t_1 = 18$ s, $t_3 = 50$ s, and $t_4 = 52$ s and where the voltage and current values associated with t_0 and t_3 are taken immediately prior to the start of the pulse.

Other plots were produced from the HPPC data. These include a plot of available energy versus power. A discussion of how to generate this plot is beyond the scope of this report. Further information on these plots and other manipulations of the HPPC data is given in Appendix E of Ref. [3]. Our standard measure of pack degradation was the percent fade in the power at 300 Wh.

After successfully completing the characterization portion of the test plan, cycle life testing was conducted to assess the effects of cycle count on pack performance. A BSF of 3 was calculated from the HPPC test results. This BSF was initially used for life-cycle testing; however, after 284,649 cycles, the BSF was lowered to 2 in order to more accurately represent how the pack is used in vehicles. The life-cycle profile used was the charge-neutral, 25 Wh PNGV power assist life-cycle profile, scaled by the BSF. This profile was performed at 60% state of charge (SOC, where SOC = 100 − %DOD).

After each block of 20,000 life cycles, a reference performance test (RPT) was conducted. The RPT consisted of a C/1 rate discharge capacity test and a HPPC (at the 5 C current rate) test. End-of-life (EOL) conditions for life testing were defined based on RPT results. The pack reached EOL when it could not perform the HPPC test profile at the 40% SOC step within the defined voltage limits, or when the total available energy over the SOC range where the power goals were met fell below 300 Wh.

These tests started in May 2001; testing was completed in January 2003.

3. Results and discussion

The scaled, cycle life profiles used by PNGV as their standards are approximately charge-neutral [2]. The intent is to keep the battery SOC approximately constant during the cycling regime. The prismatic pack was cycled about 60% SOC using the 25 Wh profile. Here, only a small fraction of the total battery capacity was removed during discharge, 5.7×10^{-3} Ah (BSF = 3) and 8.7×10^{-3} Ah (BSF = 2). Thus, the battery cycled between about 59 and 61% SOC with BSF = 3 and about 58 and 62% SOC with BSF = 2.

The 25 Wh profile is a constant power profile and is named by the amount of energy that the 9 s discharge pulse removes. Detailed information about the profile is given in Ref. [2]. For the battery pack, 60% SOC is approximately 156.8 V. During the discharge pulse, the minimum battery voltage was 153.8 V (BSF = 3) and 148 V (BSF = 2). Using these conditions, the discharge pulse actually removed 8.8 and 12.9 Wh, respectively, for BSF = 3 and 2.

Table 2
Life-cycle test results

Measurement/test description	Units	PNGV goal	BSF = 3		BSF = 2	
			Initial value	Final value	Initial value	Final value
Pulse discharge power[a]	kW	25 (18 s)	36.3	40.8	26.8	27.4
Total available energy[a] (over SOC range where power goals are met)	Wh	300	2350	2751	749	757
Round-trip efficiency	%	90	94.2	94.5	91.6	91.7
Cycle life	Cycles	300,000	–	284,648	284,648	517,211[b] (232,563)
Self-discharge rate	Wh day^{-1}	<50	6.25	–	–	–

[a] Scaled by BSF.
[b] Total cycles; number in parentheses is net cycles with BSF = 2.

As stated above, only one pack was characterized. The pack was characterized in terms of C/1 capacity, using HPPC and stand tests. The results of these characterization tests are summarized in Table 2, along with the relevant PNGV goals. As the table shows, the test pack initially exceeded the PNGV goals at the beginning of life. The results of the life-cycle test are also given in Table 2; the table shows that, after 517,211 life cycles (of those cycles, the last 232,563 used a BSF of 2), the pack still exceeded PNGV round-trip efficiency, power, and energy goals.

During the life-cycle experiment, RPTs were conducted on a periodic basis. From the RPT data gathered during the experiment, we gauged the effect of cycling on important performance parameters, such as capacity, resistance, and power.

3.1. Capacity

Initially, the capacity of the pack was 6.41 Ah. Fig. 2 shows the effect of cycling on pack capacity for both BSF values. The data in Fig. 2 show that, in general, the capacity of the pack declines with cycle count, as expected. Normalizing the total capacity decline to cycle count in each section shows that the decline is approximately 5.6×10^{-6} and 4.5×10^{-6}% per cycle, respectively, for BSF = 3 and 2. Within the error of the experiment, these values are the same. Thus, the value of the BSF had very little influence on capacity fade rate. The total capacity fade after the entire experiment was on the order of 2.5%.

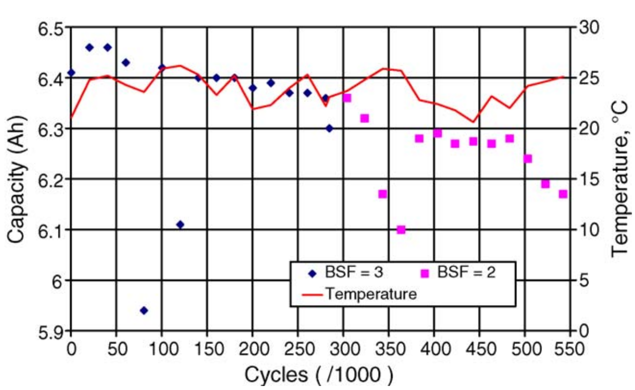

Fig. 2. Pack capacity vs. cycle count. The capacity values that are abnormally low are from extended stand times (3 days) between tests. Here, self-discharge consumed capacity and produced these low C/1 values. Temperature fluctuations added scatter to our measurements.

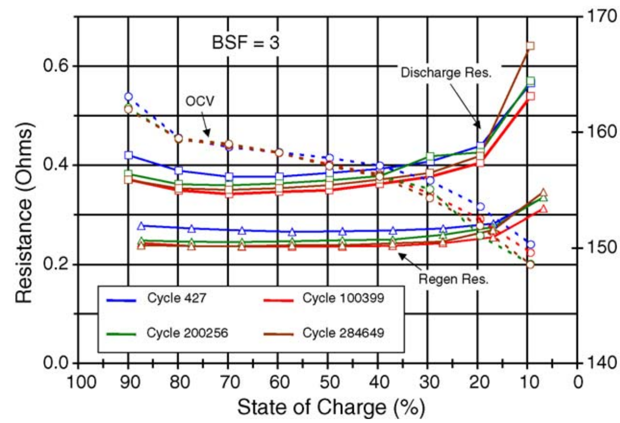

Fig. 3. Resistance and OCV as Functions of SOC and cycle count, BSF = 3.

3.2. Resistance

Figs. 3 and 4 show the pack resistance as functions of %SOC and of time for BSF = 3 and 2, respectively. Initially, resistance decreased with cycling, then remained fairly constant throughout the experiment at 0.35 Ω. This resistance value compares favorably to that given by Ito and Ohnishi (0.30 Ω) for a pack constructed of 20 conventional prismatic modules [3].

Fig. 5 shows that the resistance did not increase during the experiment; it tended to fluctuate about an average value. The figure also shows a plot of the ambient temperature when the HPPC test was run; from the figure, the ambient temperature between RPTs varied around 23 °C by approximately ±3 °C. By

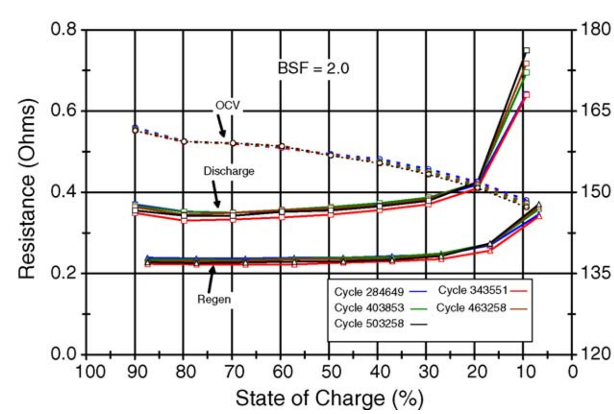

Fig. 4. Resistance and OCV as functions of SOC and cycle count, BSF = 2.

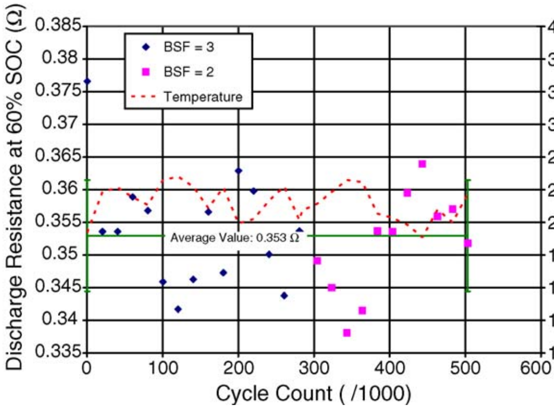

Fig. 5. Discharge resistance at 60% SOC and ambient temperature vs. cycle count.

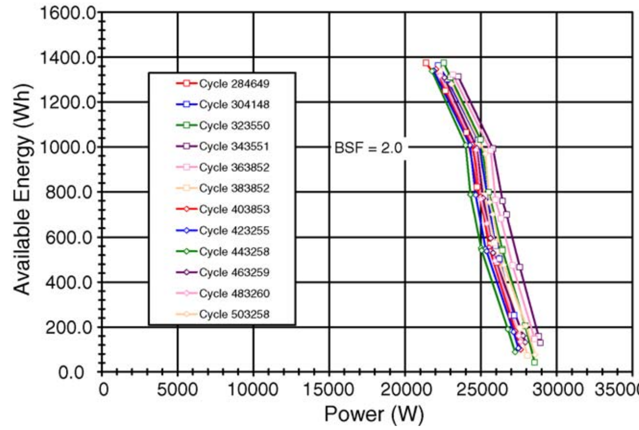

Fig. 7. BSF-scaled available energy vs. BSF-scaled power, BSF = 2.

comparing the fluctuations in pack resistance with those of the ambient temperature, it can be seen that the scatter was primarily due to the temperature fluctuations. As expected, the resistance of the pack is sensitive to temperature.

In their paper, Yamaguchi et al. [1] show that the resistance of the pack rises very slowly from approximately 0.50 to 0.55 Ω over the course of 240,000 km. In our hands, the resistance of the pack started at a lower value, 0.35 Ω, and did not increase during testing. Based on the PNGV goals of driving 160,000 km (100,000 miles) over the course of 15 years and 300,000 cycles (0.53 km cycle^{-1}), the pack "drove" the equivalent of 275,846 km when the most recent RPT was performed. Our results indicate that, over a similar driving distance of that shown by Yamaguchi et al., there was no discernible increase in pack resistance. The difference in test results may be due to the different test protocols used; Yamaguchi et al. may have used harsher conditions. Unfortunately, the protocols and the test temperature used by Yamaguchi et al. were not given in Reference [1].

3.3. Power

The available energy versus pulse power was calculated from the RPT data. Plots of these data are given in Figs. 6 and 7 for BSF = 3 and 2, respectively. From these figures, it is apparent that, after cycle 427, the power at 300 Wh did not decrease. A plot of power at the 300 Wh line (cf., see Fig. 6) as a function of cycle count is given in Fig. 8, along with the variation in ambient temperature.

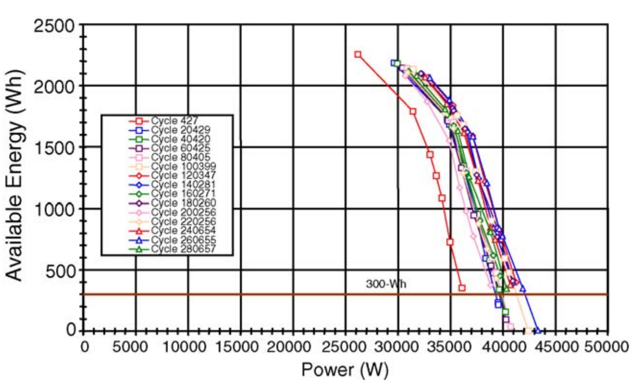

Fig. 6. BSF-scaled available energy vs. BSF-scaled power, BSF = 3.

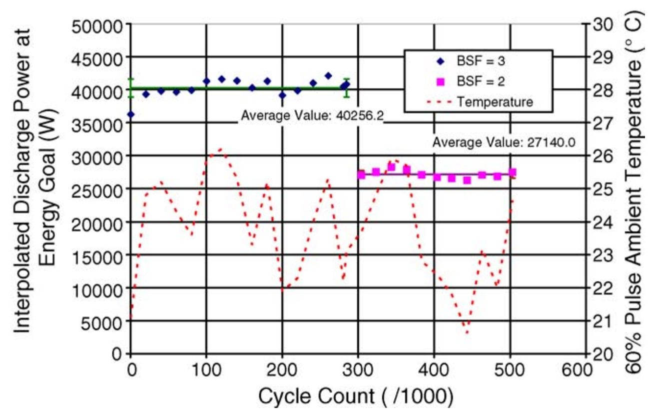

Fig. 8. Power at the 300 Wh line and temperature as functions of cycle count.

From Fig. 8, power did not decrease with cycle count. Instead, it fluctuated with ambient temperature, similar to the behavior shown in Fig. 5. Like pulse resistance, the pulse power also did not fade as cycle count increased.

These benchmarking results indicate that the pack met most of the PNGV goals. The prismatic pack represents a near-mature or mature technology. Therefore, DOE can focus its limited resources on less-mature technologies.

4. Conclusions

A first-generation, nickel/metal-hydride, prismatic battery pack from PEVE was characterized following the standard PNGV test procedures and then cycle life tested at 25 °C. The pack met, or exceeded, PNGV power and energy goals at the beginning of life. After more than 500,000 cycles, the data for discharge pulse power capability showed no measurable fade; similarly, the discharge pulse resistance at 60% DOD also showed no measurable change. After testing at two size factors, the pack still met or exceeded the PNGV goals.

Acknowledgment

This work was performed under the auspices of the US Department of Energy, Office of FreedomCAR and Vehicle Technologies, under Contract No. W-31-109-Eng-38.

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[1] T. Yamaguchi, S. Yoneda, Y. Kikuchi, Y. Shoji, Proceedings of the 17th International Electric Vehicle Symposium and Exposition, Montreal, Quebec Province, Canada, 15–18 October, 2000 (Paper No. 4B-1).
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