Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Power Sources 125 (2004) 124–134
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Studies of the energy and power of current commercial prismatic and cylindrical Li-ion cells

Kevin Sit [a], P.K.C. Li [a], C.W. Ip [a], C.W. Li [a], Levin Wan [a], Y.F. Lam [a],
P.Y. Lai [a], Jiang Fan [b,*], Doug Magnuson [b]

[a] *Sylva Industries Limited, 30 Kwai Wing Road, Kwai Chung, N.T., Hong Kong, PR China*
[b] *Gold Peak Battery Technologies, 11235 W. Bernardo Court, San Diego, CA 92127-1638, USA*

Received 30 June 2003; accepted 20 July 2003

Abstract

We studied the specific energy, energy density, specific power, and power density of current commercial 18650 cylindrical and 103450 prismatic Li-ion cells. It was found that the specific energy, energy density, specific power, and power density have been increased dramatically since 1999. The highest specific energy obtained in this study is 193 Wh/kg, which is 90% more than that reported in 1999 and is only 5% lower than 200 Wh/kg, the long-term DOE goal [The International Energy Agency Implementing Agreement for Electric Vehicle Technologies and Programs, Annex V, Outlook Document, 1996–1997, p. 16.]. The cell energy density has also doubled since 1999 and is as much as about 70% more than 300 Wh/l, the long-term DOE goal. The cells studied here can deliver over 80% of their designed energy at the specific power 200 W/kg while the 18650 cell studied previously could only deliver 10% of their designed energy at the same specific power. Various kinds of the factors in the cell-specific energy and energy density were studied. It seems that the geometric difference can cause as much as a 9% difference in the specific energy and a 12% difference in the energy density between 18650 cylindrical and 103450 prismatic cells. Use of an aluminum can seems to lead to about a 16% improvement in the specific energy of 103450 cells compared with steel can. The decrease in the cell discharge voltage can cause as much as a 9% decrease in the cell energy at the 2 C rate while it has a relatively small effect on the cell energy or specific energy at the 0.2 C rate. Compared with what has been obtained at room temperature, there are 17–35% at −20 °C, 43–76% at −30 °C, and 78–100% decreases at −40 °C, respectively, in the cell discharge energy and specific energy depending on the cell manufacturer. The decrease in the cell average discharge voltage during the cycling test can contribute as much as a 6% decrease in the cell energy at the 1 C rate after 300 cycles, which is 21% of the total energy loss.

Keywords: Li-ion cells; Energy efficiency; Capacity loss

1. Introduction

Studying commercial Li-ion cells has been an active area in recent years [1–8]. These studies have been in a very broad range from the cell cycle life to the cell impedance, including abuse tolerance, and rate capability at room and low temperatures [1–8]. These studies have led to a rich knowledge of the commercial Li-ion cell, which influences not only lithium-ion manufacturers to improve their products further but also the end users to use lithium-ion cells properly.

However, the studies on the specific energy, energy density, specific power and power density of commercial lithium-ion cells are very limited even though the battery-specific energy, energy density, specific power, and power density are among the most important characteristics for lithium-ion cell [9]. In 1999, Nagasubramanian and co-workers [10,11] did extensive studies on the cell power and energy with both commercial cylindrical and prismatic cells. The specific energy obtained by Nagasubramanian and co-workers was only around 100 Wh/kg, which is about 50% of 200 Wh/kg long-term goal set by US Department of Energy (DOE) [9]. During last 5 years, lithium-ion technologies have made a lot of progresses not only in the cell capacity (see Fig. 1) but also in other aspects, such as the rate capability at room and low temperatures [1,2], because of the market competition introduced probably by the lithium-ion cell manufacturers. Fig. 1 shows the progress of the cell capacity and specific energy since 1990. The cell capacity and specific energy have increased by over 70% in last 5 years, while the cell capacity and specific energy had

---

[*] Corresponding author. Tel.: +1-858-674-6099; fax: +1-858-674-5883.
E-mail address: jfan@gpina.com (J. Fan).

0378-7753/$ – see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/S0378-7753(03)00833-4

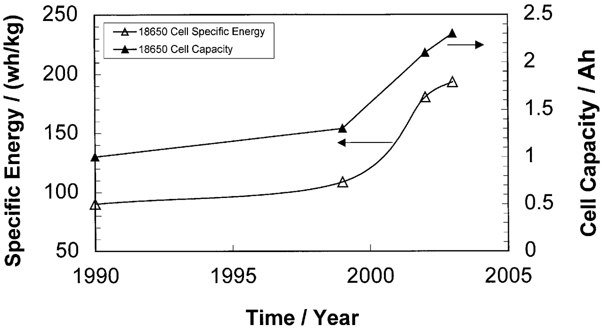

Fig. 1. Foot steps of the cell capacity and specific energy of commercial 18650 cells.

increased by less than 30% in 10 years from 1990 to 1999. Therefore, it is necessary to study again the cell-specific energy, energy density, specific power, and power density of the recent commercial lithium-ion cells.

Many new sizes and shapes of commercial lithium ion cells have been developed and manufactured in recent years because the lithium-ion cell has successfully penetrated into many markets since Sony introduced their 18650 cell in 1990. Now, there are many cylindrical lithium-ion cells like A, AA, and AAA besides the 18650 cell. The spectrum of lithium-ion prismatic cells is even broader [12]. Therefore, we must be highly selective in order to limit the scope of this work. The commercial 18650 cell is our cylindrical cell choice because it is still the most optimized cell in terms of the cell capacity due to the fierce marketing competition. The prismatic 103450 cell (10 mm thick, 34 mm wide and 50 mm high) is another natural choice because 103450 cell is becoming a serious competitor to the 18650 cell in terms of applications.

We have two objectives in this study. First of all, we will characterize the specific energy, energy density, specific power, and power density of both cylindrical and prismatic cells at room and low temperatures (i) to establish a new reference point for future lithium-ion cells, and (ii) to help the end users of lithium-ion cells to make the best choice of lithium-ion cells for their unique applications. Secondly, we will study some important factors such as the cell design, the cell geometric shape, the can materials, the cell average discharge voltage, the cell temperature, and the cycle number in the cell-specific energy and energy density. We hope that our study can lead to some more specific directions on how to increase the cell-specific energy further.

2. Experimental

All cells were obtained from the commercial market. The rated capacity is 2.0 Ah or 2.2 Ah for 18650 cylindrical cells, and 1.7 Ah or 1.8 Ah for 103450 (10 mm thick, 34 mm wide, and 50 mm high) prismatic cells according to the cell manufacturers. Typically, two or three cells from each brand were tested in every measurement except the discharge capability test for some prismatic cells in which one cell was tested because of the limitation in cell availability.

Every brand of prismatic cells was divided into two groups: one group was tested for the discharge capability at room temperature at various rates, and then at 0.2 C rate at −20, −30 and −40 °C, respectively, while another group of cells was cycled at room temperature.

For the discharge capability test of prismatic cells at room temperature, the cells were tested using the MACCOR (model 2300) battery test system in a temperature-regulated environment of 23 ± 2 °C with the following procedures: (1) charge the cells to 4.2 V for 2.5 h at 0.8 C rate, (2) rest for 5 min, (3) discharge to 2.8 V at 0.2 C rate, (4) rest for 10 min, (5) charge to 4.2 V for 2.5 h at 0.8 C rate, (6) rest for 5 min, (7) discharge to 2.8 V at 0.5 C rate, (8) rest for 10 min, (9) charge to 4.2 V for 2.5 h at 0.8 C rate, (10) rest for 5 min, (11) discharge to 2.8 V at 1 C rate, (12) rest for 10 min, (13) charge to 4.2 V for 2.5 h at 0.8 C rate, (14) rest for 5 min, (15) discharge to 2.8 V at 2 C rate, and (16) end.

For the discharge test of the prismatic cells at −20, −30 and −40 °C, the fully charged cells were discharged at the 0.2 C rate to 2.8 V using the Dragon Wise 32-pt Cycler after the cells were placed in the ESPEC Mini-Subzero Mc-711 low-temperature oven for 4 h at the target low temperatures. Prior to the discharge test at low temperatures, the cells had been charged to 4.2 V for 2.5 h at the 0.8 C rate, then discharged to 2.8 V at the 0.2 C rate, and finally charged up to 4.2 V for 2.5 h at 0.8 C in a temperature-regulated environment of 23 ± 2 °C.

For the cycling test of the prismatic cells, the cells were tested in a temperature-regulated environment of 23 ± 2 °C using Dragon Wise 32-pt Cycler with the accelerated cycle life testing procedure described in the previous report [1].

3. Results

3.1. Specific energy and energy density at 0.2 C rate and at room temperature

Table 1 lists the cell weight, volume, rated capacity, measured capacity and energy, specific energy and energy density for the cells as received (“fresh cells”). Please note that the previously reported designation [1] is followed for lithium-ion cell manufacturers. A is the Japanese manufacturer; C–E, and GP are the manufacturers outside Japan. There are three points in Table 1. Firstly, the 18650 cell manufactured by E shows the highest specific energy 193 Wh/kg and energy density 514 Wh/l among all studied cases. Secondly, GP 103450 prismatic cell has the highest specific energy 180 Wh/kg and energy density 407 Wh/l in the studied prismatic cells. Thirdly, the specific energy varies from 163 to 180 Wh/kg for the 2 Ah 18650 cells manufactured by C–E and GP even though their measured capacity is very similar (2.01–2.02 Ah).

Table 1
Cell weight, volume, 0.2 C capacity, specific energy and energy density

Maker	Cell type	Can type	W_{Cell} (g)	V_{Cell} (l)	Rated capacity (Ah)	Measured capacity (Ah)	Measured energy (Wh)	Specific energy (Wh/kg)	Energy density (Wh/l)
A	18650	Steel	44.4	0.0165	2	1.95	7.3	165	442
C	18650	Steel	45.8	0.0165	2	2.01	7.5	165	456
D	18650	Steel	42.8	0.0165	2	2.02	7.6	178	461
E	18650	Steel	44.3	0.0165	2	2.02	7.6	171	458
E	18650	Steel	44	0.0165	2.2	2.28	8.5	193	514
GP	18650	Steel	42.3	0.0165	2	2.01	7.6	180	461
A	103450	Al	39.5	0.017	1.7	1.80	6.8	172	400
C	103450	Steel	45	0.017	1.8	1.83	6.8	151	400
GP	103450	Al	38.5	0.017	1.8	1.82	6.9	180	407

3.2. Specific energy and energy density at different rates and at room and low temperatures

Table 2 lists the specific energy, energy density, specific power, and power density at different currents for fresh 18650 cells manufactured by E and GP. The 2 Ah 18650 cells from the manufacturers A, C, and D are not included (i) to simplify the study and (ii) because the specific energy or energy density of these cells did not create a different scenario in terms of the specific energy or energy density in relation to the discharge currents. It is noted that the specific energy of the 2.2 Ah 18650 E cell at ∼0.2 C rate is only about 6.7% higher than that of the 2 Ah 18650 GP cell, even though the cell capacity of 2.2 Ah 18650 E cell is about 11% higher than that of 2 Ah 18650 GP cell. Further, the specific energy of 2 Ah 18650 GP cell is very similar to that of 2.2 Ah 18650 E cell at 2 C rate. It is also noted that the cell-specific energy or energy density depends on the discharge currents more strongly than the cell capacity does. For instance, when the discharge current increases to 4 A from 0.4 A, for 2.2 Ah 18650 E cell, the specific energy is decreased by 22% (=100% × (1 − 150/193)) while the capacity is decreased by only 9.6% (100% × (1 − 2.06/2.28)). Similarly, for 2 Ah 18650 GP cell, the specific energy is decreased by 17% (=100% × (1 − 149/180)) while the cell capacity is decreased by 5% (100% × (1 − 1.92/2.02)) when the discharge current increased to 4 A from 0.4 A.

Table 3 lists the specific energy, energy density, specific power, power density at different currents for fresh 103450 prismatic cells manufactured by A, C and GP. Three things are noticed. First of all, the specific energy of the 103450 prismatic C cell is lowest even though the cell capacity is not lowest, which is due to its steel can discussed later. Secondly, the rate capability of the prismatic C cell is worst in view of its lowest ratio 0.9 of 2 C capacity versus 0.2 C capacity among the studied prismatic cells. Thirdly, like the 18650 cells, the cell-specific energy or energy density depends on the discharge current more strongly than the cell capacity. For instance, for the prismatic C cell, the specific energy is decreased by 22% (=100% × (1 − 117/151)) while the capacity is decreased only by 10% (=100% × (1 − 1.636/1.817)) when the discharge current increases from 0.36 A (0.2 C) to 3.6 A (2 C). For prismatic A cell, the specific energy is decreased by 14% (100% × (1 − 149/172)) while the cell capacity is decreased by 5.4% (=100% × (1 − 1.692/1.788)). For prismatic GP cell, the specific energy is decreased by 8.3% (=1 − 165/180) while the cell capacity is decreased by 1% (100% × (1 − 1.804/1.82)) when the discharge current increases from 0.36 A (0.2 C) to 3.6 A (2 C).

Fig. 2 shows (a) the specific energy in relation to the specific power and (b) the energy density in relation to the energy density for both fresh 103450 prismatic and 18650 cylindrical cells. For a comparison, it is also shown in the literature data reported in 1999 with 1.3 Ah 18650 Sanyo cell and 0.55 Ah Sanyo prismatic cell [10].

Table 4 lists the cell capacity, energy, and specific energy at 0.2 C rate and low temperatures. There are three points in Table 4. First of all, the specific energy of 103450 GP cell

Table 2
Specific energy, energy density, specific power, and power density of 18650 cylindrical cells from the manufacturers B and GP

Maker	Current (A) (C rate)	Cell capacity (Ah)	Specific power (W/kg)	Specific energy (Wh/kg)	Power density (W/l)	Energy density (Wh/l)
E (2.2 Ah)	0.4 (0.18)	2.28	34	193	91	515
	1 (0.46)	2.23	83	185	221	493
	2 (0.91)	2.20	160	175	425	468
	4 (1.82)	2.06	292	150	779	401
GP (2 Ah)	0.4 (0.2)	2.02	36	180	91	461
	1 (0.5)	1.995	87	174	224	446
	2 (1)	1.97	168	166	430	425
	4 (2)	1.92	311	149	800	382

Table 3
Specific energy, energy density, specific power, and power density of 103450 prismatic cells from the manufacturers A, C, and GP

Maker	Current (A) (C rate)	Cell capacity (Ah)	Specific power (W/kg)	Specific energy (Wh/kg)	Power density (W/l)	Energy density (Wh/l)
A (1.7 Ah)	0.36 (0.2)	1.788	35	172	81	400
	0.9 (0.5)	1.777	85	168	198	390
	1.8 (1)	1.762	165	162	382	376
	3.6 (2)	1.692	318	149	740	345
C (1.8 Ah)	0.36 (0.2)	1.817	30	151	79	400
	0.9 (0.5)	1.79	72	144	192	382
	1.8 (1)	1.757	139	136	369	361
	3.6 (2)	1.636	255	117	674	309
GP (1.8 Ah)	0.36 (0.2)	1.82	36	180	81	407
	0.9 (0.5)	1.814	88	177	198	400
	1.8 (1)	1.812	171	173	387	391
	3.6 (2)	1.804	327	165	741	373

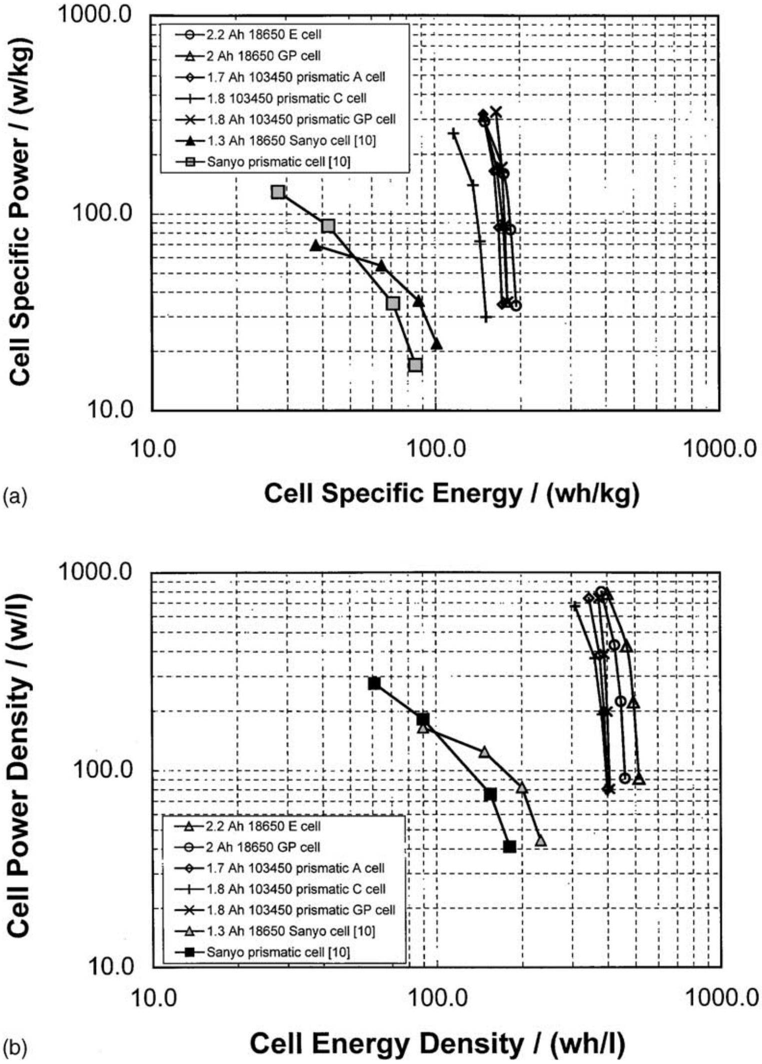

Fig. 2. Ragone plots of (a) specific energy vs. specific power, and (b) energy density vs. power density for the cells manufactured by A, C, E and GP. For a comparison, the specific energy, energy density, specific power, and power density reported in 1999 [10] of Sanyo cells are also included. The 18650 Sanyo cell was chosen because it had the highest capacity among the cells studied in 1999 [10].

Table 4
Cell capacities, energy, and specific energy at 0.2 C rate and at low temperatures

Maker	Cell type	−20 °C			−30 °C			−40 °C		
		Capacity (Ah)	Energy (Wh)	Specific energy (Wh/kg)	Capacity (Ah)	Energy (Wh)	Specific energy (Wh/kg)	Capacity (Ah)	Energy (Wh)	Specific energy (Wh/kg)
E (2.2 Ah)	18650	1.77	5.47	124	0.77	2.26	51	0	0	0
GP (2 Ah)	18650	1.76	5.81	137	1.41	4.41	104	0.63	1.85	44
A	103450	1.6	5.42	137	0.81	2.49	63	0	0	0
C	103450	1.4	4.4	98	0.55	1.61	36	0	0	0
GP	103450	1.6	5.65	147	1.2	3.93	102	0.49	1.48	38

is 147 Wh/kg at −20 °C, which is the highest in the studied cases. Secondly, both 18650 GP and 103450 GP prismatic cells can deliver as much as 44 Wh/kg at 0.2 C rate and −40 °C while other studied brand cells cannot deliver any significant energy. Thirdly, the energy of 2.2 Ah 18650 E at 0.2 C and −20 °C is 6% (100 × (1 − 5.47/5.81)) less than that obtained with 2 Ah 18650 GP cell even though there is no substantial difference in the cell capacity, which indicates that the cell energy depends on the temperature more strongly than the cell capacity.

3.3. Cell discharge voltage profiles at different rates and temperatures

Fig. 3 shows the typical discharge voltage profiles at different rates for the fresh 2.2 Ah 18650 E cell. The discharge voltage profiles of other 18650 cells can be found in our previous report [1] for reference. Fig. 4 shows the typical discharge voltage profiles at different rates for fresh 103450 prismatic cells manufactured by (a) A, (b) C, and (c) GP. The discharge profiles at 0.2 C rate are flat and similar for all the cases; therefore, all cells studied here should be made by $\mathrm{LiCoO_2}$ positive and graphite negative.

Fig. 5 shows the cell discharge voltages versus the cell capacity at 0.2 C rate and at (a) −20 °C, (b) −30 °C, and (c) −40 °C. It is noted that there is significant difference in the discharge voltage among the studied cells, which will have significant impact on the cell energy even though the cell capacity may be similar.

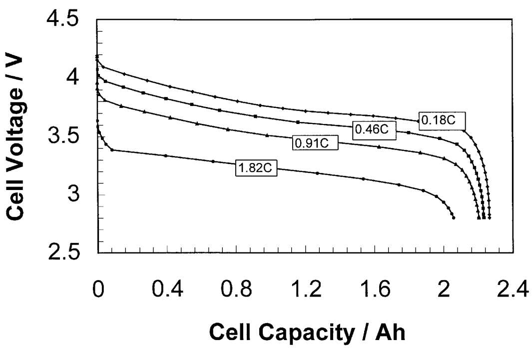

Fig. 3. Discharge voltage vs. the cell capacity at room temperature and various C rates for the 2.2 Ah 18650 cell manufactured by E.

3.4. Cycle life and the discharge voltage profiles during the cycling at room temperature

Fig. 6 shows the cell capacity versus the cycle number at (a) 0.2 C rate and (b) 1 C rate for the 18650 cells made by E and GP and the 103450 prismatic cells manufactured by A, C and GP.

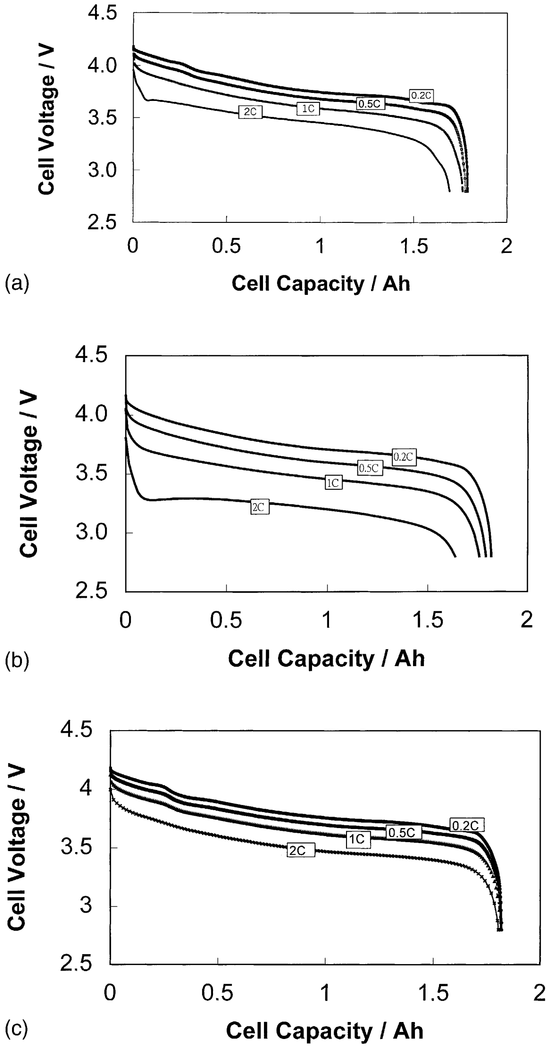

Fig. 4. Discharge voltage vs. the cell capacity at room temperature and various C rates for 103450 prismatic cells manufactured by (a) A, (b) C, and (c) GP.

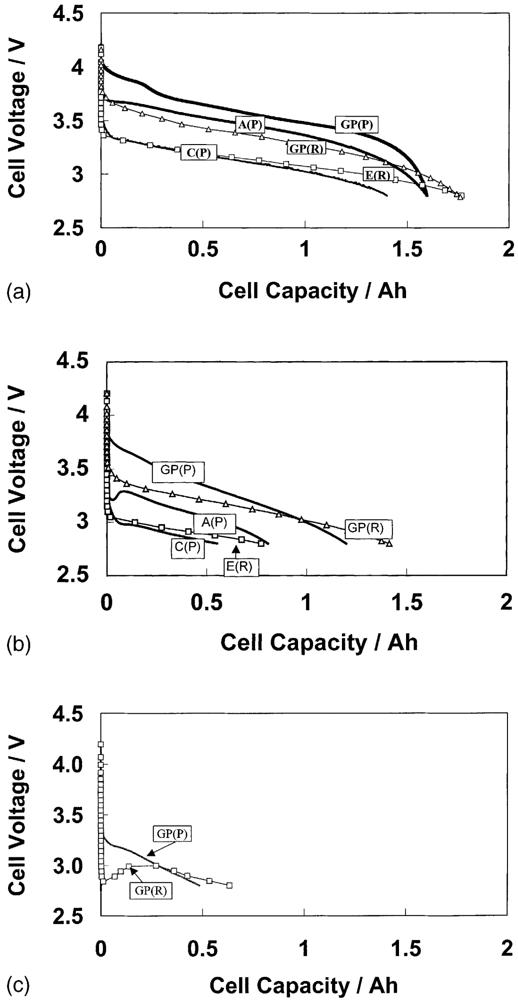

Fig. 5. Discharge voltage vs. the cell capacity at 0.2 C rate and at (a) −20 °C, (b) −30 °C, and (c) −40 °C for the cells manufactured by A, C, E, and GP. Please note that GP(R) and E(R) are 2 Ah 18650 GP cell and 2.2 Ah 18650 E cell, and A(P), C(P), and GP(P) are 103450 prismatic A, C, and GP cells. It is noted that the biggest difference in the discharge voltage among the studied cells is about 0.43 V at −20 °C and 0.35 V at −30 °C, which will impact the cell discharge energy significantly.

Fig. 7 shows the discharge profiles at 1 C rate and at 1st, 100th, and 300th cycle for (a) 2.2 Ah 18650 E cell and (b) 2 Ah 18650 GP cell. The decrease in the cell discharge voltage of 2.2 Ah 18650 E cell is more than that of 2 Ah 18650 GP cell.

Fig. 8 shows the discharge voltage profiles at 0.2 and 1 C rates after 1 and 300 cycles for the 103450 prismatic cells manufactured by (a) C and (b) GP. The 103450 A cell was not included because there was no data after 300 cycles. Two things are worthwhile to be pointed out. First, the discharge voltage of 103450 C cell is lower than that of 103450 GP cell. Secondly, after 300 cycles, there is no decrease in the discharge voltage for 103450 GP prismatic cell at both 0.2 and 1 C rates while the discharge voltage is decreased substantially for 103450 C cell.

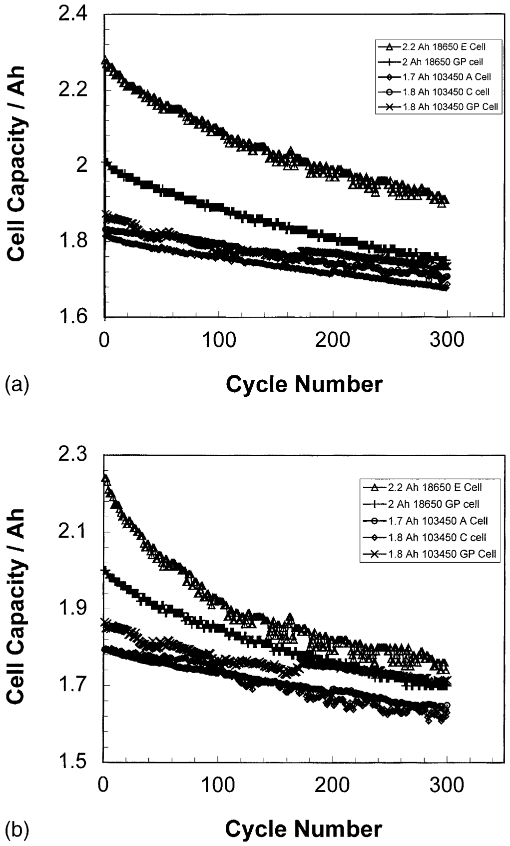

Fig. 6. Cell capacity vs. the cycle number at (a) 0.2 C and (b) 1 C rates. The capacity fading rate of the prismatic cells is lower than that of 18650 cells. The capacity fades fastest for 2.2 Ah 18650 E cells at 1 C rate while the 103450 GP prismatic cell gets the lowest fading rate.

4. Discussions

4.1. *Specific energy, energy density, and specific power at room temperature*

In view of the information in Tables 1–3 and Fig. 2, the cell-specific energy and energy density have been increased dramatically since 1999. There has been as much as 90% (100% × (193 − 100)/100) increase in the cell-specific energy and 100% (100% × (514 − 232)/232) increase in cell energy density for 18650 cells since 1999 [10,11]. For prismatic cells, the increase is even more. It is about 110% (100% × (180 − 85)/85) for the cell-specific energy and about 125% (100% × (407 − 181)/181) for energy density since 1999 [10,11]. The increase in last 5 years since 1999 is four times more than that in about 10-year period from 1990 to 1999. The specific energy was increased to about 100 Wh/kg for 18650 cell in 1999 after Sony introduced their first 18650 cell (∼90 Wh/kg) in 1990 [2]. As mentioned in the Section 1, the rapid development in Li-ion technologies in last 5 years is probably due to the fierce market competition introduced by non-Japanese Li-ion manufacturers [2].

The specific energy 193 Wh/kg of the commercial 18650 cylindrical cell is only 3.5% less than 200 Wh/kg, the

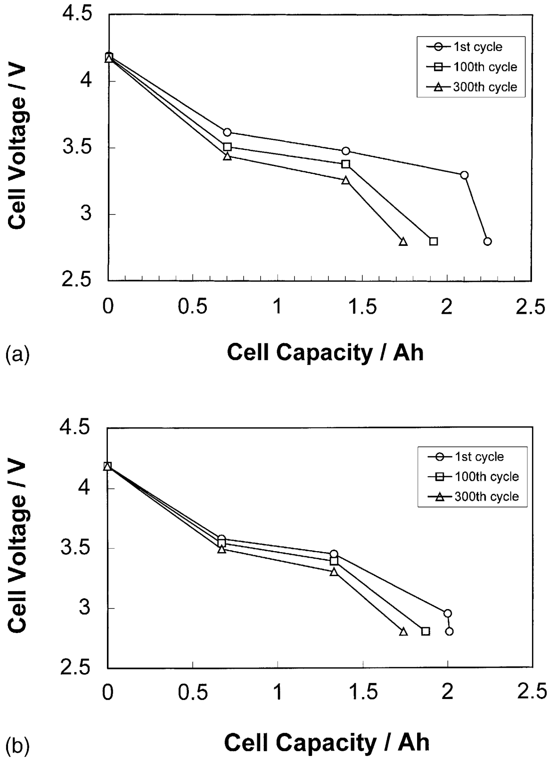

Fig. 7. Discharge voltage vs. the cell capacity at 1 C rate at 1st, 100th, and 300th cycle for (a) 2.2 Ah 18650 E cell and (b) 2 Ah 18650 GP cell. The rough discharge voltage profile is due to insufficient data being recorded during the cycling test.

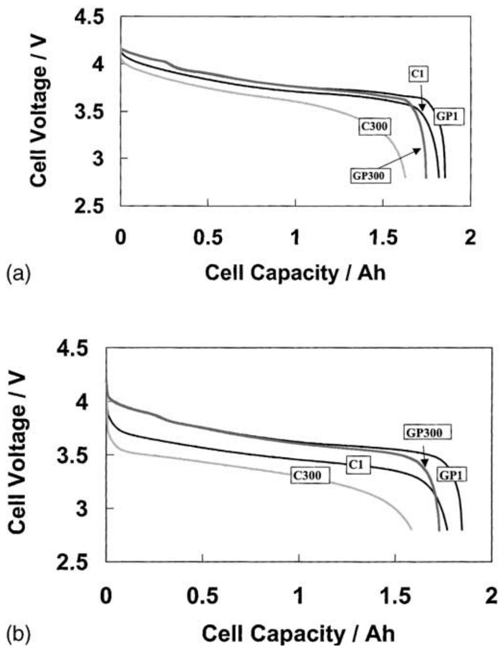

Fig. 8. Discharge voltages at 0.2 and 1 C rates vs. the cell capacity after 300 cycles for 103450 prismatic cells manufactured by C and GP. C1 and GP1 are the discharge voltage of 103450 prismatic C and GP cells in the first cycle, while C300 and GP300 are the discharge profiles after 300 cycles. The discharge voltage of the 103450 C cell decreased significantly after 300 cycles while that of 103450 GP cells did not.

long-term DOE goal of the specific energy for lithium-ion battery [9]. Considering the fact that there is 2.4 Ah 18650 cell in the market [13], the 18650 cell-specific energy probably exceeds 200 Wh/kg, the long-term DOE goal. Further, the cell energy density in all studied cases exceeds significantly 300 Wh/l, the long-term DOE goal of the battery energy density. For 18650 cells, it exceeds 300 Wh/l by 50–70% [9] (see Table 1). For prismatic cell, it exceeds by about 33% [9] (see Table 1). In view of above discussions, commercial lithium-ion technology has made milestone progress.

The cell power has also been improved significantly since 1999 in view of the information in Tables 2 and 3 and Fig. 2. For instance, at the specific power, 200 W/kg, the cells studied here can still deliver over 80% of their designed energy while the 18650 cells studied in 1999 delivered about 10% of their energy obtained at a low specific power like 30 W/kg [10]. The improvement in the cell power will open more windows in the application for lithium-ion cells.

4.2. Factors in the cell-specific energy and energy density at room temperature

Many factors can affect the cell energy and energy density. Here, we will focus on the effects from the cell design, the cell geometric shape, the can material, the cell discharge voltage, the temperature, and the cycle number.

4.2.1. Cell design

In view of Table 1, for the 18650 cells with about 2 Ah capacity, the specific energy at 0.2 C rate ranges from 165 to 180 Wh/g, which is about 9% variation. This 9% variation matches roughly the weight difference among the studied cells. The weight difference between 18650 C and GP cells is 8.3% (100% × (45.8 − 42.3)/42.3). The weight difference should be due to the combination of the weight differences in the can (due to the difference in the can wall thickness), cell header, electrolyte, and electrodes among the studied cells. This observation suggests that the cell-specific energy can be improved by 9% with (i) minimizing the weight of the can and cell header, and (ii) optimizing electrode formulation and electrolyte amount.

4.2.2. Cell geometric shape and can material

For a given can material and cell design, it is common knowledge in the industry that the specific energy and energy density of prismatic cells are usually lower than that of the cylindrical cells because the prismatic jelly flat is normally less compacted than the round jellyroll. Indeed, for the same steel can and same manufacturer C, the specific energy of 103450 prismatic cell is about 9% (100% × (1 − 165/151)) lower than that obtained with 18650 cells even though the total volume of 103450 prismatic cell is 2% larger than that of 18650 cell. Therefore, from this point of view, the cylindrical cell should be a better choice in the application where there is no limitation in the dimensions such as the thickness.

Table 5
Average discharge voltage (*V*) at 0.2 C rate for 18650 and 103450 prismatic cells

	Maker								
	A	C	D	E	E	GP	A	C	GP
Type	18650 (2 Ah)	18650 (2 Ah)	18650 (2 Ah)	18650 (2 Ah)	18650 (2 Ah)	18650 (2 Ah)	103450 (1.7 Ah)	103450 (1.8 Ah)	103450 (1.8 Ah)
$V_{0.2\,\mathrm{C}}$	3.77	3.75	3.78	3.75	3.73	3.78	3.80	3.74	3.80

As expected, the can material can affect the cell-specific energy significantly. The specific energy of prismatic C cell with the steel can is 16% (=100% × (1 − 151/180)) (see Table 3) less than that of GP prismatic with an aluminum can. This 16% improvement with Al can is lower than 30% improvement reported by Narukawa et al. [14] because the cell size studied by Satoshi was 5.6 mm thick, 16.4 mm wide, and 67 mm high where the can effect is much larger than that of 103450 prismatic cell studied here. Please note that the ratio of can volume versus can surface is 6.69 $(17000/2540 = (10 \times 50 \times 34)/(2 \times (50 \times 34 + 10 \times 50 + 10 \times 34))$ for 103450 prismatic cell while it is 1.96 (=6153.3/3131.68) for the prismatic cell studied by Satoshi et al. [14]. The can weight in the total cell weight of the prismatic cell studied by Narukawa et al. [14] is much more significant than that of 103450 cell in the total weight. The aluminum can should also be responsible for the fact that the specific energy of GP prismatic cell (Al can) is only about 6.7% (100% × (1 − 180/193)) (see Table 1) lower than that of 2.2 Ah 18650 E cell, while the energy density of GP prismatic cell is about 21% lower than that of 18650 2.2 Ah E cell (steel can). The aluminum can will improve the cell-specific energy but not the cell energy density. The prismatic cells with an aluminum can may be more attractive to the applications where both the specific energy and thickness are important.

4.2.3. The cell discharge voltage

The cell energy is different from the cell capacity because the cell discharge voltage is not a factor in the cell capacity while the cell energy is proportional to the cell discharge voltage. Such difference is why the cell energy depends on the discharge rate more strongly than the cell capacity as described in the Section 3. The cell energy is more sensitive to the cell impedance than the cell capacity because the discharge voltage, especially at high C rate, can be affected greatly by the cell impedance. To evaluate the effect on the cell-specific energy from the discharge voltage among the studied cells, the average discharge voltage is a good base for making a right comparison since the average discharge voltage is mainly determined by the cell electrode chemistry and the cell impedance. The average discharge voltage is obtained with the equation $V = E/(I \times t)$ where t is the total discharge time (h), I is the discharge current (A), and E is the discharge energy (Wh). Tables 5 and 6 list all average discharge currents at different rates obtained from Tables 1–3, and Figs. 3 and 4.

From Table 5, it can be seen that the average discharge voltage at 0.2 C rate varies from 3.73 to 3.80 V among all studied cells, which will cause about 1.8% variation (100% × (1 − 3.73/3.8)) in the cell energy or specific energy. This is understandable because the voltage drop at 0.2 C rate is low in general even when there is significant difference in the cell impedance. For instance, the dc impedance of 2 Ah 18650 C cell was 0.37 Ω, which is 100% more than that (0.17 Ω) of 2 Ah GP cell [1]. However, the difference in the voltage drop at 0.4 A or 0.2 C rate is about 0.08 V (0.4 × 0.37 − 0.4 × 0.17), which matches roughly the variation seen in Table 5. Therefore, the cell energy at 0.2 C rate is mainly determined by the cell chemistry, i.e. the kinds of positive and negative electrodes that can affect the cell open circuit voltage.

Optimizing the cell rate capability or minimizing the cell dc impedance will have a relatively small effect on the cell energy or specific energy at 0.2 C rate.

Now, let us look at the result at higher discharge current or higher C rate. From Table 6, it can be seen that the average discharge voltage at 1 C rate varies from 3.48 V (103450 C prismatic cell) to 3.66 V (103450 prismatic GP cell), which will cause about 5% (100% × (1 − 3.48/3.66) variation in the cell energy or specific energy. At 2 C rate, the average discharge voltage varies from 3.18 V for 103450 C prismatic cell to 3.50 V for 103450 GP prismatic cell, which will cause about 9% (=100% × (1 − 3.18/3.5)) variation in the cell discharge energy or specific energy. This is conceivable

Table 6
Average discharge voltage (*V*) at different C rates for 18650 and 103450 prismatic cells

Maker	Cell type	$V_{0.2\,\mathrm{C}}$	$V_{0.5\,\mathrm{C}}$	$V_{1\,\mathrm{C}}$	$V_{2\,\mathrm{C}}$
E	18650 (2.2 Ah)	3.73	3.65	3.50	3.22
GP	18650 (2 Ah)	3.78	3.68	3.55	3.30
A	103450 (1.7 Ah)	3.80	3.74	3.61	3.49
C	103450 (1.8 Ah)	3.74	3.62	3.48	3.18
GP	103450 (1.8 Ah)	3.80	3.74	3.66	3.50

because the higher current will maximize the effect on the cell discharge voltage from the variation in the cell impedance. Further, the relatively high-energy loss at the high rate justifies a relatively large increase in the cell temperature during the high C rate discharge reported previously [1]. In view of above discussion, there will be a significant gain not only in the cell energy or specific energy but also in minimizing the cell self-heating at high C rate if the cell rate capability is optimized.

As a last point in Table 6, it appears that the average discharge voltages of 103450 prismatic GP cell is highest overall. The high average discharge voltage should be one of the major factors (besides Al can) for the fact that the specific energy of prismatic GP cells at 1 C or 2 C rate is similar to or above that of 2.2 Ah 18650 E cells even though the specific energy of 2.2 Ah 18650 E cell is highest at 0.2 C rate. This observation suggests that the 1.8 Ah 103450 prismatic cells from GP could be better choice than 2.2 Ah 18650 E cell in a high rate application or in the case that the cell self heating is a problem.

4.2.4. Temperature

Like the cell capacity, the cell energy and specific energy is inversely proportional to the temperature. Compared with the cell energy obtained at room temperature, the decrease in the cell energy or specific energy at 0.2 C rate and at −20 °C ranges from 17% (=100% × (180 − 137)/180 103450 GP prismatic cell) to 35% (=100% × (193 − 124)/193 2.2 Ah 18650 E cell) depending on the cell type and manufactures. The decrease at −30 °C varies from 43 to 76% depending on the manufacturer. At −40 °C, the cells from the manufacturers A, C and E could not deliver any significant energy while the cells from GP can still deliver about 40 Wh/kg which is ∼22% (=100% × 40/180) (or 78% decrease) of the cell-specific energy obtained at room temperature.

The cell energy and specific energy depend on the temperature more strongly than the cell capacity. For instance, the cell energy or specific energy of the 2.2 Ah 18650 E cell was decreased by as much as 35% as mentioned above, while the cell capacity was only decreased by 22% (100% × (2.28 − 1.77)/2.28). Other cells behave similarly. The decrease in the cell discharge voltage is the key factor in such difference in the temperature dependence for the cell capacity and energy or specific energy. Indeed, the average discharge voltage is decreased by about 17% (from 3.73 to 3.10 V, see Table 7), which roughly matches the 13% more decrease (=35% − 22%) in the cell energy for the 2.2 Ah 18650 E cell. Further, the biggest difference in the cell average discharge voltage among the studied cells at −20 °C is 0.43 V (=3.53 − 3.1), which is between 2.2 Ah 18650 E cell and 1.8 Ah 103450 GP prismatic cell. This observation means that the cell discharge voltage due to the difference in the cell impedance can cause as much as 12% (100% × 0.43/3.53) variation in the cell discharge energy at −20 °C. This 12% variation is significant in view of the fact that the decrease in the cell capacity is typically less than 20% compared with the rated capacity when the temperature decreases to −20 °C. Therefore, the discharge energy is a better property to gauge the cell discharge capability at low temperatures compared with the cell capacity normally used in the characterization of the cells at low temperatures.

4.2.5. Cycle number

It is well established that there is not only a capacity loss but also a decrease in the cell discharge voltage due to the increase in the cell impedance during the cycling test. Both the capacity loss and the decrease in the cell discharge voltage will cause a decrease in the cell energy and specific energy. Now, we will examine them quantitatively.

To study the effect from the decrease in the cell discharge voltage quantitatively during the cycling test, the average discharge voltages were estimated from Figs. 7 and 8 and are shown in Fig. 9. The average discharge voltage at 1 C rate was decreased to 3.4 V from 3.5 V for 2.2 Ah 18650 E cell, and to 3.51 V from 3.55 V for 2 Ah 18650 GP cell after 100 cycles. These decreases in the average discharge voltages correspond to 3% decrease (=100% × (3.5 − 3.4)/3.5) in the cell discharge energy for 2.2 Ah 18650 E cell and 1% decrease (100% × (3.55 − 3.51)/3.55) for 2 Ah 18650 GP cell. By following this calculation, all decreases in the cell energy for the 18650 cells and 103450 prismatic cells were calculated and listed in Table 8. For a comparison, Table 8 also lists the specific energy and the energy loss due to the capacity decrease shown in Fig. 7.

The energy loss due to the decrease in the cell discharge voltage during the cycling test depends on the cell manufacturer. For instance, the energy loss at 1 C rate after 300 cycles for the 2.2 Ah 18650 E cell is 6%, which is 21% of total 28% energy loss (=22 + 6) while it is 3% for 2 Ah 18650 GP cell; the energy losses at 0.2 and 1 C due to the decrease in the cell discharge voltage are negligible for 1.8 Ah 103450 GP cell while it is 3–4% for 1.8 Ah 103450 C cell

Table 7
Average discharge voltages at 0.2 C rate and at low temperatures

	2.2 Ah 18650 E cell (V)	2 Ah 18650 GP cell (V)	1.7 Ah 103450 A cell (V)	1.8 Ah 103450 C cell (V)	1.7 Ah 103450 GP cell (V)
23 °C	3.73	3.78	3.80	3.74	3.80
−20 °C	3.1	3.30	3.39	3.14	3.53
−30 °C	2.94	3.13	3.07	2.93	3.28
−40 °C		2.91			3.02

Table 8
Cell energy loss caused by the decreases in the cell capacity and discharge voltage at different rates during the cycling test

Cell type	100th cycle (0.2 C)			100th cycle (1 C)			300th cycle (0.2 C)			300th cycle (1 C)		
	Capacity loss (%)	Voltage loss (%)	Specific energy (Wh/kg)	Capacity loss (%)	Voltage loss (%)	Specific energy (Wh/kg)	Capacity loss (%)	Voltage loss (%)	Specific energy (Wh/kg)	Capacity loss (%)	Voltage loss (%)	Specific energy (Wh/kg)
2.2 Ah 18650 E	8		178	14	3	145	16		162	22	6	126
2 Ah 18650 GP	6		169	7	1	153	11		160	13	3	139
1.8 Ah 103450 C							11	3	130	10	4	117
1.8 Ah 103450 GP							4	0.1	173	5	0.1	164

(see Table 8), which accounts for about 21% of the total energy loss after 300 cycles. It is interesting to note that the discharge voltage of 103450 GP cell is not affected by the cycle number, which suggests that the impedance increase in 103450 GP cell is the lowest during the cycling test.

The combined effect from the loss in the cell capacity and the decrease in the cell discharge voltage during the cycling test creates a very interesting situation. After 100 cycles, the specific energy of 2.2 Ah 18650 E cell at 1 C rate is 5.3% lower (100% × (1 − 145/153), see Table 8) than that obtained with 2 Ah 18650 GP cell, even though the initial specific capacity of 2.2 Ah 18650 E cells is about 5% higher than that of 2 Ah 18650 GP cell. The specific energy of 103450 prismatic GP cell probably exceeds that of 2.2 Ah 18650 E cell in very early stage at 1 C rate and around 100 cycles at 0.2 C (see Tables 2, 3 and 8). This observation means that 1.8 Ah 103450 prismatic GP cell will perform better than 2.2 Ah 18650 E cell in the very early stage in terms of the specific energy at 1 C rate, and after 100 cycles in terms of the specific energy at 0.2 C rate. Considering the fact that the generally accepted cycle life is 300 cycles, 1.8 Ah 103450 prismatic cells will perform better than 2.2 Ah 18650 cell in 66% (100% × (1 − 100/300)) of their lifetime even at 0.2 C rate. Therefore, the cell with a lower specific energy and degradation may be more suitable for the applications that require high number of cycles.

As a last point on the cycle life effect, the small decrease in the cell discharge voltage correlates with the low loss in the cell capacity. For instance, the 2 Ah 18650 GP cell and 103450 prismatic GP cells showed both low loss in the cell capacity and small decrease in the cell discharge voltage. This phenomenon suggests that the origins in the decrease of the cell discharge voltage may be similar to that of the loss of the cell capacity to a large degree.

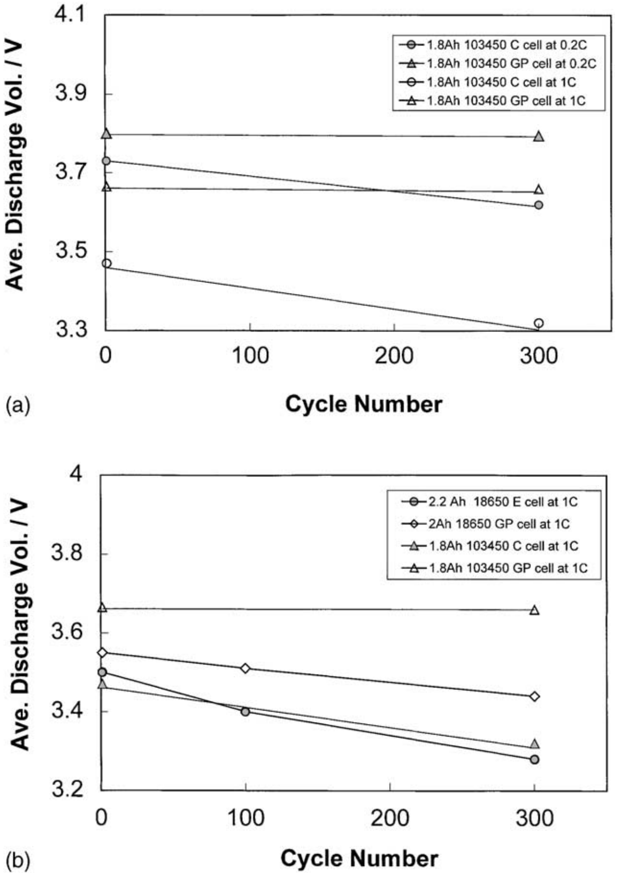

Fig. 9. Average discharge voltages at (a) 0.2 C and (b) 1 C rates vs. cycle number for 18650 cylindrical and 103450 prismatic cells made by C, E, and GP. The slope at 1 C rate follows the order: 2.2 Ah 18650 E cell > 1.8 Ah 103450 prismatic C cell > 2 Ah 18650 GP cell > 103450 prismatic GP cell. The slope at 0.2 C rate is 103450 prismatic C > 103450 prismatic GP.

5. Conclusions

The specific energy, energy density, specific power, and power density have increased dramatically since 1999. The highest specific energy obtained in this study is 193 Wh/kg, which is 90% more than that obtained in 1999 and is only 3% lower than 200 Wh/kg, the long-term DOE goal [9]. The cell energy density has been even doubled since 1999 and is 33–70% more than 300 Wh/l, the long-term DOE goal [9]. The continuous specific power or power density is also increased significantly in last 5 years. At the specific power, 200 W/kg, the cells studied here can still deliver over 80% of their designed energy while the 18650 cells studied in 1999 delivered about 10% of their energy obtained at a low specific power like 30 W/kg. The cell-specific energy and energy density are affected significantly by the cell geometric shape, the material of the can, the cell discharge voltage, the cell temperature, and the cycle number. It seems that the geometric difference between the cylindrical 18650 and prismatic 103450 cells can cause as much as 9% difference in the cell-specific energy and 12% difference in the cell energy density even though the total volume of 103450 prismatic cell is 2% larger than that of 18650 cell. The aluminum can should be the main factor in about 16% improvement in the cell-specific energy of 103450 prismatic cell compared with the cell made with the steel can. The effect on the cell energy or specific energy from the cell discharge voltage depends on the discharge currents. The variations in the cell discharge voltage do not have any significant impact on the cell-specific energy at 0.2 C rate among the fresh cells while it can affect significantly the cell-specific energy at the high rate like 1 C or above in both fresh and cycled cells. The difference in the cell discharge voltage among the fresh cells made by different manufacturers can cause as much as 9% variations in the cell energy and cell-specific energy at 2 C rate. The decrease in the discharge energy and specific energy ranges from 17 to 35% at −20 °C, from 43 to 76% at −30 °C, and from 78 to 100% at −40 °C, which is much more than the decrease seen in the cell capacity. The cell discharge energy is a more proper attribute to gauge the cell discharge capability at low temperatures. For the cycled cell, the decrease in the cell discharge voltage can cause as much as 6% decreases in the cell energy at 1 C rate after 300 cycles, which is about 21% of the total energy loss. Considering the effect on the cell energy from the loss in the cell capacity and the decrease in the cell discharge voltage, the cell with the highest initial capacity may not be a best choice in the application that requires many cycles.

Acknowledgements

Authors would like to thank Mr. Mark Titerman for conducting the tests, and Mr. David Manis for his critical comments.

References

[1] J. Fan, J. Power Sources 117 (2003) 170–178.

[2] J. Fan, IEEE Aerosp. Electron. Syst. Mag. 17 (2002) 7–10.

[3] G. Au, L. Cristo, D. Bennington, A. Pellegrino, in: Proceedings of the IEEE 17th Annual Battery Conference on Applications and Advances, Long Beach, CA, January 2002.

[4] J. Fan, D. Magnuson, in: K.M. Abraham, E.S. Takeuchi, M. Doyle (Eds.), Rechargeable Lithium Batteries, PV 2000–2021, The Electrochemical Proceedings Series, Pennington, NJ, 2000.

[5] G. Nagasubramanian, D. Doughty, J. Baker, P. Shah, in: The 196th Meeting Abstract of the Electrochemical Society, Abstract 374, Honolulu, Hawaii, USA, 17–22 October 1999.

[6] R.A. Marsh, S. Vukson, S. Surampudi, B.V. Ratnakumar, M.C. Smart, M. Manzo, P.J. Dalton, J. Power Sources 97/98 (2001) 25–27.

[7] P. Ramadass, B. Haran, R. White, B.N. Popov, J. Power Sources 111 (2002) 210–220.

[8] (a) A. Johnson, R.E. White, J. Power Sources 70 (1) (1998) 48;
(b) S.-i. Tobishima, K. Takei, Y. Sakurai, J.-i. Yamaki, J. Power Sources 90 (2000) 188–195.

[9] The International Energy Agency Implementing Agreement for Electric Vehicle Technologies and Programs, Annex V, Outlook Document, 1996–1997, p. 16.

[10] G. Nagasubramanian, R.G. Jungst, D.H. Doughty, J. Power Sources 83 (1999) 193–203.

[11] G. Nagasubramanian, R.G. Jungst, J. Power Sources 72 (1998) 189–193.

[12] http://www.gpina.com.

[13] http://www.samsungsdi.com.

[14] S. Narukawa, T. Amazutsumi, H. Fukuda, K. Itou, H. Tamaki, Y. Yamauchi, J. Power Sources 76 (1998) 186–189.