Journal of Power Sources 100 (2001) 117–124

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Development of nickel/metal-hydride batteries for EVs and HEVs

Akihiro Taniguchi*, Noriyuki Fujioka, Munehisa Ikoma, Akira Ohta

Panasonic EV Energy Co., Ltd., 555 Sakaijuku, Kosai, Shizuoka 431-0452 Japan

Abstract

This paper is to introduce the nickel/metal-hydride (Ni/MH) batteries for electric vehicles (EVs) and hybrid electric vehicles (HEVs) developed and mass-produced by our company. EV-95 for EVs enables a vehicle to drive approximately 200 km per charge. As the specific power is extremely high, more than 200 W/kg at 80% depth of discharge (DOD), the acceleration performance is equivalent to that of gasoline fuel automobiles. The life characteristic is also superior. This battery gives the satisfactory result of more than 1000 cycles in bench tests and approximately 4-year on-board driving. EV-28 developed for small EVs comprises of a compact and light battery module with high specific power of 300 W/kg at 80% DOD by introducing a new technology for internal cell connection. Meanwhile, our cylindrical battery for the HEV was adopted into the first generation Toyota Prius in 1997 which is the world's first mass-product HEV, and has a high specific power of 600 W/kg. Its life characteristic was found to be equivalent to more than 100,000 km driving. Furthermore, a new prismatic module in which six cells are connected internally was used for the second generation Prius in 2000. The prismatic battery comprises of a compact and light battery pack with a high specific power of 1000 W/kg, which is approximately 1.7 times that of conventional cylindrical batteries, as a consequence of the development of a new internal cell connection and a new current collection structure.

Keywords: Nickel/metal-hydride battery; EV; HEV; Specific power; Cycle life; Cylindrical; Prismatic

1. Introduction

Now-a-days [1], global environmental issues such as acid rain due to NO_x and SO_x, the green house effect caused by the CO_2 gas, and the practical use of various energy sources are important issues. The development and commercialization of low fuel consumption vehicles and zero emission vehicles (ZEVs) have become a key factor in the resolution of these matters. Regulations and projects for low emission, low fuel consumption vehicles are beginning worldwide. In USA, the ZEV regulation in California, which obliges manufacturers to sell 10% ZEV in total car sales will start in 2003, and the 3-l car development of the partnership for new generation of vehicles (PNGVs) is due to be completed by 2004. In Europe, there is a target for a corporate average CO_2 emission of 140 g/km from 2008. In the 3rd Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP3) held in Kyoto, Japan in 1997, the target to reduce CO_2 emission was agreed among advanced countries. Under these circumstances, car manufacturers in Japan and many other countries are extensively developing practical hybrid electric vehicles (HEVs) and electric vehicles (EVs) having superior performance over gasoline vehicles. The success of these EVs depends primarily on the performances of the battery that is adopted for the vehicles and it is important to develop new types of batteries with high energy density and high specific power as well as to improve conventional batteries.

2. State-of-the-art for battery development

2.1. Ni/MH batteries for EVs

In response to the demand for a range between changes of 100 miles (160 km), the nickel/metal-hydride (Ni/MH) battery is considered a promising interim solution. Secondary lithium batteries such as lithium ion (Li-ion) or lithium polymer (Li-polymer) also appear to be promising, and driving tests have been conducted. In addition to these, the proton electrolyte fuel cell (PEFC) is expected to join the new power sources for EVs. Many new types of battery have been evaluated in vehicles. Pilot production of Ni/MH batteries has been launched and these are available in the market. A limited production of Li-ion batteries has been launched and domestic sales and leases of these batteries mounted in EVs have started.

* Corresponding author. Tel.: +81-53-577-3112; fax: +81-53-577-3114.
E-mail address: pan27193@pas.mbi.mei.co.jp (A. Taniguchi).

0378-7753/01/$ – see front matter
PII: S0378-7753(01)00889-8

2.2. Ni/MH batteries for HEVs

Various HEV systems have been designed. Generally, HEV batteries are required to exhibit high specific power for both input and output, and a long life. Ni/MH batteries and secondary Li-ion batteries, in which improvement of battery design is reducing internal resistance in order to achieve high specific power, are being robustly developed.

Highly accurate detection of remaining battery power by integrating charge and discharge capacity is necessarily due to the complicated pulse charge and discharge service in HEVs. Battery performance enhancement and battery management technology are both critical.

This paper reports the state-of-the-art of Ni/MH batteries for EV application under pilot production and for HEV application, for which mass-production has been launched.

3. Ni/MH batteries for EVs [2]

Fig. 1 shows the EV-95 (95 Ah) and EV-28 (28 Ah) units developed for EVs. EV-95, which has long life characteristics of more than 1000 cycles and 4-year on-board driving, shows excellent total performance for vehicle driving. At the present moment, we are actively pressing ahead with mass-production of these batteries, and they are on sale and being leased for EVs. EV-28 was developed, targeting compact EVs (commuter vehicles and so on) and the HEVs market.

3.1. Battery structure

We have developed the Ni/MH battery by combining some critical technologies as follows:

- optimization of additives (Y_2O_3 and so on) for excellent charge efficiency of the positive electrodes [3];
- $MmNi_5$ (AB_5 type) system of hydrogen-absorbing alloy for the negative electrodes [4–6];
- high performance, hydrophilic-treated polypropylene separator.

The structure of the EV-95 will be simply explained. The electrode groups consist of alternately stacked positive electrodes and negative electrodes inter-leaved with separators. Inserting these electrode groups into a resin battery case and sealing with a cover equipped with a valve after filling with alkaline electrolyte forms the cell. A battery module consists of 10 cells connected in series by metal plates, and these are configured to permit airflow between the cells to ensure a uniform temperature distribution.

EV-28 achieves further realized miniaturization and high specific power by the following technologies:

- fundamental technologies as for EV-95;
- newly designed module case to ensure cooling between cells;
- new internal connection structure where bus bars between cells are formed within the module case.

3.2. Battery basic characteristics

Table 1 shows the dimensions, weights and basic characteristics of EV-95 and EV-28.

3.2.1. Discharge characteristics

The specific power of EV-95 and EV-28 modules was evaluated. In practical driving, the discharge behavior is similar to pulse discharge due to the complicated patterns of

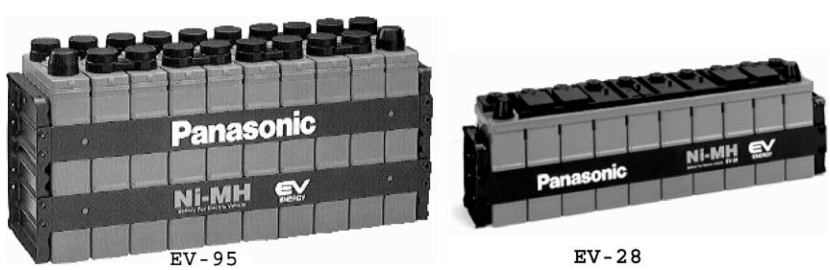

Fig. 1. Ni/MH battery modules for EV application.

Table 1
Basic characteristics for EV-95 and EV-28 module

	EV-95	EV-28
Dimensions, width × height × length (mm × mm × mm)	116 × 175 × 388	75 × 110 × 388
Nominal voltage (V)	12	12
Nominal capacity (Ah)	95	28
Weight (kg)	18.7	6.0
Specific energy (Wh/kg)	65	58
Specific power, 80% DOD (W/kg)	200	300
Self-discharge at 45°C, 1 month (%)	20	20
Cycle life at 25°C ambient temperature, 80% DOD (cycles)	>1000	>1000

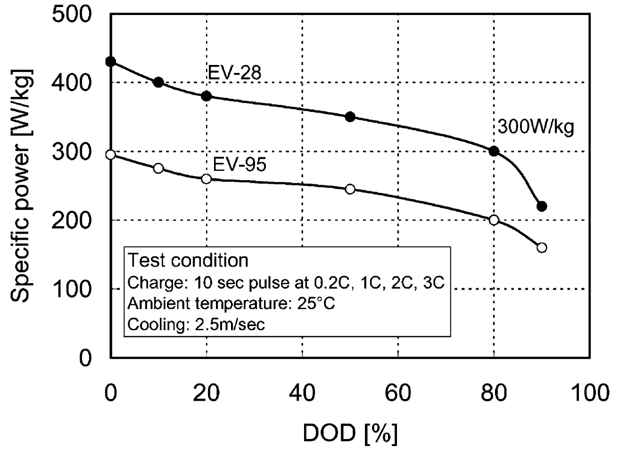

Fig. 2. Specific power of EV-95 and EV-28 battery module at different DOD.

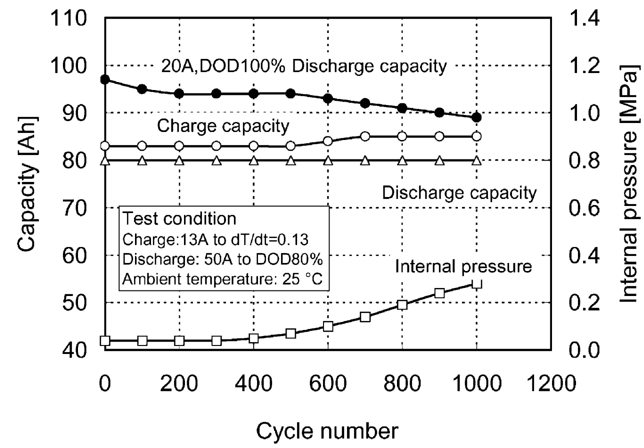

Fig. 4. Cycle life characteristics of EV-95 battery module.

acceleration, deceleration, driving at a constant speed and regenerative charge. Fig. 2 shows the specific power at different depth of discharge (DOD) through a pulse discharge regime.

Output power for both EV-95 and EV-28 was stable until the DOD reached 80–90%. A new internal cell connection structure applied to EV-28 has achieved the high specific power of 300 W/kg, which is approximately 1.5 times higher than that of EV-95.

3.2.2. Charge characteristics

Superior discharge capacity per charge over a wide temperature range is crucial for on-board driving. Fig. 3 shows the results of charge efficiency tests in the temperature range from −20 to 55°C.

Both EV-95 and EV-28 show superior discharge capacity over the wide temperature range. Charge efficiency characteristics were found to be excellent even at high temperature, for example, 86% at 45°C for EV-95 and 97% at 25°C for EV-28.

3.2.3. Life characteristics

Fig. 4 shows the results of cycle life test for the EV-95 module. Stable characteristics were observed without deterioration of discharge capacity after 1000 cycles, whereby life for actual vehicle driving is estimated to be approximately 150,000 km.

4. Cylindrical Ni/MH battery for HEVs [7]

Fig. 5 shows single cell and a module developed for HEV application. This Ni/MH battery has high performances for the specific power, the energy density and the charge efficiency. Since, in particular, their ampere-hour (Ah) efficiency is 100% and Watt-hour (Wh) efficiency is 90–95% in the intermediate state of charge (SOC), this battery is very suitable for HEV application. This battery module is very safe due to its excellent resistance to over-charging and over-discharging. In addition, it has favorable durability in the HEV application, where charge and discharge are repeated in

Discharge Energy of Battery Module

	25 °C	45 °C	45 vs 25 °C
EV-28	350Wh	340Wh	97%
EV-95	1150Wh	1000Wh	86%

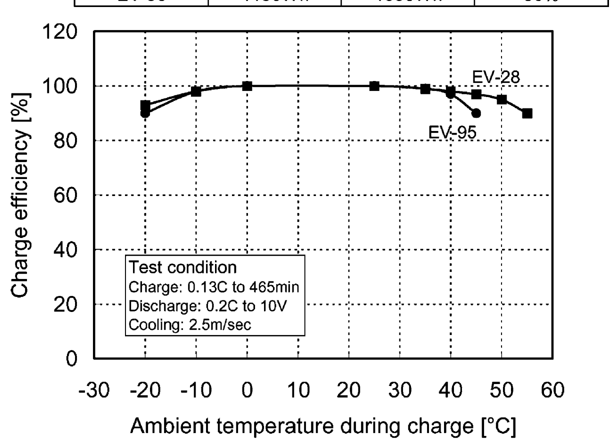

Fig. 3. Charge efficiency of EV-95 and EV-28 modules at different temperatures.

Fig. 5. Cylindrical single cell and module for HEV application.

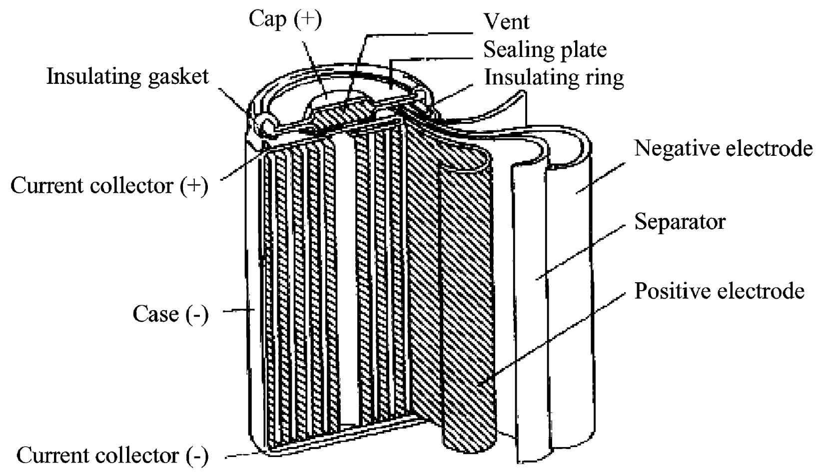

Fig. 6. Structure of cylindrical battery cell.

an intermediate SOC, because the reactions of the battery do not involve any dissolution and/or precipitation.

4.1. Battery structure

The single cell shown in Fig. 5 is a sealed cylindrical battery of D-size with the diameter of 32 mm and the height of 60 mm. Fig. 6 shows the structure of this battery. A sealing plate is equipped with a valve to prevent bursting with an increase of internal pressure. The battery case is made of steel, and both positive and negative electrodes are coiled and separated by the separator. This battery has been developed by optimizing the reaction area of the electrodes, reducing resistance for current collection and improving an electrolyte composition to obtain high power characteristics. The nominal battery capacity is 6.5 Ah and the maximum output power is more than 100 W per cell. It is required to reduce the internal resistance of the cell connection to form one module. Resistance against vibration and impact per module is also required to mount the modules on a vehicle. To satisfy these requirements, disk plates were inserted for cell connection. Shortening of the connection distance and reduction of the connection resistance were realized. The weight of the connection plate was also decreased.

4.2. Battery characteristics

Table 2 shows the basic characteristics of single cell and a battery. The energy density and specific power were found to be suitable for HEV use.

Table 2
Basic characteristics of cylindrical battery cell and module[a]

	Module (six cells)	Cell
Output power (10-s pulse)	600 W/kg, 2070 W/l	625 W/kg, 2160 W/l
Input power (10-s pulse)	480 W/kg, 1660 W/l	500 W/kg, 1720 W/l
Energy density	43 Wh/kg, 161 Wh/l	45 Wh/kg, 172 Wh/l
Nominal voltage	7.2 V	1.2 V

[a] Cut-off voltage of output power test is 6.0 V/module.

4.2.1. Discharge power characteristics

Fig. 7 shows the specific power characteristics of a battery module that consists of six cells at different SOC. A high power of approximately 800 W in a 2-s output and 650 W in a 10-s output can be obtained, and the equivalent specific power can also be obtained even at a low SOC. Such characteristics ensure constant input and output, which will be very advantageous for vehicle operation.

4.2.2. Charge efficiency

For practical use, high charge efficiency is required over a wide temperature range. Fig. 8 shows the charge efficiency. This shows that the battery has a very high charge efficiency, which provides high regenerative acceptability, over the SOC range mostly used during normal HEV operation. The Ah charge efficiency is nearly 100%. With this characteristic, a battery would be able to collect a lot of energy during deceleration with the regenerative brake system. Also because of the very small energy loss, the heat generation of the battery can be minimized. In addition, detection of the remaining capacity by current integration is practicable.

4.2.3. Life characteristics

For HEV application, the battery will be controlled so as not to be fully charged or fully discharged and will always be

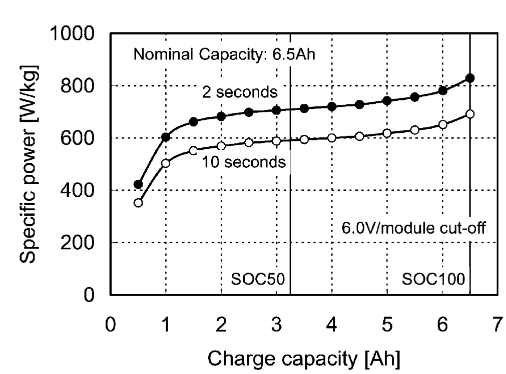

Fig. 7. Specific power of cylindrical battery module at different SOC.

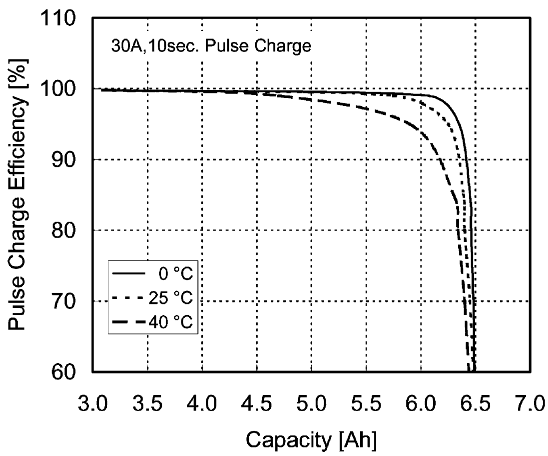

Fig. 8. Pulse charge efficiency of cylindrical battery module at different temperatures.

able to input or output energy. Considering this usage, a life test was done under various conditions. Fig. 9 shows an example of a life test in which the input and output power simulate real vehicle driving at 35°C.

As a result, the durability was found to be equivalent to more than 100,000 km driving and neither changes nor deterioration in battery characteristics were observed. These results lead to the conclusion that replacement of the battery will not be necessary before the end of life of the vehicle.

As described above, it is concluded that this battery is very suitable for the HEV application.

4.3. Battery pack for HEVs

A battery pack using these battery modules has high performance. The output power of this battery module is approximately 650 W. More than 20 kW of output power is easy for a pack which consists of 40 modules. Fig. 10 shows an example of a battery pack system. This battery pack system has a battery management system and a cooling system, which ensure high reliability, safety, long life as well as a high power of 21 kW.

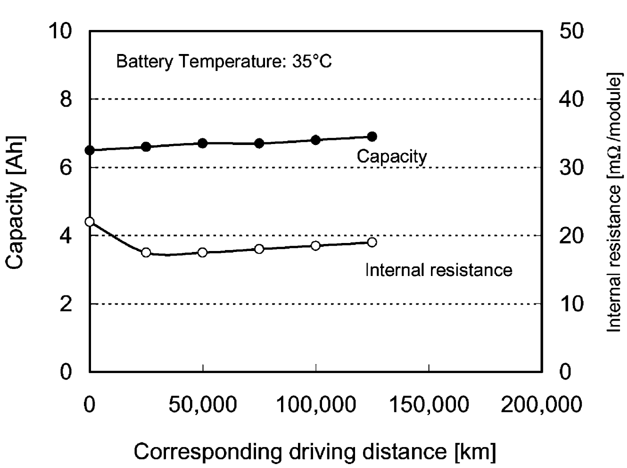

Fig. 9. Cycle life characteristics of cylindrical battery module with simulated actual driving pattern.

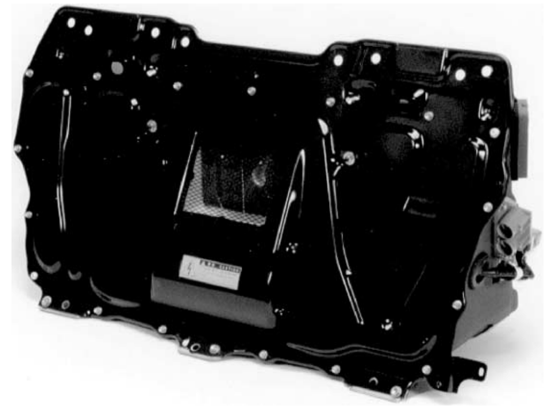

Fig. 10. Battery pack system for first generation Toyota Prius.

5. Prismatic Ni/MH battery for HEVs [8]

5.1. Module structure

To improve power and to reduce the cost of the battery system, a module of the prismatic design consists of six cells in series and this contributes to reduce the number of connecting parts. Fig. 11 shows the appearance of a prismatic module. The conventional cylindrical module has connecting plates to connect cells, and plastic insulating rings to prevent external short circuits. For the prismatic module, because internal connection is adopted, these parts are no longer necessary and as a result, a shorter current path has been accomplished. Also by investigation of electrode dimensions and current collector design, current flow path has been shortened. By thinning the positive and negative electrodes, the number of electrodes has been increased, which increases the reaction area and decreases the current density.

Resin material, which we use for pure EV battery, is adopted for the battery case to satisfy safety and reliability. The resin material can make it easy to design bumps and ribs on the side of the battery case. As shown in Figs. 11 and 12, in consequence of securing a path for cooling by bumps and ribs, the entire pack volume was enormously reduced by 40% in volume and 20% in weight compared to the cylindrical battery pack, because the module could be stuck together without any holder. Six cells connected internally form one module. This means that external connection parts like bus bars and connecting plates are not required. The high power prismatic Ni/MH battery for HEV was developed by combining the development of internal cell connection explained above and improvement in the materials of our 95 Ah battery for EV application.

Fig. 13 shows how we improved the power characteristics and reduced the internal resistance of the battery. The main

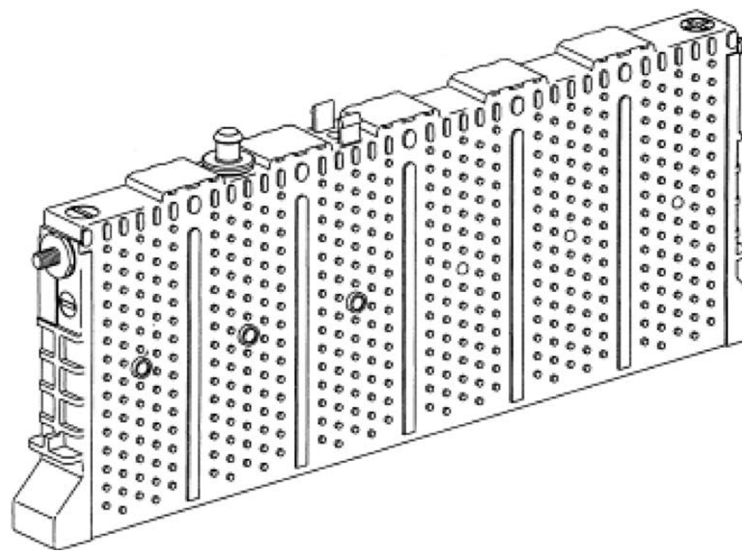

Fig. 11. Prismatic battery module for HEV application.

Fig. 12. Example of battery pack using prismatic modules.

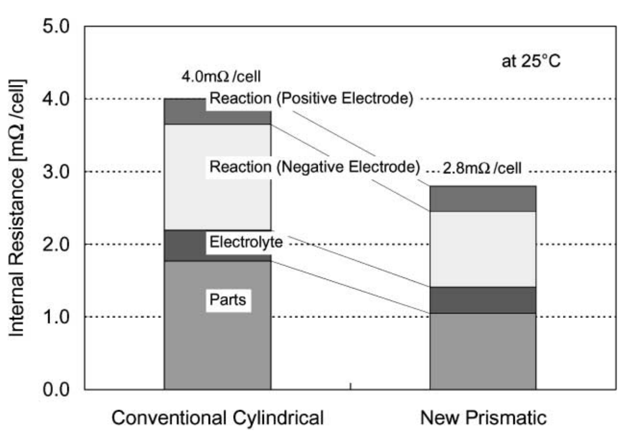

Fig. 13. Internal resistance of prismatic and cylindrical battery cell at initial stage (before activation).

source of the reduction is the components. The design for current collection was improved, and an internal cell connection was adopted. As a result, a high specific power of 1000 W/kg, which is higher than that of the conventional cylindrical battery, was achieved.

5.2. Module characteristics

Table 3 shows the basic characteristics of the module. The power characteristics are largely improved by the reduction of the internal resistance explained in Fig. 13.

5.2.1. Discharge power characteristics

Fig. 14 shows the power characteristics of the prismatic module at different SOC. This battery has a very high power, 1000 W/kg for 10-s power and 1150 W/kg for 2 s. Fig. 14

Table 3
Basic characteristics of prismatic battery module for HEV application[a]

	Prismatic module	Cylindrical module
Nominal voltage (V)	7.2	7.2
Nominal capacity (Ah)	6.5	6.5
Specific power (W/kg)	1000	600
Specific energy (Wh/kg)	46	43
Weight (g)	1020	1090
Dimensions	19.6 mm (width) × 106 mm (height) × 275 mm (length)	35 mm (diameter) × 384 mm (length)

[a] Cut-off voltage of specific power test is 6.0 V/module.

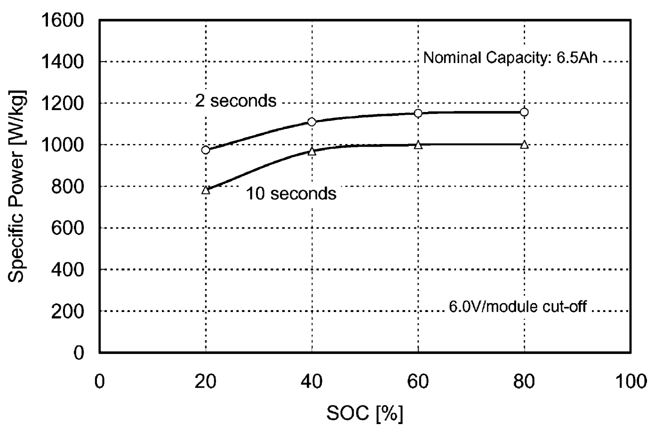

Fig. 14. Specific power of prismatic battery module at different SOC.

also shows that this battery has very high power even at low SOC, about 800 W/kg for 10-s and 1000 W/kg for 2-s power at 20% SOC.

Fig. 15 shows the power characteristics with temperature dependence of the conventional cylindrical battery and the new prismatic battery. The power characteristics at low temperature have improved from the cylindrical battery, (490 W/kg at 0°C and 120 W/kg at −30°C). Also the

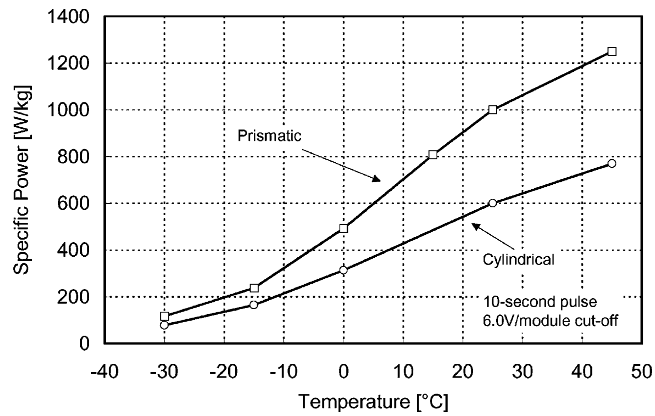

Fig. 15. Specific power of prismatic and cylindrical battery module at different temperatures.

temperature where power discharge of 200 W/kg is possible has been reduced by about 10°C from the cylindrical battery case.

5.2.2. Life characteristics

For HEV application, the battery will be controlled so as not to be fully charged or fully discharged and will always be able to input or output energy. Considering this usage, the life test was carried out under various conditions. Fig. 16 shows an example of a life test in which the input and output power simulate real vehicle driving.

Pattern A represents a normal driving profile, with a maximum SOC deviation of 15%, and pattern B represents a high load driving profile with a maximum SOC deviation of 30%. After testing corresponding to a driving distance of 300,000 km with pattern A at 35°C, there was no deterioration observed in battery performance. Also, with pattern B at 55°C, the battery showed no problem for achieving the driving distance of 200,000 km. This test is still going on. These results show that the newly developed prismatic Ni/MH battery possesses suitable characteristics for HEV applications.

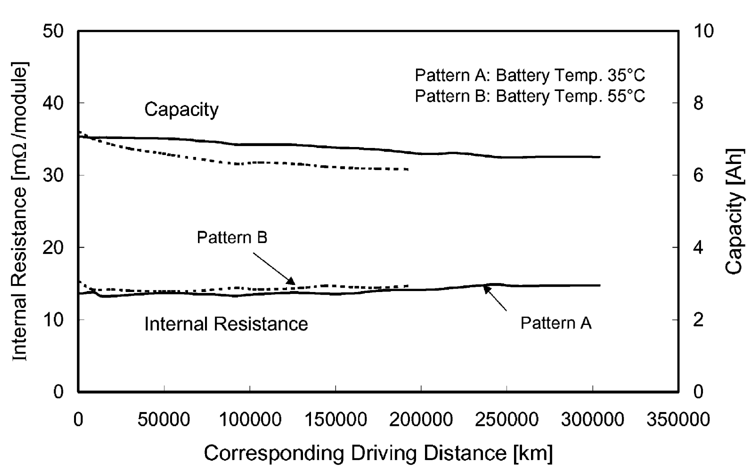

Fig. 16. Cycle life characteristics of prismatic battery module with simulated actual driving pattern.

6. Conclusion

EVs equipped with a high efficiency driving system (motor, inverter and so on) under development and a new type of battery have wiped out the old image of EVs that move at a snail's pace. They have achieved almost equivalent driving performance to gasoline fuel automobiles, and have contributed to remarkable progress toward practical use. HEVs have also been commercialized, and the development of eco-friendly and energy saving EVs and HEVs are expected to be a key technology in the 21st century.

The first generation Toyota "Prius", which is the world's first HEV in mass-production since the end of 1997 has a driving system with both a gasoline engine and an electric motor. The Ni/MH battery pack with the high power characteristics shown in Fig. 10 has achieved low energy consumption of 28 km/l which is equivalent to double the range achieved by 1.5 l gasoline fuel automobiles. The vehicle has realized a long driving distance, more than 100,000 km, which conventional vehicles had not attained.

An enormous reduction in emission gas has been concurrently attained, so that Prius ranks as the gasoline fuel automobile of the next generation. In addition, Honda has put the "Insight" on the overseas market since the end of 1999. The development and introduction of HEVs to the market by auto-manufacturers will be accelerated further. For success with EVs, development of a new type of battery is crucial. The battery will play a roll of "the heart of the EV" and it is necessary to establish a power system having high performance, reliability and safety.

References

[1] M. Ikoma, N. Fujioka, Kagaku to Kogyo 49 (1998) 45–51.
[2] M. Takaki, N. Fujioka, M. Ikoma, Development of small and medium sized sealed-type nickel/metal-hydride battery for electric vehicle, in: Proceedings of the 14th International Electric Vehicle Symposium, 1997.
[3] K. Ohta, K. Hayashi, H. Matsuda, Y. Toyoguchi, M. Ikoma, Nickel hydroxide: improvement of charge efficiency at high temperature, in: P.D. Bennett, T. Sakai (Eds.), Hydrogen and Metal Hydride Batteries, The Electrochemical Society, NJ, 1994, pp. 296–302.
[4] H. Ogawa, M. Ikoma, H. Kawano, I. Matsumoto, Metal hydride electrode for high energy density sealed nickel-metal hydride battery, Power Sources 12 (1988) 393–410.
[5] M. Ikoma, R. Umeo, H. Kawano, N. Yanagihara, Y. Ito, I. Matsumoto, Extended Abstracts of the 27th Battery Symposium, Japan, 1986, pp. 89–90.
[6] M. Ikoma, H. Kawano, Y. Ito, S. Ikeyama, I. Matsumoto, Extended Abstracts of the 28th Battery Symposium, Japan, 1987, pp. 113–114.
[7] T. Kimura, M. Ikoma, K. Kanamaru, Nickel/metal-hydride battery for power assist application, in: Proceedings of the 14th International Electric Vehicle Symposium, 1997.
[8] A. Taniguchi, N. Fujioka, K. Kanamaru, M. Ikoma, Development of prismatic nickel/metal-hydride battery for HEV, in: Proceedings of the 17th International Electric Vehicle Symposium, 2000.