Automotive Lithium-ion Batteries

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OVERVIEW: Activity has been picking up in the fields of hybrid and plug-in hybrid electric vehicle development because of the role they can play in solving increasingly severe global environmental problems. Hitachi is working on the development of lithium-ion batteries, the key devices for these vehicles. Development of the third generation of cylindrical batteries is now complete and they have been selected for use in hybrid vehicles to be produced by US firm General Motors Company from 2011. Also currently under development are a fourth generation of high-output batteries and new prismatic cells for plug-in hybrid vehicles.

INTRODUCTION

WITH the need to deal with global environment problems growing in importance, attention is being directed toward solutions to the problems of energy use. HEVs (hybrid electric vehicles), PHEVs (plug-in hybrid electric vehicles), and other vehicles that use rechargeable batteries have been commercialized and their use is rapidly becoming more widespread due to both their environment performance and economics. Although the rechargeable batteries currently used in most of these vehicles are Ni-MH (nickel metal hydride) cells, lithium-ion batteries have higher output and energy density and their use is growing.

This article describes the third-generation HEV lithium-ion batteries selected by General Motors Company (GM) for use in their HEVs, Hitachi's work on the next generation of HEV and PHEV batteries currently under development, and the outlook for these products.

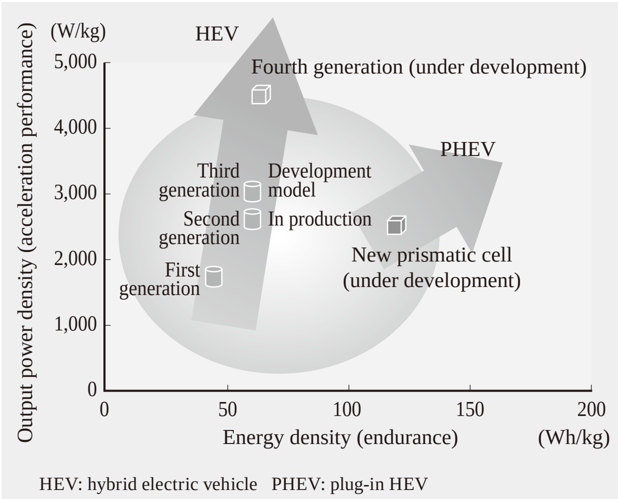


Fig. 1—Improving Performance of Hitachi Automotive Lithium-ion Batteries.
Hitachi has been working on improving battery output power and energy density through in-house development using manganese-based cathode materials as a base.

PAST ACTIVITIES

Hitachi has been developing automotive lithium-ion batteries since the 1990s and led the world in the production and bringing to market of batteries with high performance and long life.

Fig. 1 shows the evolution of battery performance over successive generations.

Although energy density and output power density are conflicting performance attributes, steady progress has been made through ongoing development of the active materials that play a key role in batteries.

These batteries have been used in a diverse range of vehicles since the release of the first generation and have already built up a market track record spanning more than ten years (see Fig. 2). The

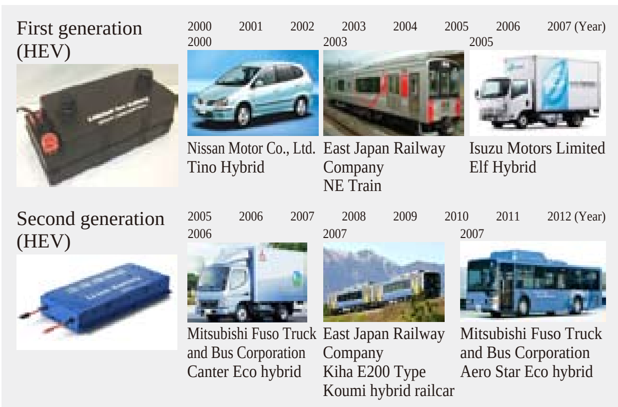


Fig. 2—Electric Vehicles Equipped with HEV Lithium-ion Batteries.
Hitachi's batteries have been used in a wide range of different vehicles where they have demonstrated a high level of system reliability.

second-generation batteries now in full production have an output power density of 2,600 W/kg and have recorded total sales in excess of 1.2 million cells.

THIRD-GENERATION HEV LITHIUM-ION BATTERY

Hitachi developed its third generation of lithium-ion batteries with high output power and long life to improve the performance of HEVs.

Battery Features and Performance

Table 1 lists the main specifications of the second- and third-generation batteries.

The third-generation batteries feature a high output power density of 3,000 W/kg together with small size and light weight. Materials-based changes aimed at improving the output power included optimizing the proportion of lithium and other metals in the manganese-based cathode and microstructure control to reduce the charge transfer resistance of the active material surface. Also, the battery's structure was designed to minimize the length of the cathode and anode leads and improvements were made to the welding methods to reduce the electrical resistance.

Fig. 3 shows a photograph of the third-generation battery, Fig. 4 shows a comparison of the input and output power characteristics of the second- and third-generation batteries, and Fig. 5 shows how the output power of the third-generation battery varies with temperature.

Another key objective during battery development was to improve its calendar life. HEVs require batteries with a life of ten years or more. Having excellent battery life characteristics means that the

TABLE 1. Main Specifications and Production Status of Second- and Third-generation Batteries

The main specifications of the second-generation lithium-ion battery currently in full production and the third-generation battery due to go into production in 2011.

	Second-generation battery	**Third-generation battery**
Status	In production	Enters production in 2011
Cell shape	Cylindrical	Cylindrical
Cathode material	Manganese-based	Improved manganese-based
Anode material	Amorphous carbon	Amorphous carbon
Capacity (Ah)	5.5	4.4
Weight (kg)	0.30	0.26
Power density (W/kg)	2,600	3,000

Fig. 3—Third-generation Lithium-ion Battery.
The new generation is based on a highly reliable cylindrical battery of which more than 1.2 million cells have already been sold.

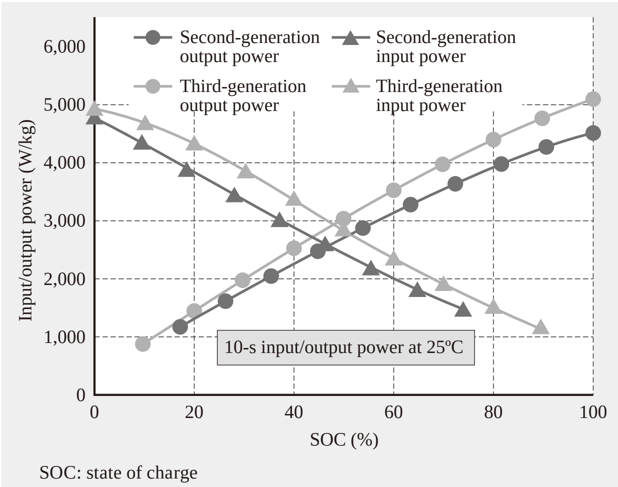


Fig. 4—Input and Output Power Characteristics of Second- and Third-generation Batteries.
The third-generation battery has an output power density of 3,000 W/kg at a 50% SOC.

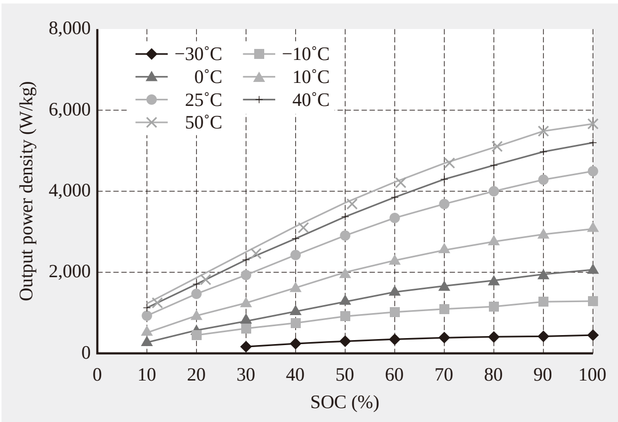


Fig. 5—Output Power Variation with Temperature for Third-generation Battery.
At -30ºC, the battery has an output power density of 300 W/kg at a 50% SOC.

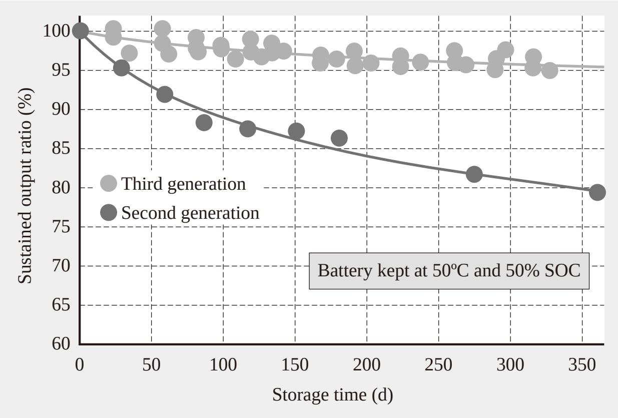


Fig. 6—Calendar Life Characteristics of Second- and Third-generation Batteries.
The significant improvement in the characteristics of batteries kept at high temperature allowed battery size to be reduced.

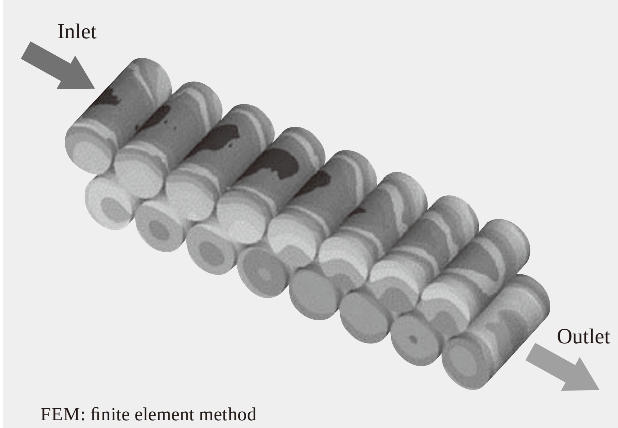


Fig. 7—Result of FEM Analysis of Cell Temperature in Battery Pack.
The cell layout, cooling flow, and other parameters were optimized to reduce cell temperature rise, minimize the variation in temperature between cells, and reduce pressure loss in the flow path.

TABLE 2. Abuse Test Results
No evidence of rupture or fire was seen under any of the test conditions.

Test	Test conditions	Result (EUCAR Hazard Level*)
Nail penetration	SOC 60%, 70%, 80%, 90%, 100%, @55ºC	3, 4
Crushing	255 kgw (2,500 N)-5 min SOC 60%, 70%, 75%, 80%, @55ºC	2
External short circuit	Circuit resistance: < 5 mΩ (1 mΩ) SOC 60%, 70%, 75%, 80%, @55ºC	2
Overcharge	From 100% to 200% SOC 32A-CC charge @55ºC	2
Over-discharge	From 100% to −100% SOC 1CA @55ºC	2
Hot box	Max. temperature: 250ºC, Rate of change: 5ºC/min 5ºC steps, 30 min hold time SOC 60%, 70%, 80%	3

EUCAR: European Council for Automotive R&D CC: constant current
* Level 4: More than 50% of electrolyte discharged from battery, Level 3: More than 50% of electrolyte remains in battery, Level 2: No venting or leakage

level of performance degradation is low and also helps make batteries smaller because it allows active materials to be used effectively.

Fig. 6 shows the output power temperature characteristics of the second- and third-generation batteries and the calendar life when maintained at a temperature of 50ºC.

The improvement in calendar life was achieved mainly through improvements in the anode structure and new electrolyte additives.

The safety of the lithium-ion batteries was also confirmed through extensive testing. Table 2 lists the main tests and their results. No evidence of rupture or fire was seen under any of the test conditions.

Battery Pack Development

Battery systems for HEVs require that the batteries be combined into packs made up of multiple cells connected together. Lithium-ion batteries also require a monitoring system to monitor each cell. Accordingly, Hitachi has developed battery packs that meet GM’s requirements.

Each pack consists of two 16-cell modules made up of two blocks of eight cells with the battery monitoring module located on top of the battery modules.

In addition to essential mechanical requirements such as vibration and shock resistance, a key focus in pack design is how to handle temperature management. The air cooling layout and operating conditions needed to reduce the overall temperature rise as well as inter-cell temperature variation are determined through repeated iterations of simulation and experiment. Also, to ensure the safety of the vehicle cabin if an abnormal situation arises, the pack is designed so that the cooling draft and gas exhaust grooves are entirely separate. Fig. 7 shows an example of the simulation.

A new custom ASIC (application-specific integrated circuit) with an enhanced self-diagnosis function was developed for use in the battery monitoring system. Functional safety testing was performed and an end-to-end diagnostic process that extends from the cell voltage input to the microcomputer was developed to implement a non-redundant architecture.

Each custom ASIC chip can monitor four or six cells. Fig. 8 shows the structure of the battery monitoring system.

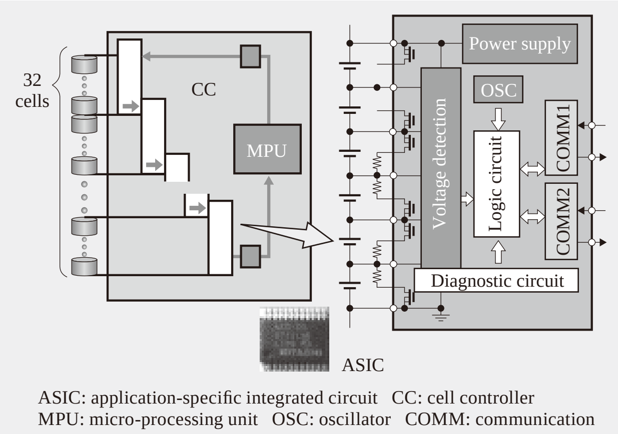
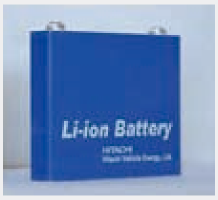


Fig. 8—Structure of Battery Monitoring System.
Hitachi has developed a new ASIC with a self-diagnosis function, conducted functional safety testing, and eliminated the backup over-voltage detection system.

Fig. 9—Production Line (Cell Assembly Line at Hitachi Vehicle Energy, Ltd.'s Tokai Plant).
The completed assembly line will have a capacity of 300,000 cells per month and will commence full-scale production in 2011.



	Third-generation	Fourth-generation
Status	Enters production in 2011	Under development
Dimensions (mm)	Φ40 × 92	120 × 90 × 18
Cell shape	Cylindrical	Prismatic
Cathode material	Improved manganese-based	Newly developed manganese-based
Anode material	Amorphous carbon	Amorphous carbon
Capacity (Ah)	4.4	4.8
Weight (kg)	0.26	0.24
Power density (W/kg)	3,000	4,500

Fig. 10—Fourth-generation Battery and Main Specifications of Third- and Fourth-generation Batteries.
The 4,500-W/kg output power density of the fourth-generation battery is among the best in the world.

Production Plants

Hitachi has completed construction of production lines for its third-generation cylindrical batteries with a capacity of 300,000 cells per month. The electrode production process will be performed at the Kyoto Plant of Hitachi Maxell, Ltd. and the cell assembly and battery pack assembly processes will be performed at the Tokai Plant of Hitachi Vehicle Energy, Ltd.

The production line will commence full-scale production of HEV batteries for GM in 2011. Fig. 9 shows part of a production line (cell assembly at the Tokai Plant of Hitachi Vehicle Energy).

DEVELOPMENT OF NEXT GENERATION OF BATTERIES

Development of Fourth-generation HEV Battery

As HEV performance improves, they require batteries that can deliver instantaneous power for engine-assist (high effective current). A prismatic battery designed to deliver high output power and heat dissipation is currently under development to meet this demand. Fig. 10 shows a photograph of this fourth-generation battery along with the main specifications of the third- and fourth-generation batteries.

The structure of the fourth-generation battery has been rigorously designed to minimize the internal resistance by determining the allowable resistance for each package model and using analysis of current flow in the current path to design the current collector and connection method. In terms of materials, the battery uses new materials designed with optimum grain size using microstructure control and other methods. Measures such as making the electrodes thinner were also used to reduce charge transfer resistance.

In performance testing, the battery demonstrated 1.5 times the output power density of the third-generation battery and good heat radiation performance. When operated continuously at 11 C (1 C is equal to the current at which the battery charges in an hour) under natural convection flow conditions, the temperature rise was approximately 23ºC and the temperature variation within the cell approximately 2ºC.

Development of Prismatic Battery for PHEVs

PHEVs have earned much attention for their ability to achieve improved gas mileage and reduced exhaust emissions by alternating between EV (electric vehicle) and HEV operation. Hitachi is developing a battery that combines high energy (for EV operation) and high output (for HEV operation) that can be used as a power source for PHEVs.

Specification	Value
Capacity (Ah)	25
Power density (W/kg)	2,400
Energy density (Wh/kg)	120
Weight (kg)	0.75
Dimensions (mm)	146×110×30

Fig. 11—Photograph and Specifications of New Prismatic Battery for PHEVs.
A prismatic battery for PHEVs with good safety characteristics and an appropriate balance of high energy (for EV operation) and high output (for HEV operation) performance is under development.

Although energy and output power are conflicting attributes in battery design, Hitachi was able to meet both objectives by using a low-resistance structure for the prismatic battery together with optimization of the electrode thickness and the composition of the active materials. Other measures undertaken to ensure that safety is maintained despite the higher battery energy included the use of a ceramic separator and development of new electrolyte additives. Fig. 11 shows a photograph of the PHEV battery and its specifications.

CONCLUSIONS

This article has described the third-generation HEV lithium-ion batteries selected by General Motors Company for use in their HEVs, Hitachi's work on the next generation of HEV and PHEV batteries currently under development, and the outlook for these products.

Hitachi sees its automotive lithium-ion battery business as providing a key pillar in the solution of global environmental problems and intends to contribute in the future through the supply of highly reliable high-performance batteries while also working actively to satisfy future market needs by taking up the challenge of further battery innovation.

REFERENCES

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