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Thermal Evaluation of Toyota Prius Battery Pack

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ABSTRACT

As part of a U.S. Department of Energy supported study, the National Renewable Energy Laboratory has benchmarked a Toyota Prius hybrid electric vehicle from three aspects: system analysis, auxiliary loads, and battery pack thermal performance. This paper focuses on the testing of the battery back out of the vehicle. More recent in-vehicle dynamometer tests have confirmed these out-of-vehicle tests. Our purpose was to understand how the batteries were packaged and performed from a thermal perspective. The Prius NiMH battery pack was tested at various temperatures (0°C, 25°C, and 40°C) and under driving cycles (HWFET, FTP, and US06). The airflow through the pack was also analyzed. Overall, we found that the U.S. Prius battery pack thermal management system incorporates interesting features and performs well under tested conditions.

INTRODUCTION

The National Renewable Energy Laboratory (NREL) performs research and development of hybrid electric vehicles (HEVs) as part of a program sponsored by the U.S. Department of Energy's (DOE) advanced automotive technologies. One purpose of the program is to benchmark commercial HEVs for potential use by Partnership for New Generation Vehicles (PNGV) partners. NREL obtained one of the first U.S. marketed hybrid vehicles, the 2000 North American version of the Toyota Prius, for system level vehicle analysis in ADVISOR vehicle simulations, evaluation of auxiliary loads such as the air conditioner's impact on fuel economy, and evaluation of battery thermal performance. This paper focuses on battery pack thermal evaluation while it was out of the vehicle, but will not present more recent in-vehicle dynamometer results. By analyzing the Prius battery pack, one can gain insight into how to design thermal management systems that can enhance battery pack performance for HEVs.

The Toyota Prius is a five-passenger compact sedan powered by a 52 kW gasoline engine and a 33 kW electric motor. It has a curb weight of 1254 kg. The Prius has a complex dual-mode hybrid configuration in which energy to and from the vehicle wheels can travel along several different pathways. Mechanical energy to the wheels passes through a planetary gear set that couples to the engine, electric motor, generator, and to the final drive. Power to the wheels can be provided solely by a (273.6 Volt Nickel Metal Hydride [NiMH]) battery pack through the electric motor, directly from the gasoline engine, or from a combination of both the motor and the engine. The battery pack can be recharged directly by energy from the wheels powering the motor (regenerative braking) or from excess energy from the gasoline engine – which turns the generator [1].

The following sections explain how the Prius battery pack is constructed, how it is thermally managed, and how the NiMH batteries perform at different temperatures under controlled laboratory conditions that simulate various drive cycles. More in-depth analyses can be found in the DOE report written by Zolot et al. [2].

BATTERY PACK DESCRIPTION

The Module. Toyota uses prismatic NiMH modules from Panasonic. Each module, shown in Fig. 1, consists of six 1.2 V cells connected in series. The module has a nominal voltage of 7.2 V, capacity of 6.5 Ah, weighs 1.04 kg, and has dimensions of 19.6 mm (W) X 106 mm (H) X 275 mm (L). Further notable features are as follows:

- A thermal well on top of the cell allows measurement of an approximate internal temperature of the electrolyte,
- A hydrogen vent provides for release of hydrogen through a manifold under gassing conditions,
- Terminals on each side provide clean connections,
- Tie down bolts secure the modules to structural supports,
- A plastic case lowers mass, and

- The side surfaces of the module provide air gaps for airflow created by dimples and protrusions when two modules are stacked.

This Panasonic design has improved in specific energy and power capabilities over the first generation cylindrical cells that are in the 1999 Japanese Prius and the 2000 Honda Insight [4].

The Pack. The Prius battery stack consists of 38 prismatic NiMH modules connected in series. It delivers a nominal 273.6 Volts and has a 6.5 Ah capacity. The modules are stacked side by side and then compressed together in a rigid, non-expandable structure that prevents expansion from internal pressures. The complete battery pack consists of the battery stack, enclosure for structural support and airflow, battery electronic control unit/monitor (left end of pack), relays and safety switch (also left end of pack enclosure). The weight of the complete battery pack is 53.3 kg. The pack, shown in Fig. 2, is horizontally positioned in the trunk of the vehicle partially under the back seat. Power electronics (inverter, DC-DC converter) are under the hood and a blower for moving air and associated air ducts are in the trunk.

We conducted hybrid pulse power characterization (HPPC) tests per the PNGV Battery Test Manual [3] to obtain power performance of a module at various states of charge (SOC) and temperatures (0°C, 25°C, and 40°C). The discharge and regenerative power performance of the pack (extrapolated from module tests) is shown in Fig. 3. Discharge power capability of the Prius pack is around 20 kW at 50% SOC with regenerative capability of 14.5 kW at 25°C. The power capability increases with higher temperatures and decreases at lower temperatures. Active thermal management can improve power capability at lower temperatures.

PACK THERMAL MANAGEMENT

Generally, the purpose of a battery thermal management system is to keep the batteries operating at a desirable temperature range; prevent the batteries from exceeding a high temperature limit that can damage the batteries and/or reduce life; and maintain battery temperature variations to low levels to prevent highly imbalanced batteries. Pack imbalances can reduce performance and can also damage the battery and/or reduce life. Thermal management of the battery pack is typically accomplished with the combination of two approaches. First, a cooling/heating system is designed to extract/supply heat to the battery pack. Second, the battery controller adjusts the vehicle's use of the battery pack based on the conditions in the batteries.

Forced Air System. The Prius supplies conditioned air from the cabin as thermal management for cooling the batteries. The pack's forced air system consists of two vents located in the cabin under the middle brake light (exhaust from the cabin or inlet to the pack); ducting to the battery pack enclosure; the enclosure manifold; air gaps between modules; ducting out of the pack to a blower that pulls the air through the system; and two exhausts (one to the trunk and the other to the outside). A hydrogen vent from each module is connected in series with tubing. Any gases released are exhausted from the vehicle through the gas manifold to avoid any increased hydrogen concentration and, thus, potential for explosion.

Outside air is conditioned (heated or cooled) by the vehicle's thermal comfort system to a level comfortable for the driver. This approach has the advantage of providing air that is not only comfortable to the passenger(s), but also ideal for use in heating or cooling the NiMH batteries. However, recent in-car dynamometer tests show that the Prius does not use the forced air for heating the batteries. Moreover, the concerns with this approach are twofold: relatively slow transient time to heat or cool outside air and thus the battery pack; and the ducting between the battery and cabin, which in the event of an accident or catastrophic failure, provides hydrogen and other gases a path to the cabin.

To achieve a relatively uniform temperature distribution across the modules, a *parallel* airflow scheme is used, as suggested by Pesaran et al. [5], rather than a *series* configuration. In a parallel configuration, each module is set up to receive the same amount of airflow and thus the same cooling. To achieve this in the Prius, cabin air enters the pack through a plenum that runs beneath the battery stack horizontally from passenger side to driver side. The cross-sectional area of the plenum is largest at its entrance and linearly decreases as it goes under the modules. Then the air flows vertically through the gaps between each module (formed from dimples and protrusions on side walls). Finally, the air enters into the top plenum. This plenum's cross-section increases linearly in the direction of the flow. With this design, the pressure drop across each module is expected to be uniform and, consequently, should lead to a uniform flow rate around each module.

The air is drawn by a 12 V blower installed above the driver's side rear tire well. The air is either exhausted to the trunk or through a vent on the driver's side C-pillar. The fan has four settings, depending on the maximum temperature of four monitored batteries. Toyota also monitors the inlet and outlet air temperatures. The fan settings are off, low, medium, and high speed. We conducted airflow tests with the pack in vehicle, out of vehicle, with flow meter, and without flow meter and obtained correlations between pressure drop, flow rate, blower power, and blower settings. The blower setting depended on temperature, as shown in Fig. 4, and transitions with hysteresis depending on whether temperature is increasing or decreasing.

Table 1 summarizes the results of the flow tests for Denver elevation (1 mile above sea level, equal to 0.81 atmosphere). At sea level, the pressure drop across the pack and the required power will increase compared with tests at Denver elevation.

EXPERIMENTAL SETUP

Instrumentation. In order to acquire the appropriate data from the vehicle components, we instrumented the Prius and its battery pack with an on-board data acquisition unit (DAQ). The DAQ unit takes data while driving on the dynamometer, on the road, or during out-of-vehicle pack testing. The data is collected using a National Instruments SCXI (Signal Conditioning eXtended Interface) chassis. It provides a flexible test configuration because it is capable of handling numerous signals with a broad range of voltage levels ranging from millivolt level thermocouple signals to 300 V signals. The SCXI chassis is currently used to measure 60+ thermocouples located throughout the car and the battery pack, 20+ voltages, a handful of current shunts, and miscellaneous other signals. Finally, the SCXI multiplexes the signals and feeds them to a PCMCIA DAQ card at aggregate rates up to 20 kHz.

Vehicle environments, particularly HEVs like the Prius, add substantial EMI (ElectroMagnetic Interference). We took several precautions to eliminate, when possible, or otherwise filter out the EMI in the signals. Several of the hardware solutions were specifically chosen for their ability to eliminate noise and clean up signals. Software solutions were also incorporated to reduce noise below acceptable levels.

The batteries were thoroughly instrumented with thermocouples. Toyota instrumented four of the thermal wells, but we instrumented all 38 thermal wells in order to see the thermal gradient across the entire pack length. Also, to look at the thermal gradient across a single module, three of the module faces were instrumented. The voltage measurements we make are piggybacked off the same connections that Toyota has in place for battery monitoring. The voltage is measured across every two modules. A voltage measurement across a shunt (a resistor) is used to calculate current though the pack.

For initial tests, the pack was removed from the vehicle and was placed in an environmental chamber with controlled temperature while undergoing different charge/discharge drive cycles. Fig. 5 shows the chamber, the ABC-150 battery pack cycler in the background and the DAQ unit on the right. The battery pack with ducting and the heat exchanger are also shown in the environmental chamber in this figure.

Tests Performed. The objective of these tests was to evaluate the thermal performance of the pack at three temperatures (0°C, 25°C, and 40°C) and during different drive cycles/power profiles. The forced-air system was characterized as part of the testing as described in the previous section. The pack was cycled (charged/discharged) to determine capacity (Ah) at each temperature. After cycling, the capacity data were used to bring the pack to 50% SOC before the drive cycles were run. This start point, determined from discussions with Toyota engineers, is based on the principle that the vehicle controls the pack to a set point of approximately 50% SOC when running the vehicle at typical loads, like those seen during the federal test procedure prep-cycles on a dynamometer. Cycles were run consecutively for about 2 hours to evaluate the thermal management system, the pack's thermal response and the pack's general electrical performance during a long drive.

Many tests were conducted at the different temperatures and over four drive cycles [2]. Three of the drive cycles were standard cycles. The following are the drive cycles we used for imposing a power profile on the pack:

1. Highway Fuel Economy Test (HWFET)
2. FTP-75 Cycle
3. US06 Cycle based on ADVISOR simulations
4. SUV 25-Minute Cycle

The HWFET and FTP-75 power profile data for the battery pack were obtained directly from preliminary testing of the U.S. Prius at Environmental Testing Corporation in Denver, Colorado. The HWFET driving cycle is used to simulate highway driving and estimate typical highway fuel economy. The FTP-75 is a federal test procedure for emissions certification and urban fuel economy determination for light duty vehicles. The US06 cycle is based on the federal US06 driving schedule that simulates high speed and acceleration (aggressive driving). We simulated the US06 battery power profile for the U.S. Prius based on an ADVISOR vehicle simulation scaled to fit the control and components in the U.S. Prius. The SUV 25-minute profile was provided to us by one of our clients. This cycle is a sport utility type of duty cycle that a battery pack could experience during an aggressive 25-minute drive.

TEST RESULTS

This section describes the temperature response during the 12 consecutive ADVISOR US06 drive cycles (2 hour test duration). Focus is on the US06 results because this cycle stresses the pack more (and possibly more realistically) than the less aggressive highway and FTP cycles. Because of space limitations, only selected test data will be discussed here.

US06 Testing at 25°C. At 25°C the battery pack temperatures reach a quasi-thermal steady state during the 12 consecutive US06 cycles seen in Fig. 6. At 25°C, the maximum temperature distribution across the modules was moderately high at 5.0°C. The maximum temperatures seen by the battery are 43.0°C, and the mean battery temperature reached a maximum of 41.2°C. Toward the end of the third cycle the blower came on at low speed (at about 28 minutes). The battery temperatures went into steady state cycling about 30 minutes after the blower turned on. Since the thermal management system is able to level off the temperatures rise, the maximum temperatures and maximum temperature differentials are both attained by one hour into the test. The blower load (4.66W) resulted in a 7.1 Wh energy drain during this drive. Ultimately, during a mild day with relatively aggressive driving (maximum speed of 80.3 mph) that lasts as long as 2 hours, the U.S. Prius pack performs quite well.

US06 Testing at 0°C. The testing at 0°C indicates that the maximum temperature distribution across the modules increases more readily from the lack of airflow.

The maximum temperature differential across the pack is 11.4°C as seen in Fig. 7. The maximum temperatures the battery attained were 39.1°C, and the mean battery temperatures attained were a maximum of 37.2°C. The blower was used only for cooling at about 80 minutes into the test. The temperature differentials seen during this and the other cycles bring the thermal performance at low temperatures into question, but the cabin temperature warm-up was not simulated. However, our recent dynamometer tests showed that the battery fan does not turn on as the cabin warms up even if the battery pack is at –25°C. Since the Prius does not operate the fan at colder temperatures, high temperature differentials were seen during in-car dynamometer testing also. In recent dynamometer testing, tests more accurately represented cabin heating also.

US06 Tests. During the consecutive 40°C US06 cycles in Fig. 8 the battery pack seems to go into quasi-thermal steady state. The maximum temperature distribution across the modules was moderately high with a maximum of 4.75°C. The maximum temperature the batteries attain is 51.5°C; the mean temperatures reach a maximum of 49.4°C. The blower switched from low to medium speed after 3.6 minutes. About 1.5 hours into the test, the battery temperatures went into steady state cycling. Overall, blowing 40°C air for removing heat from the system proved effective during consecutive US06 cycles because the battery pack was able to maintain power demands, and the blower was able to limit maximum temperatures. Yet, the airflow system was not able to keep the temperature below 50°C. However, the high inlet air temperature (40°C) is an extreme for a steady state cabin temperature, so if the vehicle were under the same duty cycle with cabin air at comfortable conditions, we would expect lower steady state battery temperatures. Hence, the thermal management system would perform better under cooler cabin conditions that would realistically occur.

A top-down view of the battery modules is illustrated in Fig. 9. This plot shows the temperature distribution across the modules at the very end of the 40°C ADVISOR US06 trials. The modules at both ends are relatively cooler than the middle ones. This trend is seen throughout testing, even at room temperature and with no fan operation. This occurs because the end modules are receiving only half the heating the inner modules receive (they are the only modules with only one neighboring module). The ends of the pack are also closed off with the aluminum end plates, so the thermally conductive metal end plates will also help to remove more heat from these end modules. Additionally, this figure illustrates that the temperature is decreasing slightly (4°C) in the flow direction. This is an indication of an uneven airflow distribution across the pack.

SUV 25-Minute Test. The SUV 25-minute cycle was performed at 25°C only about 1.7 times for a total drive time of 42.6 minutes. The cycle could not be repeated for 2 hours like other cycles because at 42.6 minutes the pack temperature hit the high temperature limit of 55°C. The DAQ protected the pack by cutting the power from the cycler. The SUV 25-minute cycle, in Fig. 10, is a very aggressive cycle with significant heat generation that the Prius' thermal management system was unable to sustain after the first cycle. Calorimeter tests indicate that the heat generation over the first cycle (25 minutes) is about 27.84 W/module, nearly three times the heat generation from the ADVISOR US06 cycle. The blower used all four fan-speeds during this test. The temperature distribution steadily rose and ended the test with a distribution of about 6.8°C. It is anticipated that with the battery pack in the vehicle, the battery controller will adjust the power use when a certain battery temperature is achieved. For example, the controller may start to scale down the power the battery supplies/accepts when a battery temperature reaches 45°C. However, we did not try to simulate this behavior in the laboratory while conducting these tests.

CONCLUSION

The NiMH Prius battery pack was tested at various temperatures (0°C, 25°C, and 40°C) and under driving cycles (HWFET, FTP, US06, and SUV 25-minute). The following are selected sets of observations and conclusions from this research:

- Panasonic has incorporated several interesting features in the NiMH module from a thermal standpoint such as a thermal well on top of the module for measuring the internal temperature of the module; a hydrogen vent for release of hydrogen through a manifold under gassing conditions; and use of dimples and protrusions on the module face to create gaps for flowing air to facilitate thermal management.
- According to PNGV HPPC test procedure, discharge power capability of the Prius pack is around 20 kW at 50% SOC with regen capability of 14.5 kW at 25°C. The power capability increases with higher temperature and decreases at lower temperature.
- The Prius battery pack's thermal performance at 25°C is very good for all the cycles. The temperatures are maintained below 45°C over the 2-hour test durations for all the standard drive cycles. Temperature differentials are also managed quite well at or below 5.0°C. The battery hit the maximum temperature limit of 55°C only for the very aggressive SUV 25-minute cycle.
- At 40°C, the Prius pack also performed reasonably well. Under elevated temperature tests, the pack is able to keep temperatures maintained at levels below 52°C. Temperature differentials across the pack are very good with maximums below 5°C for all tests.
- At 0°C, temperature differentials that develop across the battery pack (>11°C at times) as it warms up are not desirable. Also, active thermal management tests resulted in average battery temperatures rising more quickly. Thus, active battery thermal management could help at cold temperatures
- The temperature distribution across the U.S. Prius pack could be improved significantly if insulation were added to the two end modules on their outside faces rather than the metal structural plates that act as heat sinks.

Overall, we found that the U.S. Prius battery pack thermal management system incorporates interesting features and performs well under tested conditions. More recent work includes dynamometer testing and on-the-road testing to evaluate how real world conditions, like cabin cool-down and temperature adjusted electric power requests, effect the battery thermal performance. Preliminary analyses of dynamometer tests have shown very good agreement with the 2-hour simulated laboratory cycles.

ACKNOWLEDGMENTS

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Table 1: Pack Air Flow Characteristics (Ambient pressure = 0.81 atmosphere)

Blower Setting	Temp. ON (C)	Temp. OFF (C)	Motor Voltage (Volts)	Motor Current (Amps)	Motor Power (Watts)	Air Flow Rate (SCFM)	Pressure Drop across Pack (in H20)
Off	-	-	0.00	0.0000	0.00	0.00	0.000
Low	35.5	33.0	3.52	1.3250	4.66	15.90	0.095
Medium	41.5	40.0	6.50	2.7000	17.55	32.60	0.350
High	50	48.0	9.90	4.9875	49.38	48.40	0.770

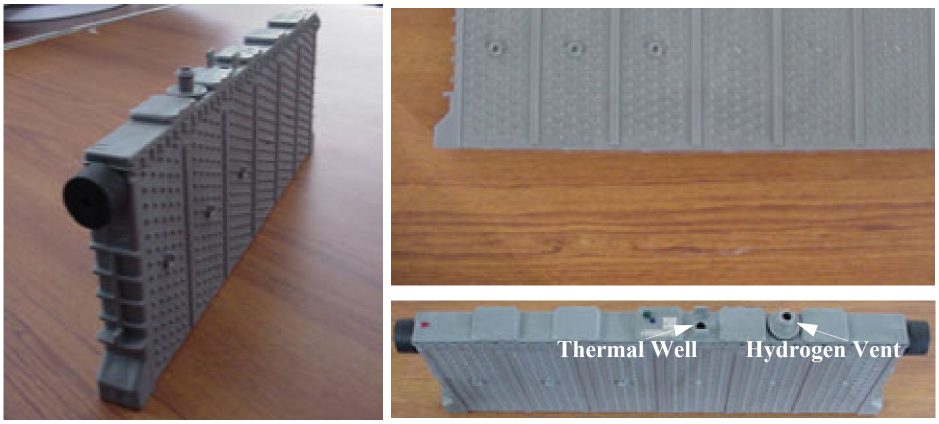

Figure 1: Panasonic Prismatic NiMH Module in the U.S. Toyota Prius

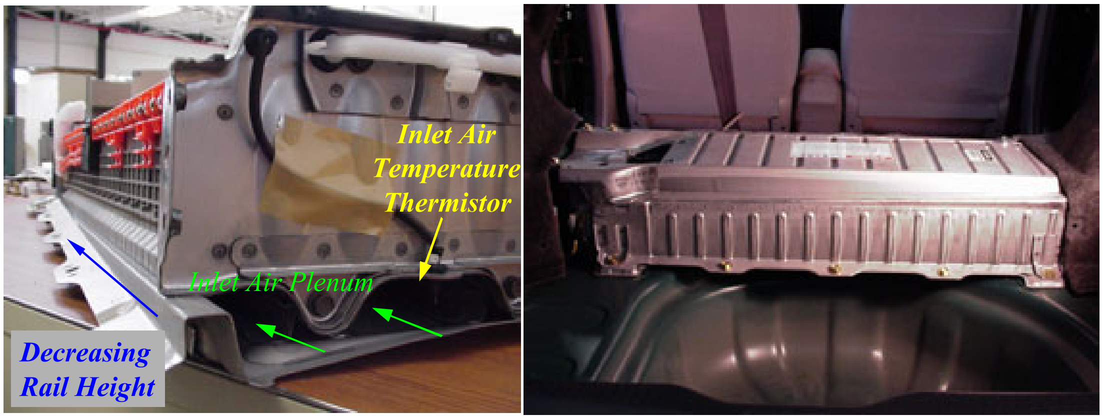

Figure 2: Prius Battery Pack

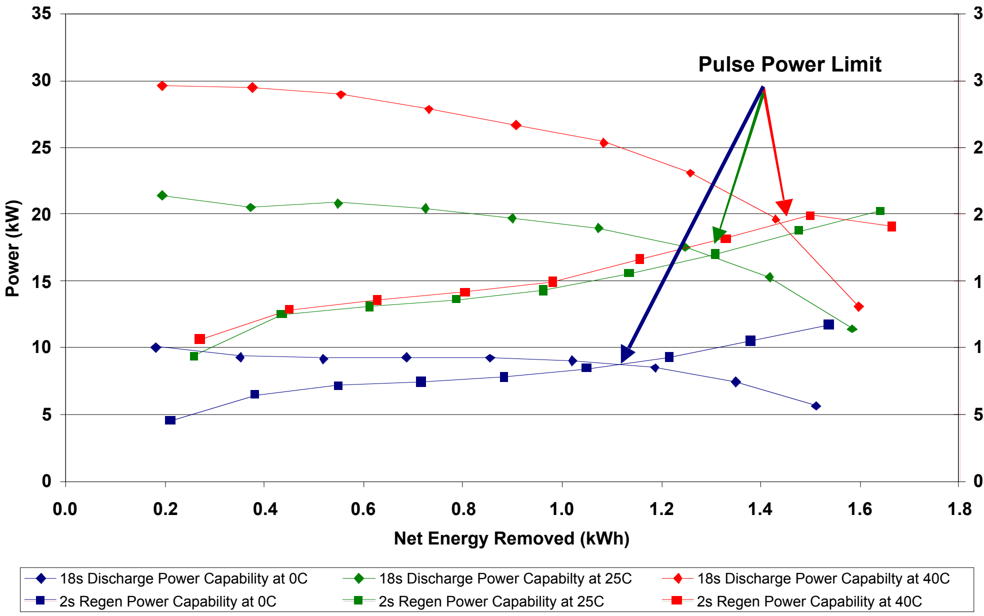

Figure 3: U.S. Prius Panasonic 6.5 Ah Pack Power from PNGV HPPC Tests
(Extrapolated from module level tests)

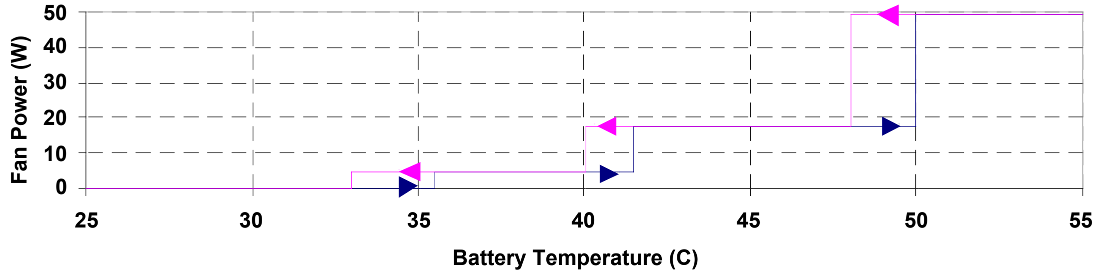

Figure 4: Battery Pack Blower Power vs. Detected Battery Temperature at Denver Elevation (0.81 atmosphere)

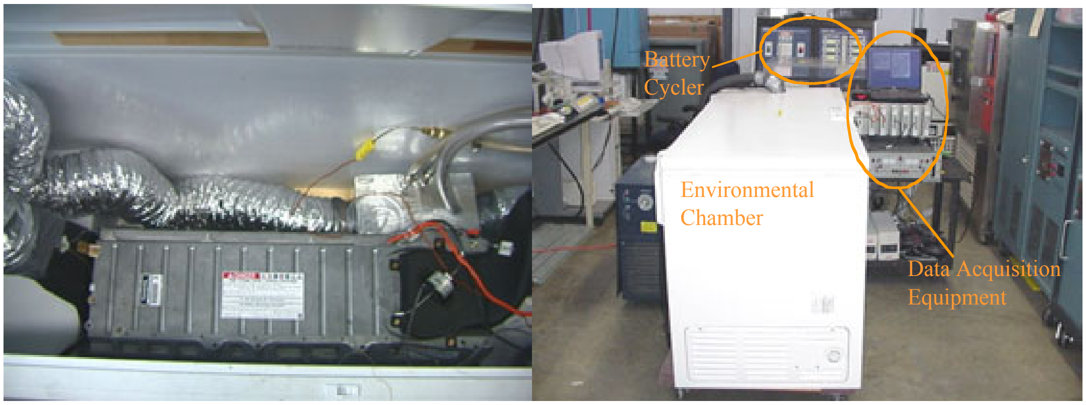

Figure 5: Experimental Set Up for Testing Prius Battery Pack

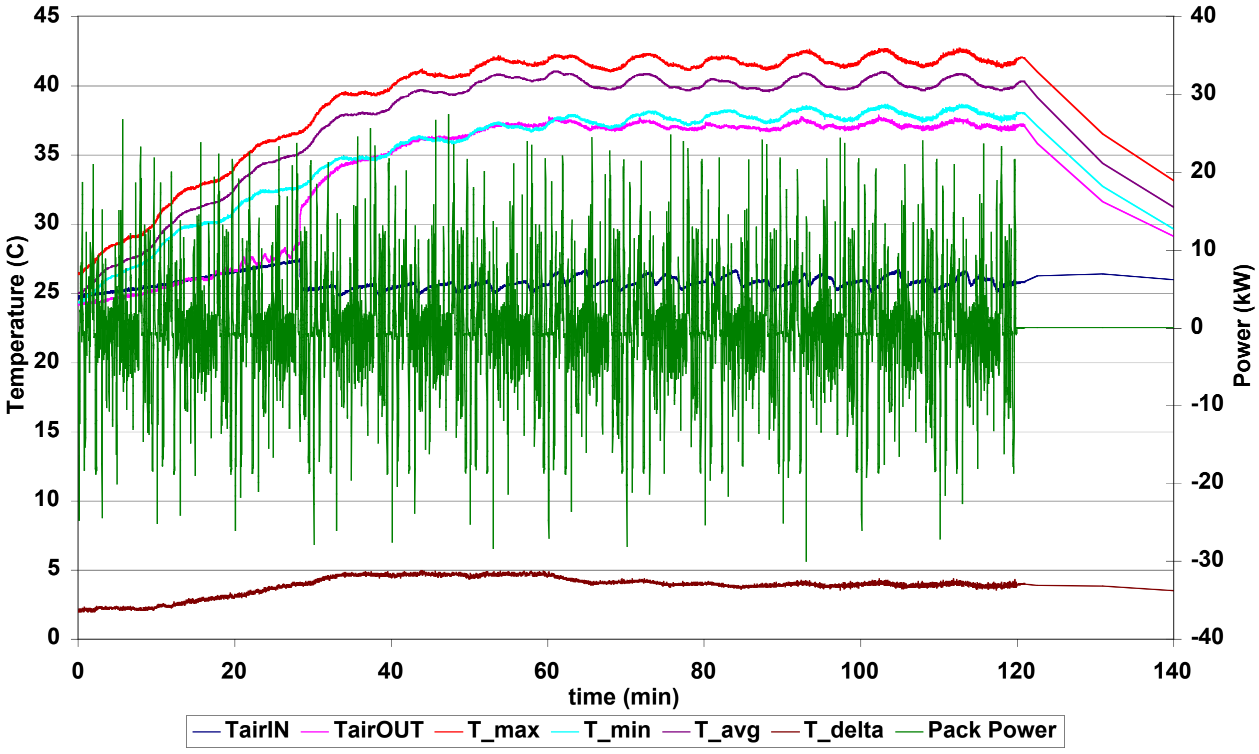

Figure 6: Thermal Response of U.S. Prius Pack to US06 Cycles at 25°C

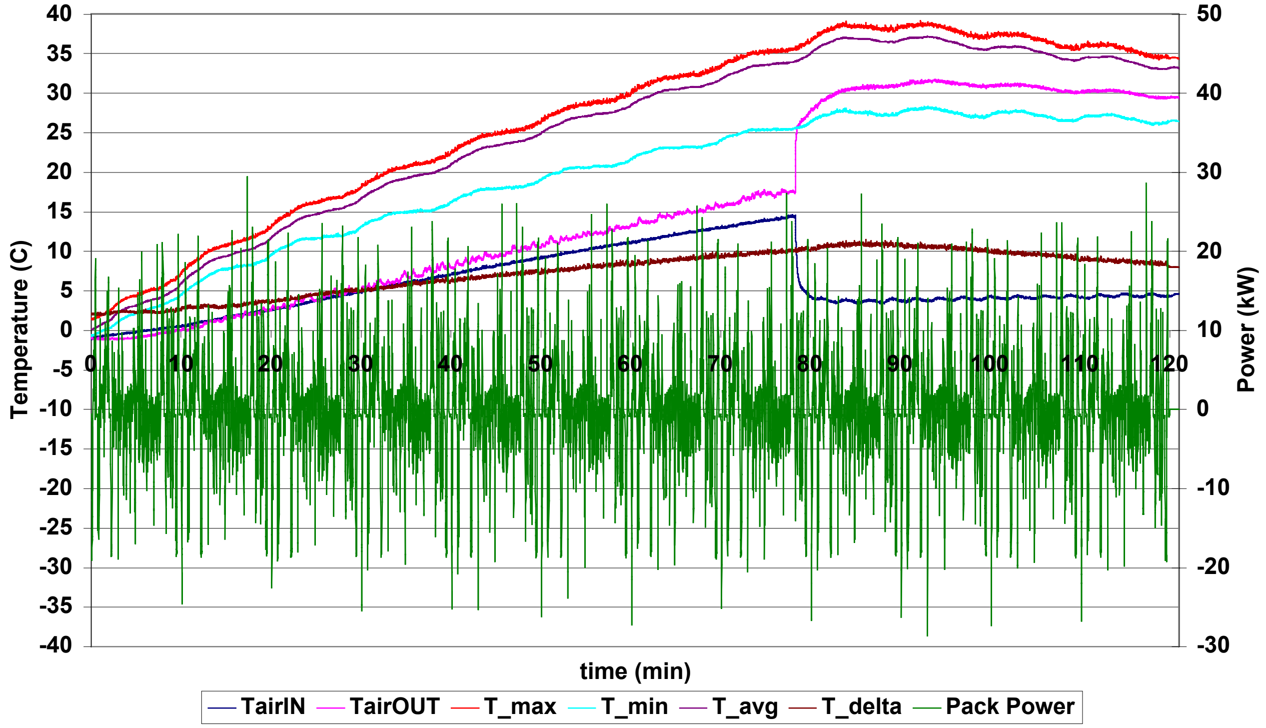

Figure 7: Thermal Response of U.S. Prius Pack to US06 Cycles at 0°C

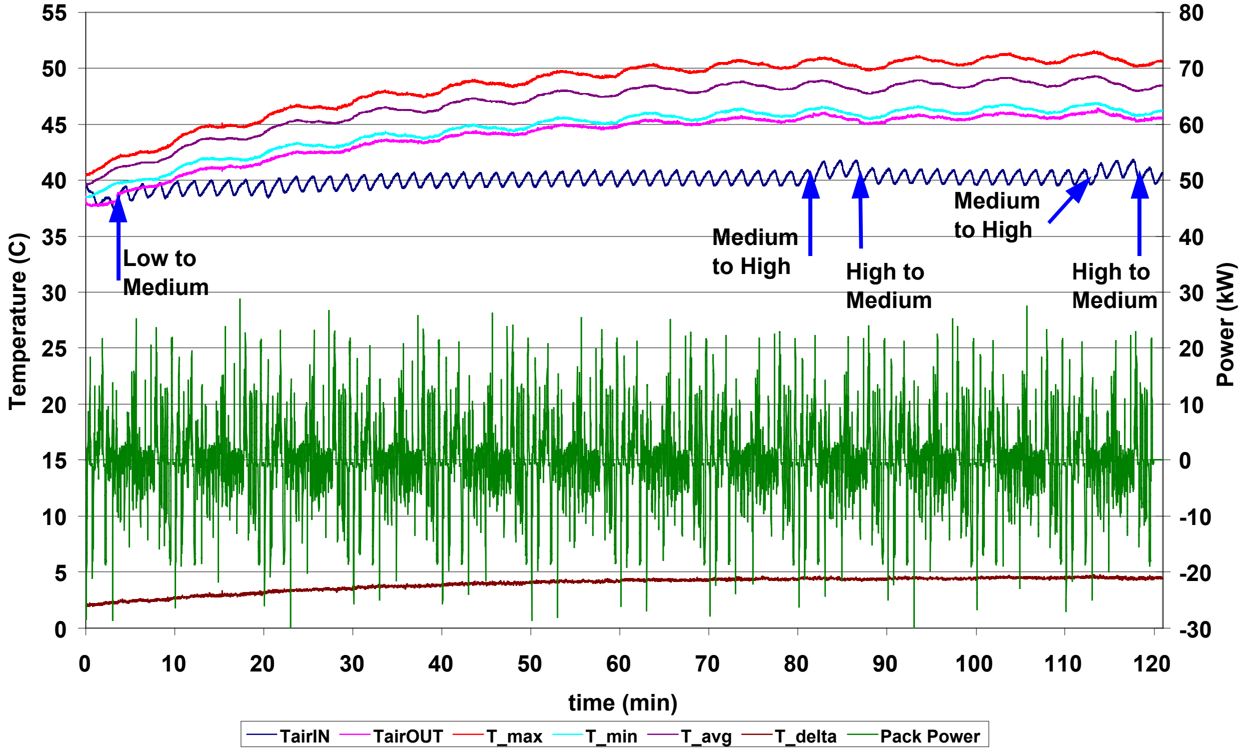

Figure 8: Thermal Response of U.S. Prius Pack to US06 Cycles at 40°C

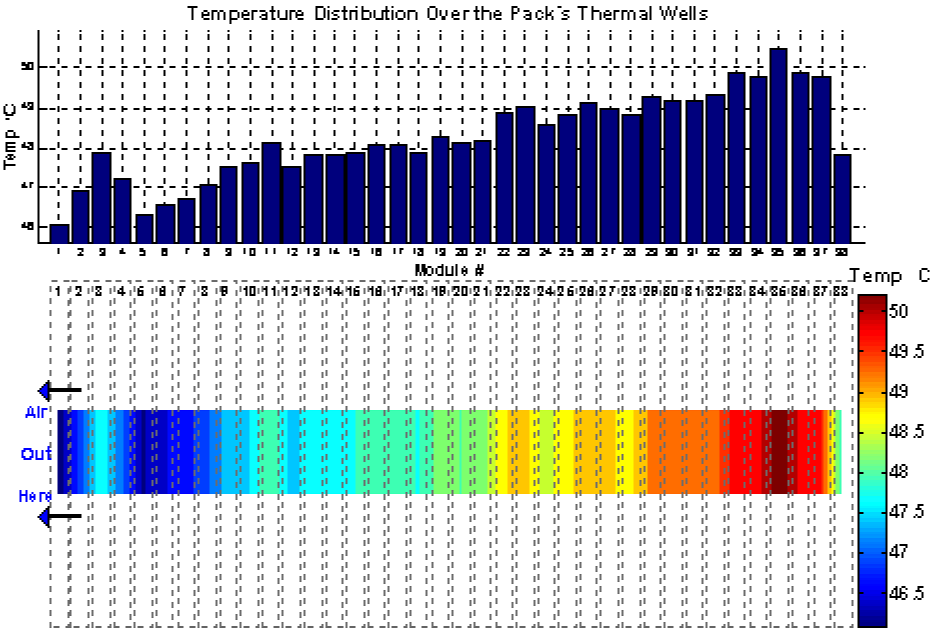

Figure 9: Temperature Distribution in Battery Pack after 12th US06 Cycle at 40°C

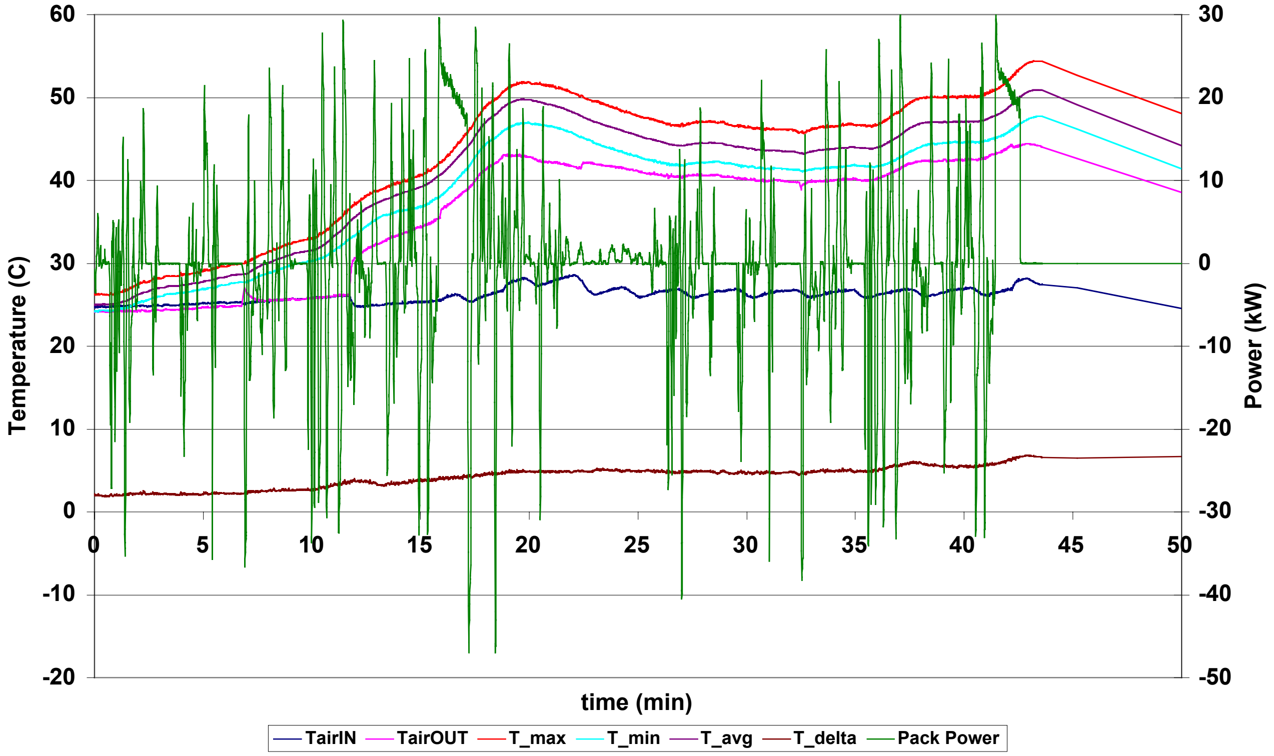

Figure 10: Thermal Response of U.S. Prius Pack to SUV 25-Minute Cycles at 25°C