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Thermal Evaluation of the Honda Insight Battery Pack

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THERMAL EVALUATION OF THE HONDA INSIGHT BATTERY PACK

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ABSTRACT

The hybrid vehicle test efforts at National Renewable Energy Laboratory (NREL), with a focus on the Honda Insight's battery thermal management system, are presented. The performance of the Insight's high voltage NiMH battery pack was characterized by conducting in-vehicle dynamometer testing at Environmental Testing Corporation's high altitude dynamometer test facility, on-road testing in the Denver area, and out-of-car testing in NREL's Battery Thermal Management Laboratory. It is concluded that performance does vary considerably due to thermal conditions the pack encounters. The performance variations are due to both inherent NiMH characteristics, and the Insight's thermal management system.

INTRODUCTION

The Hybrid Electric Vehicle Group at National Renewable Energy Laboratory (NREL) has tested the first U.S. market intended hybrid vehicle, the Honda Insight, for benchmarking, system analysis validation, battery thermal evaluation, and auxiliary load analysis as part of the U.S. Department of Energy's hybrid electric vehicle research program. This paper focuses on the Honda Insight's battery thermal management, the vehicle's performance with its nickel metal hydride (NiMH) batteries at various temperatures, and evaluation of the NiMH pack over its full range of functionality. By analyzing the Insight battery pack, further improvements can be made in how packaging, thermal management, and electronic management can enhance battery packs for hybrid electric vehicles. The NREL Battery Thermal Management Team's involvement in this evaluation aims to help improve battery economics, performance and reliability.

NOMENCLATURE

DOD–Depth of Discharge
HPPC–Hybrid Pulse Power Characterization.
NiMH–Nickel Metal Hydride
PNGV–Partnership for a New Generation of Vehicles
US06–U.S. EPA's aggressive emission certification drive cycle
SOC–State of Charge

HYBRID SYSTEM DESCRIPTION

The Honda Insight is a 65 mile/gallon (27.6 km/l) parallel hybrid-electric vehicle. It is a two-seater with a lightweight aluminum body that is powered by Honda's Integrated Motor Assist (IMA) powertrain. The 67 hp (50 kW), 66 lb.-ft. (89.5 Nm) gasoline engine and a closely coupled 10kW electric motor comprise the IMA system. Cumulatively, the IMA powertrain produces 73 hp (54.46 kW) and 91 lb.-ft (123.4 Nm) of torque. At 6.5Ah rated capacity, the 144V NiMH battery powers the electric motor.

The battery pack is shown in Figure 1 (removed from the vehicle for instrumentation). It is series configured with 20 7.2V modules. Each module (see Figure 2) consists of 6 D-size cells that are rated at 1.2V and 6.5Ah.

US06 DYNAMOMETER TEST PROCEDURES

The U.S. Environmental Protection Agency's relatively aggressive US06 drive cycles were performed on the dynamometer at 0°C, 25°C, and 40°C. Due to its relatively harsh nature, the US06 provided a good assessment of the in-car battery pack performance over these temperatures. NREL and Environmental Testing Corporation designed a test procedure that will be discussed briefly before the US06 data are presented.

Each test at Environmental Testing Corporation's dynamometer laboratory was preceded by a state of charge (SOC) conditioning cycle, adjusted to the specific drive cycle requirements. This process was derived from the SAE J1711 standard for fuel economy/emissions testing on hybrid vehicles. From a battery outlook, the conditioning also provided valuable information on the Insight's battery management approach. The general test procedure is as follows:

1. Perform an SOC conditioning cycle to set the battery to an appropriate SOC per the SAE J1711 specifications.
2. Soak at the respective test temperature to allow the battery pack to regain thermal equilibrium.
3. Perform a "warm-up" US06 cycle per federal test procedures and SAE J1711 specifications.
4. Immediately follow the warm-up with an "official" US06 cycle during which emissions are actively sampled.

Figure 1: Side of the pack with the end plate removed

Figure 2: Two Modules, each module consists of six D-size cells

USABLE BATTERY CAPACITY

The capacity of each cell (and thus the series configured pack) is rated at 6.5Ah. More importantly, while the battery is in use in the Insight, the "usable capacity," or the amount of available capacity that is electronically controlled by the battery control module, is limited to approximately 3.8 Ah. Plot 1 (see appendix) shows data from a trial that confirmed the usable capacity in the pack. The plot also shows average, hot and cold cell temperatures throughout the pack. For the in-car capacity tests, the dynamometer is programmed to maintain constant speed, and the car is driven in a manner that simulates driving up an incline until the pack is "fully discharged." At the "fully discharged" state, the car is driven in a manner to create a constant charge, or to simulate driving downhill until the "fully charged" state is reached. (The "fully discharged" and "fully charged" terminology refers only to the electronically controlled limits that are allowed for vehicle operation. The battery pack has the potential for further charge/discharge outside these electronic limits.) Capacity trials were performed at battery temperatures of 23°C to about 55°C; the usable capacity for discharge and charge consistently resulted in 3.8Ah (±3%).

TEMPERATURE ADJUSTED CHARGE/DISCHARGE

Plot 1 illustrates that the first charge increases the average battery temperature from around 36°C to about 47°C. On the second charge, the battery charge currents were limited. This demonstrates that the Insight takes battery temperatures into account for determining use of the battery pack. Data sets also show temperature compensated discharge schemes. The primary purpose of these adjustments seems to be for thermal management. Adjusting the current to a smaller value slows the rate of heat production in the batteries, thus avoiding rapid increases in the cell temperatures. However, compensating current on charges reduces energy recovery (see Plot 2) from the engine and/or brakes, and for discharges this reduces the current and power delivered for hybrid assists. If power is reduced during an assist, the hybrid control will have to request more torque from the engine to maintain performance, or at maximum engine output levels will reduce performance. Therefore, this method alone is not an ideal thermal management solution, especially if the pack can reach this temperature range during typical operation. However, these cycles are extreme; temperature rises of this magnitude were not encountered during our normal driving conditions.

Another explanation of the power adjustments could be that a temperature-dependent SOC model may be used to determine battery use and limitations. The relationship for voltage versus SOC varies with temperature. However, SOC estimates are often difficult for NiMH batteries' because the voltage curve is relatively flat over a wide SOC. Also, the charge limiting has only been observed above 50°C, so these power adjustments are more likely a thermal management strategy that is limited to temperatures above 50°C. Overall, the sizing of the Insight's fan was apparently not intended to handle prolonged, constant battery use. Instead, as seen in the US06 cycle data, the battery is typically used for short transient assist or regenerative braking demands.

US06 TEST RESULTS

The results of the dynamometer tests point out some valuable characteristics that readily transfer to real-world driving conditions varying from ambient temperatures of 0°C to 40°C. Withstanding a professional trace driver's variation in following the US06 drive cycle, the following data were carefully synchronized to match to within typically 1 second. Each trace represents the average performance over multiple drive cycles at each respective temperature.

Plot 3 illustrates the first 200 seconds of the warm-up US06. The vehicle's performance and battery power are lacking at 0°C compared to the mid and high-temperature trials. In fact, at 0°C the power into and out of the pack does not reach ±5kW. Yet the power into and out of the pack for the higher temperature trials reaches about ±10kW. The reduced power delivered by the battery pack at 0°C, and consequently reduced hybrid assist, are due to an increase in the internal resistance of the batteries at low temperatures, as shown later in Table 1.

The batteries' internal resistance electro-chemically increases because at lower temperatures the ions in the battery diffuse at a lower rate.

In the final 400 seconds of the warm-up US06 cycle (see Plot 4), the battery and vehicle performance for all the temperatures look quite similar. This is somewhat misleading because most of this segment of the US06 has a relatively constant speed. As a result, less than ±5kW pack power is generally demanded. Yet the 0°C battery still warms throughout this period. The fan typically shut off about six minutes into the 0°C test as the battery temperatures approached 6°C. It should be noted that the time until warm-up isn't directly comparable to real-world conditions because the cabin heater and defrost were off during these tests.

In the final run (last 600 seconds) of the US06 cycle (see Plot 5), the 0°C trials easily outperform the 25°C and 40°C trials. This result is probably the combination of two forces. First, the previously cold battery is now at a higher operating temperature that allows stronger performance. Second, the battery in the 25°C and especially 40°C tests continue to warm to even higher levels (35-45°C).

The main question of concern for the hot batteries is whether their performance suffers due to heating and/or whether they are limited by the Insight's battery control module. That question cannot be fully answered without trying to back out the Insight's complete battery control strategy, which we will not pursue. However, additional data shows that the fan is constantly on over the entire 40°C tests (the low fan-on threshold is about 37°C, and high about 53°C). This helps to explain why the average 40°C pack temperatures are rising slower than the other temperature traces. Note, this data is also not directly translatable to a real-world scenario because neither the cabin fan nor the air conditioning were on, and the solar load during a 40°C day could raise the ambient cabin temperature of a sitting car in excess of 60°C.

Finally, an extra US06 test at -20°F was attempted, but various data acquisition equipment was unable to function properly. Nonetheless, a qualitative drive was taken and the performance degradation was quite significant. In order for the vehicle to hold the trace acceptably, a high revving schedule was substituted for the normal shift schedule. The battery performance was surely the cause, since similar behavior was observed when we switched the battery pack off. Further, an *Automotive News* interview with Honda reported that in cold weather, power is returned to the Integrated Motor Assist system when the car has been able to warm sufficiently.

TEMPERATURE MANAGEMENT IN THE PACK

The battery pack temperature is conditioned by forced air. The forced air is routed from the passenger compartment to an air inlet, through the pack, and then exits the pack by being indirectly exhausted outside the car. Since the air temperature is near the passenger comfort level, the forced air can provide a cooling effect in hotter weather and a warming effect in colder weather.

As illustrated in Figure 3, the modules are arranged three high by seven deep, except for the last column, which has one blank row on top. Figure 4 shows that the air flows through the pack from front to back, and travels perpendicular to the length of the modules. The modules are arranged in a regular pattern, but the holder's geometry around them varies. The varying geometry of the holders is shown in Figures 3 and 4. The geometry's purpose is to maintain an even temperature distribution over the batteries by causing a turbulent air flow with a varying air velocity from entrance to exit. Also, the front modules are wrapped with a sleeve of heavier plastic. This extra insulation aims to increase the front module temperature to be closer to the modules in the rest of the pack.

The temperature management system will attempt to accomplish two main goals: 1) Maintain a reasonable temperature differential across the cells. 2) Keep the pack below a maximum temperature (usually 50-60°C for NiMH). The temperature management system comprises the fan control for air-cooling and the battery control to manage heat generation. The following analysis, with representative results, presents temperature spread from a thermocouple grid installed throughout the battery pack. The color mapping for the figures is optimized for each specific temperature range, so comparison between figures must be made carefully.

Analyses under various hot conditions show that the batteries toward the front of the pack are hotter than those toward the back (by the fan). The temperature spread after a 40°C US06 trial illustrates a representative result (see Figure 5). The batteries toward the front (top of Figure 5) were warmer by 2-5°C than those toward the back (by the fan). During this "hot day" type cycle, the battery fan reached low speed. The temperature management system was able to decrease the temperature differential over the cycle by -0.06 to -0.25°C/min. However, the maximum temperatures continued to rise throughout the cycle to 50°C in only 20 minutes.

The temperature spreads during and after the 25°C US06 driving trials were milder at 1.2 to 3°C (see Figure 6 and Figure 7). Figure 7 also illustrates that the fan successfully pulls some heat toward the back of the pack, but this condition still results in increased temperatures, increased temperature differentials, and nonuniform temperature differentials throughout the cycle. The maximum temperature was 38°C by the end of the 20-minute cycle. Temperature differentials increased at a rate of 0.05 to 0.12°C/min even during low fan speed operation. The differentials were generally found between the front half (columns 1-4) especially along the driver's side of the pack (left side of the plots) and the colder modules along the right side of the pack and in the last three columns by the fan.

The 0°C US06 temperature mapping (see Figure 8) is the most uniform in distribution across the pack, even though the absolute span is still around 3°C. To help the batteries heat up, the fan was on from the beginning of test until the pack temperatures approached 6°C. The front driver's side region of the pack starts to heat more quickly, probably due to the power electronics. Yet the cells in the middle are more consistently hot because the heat generation in the batteries seems to play the largest role in heating the pack at lower temperatures. The maximum cell temperatures were around 19°C. The temperature differential across the pack was fairly steady until the fan shut off, after which the differential rose at about 0.2°C/min for the remainder of the test.

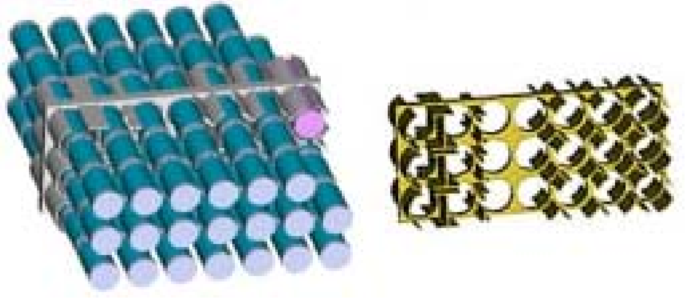

Figure 3: Pack showing batteries and center holder geometry section (two holders on each side are not shown)

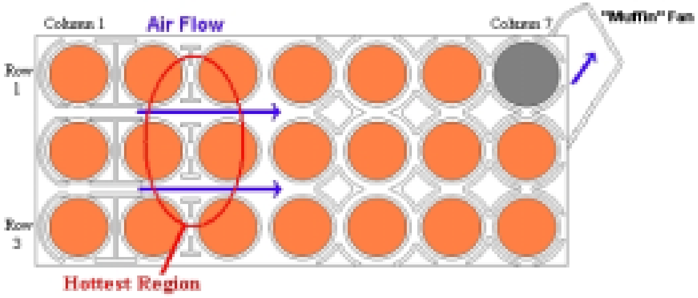

Figure 4: Holder directs airflow around modules. The solid orange indicates modules, grey indicates the blank.

Typically, the cells toward the front of the pack would be expected to be the "coolest" because the air is coolest when it first enters into the serial flow pattern. However, the hot, front section is likely the result of two forces: 1) An excessively reduced heat transfer rate caused by the varying cross sectional airflow and extra insulation in the front of the pack. Further, before the fan comes on, the extra insulation retains more of the heat generated in these front cells. 2) The front driver's side of the pack is located next to the power electronics, which also create considerable heat.

Overall, the temperature distributions vary depending on vehicle conditions, but with the combination of fan use and adjusting battery use, the differential generally approaches 3-4°C. The fan has two positive impacts: First, the temperature appears to spread across the columns more evenly. Second, the temperature differential is roughly maintained over the cells. However, the absolute temperature in the pack continues to increase, and during the extreme charge/discharge trial, the pack reached temperatures above 60°C. Figure 4 shows the general hot area as it relates to holder geometry and module configuration. Considering the capability of the forced-air cooling system to cool the Insight pack, regulating power usage to/from the pack at rising temperatures seems necessary.

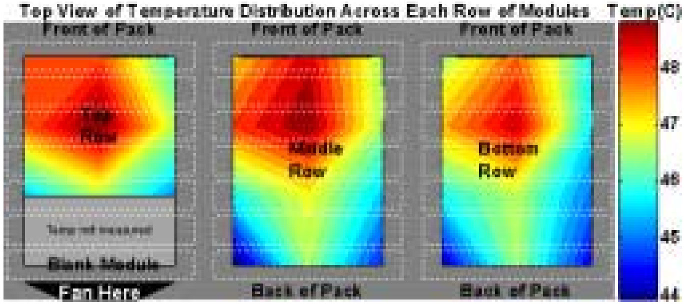

Figure 5: US06 at 40°C after test completion (fan on)

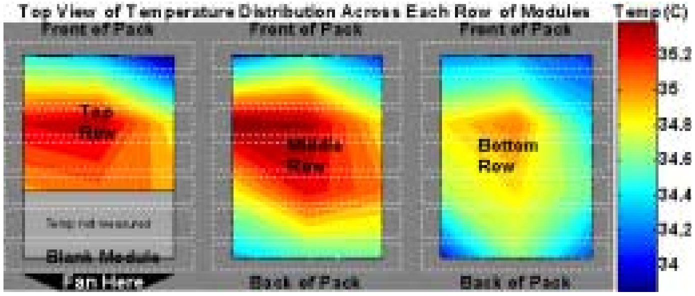

Figure 6: US06 at 25°C before the fan kicks on for cooling

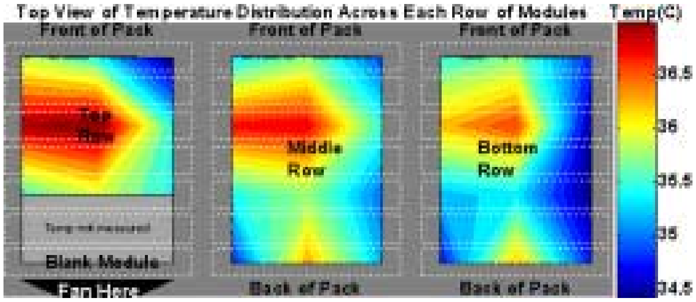

Figure 7: US06 at 25°C with fan on at test completion

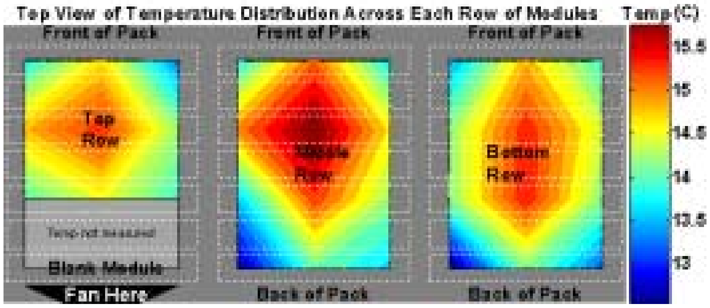

Figure 8: US06 at 0°C after test completion

LABORATORY CHARACTERIZATION

The Insight pack is undergoing laboratory tests that allow more in-depth analysis of the NiMH battery pack. Laboratory testing includes conducting tests according to the Partnership for a New Generation of Vehicles' (PNGV) Battery Test Manual. The forced-air cooling system will also be evaluated in more depth and analyzed for optimal sizing for the pack's heat load. This section of the paper will focus on the initial lab work completed. Specifically, the Hybrid Pulse Power Characterization (HPPC) test results are discussed at test temperatures of 0°C and 25°C.

As discussed previously, the Insight's performance suffered noticeably at freezing temperatures. Since the Insight allows the pack to cycle between 20% to 80% SOC, Table 1 lists this range of resistances at 0°C and 25°C, which are determined from the HPPC tests. The resistance at 0°C is significantly higher than at 25°C, which results in the pack's lower power capability at these temperatures.

Table 1: Resistance Range (Ohms) of the Insight Pack over Usable SOC Range

	25°C	0°C
Discharge Resistance	0.494-0.63	0.774-0.94
Charge Resistance	0.36-0.424	0.595-0.68

Plot 6 further illustrates the discharge and regenerative power capability over the depth of discharge (DOD) range where the Insight operates. The power curves shown are for the medium HPPC current level. However, the voltage limits used to calculate the available power were modified to those seen while driving the Insight. Thus, the PNGV 3:4 voltage ratio is not adhered to because seeing the actual power the car has available is more valuable in this case. As Plot 6 illustrates, the discharge power is definitely limited to around 5kW at 0°C. These power calculations are for the HPPC's 18-second discharge and 2-second charge pulses.

Current work focuses on determining the heat load generated during various cycles. The heat generation and heat capacity work is being conducted in NREL's unique large calorimeter that holds a full Insight battery module. After the forced-air cooling system is fully characterized, an appropriate level of cooling and even heating will be evaluated.

CONCLUSION

The pack enclosure is designed to cool the batteries serially with forced air. Strategically designed holders attempt to maintain an even temperature distribution through out the batteries by routing the air through the pack at varying velocities. Data from various drive cycles confirmed that the temperature differential does vary, but that the pack is generally managed such that the differential is roughly below 4°C. Active fan operation maintains more uniform temperature differentials across the pack to a certain extent. However, absolute battery temperatures continue to increase. Moreover, the power electronics seemed to have a role in heating the battery pack.

The Insight battery pack has done a reliable job in assisting the vehicle to meet performance requests. The mild battery management and control strategies in place seem to have the most drawbacks for increasingly hot conditions, and at 0°C or colder temperatures. In cold conditions, the NiMH batteries suffer from low output until adequate warm-up times are achieved. Ultimately, the vehicle performance is affected quite significantly during temperature extremes. The Insight's intended driving demographic is sure to encounter the hot temperature extremes in Arizona for example, and cold extremes in the Northern states. Further, now that the Insight is being sold in Canada, cold weather performance lags, similar to the results of the –20°F test, may be encountered.

Overall, the battery thermal management is adequate on this mild hybrid, but does not aggressively manage extremes that can be encountered outside of mild climates. This strategy may seem reasonable, but if harsh conditions are encountered repeatedly, this may lead to failures and/or reduced cycle life for the battery pack. Thorough life tests are beyond the scope of this case study, but a mild management strategy will surely reduce the robustness of the pack over time.

ACKNOWLEDGMENTS

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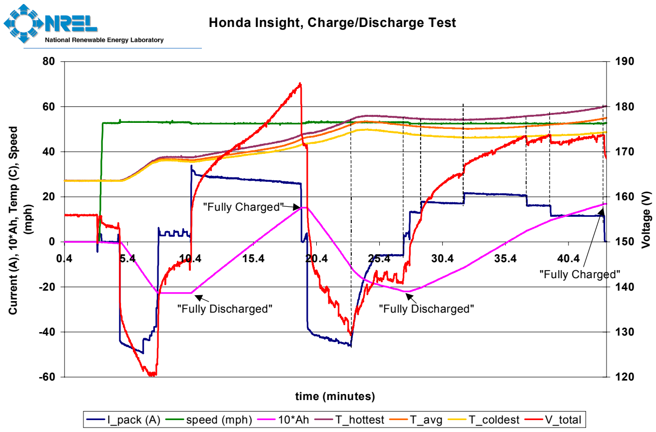
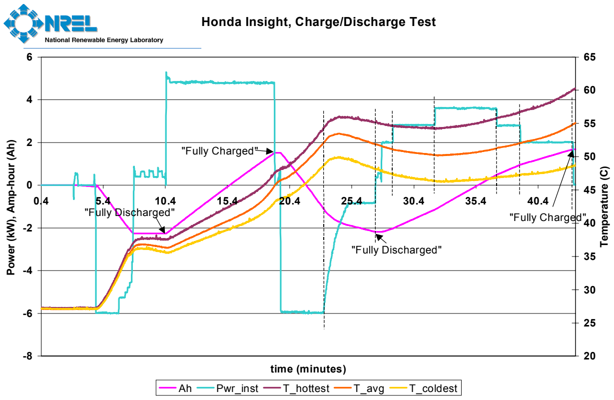
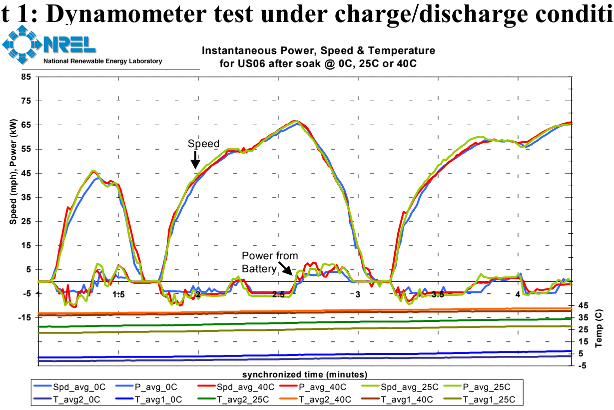
Appendix A: Data Plots



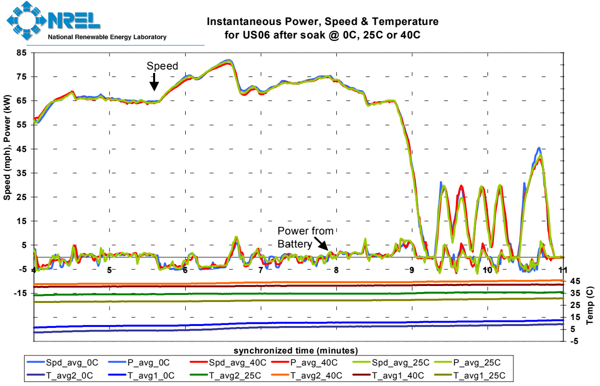
Plot 1: Dynamometer test under charge/discharge conditions



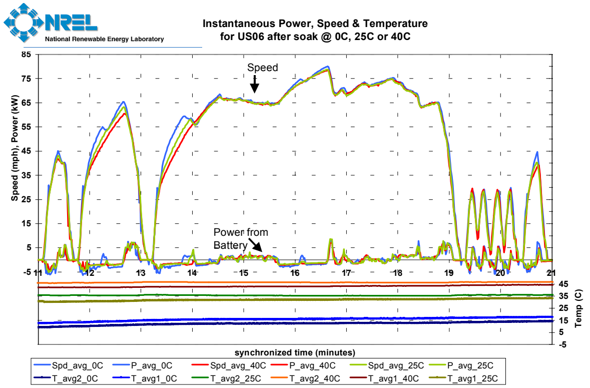
Plot 2: Power delivery adjusted during temperature compensated charging



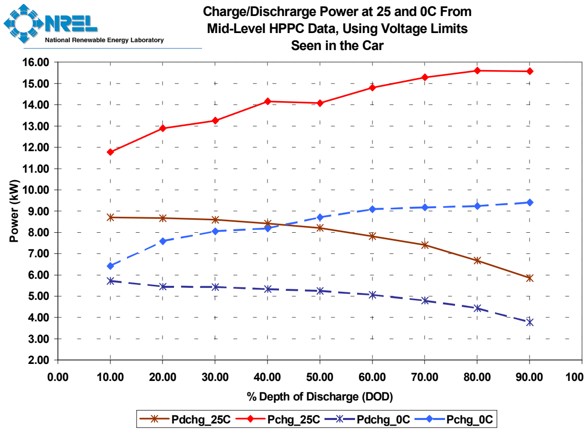
Plot 3: First 200 seconds of US06 warm-up cycle at 0°C, 25°C, and 40°C



Plot 4: 180–600 seconds from US06 warm-up cycle at0°C, 25°C, and 40°C



Plot 5: The 2nd US06 cycle with a contrasting result caused by higher temperatures



Plot 6: Power versus DOD at 25 and 0C, Note: DOD=1-SOC

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