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Thermal Evaluation and Performance of High-Power Lithium-Ion Cells

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Abstract: Under the sponsorship of the United States Advanced Battery Consortium (USABC) and the Partnership for a New Generation of Vehicles (PNGV), Saft has developed high-power lithium-ion (Li-Ion) batteries for hybrid electric vehicles (HEVs). These high-power Li-Ion batteries are being evaluated for the U.S. Department of Energy's (DOE) Hybrid Vehicle Propulsion Program. As part of this program, the National Renewable Energy Laboratory (NREL) characterized the thermal performance of the Saft (6-Ah) Li-Ion cells. The characterization included (1) obtaining thermal images of cells under a specified cycle, (2) measuring heat generation from the cells at various temperatures and under various charge/discharge profiles, and (3) determining the cells' capabilities for following a simulated power profile (driving cycle) at various initial states of charge and temperatures.

Key words: thermal management, lithium-ion, electric vehicles, hybrid electric vehicles

1. Introduction

The performance, life cycle cost, and safety of electric and hybrid electric vehicles (EVs and HEVs) depend strongly on those of the vehicle's energy storage system. Advanced batteries such as lithium-ion (Li-Ion) batteries are considered one of the major options for storing energy in EVs and HEVs. Under the sponsorship of the U.S. Partnership for a New Generation of Vehicles (PNGV) and the United States Advanced Battery Consortium (USABC), Saft has developed 6-Ah and 12-Ah high-power Li-Ion cells as energy storage devices for HEVs [1,2]. The cells have high power characteristics (1350−1500 W/kg) and relatively good specific energy (64−70 Wh/kg).

Participants in the U.S. Department of Energy's (DOE) Hybrid Vehicle Propulsion Program are collaborating to test a battery pack consisting of these high-power Li-Ion cells. The battery pack and its management system are designed to achieve certain performance, life, and safety goals. Based on analysis and predictions, Saft designed the cells to exhibit improved thermal performance and also proposed a pack thermal management system to help meet required performance, life, and safety requirements.

Actual data on the thermal behavior of Li-Ion cells, such as heat generation rate and temperature rise under a specified power cycle, were needed to verify the expected thermal performance of the cells and also to fine tune the pack thermal management system. Because of its facilities and experience [3,4,5], the National Renewable Energy Laboratory (NREL), a participant in the DOE program, conducted tests to evaluate thermal behavior of the 6-Ah Saft cells. NREL's facilities include a unique calorimeter that is large enough to hold multiple cells, high-power battery cyclers capable of simulating any driving cycle, and state-of-the-art thermal imaging and heat transfer equipment. We conducted tests to (1) obtain thermal images of cells under load, (2) measure heat generation rate from the cells at various temperatures and under various charge/discharge profiles, and (3) evaluate the capability of the cells to follow a specified power profile (driving cycle) at various initial states of charge and temperatures. This paper presents the non-proprietary results of these tests.

2. Background

2.1 Saft li-ion cell

The technology used in the Saft Li-Ion cylindrical spiral-wound cells consists of a plastified carbon anode, a lithiated metal oxide cathode, and an organic electrolyte [1,2]. Table 1 gives the published characteristics of the 6-Ah cells, and Figure 1 shows a picture of the cell. The cell has three features designed to have positive impacts on the thermal and electrical performance of the cells: a hollow core for faster heat removal, a steel case for faster heat dissipation, and symmetrical position of terminals on each end of the cell for uniform heat generation.

2.2 NREL calorimeter

NREL uses a custom-made, single-ended, conduction-type calorimeter to measure heat capacity and heat generation from a cell or module. The calorimeter's aluminum cavity holds the module, which is surrounded by an isothermal bath. Any heat released from (or absorbed by) the module is passed through the walls of the cavity, which is instrumented with heat flux meters. The calorimeter cavity is 39 cm L x 28 cm H x 21 cm W and could hold EV-size modules. The calorimeter can measure heat as low as 10 J with a heat rate of 10 mW. It is designed to measure heat rates up to 100 W with an accuracy of better than ±5%. A module in the calorimeter is charged/discharged by a high-power battery cycler. Pesaran et al. [4] provides a detailed description of the calorimeter. For these tests, we used AeroVironment's ABC-150 battery cycler.

3. Results and discussion

3.1 Thermal tests and thermal imaging

For thermal evaluation, we connected three 6-Ah cells in series and placed them in a Plexiglas™ enclosure (shown in Figure 2). We used three small fans to flow ambient air around and through the cells. Cells were instrumented to measure voltage, current, and temperature. Thermocouples were mounted on the exterior and interior walls of the cells. We brought the cells to 50% state of charge (SOC) and then charged/discharged them according to the US06 (10-minute driving cycle) power profile, shown in Figure 3, with fans on or off. We adjusted the power level of this US06 cycle so that the results of this three-cell test could be translated to the pack level.

Figure 4 shows that the average temperature of the three cells increases with cycling. With fans on, so that the ambient air was cooling, the average temperature reached steady state after three US06 cycles. The temperature rise was about 2°C. With fans off, and no ambient air cooling, the average temperature rise after ten US06 cycles was about 8°C. As expected, cooling the air lowers the average temperature of the cell.

We used NREL's infrared thermal imaging equipment to obtain thermal images of the cells. Because the Plexiglas™ enclosure cover was not infrared-transparent, we removed it for imaging. Figures 5 and 6 show the thermal image of the exterior cells after eight US06 cycles with and without ambient air-cooling. Images show that the temperature distribution on the cell walls was relatively uniform (±0.75°C with air-cooling, and ±1°C without air-cooling).

Under the US06 cycling, the thermal tests and thermal imaging showed that the cells have a good thermal performance (low temperature rise and uniform temperature distribution). This is attributed to the hollow core, highly conductive steel case, low thermal mass, and uniform heat generation (which results from the symmetrical position of the terminals).

3.2 Heat generation

To measure the heat generation rate, we connected three Saft cells in series and placed them in the cavity of the calorimeter (as shown in Figure 7). The cells were tested at +50°C, +22°C, 0°C, and - 20°C (initial and final temperatures). At initial states of charge of 30%, 50%, or 80%, we subjected the three Saft cells to one US06 cycle. The calorimeter response shown in Figure 8 for one case was used to calculate the total amount of heat released from the cells (area under the curve). We calculated the average heat generation rate for each case by dividing the total amount of heat generated by the cycle duration (10 minutes).

Figure 9 shows that the heat generated at various temperatures and states of charge with this cycle was between 1.2 W and 12.3 W per cell. In general, as temperature increases, the amount of heat generated decreases because the cell resistance decreases and it becomes more efficient. We would expect that as the state of charge decreases, the resistance and thus the heat generation rate would also decrease; however, we did not observe this trend here because the cells did not follow the requested power profile in all cases. As described in the next section, at low temperatures the discharge rate was less than the discharge rate at high temperatures; at high states of charge, the charge acceptance was not as high as with low states of charge. As a result, less energy passed through the cells in these cases, causing less heat to be generated.

3.3 Electrical performance

We kept the cells at the specified temperature of the calorimeter cavity and recorded their current and voltage response. The electrical response was obtained for the three cells at initial states of charge of 30%, 50%, or 80% at temperatures of -20°C, 0°C, +22°C, and +50°C. Figures 10 and 11 show typical results. Although the commanded (charge/discharge) power by the cycler was the same for all cases according to the US06 profile, the actual discharge/charge power from/to cells differed. For example, at 50% state of charge, the cells discharged power according to the requested power at almost all temperatures. However, at below 0°C, the cells did not accept charge at some power peaks according the commanded power.

The data indicated that the Saft cells performed very well in response to the requested/commanded power of the US06 cycle above 0°C and between 30% and 80% states of charge.

4. Summary

Saft has developed 6-Ah high-power Li-Ion cells under USABC/PNGV programs. NREL evaluated the thermal performance of these cells for use in an HEV battery pack. We conducted this evaluation with a US06 power profile. Under the US06 cycling, the thermal tests and thermal imaging indicated that the cells demonstrated good thermal performance (low temperature rise and uniform temperature distribution). This is attributed to three design factors: the hollow core, the highly conductive steel case, and the uniform heat generation that results from the symmetrical position of the terminals. With ambient air-cooling, the cell temperature rise was lower and the wall temperature distribution was more uniform.

The heat generated at various temperatures and states of charge with the US06 cycle varied between 1.2 W and 12.3 W per cell. Data indicated that the Saft cells performed very well in response to the requested/commanded power of the US06 cycle above 0°C and between 30% and 80% states of charge.

5. Acknowledgments

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Table 1. Characteristics of Saft 6 Ah Li-Ion Cells [1,2]

Electrical Characteristics	
Nominal voltage	3.6 V
Charge voltage limit	3.9 V
Discharge voltage limit	2.1 V
Capacity at C/3	6.5 Ah
Specific energy	64 Wh/kg
Energy density	135 Wh/dm^3
Specific power	1500 W/kg
Power density	3100 W/dm^3
Mechanical Characteristics	
Diameter	47 mm
Height	104 mm
Weight	375 g
Volume	0.18 dm^3
Operating temperature range	-10°C to 45°C

Figure 1. Saft 6 Ah Li-Ion cell [2]

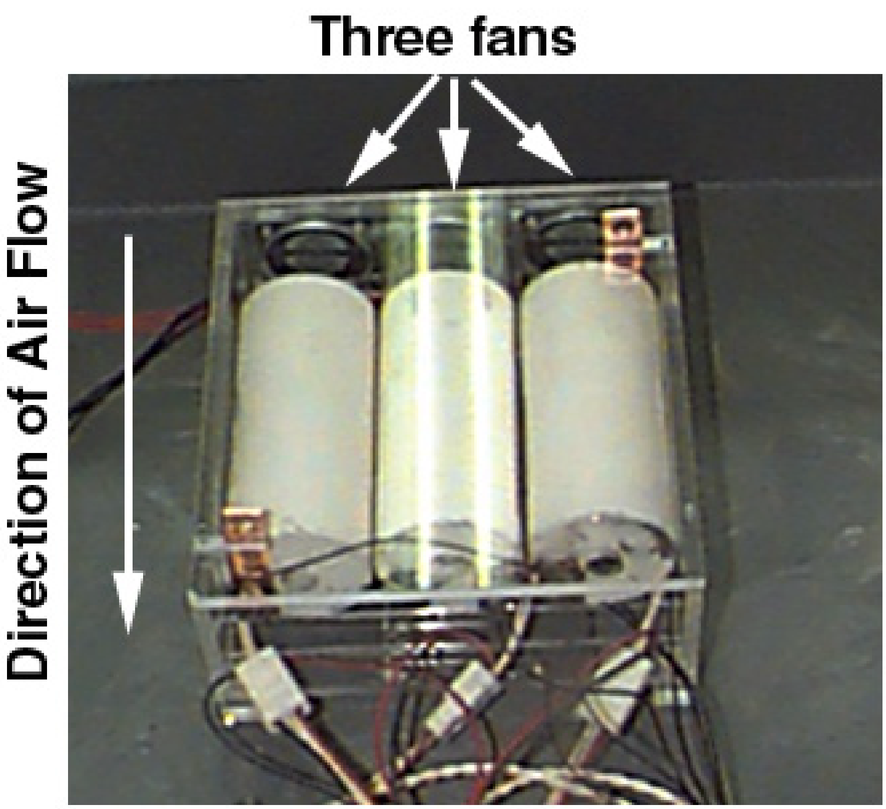

Figure 2. Experimental setup for thermal evaluation of three Saft cells

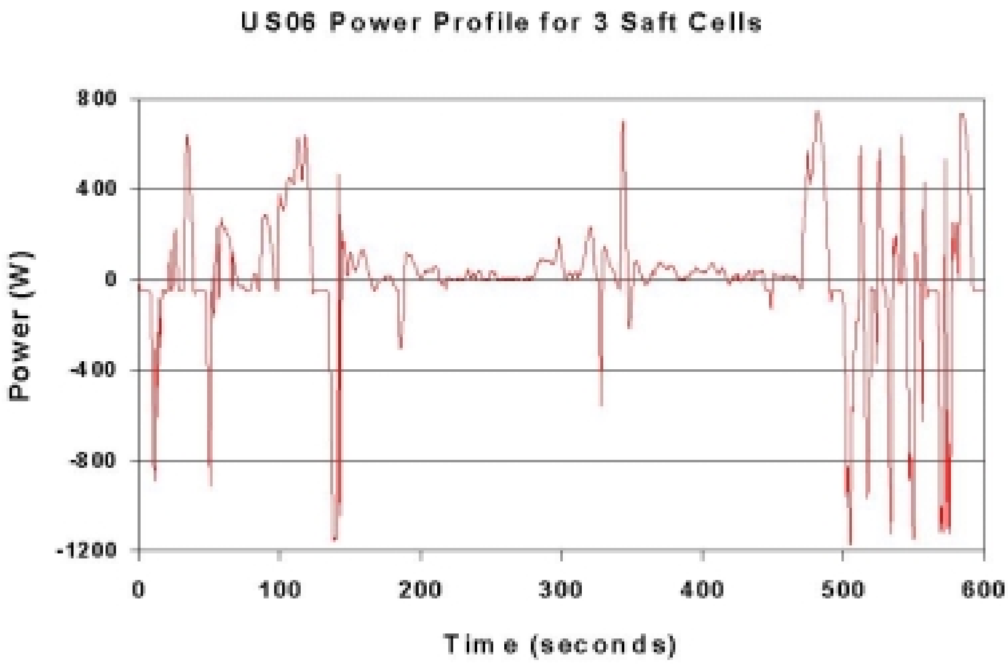

Figure 3. The US06 driving cycle power profile adjusted for three Saft cells

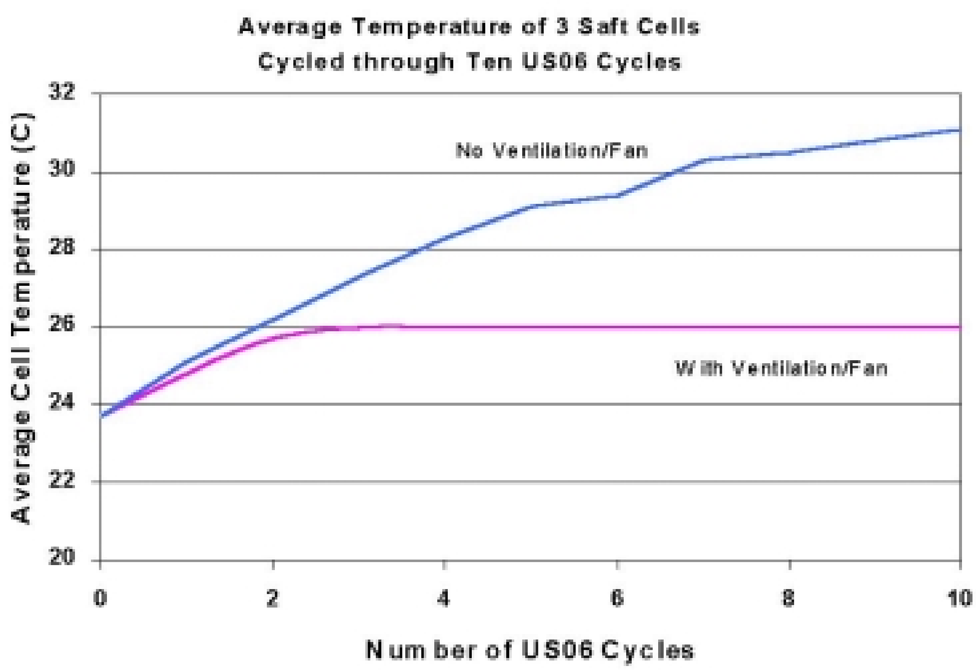

Figure 4. Average temperature of the cells with and without air-cooling

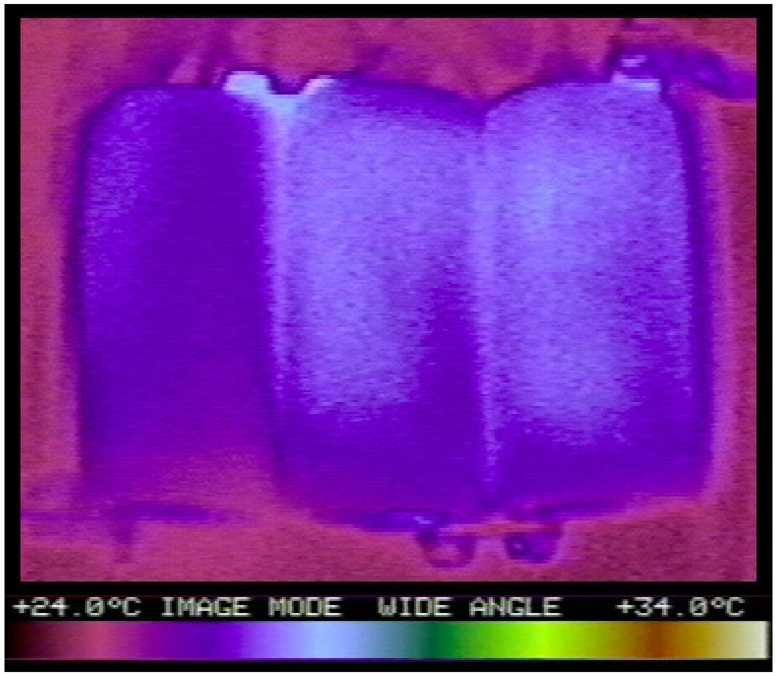

Figure 5. Infrared thermal image of the three Saft cells *with* air-cooling after eight US06 cycles

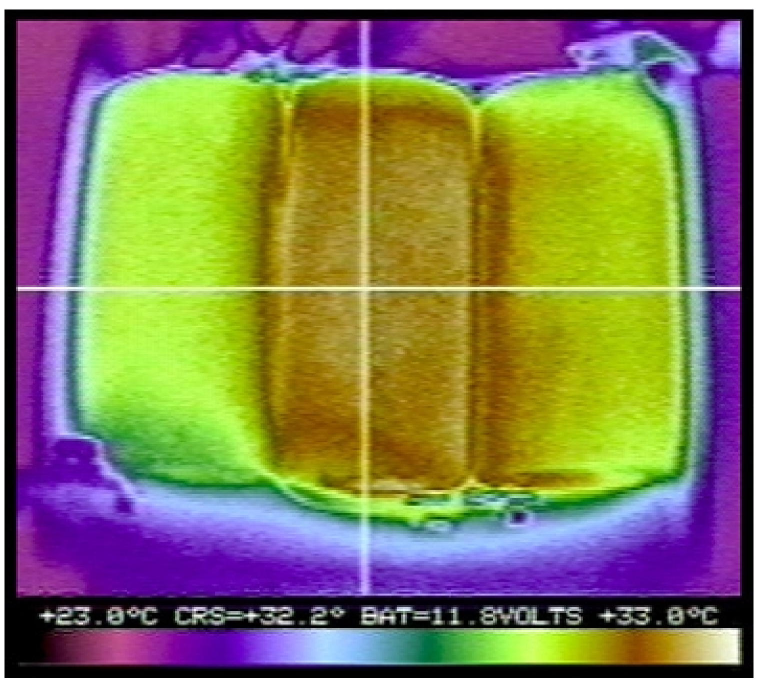

Figure 6. Infrared thermal image of the three Saft cells *without* air-cooling after eight US06 cycles

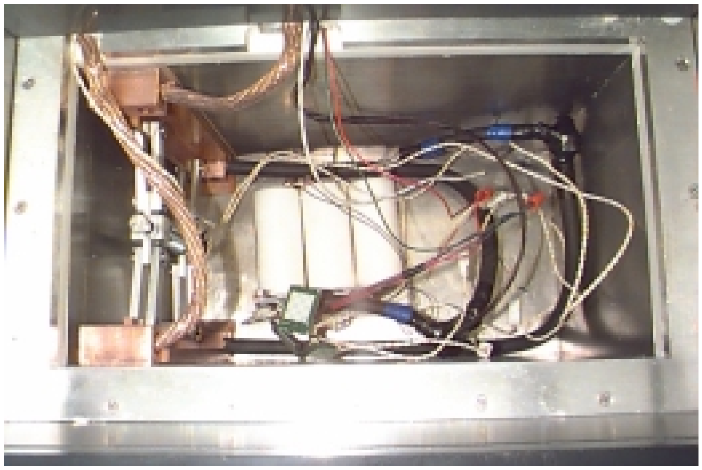

Figure 7. Three Saft cells in NREL's calorimeter cavity for heat generation measurements

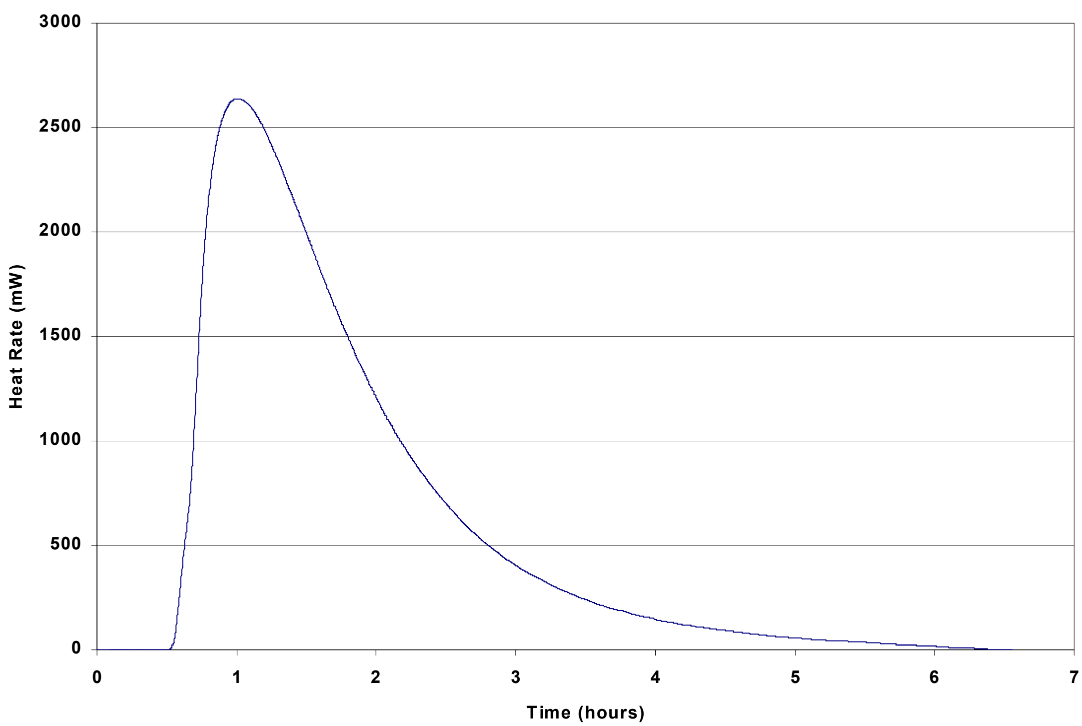

Figure 8. A typical calorimeter response from the Saft cells under one US06 cycle
(Isoc = 50%, T = 22 °C)

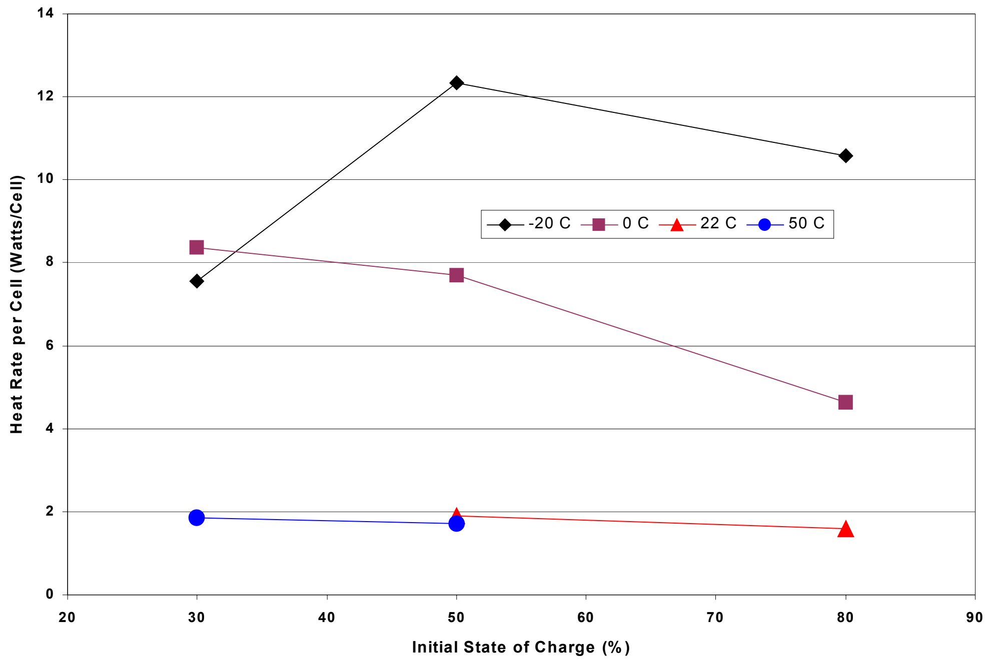

Figure 9. Heat generated from one Saft cell during one US06 cycle at various temperatures and initial states of charge

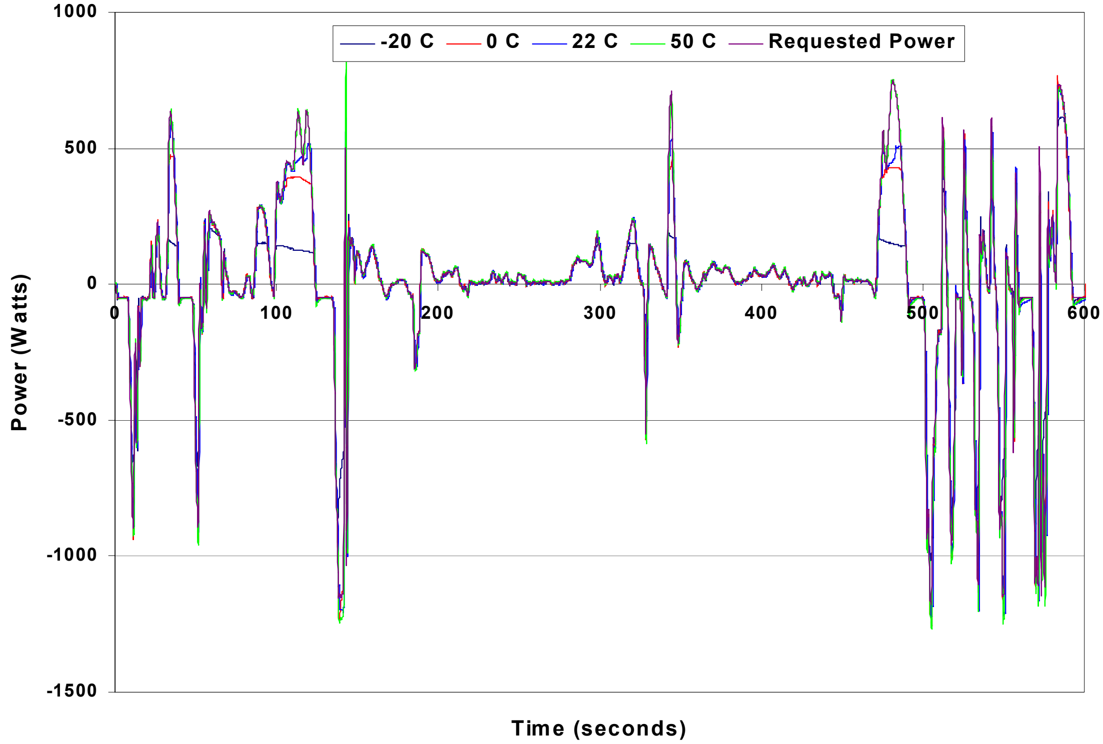

Figure 10. Performance of the three Saft Cells under US06 cycles with an initial state of charge of 50% at various temperatures

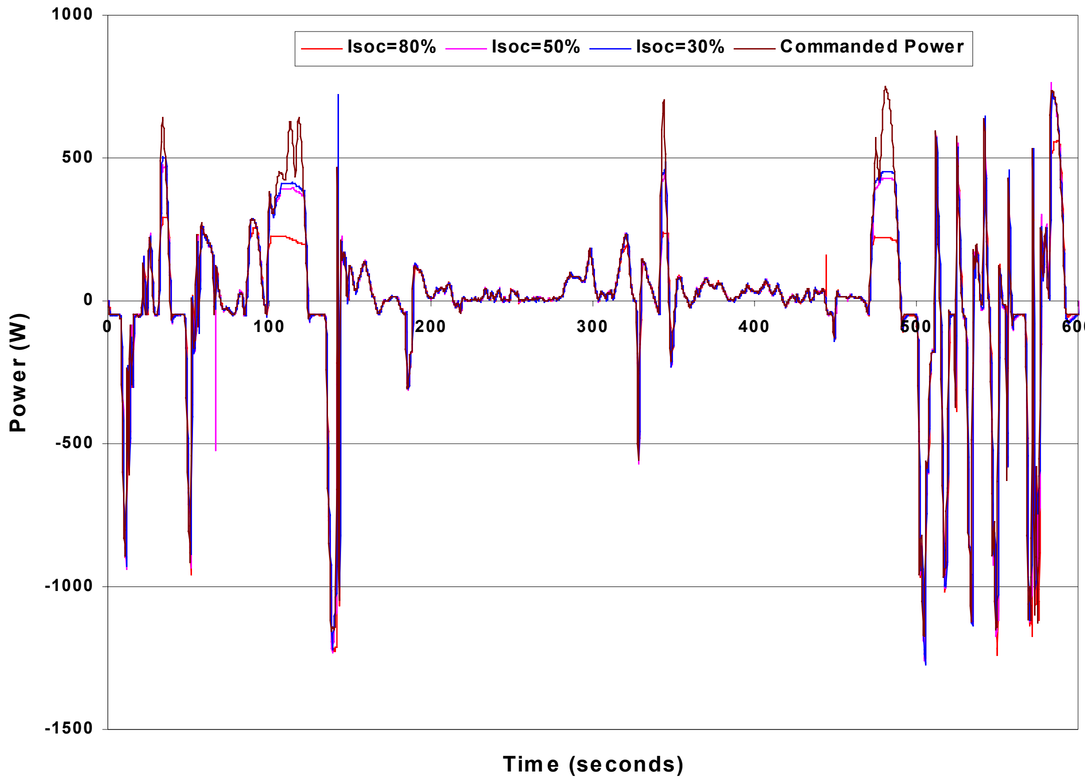

Figure 11. Performance of the three Saft cells under US06 cycles with an initial temperature of 0°C with various initial states of charge