Thermal Characterization of Advanced Lithium-Ion Polymer Cells

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ABSTRACT

Compact Power Incorporated (CPI) and LG Chem have been developing high-power lithium-ion (Li-Ion) polymer batteries over the past few years. The National Renewable Energy Laboratory (NREL) has supported this development with thermal characterization and analysis of three generations of CPI prototype Li-Ion polymer cells. All generations of the cells use a manganese-dioxide material for their cathode and graphite anodes. NREL measured the heat generation and subjected the cells to thermal imaging. The first- and second-generation cells showed signs of localized heat during thermal imaging underneath the positive electrode during discharge. As the cell was improved and better electrodes designed, the third-generation cell became relatively uniform in temperature and was the most efficient of the cells tested. It exceeded an efficiency of 91% for all currents below 48 amps. In comparison, the second-generation CPI cell was only 78% efficient at 30 amps. CPI is incorporating its latest Li-Ion cells in a stand-alone battery pack for vehicle applications.

1.0 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) polymer batteries are considered viable options for storing energy in EVs and HEVs. Compact Power Inc. (CPI) of Colorado, USA and LG Chem Ltd. (LGC) of South Korea have been developing large Li-Ion polymer cells and batteries for EV, HEV, and other applications. The technology is based on LGC's small Li-Ion cell portable power applications.

Early on, CPI realized that thermal issues are important for operating high-power Li-Ion polymer batteries. Actual data on the thermal behavior of polymer 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 to fine tune the cell and pack thermal management system. Because the National Renewable Energy Laboratory (NREL) has unique facilities and experience [1,2,3], CPI asked the laboratory to conduct tests to evaluate thermal behavior of its polymer 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. CPI and NREL collaborated to conduct tests to (1) obtain thermal images of cells under load and (2) measure heat generation rate from the cells under various charge/discharge profiles.

2.0 Background

2.1 Compact Power Li-ion Polymer Cell

Figure 1 pictorially shows the cells. Table 1 gives the published characteristics of the three generations of Li-Ion polymer cells.

Figure 1: (Counterclockwise from upper left) CPI Gen I cell, Gen II cell, and Gen III cell.

Table 1: Physical and electrical characteristics of CPI's Li-Ion polymer cells. Upper voltage limit = 4.2 V and lower voltage limit = 3.0 V.

Cell	Ah Cap. (Ah)	Max Dis. Current (Amps)	Mass (grams)	Specific Energy (Wh/kg)	Size (L x W x H) (mm)
Gen I	4.5	45	144.6	118	105x125x3
Gen II	5.0	75	201.3	94	122x118x11
Gen III	8.0	140	300.8	95	243x125x6

The latest version of the cell, Gen III (manufactured by LGC) uses high-capacity artificial graphite anodes and spinel lithiated manganese-dioxide cathodes. The anodes and cathodes are laminated together with the separator and assembled using a proprietary winding-stacking technique. The result is a cell that requires no external pressure and shows exceptional cycle life, very high power (2,000 W/kg), and high specific energy (95 Wh/kg). Figure 2 shows the 18-second discharge power and 2-second regen power capability of the Gen III cell as a function of depth of discharge. The test protocol used to determine the power capabilities is the Partnership for a New Generation of Vehicles (PNGV) Hybrid Pulse Power Capability (HPPC) test [4]. Using the HPPC results for an individual cell, the battery sizing factor, i.e., the number of cells, necessary to meet the PNGV goals of 25 kW on discharge and 30 kW on regen at end of life was calculated to be 75.

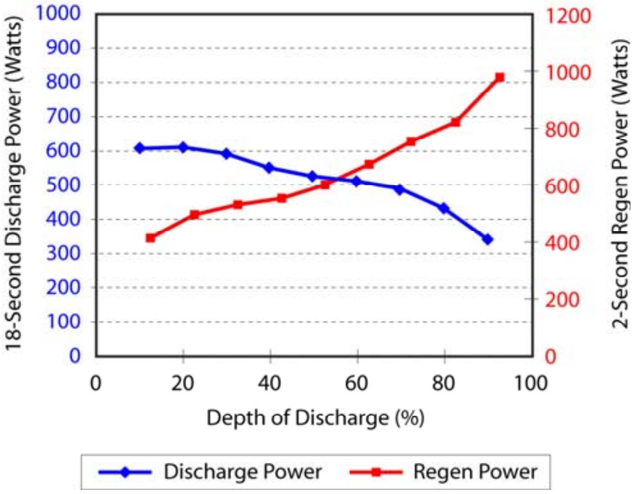

Figure 2: Power capability of the CPI Gen III cell under HPPC profile.

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 [2]. The calorimeter can measure heat as low as 10 J with a heat rate as low as 10 mW. It is designed to measure heat rates as high as 100 W with an accuracy of ±2%. A module in the calorimeter is charged and discharged by a high-power battery cycler.

3.0 Heat Generation Testing

NREL's calorimeter was used to measure the heat generation of the CPI cells. Depending on the cell, the heat generation was measured at 25°C for the following conditions.

1. Constant current discharge at a C/5, C/1, 2C, and 6C rate until voltage reached CPI's specified lower voltage limit (3.0 V) – 100% state of charge (SOC) to 0% SOC.

2. Under CPI's recommended charging scheme, C/2 current was applied to the cell until it reached 4.2 V. The voltage was then held at 4.2 V until the current decayed below 250 mAmps.

The energy efficiency of the cell during constant charge/discharge cycles was determined by the following equation.

$$Eff = \left[1 - \left(HeatGenerated / Energy(Input \ldots Output)\right)\right] * 100$$

The heat generated by the cell is due to the I^2R losses in the cell and the chemical changes within the cell as measured by the calorimeter. The energy (input…output) is the electrical energy supplied or taken away from the cell over the testing cycle. Both the heat generated and the electrical energy are measured in Joules. The average cell heat rate in Watts is determined by the following equation.

$$AverageCellHeatRate = \frac{HeatGenerated}{CycleTime}$$

The heat generated is divided by the cycle time in seconds (the time over which the charge or discharge to the battery was completed). For instance, a C/1 discharge from 100% to 0% SOC takes approximately 60 minutes (3600 seconds).

Figure 3 shows the efficiency of the cells as a function of discharge current at 25°C. Each cell was discharged from 100-0% SOC with 3.0 V representing a fully discharged cell. The efficiency for all generations of cells decreases as the current increases. Furthermore, the Gen III cell has the highest efficiency for any given current. For instance, the Gen III cell has an efficiency of 94.4% at a current of 30.0 amps, whereas the Gen II cell has an efficiency of 78.8% at the same current. Figure 4 shows the average heat rate of the cell as a function of discharge current at 25°C. The heat rate for each cell increases with increasing current. The Gen III cell is the most efficient cell and therefore has the lowest average heat rate for a given current, which indicates improvements between generations. At 30 amps, the Gen III average heat rate was 5.6 W compared to the Gen II cell average heat rate of 21.1 W. The efficiency of the cells was also measured under CPI's recommended charging scheme. The Gen III cell was the most efficient at 99% under the recommended charging scheme compared to an efficiency of 95% for Gen I and Gen II.

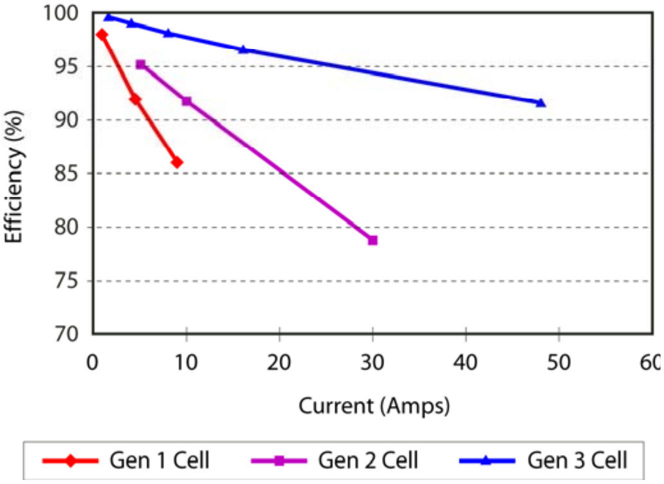

Figure 3: Efficiency data for CPI's Li-Ion polymer cells at 25°C.

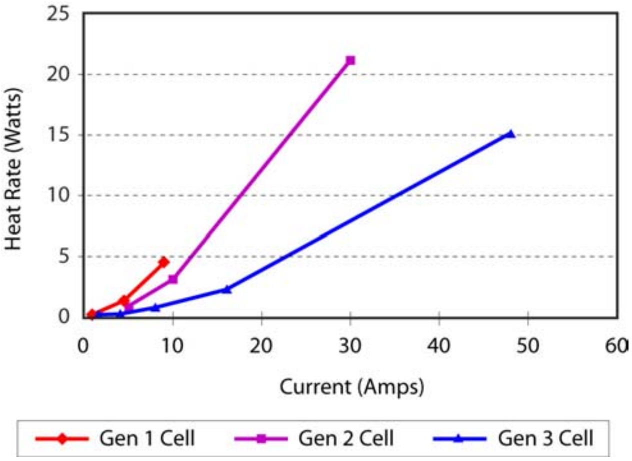

Figure 4: Heat rate data for CPI's Li-Ion polymer cells at 25°C.

Figure 5 shows the calorimeter response and voltage curve of the Gen III cell under a C/5 full discharge. The total discharge lasted approximately 4.5 hours. At the beginning of the cycle, the cell is initially endothermic – a negative heat rate represents an endothermic reaction, heat being pulled from the constant temperature bath surrounding the calorimeter to the battery. The heat rate does not go completely exothermic until approximately 2.5 hours. The cell then peaks at a heat rate of 0.11 W at 3.56 hours and then slightly decreases –possibly because of a phase change. Finally, the heat rate increases at the exact moment that the voltage precipitously dips, 3.95 hours into the test.

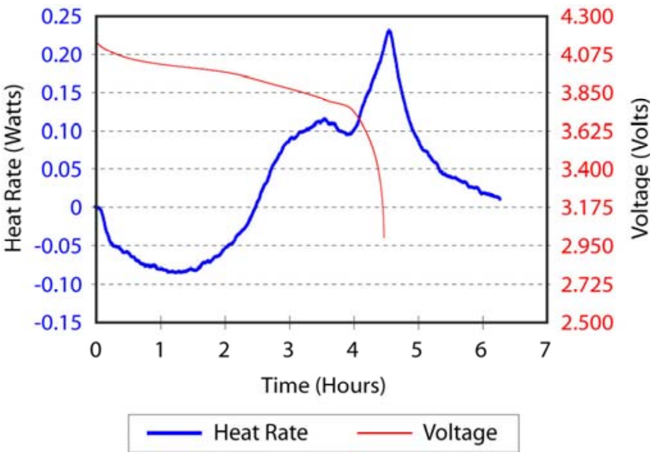

Figure 5: Heat rate data for CPI's Gen III cell under a C/5 discharge.

4.0 Cell Infrared Testing

Figure 6 shows the thermal imaging set-up for the Gen III Compact Power cell - all cells were tested in a vertical configuration. The present aluminum packaging of the cells has too low of an emissivity for accurate IR imaging. Therefore, the exterior of the cell was coated with boron nitride that has an emissivity of approximately 0.8. A high emissivity surface effectively eliminates reflections from the object being imaged. The boron nitride coating can also be easily removed with isopropyl alcohol.

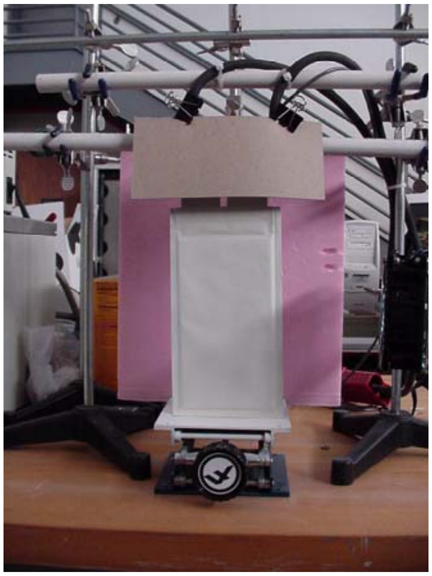

Figure 6: CPI Gen III cell thermal imaging set-up.

The polymer cells were thermally imaged under various cycles at room temperature. Figure 7 shows the thermal images taken at the end of the discharge for the three generations of cells. The cell was fully discharged from 100% to 0% SOC and the thermal image was taken right after the cell completed the discharge. The Gen I cell was limited to a 9.0-amp discharge by the manufacturer, whereas the Gen II and Gen III cells were subjected to infrared imaging after completing a 30-amp discharge. Table 2 shows the minimum and maximum temperatures of the cells for two different areas. In Figure 7, a blue and a red box outline the two separate areas. Essentially, the active cell area (blue box) is where the cathode, separator, and anode are physically located. The second area (red box) is the area between where the electrodes enter the cell and the active area. The two areas are analyzed separately to emphasize the improvement in the electrode design between generations.

For the active area, Gen III has the lowest spread in temperature, 3.0^{o}C, compared to Gen II, which has a temperature spread of 13.5^{o}C at the same current, 30 amps. Even though the current through the Gen I cell is only 9.0 amps, it has a larger temperature spread, 5.6^{o}C, as compared to the Gen III cell over the active area. Furthermore, the Gen I cell has differential heating across the cell – the cell heating is biased underneath the positive electrode. The Gen II cell shows biased heating underneath both electrodes – essentially, the cell heating (current density) decreases as the distance from the electrodes increases. Neither of these differential-heating modes was observed with the Gen III cell – the cell temperature is relatively uniform over the entire active area. The mottled infrared appearance of the cell in Figure 7c resulted from the cell jacket making contact with the active material, not to localized heating.

In looking at the area (red box) between the electrodes and the active cell area, the Gen III cell once again has the lowest temperature difference, 4.8^{o}C, compared to the Gen II cell that has the highest temperature difference at 10.6^{o}C. The Gen II cell heating is biased toward the positive electrode and the maximum temperature is greater than 50^{o}C. The positive electrode shows slightly higher temperatures due to the electrical resistivity of aluminum compared to the negative electrode that is copper. Furthermore, the electrode design for the Gen I and Gen II cells didn't provide for a large enough cross-sectional area for the current demand – CPI therefore modified the cross-sectional area of the electrodes in the Gen III cell.

Table 2: Temperature distribution of the CPI cells under various discharge currents.

Cell	Current (Amps)	Active Area (blue box)		Area between Bottom of Electrodes and Active Area (red box)	
		Min. Temp. (°C)	Max. Temp. (°C)	Min. Temp. (°C)	Max. Temp. (°C)
Gen I	9.0	33.0	38.6	29.6	37.0
Gen II	30.0	34.0	47.5	39.4	> 50.0
Gen III	30.0	35.7	38.7	32.2	37.0

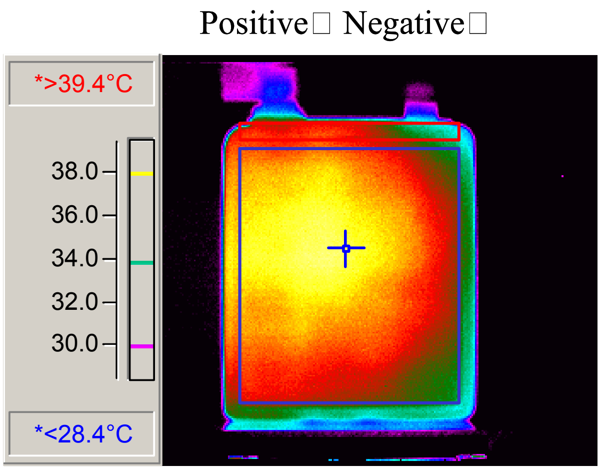

Figure 7a: Thermal image of Gen I cell after 9.0-amp discharge.

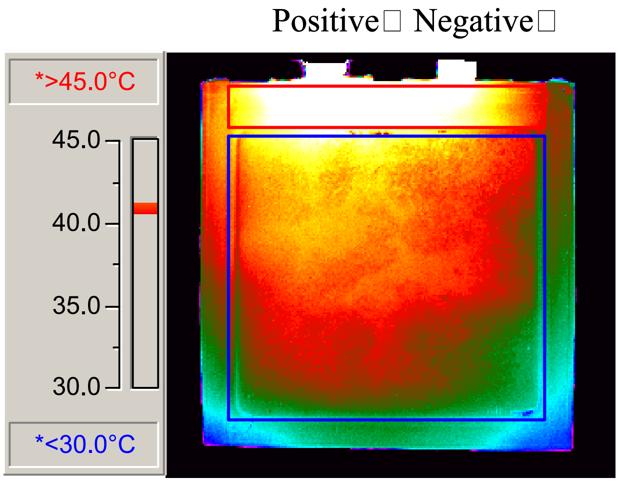

Figure 7b: Thermal image of Gen II cell after 30.0-amp discharge.

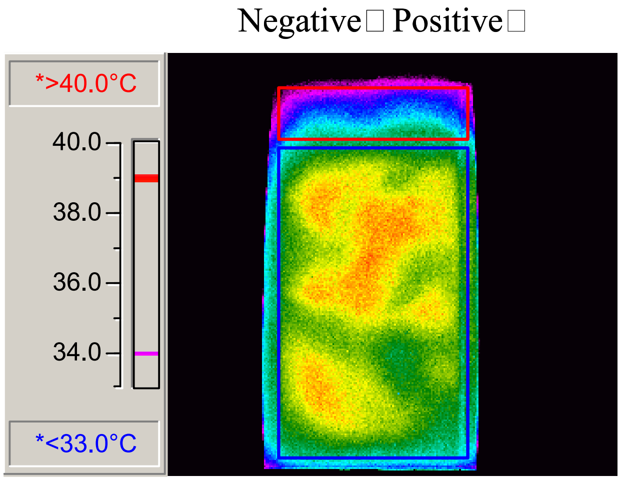

Figure 7c: Thermal image of Gen III cell after 30.0-amp discharge.

5.0 Conclusions and Summary

NREL has been supporting the development of CPI's high-power Li-Ion polymer cell using thermal characterization and analysis. Three generations of CPI prototype Li-Ion polymer cells were studied. All generations of the cells use a manganese-dioxide material for cathode and graphite anodes. The first- and second-generation cells showed signs of localized heat during thermal imaging underneath the positive electrode during discharge, whereas the Gen III cell remained relatively uniform in temperature. As the cell was improved and better electrodes designed, the Gen III became the most efficient of the cells tested. It exceeded an efficiency of

91% for all currents below 48 amps. In comparison, the Gen II CPI cell was only 78% efficient at 30 amps. Furthermore, the Gen III cell showed signs of being slightly endothermic during the initial 2 hours of a C/5 discharge and showed that the heat generation during a C/5 discharge is not constant and highly dependent on the SOC of the cell. Gen III has shown exceptional cycle life, very high power (2,000 W/kg), and high specific energy (95 Wh/kg). CPI has developed battery packs based on Gen III for HEV applications.

6.0 References

[1] Pesaran, A.A., Vlahinos, A., and Burch, S.D., "Thermal Performance of EV and HEV Battery Modules and Packs," Proceedings of the 14th International Electric Vehicle Symposium, Orlando, Florida, December 15–17, 1997.

[2] Pesaran, A.A., Russell, D.J., Crawford, J.W., Rehn, R., and. Lewis, E.A., "A Unique Calorimeter-Cycler for Evaluating High-Power Battery Modules," Proceedings of the 13th Annual Battery Conference: Applications and Advances, Long Beach, California, January 13–16, 1998.

[3] Pesaran, A.A., Swan, D., Olson, J., Guerin, J.T., Burch, S., Rehn, R., and Skellenger, G.D., "Thermal Analysis and Performance of a Battery Pack for a Hybrid Electric Vehicle," Proceedings of the 15th International Electric Vehicle Symposium, Brussels, Belgium, October 1–October 3, 1998.

[4] “PNGV Battery Test Manual, Rev III,” DOE/ID-10597, February 2001.