



# Performance Characterization of High Energy Commercial Lithium-ion Cells

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# **Performance Characterization of High Energy Commercial Lithium-ion Cells**

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## **Abstract**

The NASA Glenn Research Center Electrochemistry Branch performed characterization of commercial lithium-ion cells to determine the cells' performance against Exploration Technology Development Program (ETDP) Key Performance Parameters (KPP). The goals of the ETDP Energy Storage Project require significant improvements in the specific energy of lithium-ion technology over the state-of-the-art. This work supports the high energy cell development for the Constellation customer Lunar Surface Systems (LSS). In support of these goals, testing was initiated in September 2009 with high energy cylindrical cells obtained from Panasonic and E-One Moli. Both manufacturers indicated the capability of their cells to deliver specific energy of at least 180 Wh/kg or higher. Testing is being performed at the NASA Glenn Research Center to evaluate the performance of these cells under temperature, rate, and cycling conditions relevant to the ETDP goals for high energy cells.

The cell-level specific energy goal for high energy technology is 180 Wh/kg at a C/10 rate and 0 °C. The threshold value is 165 Wh/kg. The goal is to operate for at least 2000 cycles at 100 percent DOD with greater than 80 percent capacity retention. The Panasonic NCR18650 cells were able to deliver nearly 200 Wh/kg at the aforementioned conditions. The E-One Moli ICR18650J cells also met the specific energy goal by delivering 183 Wh/kg. Though both cells met the goal for specific energy, this testing was only one portion of the testing required to determine the suitability of commercial cells for the ETDP. The cells must also meet goals for cycle life and safety. The results of this characterization are summarized in this report.

## **Introduction**

In support of the Exploration Technology Development Program Energy Storage Project, NASA Glenn Research Center, in conjunction with Johnson Space Center (JSC), Jet Propulsion Laboratory (JPL) and contracted efforts, is developing high energy (HE) and ultra-high energy (UHE) lithium-ion cells. These components are being developed to address NASA's need for lighter, higher energy technologies with cycle capability to meet projected mission life requirements. Specific energy goals at the cell level are 180 and 260 Wh/kg for HE and UHE cells, respectively. The goals are at specific conditions of a C/10 discharge rate and 0 °C. While this would offer a 50 to 100 percent increase in specific energy over state-of-the-art lithium-ion technology, the cells must also meet safety and cycle life requirements. HE cells must meet 2000 cycles at 100 percent depth-of-discharge (DOD) while retaining 80 percent of their initial capacity and UHE cells 200 cycles under the same conditions.

In support of this development, testing was initiated to assess the capability of current commercial cell technology to meet ETDP Key Performance Parameter (KPP) goals for high energy cells. If a commercial cell were to meet or exceed the goals in terms of specific energy, safety, and cycle life, it is possible the cell could be included for use in the program.

Several cells were obtained from Panasonic (through Quallion) and E-One Moli Energy on the basis of high specific energy reported by the manufacturers. This report describes characterization testing performed on these commercial lithium-ion cells.

## Test Articles

Cells from Panasonic and E-One Moli Energy were chosen for evaluation. The first, model NCR18650 from Panasonic, is a 2.9 Ah cylindrical 18650 cell containing a graphitic anode and  $\text{LiNiCoAlO}_2$  cathode (NCA). Vendor data indicated the cell could deliver 235 Wh/kg at room temperature from vendor data. The second cell, model ICR18650J from E-One Moli, had a 187 Wh/kg specific energy at room temperature according to vendor data. The ICR18650J is a cylindrical 18650 cell containing a graphitic anode and  $\text{LiCoO}_2$  cathode. Table 1 lists characteristics of each cell provided by the vendor.

These cells are shown in Figure 1. Both cells are cylindrical 18650 geometry. The Panasonic cells arrived with welded tabs at each terminal, whereas tabs had to be welded to the E-One Moli cells in-house.

TABLE 1.—VENDOR CELL CHARACTERISTICS

Vendor	Model	Nameplate capacity, Ah	Nominal voltage, V	Cell mass, g	Discharge temperature range, °C
Panasonic	NCR18650	2.9	3.6	44.5	–20 to 60
E-One Moli	ICR18650J	2.37	3.76	48	–20 to 60



(a)



(b)

Figure 1.—(a) Panasonic and (b) E-One Moli Li-ion Test Cells.

## Incoming Cell Inspection

All cells were inspected upon receipt. The cells were inspected to determine the state of the cell; weights and dimensional measurements, open-circuit voltages and case polarity were measured and recorded. Cell weights from inspection were used to calculate the cell-level specific energy. Tables 2 and 3 show data from the cell inspections. As cell weights and open-circuit voltages were very similar, cells were randomly selected for testing from each batch.

TABLE 2.—PANASONIC NCR18650 CELL INSPECTION

	MANUFACTURER:		Panasonic					PART/LOT #	NCR18650 Lot B8502		
								DATE RCV'D	1-Oct-09		
Internal Designation	Serial Number	Weight (grams)		Dimensions (cm)				Voltage (volts)			
		Bare Cell*	With Harware	Diameter	Length	Width	Height	OCV Neg. to Pos.	Neg. to Case	Pos. to Case	
1	3-8 E49 0N3	45.953		18.15			65.55	3.564	0	3.564	
2	3-8 E4A ???	45.872		18.15			65.38	3.563	0	3.563	
3	5-8 34A FE5	45.911		18.15			65.41	3.561	0	3.561	
4	5-8 64A CE5	46.098		18.17			65.43	3.563	0	3.563	
5	3-8 94A EE3	45.977		18.13			65.43	3.564	0	3.564	
6	3-8 44A AA?	45.881		18.2			65.39	3.562	0	3.562	
*Bare cell weight includes tabs welded at each terminal											
Note: ? in serial number indicates illegible characters											

TABLE 3.—E-ONE MOLI ICR18650J CELL INSPECTION

		MANUFACTURER:		E-One Moli							
								PART/LOT #		ICR-18650J	
								DATE RCV'D:		19-Jun-08	
Internal Designation	Serial Number	Weight (grams)		Dimensions (cm)				Voltage (volts)			
				Bare Cell	With Harware	Diameter	Length	Width	Height	OCV Neg. to Pos.	Neg. to Case
1	71A01	47.284		18.23			65.03	3.734	0	3.734	
2	71A02	47.272		18.23			65.03	3.733	0	3.733	
3	71A03	47.436		18.19			65.05	3.731	0	3.731	
4	71A04	47.297		18.16			65.04	3.733	0	3.733	
5	71A05	47.31		18.11			65.06	3.734	0	3.734	

## Experimental

The test program initiated for commercial and developmental lithium-ion cells included characterization testing and cycle life testing. Destructive physical analysis of cells from each vendor is also planned.

Characterization testing was performed to assess cell performance under various rate and temperature conditions. Four of five cells from E-One Moli were tested due to limited equipment availability. Four of the six Panasonic cells were tested, allowing the remaining two cells to be stored for cycle life testing or destructive physical analysis (DPA).

A test plan was developed prior to testing and modified for each cell based on vendor testing recommendations; the test conditions are shown in Table 4.

With the exception of initial room temperature testing of the E-One Moli cells, 20 °C was considered room temperature for all tests.

TABLE 4.—CELL TESTING OUTLINE

Test (in order)	Charge rate <sup>a</sup>	Charge temperature, °C	Discharge rate <sup>a</sup>	Discharge temperature, °C
Conditioning	C/5	20	C/2	20
Temperature characterization	C/5	20	C/10	30, 20, 10, 0
20 °C rate characterization	C/5	20	C/10, C/5, C/2	20
20 °C/0 °C rate characterization	C/5	20	C/10, C/5, C/2	0
0 °C rate characterization	C/5	0	C/10, C/5, C/2	0

<sup>a</sup>Cells charged and discharged within manufacturer-recommended rates and voltage limits.

Hour-long rests following both charge and discharge were incorporated into all tests to allow the cells to equilibrate and temperature to stabilize. Though the manufacturers indicated both cells could be discharged to 2.50 V and some data is presented at the 2.50 V cutoff, the KPP goals are stated at 100 percent DOD to 3.00 V.

### Cell Conditioning

Conditioning cycles were performed to be sure the cells had consistent, stable performance and provide an actual capacity for each cell. Conditioning consisted of a minimum of five cycles at 20 °C. The cells were charged at constant current (CC) at C/5 with “C” as the nameplate capacity followed by a constant voltage (CV) charge until the current tapered to C/50. Following a 1-hr rest the cells were then discharged at a C/2 rate. Testing was repeated until the cells reached at least five cycles and the change in capacity between cycles was less than  $\pm 1$  percent. Current values for charge and discharge of all subsequent testing used the actual capacity “C” found from this conditioning.

In the case of the E-One Moli cells, room temperature characterization had been previously performed and conditioning was not performed on these cells. The actual capacity of these cells was taken from room temperature characterization.

### Temperature Characterization

Temperature characterization was performed to provide baseline performance data for the cells at beginning-of-life at various temperatures. The operating temperature range of interest is 0 to 30 °C. The cells were charged at a CC C/5 rate followed by a CV taper to C/50 at room temperature (20 °C). The cells were then discharged at a C/10 rate at discharge temperatures of 0, 10, 20, and 30 °C with three cycles performed at each temperature.

To preserve the order in which tests were performed, E-One Moli cells were not subjected to temperature characterization since room temperature characterization had already been performed. Temperature characterization of new cells recently received from E-One Moli is planned.

### **Rate Characterization**

Rate characterization was performed to determine the ampere-hour (Ah) capacity of the cells when discharged at different rates at room temperature and 0 °C conditions. The cells were charged at a CC C/5 rate and CV taper to C/50 for all tests. Discharge was performed at C/10, C/5, and C/2 discharge rates for three cycles each. This rate characterization was performed at room temperature for both charge and discharge (RT/RT), 0 °C for both charge and discharge (0/0), and with a room temperature charge followed by 0 °C discharge (RT/0) (“low temperature discharge”). This allowed an evaluation of the effect of a 0 °C charge on the specific energy of the cell compared to room temperature charging conditions.

E-One Moli rate testing at 23 °C was the one exception to the above test conditions. The cells had been held at 23 °C and charged with CC at C/10 with a CV taper to C/50. A 15-min rest followed, then C/10, C/5, C/2, and a final set of C/10 CC discharges were performed with five cycles at each rate. Another 15-min rest was incorporated after discharge.

### **Test Equipment**

Cells were housed in a Russells environmental chamber for temperature control with a nitrogen purge to provide an inert environment. Sufficient soak time was allowed between charge and discharge to allow the cells to equilibrate. The cells were setup in the chamber with appropriately sized wiring, connectors, and fuses. An Arbin BT2000 Battery Testing System was used to provide current control during testing. The MITS Pro companion software was used to control the charge and discharge profiles, monitor safety limits, and collect data. The Arbin also has auxiliary temperature channels that were used to monitor the cell and ambient temperatures during testing.

## **Results and Discussion**

### **Panasonic NCR18650**

According to manufacturer recommendations, the 2.9 Ah NCR18650 cells were cycled between 2.50 and 4.20 V. Figure 2 represents a typical discharge curve of cell voltage versus specific energy in watt-hours per kilogram. This figure shows the performance as a function of temperature. Actual cell weights were used for each individual cell to calculate specific energy values.

All cells delivered similar specific energies on discharge with a coefficient of variance less than 0.6 percent at each condition. Considering 20 °C performance as a baseline, there is a slight improvement in specific energy at 30 °C. The cells delivered an average of 227 Wh/kg at 20 °C down to 3.0 V while delivering only 209 Wh/kg at 0 °C, a reduction of about 10 percent of the room temperature specific energy. Table 5 shows data collected for temperature characterization testing. Specific energy values are reported as percentages of the 20 °C baseline as well as in watt-hours per kilogram.

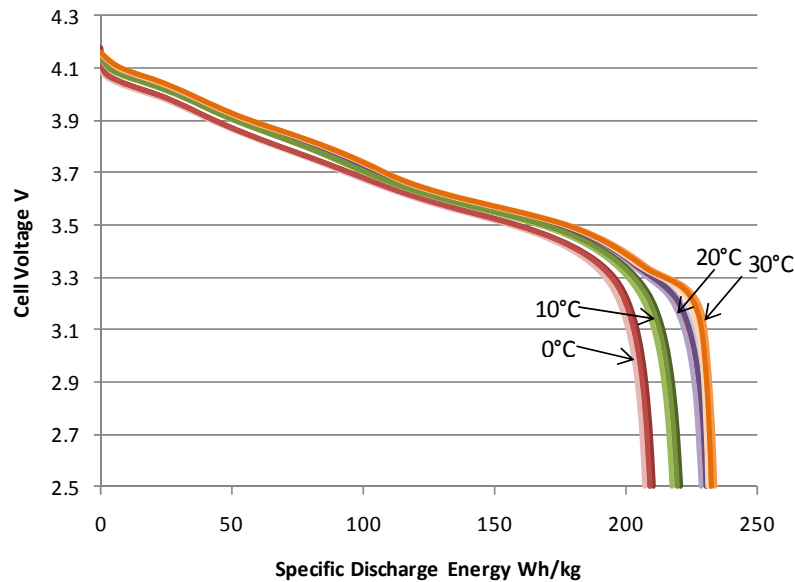


Figure 2.—Discharge curves for temperature characterization of Panasonic NCR18650 cells.

TABLE 5.—SPECIFIC ENERGY AT 3.0 V OF PANASONIC CELLS AT VARIOUS TEMPERATURES

Cell	20°C Wh/kg	30°C		10°C		0°C	
		Wh/kg	% of 20°C energy	Wh/kg	% of 20°C energy	Wh/kg	% of 20°C energy
1	224.7	229.3	102.1%	213.0	94.8%	203.0	90.4%
2	226.8	230.5	101.7%	215.6	95.1%	205.5	90.6%
3	228.3	231.2	101.3%	216.6	94.9%	206.3	90.4%
4	226.2	230.2	101.8%	215.6	95.3%	205.5	90.9%
Average	226.5	230.3	101.7%	215.2	95.0%	205.1	90.6%
Coeff of Var	0.67%	0.35%	0.32%	0.71%	0.25%	0.70%	0.25%

The next test performed was rate characterization at room temperature. These tests varied the discharge rate while the cells were held at room temperature. Figure 3 shows the specific energy trends during cycling. Data for all four cells is included, but the variability among cells is very small and thus hard to distinguish in the chart. Data for the final cycles in which cells were returned to C/10 matched the original C/10 data and is not shown in this plot.

As shown in Table 6, the Panasonic cells delivered 225 Wh/kg at C/10 and room temperature, while delivering close to 91 percent of that energy at a C/2 rate. When returned to C/10, the cells recovered to within about 1 Wh/kg of the original C/10 capacity and remained 99.8 to 99.9 percent efficient (coulombic) throughout testing.

These cells were also tested with a room temperature charge at a C/5 rate and 0 °C discharge at rates of C/10, C/5, and C/2. These conditions were utilized to examine the effects of harsh thermal environments on the performance of the cell. Within the scope of the ETDP Energy Storage Project, the cells may be subjected to temperatures as low as 0 °C, which is known to have a significant impact on the energy and rate performance of lithium-ion cells. The LSS Constellation customer has indicated that charging is likely to be performed in a controlled environment around 20 °C; however, the need may arise to charge in the field at less than optimum temperature conditions. This testing, accompanied by 0 °C (0/0) testing, was performed to assess the charging capability of the cells as a function of temperature.

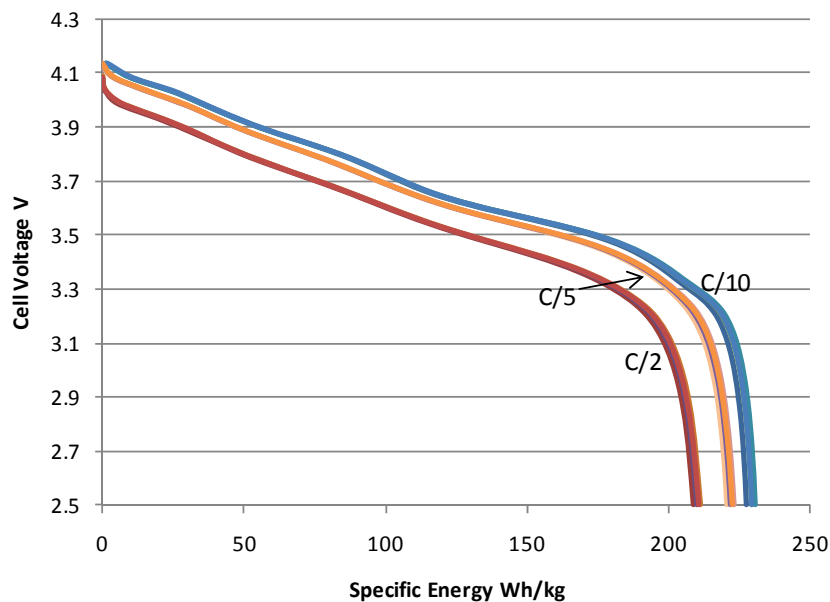


Figure 3.—20 °C rate characterization data for Panasonic NCR18650 cells.

TABLE 6.—20 °C SPECIFIC ENERGY TO 3.0 V AT VARIOUS RATES

Cell	Wh/kg delivered at 3.0V			
	C/10	C/5	C/2	final C/10
1	223.0	215.0	201.7	221.8
2	224.8	216.8	203.4	223.7
3	226.1	217.9	204.6	225.0
4	225.0	217.0	203.7	223.9
Average	224.7	216.7	203.3	223.6
Coeff of Var	0.58%	0.57%	0.60%	0.58%

Performance was evaluated keeping the cells at 0 °C for both charge and discharge. Figure 4 shows the C/10 performance at both of the above conditions compared to 20 °C performance for a representative cell.

The figure clearly shows a significant decrease in specific energy when the cells are discharged at 0 °C. However, there was little difference in the capacity between the 20 and 0 °C charge condition. The cells delivered an average of 202 Wh/kg with a 0 °C discharge and 198 Wh/kg with 0 °C charge and discharge. These values represent 90.0 and 87.9 percent of the specific energy at 20 °C charge and discharge, respectively. The 180 Wh/kg goal for specific energy was exceeded in both cases.

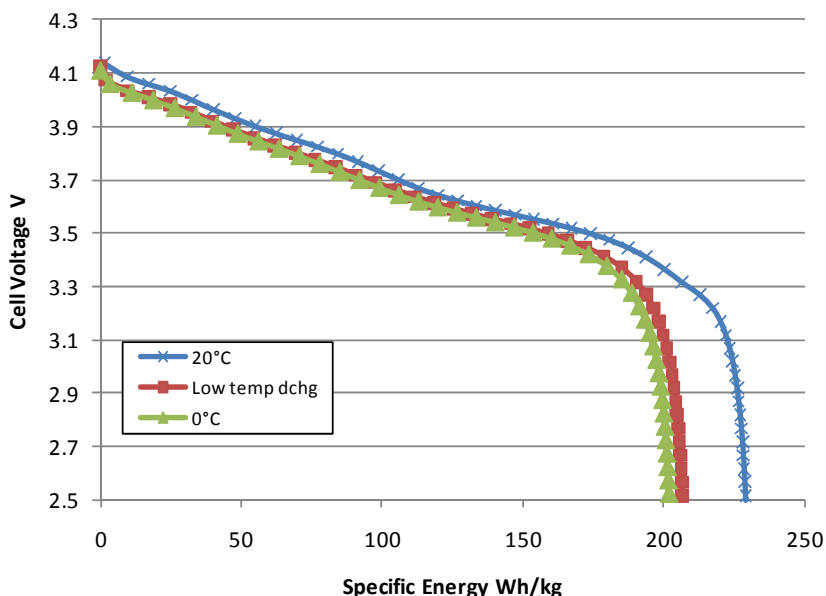


Figure 4.—Panasonic NCR18650 Cell 2 temperature effects at C/10 rate.

Several cycles at a C/10 discharge rate at 20 °C were performed after characterization had completed to determine the capacity retention after cycling. The cells retained an average of 97.4 percent of their initial capacity (taken as cycle 1 in temperature characterization) after 48 cycles. The cells delivered an average of 227 Wh/kg in cycle 1 and 221 Wh/kg in cycle 48 (Fig. 7). The capacity retention is not indicative of cycle life of the cell due to differences between capacity characterization and cycle life testing procedures. Cycle life testing includes alternating C/10 and C/2 discharge cycles at 20 °C, while capacity characterization includes C/5 and low temperature testing.

### E-One Moli Energy ICR18650J

The ICR18650J 2.37 Ah cell was cycled between voltage limits of 3.00 and 4.20 V. According to manufacturer data, the cell was capable of delivering specific energy of 187 Wh/kg at room temperature conditions.

These cells delivered an average of 190 Wh/kg at room temperature and a C/10 discharge rate. Figure 5 shows specific energy trends at different discharge rates. Figure 5 illustrates the discharge curves of the four cells tested. The cells exhibited roughly a 4.5 percent decrease in capacity at a C/2 discharge rate. The cells also maintained coulombic efficiencies of 99.6 to 99.8 percent throughout testing. The E-One Moli cells exhibited less rate effects than the Panasonic cells, which had shown a 9 percent decrease in capacity at C/2. Specific energy data can be found in Table 7.

A RT charge, 0 °C discharge characterization was performed on the E-One Moli cells identical to test procedures for the Panasonic cells. Due to an equipment malfunction, no additional testing was performed on cell 4 following room temperature testing; the cell was not damaged and a capacity check performed at the end of testing revealed no loss in capacity. The remaining three cells delivered 187.3 and 183.4 Wh/kg at 0 °C when charged at RT/0 °C conditions, respectively, or 99.0 and 96.7 percent of room temperature performance. Negative low temperature effects on these cells were minimal. Figure 6 shows the effects of temperature on the performance of the cells. As with the Panasonic cells, there was little difference in performance whether charging was performed at 20 or 0 °C.

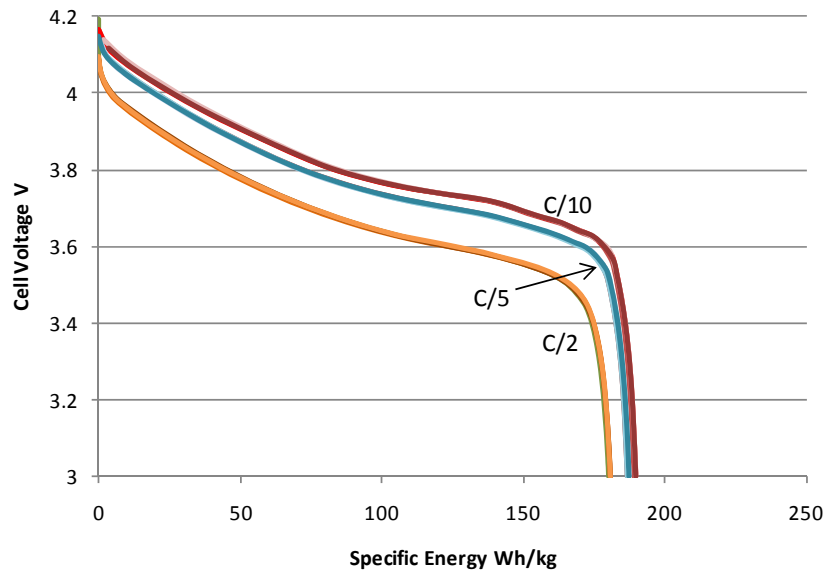


Figure 5.—Room temperature rate characterization of E-One Moli.

TABLE 7.—ROOM TEMPERATURE RESULTS FOR E-ONE MOLI

Cell	C/10 Wh/kg delivered	C/5 as % of C/10	C/2 as % of C/10	final C/10 as % of C/10
2	189.3	98.7%	95.4%	99.3%
3	189.9	98.6%	95.3%	99.3%
4	189.7	98.7%	95.3%	99.3%
5	189.7	98.8%	95.6%	99.4%
Average	189.7	98.7%	95.4%	99.3%
Coeff of Var	0.12%	0.08%	0.13%	0.07%

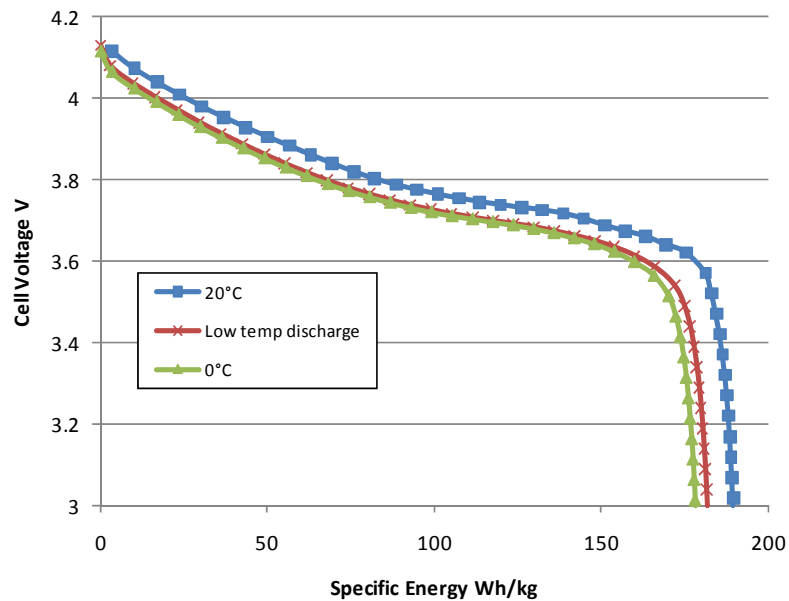


Figure 6.—E-One Moli Cell 71A05 temperature effects at C/10 rate.

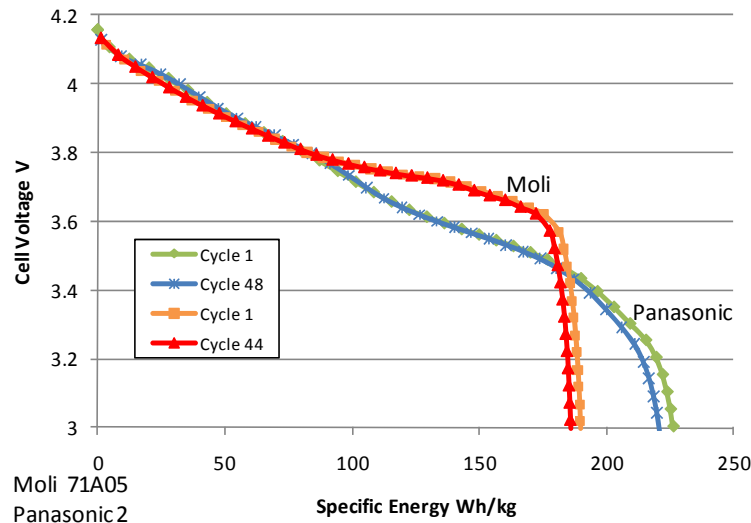


Figure 7.—Comparison of discharge curves over cycles.

These cells met the ETDP goal for specific energy by delivering 183.4 Wh/kg at a C/10 rate and 0 °C.

The cells were returned to room temperature and a C/10 discharge rate following characterization to determine capacity retention. Since no temperature characterization tests were performed for these cells, the initial capacity was taken as the first cycle room temperature capacity. After 44 cycles, the cells retained 97.8 percent of their initial capacity, delivering 185.6 Wh/kg. Figure 7 shows the change in capacity over cycles for a representative cell from each vendor. Little capacity loss was seen with cells from both vendors. Additionally, the difference in discharge profiles due to the different cell chemistries is seen.

## Future Planned Work

Cycle life testing is planned for both E-One Moli and Panasonic cells. The cycle life testing will provide an idea of the cycling capabilities of currently available technology at the ETDP KPP test conditions. The ETDP's high energy cell is required to deliver at least 80 percent of its initial capacity (180 Wh/kg at C/10 and 0 °C) after 2000 cycles. Preliminary cycle life and safety tests on the Panasonic NCR18650 cells were performed at JSC. Initial observations show capacity degradation of roughly 4.3 percent over 200 cycles at a C/5 charge and C/10 discharge rate at room temperature. Applying a simple linear fit to cycle life data shows the Panasonic cells delivering less than 80 percent capacity after 973 cycles. This initial work at JSC indicates that the Panasonic cell would not meet all ETDP goals. Safety testing resulted in excessive heat and fire for internal short circuit and heat-to-vent tests, which represented 2 of 5 safety tests performed. The cells were not functional after any test except external short circuit (Ref. 1). Additional cells from both vendors have been procured to allow cycle life testing under updated conditions. Updated cycling procedures include alternating discharges of C/10 and C/2 rather than only C/10 as performed at JSC. Several cells will also be set aside for DPA and shelf life observations.

## Conclusions

Many of the trends seen in the characterization of these commercial cells are typical of lithium-ion technology; the Panasonic and E-One Moli cells exhibited reduced performance at low temperatures with further reduction at high discharge rates. The cells from E-One Moli were less sensitive to changes in temperature and discharge rate when compared with the Panasonic cells, though the Panasonic cells delivered higher specific energy. While the cells do not contain the same chemistries, the Panasonic

contains an NCA cathode while the E-One Moli cathode is  $\text{LiCoO}_2$ , these chemistries have similar theoretical capacities. DPA may reveal differences in cell construction and provide insight into the differences in performance of the cells.

When comparing the results of capacity characterizations to the KPP metrics, both the E-One Moli ICR18650J and Panasonic NCR18650 cells met the HE specific energy goal of 180 Wh/kg at a C/10 rate at 0 °C. The Panasonic cells exceeded goals by delivering 198 Wh/kg at 0 °C, while the E-One Moli cells met the goal by delivering 183 Wh/kg under the same conditions. The cells will also be evaluated for cycle life performance to determine their ability to meet the ETDP cycle life requirement of greater than 80 percent capacity retention after 2000 cycles.

## References

1. Read, Jon, Jeevarajan, Judith, Patel, Pranav, Bytella, Joe, and Symmetry Resources, Inc., “Performance and Safety Testing of Panasonic 2.9Ah Li-ion NCR18650 Cells,” 2009 NASA Aerospace Battery Workshop, November 17–19, 2009.

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14. ABSTRACT <p>The NASA Glenn Research Center Electrochemistry Branch performed characterization of commercial lithium-ion cells to determine the cells' performance against Exploration Technology Development Program (ETDP) Key Performance Parameters (KPP). The goals of the ETDP Energy Storage Project require significant improvements in the specific energy of lithium-ion technology over the state-of-the-art. This work supports the high energy cell development for the Constellation customer Lunar Surface Systems (LSS). In support of these goals, testing was initiated in September 2009 with high energy cylindrical cells obtained from Panasonic and E-One Moli. Both manufacturers indicated the capability of their cells to deliver specific energy of at least 180 Wh/kg or higher. Testing is being performed at the NASA Glenn Research Center to evaluate the performance of these cells under temperature, rate, and cycling conditions relevant to the ETDP goals for high energy cells. The cell-level specific energy goal for high energy technology is 180 Wh/kg at a C/10 rate and 0 °C. The threshold value is 165 Wh/kg. The goal is to operate for at least 2000 cycles at 100 percent DOD with greater than 80 percent capacity retention. The Panasonic NCR18650 cells were able to deliver nearly 200 Wh/kg at the aforementioned conditions. The E-One Moli ICR18650J cells also met the specific energy goal by delivering 183 Wh/kg. Though both cells met the goal for specific energy, this testing was only one portion of the testing required to determine the suitability of commercial cells for the ETDP. The cells must also meet goals for cycle life and safety. The results of this characterization are summarized in this report.</p>					
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