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Performance Assessment of Baseline Cells for the High Efficiency Space Power Systems Project

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Abstract

The Enabling Technology Development and Demonstration (ETDD) Program High Efficiency Space Power Systems (HESPS) Project, formerly the Exploration Technology Development Program (ETDP) Energy Storage Project is tasked with developing advanced lithium-ion cells for future NASA Exploration missions (Ref. 1). Under this project, components under development via various in-house and contracted efforts are delivered to Saft America for scale-up and integration into cells. Progress toward meeting project goals will be measured by comparing the performance to these cells with cells of a similar format with Saft's state-of-the-art aerospace chemistry. This report discusses the results of testing performed on the first set of baseline cells delivered by Saft to the NASA Glenn Research Center. This build is a cylindrical "DD" geometry with a 10 Ah nameplate capacity. Testing is being performed to establish baseline cell performance at conditions relevant to ETDD HESPS Battery Key Performance Parameter (KPP) goals including various temperatures, rates, and cycle life conditions.

Data obtained from these cells will serve as a performance baseline for future cell builds containing optimized ETDD HESPS-developed materials. A test plan for these cells was developed to measure cell performance against the high energy cell KPP goals. The goal for cell-level specific energy of the high energy technology is 180 Wh/kg at a C/10 discharge rate and 0 °C. The cells should operate for at least 2000 cycles at 100 percent DOD with 80 percent capacity retention. Baseline DD cells delivered 152 Wh/kg at 20 °C. This number decreased to 143.9 Wh/kg with a 0 °C discharge. This report provides performance data and summarizes results of the testing performed on the DD cells.

Introduction

To address the need for improved energy storage devices with high specific energy, long cycle life, and improved safety for future NASA missions, the ETDD High Efficiency Space Power Systems Project (HESPS) is developing components for integration into high energy lithium-ion cells. This work began under the Exploration Technology Development Program Energy Storage Project. The Key Performance Parameters (KPP) for high specific energy cells include specific energy of 180 Wh/kg at 0 °C and a C/10 rate, 80 percent capacity retention after 2000 cycles at 100 percent depth-of-discharge (DOD), and safe and reliable performance. The HESPS Battery KPP values are provided in Table 1.

To support this effort, NASA teamed up with an industrial partner, Saft America, to scale-up materials and build evaluation and flight cells. Materials developed under multiple NASA Research Announcement contracts were delivered to the NASA Glenn Research Center (GRC), Johnson Space Center (JSC), and Jet Propulsion Laboratory (JPL) for performance screening. Once the materials were screened and met certain minimum performance requirements, the materials were passed on to Saft for scale-up and associated activities (Ref. 2).

In October 2009, Saft delivered a build of cylindrical DD cells containing their baseline electrode chemistry to the NASA GRC. This cell was chosen because it is a flight heritage design and easily manufactured at Saft. The cell assessment would serve as a baseline for comparison against future cell deliveries.

The NASA ETDD HESPS project team created the test plan to assess the performance of candidate cells against the KPP goals. The cells were subjected to temperature, rate, and cycling conditions relevant to the ETDD high energy goals. This report summarizes the results of performance characterization of Saft's DD baseline cells.

TABLE 1.—KEY PERFORMANCE PARAMETERS

Key Performance Parameters for Battery Technology Development

Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
Safe, reliable operation	No fire or flame	Instrumentation/controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a small reduction in performance using safer electrolytes and cathode coatings	Tolerant to electrical and thermal abuse such as over-temperature, overcharge, reversal, and short circuits with no fire or thermal runaway****	Tolerant to electrical and thermal abuse such as over-temperature, overcharge, reversal, and short circuits with no fire or thermal runaway****
Specific energy Lander: 150 – 210 Wh/kg 10 cycles Rover: 160-200 Wh/kg 2000 cycles EVA: 270Wh/kg 100 cycles	**Battery-level** specific energy* [Wh/kg]	90 Wh/kg at C/10 & 30 C 83 Wh/kg at C/10 & 0 C (MER rovers)	160 at C/10 & 30 C (HE) 170 at C/10 & 30 C (UHE) 80 Wh/kg at C/10 & 0 C (predicted)	**135** Wh/kg at C/10 & 0 C “High-Energy”** **150** Wh/kg at C/10 & 0 C “Ultra-High Energy”***	**150** Wh/kg at C/10 & 0 C “High-Energy” **220** Wh/kg at C/10 & 0 C “Ultra-High Energy”
	Cell-level specific energy [Wh/kg]	130 Wh/kg at C/10 & 30 C 118 Wh/kg at C/10 & 0 C	199 at C/10 & 23°C (HE) 213 at C/10 & 23°C (UHE) 100 Wh/kg at C/10 & 0°C (predicted)	**165** Wh/kg at C/10 & 0 C “High-Energy” **180** Wh/kg at C/10 & 0 C “Ultra-High Energy”	**180** Wh/kg at C/10 & 0 C “High-Energy” **260** Wh/kg at C/10 & 0 C “Ultra-High Energy”
	Cathode-level specific capacity [mAh/g]	180 mAh/g	252 mAh/g at C/10 & 25°C 190 mAh/g at C/10 & 0°C	**260** mAh/g at C/10 & 0 C	**280** mAh/g at C/10 & 0 C
	Anode-level specific capacity [mAh/g]	280 mAh/g (MCMB)	330 @ C/10 & 0°C (HE) 1200 mAh/g @ C/10 & 0°C for 10 cycles (UHE)	**600** mAh/g at C/10 & 0 C “Ultra-High Energy”	**1000** mAh/g at C/10 0 C “Ultra-High Energy”
Energy density Lander: 311 Wh/l Rover: TBD EVA: 400 Wh/l	**Battery-level** energy density	250 Wh/l	n/a	**270** Wh/l “High-Energy” **360** Wh/l “Ultra-High”	**320** Wh/l “High-Energy” **420** Wh/l “Ultra-High”
	Cell-level energy density	320 Wh/l	n/a	**385** Wh/l “High-Energy” **460** Wh/l “Ultra-High”	**390** Wh/l “High-Energy” **530** Wh/l “Ultra-High”
Operating environment 0°C to 30°C, Vacuum	Operating Temperature	-20°C to +40°C	0°C to +30°C	**0°C** to **30°C**	**0°C** to **30°C**

Assumes prismatic cell packaging for threshold values. Goal values include lightweight battery packaging.
* Battery values are assumed at 100% DOD, discharged at C/10 to 3.0 volts/cell, and at 0°C operating conditions
** ”High-Energy” = mixed metal oxide cathode with graphite anode
*** “Ultra-High Energy” = mixed metal oxide cathode with Silicon composite anode
**** Over-temperature up to 110°C; reversal 150% excess discharge @ 1C; pass external and simulated internal short tests; overcharge 100% @ 1C for Goal and 80% @ C/5 for Threshold Value.

Revised 9/20/10

Test Articles

The 10 Ah capacity DD cell configuration was chosen for the screening process due to its flight heritage design and ease of manufacturing by Saft. Ten DD cells were delivered to the NASA GRC in October 2009. The cells are spiral-wound cylindrical cells with a stainless steel container. Cells contain a burst disc at the negative end and came with tabs welded at each terminal. Table 2 lists pertinent measurements taken during the incoming physical and electrical inspection. Cells contain Saft's baseline chemistry and "space" organic electrolyte. The baseline chemistry is a nickel alloy-based cathode and graphite-based anode.

With the above components, each cell should nominally deliver 10 Ah of capacity, or 140 Wh/kg based on a nominal discharge voltage of 3.5 V and cell mass of 0.25 kg. The cell-level specific energy during testing was calculated using the individual cell masses listed in Table 2, which included welded tabs, and capacity taken as the average Ah delivered for all cells. Figure 1 depicts a DD cell with tabs and an attached thermocouple.

TABLE 2.—SAFT DD CELL INSPECTION DATA

Inspection Date: Oct 16, 2009			BATTERY CELL PHYSICAL AND ELECTRICAL			
Inspected by: BTS & DEY			INSPECTION DATA			
MANUFACTURER:		Saft			PART/LOT #	1054
	DATE OF MANUFACTURE:				DATE RCV'D:	6-Oct-09
Serial Number	Weight (grams)	Dimensions (cm)			Voltage	
	Bare Cell with tabs	Diameter	Height	Height w' Terminals	OCV Neg. to Pos.	Pos. to Case
21	251.2	3.35	12.38	12.53	3.610	3.610
30	250.2	3.34	12.35	12.55	3.602	3.602
32	251.2	3.36	12.32	12.46	3.602	3.602
33	249.4	3.34	12.32	12.51	3.601	3.601
37	249.3	3.36	12.33	12.42	3.603	3.603
39	249.9	3.33	12.26	12.43	3.603	3.603
41	250.3	3.34	12.36	12.51	3.604	3.604
43	250.1	3.35	12.31	12.44	3.603	3.603
48	250.4	3.34	12.29	12.44	3.602	3.602
49	251.7	3.34	12.37	12.45	3.603	3.603

Figure 1.—DD design.

Experimental

The test program initiated for developmental and commercial lithium-ion cells includes characterization and cycle life testing. Test plans were developed to evaluate performance against KPP metrics.

Characterization tests were performed on all ten cells to assess their performance at several temperature and discharge rate conditions. Table 3 outlines the test conditions the cells were subjected to during characterization. Cycle life testing is also currently in progress.

TABLE 3.—CELL TESTING OUTLINE

Test (in order)	Charge rate[a]	Charge temperature, °C	Discharge rate[a]	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
Cycle Life (bulk w/out diagnostics)	C/5	20	9 cycles C/10, 1 cycle C/2 repeated	20 and 0 in parallel

[a]The cells were cycled between voltage limits of 3.00 and 4.10 V. KPP goals for cell-level specific energy are stated at 100 percent Depth of Discharge (DOD) to 3.00 V and data is presented to that cutoff voltage.

Cell Conditioning

Conditioning cycles were performed to ensure the cells had consistent, stable performance and to provide an actual capacity for each cell. Conditioning consisted of a minimum of five cycles at 20 °C. Cells were charged at constant current (CC) at C/5 to 4.10 V with a "C" of 10 Ah followed by a constant voltage (CV) charge until the current tapered to C/50. Following a 1-hr open circuit rest the cells were then discharged at a C/2 rate to 3.00 V. This cycle was repeated until the cells reached at least five cycles and the change in capacity between cycles was less than ±1 percent. Values for charge and discharge current of all subsequent testing used the average of the cells' actual capacities determined from this conditioning as "C".

Temperature Characterization

Temperature characterization was performed to evaluate capacity as a function of discharge temperature. The cells were charged at room temperature (20 °C) for all cycles and discharged at temperatures of 0, 10, 20, and 30 °C. Cells were allowed to soak for 2 hr between charge and discharge to allow for temperature equilibration. The cells were charged at a CC C/5 rate to 4.10 V followed by a CV taper to C/50. Discharges were performed at a CC C/10 rate to 3.00 V at all temperatures.

Rate Characterization

Rate characterization was performed to determine the performance 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 to 4.10 V 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 ("20 °C"), a 20 °C charge followed by 0 °C discharge ("20/0 °C"), and 0 °C for both charge and discharge ("0 °C"). This allowed an evaluation of the effect of a 0 °C charge on the performance of the cell compared to 20 °C charging conditions. Some of the tests from "Temperature Characterization" were repeated with this method, including the C/10 rate discharge at 20 °C and 20/0 °C.

For tests with alternating temperature conditions between charge and discharge, such as the 20/0 °C rate characterization and temperature characterizations, a 2-hr soak period was used to allow for stabilization of the cell core temperature. All other tests included 1-hr rests following charge and discharge to allow the cells to equilibrate within the environmental chamber.

Cycle Life Testing

The cycle life test regime assesses the KPP high energy requirement of 2000 cycles at 100 percent DOD with at least 80 percent capacity retention. The test regime includes periodic diagnostic cycles to assess the current state of the cell every 200 cycles. The diagnostics are performed at 0, 20, and 30 °C. The cells are cycled with a CC C/5 charge rate to 4.10 V followed by a CV taper to C/100 and discharged at C/10 except for a C/2 discharge every tenth cycle, to a 3.00 V cutoff. This step is meant to periodically gauge the C/2 performance.

Cycle life testing is performed at two different temperature conditions. Five cells are held at 20 °C (excluding diagnostics every 200 cycles) and the remaining cells are charged at 20 °C and discharged at 0 °C. Other than the temperature difference and temperature dwell times, the test procedures remain identical for all cells.

Test Equipment

All cells are housed in environmental chambers for temperature control with a nitrogen purge to provide an inert environment. An Arbin BT2000 Battery Testing System is used to provide current control during testing. The MITS Pro companion software is used to control the charge and discharge profiles, monitor safety limits, and collect data. The Arbin’s auxiliary temperature channels are used to monitor the cell and ambient temperatures during testing.

Results and Discussion

Cell Conditioning

The cells completed five conditioning cycles, although the capacity stabilized to less than ±1 percent in the second cycle. “C” was determined by averaging the discharge capacity of all cells in the fifth cycle and determined to be 10.0 Ah. The capacity amongst cells was uniform, varying by no more than ±1 percent of the average “C.” The cells delivered 10.3 Ah during similar testing at Saft; however the tests were performed at 30 °C as opposed to 20 °C at NASA GRC. Data shows a capacity increase of 2.1 percent when the temperature is increased from 20 to 30 °C, which may partially explain the differences in these data.

Temperature Characterization

Temperature characterization provided baseline performance data for the cells at a C/10 discharge rate at several temperature conditions. Figure 2 shows the discharge curves for each DD cell at 20 °C only, illustrating that there is very little variability amongst the ten cells. The variability can also be seen in data from Table 4, which lists the specific energy delivered for each cell at 20 °C and also provides the 0, 10, and 30 °C specific energies as both values and percentages of the 20 °C performance. The cells delivered 157.2 Wh/kg at 20 °C. The cells showed a slight improvement at 30 °C, delivering 160.6 Wh/kg. Cells delivered 150.4 and 143.1 Wh/kg at 10 and 0 °C, respectively.

Figure 3 shows the C/10 performance for a representative cell over the 0 to 30 °C temperature range. Baseline performance was taken at 20 °C at which point the cells delivered 157.2 Wh/kg. The impact of discharge temperature on the specific energy can be easily seen in the plot. Specific energy decreased by 9.0 percent when the cells were discharged at 0 °C. Discharge temperature did not affect the coulombic efficiency, but the energy efficiency decreased with decreasing temperature, falling from 97.3 percent at 30 °C to 96.8 percent at 0 °C. Table 5 lists the coulombic and energy efficiency of each cell.

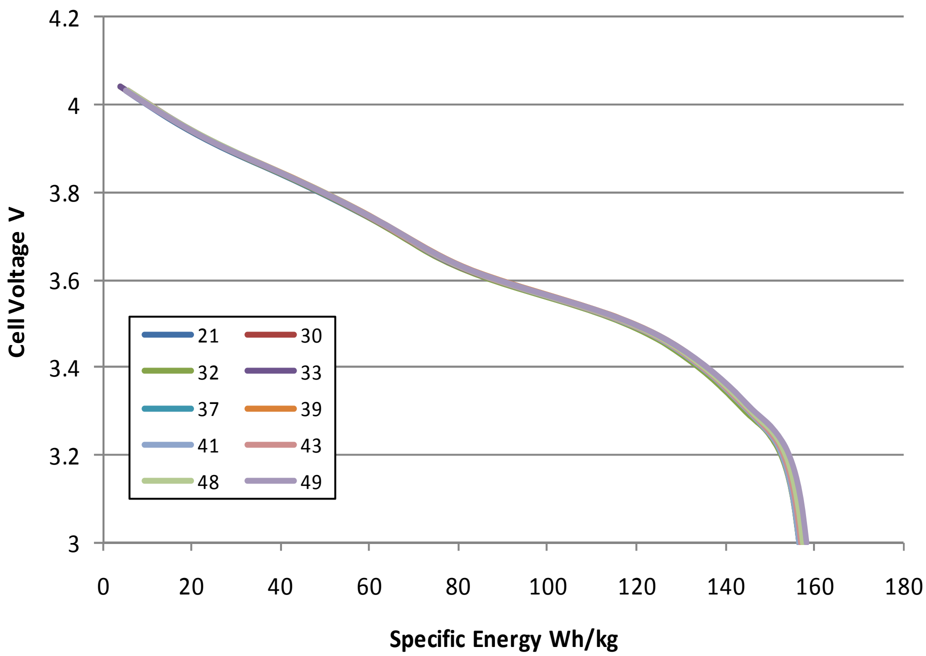

Figure 2.—The 20 °C C/10 discharge voltage versus specific energy for ten DD cells.

TABLE 4.—THE C/10 TEMPERATURE CHARACTERIZATION DATA FOR DD CELLS

Cell	20°C Wh/kg	30°C Wh/kg	30°C % of 20°C energy	10°C Wh/kg	10°C % of 20°C energy	0°C Wh/kg	0°C % of 20°C energy
21	156.7	160.1	102.2%	149.9	95.7%	142.8	91.1%
30	157.3	160.6	102.1%	150.4	95.6%	143.0	91.0%
32	156.7	159.9	102.1%	149.8	95.6%	142.5	91.0%
33	157.6	161.0	102.1%	150.7	95.6%	143.3	90.9%
37	157.0	160.7	102.3%	150.3	95.8%	143.1	91.2%
39	157.7	161.1	102.2%	150.9	95.7%	143.6	91.1%
41	156.6	160.3	102.3%	149.8	95.7%	142.6	91.1%
43	156.8	160.4	102.3%	150.0	95.7%	142.8	91.1%
48	157.5	160.8	102.1%	150.7	95.7%	143.4	91.1%
49	158.2	161.0	101.8%	151.3	95.6%	144.0	91.0%
Average	157.2	160.6	102.1%	150.4	95.7%	143.1	91.0%
Coeff of Var	0.34%	0.25%	0.16%	0.33%	0.04%	0.33%	0.09%

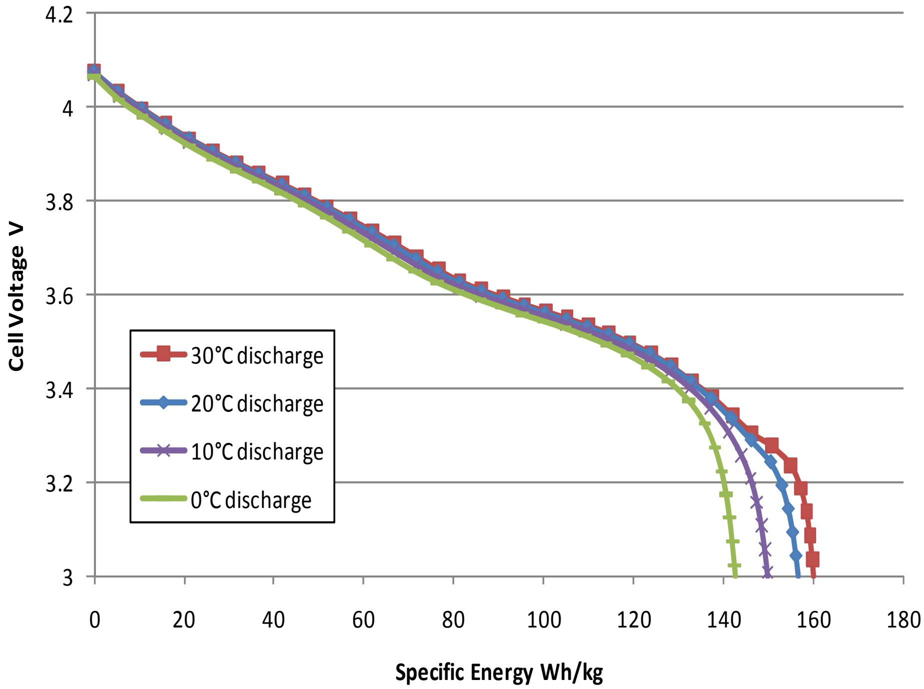

Figure 3.—The C/10 temperature characterization for DD cell 32.

TABLE 5.—EFFICIENCY DATA FOR TEMPERATURE CHARACTERIZATION AT C/10

Temperature	Coulombic Efficiency	Energy Efficiency
30°C	99.8%	97.3%
20°C	99.9%	97.2%
10°C	99.8%	97.1%
0°C	99.8%	96.8%

Rate Characterization

Next, cells were assessed for 20 °C rate performance. Similar to results from temperature characterization at C/10, the cells delivered 157.2 Wh/kg (10.82 Ah) at a C/10 rate. All showed decreasing energy with increasing discharge rate. The tests were run from the lowest (C/10) discharge rate to the highest (C/2) with the C/10 discharge repeated after the higher rate characterization cycles. There was no observable difference in specific energy after the 12 rate capability cycles and the coulombic efficiency remained 99.9 percent at all rates. The cells experienced a 9 percent reduction in capacity at a C/2 discharge rate when compared to C/10, delivering 143.1 Wh/kg at C/2. Table 6 and Figure 4 show the performance of the cells at various rates at 20 °C and each discharge curve in Figure 4 is an average of all ten cells on test. Specific energy values are presented as percentages of the C/10 specific energy. Additionally, little variability among cell performance was observed.

Rate characterization at lower temperatures was performed to determine the ability of the cells to discharge at lower temperatures. Cells were charged and discharged under the 20/0 °C rate conditions. These tests were meant to simulate actual temperature conditions a cell may experience while in use by any of the ETDD’s customers where charging would occur in a controlled environment and batteries would be exposed to ambient conditions during discharge.

TABLE 6.—DD RATE CHARACTERIZATION AT 20 °C

Cell	C/10 Wh/kg	C/5 as % of C/10 Wh/kg	C/2 as % of C/10 Wh/kg	final C/10 as % of C/10 Wh/kg
21	156.8	96.7%	91.0%	99.8%
30	157.2	96.7%	91.0%	99.8%
32	156.7	96.7%	90.9%	99.8%
33	157.7	96.7%	91.1%	99.8%
37	157.1	96.7%	91.0%	99.8%
39	157.7	96.7%	91.2%	99.8%
41	156.6	96.7%	91.1%	99.8%
43	156.8	96.7%	91.0%	99.8%
48	157.5	96.8%	91.2%	99.8%
49	158.2	96.7%	90.9%	99.8%
Avg	157.2	96.7%	91.0%	99.8%
Coeff of Var	0.3%	0.0%	0.1%	0.0%

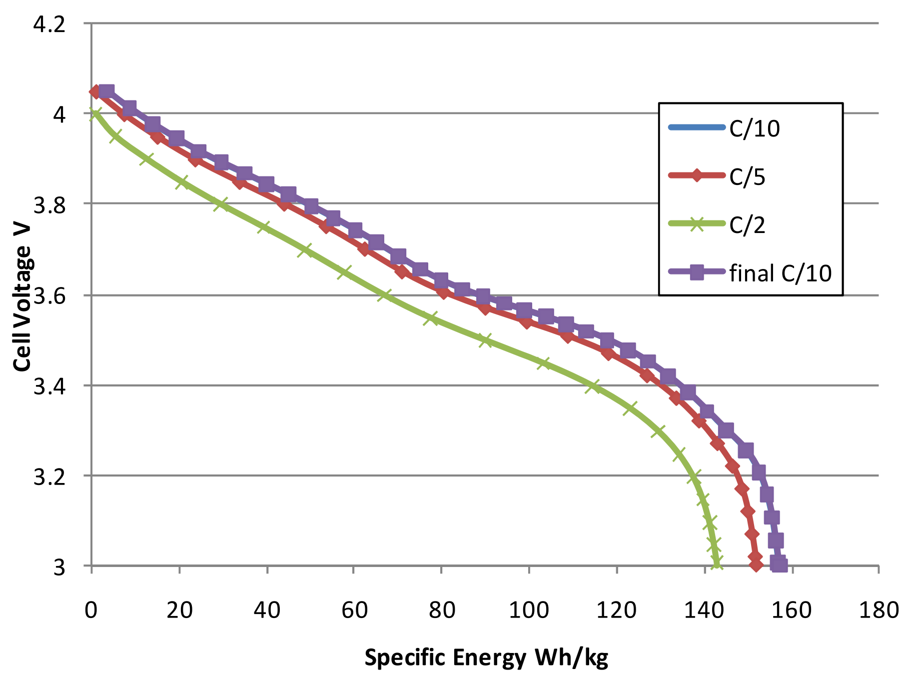

Figure 4.—The 20 °C DD rate characterization discharge curves.

Cells were tested under these conditions for comparison with 20 °C performance. The cells delivered an average of 143.9 Wh/kg at a C/10 rate and 0 °C; this is approximately 91.6 percent of the 20 °C performance. The cells delivered 128.8 Wh/kg at C/2, 89.5 percent of the C/10 energy under these temperature conditions. The performance hit between C/10 and C/2 for these conditions is slightly worse than at 20 °C (91.0 percent from C/10 to C/2). Figure 5 and Table 7 illustrate the data collected for 20/0 °C testing. The average voltage during discharge was comparable to 20 °C at C/10 and C/5 discharge rates; however the average voltage for the C/2 discharge rate was roughly 20 mV lower for the 20/0 °C condition. The energy efficiency at every discharge rate was lower for this testing than 20 °C, and the energy efficiency experienced a larger decline between C/10 and C/2. The general observation is the 0 °C discharge has a greater effect on the cell performance as discharge rate is increased.

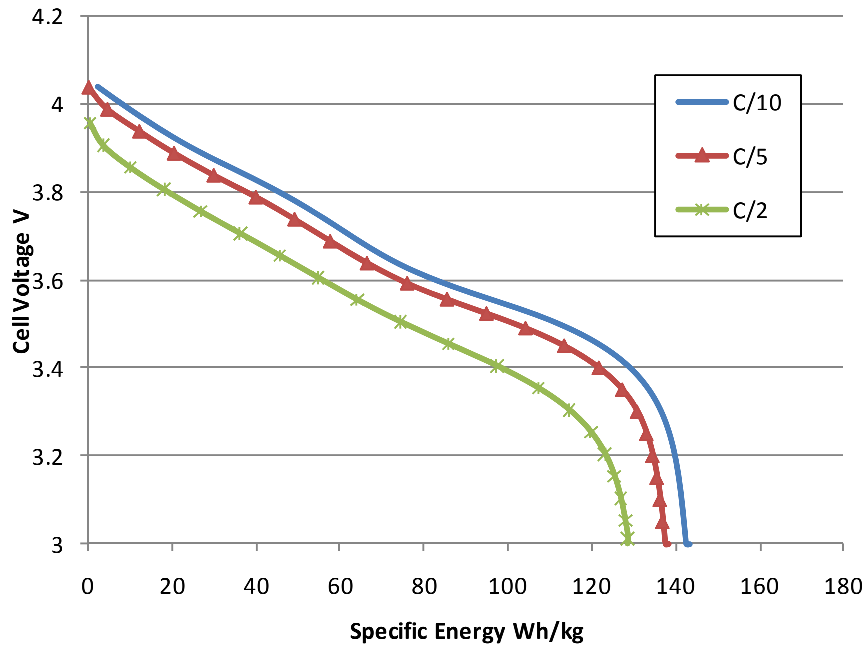

Figure 5.—The 20/0 °C rate characterization.

TABLE 7.—THE 0 °C DD RATE CHARACTERIZATION

Cell	C/10 Wh/kg	C/5 as % of C/10 Wh/kg	C/2 as % of C/10 Wh/kg
21	143.5	95.6%	89.7%
30	143.8	95.5%	89.5%
32	143.3	95.5%	89.4%
33	144.3	95.5%	89.6%
37	144.0	95.5%	89.4%
39	144.3	95.6%	89.7%
41	143.5	95.5%	89.4%
43	143.7	95.5%	89.4%
48	144.3	95.6%	89.5%
49	144.8	95.5%	89.2%
Avg	143.9	95.5%	89.5%
Coeff of Var	0.3%	0.1%	0.2%

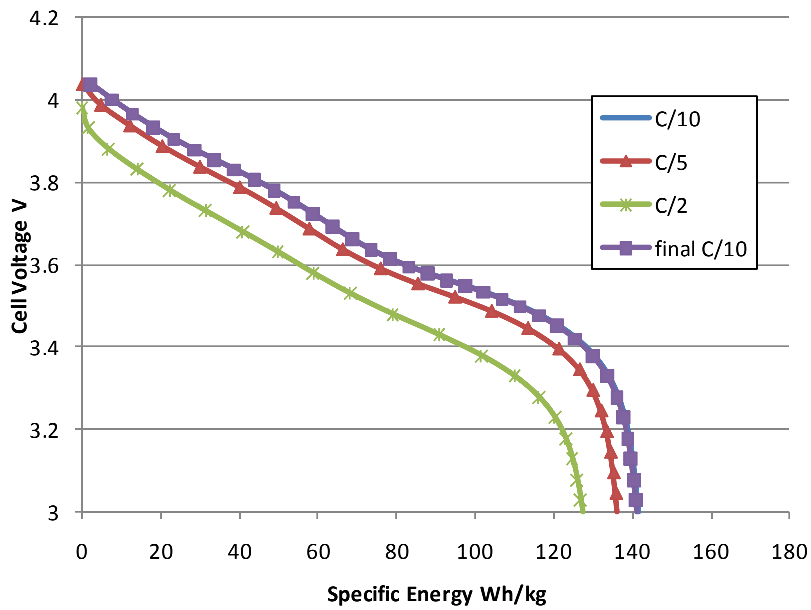

Figure 6.—DD rate characterization at 0 °C.

Rate characterization was also performed while both charging and discharging the cells at 0 °C. Performance at C/10 was similar to results obtained with 20/0 °C characterization. An average of 141.3 Wh/kg (9.68 Ah), or 89.9 percent of the 20 °C specific energy, was observed and the cells did not experience a severe drop in performance at higher rates. A capacity drop of 10 percent from C/10 to C/2, similar to the drop at 20 °C, was also seen at this temperature as seen in Figure 6. Note that the discharge curves in Figure 6 corresponding to “C/10” and “final C/10” discharge rates overlap, resulting in the original “C/10” curve disappearing in the plot. In comparison, the average voltage during charge for 0 and 20/0 °C testing was 3.74 V, versus 3.70 V for 20 °C testing. The 0 and 20/0 °C tests reached the 4.10 V charge cutoff more quickly than the testing at 20 °C, and accumulated less capacity during charge as a result. These tests also resulted in the most significant voltage recovery during the hour-long open circuit rest following discharge. The voltage recovered from 3.00 V at the end of discharge and ranged from 3.34 to 3.42 V at the beginning of the following charge. Voltage recovery for 20 °C tests ranged from 3.23 to 3.29 V after discharging to 3.00 V. These cells then had a larger charge voltage window and accumulated more capacity during charge than tests incorporating the 0 °C discharge. Figure 7 shows the voltage profile of a representative cell during charge at each condition. While the charge profiles appear similar at the 0 and 20/0 °C conditions, the data also leads to the conclusion that the act of performing discharging at 0 °C had a more significant effect on the performance of the cell than the charge condition, whether it was 0 or 20 °C.

To make an overall performance comparison, Figure 8 compares the C/10 performance during rate characterization of the cells at each of the three temperature condition described above and shows little difference in the results of tests performed at low temperatures.

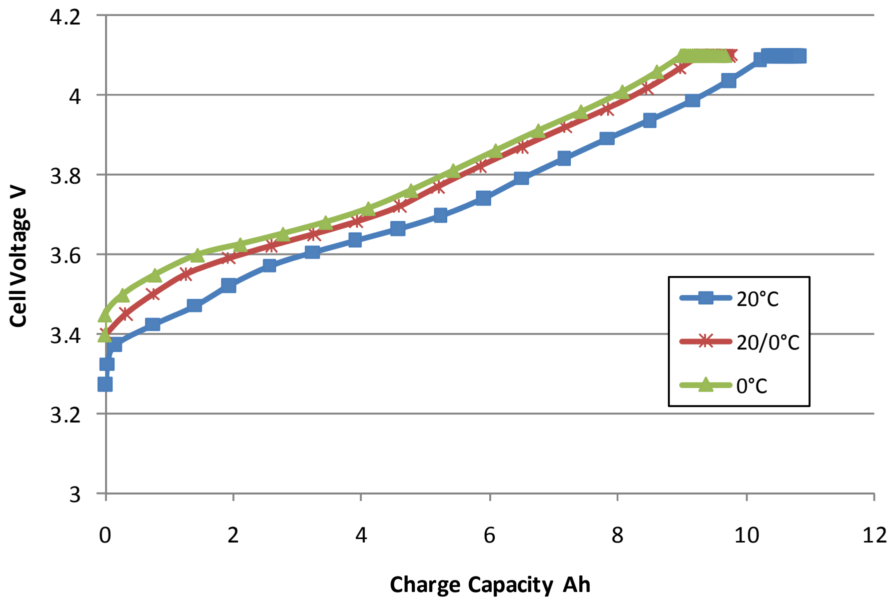

Figure 7.—Cell 33 C/5 charge profiles.

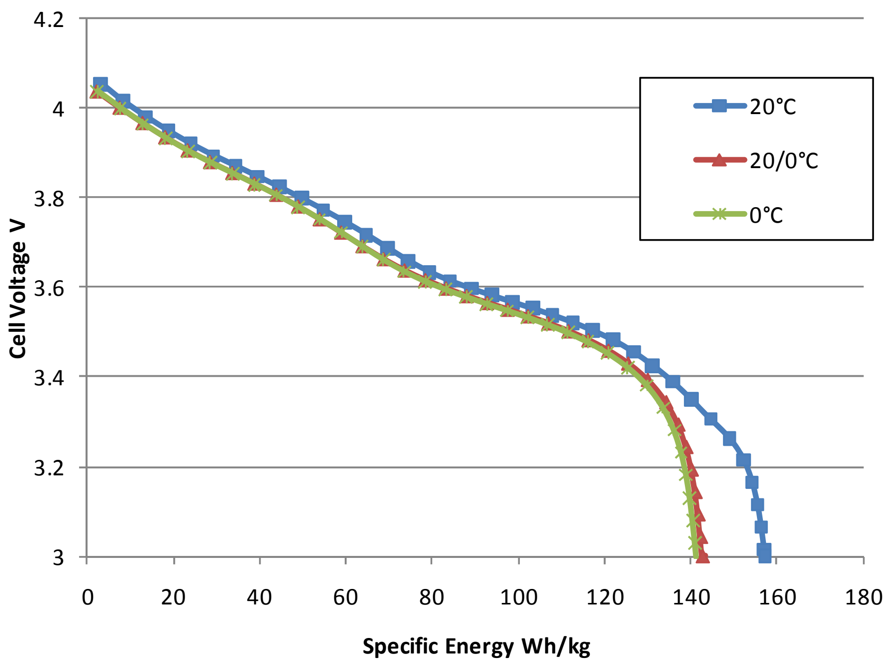

Figure 8.—DD Cells at C/10 in rate characterization.

Cycle Life Performance

Cycle life testing was initiated in October 2010 and as of April 2011, the DD cells cycling at 20 °C had completed 205 cycles. Figure 9 compares the capacity of the five cells being cycled. The noticeable decrease in capacity every tenth cycle corresponds to a C/2 discharge. Although the cells have demonstrated consistent performance with a low capacity fade rate, the cells that began with a slightly higher capacity have shown slightly less fade than the remaining cells. Table 8 shows the original capacity and capacity retention to 205 cycles as a percentage of the initial capacity. Initial capacity for the cells is taken as cycle 2 on the plot, which does not include diagnostics performed prior to cycling. On average, the cells have retained 96.2 percent of the initial capacity after 205 cycles under life testing conditions. Cells 41 and 48, the cells with the highest initial capacities, also have slightly higher capacity retention after 205 cycles. Assuming the capacity continues to fade at the same rate, the cells will reduce to 80 percent capacity retention after 946 cycles. The cells will continue to cycle until this point has been reached.

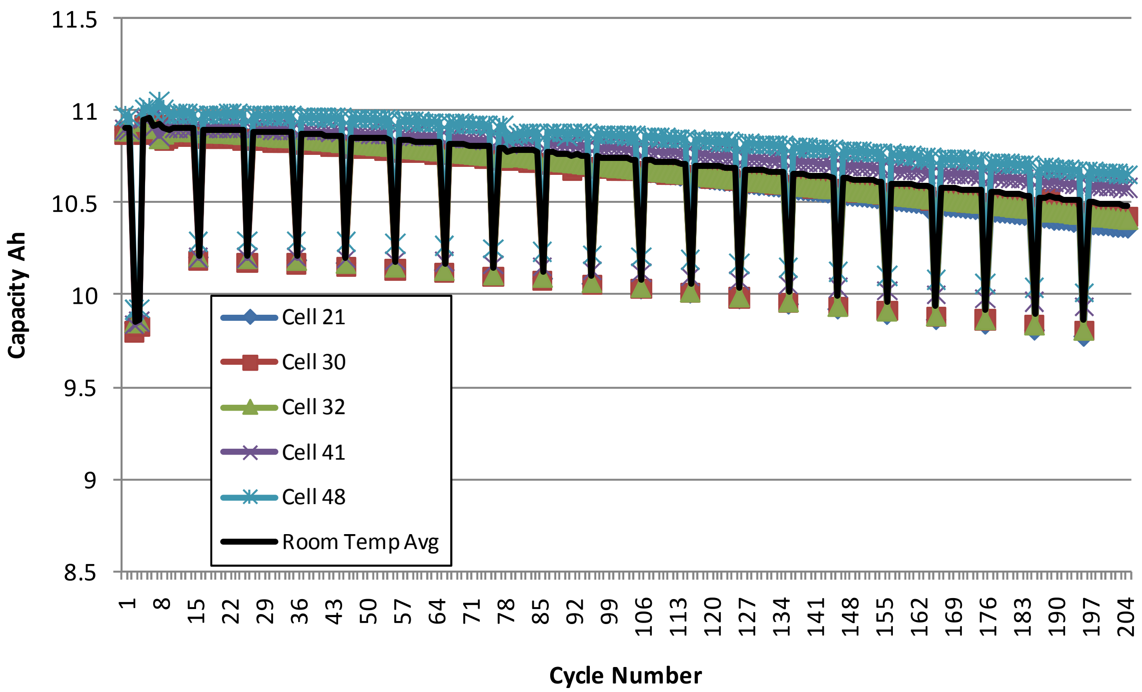

Figure 9.—Cycle life capacity of DD cells at 20 °C.

TABLE 8.—20 °C CYCLE LIFE CAPACITY RETENTION TO 205 CYCLES

Cell	Initial Ah	% of initial capacity retained
21	10.89	95.2%
30	10.85	96.0%
32	10.89	95.6%
41	10.90	97.0%
48	10.98	97.0%
Average	10.90	96.2%

As of March 2011, four cells cycling with a 0 °C discharge have completed 99 cycles (Fig. 10). As noted on the plot, there were several occasions during which the temperatures were not correctly matched to charge or discharge states. For example, during the period marked "temperature mismatch," cycles 12 through 19, the cells began to discharge while the chamber temperature was still at 20 °C, leading to a higher capacity than expected at 0 °C. From cycles 30 to 63 the environmental chamber was experiencing icing issues. Several cells experienced colder temperatures due to their proximity to the ice formation, and some were further away and were not as greatly affected. Charge data for cell 37, which experienced the most severe temperature drop due to its location in the chamber, is in Figure 11. Cycles 9 and 118 in the plot represent cycles before and after the icing occurred. It is obvious from the charge curve of Cycle 57 that the average charge voltage was higher than the other cycles by roughly 1 percent during the icing period. The charge curve for Cycle 118, well after the temperature conditions were brought back to normal, returned to the original profile. The cells experienced brief periods of rest time intermittently while various attempts were made to repair the chamber, however, the issue was solved after cycle 63 and the cells have been cycling continuously since. Figure 10 clearly shows the difference in capacity during the period described above.

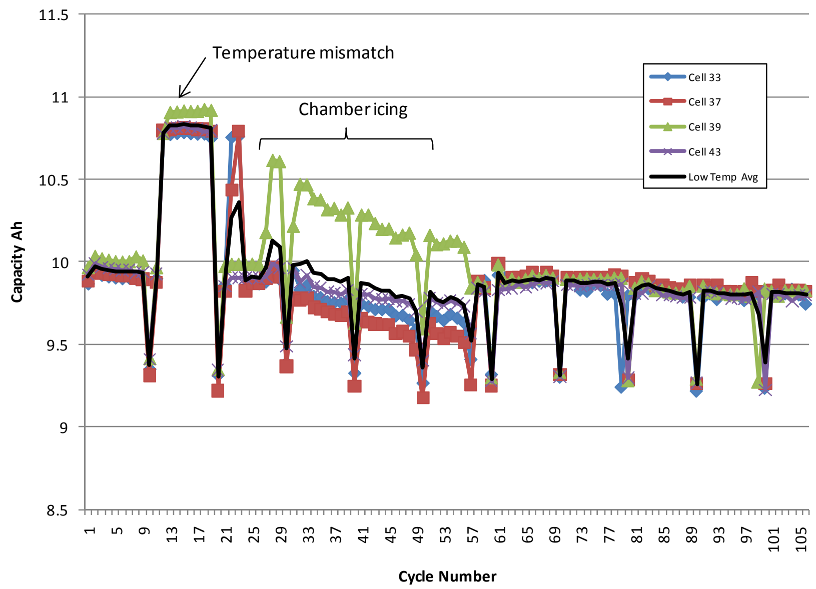

Figure 10.—Cycle life discharge capacity with 0 °C discharge.

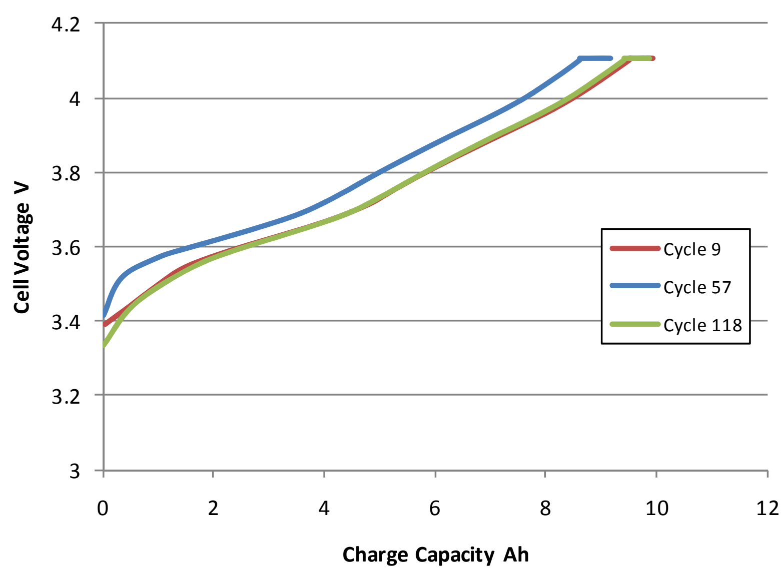

Figure 11.—Cell 37 charge curves.

Table 9 lists capacity retention for individual cells, including that after 99 cycles the cells have retained an average of 98.4 percent. Cell 49 is not listed in Table 9 as testing was halted early in cycling due to failure for unknown reasons. In comparison, the cells cycling at 20 °C retained 98.3 percent of their initial capacity after 99 cycles. Figure 12 illustrates the trends of both cycle life tests and shows that capacity fade does not seem to be affected by discharge temperature.

TABLE 9.—0 °C DISCHARGE CYCLE LIFE CAPACITY RETENTION TO 99 CYCLES

Cell	Initial Ah	% of initial capacity retained
33	9.93	98.7%
37	9.95	99.3%
39	10.04	97.6%
43	9.99	97.9%
Average	9.98	98.4%

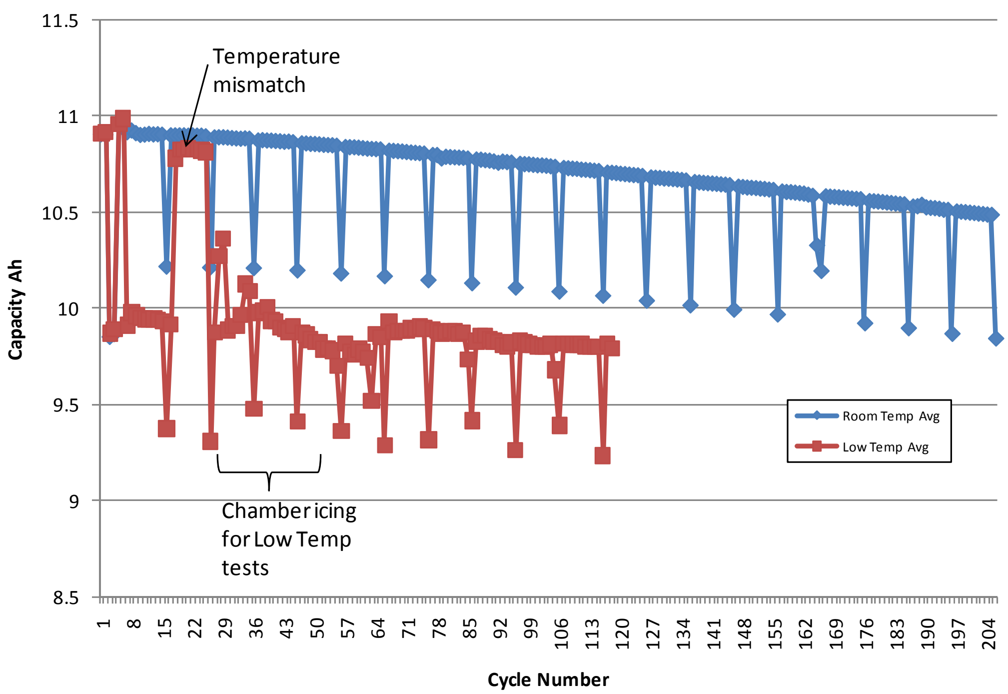

Figure 12.—Comparison of 20 °C vs. 20/0 °C cycle life.

Conclusions

The Saft DD baseline cells delivered 157.2 Wh/kg at 20 and 0 °C testing yielded roughly 90 percent of the energy at 20 °C, while increasing the discharge current to a C/2 rate decreased the energy of the cell by roughly 10 percent. Minor differences in performance were observed when the cells were tested with a 0 °C discharge only versus 20/0 °C charge and discharge conditions. Cycle life tests revealed that the capacity fade rate to 205 cycles has not been affected by a 0 °C discharge versus tests run completely at 20 °C. Although these cells serve as a baseline and are not designed to meet the KPP metrics for capacity and cycle life, it is encouraging that the capacity and cycle life performance are not greatly affected by lower temperatures listed as the KPP metrics. Data collected for these cells will serve as a basis for comparison with future cell builds to track the progress of cell development for the High Efficiency Space Power Systems Project.

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14. ABSTRACT Abstract The Enabling Technology Development and Demonstration (ETDD) Program High Efficiency Space Power Systems (HESPS) Project, formerly the Exploration Technology Development Program (ETDP) Energy Storage Project is tasked with developing advanced lithium-ion cells for future NASA Exploration missions. Under this project, components under development via various in-house and contracted efforts are delivered to Saft America for scale-up and integration into cells. Progress toward meeting project goals will be measured by comparing the performance to these cells with cells of a similar format with Saft’s state-of-the-art aerospace chemistry. This report discusses the results of testing performed on the first set of baseline cells delivered by Saft to the NASA Glenn Research Center. This build is a cylindrical “DD” geometry with a 10 Ah nameplate capacity. Testing is being performed to establish baseline cell performance at conditions relevant to ETDD HESPS Battery Key Performance Parameter (KPP) goals including various temperatures, rates, and cycle life conditions. Data obtained from these cells will serve as a performance baseline for future cell builds containing optimized ETDD HESPS-developed materials. A test plan for these cells was developed to measure cell performance against the high energy cell KPP goals. The goal for cell-level specific energy of the high energy technology is 180 Wh/kg at a C/10 discharge rate and 0 °C. The cells should operate for at least 2000 cycles at 100 percent DOD with 80 percent capacity retention. Baseline DD cells delivered 152 Wh/kg at 20 °C. This number decreased to 143.9 Wh/kg with a 0 °C discharge. This report provides performance data and summarizes results of the testing performed on the DD cells.						
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