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Evaluation of Saft Ultra High Power Lithium Ion Cells (VL5U)

by Jan L. Allen, Jeff Wolfenstine, Kang Xu, Donald Porschet, Thomas Salem, Wesley Tipton, Wishvender Behl, Jeff Read, T. Richard Jow, and Sonya Gargies

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14. ABSTRACT
We evaluated Saft Ultra High Power (UHP) cells (Saft designation VL5U) to determine their rate capability, low temperature performance, storage, and cycle life. The energy and power density at 5 A (1C) were 45 Wh/kg and 55 W/kg, respectively; at 1000 A (200C) were 25 Wh/kg and 10 kW/kg, respectively; and at a 500 A rate, the energy densities were 35, 29, and 29 Wh/kg at 20, –20, and –40 °C, respectively, and the power densities were 4.3, 3.9, and 3.6 kW/kg, respectively. The VL5U showed a high rate of self-discharge (tested at 70 °C). Our cycling testing showed that high rate cycling degrades the cell faster than high temperature cycling, revealing significant self-heating at high rates of discharge. These results indicate the cell design is immature; further development will remediate the high self-discharge rates and the self-heating during high rate discharge. Pulse discharge testing using a capacitive load showed that, at an output voltage of 2 V, a pulsed current of 8750 A may be achieved. The minimum cell resistance from the pulse testing was measured to be about 0.23 mΩ.

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Contents

List of Figures

List of Tables

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1. Introduction

The objective of this report is to evaluate the performance of Saft Ultra High Power (UHP) (Saft designation VL5U) lithium-ion cells and determine applicability for Army applications. This report includes the data and their analysis. The characteristics of the Saft VL5U cells are shown in table 1.

Table 1. Characteristics of the Saft VL5U cells.

Mass: ~350 g	**Dimensions**: 15.23 cm length x 3.37 cm diameter cylindrical	**Volume**: ~136 mL
Capacity: ~5 Ah	**Energy**: ~20 Wh (72 Joules)	**Avg. Discharge Voltage**: ~3.8 V
Energy Density: ~57 Wh/kg (163 Wh/liter)		
Chemistry of Electrodes: $LiNi_{1-x-y}Co_xAl_yO_2$ / Carbon		
Impedances: Via Pulse Discharge: 0.21-0.24 mΩ (see§3.7) AC-1000Hz: 0.3 mΩ (data provided by Saft) 2 sec: 0.8 mΩ (data provided by Saft)		

2. Approach

Saft UHP cells were subjected to high rate discharge testing at currents up to 1000 A (200C) using a Maccor battery cycler and pulse discharge testing using a capacitive load. In order to obtain the baseline capacity, cells were first equilibrated at 20 °C in an environmental chamber and then charged at a constant 5 A current to 4.1 V, followed by a constant voltage charge at 4.1 V until the charging current was less than 0.1 A. We then measured the baseline capacity using a constant current discharge at 5 A to 2.5 V, and conducted temperature testing from 70 °C down to –40 °C. Prior to discharge, we determined a baseline performance of each cell by cycling at 1C (5 A) rate at room temperature, and after the low and high temperature discharge, we again cycled the cell at the 1C rate (room temperature) to determine if the performance had degraded as a result of the low/high temperature discharge. Additionally, we evaluated the cycle life by cycling at a 1C rate at elevated temperature (70 °C) and at 200C at 20 °C. Figure 1 shows a cell as configured for discharge. A thermocouple was attached to the exterior of the cell by black electrical tape.

Figure 1. Configuration of Saft UHP cell during discharge. The cell was discharged inside an environmental chamber and the exterior temperature of the cell was monitored by a thermocouple.

3. Results

3.1 Discharge Behavior at Room Temperature

The discharge capacity was evaluated at 500 A (100C) and 1000 A (200C). We set the cutoff voltage of the discharge at 2.5 V for 20 °C testing. We also obtained the discharge capacity at 250 A at room temperature. Figure 2 shows the discharge capacity of a single cell as a function of the rate of discharge at 20 °C, normalized to 1C capacity. The cell is able to deliver about 75% of the 1C (5 A) discharge capacity while discharging at the 200C (1000 A) rate. Clearly, the voltage is significantly lower at 1000 A; the average voltage during discharge at 1C is about 3.6 V and at 200C around 3.1 V.

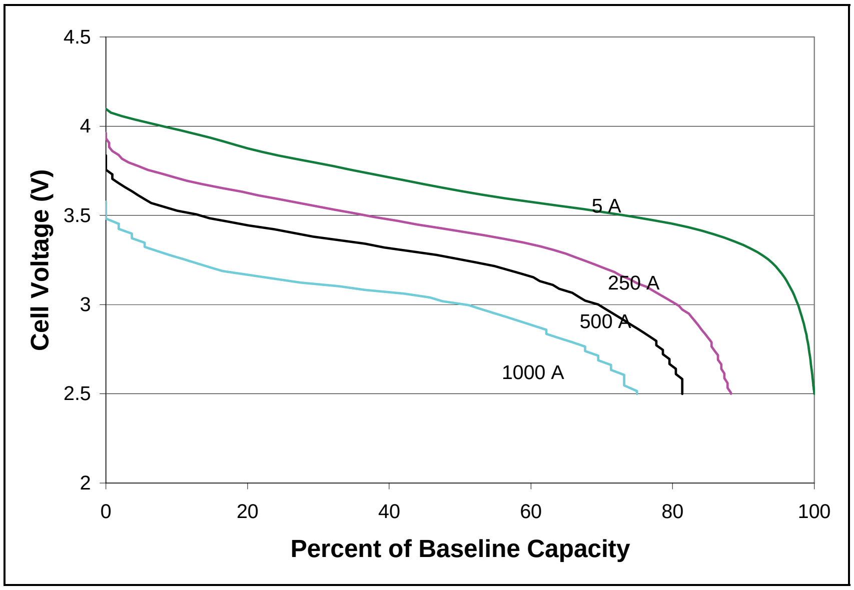

Figure 2. Voltage and discharge capacity as a function of rate of discharge at 20 °C. The baseline capacity is ~5 Ah at room temperature.

As a means to compare the data in the context of the current state of the art for rechargeable cells, we plotted the 20 °C discharge data on a Ragone-type plot of specific energy versus specific power. The baseline chart was provided courtesy of Saft. Figure 3 shows these data and table 2 tabulates them. In figure 3, the data points for the Saft UHP cells are shown as red rectangles and the rate of discharge is indicated next to each rectangle in red text as C-rate, C = 5 A.

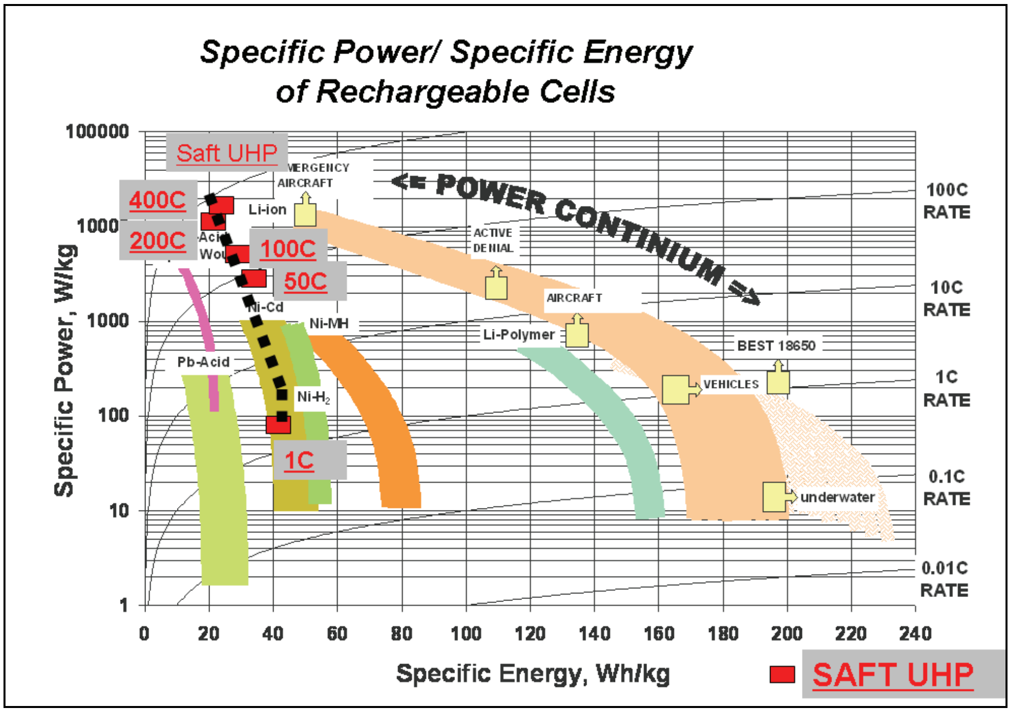

Figure 3. Room temperature performance plotted as a specific energy versus specific power chart (Ragone plot). The data points are shown in red and a trend line is shown as a dotted black line.

Note: The data point at 400C is from the IAT (University of Texas) data and the baseline chart is courtesy of Saft.

Table 2. Room temperature energy and power of Saft VL5U cell as a function of rate of discharge.

Rate	Energy		Power	
	Wh / kg	Wh / liter	kW / kg	kW / liter
1C (5 A constant)	57	146	0.052	0.13
50C (250 A constant)	47	121	0.58	1.5
100C (500 A constant)	42	108	4.7	12
200C (1000 A constant)	36	93	8.7	22
400C (2000 A constant)[a]	27	69	14	36

[a] The data point at 400C is from the IAT (University of Texas) data.

It is clear that the cell has been optimized for high specific power at the expense of specific energy. A lithium ion cell optimized for specific energy can attain close to 200 Wh /kg, but the specific power of such a cell is generally in the 10 to 100 W/kg range, which is much lower than the 14 kW/kg attained for the Saft UHP cell at 400C.

3.2 Discharge at Subzero Temperatures (–20 °C and –40 °C)

We next evaluated the performance at high rate and subzero temperature. The cutoff voltage was 2 V for these subzero tests. At 1000 A, the cell voltage dropped below the cutoff voltage of 2 V and minimal discharge capacity was observed. At a 500 A discharge, the voltage drops very close to 2 V at –40 °C, but remains above 2 V so we were able to obtain discharge capacities at three temperatures at this rate. Figure 4 shows these results. The baseline capacity refers to the 1C capacity of each cell at room temperature. We observed an initial voltage drop at the subzero temperatures. The voltage recovers as the cell self-heats and the cells are able to attain close to the same discharge capacity at all three temperatures with a penalty in voltage at the subzero temperatures. As noted, discharge at –40 °C and –20 °C and 1000 A for a single cell led to an immediate drop to below the cutoff voltage of 2 V, the lower limit of our Maccor battery cycler; therefore, we then discharged two cells in series to overcome this equipment limitation. Figure 5 shows the experimental setup.

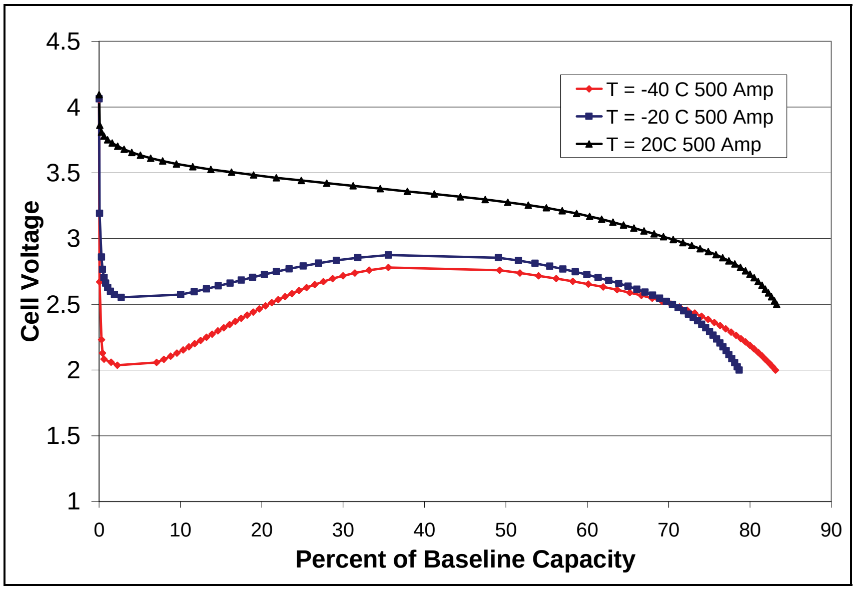

Figure 4. Discharge capacity and voltage of Saft UHP cells as a function of temperature at fixed rate of 500 A. All cells were charged at 1C (5A) and 20 °C and discharged at 100C (500 A) at three temperatures; the baseline capacity is the capacity obtained using a 5 A discharge at 20 °C.

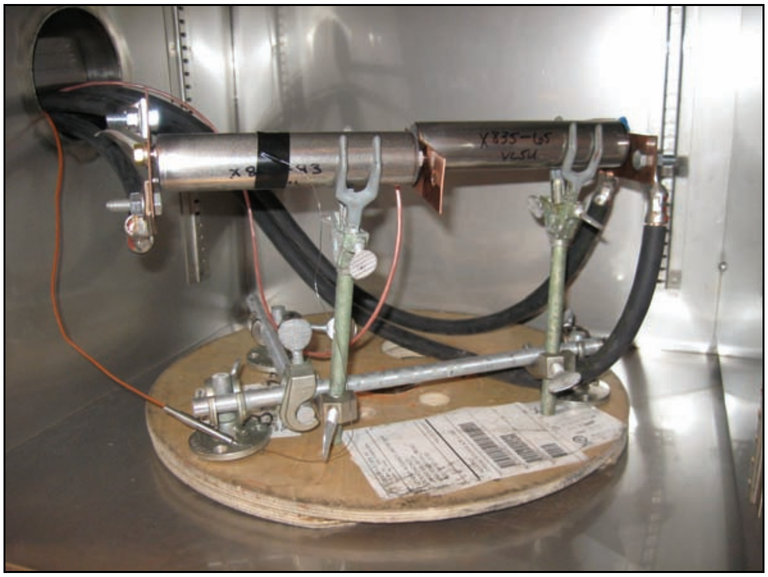

Figure 5. Two cells in series configuration used for testing of discharge at –40 and –20 °C and 1000 A.

The discharge curves of the two cells in series at –40 and –20 °C are shown in figures 6 and 7, respectively. At –40 °C, there is an immediate drop of about 3.6 to 4.5 V (2.25 V single cell equivalence). The voltage further drops to a minimum of 2.77 V (1.39 V single cell). The voltage begins to recover as self-heating of the cell occurs and reaches a maximum voltage of 5.11 V (2.56 V single cell equivalence) before sloping back down as the cells are discharged. At –20 °C, there is an immediate drop of about 2.4 to 5.7 V (2.85 V single cell). The voltage further drops to a minimum of 4.4 V (2.2 V single cell). The voltage begins to recover as self-heating of the cell occurs and reaches a maximum voltage of 5.02 V (2.51 V single cell) before sloping back down as the cells are discharged.

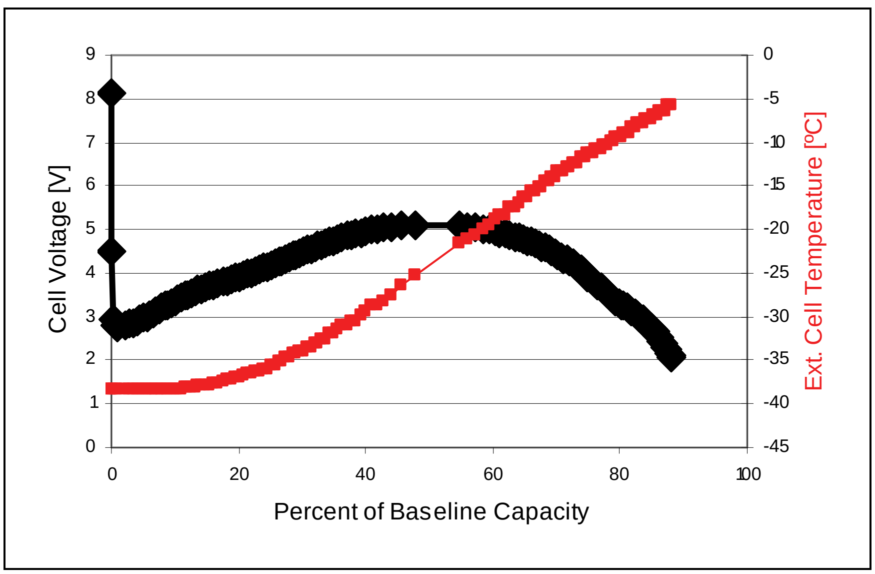

Figure 6. Discharge curve of two cells in series at –40 °C and 1000 A. The black curve is voltage and the red curve is exterior cell temperature.

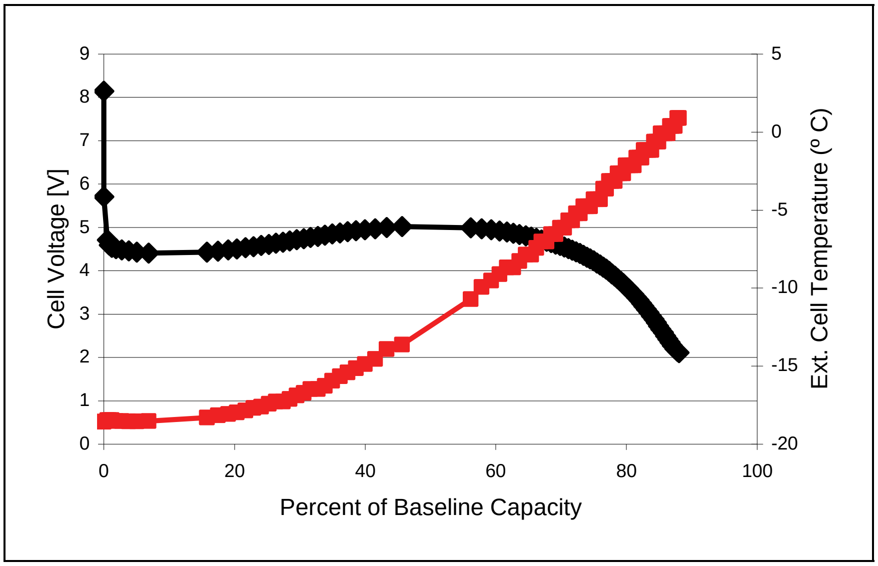

Figure 7. Discharge curve of two cells in series at –20 °C and 1000 A. The black curve is voltage and the red curve is exterior cell temperature.

3.3 Self-Heating of Cells During High Rate Discharge

Figures 6 and 7 also show the heat rise during the 1000 A discharge at –20 °C and –40 °C, respectively. In figure 6, we observe a rise in temperature from –40 to –6 °C. In figure 7, we observe a rise in temperature from –20 to 1 °C.

Figures 8 and 9 shows the heat rise during the 500 A discharge at –20 °C and –40 °C, respectively. In figure 8, we observe a rise in temperature from –40 to –10 °C. In figure 9, we observe a rise in temperature from –20 to 5 °C.

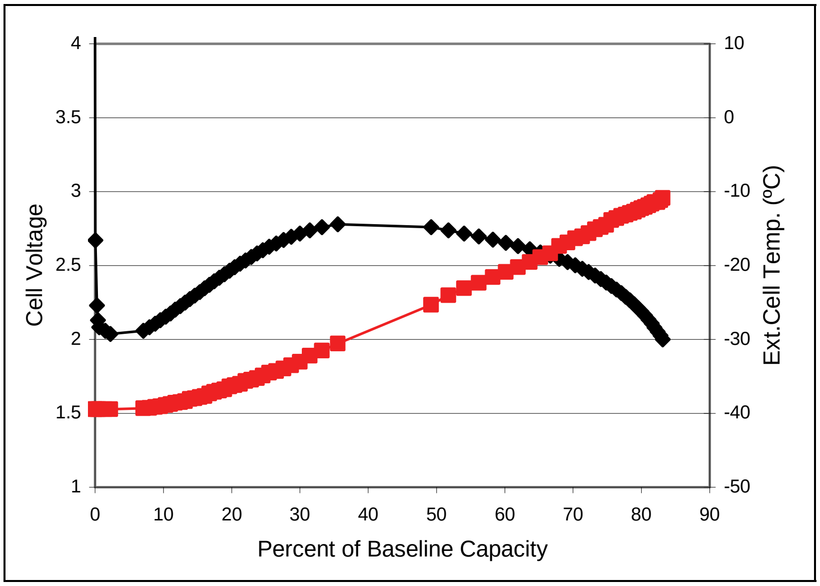

Figure 8. Self-heating of Saft UHP cell during 500 A, –40 °C discharge.

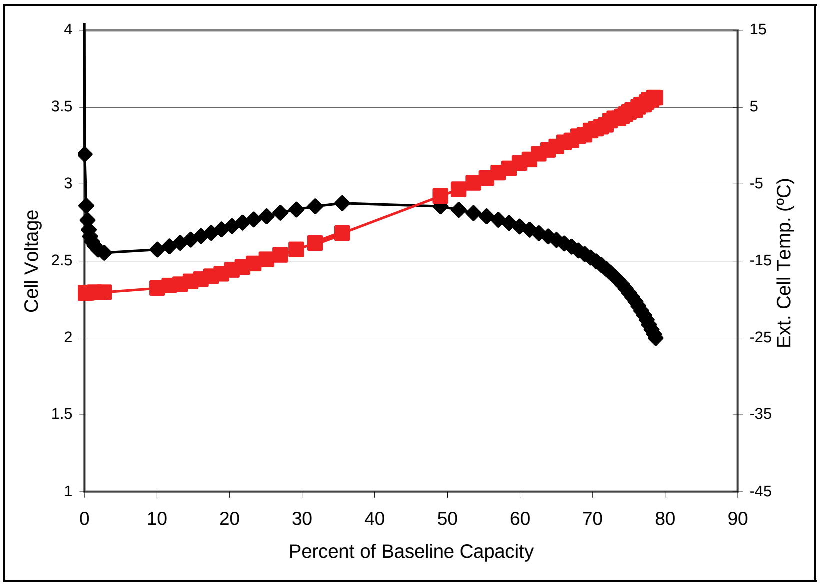

Figure 9. Self-heating of Saft UHP cell during 500 A, –20 °C discharge.

3.4 Discharge at 60 °C

The performance at 60 °C at multiple discharge rates and 5 A (1C) charging rate is shown in figure 10. The discharge currents used were 5 A, 250 A, 500 A, 600 A, 800 A, and 1000 A. At the elevated temperature, the cells are able to achieve close to 90% of the discharge capacity up to 1000 A. The voltage is reduced about 0.3 V for the 1000 A discharge compared to the 5 A discharge.

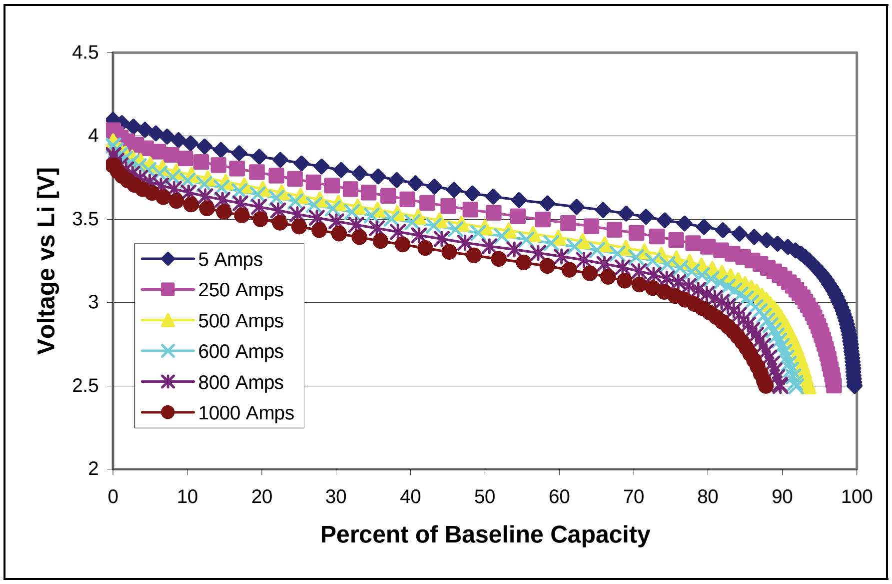

Figure 10. Discharge capacity at 60 °C as a function of discharge rate.

3.5 Summary of Temperature Testing

Temperature testing is summarized in table 3. The data at rates of 100C and 200C are plotted in figure 11 in order to show more clearly the effect of temperature on the specific power and specific energy of the cell. There is a clear drop in both specific energy and specific power as the temperature is decreased and the rate decreases. The effect of a drop in temperature from 60 to –40 °C is more pronounced than the difference caused by the increase in rate. Figure 12 illustrates the effect on voltage of change in temperature during discharge. There is a large drop in the voltage as the temperature decreases.

Table 3. Summary of rate and temperature testing.

Temp. °C	C Rate (1C = 5A)	$\Delta V_{t=0}$	Energy Density		Power Density	
			Wh/kg	Wh/liter	kW/kg	kW/liter
20	1C	0.0	57	146	0.055	0.14
60	1C	0.0	55	141	0.052	0.13
20	50C	0.1	47	121	0.58	1.5
60	50C	0.1	52	134	2.5	6.4
–40	100C	1.4	29	75	3.6	9.3
–20	100C	0.9	29	75	3.8	9.8
20	100C	0.3	42	108	4.7	12
60	100C	0.1	49	126	4.9	13
60	120C	0.2	48	123	5.9	15
60	160C	0.2	46	118	7.7	20.
–40	200C	1.8	26	67	5.9	15
–20	200C	1.2	24	62	6.3	16
20	200C	0.6	36	93	8.7	22
60	200C	0.3	44	113	9.5	24

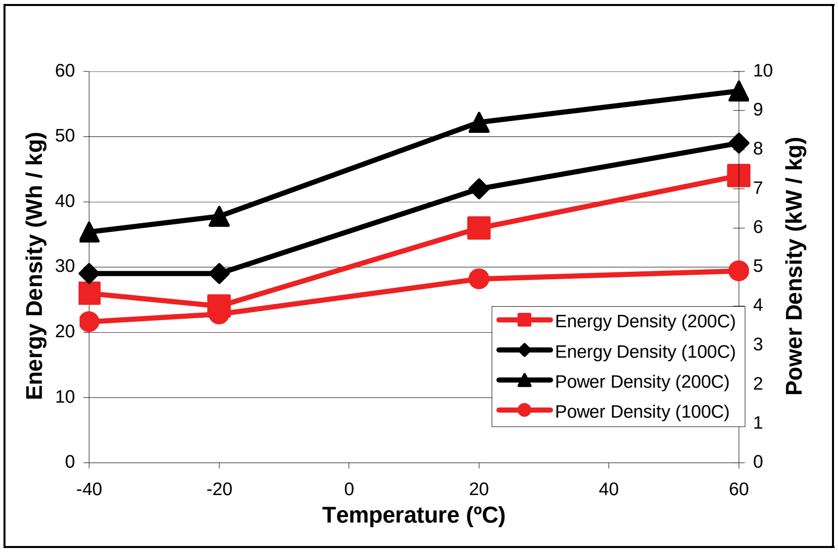

Figure 11. Specific energy and power density at 100C and 200C rates as a function of temperature.

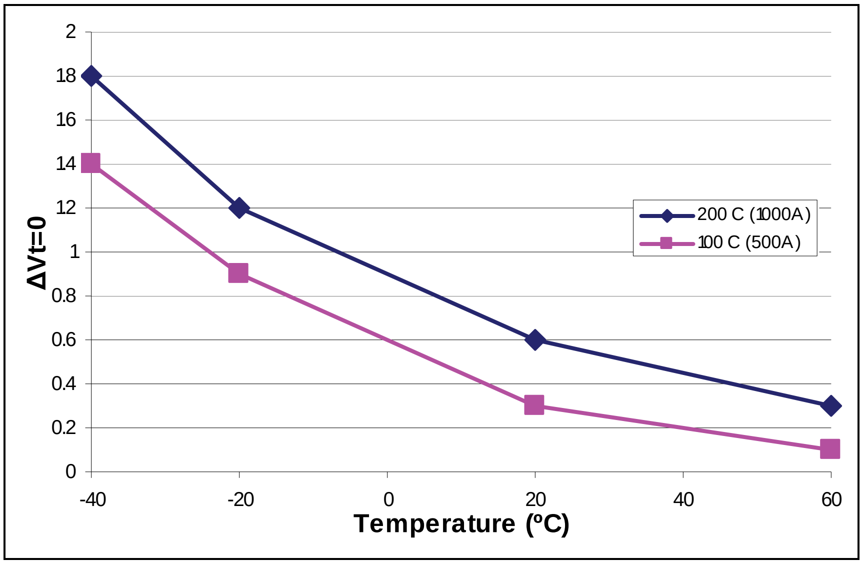

Figure 12. Initial voltage drop at 100C and 200C as a function of temperature.

Clearly from these data shown in figures 11 and 12, there is room for improvement in the low temperature performance of these cells, though the decrease in performance at low temperature is probably not worse than state-of-the-art lithium ion cells. We would need comparable data from a similar cell for comparison.

3.6 Storage Life at Elevated Temperature (70 °C)

We evaluated the storage life of the cells at 70 °C after 7 days of storage. Figure 13 shows those results. It seems the cell has high self-discharge rate.

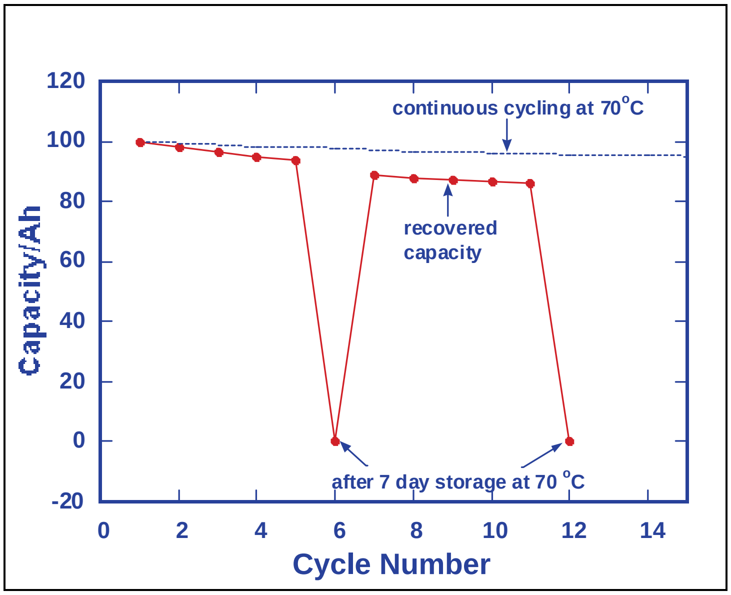

Figure 13. The temporary and permanent capacity loss of Saft UHP cells after periods of 7-day storage at 70 °C. The 70°C cycling data are also plotted for comparison.

The capacity will be almost entirely lost after 7-days storage. Although about 80% of nominal capacity can be recovered by recharging, the fade rate is even higher than 70 °C cycling. This test is incomplete and ongoing; more data from different cells are needed for confirmation.

3.7 Capacity Retention Under Different Cycling Conditions

We evaluated the capacity retention of the cells under different cycling conditions. The results (figure 14) suggest that a high discharge rate degrades the cell capacity *faster* than high temperature cycling does. The reason might be the buildup of interfacial resistance caused by electrolyte decomposition. The core temperature of the cell during the 1000 A discharge must be higher than 70 °C. Suggestion: An improved cell design with a better heat-dissipation mechanism might be able to significantly enhance the capacity retentions under the condition of high rate discharge.

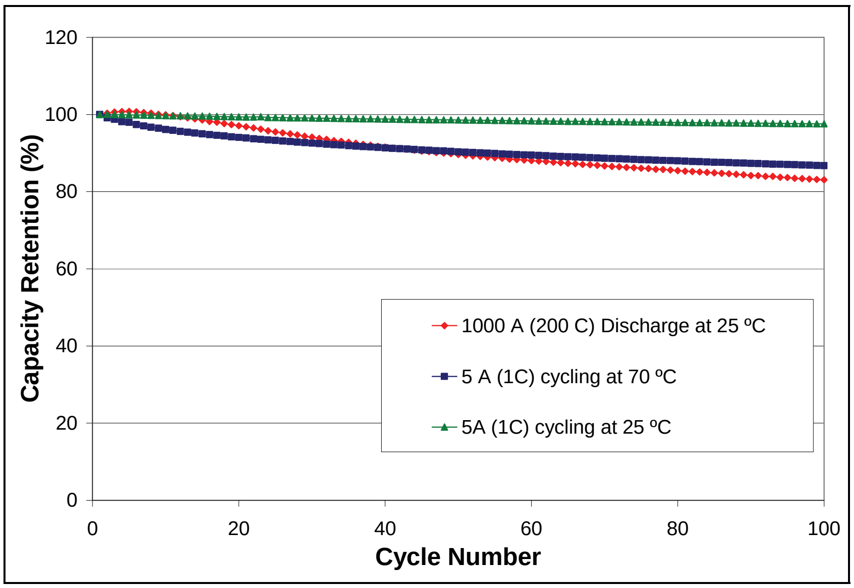

Figure 14. The capacity retention of Saft UHP cells under different conditions: (1) charged at 1C (5 A) and then discharged at 200C (1000 A) at room temperature; (2) cycled at 1C (5 A) at high temperature and (3) cycled at 1C (5 A) at room temperature as benchmark. The cutoff range of 2.5 ~4.1 V corresponds to 100% of the designed depth-of-charge.

3.8 High Pulsed-current Discharge Measurements

We assessed the high pulsed-current capability of the VL5U cells by using a capacitive load, as shown in the schematic of figure 15. We series-connected two, cells (DUT1 and DUT2) with the capacitor load using a thyristor. The capacitive load allowed us to tailor the pulse shape and ensure that a short-circuit condition was not inadvertently applied to the cells. Next, we connected 40 electrolytic capacitors (Cornell-Dubilier, CGS253U016R4C) in parallel using a pair of copper plates giving a total capacitance of approximately 1 F and an equivalent series resistance(ESR) of approximately 0.4 mΩ. Once gated on, the thyristor (Vishay, ST333C08CFM0) completed the circuit allowing the capacitor bank to charge. Because the on-state voltage of the thyristor is approximately 3 V at 5000 A and, under load, the output voltage of the VL5U battery was expected drop from 4.1 V to 2.5 V, two cells were required. The resistor-capacitor snubber circuit connected across the thyristor prevented inadvertent d*V*/d*t* triggering of the thyristor as the circuit was being assembled. Also, the capacitor bank was completely discharged through a 1 kΩ resistor prior to each test.

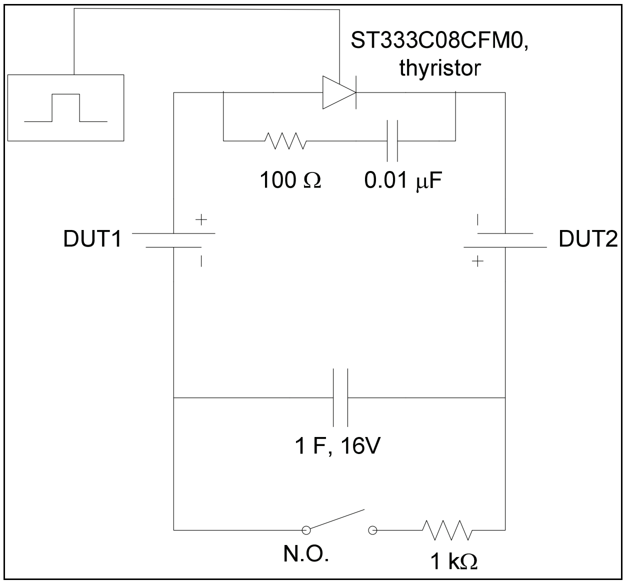

Figure 15. Simplified schematic of the pulsed-current battery test circuit.

Figure 16 shows a photograph of the test stand. We mounted the two batteries-under-test on the capacitor load and mounted the thyristor at the opposing ends of the batteries. We used Rigowski current probes (PEM, CWT30) to measure the pulsed currents.

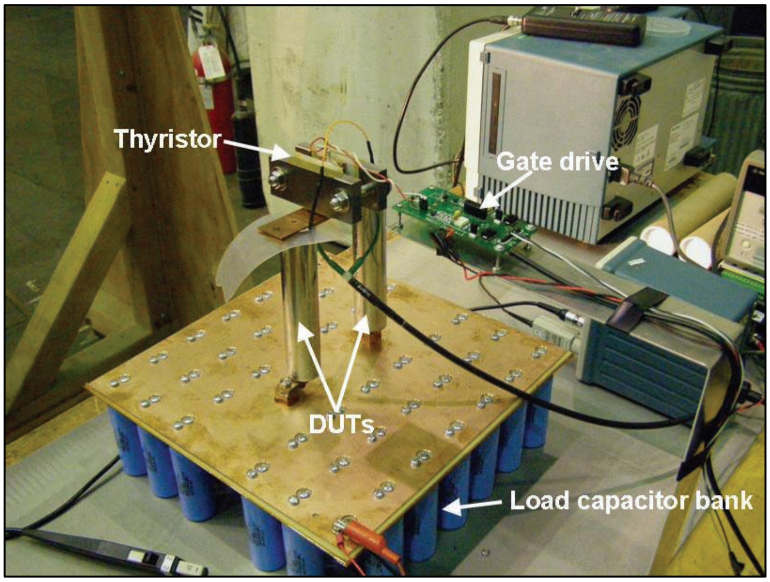

Figure 16. Pulsed-current battery evaluation stand.

Figure 17 shows the responses of the VL5U cells taken at a case temperature of 18 °C. Prior to testing, the cells were fully charged. The green trace of figure 16 shows the instantaneous voltage of cell X835-40 during the first discharge pulse and the red trace shows the instantaneous voltage of cell X835-22 during the fourth discharge pulse. The blue trace is the cell current and shows a rise-time (10–90%) of 250 μs. From this data, the minimum cell resistances are 0.21 mΩ and 0.24 mΩ for cell X835-40 and X835-22, respectively.

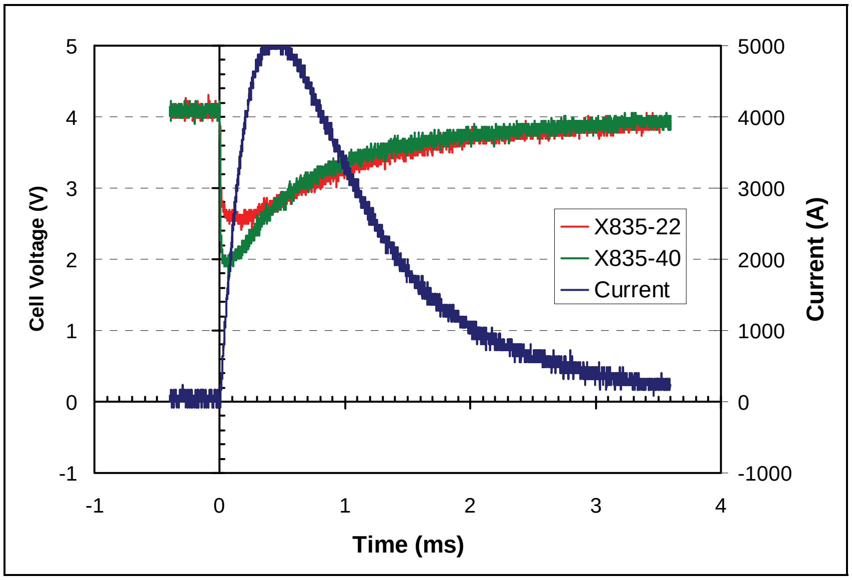

Figure 17. Pulsed response of two, VL5U cells connected in series. A peak current of 4840 A with a pulse-width of 1.1 ms (full width at half maximum) is given by the blue trace and instantaneous cell voltages are given by the red and green traces.

Parasitic impedances limit the maximum peak currents obtainable in this test configuration. The capacitor bank has an ESR of approximately 0.4 mΩ and the thyristor on-state resistance is approximately 0.5 mΩ at high current levels. By matching experimental data with circuit simulations, we estimated the total circuit inductance to be 220 nH. Figure 18 gives the projected cell performance assuming an ideal short-circuit load. At an output voltage of 2 V, a pulsed output current of approximately 8750 A may be achieved.

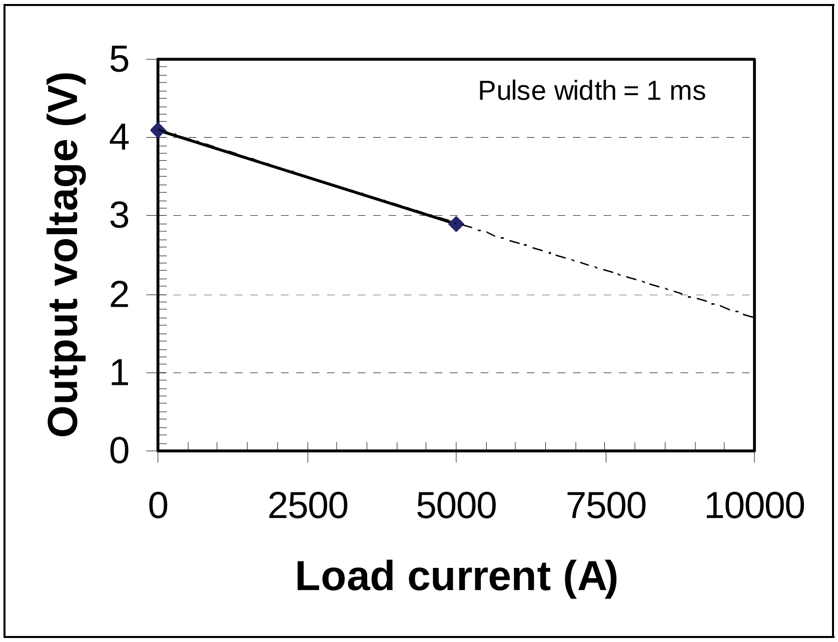

Figure 18. Projected cell output voltage as a function of pulsed load currents.

3.9 Future Plans

Additional pulsed discharge cell characterizations are needed to better understand the VL5U lithium-ion cell technology. These characterizations may include testing over the military temperature range, maximum charging rate, and short-circuit survivability. Repeating select tests may be useful in order to assess cell to cell variability.

4. Conclusions

Our results show that the Saft UHP cells have a high rate capability with about 80% of baseline capacity (5 A, 1C rate, room temperature) accessed at a 1000 A (200C) rate of discharge—the voltage was depressed during the high rate discharge by about 0.6 V. At low temperatures, –20 °C and –40 °C, we obtained about 80% of the baseline capacity at a 500 A (100C) rate; however, the voltage was further depressed to a remaining voltage below 3 V during the entire discharge. At –20 °C, the voltage was depressed by up to 1 V relative to the room temperature discharge during the initial time of discharge and at –40 °C, the voltage was depressed by up to 1.7 V during the initial time of discharge. Storage life testing at 70 °C suggests a high rate of self-discharge. Cycling at different conditions suggests that high rate cycling degrades the cell faster than high temperature cycling, which implies that significant self-heating occurs at high rates of discharge. Measurements of cells tested at –40 °C and –20 °C showed an external cell temperature of –10 °C and 5 °C, respectively, at the end of discharge. The core cell temperatures were clearly higher.An improved cell design with a better heat-dissipation mechanism might be able to significantly enhance the capacity retention under the condition of high rate discharge. The storage life is not as good as other versions of cells; improvement is needed. Finally, pulse discharge testing using a capacitive load showed that, at an output voltage of 2 V, a pulsed current of 8750 A may be achieved.

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