SSC14-VII-9

Li-ion battery and super-capacitor Hybrid energy system for low temperature SmallSat applications

K.B. Chin, M.C. Smart, E.J. Brandon, G.S. Bolotin, N.K. Palmer
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109; 818-354-4051
Keith.B.Chin@jpl.nasa.gov

S. Katz, J.A. Flynn
California State University, Northridge
Dept. of Electrical and Computer Engineering
Northridge, CA 91330-8346; 818-677-5693
Sharlene.Katz@csun.edu

ABSTRACT

A novel hybrid energy storage system consisting of a low temperature Li-ion cell and a bank of super-capacitors is evaluated for performance enhancements at high power and low temperature for future deep-space CubeSat applications. Although no significant improvements are observed in terms of the energy storage as compared to a CubeSat polymer battery, the hybrid power system exhibited substantial gains in power with high current (15A) pulse testing. The minimum discharge voltage is about 2.0 V higher than the standalone Li-ion cell at the worst case initial 50% SOC. The low impedance of the hybrid system which is responsible for the observed performance improvement is about 5 mOhm at a -40 ^{o}C operating temperature and is substantially lower than the CubeSat baseline polymer battery of about 1000 mOhm. To advance the technology for future aerospace applications, JPL is planning to design and to test a hybrid energy storage system in a space environment that will be based on the results of this investigation which is a part of a SmallSat Collaborative Agreement with the California State University, Northridge.

INTRODUCTION

As SmallSat programs are deployed beyond low-earth-orbit (LEO), their energy storage systems will have to operate at lower temperatures and under wider ranges of load capabilities. This is to support the higher power demands of on-board hardware and instruments, such as deep space transponders, radars, and thrusters. Thus, a hybrid system combining both the benefits of high power density from super-capacitors and high energy density from Li-ion batteries could represent a new technology yet to be realized for NASA applications.

Remarkable in terms of providing energy, Li-ion technology is severely limited in terms of power density especially at low temperatures (< -20 ^{o}C). In addition, the charge acceptance characteristics of Li-ion cells is generally very poor at very low temperature, with the possibility of lithium plating occurring which can limit the life [1]. Super-capacitor technology, on the other hand, is ideally suited for high power, low duty cycle applications and operates very well at low temperatures without degradation due the lack of faradaic processes. The technology, however, suffers from a low energy standpoint. Hence, super-capacitors complement Li-ion chemistries very well for low temperature and high power applications.

A hybrid energy systems consisting of a Li-ion battery and super-capacitor technologies have already been proven to offer significant performance enhancements in terms of battery cycle life and especially power density under pulse load conditions with short duty cycles [2,3]. Based on design and functional requirements, numerous examples of hybrid systems are either in various stages of development or are in full deployment [4]. Specific to NASA SmallSat deep-space programs, the main benefit in using a hybrid system is to overcome the relatively weak power density of Li-ion batteries during high current pulses at low temperatures (< -20^{o}C), which could have deleterious consequences to battery life as well as an inability to meet required performance metrics.

In this paper, the performance characteristics of Li-ion cells incorporating a novel low temperature electrolyte developed at JPL [5,6,7] along with low temperature super-capacitors (> 1 Farads) is investigated under flight-like conditions. The main motivation of this investigation, however, is not to mitigate degradation mechanisms (i.e., the possibility of lithium plating), but rather to improve the power density at low temperatures. We will highlight some of the physical properties (low mass and low volume) which make them ideal for SmallSat or CubeSat applications. Finally, we will demonstrate the benefits of improved performance at temperatures as low as -40 ^{o}C under high pulse load conditions (up to 10C-rate) of a representative hybrid energy system in a parallel electrical configuration.

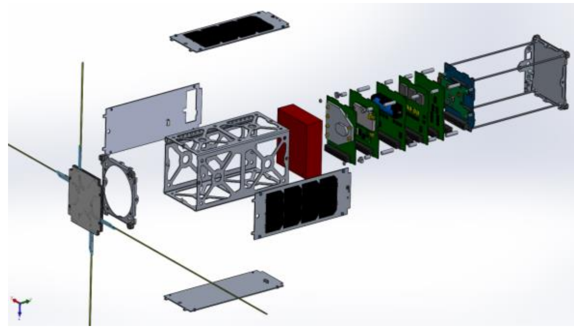

Figure 1: JPL/CSUN CubeSat Assembly. The "red brick" is the volume allocated for the hybrid energy storage system payload.

BACKGROUND

As part of a NASA Space Technology Mission Directorate SmallSat Cooperative Agreement, JPL and the California State University, Northridge (CSUN) are developing a 2U CubeSat with a hybrid energy storage system. JPL and CSUN partnered in January 2013 to establish a stronger relationship in developing future engineers. Currently, a team of four CSUN faculties is working with over 25 students to design, build, and test the 2U CubeSat that will carry this hybrid energy system into low earth orbit. The primarily undergraduate student team includes computer, electrical, and mechanical engineering, and computer science majors. Many of the 35 students who have worked on the project to date have been hired by JPL for internships and/or full time positions upon graduation.

Along with ground operations and spacecraft control, CSUN will also control the payload experiment in flight. They have allocated sufficient mass and volume in the CubeSat spacecraft as shown in Figure 1 to evaluate the proposed payload hybrid power system. JPL will design the hybrid payload consisting of a single Li-ion battery cell and super-capacitor bank. Payload control electronics and resistive loads are also included in the payload design. The payload assembly is shown in Figure 2. Including the housing case, the total mass (Table 1) of the payload assembly is about 500 gm (including the housing chassis) along with a total volume of 484 cm^3.

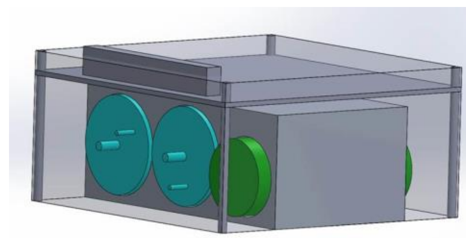

Figure 2: JPL Hybrid energy storage system payload.

Table 1: Physical properties of the proposed Hybrid Energy Storage Unit Assembly designed at JPL.

Physical Parameter	Value
Total Mass (gm)	499.0
Width (cm)	9.0
Length (cm)	9.6
Thickness (cm)	4.7
*Total Volume (cm^3)	483.8

*Total volume includes the payload control board.

EXPERIMENTAL TESTING

As part of the CubeSat program, extensive ground testing at JPL's battery test facilities has been conducted to evaluate suitable Li-ion cell and super-capacitor chemistries for the hybrid design. For comparison purposes, performance characterization was initially performed on a baseline CubeSat lithium polymer battery obtained from Clyde Space (Part No. CS-SBAT2-10). The hybrid system Li-ion cell is a

26650-size cell built by Navitas/A123 Systems that incorporates a low temperature electrolyte (1.2M $LiPF_6$ in EC+EMC+MB (20:20:60 vol%) + 2% VC) designed at JPL. Environmental testing on the Li-ion cell includes rate characterization at temperatures ranging from 20 to -40 ^{o}C. Numerous super-capacitor sizes were also evaluated for optimization of energy density including 350F, 310F, 150F, 100F, and 50F size cells from Maxwell Technologies, Inc. Super-capacitor testing includes capacitance and ESR measurements ranging from 20 to -40 ^{o}C. High rate pulse testing at current rates up to 15A and at various duty cycles were also performed on all individual energy storage chemistries and at temperatures down to -40 ^{o}C or lower. Finally, a full mockup hybrid system was fully evaluated for performance enhancements under the same test protocols.

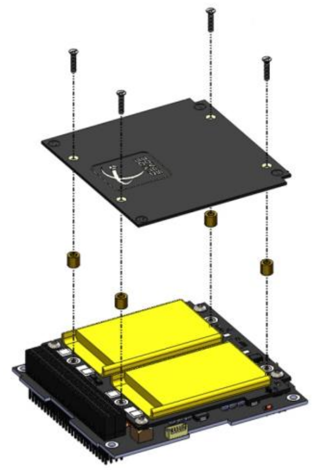

Figure 3: Baseline polymer Li-ion battery assembly from Clyde Space.

RESULTS AND DISCUSSIONS

The results of JPL's extensive ground testing on various energy storage systems has demonstrated significant performance enhancements that can be mission enabling by deploying such a hybrid power system on SmallSats and JPL/NASA applications. Highlights of the test results on the low temperature Li-ion battery, super-capacitor, and a mockup hybrid energy storage system are discussed in the following sections.

Table 2: Physical properties of the baseline polymer Li-ion battery assembly.

Physical Parameter	Value
Total Mass (gm)	125.0
Width (cm)	9.0
Length (cm)	9.5
Thickness (cm)	2.0

Baseline lithium polymer battery test results

The polymer-based Li-ion battery assembly from Clyde Space has been previously fully qualified for space applications [8] and consists of 2 individual cells in series operating over a voltage range of 6 to 8.2V. The nameplate capacity of the individual polymer cells is 1.0 Ah and the total energy of the battery is rated at 10 Wh. The battery management system (BMS) is included in the assembly as shown in Figure 3. As listed in Table 2, the total mass of the baseline battery is 125 gm and the estimated volume is about 172 cm^3 making it ideally suitable for CubeSat applications. However, the polymer Li-ion chemistry is severely limited in terms of the low temperature performance, as it is not capable of supporting effective operations below –10 ^{o}C.

The performance characterization of the baseline polymer battery over a wide range of operating temperatures is summarized in Figure 4. The maximum discharge capacity of the baseline battery was determined to be 1.04 Ah at 20 ^{o}C. The corresponding discharge energy was lower than expected at 7.87 Wh, and is attributable, in part, to non-optimal charge rate differences during testing (i.e., C/10-rate vs C/2-rate). The main disadvantage of the baseline Li-ion battery is the poor performance at lower temperatures. At -20 ^{o}C, the discharge capacity was at approximately 79% of the maximum capacity and drops precipitously to 17% at -30 ^{o}C. Such poor low temperature performance is potentially mission limiting for deep-space applications.

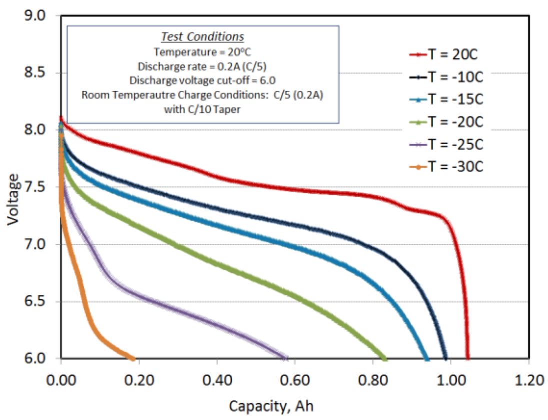

Figure 4: CubeSat baseline battery discharge capacity results over various temperatures down to -30 °C. Discharge capacity was determined after room temperature charge at C/5 (0.2A) rate with C/10 taper charge current.

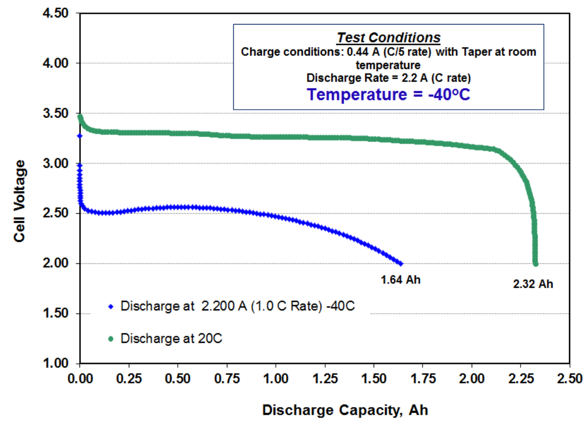

Figure 5: 26650 Li-ion cell discharge capacity results at -20 °C and -40 °C. The 20 °C discharge rate is 0.44 A (C/5-rate). The -40 °C discharge rate is at 2.2 A (C-rate).

Low temperature Li-ion cell test results

A JPL proposed Li-ion cell of size 26650 was characterized for enhanced low temperature performance. As shown in Table 3, the mass of the cell is 70 gm and the volume is 34.5 cm^3. The cell incorporates a low temperature electrolyte formulation developed at JPL. As shown in Figure 5, the room temperature discharge capacity of the cell is more than a factor of 2 higher than the baseline battery at 2.32 Ah. The measured total output energy is 7.51 Wh which corresponds to an energy density of 105.79 Wh/kg. Under worse case operating conditions of -40 °C and 1-C discharge rate (2.2 A), the discharge capacity of 1.64 Ah was retained (about 71% of maximum capacity). This represents a substantial improvement in performance over the baseline battery at low temperatures and could potentially enable future missions.

Table 3: Physical properties of 26650 Li-ion cells.

Physical Parameter	Value
Total Mass (gm)	70.0
Width (cm)	6.5
Length (cm)	2.6
Thickness (cm)	34.5

Super-capacitor test results

For our proposed hybrid payload design, a minimum of two super-capacitors is necessary to maintain a minimum battery voltage of greater than 2.0V. Numerous sizes of super-capacitors were evaluated with a focus upon maintaining the minimum bus voltage requirements. The cell values ranged from 50F to 310F as shown in Figure 6. Table 4 summarizes the mass and voltage of the super-capacitor test cells. Pulse test results at high rate and low duty cycle (20%) are shown in Figure 7. Under worse case conditions of 15A pulse rate and -40 °C, most super-capacitor cells (310F, 150F, 100F) maintained a minimum voltage of greater than 1.0 V even at 50% state-of-charge (SOC). Thus, a super-capacitor of size 100F or greater will meet the required minimum voltage of the proposed hybrid design which couples a single Li-ion cell with two super-capacitor cells at the minimum operating temperature of -40 °C.

Figure 6: Tested super-capacitors from Maxwell Technologies, Inc. Sizes range from 50F (Left) to 310F (Right).

Table 4: Physical properties of tested super-capacitor cells.

Cell Size (F)	Mass (gm)	Length (cm)	Diameter (cm)	Volume (cm^3)
310	60.0	6.0	3.3	52.3
150	32/0	3.2	2.5	15.7
100	22.0	2.2	2.2	8.4
50	13.0	1.3	1.8	3.3

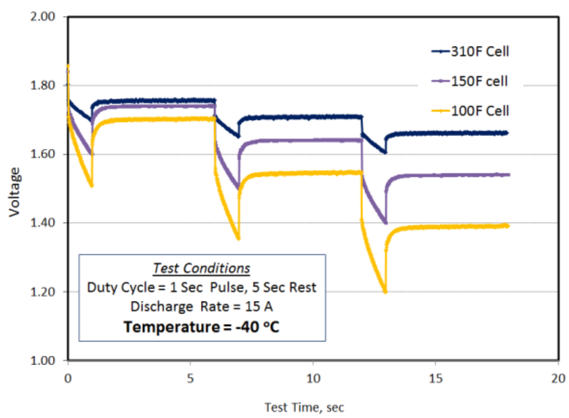

Figure 7: Super-capacitor pulse testing comparison. Duty cycle = 20%, Discharge rate = 15A.

Hybrid Mockup test results

A substantial set of thermal testing was conducted on a representative hybrid design including both energy and power characterization under the expected flight temperature range. A mockup of the hybrid build is shown in Figure 8 which consists of two 310F super-capacitors connected to a single Li-ion cell in a parallel electrical arrangement. The total mass is about 190 gm excluding the housing chassis and control electronics as shown in Figure 2. The hybrid system described was designed to achieve maximum performance enhancement in terms of the low temperature power capability. It should be noted the specific energy of this configuration has not been optimized and further improvements can be made by reducing the size of the super-capacitors based on unique mission power requirements. For our proposed CubeSat, an energy density of about 70 Wh/kg (excluding housing chassis and control electronics) is achievable using 100F super-capacitors as shown in Figure 9.

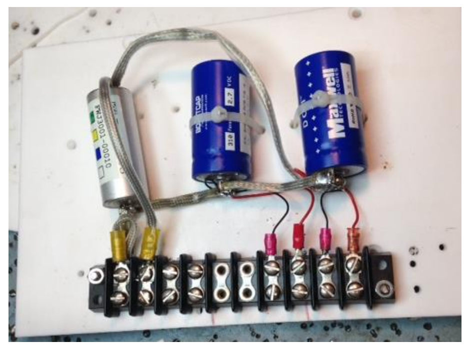

Figure 8: Mockup hybrid test unit using 310F super-capacitor cells. The estimated energy density of this build is about 40 Wh/kg.

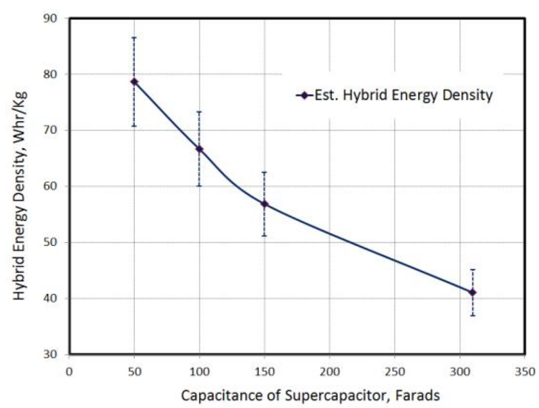

Figure 9: Estimated energy density from various super-capacitor sizes. A 10% design margin is added to account for wiring/connection masses.

As expected, the hybrid power system demonstrated insignificant improvement over the standalone Li-ion cell in terms of energy storage. Figure 10 compares the discharge capacities of the standalone Li-ion cell vs the hybrid. Even with 310F super-capacitors, the actual increase in discharge capacity is about 0.10 Ah (5% increase) over the standalone Li-ion cell at 20 °C. However, excellent discharge capacity is observed -40 °C with 1.44 Ah being delivered, which is equivalent to about 63% of the maximum discharge capacity observed at room temperature. Ostensibly, the Li-ion cell is mainly responsible for this high energy storage capability at the lowest temperature of -40 °C with little contribution from the added super-capacitors.

Dramatic performance enhancement of the hybrid energy storage system was observed from the high power low duty cycle testing. Figure 11 highlights the comparison results between the standalone Li-ion cell and the hybrid system for the worse case test scenario of 15A discharge rate at 20% duty cycle and -40 °C starting at 50% SOC. The standalone Li-ion cell exhibited about a 2.0 V drop in voltage over the pulse test sequence. The minimum cell voltage of 0.86 V is below the nominal cell operating voltage which may lead to permanent cell damage. In contrast, the hybrid minimum voltage remained well above the nominal at 2.79 V which indicates the super-capacitors performed as expected in buffering the high loads and minimizing battery voltage polarization which ultimately maintain excellent long-term battery state-of-health.

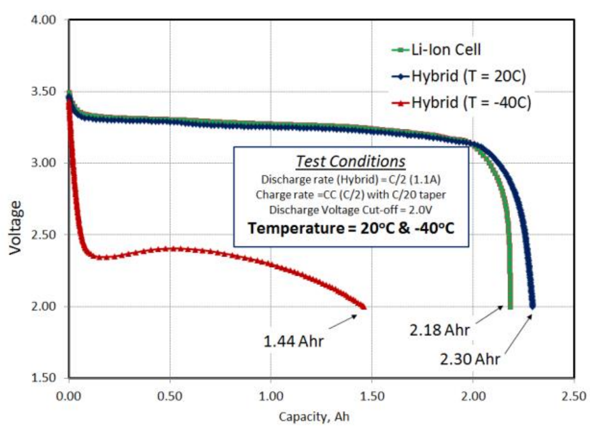

Figure 10: Discharge capacity comparing the standalone Li-ion cell and the hybrid at 20 °C and -40 °C.

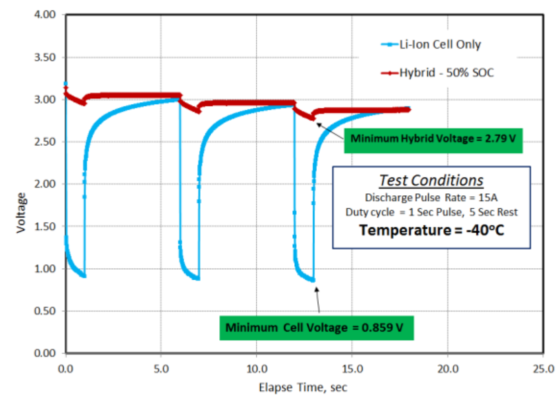

Figure 11: High rate pulse testing comparing the standalone Li-ion cell and the hybrid at -40 °C. Discharge rate = 15A. Duty cycle = 20%.

The measured d.c. ohmic impedances of all of the energy storage devices tested in this investigation are directly related to their performances, and thus, provide physical insights on their relative performance improvements especially from the hybrid energy system. As shown in Figure 12, the polymer battery exhibited the highest impedance over all measured temperatures at about 1000 mOhm. The Li-ion cell exhibited substantially lower impedance values ranging from about 10 mOhm at 20 °C to 100 mOhm at -40 °C. By comparison, the cell impedance of the super-capacitor is appreciably lower temperature than the Li-ion cell at about 10 mOhm down at -40 °C. From the known impedances of both the Li-ion cell and the super-capacitors, effective ohmic impedance (Z_{eff}) of the hybrid can be predicted using

$$Z_{eff} = \frac{Z_{cap} Z_{batt}}{Z_{cap} + Z_{batt}}$$

where Z_{cap} is the impedance of the super-capacitor and Z_{batt} is the impedance of the Li-ion cell. The actual measured ohmic impedance was lower than the predicted at less than 5 mOhms down to -40 °C as shown in Figure 12. This suggests a synergistic effect on load sharing attributable to optimum current distribution between the low temperature Li-ion cells and super-capacitors upon discharge. Our results are consistent with previous investigations on such hybrid energy storage systems [9].

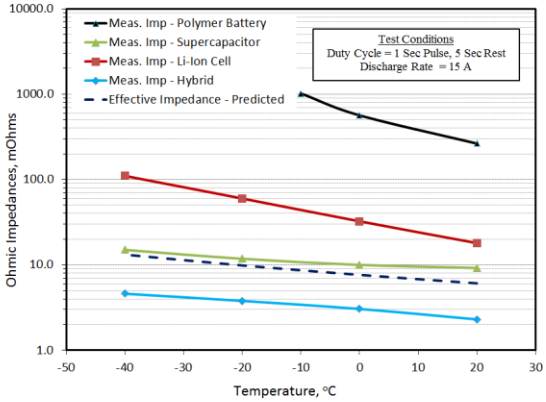

Figure 12: Summary of ohmic impedances of all energy storage systems from ground testing. The hybrid demonstrated even better than predicted ohmic impedance down to -40 °C.

CONCLUSIONS

Environmental thermal ground test results are presented in this investigation to demonstrate the improved power performance of a novel energy storage hybrid system composed of a Li-ion cell with a JPL formulated low temperature electrolyte and super-capacitor technologies. Compared with the standard polymer baseline battery, this Li-ion cell demonstrated a substantial increase in capacity by more than a factor of 2 and more than 70% capacity retention relative to the maximum capacity (2.3 Ah) at temperatures down to -40 °C. Combined with the super-capacitors, the low temperature Li-ion chemistry was also capable of supporting substantially higher pulse loads (up to 15A). The minimum operating cell voltages of 2.79 V is achieved at temperatures down to -40 °C even at 50% initial SOC. These performance enhancements by the hybrid configuration are attributable to the effective ohmic impedance which was observed to be better than predicted suggesting optimum load sharing conditions and a synergistic effect on discharge. In collaboration with CSUN, JPL will test a similar prototype hybrid energy storage system combining Li-ion battery cell and super-capacitor technologies in the space environment on a Cubesat.

ACKNOWLEDGEMENT

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA) and supported by the NASA STMD 2013 SmallSat Technology Partnerships Cooperative Agreement Notice.

REFERENCES

1. J.B. Goodenough and Y. Kim, *Chemical Materials*, **22**, 587-603 (2010).

2. C.E. Holland, J.W. Weidner, R.A. Dougal, and R.E. White, *Journal of Power Sources*, **109**, 32-37 (2002).

3. R.A. Dougal, S. Liu, R.E. White, *IEEE Transactions on Conponents and Packing Technologies*, **25**, no. 1, 120 (2002).

4. S. Y. Kan, M. Verwaal, H. Broekhuizen, , *Journal of Power Sources*, **162**, 971-974 (2006).

5. M. C. Smart, B. L. Lucht, S. Dalavi, F. C. Krause, and B. V. Ratnakumar, *J. Electrochem. Soc.*, **159 (6)**, A739-A751 (2012).

6. M. C. Smart, A. S. Gozdz, L. D. Whitcanack, and B. V. Ratnakumar, “Improved Wide Operating Temperature Range of High Rate Nano-Lithium Iron Phosphate Li-Ion Cells with Methyl Butyrate-Based Electrolytes”, *220th Meeting of the Electrochemical Society*, Boston, MA, October 11, 2011.

7. M. C. Smart, B. V. Ratnakumar, K. B. Chin, L. D. Whitcanack, and S. Surampudi, “Performance Characteristics of Lithium-Ion Technology Under Extreme Environmental Conditions,” *1st International Energy Conversion Engineering Conference, IECEC*, Portsmouth, VA, Aug. 17–21 2003.

8. N. Navarathinam, R. Lee, and H. Chessar, *Acta Astronautica*, 68, 1752-1760 (2011).

9. G. Sikha, B.N. Popov, *Journal of Power Sources*, **134**, 130-138 (2004).