Rapid Development of High Endurance nano-UAS Mission Batteries

James Pander, Devon Shedden, and Christopher Lang
Imperia Batteries, a division of Physical Sciences Inc.,
20 New England Business Center, Andover, MA USA 01810
jpander@psicorp.com / 1-978-738-2257

Abstract

Physical Sciences Inc. (PSI)'s Imperia Batteries division developed and demonstrated a high energy density Li-ion battery with a silicon nano-wire anode targeted for nano-unmanned aerial systems (nUAS). This included development of the cell design to address the size, weight, and energy requirements of nUAS vehicles, scale-up of the chemical vapor deposition (CVD) process to produce anode active material for the effort, a thorough screening of cathode materials to find one that meets the performance requirements, cell production, thorough electrochemical validation, and delivery of 20 prototype cells to the customer.

Key Words

Silicon anode; high energy density; nano-UAS; nano-UAV; 18650

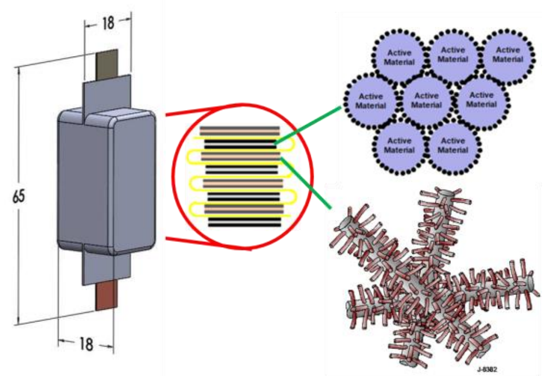


Figure 1. Schematic design of Imperia's nUAS cell design with equivalent length, width, and height to an 18650. Pop-outs illustrate the component cathode and anode technologies employed to improve energy density over commercial solutions.

Introduction and Prior Work

In order to improve mission duration and flight time of nano-unmanned aerial systems (nUAS) and maximize soldier field effectiveness, it is necessary to develop high energy density battery technologies. To that end Physical Sciences Inc's Imperia Batteries® division developed a high energy density battery solution targeted for nUAS applications. The initial form factor for the battery was determined to fit within the length, width, and height of a standard 18650 cell so that one-to-one comparisons to commercial cells could be straightforwardly made. Figure 1 demonstrates an initial conceptual cell design, as well as the component technologies that enabled the improved energy density of the system at such a small form-factor.

In order to improve cell level energy density, Imperia leveraged patented cathode and anode technologies, as well as a larger-scale baseline UAS cell and battery design. Imperia Batteries® has designed and produced 185 Wh UN certified Mission Batteries for use in military small-Unmanned Aerial System (sUAS).[5] The Mission Battery was developed and delivered in <12 months and improves vehicle endurance over consumer-off-the-shelf (COTS) solutions by 100%.[1] Utilizing this current product as a design baseline, Imperia resized the cell and incorporated supporting technologies to improve vehicle endurance in nano-UAS vehicles. On the cathode side, Imperia's high active (HA) coating technology enables the design of a battery that delivers the required energy and power density by maximizing the active content in the electrodes.[2,3] This technology minimizes the required electrode thicknesses, reducing the electrolyte required and maximizing rate performance by decreasing ion transport distances. The HA coating was applied to commercial high energy cathode materials, enabling an increase in energy density of the cells by 10-12% while requiring less cathode material.[2,3] On the anode side, Imperia employs a patented composite silicon anode material that is formed by growing silicon whiskers on a commercially carbon substrate.[3,4] This Si anode material has been demonstrated to have a tailorable reversible capacity >1200 mAh/g-composite. Imperia has developed custom electrolyte blends and formation procedures that enable high energy designs with good cycle life.[4,5]

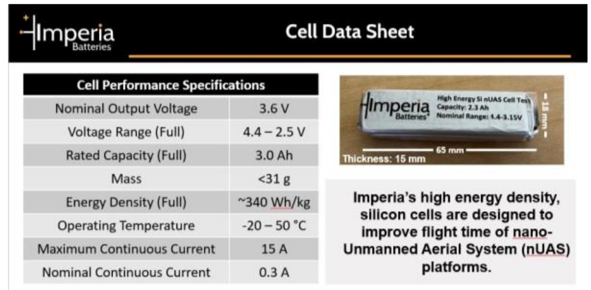
Prototype Cell Design and Build

To increase the cell capacity and energy, a high energy cathode material was used. Imperia screened a number of commercial high capacity cathode

Figure 2. nUAS Cells achieving >300 Wh/kg. Cell weight <31 grams with equivalent size (LxWxH) to 18650 battery.

materials against the performance targets (energy density, cycle life, rate performance, temperature performance, etc.). Imperia's HA coating was applied to the selected commercial NCM 811 material. Imperia has previously demonstrated that the HA cathode coating supports an increase in the active percent of the cathode material, allowing for thinner electrodes and higher energy densities.[2,3] The initial slurry consisted of 99% HA coated active material and a solids loading >80%.[2,3] The slurries were cast onto an aluminum current collector, and the cast thickness was controlled by a doctor blade for R&D cells and an automated slot-die coating machine for deliverable cells. The electrodes were dried under vacuum at 100 °C overnight. After drying, the electrodes were calendared to a final density of >3.5 g/cc and punched to the target electrode shape.

Imperia's patented silicon composite material is produced through a CVD reaction where silicon is grown off of a graphite-based precursor.[4,5] The precursor uses nanoparticles that are adhered to a graphite surface by mechanical mixing. During the CVD process the precursor interacts with gaseous silane forming a liquid eutectic to grow solid nanowhiskers on the graphite substrate.[4,5] The formation of whiskers improves the performance of the silicon anode due to the single crystal direction growth of the whisker and the direct connection path to a conductive current collector. The nanoparticle size defines the width of the whiskers and the population of nanoparticles on the graphite surface define the packing density of the whiskers.[4,5] To ensure that the anode material produces a sufficiently smooth slurry, the material produced by CVD was mechanically sieved. Anode electrode rolls were prepared by casting using a slurry consisting of 85 wt% silicon composite material. The slurry was cast onto a copper current collector with the cast thickness controlled by a doctor blade. Prior to use, the electrodes were dried under vacuum at 100 °C overnight and then punched to the target electrode shape.



Cell Performance Specifications	
Nominal Output Voltage	3.6 V
Voltage Range (Full)	4.4 – 2.5 V
Rated Capacity (Full)	3.0 Ah
Mass	<31 g
Energy Density (Full)	~340 Wh/kg
Operating Temperature	-20 – 50 °C
Maximum Continuous Current	15 A
Nominal Continuous Current	0.3 A

Figure 3. Cell Specifications for Imperia's high energy density Si nUAS cell.

Pouch cells were produced by manually stacking electrodes in alternating cathode/anode pairs between a commercial Celgard separator material. The woven electrode stacks were welded together using ultra-sonic welding to the external terminals. The cells were then heat sealed in an aluminized Mylar pouch material which was pre-formed to accommodate the thickness of the electrode stack. Cells were initialized by the introduction of electrolyte to the cell, followed by vacuum diffusion cycles to ensure thorough wetting.

A limited number of prototype cells was produced and delivered for evaluation, with examples shown in Figure 2 and a summary of cell specifications shown in Figure 3. Cells provide 10.4 Wh (3.0 Ah) when fully discharged. Cells were characterized for size, mass, and energy density.

Performance Results and Discussion

When discharged at a standard C/10 rate from 4.4 V to 2.5 V, Imperia's nUAS cells provide *ca.* 10.4 Wh and 3.0 Ah, corresponding to an energy density of 337 Wh/kg (Figure 4).

The ability of the cell to support high current discharges (i.e. high power operation) is important for UAS applications. Typically, as higher currents are drawn from a cell, the capacity (and therefore energy) that is delivered by the battery is reduced due to due to increasingly challenging ion transport conditions. This effect can be seen very clearly in the initial voltage drop when increasingly larger currents are applied. It is not sufficient to raise the energy density baseline if at the operational currents very little capacity is retained. Therefore, to improve vehicle flight times, rate/power performance must also be considered.

Figure 5 shows discharge curves for Imperia's nUAS cell discharged between 4.4 V and 2.0 V at various rates between C/10 to 5C. For the target 3 Ah cell, a 5C rate corresponds to a current draw of 15 A, which is the target maximum current draw. As expected, as the current increases, the voltage drops due to cell resistance, lowering the capacity retention of the cell for a given lower voltage cutoff. At a 1C rate (a full discharge in 1 hour), the cell retains approximately 75% of the baseline capacity, whereas at 5C only 20% of the baseline capacity is retained. Dependent on the shutoff voltage for the vehicle, decreasing the lower voltage limit can allow for additional capacity to be utilized at high currents.

In order to provide reliability and expand mission capabilities, the ability to utilize nUAS cells across a range of hot and cold temperatures is of interest. Discharge capacity at elevated temperature matched or exceeded the room temperature performance without noticeable generation of gas. At cold temperatures, discharge capacity was decreased due

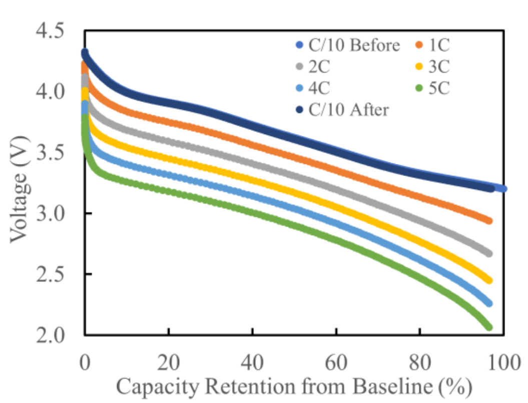


Figure 5. Discharge curves for an HA NCM811/Si composite cell at rates between C/10 and 5C. The minimum cutoff voltage is set to 2.0 V and the cutoff capacity is set to 95% of the baseline.

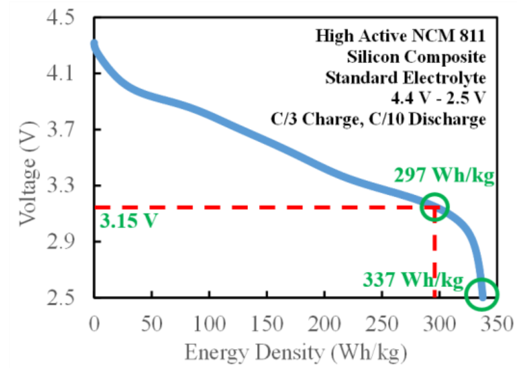


Figure 4. Full discharge of prototype cell from 4.4 V to 2.5 V at a rate of C/10. An energy density of 337 Wh/kg was obtained for the full discharge, with 297 Wh/kg obtained between 4.4 V and 3.15V.

to the increased cell resistance. At -20 °C, cells provided ca. 60% capacity retention during discharge at 1C with a lower voltage limit of 2.0 V to account for the overpotential caused by the extreme temperature.

To demonstrate the cells' capability to alternate between extreme temperatures, cells were cycled continuously while the ambient temperature was adjusted. The results of this experiment are summarized in Figure 6. The cell first underwent 3 baseline cycles at room temperature where no fade was observed. The cell then underwent 3 cycles where the charge was performed at room temperature and the discharge was performed at 0 °C, with a 1 hour thermal soak between each step to ensure the temperature equalized. At 0 °C, approximately 67% of the initial capacity was retained when discharged

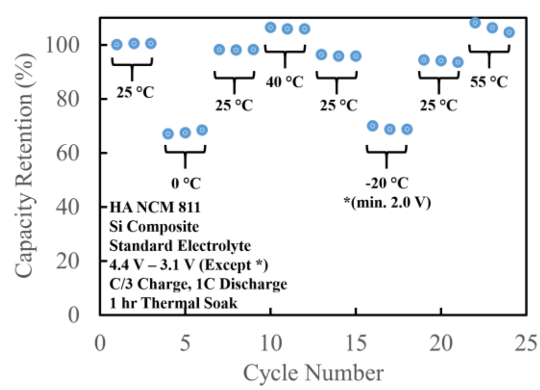


Figure 6. Alternating room temperature and operational temperature cycling of a nUAS cell between 4.4 V and 3.1 V.

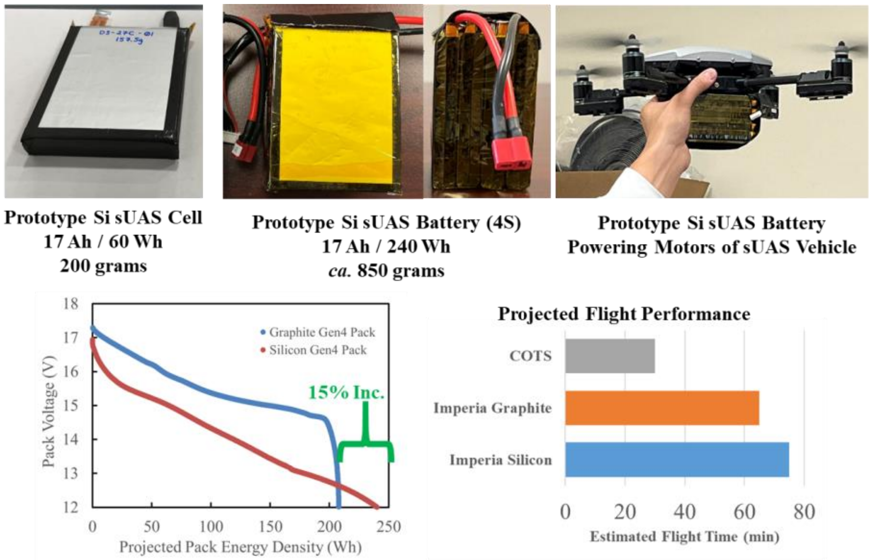


Figure 7. (top, left) Scaled-up version of NCM 811/Si battery to sUAS relevant sizes (top, center) 4S battery pack made from the scaled-up cells (top, right) Prototype battery pack powering sUAS vehicle. (bottom, left) projected energy density improvement over graphite solution (bottom, right) projected flight time improvements for sUAS vehicle.

from 4.4 V to 3.1 V. When the cell returned to cycling at 25 °C, approximately 98% of the initial capacity was retained. The process was repeated at 40 °C, where the cell performance was approximately 6% higher than the baseline. For the cycling at -20 °C, the lower voltage limit was decreased to 2.0 V to accommodate the overpotential associated with the extreme temperature. Between 4.4 V and 2.0 V at -20 °C, the cell delivered approximately 69% of the initial capacity. Finally, at 55 °C, approximately 6-8% energy above the baseline was observed; however, more cycle-to-cycle fade was observed than at other temperatures. Optimizations to the electrolyte formulation during future design iterations is expected to help to stabilize both high and low temperature operation.

In order to further demonstrate the core cell design and component technologies, Imperia scaled the cell design from the 3 Ah, 18650 equivalent cell size for nUAS to a size suitable for sUAS vehicles. The sUAS cell design chosen was the Mission Battery that was used as the baseline for the cell design. The silicon cell was designed to be the same mass as the baseline graphite cell (200 grams), resulting in an increased capacity compared to the baseline cell (17 Ah vs. 13 Ah). These cells were formed using the same procedure as the nUAS cells and then connected into a 4S battery pack (17 Ah, 240 Wh). This battery was demonstrated in-vehicle (Figure 7). Energy density and flight time were estimated to be at least 15% higher than the baseline graphite design. These rapid prototyping efforts demonstrate the efficacy of these technologies for improving energy density for UAS batteries. Moving forward, work focused on optimization of electrolyte composition and formation procedure will help to improve long term performance (cycle life, temperature stability, storage life) and processing/production optimization will help to ensure consistency and quality of solutions for these applications.

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