Acta Astronautica 68 (2011) 1752–1760

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Characterization of Lithium-Polymer batteries for CubeSat applications

Nimal Navarathinam, Regina Lee*, Hugh Chesser

Department Earth and Space Science and Engineering, York University, Toronto, Ontario, Canada M3J 1P3

ARTICLE INFO

Article history:
Received 1 October 2010
Received in revised form
27 January 2011
Accepted 6 February 2011
Available online 3 March 2011

Keywords:
Nanosatellites
Batteries
Power management

ABSTRACT

With the development of several key technologies, nanosatellites are emerging as important vehicles for carrying out technology demonstrations and space science research. Nanosatellites are attractive for several reasons, the most important being that they do not involve the prohibitive costs of a conventional satellite launch. One key enabling technology is in the area of battery technology. In this paper, we focus on the characterization of battery technologies suitable for nanosatellites.

Several battery chemistries are examined in order to find a type suitable for typical nanosatellite missions. As a baseline mission, we examine York University's 1U CubeSat mission for its power budget and power requirements. Several types of commercially available batteries are examined for their applicability to CubeSat missions. We also describe the procedures and results from a series of environmental tests for a set of Lithium Polymer batteries from two manufacturers.

1. Introduction

Recent technological advancements and fabrication techniques have drastically reduced the size and mass of key satellite components, including radio, sensors and batteries. This has enabled satellite designers to increase the performance and utility of smaller satellites. Nanosatellites, in particular, have the potential to carry out the complex work of larger satellites at a fraction of the cost. Their small designs drastically reduce launch costs and development time, allowing easy (low-cost) access to technology demonstration missions.

Advanced battery chemistries such as Lithium Polymer (LiPo) result in smaller, lightweight electrical power systems (EPS) without compromising the power capacity. In this paper, we review LiPo batteries for use on a CubeSat-based technology demonstration mission. LiPo batteries for small satellite applications are already in great demand and under consideration for several missions. Clark and Simon [1] presented a study on LiPo technologies for space applications ranging from nanosatellite to deep-space exploration missions. In their paper, it was shown that "there are definite benefits to specific space applications through the use of Lithium Polymer cells" [1].

In this paper, we focus on CubeSat applications where emphasis is often on minimizing the cost and/or selecting components that are readily available. CubeSat missions are often attempted by university or amateur groups with limited resources, limited access to technologies and/or short development time frames. LiPo technology offers a unique opportunity for CubeSat developers seeking components at low cost that are also available for educational and technology demonstration missions.

To study the applicability of LiPo battery technology for CubeSats we first examined a typical CubeSat power budget. CubeSat missions usually have a total power consumption of less than 2 W [2]. We also studied the power budget of a specific CubeSat under development at York University. In Section 3, the power budget for

* Corresponding author. Tel.: +1 416 736 2100x22095; fax: +1 416 736 5516.
E-mail address: reginal@yorku.ca (R. Lee).

0094-5765/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2011.02.004

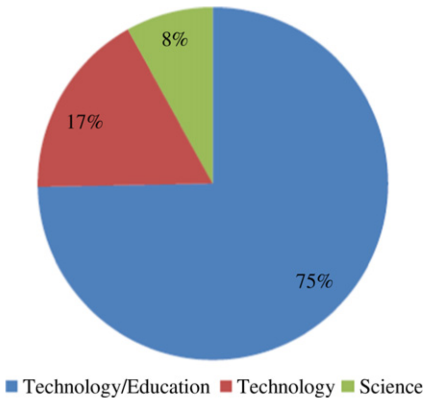

Fig. 1. Breakdown of CubeSat missions (as of 2010).

YUsend-1, a 1U CubeSat-based nanosatellite, is described. Using YUsend-1 as a baseline, we identify the minimum and maximum power requirements in safe-hold mode and in an operational mode.

Fig. 1 shows the breakdown of all the known 88 CubeSat missions that have been flown or are being planned as of 2010. Technology/Education missions, make up the majority 75%, and are used to test new designs, develop in-house infrastructure for future missions, and to train personnel in a university environment. 17% of the CubeSat missions surveyed are considered technology demonstration missions and are pursued by industrial organizations rather than educational institutions. These missions include testing new fabrication methods, new commercial off-the-self (COTS) technologies, and even running small scale experiments before committing to a more large scale implementation. CubeSat missions with a scientific objective and payload only make up 8% of the total and may increase in the future as the capabilities of CubeSats develop. Some of these scientific missions involved biological, atmospheric, and even geological experiments, such as those performed by Genesat, Radio Aurora Explorer (RAX), and Quakesat, respectively. Regardless of the type of mission, CubeSats offer reduced launched costs and development times, supporting our assumption that CubeSat designs require low-cost, readily available technologies for quick access to space.

Having established typical CubeSat mission requirements, we conducted tests of available LiPo batteries to evaluate their performance under expected on-orbit conditions. We obtained two low-cost (less than \$40 USD each), readily available COTS batteries. We review currently available battery technologies in Section 4, followed by the test procedure and results in Section 5. Conclusions and summary are provided in Section 6.

2. YUsend program

The York University Space Engineering Nanosatellite Demonstration (YUsend) program involves both graduate and undergraduate space science and engineering students to design, build, test and operate a series of nanosatellite missions. YUsend-1 is a CubeSat-based nanosatellite mission to serve as a technology demonstration of various payloads and subsystems. The EPS design (batteries, solar panels and power distribution unit) for the '1U' CubeSat is currently under development at York University. A conceptual design of the spacecraft is shown in Fig. 2. Beyond YUsend-1, the goal is to design and develop a nanosatellite mission to perform much-needed Earth observation missions in 2014.

3. YUsend-1 power budget

In this section, we outline the power budget for YUsend-1, in order to develop battery requirements. The main spacecraft payloads include: a micropropulsion unit, high speed data rate communication, and a star camera. The support subsystems include: on board computer (OBC), attitude determination and control (ADCS), communications (low data rate), and electrical power system (EPS). Of course it is important to balance the power draw of these subsystems with the incoming energy from the solar panels. One way to achieve this balance is to identify the power requirements for all spacecraft operating modes and vary the duty cycles of these modes in order to attain overall energy balance.

To develop an accurate budget requires an understanding of the mission modes which identify how the satellite behaves in orbit. YUsend-1 on-orbit mission modes include (1) separation, (2) detumble, (3) safe-hold, (4) camera demonstration, (5) thruster demonstration, and (6) high-data rate transceiver demonstration modes. For simplicity, we balance the energy over a single orbit. We assume that that the total energy required over an orbit equals the total energy supplied by the arrays (less losses) in the sunlit portion of the orbit. A sample budget is shown in Table 1. The duty cycles listed are preliminary estimates of worst case scenarios. In this particular scenario, the high data communication mode requires the most energy at roughly 4.5 Wh over an orbit. The communication demonstration is to take as long as 7–10 min. Furthermore, the satellite needs to point at the ground station which requires the operation of the ADCS. The thruster demonstration mode also requires relatively high power and roughly 4.2 Wh of energy over an orbit. The proposed thruster design is a solid propellant microthruster based on glycidyl azide polymer (GAP) and ammonium perchlorate (AP) composition. More details of this thruster development can be found in [3]. During this mode of operation, high power is demanded

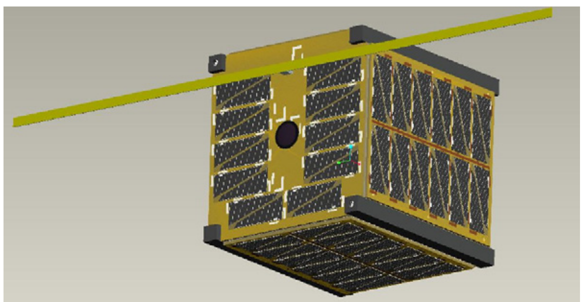

Fig. 2. YUsend-1 configuration.

Table 1
Sample power budget for YUsend-1.

Subsystem	Component	Power (mW)	Duty cycle for different modes per orbit (% input)						Energy use for different modes per orbit (mWh)					
			Separation	Detumble	Safe	Camera	Thruster	High data comm.	Separation	Detumble	Safe	Camera	Thruster	High data comm.
ADCS	Magnetorquer	350	0	80	50	80	80	80	0.0	460.9	288.1	460.9	460.9	460.9
	Magnetometer	5	0	50	10	50	50	50	0.0	4.1	0.8	4.1	4.1	4.1
	Reaction Wheels	300	0	20	0	20	20	20	0.0	98.8	0.0	98.8	98.8	98.8
	Rate Sensor	60	0	100	0	50	100	50	0.0	98.8	0.0	49.4	98.8	49.4
Comm.	Receiver	200	7	80	95	80	80	80	23.3	263.4	312.8	263.4	263.4	263.4
	Transmitter	3000	3	20	5	20	20	20	150.0	987.7	246.9	987.7	987.7	987.7
OBC	OBC	400	10	100	100	100	100	100	66.7	658.5	658.5	658.5	658.5	658.5
Power	PDU	40	10	100	100	100	100	100	6.7	65.8	65.8	65.8	65.8	65.8
Payload	Microthruster	4000	0	0	0	0	5	0	0.0	0.0	0.0	0.0	329.2	0.0
	Star Camera	250	5	0	0	10	0	0	20.8	0.0	0.0	41.2	0.0	0.0
	High Data Comm.	4000	0	0	0	0	0	10	0.0	0.0	0.0	0.0	0.0	658.5
		Sum (mWh)							267.5	2638.0	1572.9	2629.7	2967.2	3247.0
		Sum including path efficiencies (mWh)							374.2	3690.1	2200.2	3678.6	4150.6	4542.1
		Average power (mW)							227.3	2241.7	1336.6	2234.7	2521.43	2759.2

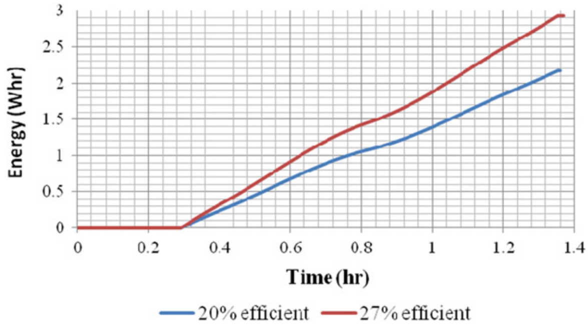

Fig. 3. Energy production from solar panels for YUsend-1 over one orbit for 20% and 27% efficiency panels.

by the thruster and also the ADCS to determine attitude information before and after the thruster has been fired.

An important mode to consider is the safe-hold mode. It has the lowest power consumption and is used to determine if the energy produced by the panels is enough to operate the critical subsystems and still have a surplus of energy to charge the batteries. This mode is where the satellite spends most of its time and allows the batteries to recharge. This may take several orbits depending on how deeply the battery has been discharged and how much surplus energy is available. Compared to the energy requirements of the other modes, the safe-hold mode requires relatively low energy at about 2.2 Wh. Satellite Tool Kit (STK) simulations were used to show that it was possible to produce more than 2.2 Wh, seen in Fig. 3, for panels using cells that have an efficiency of more than 20%. Using higher efficiency cells would allow for a larger surplus of energy that could be used to charge the batteries during safe-hold mode.

Based on the above analysis, we have concluded that a typical 1U CubeSat-based nanosatellite has the maximum and minimum energy requirements of 4.5 Wh in a typical technology demonstration mode and 2.2 Wh in the safe-hold mode. The maximum energy required sets the minimum energy that needs to be provided by the batteries—depth of discharge (DOD).

For a 700 km low Earth orbit (LEO), typical for nanosatellites, the eclipse takes up 35.72% of the orbit period. So of the 4.5 Wh needed for the entire orbit, the batteries need to be able to provide a minimum of 1.6 Wh during eclipse. However, the batteries may also need to be tapped into during the daylight part of the orbit to help supplement the power coming from the panels as well. This results in a further increase in the DOD. Therefore, it was selected to have the batteries be able to provide 70% of the maximum required energy, approximately 3.2 Wh, from the DOD. Table 2 summarizes the battery requirements.

4. Battery technologies

Table 3 compares off-the-shelf battery technologies available for spacecraft designers. We restricted our study to commercially available cells because for CubeSat missions the use of custom designed "space grade" cells usually does not fit within budget or time constraints. We examined cells which have space flight heritage including Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), and Lithium-Ion (Li-Ion). Nickel Hydrogen (NiH_2) cells have also been extensively used in the past for larger satellite missions. Though they offer advantages over the NiCd and NiMH cell types, they are not considered because they are much larger compared to the other types.

As seen from Table 3, the LiPo batteries have significant advantages over the previously used cells. Their popularity in portable electronics stems from their higher energy and slimmer profile. These factors are also highly beneficial for space applications, especially nanosatellites. Their cell packaging and geometric flexibility is highly advantageous to satellites where there are stringent mass and volume constraints. However, due to the cells being relatively new in the space industry, there is not a lot of data available on its characteristics in space conditions. The manufacturing processes also vary from supplier to supplier. Depending on the way the layers are folded within the foil, the cell exhibits varying characteristics in space conditions. Some cells have been shown to be severely affected in a vacuum due to the foil bulging, caused by the layers separating from the layering process [4].

Also, the large temperature swings expected in LEO may cause the electrolyte to solidify thereby increasing resistance and eventually resulting in premature cell failure. LiPo cells have an expected life of about 500 cycles when it is charged and discharged at 0.5 C to a 100% DOD. For LEO missions, a satellite is in and out of an eclipse at least 5000 times per year. Therefore, optimal charge and discharge rates must be established along with a proper DOD in order to maximize the battery life for the mission.

Table 2
Summary of battery requirements.

Max energy required (high data Comm. mode)	4.5 Wh
Safe-hold mode energy requirement	2.2 Wh
Max energy provided by battery pack's DOD (70% of max energy required)	3.2 Wh
Max. charge current	0.5 C
Max. discharge current	0.5 C
Max. mass of battery pack	52 g

5. Testing of Lithium polymer cells for CubeSat applications

Table 4 is a comparison of a space qualified Li-ion cell from Saft [5] with the LiPo cells from two commercial manufacturers that were used in the tests. For commercial sensitivity reasons, we refer to the batteries being from suppliers as 'A' or 'B' hereinafter. We note that both batteries were readily available from the suppliers and in

Table 3
Comparison of battery technologies.

	Battery chemistry			
	NiCd	NiMH	Li-ion	LiPo
Discharge terminate voltage (V)	1.00	1.00	2.80	2.80
Charge terminate voltage (V)	1.55	1.55	4.20	4.20
Nominal discharge voltage (V)	1.25	1.25	3.70	3.70
Operational Temperature (°C)	−20 to 50	−10 to 50	−20 to 60	−20 to 60
Sensitivity to overcharging	Medium	High	Very high	Very high
Gravimetric energy (Wh/kg)	40–60	30–80	100–200	130–250
Volumetric energy (Wh/l)	50–150	140–200	150–250	150–300
Gravimetric Power (W/kg)	150–200	150–1000	200–500	> 1000
Comments	Suffers memory effects, has good space heritage	Minimal memory effects, capable of high discharge currents	Capable of higher voltages per cell then other cells, relatively new to space industry	Same as Li-Ion but often much lighter due to lack of metal shell casing

Table 4
Comparison of space grade Li-ion and commercial LiPo batteries.

Characteristics	Saft	A	B
Type	Lithium ion	Lithium polymer	Lithium polymer
Capacity (A h)	5.8	1.4	1.1
Nominal Voltage (V)	3.6	3.7	3.7
Energy (Wh)	20.88	5.18	4.07
Mass (g)	150	23.6	23.5
Dimensions (cm)	$6.5 \times 6.5 \times 1.6$	$5.9 \times 3.7 \times 0.5$	$5.2 \times 3.8 \times 0.6$
Volume (cm^3)	67.6	10.92	11.86
Gravimetric Energy (Wh/kg)	139.2	219.49	173.19
Volumetric Energy (Wh/cm^3)	0.31	0.47	0.34
Price	Unknown	$30	$35

some cases, sample cells were provided for testing and development.

Li-ion cells, in general, have a larger capacity compared to the LiPo cell. However, the LiPo cells have a volume that is 16–17% of the Li-ion cell and has a gravimetric energy capacity that is 1.2–1.6 times larger. Such features are well suited for nanosatellite missions. The LiPo cells also have built-in circuits for over charge and discharge protection. This helps prolong the life of the battery by protecting it from unexpected events.

5.1. High discharge rate at STP

Three cells, each from 'A' and 'B', were tested for their performance at a high discharge rate of 1 C and a 100% DOD in standard temperature and pressure (STP) conditions. It is the worst case scenario where the satellite is drawing large amounts of current from the battery within a short amount of time. This type of cycling is typically very damaging to cells and can lead to a reduction in the number of cycles for the batteries. The test was to evaluate its characteristics under the extreme conditions and to examine the capability to remedy itself after a few cycles at lower discharge rates.

The batteries were attached to a Cadex analyzer (shown in Fig. 4), three at a time and three charge and discharge cycles were performed. The three batteries from 'B' performed well with the high discharge rate. They were able to discharge 90% of their capacity at 1 C. However, the 'A' cells performed poorly under the same conditions. All three cells from 'A' were only capable of discharging on average 67% of their capacity at 1 C. We noted that 'A' cells were discharging a much larger current of 1400 mA whereas the 'B' cells were outputting 1100 mA. The loss in capacity may be due to the increase in internal resistance with excessive current loads causing the layers in the cell to slightly heat up. When comparing the actual amount of discharged capacity, the 'B' cells discharged on average 990 mA h whereas the 'A' cells discharged on average 940 mA h.

5.2. Normal discharge rate at STP

Following the high discharge rate tests at STP, the same batteries were tested with the normally expected discharge rate of 0.5 C. Though the 'A' cells were not able to perform well at the high discharge rates, all three cells were able to recover the lost capacity. They discharged 90% of their rated capacity, totaling on average 1260 mA h, for 25 cycles. The 'B' cells achieved to output 83% of their rated capacity, totaling on average 913 mA h, for 25 cycles. We noted that the 'A' cells recovered from the high discharge rate situation and performed at expected levels under normal conditions.

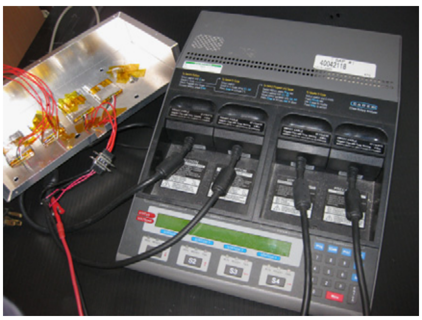

Fig. 4. Battery test setup using Cadex analyzer.

5.3. Vacuum testing

Two batteries from each of the manufacturers were placed in the thermal-vacuum chamber at York University, shown in Fig. 5, and cycled at reduced pressures.

The charge and discharge rates were set at 0.5 C for both types of cells and the pressure was set 10^{-7} Torr. The test was to determine their performance at reduced pressures with potential bulging effect that has been reported to cause capacity loss in [4]. The batteries from both manufacturers were tested for a total of 10 charge/discharge cycles at reduced pressure. Both of the 'B' cells showed reduction in their capacity by approximately 10% after the first cycle in vacuum; the capacity dropped from 83% to roughly 72%. After two cycles, one of the 'B' batteries failed completely in the vacuum. Figs. 6 and 7 show the discharge curve and the charging current curve for the 'B' batteries, respectively, in vacuum and STP

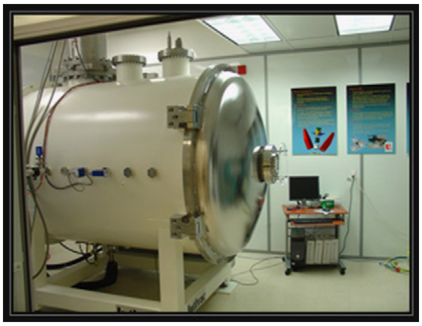

Fig. 5. Thermal chamber at York University, image credit: Thoth Technology, Inc.

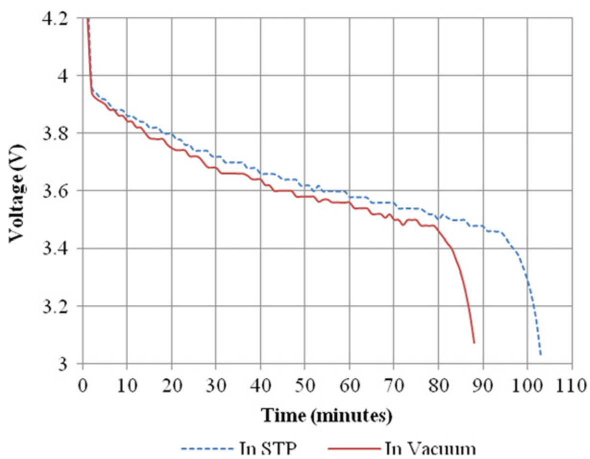

Fig. 6. Discharge cycle for 'B' in STP and vacuum.

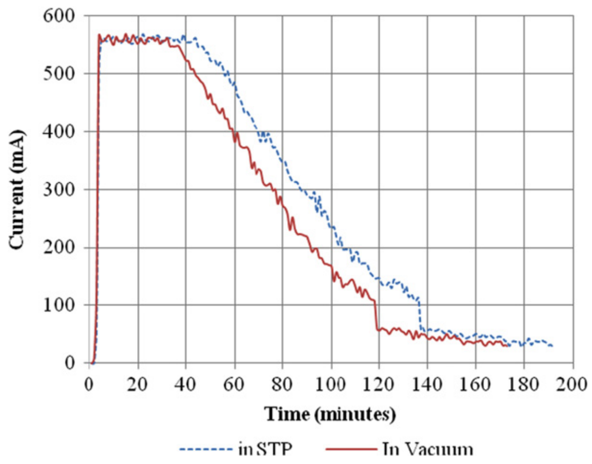

Fig. 7. Charge cycle for ‘B’ in STP and vacuum.

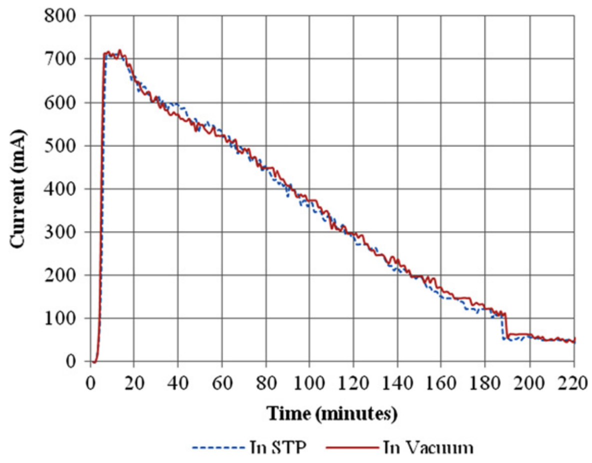

Fig. 9. Charge cycle for ‘A’ in STP and vacuum.

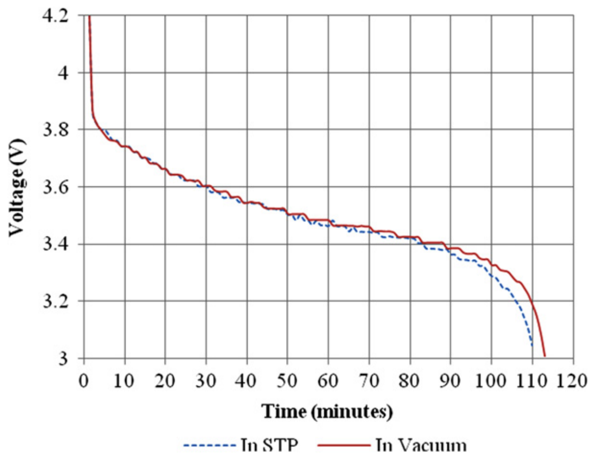

Fig. 8. Discharge cycle for ‘A’ in STP and vacuum.

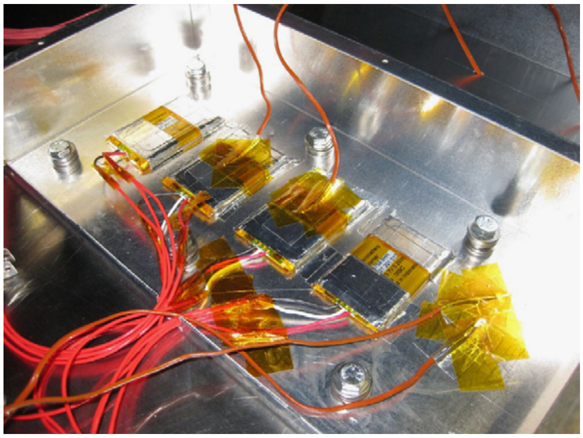

Fig. 10. ‘A’ batteries setup in thermal-vacuum chamber for LEO charge/discharge simulation.

conditions. In vacuum there is a significant change in the discharge and charge profiles.

The ‘A’ batteries, on the other hand, did not exhibit any noticeable depreciation of capacity in the vacuum. The capacity discharged in vacuum was on average within 1% of the capacity discharged in STP conditions, as shown in Figs. 8 and 9. Over the course of 10 cycles, all the ‘A’ batteries were able to maintain similar performance levels.

5.4. Temperature cycling in vacuum

Since the ‘B’ batteries lost a significant amount of capacity during the first cycle and one of the batteries completely failed in vacuum, it was decided to no longer pursue testing with the ‘B’ cells. The ‘A’ batteries, however, showed characteristics promising for space applications. In the next set of tests, four new ‘A’ cells were characterized for space environments.

The cells, shown in Fig. 10, were charged and discharged in the vacuum chamber with temperatures simulating what would be expected within the satellite structure during the eclipse and daylight periods.

The tests started with the batteries fully charged in the vacuum chamber. The pressure was set to 10^{-7} Torr and the batteries were all discharged with an output current of 600 mA for 35 min which gave a DOD of 25%. The test was to simulate what an individual battery would have to be able to provide in the worst case scenario in safe-mode during an eclipse at a 700 km altitude. The batteries were then charged for 63 min which simulates the duration of light available in an orbit. All four ‘A’ cells behaved as expected. These initial tests provided benchmarks for comparison of performance for the next set of tests where the temperatures varied.

Once the batteries were charged again, the temperature of the vacuum chamber was set to $-20\,^{\circ}$C and the discharge sequence was repeated. All four ‘A’ batteries were incapable of discharging 600 mA at $-20\,^{\circ}$C in a vacuum, most likely due to the freezing of the electrolyte and subsequently adding a large resistance to the flow of charges. The batteries did, however, discharge at 100 mA for the duration of the eclipse at $-20\,^{\circ}$C. The test was repeated with a higher temperature of $-10\,^{\circ}$C, with a discharge current of 100 mA and then with 600 mA. The battery was capable of discharging the expected capacity at the −10 °C case at both discharge rates.

Fig. 11 shows the discharge curve for one of the four batteries when it was outputting 100 mA for the duration of the eclipse period. At −20 °C the voltage steadily decreased towards the cut-off voltage, at −10 °C the voltage increased slightly and stayed relatively constant after 10 min. Under normal condition, as the battery is discharged the voltage decreases but not at −10 °C.

We noted that the while the cell is discharged, heat is generated which may keep the electrolyte in its gel-like state. As current was drawn, more heat is generated and the electrolyte becomes more viscous until an equilibrium is reached. At −20 °C the heat is not sufficient to affect the voltage output.

The increasing voltage is also seen in Fig. 12 in the −10 °C case where 600 mA of current was being drawn. The voltage output increased for the first 15 min before it leveled out around 3.5 V. The discharge curve at 25 °C, on the other hand, shows steady decrease. Another important fact to note is that the colder temperatures also decreased the initial potential output of the battery. Fig. 12 shows that at 25 °C, the output potential started at 3.8 V.

In comparison, at −10 °C, the same battery started at 3.4 V. Again, we suspect that this is caused by the electrolyte starting to solidify and increasing the internal resistance of the cell.

With the batteries discharged from the LEO simulation, the temperature of the chamber was increased to 50 °C and the charge cycle was initiated. The LiPo cells are charged initially with a constant voltage–constant current method with a 0.5 C charge rate until the maximum battery voltage is reached. It is then followed by a constant voltage–taper charge method. The charging scheme is shown in Fig. 13 at 25 and 50 °C. The charge keeps increasing until the battery has reached its cut-off voltage and the current starts to taper off until the period of sunlight is over. Since the battery only had a DOD of 25%, it did not take long for the battery to get back up to its cut-off voltage of 4.2 V.

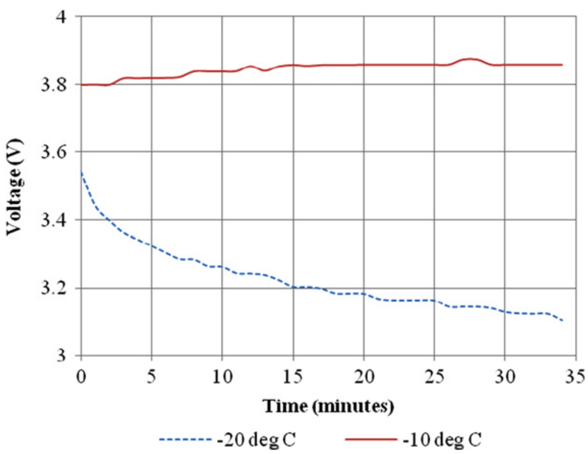

Fig. 11. 100 mA discharge during eclipse period in thermal-vacuum chamber at different temperatures.

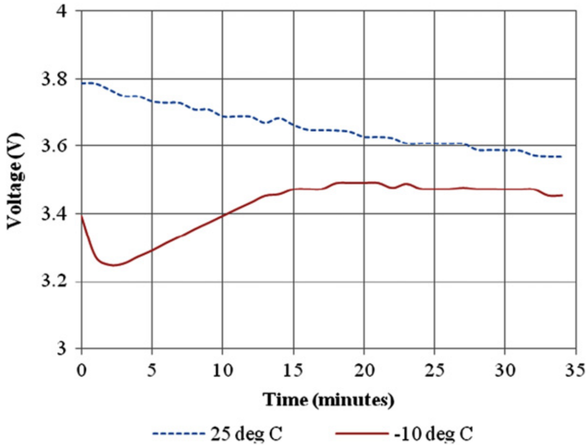

Fig. 12. 600 mA discharge during eclipse period in thermal-vacuum chamber at different temperatures.

However, if it was fully discharged then the battery would take longer to get to 4.2 V and the current would have kept increasing to 0.5 C. As shown in Fig. 13, the charge cycle at the increased temperature behaves as expected with negligible difference from the performance in STP conditions.

5.5. *Lifecycle testing*

The battery end-of-life is defined as the point at which the capacity of the battery has dropped below a specified threshold, often set by the user. The rate at which capacity is lost from the battery depends on several factors such as battery chemistry, operating temperature, charge and discharge rates, and most importantly the DOD. These determine how many charge/discharge cycles are possible from a battery. For satellite missions, the charge/discharge cycles are determined by how many eclipses are seen throughout the mission lifetime. In LEO at an altitude of 700 km, more than 5300 cycles per year is expected. Such long cycle life requirements can be met by minimizing the DOD. Therefore, the DOD must be selected such that the EPS can provide the required power during the number of eclipses that will be experienced.

The ‘A’ batteries were characterized over approximately 700 cycles during a period of 6 months in STP at a rate of 0.5 C with a 100% DOD. Fig. 14 shows the capacity decreasing as the number of cycles increased. After 500 cycles, the capacity dropped by nearly 15%. Normally in LEO missions however, the batteries are rarely ever discharged 100%. A typical DOD for a satellite in LEO is 30% [6].

Since the degradation is known for the 100% DOD for the ‘A’ batteries after 500 cycles, the number of cycles are approximated for a different DOD value with a different acceptable degradation using a simple ratio [7]:

$$500 \times \frac{100\%\ \text{DOD}}{15\%\ \text{loss}} \times \frac{\text{acceptable Loss}}{\text{acceptable DOD}}$$

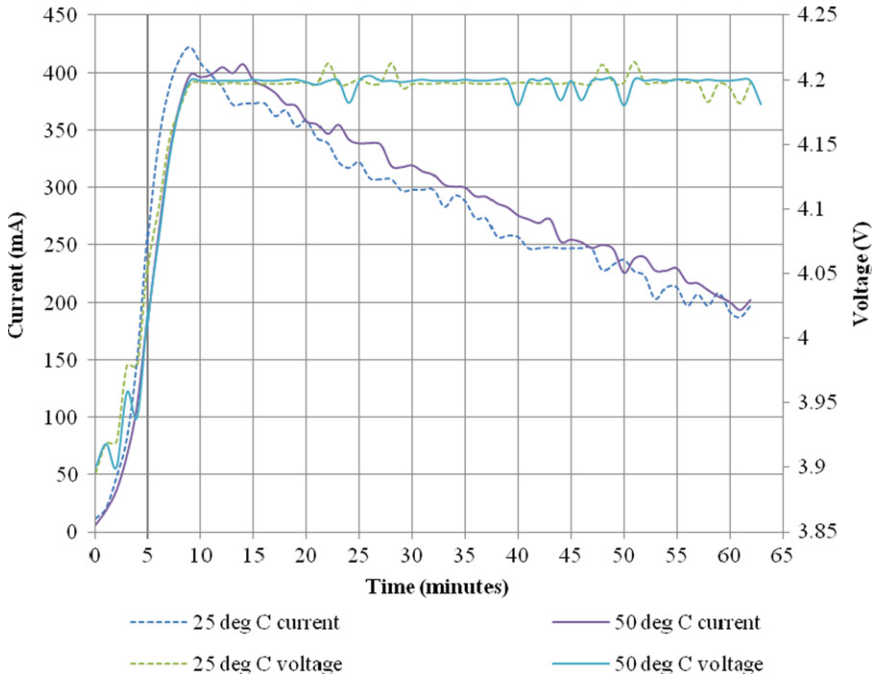

Fig. 13. 0.5 C charging during daylight period in thermal-vacuum chamber at different temperatures.

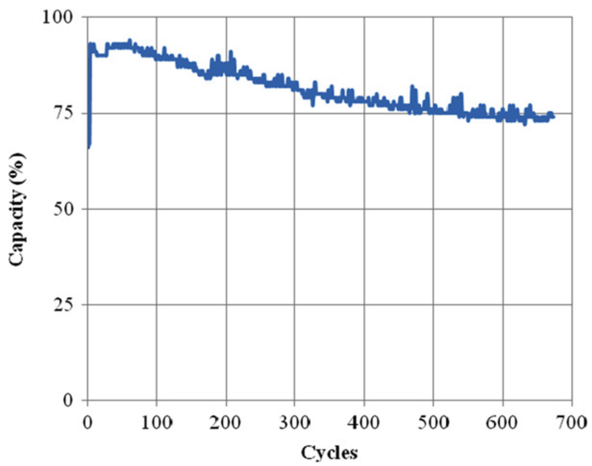

Fig. 14. Capacity decrease with respect to number of cycles for 'A'.

Having an acceptable loss in capacity of 50% and an acceptable DOD of 30% yields more than 5500 cycles. The 30% DOD also yields 1.6 Wh of energy from one battery. Most CubeSat missions, including YUsend-1, utilize two or more batteries, thus providing an output of 3.2 Wh which meets the requirement set earlier.

6. Final remarks

The advent of LiPo cells with their higher volumetric and gravimetric energy densities have created a potentially new opportunity to improve nanosatellite EPS. We examined the use of commercially available LiPo batteries for a CubeSat-based mission, YUsend-1. However, as mentioned, it was important to test these commercial products in order to develop a degree of confidence in their performance in a thermal-vacuum environment before incorporating them into a satellite design.

Of the two commercial cells tested, 'A' batteries show promise of being able to meet the requirements of the YUsend mission. Unlike the 'B' cells tested, 'A' cells showed no loss of charge capacity during vacuum testing. 'A' cells were also able to output 600 mA of current for 35 min in a vacuum at $-10\,^{\circ}$C. The performance of these cells in colder temperatures could be improved by the use of Kapton heaters if needed for other types of missions.

Aside from being able to perform in a vacuum environment with large temperature swings, the LiPo batteries must also be able to survive the vibration and shock loads experienced during launch. Roberts [8] presented a study outlining tests that were performed to ascertain the mechanical feasibility of similar LiPo batteries. It was shown that there was no measurable degradation experienced by the batteries when subjected to launch loads. Furthermore, the author goes on to show how the batteries could be integrated as structural elements of nanosatellites in order to reduce overall mass. Vibration testing will be performed at the satellite level for YUsend-1 as it is being completed and the battery performance will be analyzed further at that time.

The use of two 'A' cells in parallel, a mass of only 47.2 g, are envisaged for YUsend-1 giving an output voltage of 3.7 V and a capacity of 2800 mA h; this equals 10.4 Wh of total energy. As noted in Section 2, the required amount of energy in the safe-hold mode is only 2.2 Wh which is just 21% of the total capacity. Therefore, it would be able to meet the lifetime requirement as well since the energy needed for the entire orbit in safe-hold mode is less than the DOD of 30%.

The selection of the flight cells will need to be batch tested carefully. It is important to characterize their performance without putting too much strain on them before the actual flight. Since two batteries will be used in parallel, one of the most important characteristics to check for is capacity and internal resistance. These two parameters of the two batteries used have to be near identical or one of the batteries will be over stressed during the mission and lead to rapid cell and performance degradation. This can be easily determined by fully cycling the batteries at 0.5 C until the capacity readings of the cycles stabilize to within 1% of the previous cycle. This usually takes about 10 cycles. Commercial batteries may not have the highest level of uniformity and so there may be slight discrepancies with the capacity output. The batteries that have the similar capacity drop should be paired together to avoid burdening one of the batteries more than the other.

Further testing is planned to improve the confidence level of LiPo batteries for space use for the YUsend program. There is a synergy between LiPo cell technology and CubeSats: LiPo cells can be used to improve the performance of CubeSats, and CubeSats in turn can help build space heritage for LiPo cells and provide more confidence in its use for larger satellite missions.

References

[1] C. Clark, E. Simon, Evaluation of Lithium Polymer technology for small satellite applications, Conference Proceedings of the 21st Annual AIAA/USU on Small Satellites, Logan, Utah, 2007.

[2] M. Polaschegg, Study of a CubeSat Mission, M.Sc. Dissertation, Karl Franzens University of Graz, Graz, Austria, 2005.

[3] K. Sathiyanathan, R. Lee, H. Chesser, et al., YuSEND-1 solid propellant microthruster design, fabrication and testing, Conference Proceedings of 24th Annual AIAA/USU Small Satellites Conference, Paper no. SSC10-X-2, Logan, Utah, 2010.

[4] I. Buchmann, Batteries in a Portable World—A Handbook on Rechargeable Batteries for Non-Engineers, Retrieved: May 2010 〈http://batteryuniversity.com〉.

[5] Saft Space MPS Li-Ion Battery Datasheet, Retrieved: May 2010 〈http://www.saftbatteries.com/Produit_Space_MPS_cell_range_301_60/Default.aspx〉.

[6] K. Sarda, C. Grant, et al., Canadian Advanced Nanospace Experiment 2 On-Orbit operations; Two years of pushing the nanosatellite performance envelope, Conference Proceedings of CASI ASTRO 2010, Toronto, Canada, 2010.

[7] D. Guckenberger, T. Graziano, et al., Cornell CubeSat Power Subsystem, 2003.

[8] S.C. Roberts, An investigation of the feasibility of a spacecraft multifunctional structure using commercial electrochemical cells, Doctoral Dissertation, University of Southhampton, United Kingdom, 2009.