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Evaluation of Lithium Polymer Technology for Small Satellite Applications

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ABSTRACT

As small satellite designers strive to squeeze greater performance into yet a smaller spacecraft volume, there is a great temptation to use emerging technologies from the consumer electronics world. However, as we are acutely aware, great care must be taken before relying on such technologies on a space mission. This applies to most elements of the spacecraft, but the battery is perhaps the most critical of subsystems to risk on a new technology. This reluctance to utilize new battery technologies in space is evident by the fact that many small satellite designers continue to use nickel cadmium as the technology of choice for energy storage; a technology that offers less than a fifth of the specific energy of a comparable lithium polymer battery.

A recent study commissioned by ESA reviewed the global state-of-the-art in lithium polymer technology. The recommendations from the study were that small satellites in particular were a killer application for a lithium polymer battery, as its geometric flexibility is then an asset, and initial tests demonstrate that they also promise the kind of performance expected for LEO small satellite missions.

This paper provides an overview of the technology, the application evaluation for small satellites, the variety of the tests performed on the cells and the results of these tests. To conclude, the paper will discuss the way forward with the technology and planned future missions that will use lithium polymer as the primary means of energy storage.

INTRODUCTION

Power storage and generation are amongst the most widely discussed topics in almost all fields of engineering at this present time. For example, consumer electronics are demanding longer battery life so that laptops, PDAs and cell phones can last longer without charge whilst at the same time performing more tasks; renewable energy systems are looking for mediums in which to store large quantities of energy when the renewable energy source is not available; in the military domain, the army wants soldiers to carry more electronic equipment, but at the same time reduce the mass of the accompanying battery.

Of course, in the space industry, the need for reliable and efficient energy storage has always been a pressing issue, and although governments have made resources available for space battery development for many years, there is nothing quite like consumer commercial incentive to push the boundaries of technology; as a

result we are now seeing significant improvements in the specific energy of battery technology, with 200Whr/kg already a reality and the promise of higher energy densities in the next few years. From a spacecraft designer's perspective, the question is one of if and how we can successfully use emerging commercial battery technologies in space.

ABSL Space Products have, for many years, successfully supplied spacecraft batteries based on the SONY HC18650, a cell that has effectively been around in commercial form since the early 1990s. Compared to the current state-of-the-art, the SONY HC18650 offers close to half the specific energy; although the heritage and service life of the technology are enough to counter balance the pros and cons of the technology used in the cell.

The main hurdle, it seems, in finding reliable, predictable commercial cells for the space industry is that the drivers for battery development in the

commercial world are very different to that of the space industry. Longevity of service life is not a major design driver, especially not for military applications; the focus is primarily on the reduction of mass and volume for the same energy stored.

In 2004, the European Space Agency recognized that there may be potential in the new battery technology of choice for consumer electronics; lithium polymer. In order to evaluate the technology from a space use perspective, ESA commissioned a study into the technology.

Surrey Satellite Technology Ltd (SSTL) were selected to undertake the study along with ABSL Space Products (previously AEA Technology PLC). The combined experience of SSTL and AEA on this project provided a strong basis of technical knowledge and experience enabling all aspects of the study to be thoroughly investigated. SSTL provided a wealth of knowledge in spacecraft engineering and innovative techniques to meet mission requirements, as well as a long history of using commercial-off-the-shelf electronics components and batteries in space. ABSL Space Products brought substantial expertise in not only the design of lithium ion and lithium polymer cells for a range of applications, but also as one of the leading providers of Lithium ion batteries to the space market. [N.B. Craig Clark was study manager whilst still in the employ of SSTL].

The first part of the study was to identify space applications benefiting from the replacement of standard Lithium ion by Lithium ion polymer battery. The technology was evaluated from a cell perspective, and subsequently potential applications were investigated based on geometric flexibility, ruggedness and operating properties of cells. Then, SSTL identified a range of typical space missions already using or intending to use liquid electrolyte lithium ion technology, and have evaluated the potential advantages of the switch to the use of Lithium Polymer technology. As expected, many of the applications identified directly fed into the advantages of the technology on typical space missions.

In the study, 80 companies offering Lithium Polymer cell technologies were identified by ABSL Space Products. These were down-selected to 39 companies with the capability to provide cells to the space industry. These 39 companies were then down-selected to 10 organisations demonstrating an interest in supplying product into the space industry. Finally a detailed analysis of these cells were performed, leading to the selection of 5 candidate cell technologies for evaluation testing, performed independently by ESA.

A test philosophy was adopted, intended to probe the potential weaknesses of Lithium Polymer cells for space applications. These tests included vacuum performance testing, gamma radiation testing, low and high temperature performance testing, cycle life, self discharge and destructive parts analysis. An overview of the results of these tests, conducted on five cells selected from the survey results, are included in this paper. Finally, an overview of subsequent work in this area is presented along with conclusions.

POTENTIAL SPACE APPLICATIONS

The experience and expertise at SSTL was ideal for assessing the potential applications of Lithium Polymer technology. The result of the assessment presented numerous advantages of the technology for a range of potential space applications. It was clear that the geometric flexibility of the cell has the potential to revolutionise the way that batteries are configured in structures, especially in the context of small and miniature spacecraft. Of most note were the following findings:

- The cell packaging and geometric flexibility is of most interest to spacecraft that are inherently volume limited, such as very small spacecraft (i.e. nanosatellites and smaller) where this technology can enable structural designs not previously possible. This was shown to be the case in the analysis of the SNAP-1, SNAP-2 and PalmSat spacecraft.

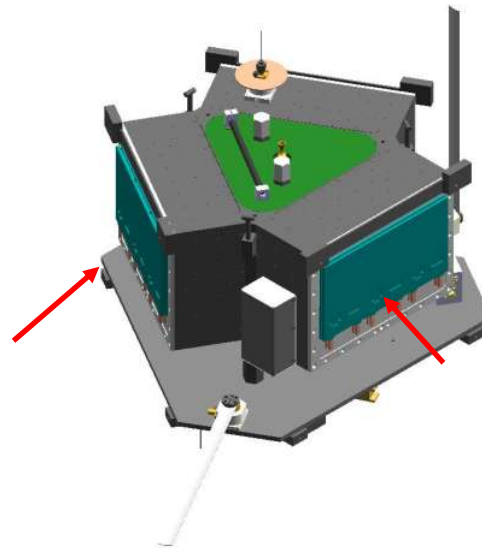


Figure 1 SNAP-2 with potential Li-polymer battery packs locations arrowed.



Figure 2 Example Palmsat Ni-Cd battery pack

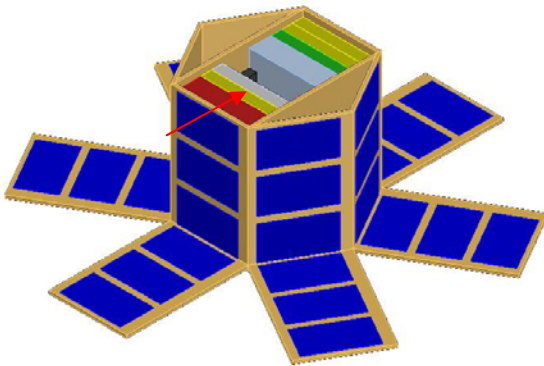


Figure 3 Palmsat isometric view showing Ni-Cd battery compartment

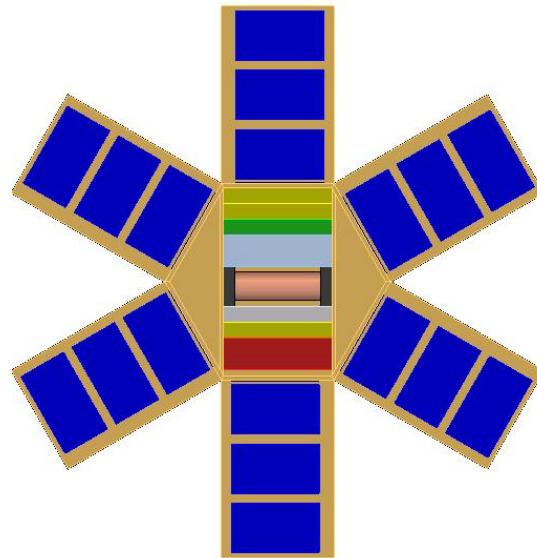


Figure 54 Top view showing orientation of NiCd batteries

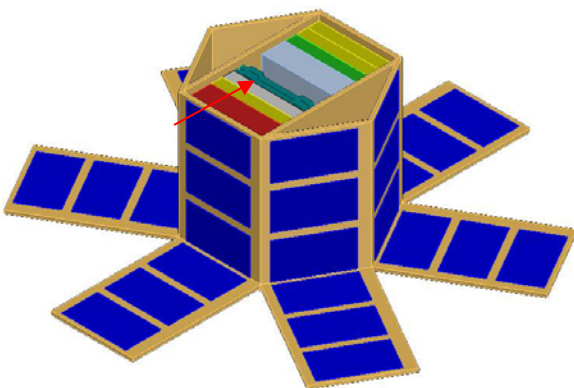


Figure 5 Palmsat isometric view showing Li-P cells (arrowed) arranged in 2s1p or 1s2p configuration, with connector tabs uppermost

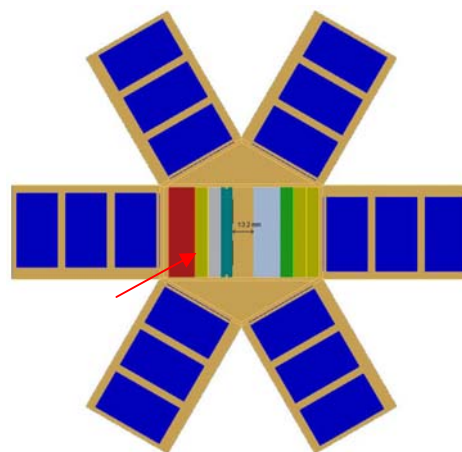


Figure 6 Top view showing orientation how 2 x Li-P cells leave 13.2mm wide gap in space vacated by NiCd batteries

It is on these miniature spacecraft that we can see the most potential for lithium polymer, perhaps even in a 'mission enabler' capacity where cylindrical or liquid electrolyte prismatic cells are not able to provide the necessary combined mechanical and electrical performance.

- For microsatellite (i.e. 50kg- 150kg) class spacecraft, there is increasing pressure of mission designers to increase the capability of the spacecraft without a significant increase in spacecraft volume and mass. Lithium polymer batteries can offer some volume and mass savings for this spacecraft type, but the gains are possibly not significant enough to entice spacecraft designers away from the now proven lithium ion cell technology.
- Lithium polymer looks like the perfect technology for high impact/shock applications, due to being inherently mechanically robust. However, to use lithium polymer technology on surface landers they need to be able to survive the low temperatures experienced during the eclipse period. The operating and storage temperature limitations of lithium polymer technology is the first hurdle for landers, especially for missions to planets and NEOs further from the Sun than Earth and for high latitude landings.
- It was identified that there is considerable synergy with spacecraft propulsion systems is possible, particularly where spacecraft propellant tanks are concerned (especially so if the thermal properties of the cells are favourable).

Other applications that benefit from this technology specifically included; Low Altitude missions, Magnetic Cleanliness, Radiation shielding, Bipolar cell for HV applications, Mechanical housing sharing and Spin balancing.

For current battery technologies, the battery location is amongst one of the main drivers for the structural configuration and the removal of this requirement through the use of lithium polymer cells could herald significant advancement in the structural and electrical design of future spacecraft.

It is undeniable that there is a current need that is ideal for lithium polymer on miniature spacecraft platforms.

COMPARATIVE PERFORMANCE EVALUATION

In support of the space applications review, a series of top level mission analyses were performed. The

objective of this activity was to establish the suitability of Lithium Polymer cells for space applications, highlighting potential benefits and or shortfall in the battery performances.

The methodology employed was to perform an initial conceptual battery design for each of the candidate missions using a currently available Lithium Polymer cell as a baseline and compare the performance of this to the performance of a comparable Li-Ion battery design to highlight the potential benefits and any disadvantages.

A cell was chosen primarily because of the similar capacity (1600mAh) to the control cell X (1500mAh) which was used as a benchmark for battery performance evaluation.

- The design analysis performed for each mission included:
- Estimates of fade to EOL capacity under mission cycling, thermal and ageing conditions
- Battery sizing for Lithium Polymer cell and Lithium-ion batteries
- Structural mass calculations from concept designs
- BOL and EOL performance evaluation

This analysis was performed for each of 7 missions, selected to span the range from nanosats through to large platforms, and to include unique missions such as planetary landers and deep-space probes:

- Palmsat
- Herschel Planck
- Rosetta (as flown)
- Rosetta (redesigned to optimise for Lithium Polymer)
- Venus Express
- Eurostar3000
- Beagle2

Graphical comparative results of the seven mission analysed are presented in Figure 7. The clearest benefits of Lithium Polymer technology utilisation were identified in two configurations:

1. Nanosat missions, where the benefit of flexible energy storage with minimum cell structural mass and high utilisation of the available volume is a driver.
2. Large communications platforms where the improvement in cell energy density results in a mass saving over traditional Lithium-ion cells.

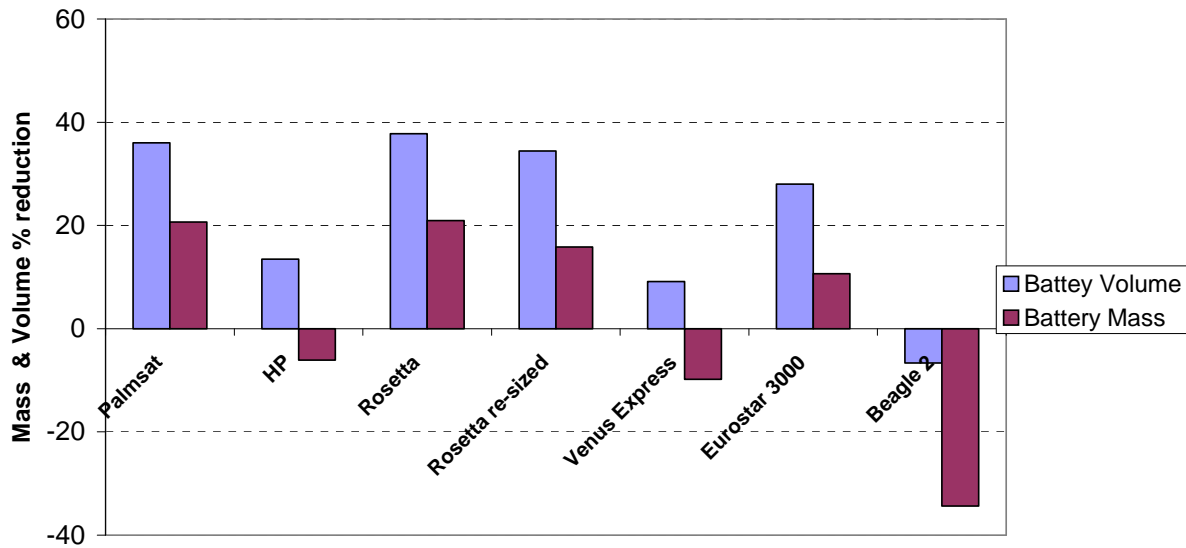


Figure 7 Mass and Volume percent reduction over Lithium-ion baseline X (Battery level)

Cell Selection

The state of the art world-wide capability in Lithium Polymer cell production was investigated with the aim of identifying potential suppliers of Lithium Polymer cells for space applications. The extensive market research revealed 80 potential suppliers.

Of the 80 companies identified 39 were short listed based on their technology maturity and pertinence, potential interest in the space market and accessibility.

In order to review the capabilities of these companies, a survey was designed to identify the suitability for a space application. The survey included information on:

- Company activity, including specialism in technology development, cell manufacturing and battery pack production, type and range of technology and production volume
- Basic cell performance and cell-to-cell production uniformity
- Cycle life
- Materials compatibility
- Mechanical and electrical safety testing

The 39 companies were contacted with this survey. The survey was concluded with 10 successful candidate suppliers each presenting two alternative cell candidates. For reasons of commercial sensitivity, these cell candidates will not be identified in this paper.

The evaluation criteria used in the selection of the most promising cells is shown in Table 1.

Table 1 Evaluation Criteria and Scoring

Evaluation Criteria	Weight	Scoring
<i>Technical</i>		Total of 30 points for technical
Energy Density	10	
Cycle Life	5	
Radiation Tolerance	10	
Outgassing	5	
Survey Responsiveness	15	Willingness to participate in space applications
Commercial	20	Geopolitical factors, economic stability
Flexibility	10	Capability to manufacture different chemistry and size variants.
Manufacturing Volume	10	Favours small production volumes over prototyping/high vol.
Space Heritage	15	Cell heritage

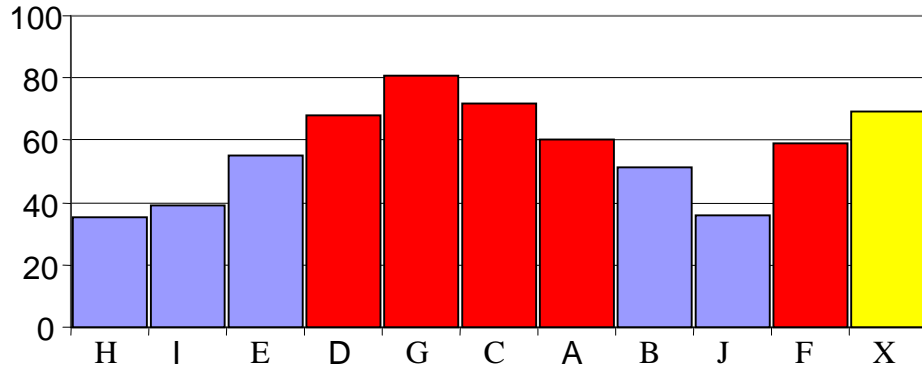


Figure 8 Cell Rating On Overall Performance

The overall scores are presented in Figure 8. From these results, the five companies scoring highest were suppliers A, C, D, F and G. Cells from these five companies were proposed for independent evaluation testing at ESBTC (European Space Battery Technology

Centre) at ESA ESTEC. The performance characteristics of these five cells are illustrated in Table 2 below.

Table 2 Summary of selected cell performance

Code	Weight	Dimensions	Capacity	Voltage	Energy Density	
	/ g	/ mm	/ A hr	/ V	/ W hr kg ⁻¹	/ W hr litre ⁻¹
A	65.5	5.3 x 64.0 x 95.0	3.30	3.70	186	383
C	33.0	3.4 x 55.0 x 85.0	1.60	3.70	179	372
D	44.0	4.8 x 55.0 x 84.5	2.00	3.70	168	332
F	22.0	5.0 x 37.0 x 59.0	1.02	3.70	172	346
G	175	6.4 x 94.0 x 127.0	9.13	3.70	197	454

EVALUATION TESTS

A number of key discriminators were identified for the cell candidates:

- Capability to operate in vacuum conditions.
- The capacity to sustain radiation doses representative of space environment.
- Good operational capability over a wide range of temperatures

The evaluation tests were designed to address these potential “show-stoppers”. The testing focused on radiation testing, thermal vacuum and destructive parts analysis in addition to EMF versus SOC, internal resistance, self discharge, capacity at C/10 and capacity under three mission scenarios

Vacuum test

The vacuum test performed on the cells candidates revealed that only Cell F presented during vacuum the same capacity as prior and post vacuum test. This

successful behaviour can most likely be attributed to the stacked internal configuration less prone to separation.

None of the cells tested gave apparent indication of packaging or cell outgassing.

DPA

A qualitative analysis of the cells components was performed on relatively fresh cells and cells that underwent vacuum test. The test revealed that:

- C and A could be described as “liquid in a bag cells” and were based on partially folded configuration (separator only folded)
- D could also be classified as a “liquid in a bag cell”, however the configuration was based on a wound configuration
- F differed from all the others, presenting a volatile solvent and a fully stacked configuration, indicating that cell could be a Lithium-ion based cell

- G based on a “concertina” folding also presented a volatile solvent, suggesting a Lithium-ion based cell

None of the cells presented an apparent seal damage after vacuum testing

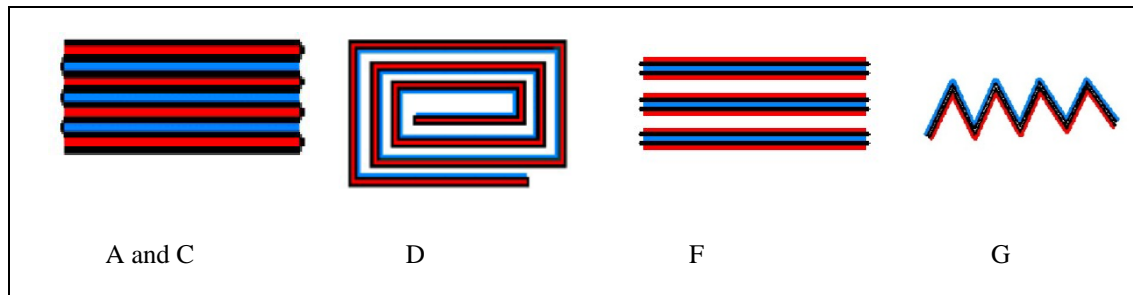


Figure 9 Cell Construction

Radiation

All of the cell candidates were irradiated with a cobalt source from 10 to 500krad at 50 rad/min, a post test capacity measurement revealed no degradation of cells capacity.

Capacity and Resistance versus Temperature

The capacity measurements performed consisted of a C/10 rate constant current discharge, charge and discharge cycle between the voltage limits defined by the manufacturer for each cell type at four temperatures (-10°C, 0°C, and 40°C).

The best performances for cold case were exhibited by cell C, followed by F. Cells A and D almost doubled the capacity loss of the two best performers at 0 deg C. The same trend was observed for the -10°C case. Cell G showed particularly poor performance at -10°C where a cycle could not be sustained.

As expected for all the specimens the Internal Resistance (IR) increased with the decreasing temperature.

Self Discharge

The cells were subjected to a C/10 discharge/charge cycle, after which were stored (open circuit) for the duration of 24 hours. The storage period was followed by a C/10 discharge to the minimum voltage indicating the following loss of capacities 3%, 0.7% for cells G, D and less than 0.5% for cells C, F and A.

Capacity under Mission Scenarios LEO, GEO and Lander

LEO cycling at 0°C

The cells were cycled using a C/4 discharge and a C/2 charge (5 cycles). D, C, A and F cells could sustain such cycling without capacity loss between the first and the 5th cycle. Cell G could not sustain these cycles.

GEO Cycling at 0°C

The cells were cycled using a C/2 discharge and C/10 charge (5 cycles). D, C, A and F cells could sustain such cycling without capacity loss between the first and the 5th cycle. G could not sustain these cycles.

Lander cycling at 0°C, 20°C and 40°C

The cells were cycled with a C/15 discharge and C/10 charge rate (5 cycles, increasing to 10 cycles if unstable after the first four cycles). D, C, A and F cells could sustain a Lander cycling in these conditions at 0°C., whereas G once again struggled.

Repeating the Lander cycling conditions at 20°C and 40°C, all of the cells successfully sustained the regime

EMF versus SoC

By cycling the cells at a very slow rate (C/50) the EMF vs SoC characteristic of the cells were obtained.

Evaluation Tests Conclusion

Of the 80 companies initially identified, only 39 were evaluated as suitable suppliers for space applications. Of these, only 10 companies demonstrated real interest in accessing the space market. Five of these suppliers

were evaluated in independent cell testing performed by ESA under this contract.

Of these five candidate cell technologies, cell G failed the cycle testing and yielded a high self-discharge relative to the other cell technologies and failed to operate at -10°C .

Cells A, C and D all passed the cycle testing, but demonstrated a reduced performance under vacuum conditions. Of these, cells A and D also showed poor performance at low temperature (0°C), favouring cell C.

Cell F, meanwhile, passed both the cycle testing and vacuum testing with no performance reduction, and performed well at low temperature. This cell differs from the others tested in two ways:

- The internal configuration was electrode stacking rather than either winding or folding
- The sealing method used an ultrasonic weld rather than thermal sealing technique

SUBSEQUENT EVALUATION

Having demonstrated the potential of the technology for space applications, some additional testing (life-testing) was carried out on cells from manufacturer F. These tests were devised and administered by ESA at the ESBTC.

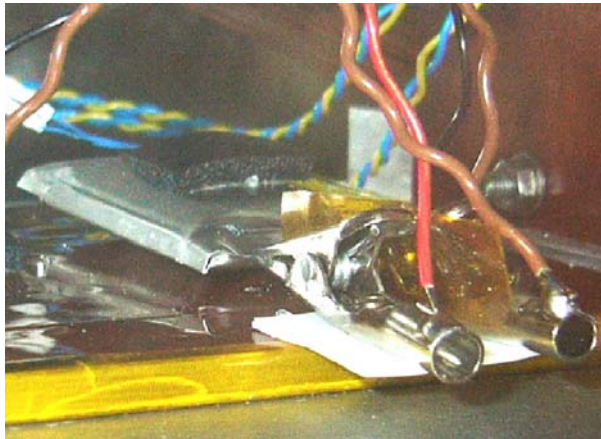


Figure 10 Cell test under reduced pressure

The cells were cycled under reduced pressure (15-20 mbars). The cells were cycled using a 30% and 80% Depth of Discharge (DoD) cycling at 20°C with a capacity check every 50 cycles. The discharge rate was C and charge rate $C/2 + \text{tapering}$.

For the reduced pressure test, a capacity check using $C/10$ discharge rate was performed prior constant cycling. The temperature of the cell was controlled at

20°C by a plate cooled down via a water-loop. The cells were isolated from the metallic plate with a Kapton® film.

When the cells were placed under reduced pressure, the cells were “inflated” as the pressure inside the packaging becomes greater than the pressure outside. (see Figure 10). The capacity measured under atmospheric pressure was 1.043 Ah and under reduced pressure (15-20 mbar) the capacity measured in the same conditions was 1.033 Ah. Therefore the lost of capacity under vacuum is small, 1%, for cell F.

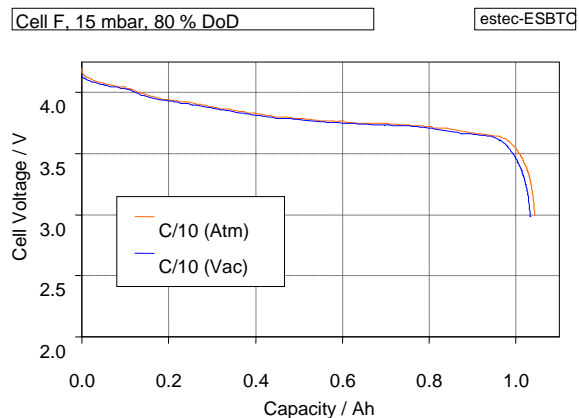


Figure 11 Capacity check under atmospheric pressure and reduced pressure

80% DOD test

During the test, it was found that the end of discharge voltage (EODV) dropped quickly to 3.0 V after only 50 cycles. So the discharge rate was modified and set up to $C/3$ as it was decided that the C rate discharge was too demanding for the cells. The charge conditions remained unchanged.

During the test, the end of discharge temperature raised to 29°C when using the C discharge rate, but decreased to about 23°C when the discharge rate was reduced to $C/3$. [The end of charge temperature did not change and was around 20°C].

The energy efficiency of the cell was less than 90% at the beginning of the test. This decreased to about 80% with the C discharge rate, and increased to 85% when the discharge rate was reduced to $C/3$.

It is suspected that the cell was damaged during first 180 cycles at C rate, accelerating the ageing. This resulted in the cell reaching 80% of the initial capacity after only 300 cycles, resulting in the end of the test for this cell.

All the tests were modified as a result of this finding, and the discharge rates were reduced to C/3 from C.

30% DOD test

The 30% DOD test reveals more information about the cell's likely performance in a LEO environment which typically sees frequent shallow charge/discharge cycles. As with the 80% DOD test, the discharge rate was changed part way through the test.

Over the duration of the life test, the capacity of the cell decreased due to ageing. The evolution of the full capacity during the cycling is shown in the figure below.

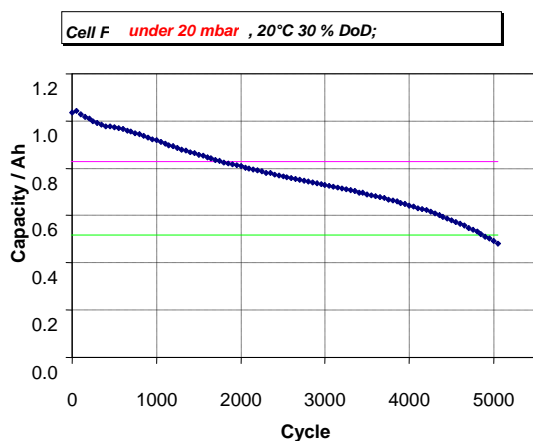


Figure 12 100% DoD capacity check every 50 cycles during constant cycling at C rate for the first 350 cycles and at C/3 for the remaining cycles.

The evolution of the cell internal resistance is shown in Figure 13. At the start of the cycling, the cell resistance was around 120mohm and raised quite rapidly to 150mohm. When the discharge rate was changed from C to C/3 (at 350 cycles), the internal cell resistance increased more slowly.

Over the duration of the test the End of Discharge Voltage (EODV) decreased rapidly from 3.66V to 3.57V for the first 350 cycles (C rate discharge). Once the discharge rate was reduced the EODV was 3.78V and decreased more slowly. After 2550 cycles, the EODV was 3.57V and after 5050 cycles, the EODV was 3.10V.

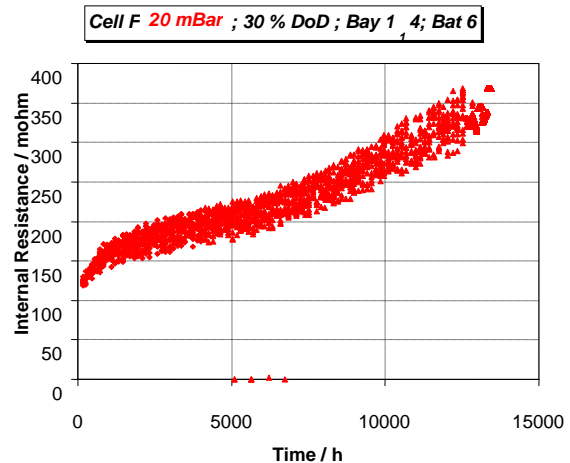


Figure 13 Internal cell resistance during constant cycling at C rate then C/3, to 30% DoD under reduced pressure.

The evolution of the energy efficiency of Cell F is shown on the graph below. At beginning of the test, the energy efficiency was around 92%, but decreased rather rapidly under the C rate discharge conditions to get to 90%. After changing the discharge rate to C/3, the energy efficiency was 94% and after 2500 cycles, it was 89%.

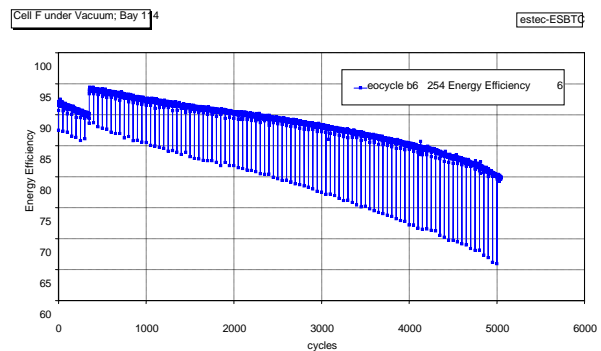


Figure 14 Evolution of the Energy Efficiency during constant cycling at C rate and then C/3, 30% DoD.

The cycling test of Cell F under reduced pressure was stopped at 5050 cycles (approximately 1 year in LEO), as the remaining capacity was just under 50% of the initial capacity.

Conclusions from cycling tests of Cell F.

It was found that vacuum has no effect on the cell capacity with the capacity measured under atmospheric pressure and under vacuum varying by 1% or less. This can be explained by the cell architecture: it is a stack configuration. This means that, although the cells are

bulged under vacuum, the contact between the electrodes and the separator remains good.

On the down side, Cell F was unable to sustain a C discharge rate, which is usually used for this type of test.

For the 80% DOD test, even with a reduction in the discharge rate, the EODV reached rapidly 3.0V and the internal cell resistance was multiplied by about 3 from start to end of the test (300 cycles).

For the 30% DOD test, under reduced pressure the cell sustained 1750 cycles before reaching 80% of initial capacity and almost 5000 cycles before reaching 50% of initial value. Meanwhile, the internal cell resistance was multiplied by 3 from the start to the end of the test (120mohm at beginning, to 350mohm at the end).

Given that the charge/discharge rates that the cells were subjected to are significantly greater than a typical mission, Cell F performs very well under cycling conditions.

PLANNED USE OF LITHIUM POLYMER IN SPACE

Clyde Space Ltd, in Glasgow, Scotland, have been actively developing a lithium polymer battery for small and miniature spacecraft applications.

Following the award of an innovation grant from the Scottish Executive to develop an electrical power system (EPS) for CubeSats, this was an ideal opportunity to include a battery in the design.



Figure 15 Clyde Space CubeSat Lithium Polymer Battery

The decision was taken to develop a battery system that integrated with the EPS and that the battery could be scaled to increase the capacity. It was also decided that each battery would have; an integrated battery heater with thermostat, battery cell voltage, terminal voltage,

current and temperature monitor on every battery. Each battery is also equipped with electronics to protect the cells from over-current and from over charge and discharge.

Figure 15 shows a prototype of the battery board design with two lithium polymer cells. The cells are coated in Kapton® to prevent the aluminium foil bag of the cell causing short circuits when the package bulges in vacuum. The cells are held onto the PCB using thermally conductive adhesive.

Figure 16 shows a picture of the Clyde Space CubeSat EPS. Note the aluminium PCB mount threaded stand-offs on to which the battery will be mounted to the EPS board.

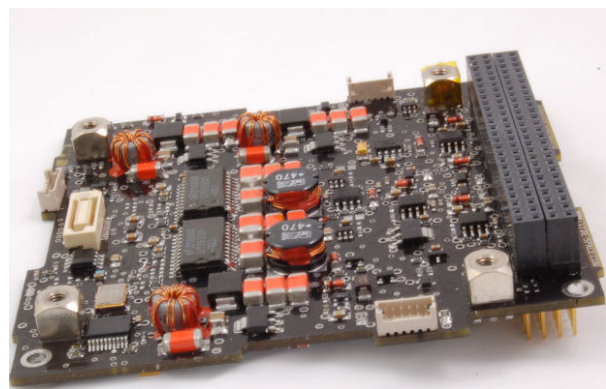


Figure 16 Clyde Space CubeSat Power board

Figure 17 shows the battery and EPS fully integrated with 2 lithium polymer batteries in parallel, providing approximately 20Whrs of capacity.

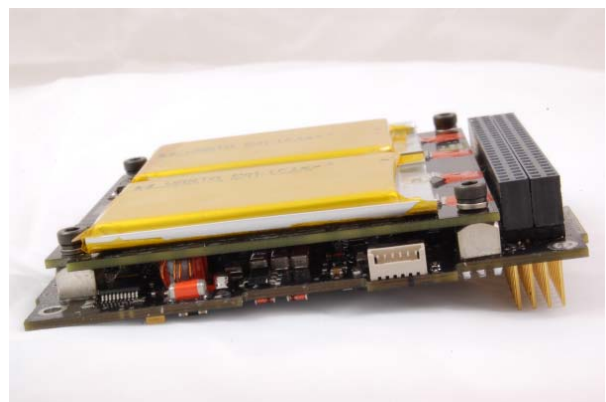


Figure 17 Clyde Space CubeSat Power board and integrated lithium polymer battery

With one battery integrated onto the EPS, the total height of the unit is 14mm from the EPS board surface; with two batteries this is 21mm. The mass of the EPS is 80g and the mass of one, two cell, 10Whr battery is 62g.

The complete system is extremely mass and volume efficient and is a perfect example of how lithium polymer technology can be utilized to maximize the use of internal spacecraft volume. In addition, through the use of PCB technology, the manufacturing costs can be greatly reduced; another winning factor for budget restricted small satellite missions.

CONCLUSIONS

The objective of the ESA study was to evaluate advanced lithium polymer cells for space applications. During the study, a wide range of space applications were assessed to determine whether there are actual advantages through the use of lithium polymer battery (LPB) and its geometric flexibility over the liquid electrolyte cell. Whereas the benefits to many applications were not obvious or significant enough to induce change, there were specific applications of LPBs that yield definite advantages over the use of liquid electrolyte cells:

- The geometric flexibility of LPB seems to be of most interest to spacecraft that are inherently volume limited, such as very small spacecraft (e.g. nanosatellites).
- In addition, the use of integrated power sources for miniature spacecraft such as Chipsats may be of specific interest to reduce production costs, size and mass.

Given the specialised nature and low production volume of battery supply to the space market, it is of no surprise that response to the manufacturer survey issued was poor. Out of 39 selected suppliers, only 10 companies responded with a willingness to participate in the study. From the results of the survey, 5 manufacturers were selected to participate in the tests performed at ESA.

These cells were evaluated under test and two of the five cells showed promising results for operation in space.

The study concluded that there are definite benefits to specific space applications through the use of Lithium polymer cell, most specifically in small satellite applications. As the technology is incorporated into miniature spacecraft and the life testing of the technology matures, it will be of interest to observe how the take up of this technology will progress in the space industry in general over the coming years.

The life tests demonstrated that Cell F has potential to be used on small spacecraft with mission durations of a year or more. Further tests are planned by Clyde Space in order to evaluate the conditions under which mission

durations of up to and above 5 years can be achieved. Reducing the DOD, charge and discharge rates should have a significant effect on the potential of the cell for longer duration missions.

With many CubeSat missions planning to use lithium polymer cells on future missions, taking advantage of the mass and volumetric efficiency of the technology, it will be interesting to monitor the performance of the cells over and beyond the planned mission durations. There is certainly scope for this technology to be adopted on other small satellite platforms in the near future.

Acknowledgments

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