Advances In Battery Technology Relevant For Planetary Probes

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ABSTRACT

This paper gives an overview of the advances in battery technology that have occurred in recent years, and are currently taking place, that are relevant for planetary probe missions. ABSL Space Products (ABSL) pioneered the current state of the art rechargeable battery technology, Lithium-ion, and has recently qualified a Lithium primary cell.

ABSL has supplied batteries for spacecraft destined to land on the planet Mars and a comet in deep space. Both of these missions drove unique battery requirements that were successfully solved by ABSL. Presently, ABSL is working on preliminary designs for batteries to power European and American planetary landers.

1. INTRODUCTION

ABSL has established the reputation as the industry leading supplier of rechargeable (secondary) battery technology utilizing the current state of the art: Lithium-ion. The first half of this paper explains the unique approach of ABSL of using commercial Lithium-ion cells, The Small-Cell Approach. The second half of the paper examines how ABSL is now able to offer cutting-edge primary cell technology, once more using commercially available cells.

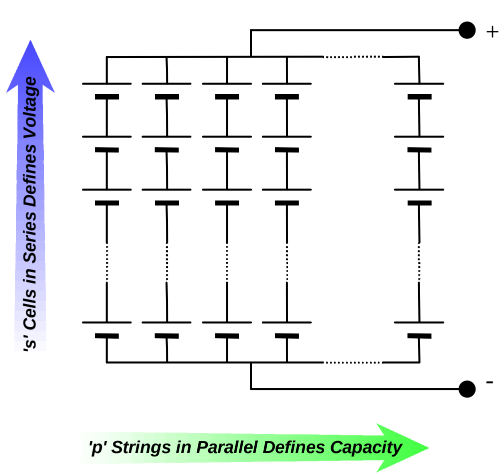

Fig 1 The ABSL Small-Cell battery configuration

2. THE ABSL SMALL-CELL APPROACH TO LITHIUM-ION

In the past, space batteries consisted of one or two strings of large capacity cells connected in series. This practice had been continued with advances in cell chemistries until the dawn of Lithium-ion. ABSL realized that there were huge benefits to the space industry in adopting smaller capacity Commercial Off The Shelf (COTS) Lithium-ion cells connected in a two-dimensional array as shown in Figure 1. ABSL term this concept the '***s-p***' topology. The battery voltage is determined by the number of cells connected in series ("s") and the battery capacity is determined by the number of such series "strings" connected in parallel ("p").

This unique utilization of small capacity cells arranged in arrays presents huge benefits for flexibility in battery configuration to meet capacity and volume layout to best meet mission demands. In the past (to optimize a battery for a particular program) the cost, risk and delay of a dedicated cell qualification program was necessary. However with ABSL concept by varying the "s" and "p" of the cell array, tailoring of battery performance became simpler and less costly.

The ABSL "Small-Cell" approach is similar in configuration to that of the Solar Array, and delivers two unique and invaluable benefits over large-cell battery options:

- ***Automatic Fault Tolerance***: - The in-built cell protection mechanisms, necessary to meet the safety demands of the consumer electronics market, ensure that a single-point failure in a cell leads to open circuit disconnection of a string. Combined with the small cell capacity used with the ABSL approach, this means almost negligible capacity reduction at battery level and no voltage level impact. The autonomous nature of protection and zero power dissipation deriving from ABSL proven approach are in strong contrast to dedicated cell by-pass electronics used in large cells battery systems. ABSL approach simplifies thermal design, and eliminates problems associated with component stress following activation. The result is an exceptional level of reliability and robustness.

- ***Full Capacity Flexibility: -*** Capacity can be easily fine-tuned by altering the number of parallel strings without the cost, risk and schedule implications of a cell qualification program. Thus, our customers have scope to modify requirements early in the battery program, as a result of system-level technical development, without substantial risk, program delay and cost increase.

- ***Battery Simplicity:*** - Customers have consistently lauded the benefits of our battery simplification from the elimination of cell balancing electronics (essential on traditional Large-Cell batteries) as described in [1] as this reduces the complexity and cost of the power system, returning benefits at both technical and programmatic level. The checkout of cell balancing software can be notoriously costly and time consuming. Furthermore, the reduction in the number of telemetry channels and absence of telecommand requirement for safe battery monitoring and operation allows other subsystems to benefit.

Overall, the reduced risk of imperfection through utilizing small cells from modern, state-of-the-art production, compared to the traditional 'small batch' approach with large cells, has proven extremely valuable to customers ranging from small satellite manufacturers to major primes and national/international space agencies. Today, ABSL has received battery contracts for more sixty spacecraft and launch vehicles using the Small-Cell concept.

3. UTILIZING COTS LITHIUM-ION CELLS FOR SPACE APPLICATIONS

The maturity of commercial products and the consistency of their build standard are of primary importance for the use of such components in long-term space applications The ABSL 18650HC cell (the heritage spacecraft cell that has successfully clocked over 2,500 cell years of space operation without failure) has been in production since 1992. The raw materials, procedures and processes used have remained consistent and unchanged since 1996, when this cell was first released to market. These will continue in production unchanged so that it is expected our next generation cells will be offered to space customers alongside this heritage cell. The consistency associated to COTS cells provides crucial advantages over small-batch production cells for space applications:

- Performance measurements between cells, and indeed batches of cells, exhibit a very high level of uniformity.
- Security of supply of a cell with the necessary technical specification is crucial for space projects that can span long time durations. Customers are assured by the fact that ABSL holds a rolling stock of cells to satisfy the demands of the space market for a number of years in the future.

The performance uniformity and quality of COTS cells that are produced in vast quantities on highly automated production lines has been exploited in the ABSL space battery product, with the resulting benefits of a decreased cost and complexity for our customers. These benefits are derived from removing the need for charge management electronics, traditionally employed to balance differences in individual large-cell space batteries. Such management systems are complicated requiring cell-level monitoring devices in addition to the charge control functionality itself.

ABSL procures large batches (tens of thousands) of cells direct from commercial manufacturers and performs a strict Lot Acceptance Test (LAT) to ensure that the batch is suitable for use in space flight. The LAT procedure was originally developed for the ABSL 18650HC in cooperation with ESA using a similar process that is used for employing commercial capacitors for space use.

Fig 2 COTS Cell LAT and Screening Process

The exact details of the LAT procedure are sensitive proprietary information but an overview is presented below:

- A random subset of batch cells is selected for LAT testing.
- The electrical properties of cells are measured to ensure performance is within pre set limits.
- A number of the subset sample cells are subject to destructive physical analysis. (DPA), during which mechanical and chemical testing of cell components is performed

The remainder of the subset is split into three groups for endurance, abuse and environmental test.

- Endurance testing ensures that, following accelerated life-test, cell calendar and cycle life are within pre-set limits.
- The abuse group of test ensures the correct functionality of the cell protection devices.
- During the environmental group of tests vibration testing is performed on several cells. Following this test some of the cells are subject to DPA whilst the rest undergo rapid thermal cycling. Following cycling the cell seal is tested for integrity.

It is essential to understand that for ABSL to deem a LAT testing successful each individual test must be passed. The failure of a single cell during one of the tests leads to rejection of the entire batch. Following successful LAT testing, each cell in the batch is individually electrically tested and screened using high precision equipment for performance validation against pre-set limits. Individual cell test results are stored electronically on ABSL Database and record-matched against individual cell bar-codes. Using this information, when a specific number of cells are required for a flight program, a unique (proprietary) matching algorithm is used to select the group of cells that present the most closely matched performance characteristics. It is the rigor and proven maturity of this ABSL proprietary LAT, screening and matching process that eliminates the need for charge management electronics as described in [2].

4. ABSL SECONDARY LANDER BATTERIES

ABSL has delivered Lithium-ion batteries for the British National Space Centre (BNSC) Beagle 2 Mars lander and the French National Space Agency (CNES) Philae lander which aims to land on Comet 67P/Churyumov-Gerasimenko. Both landers adopted ABSL Small-Cell batteries as it was the ideal solution to the need to pack a high energy density battery within a tight mass and volume budget.

The Philae lander actually carries two lander batteries built by ABSL although both are mechanically identical and carry the same cell, the ABSL 18650HC. A photograph of one of the lander batteries is shown in Figure 3 where it can be seen that fourteen cells have been sandwiched between Glass Re-enforced Plastic (GRP) plates given additional structural support via Aluminium cross bracing. The battery also carries a thermofoil heater bonded to the upper side of the top GRP plate.

Fig 3 A 7s2p Rosetta Battery

Figure 3 shows that the distribution of the cells within the battery was not uniform and was actually staggered. Using this arrangement, ABSL was able to reduce the footprint of the battery over our traditional designs where cells are uniformly distributed by approximately 19mm.

In line with the two spacecraft power buses on Philae, two different battery designs were built: 7s2p and 2s7p. The nominal voltage of the ABSL 18650HC cell is 3.5V so that the nominal voltage of the batteries are 7V and 24.5V. Table 1 gives further information on the key performance parameters of the two batteries.

Parameter	2s7p	7s2p
Max Voltage	8.4	29.4
Min Voltage	5.0	17.5
Capacity (Ah)	10.5	3.0
Mass (kg)	0.72	0.72
Height (mm)	71	71
Footprint (mm)	118.5	63.2

Table 1 Philae Battery Performance

On 2nd March 2004, the European Space Agency (ESA) spacecraft Rosetta was launched carrying the Philae lander. Both spacecraft are powered by ABSL batteries (although Rosetta's are more than ten times bigger) and are currently en route to dock with Comet 67P/Churyumov-Gerasimenko. This journey will take over ten years finally reaching the comet on May 2014 after multiple gravity assists from both

Mars and Earth. The spacecraft will then slow to enter orbit around the comet at which point the lander Philae will be released to descend to the comet surface where it will operate for a number of weeks taking images, sampling the comet soil, its atmosphere and the changes it undergoes as the nucleus approaches the Sun.

The most challenging part of the mission is the extended hibernation phase during the ten-year journey to the comet before operations commence. Although spacecraft checkout has shown that the batteries are operating nominally on Philae, the real test will start after more than ten years in the harsh environment of deep space.

The Beagle 2 lander required a battery that would support both the nominal night-time operations on the cold Martian surface but also the power loads that had to be supported during the landing phase. For instance, sharp pulse loads had to be supported during the parachute deployment phase.

The Beagle 2 spacecraft was very much a custom lander design and had to pack a large array of instruments and electronics into a package of a similar size and shape to a trash can lid as shown in Figure 4.

Fig 4 The Beagle 2 Lander

The space available for the battery was a 'kidney-shaped' cavity and, to make use of the odd shape, it made obvious sense to a battery made of small cells to minimize redundant space. The Beagle 2 battery is shown in Figure 5 and the pillars on the top of the battery actually formed part of the greater spacecraft structure.

Fig 5 The Beagle 2 Mars Lander Battery

The performance of the Beagle 2 battery is shown in Table 3. This battery did not employ a heater and instead, to be able to operate in the harsh conditions of the Martian night, used the heat generated naturally during discharge to lift battery temperature and lower internal resistance. Even though the battery was designed to use this self-heating effect, it was still expected to operate with cells at a temperature around -30°C. During ground testing, ABSL even performed survival tests that proved the battery could still be used after being subjected to conditions of -50°C.

Parameter	**6s9p**
Max Voltage	**25.2**
Min Voltage	**15.0**
Capacity (Ah)	**13.5**
Mass (kg)	**2.6**
Height (mm)	**66 (107 pillars)**
Footprint (mm)	**266x138 max**

Table 2 Beagle2 Battery Performance

On 2nd June 2003, the ESA Mars Express spacecraft was launched towards Mars carrying the Beagle 2 spacecraft. As with Rosetta and Philae, both lander and host spacecraft were powered by ABSL Lithium-ion batteries. After a six-month cruise phase, Mars Express has been in a highly elliptical inclined Martian orbit performing a host of scientific experiments. The spacecraft has operated even better than planned with a mission extension already granted. Battery performance has been in line with software predictions as described at [3].

Just before Mars Express performed thruster firings to enter orbit around Mars, Beagle 2 was jettisoned towards Mars (on Christmas Eve 2003). Prior to jettison, checkout of Beagle 2 was successful and all systems appeared to be functioning nominally. The mission design called for no further communication with Beagle 2 until the lander had successfully landed and deployed solar panels and the communications antenna. Unfortunately no signal was ever received from Beagle 2 and the reason for spacecraft loss remains unknown.

5. NEXT GENERATION LITHIUM-ION CELLS

ABSL lodged one of the original patents that allowed the commercialisation of Lithium-ion cell technology. As well providing an excellent revenue stream through various license and sub-license arrangements, it also cemented strong relationships with the leading commercial cell manufacturers that still exist today. Consequently, ABSL continually evaluates prototype COTS cells from around the world to assess their suitability for space applications. Importantly, due our presence in niche markets (such as space) we are not seen as a direct competitor but instead able to offer independent evaluation and advice.

In this way, ABSL has assembled a suite of Lithium-ion cells with exceptional performance for space applications. ABSL has also looked, wherever possible, to continue to utilize cells adopting the industry standard 18650 size (18mm diameter and 65mm high) so that existing space battery designs can be leveraged in a plug n play approach that minimizes Non Recurring Engineering (NRE) and hence battery cost.

There are two main drivers for performance in cells for space applications: energy density and power density. Energy density is basically a measure of the ability of a cell to store energy within a unit mass. For example, the ABSL 18650HC has a cell level energy density of 133Wh/kg. In contrast, at various levels of space qualification, ABSL has access to cells with energy densities ranging from 180Wh/kg to around 205Wh/kg.

These next-generation high energy density cells have the same dimensions as the ABSL 18650HC and so can be utilized in existing battery designs. It is therefore possible to accurately predict battery level energy density performance. In this way, ABSL can today provide batteries with an energy density in excess of 150Wh/kg and will soon be able batteries with an energy density approaching 180Wh/kg. It should be noted that these numbers include all parasitic mass (eg from wiring, connectors, structure etc).

The next generation of high energy density cells are already under lifetest and exhibit less degradation than the ABSL 18650HC. This means that batteries with these new cells could well be driven harder to higher Depth Of Discharge meaning that a lower Beginning Of Life (BOL) capacity is required - this further reduces the required battery mass.

Customers in both the USA and Europe are actively assessing these next generation cells for applications including planetary landers. In addition to high energy density, one cell also exhibits excellent low temperature performance with over 80% of nameplate capacity still available when subjected to capacity measurement at -40°C.

As already explained in the previous section, the surface exploration of Mars calls for operation in a harsh low temperature environment. Utilizing next generation Lithium-ion cells with their low temperature/low resistance electrolyte will be crucial for successful operation.

Recently, ABSL began to receive enquiries from a number of customers regarding the availability of high power density cells. Applications were emerging that required the delivery of high current pulses for short durations that were outside the scope of typical cells designed for high energy density.

In response to this need, ABSL last year qualified the ABSL 18650HR cell. This cell is now being used in a battery to power the Thrust Vector Control (TVC) system for the Korea Aerospace Research Institute (KARI) KSLV-1 program. This TVC battery will operate at a nominal voltage of 270V and is contains 168 ABSL 18650HR cells arranged in an 84s2p configuration.

Fig 6 The KSLV-1 ABSL 18650HR Based TVC Battery

Figure 6 shows a picture of the 84s2p battery. This battery was qualified for space in June 2006 following a full environmental qualification test program. The main risk area for ABSL during this qualification process was during thermal vacuum when the high voltage battery would be subjected to the conditions where critical Corona events can occur. The successful qualification showed that the design features incorporated by ABSL worked perfectly.

In addition to launch vehicles, ABSL has also received enquiries from customers interested in having a high rate capability on planetary lander spacecraft. Traditionally, surface mobility has been made possible using the traditional method of wheel and track drive. However, in order to extend the geographical zone of study, the use of hopping spacecraft is being actively explored. In this way, propulsion systems will be used to fly the spacecraft from one point of interest to another.

However, these propulsion systems required short bursts of high power. In this way the design drivers for the propulsion system can be very different from those of the rest of the spacecraft which require low-level loads over extended periods (such as night-time or crater operations which are shadowed).

For such applications, ABSL has traditionally offered customers two batteries: one employing the ABSL 18650HR cell and the other with a next generation high energy density cell. However, ABSL has performed internal research into the possibility of using a 'Hybrid' battery employing both high power and high energy density cells. Such a Hybrid would use the high energy density cells for the bulk of operations. However, when a high power demand occurs the voltage of these cells would drop below a threshold which would activate the high power cells to make up the required demand. Once this demand is over, the high energy density cells would once again take over.

Utilizing such a hybrid battery would reduce system level complexity as only a single set of interfaces (telemetry, charge control, PMAD etc) would be required. In addition there are also mass savings at battery level to be gained by using a single battery structure.

6. ABSL PRIMARY LANDER BATTERIES

In 2005, ABSL took our first contract to supply a primary battery for a space program, FOTON M3, from QinetiQ. FOTON M3 is the latest in a series of joint Russian and ESA science missions launching a capsule to perform science experiments in Low Earth Orbit (LEO) before returning to Earth after two weeks.

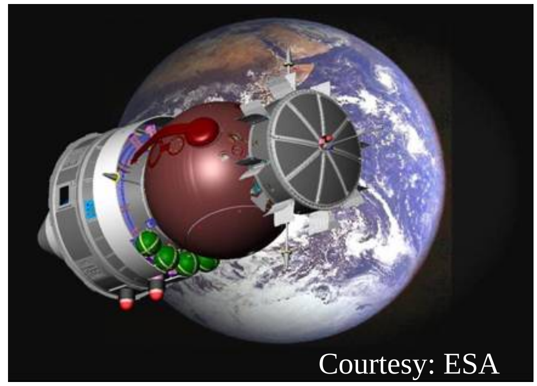

Fig 7 FOTON Capsule

Towards the end of the mission, as the capsule is commanded for the return to Earth, operators switch the power supply from the primary system and over to battery power. These batteries must then support the spacecraft during the descent until landing which is slowed by parachute and retro-rockets (activated by the battery). Following landing, the capsule switches to a low power emergency mode whilst the search for the vehicle by ground personnel is conducted.

This search can take from ten to twelve hours and during this period the battery must power essential systems such as the beacon transmitter. Due to the wide geographical area into which the capsule could fall, the battery might have to perform at temperatures as low as -20°C. As well as low temperature performance, in order to meet the mass budget for the capsule the battery must have an energy density in excess of 223Wh/kg.

ABSL was directed by QinetiQ to use a particular commercially available Lithium Sulphuryl Chloride DD cell. As reported in [4], QinetiQ performed a preliminary survey of commercially available primary cell technologies for the Mercury Surface Element (MSE) of the Bepi-Columbo mission. MSE was intended to spend a year on the ground before a 3.5year cruise phase to Mercury followed by seven days of surface operations.

Fig 8 DD Primary and 18650 Secondary cells

To perform science operations during the seven day period, a cell with a minimum energy density of 275Wh/kg was required. Additionally, the battery was needed to operate at cold temperatures down to -10°C. QinetiQ testing showed that the Lithium Sulphuryl Chloride cell was by far the best performing cell with a recorded energy density of 377Wh/kg at a temperature of 10degC (>480Wh/kg at 20°C and >500Wh/kg at 60°C). Following from the MSE work, QinetiQ realized that the same cell would be ideal for the FOTON M3 program.

The first part of the ABSL contract was to qualify the primary cell for space applications. A qualification program was executed on the cells including shock and vibration. Cells were successfully shock tested to 90g for 40ms and, in random vibration, withstood an input of $20g_{RMS}$. The cells were found to be exceptionally mechanically robust and therefore ideal for a planetary lander.

Fig 9 Primary Cells During Vibration Testing

The successful qualification of the primary cell allowed ABSL to begin formal design activities on the battery. To meet the needs of FOTON M3, 27 cells are connected in a 9s3p configuration. Figure 10 shows a CAD drawing of the battery and it should be clear that the basic battery design philosophy is very similar to our rechargeable secondary batteries.

Due to the very high energy density of the battery, safety is of paramount importance. Within the battery is fitted protection against short circuit via Positive Temperature Coefficient (PTC) devices that exhibit a large increase in resistance (reducing current flow) as temperature rises due to a high current short event. Also, primary cells must not be charged and so the battery is fitted with fuse and diode features to ensure that cells can only safely discharge.

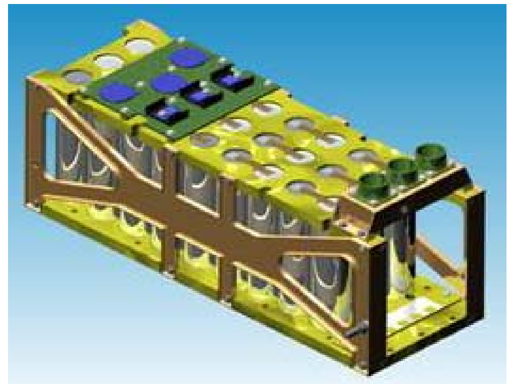

Fig 10 The 9s3p FOTON M3 Battery

It should be noted that this primary battery technology also holds great promise for high temperature applications, such as landing craft for Venus. The cell is rated to operate at temperatures as high as 90°C and ABSL is actively investigating whether, and how far, this temperature can be increased.

Despite the advances in rechargeable battery technologies for space applications, it is certain that the much higher energy density characteristics of primary cells will prove the technology of choice for some programs. This will probably remain particularly true for planetary landers where mass is absolutely critical and operations can take place over relatively short mission durations. However, for longer periods of operation and exploration the use of secondary batteries and solar arrays is mandatory.

7. CONCLUSION

ABSL has proven that the use of the Small-Cell concept has been of great gain to planetary probe missions. The flexibility of design is ideal for the custom nature of such missions where highly irregular battery envelopes can be the norm.

Batteries are available now that can offer battery level energy density over 150Wh/kg whilst being able to perform in the cold environments required for many planetary probes. It is also clear that the use of a combination of Lithium-ion high power and high energy density will be required as more complex missions are planned.

There will always be a need for primary batteries for one-off operational activities such as parachute deployment prior to touchdown. ABSL now has space qualified battery technology available so that a complete capability is now available.

8. ACKNOWLEDGEMENTS

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