

## The Use of Small Cell Lithium-Ion Batteries for Small Satellite Applications

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During solar eclipse, spacecraft rely on batteries to power all on-board electrical systems. Advances in battery technology have led to lighter products that, in turn, allow spacecraft to fly heavier and more capable payloads. AEA Technology has pioneered the current state of the art in the space community<sup>1</sup>: Lithium-ion battery technology.

Traditionally space batteries were composed of a single series connected string of cells. The cells are sized (in terms of capacity) according to mission requirements and so cell qualification programmes for individual missions are common. The small cell approach involves taking Commercially available Off The Shelf (COTS) Lithium-ion cells, qualifying the design for space, and using a strict Lot Acceptance Test (LAT) process to ensure the continued quality of cell batches for space flight.

The technology has proved to be ideal for small satellite missions due to the low-cost of small cell battery designs compared to rival large cell energy storage solutions. The maturity of the design concept, and therefore low risk of utilisation, allows Protoflight programmes to be adopted for all but the most specialised of applications. A protoflight programme reduces cost due to the lack of need for a dedicated qualification battery unit and test programme.

### 1. LITHIUM-ION BATTERY TECHNOLOGY

Space applications require lightweight technology due to the finite lift capacity of Launch Vehicles. Consequently, in order to carry the maximum quantity and quality of payload as possible, equipment that maintains the general health and maintenance of spacecraft must be as light as possible.

Batteries make up a significant portion of the dry mass of spacecraft and are mission critical items that provide electrical power for all spacecraft systems during periods of solar array shadowing. Solar array shadowing occurs naturally during missions due to eclipses of the sun by various heavenly bodies, most commonly the Earth and Moon.

This need for reduced mass in the space community has been reflected in terrestrial applications where the trend has been shrinking electronic equipment. Good examples are portable items such as mobile phones and laptop computers. To satisfy this demand, alternative and more advanced battery chemistries were employed. The reduction in mass and volume corresponding to the transgression to new battery chemistries can be seen in Figure 1.

Figure 1 demonstrates the two most important benefits of Lithium-ion battery technology:

- High gravimetric energy density (mass)

- High volumetric energy density (volume)

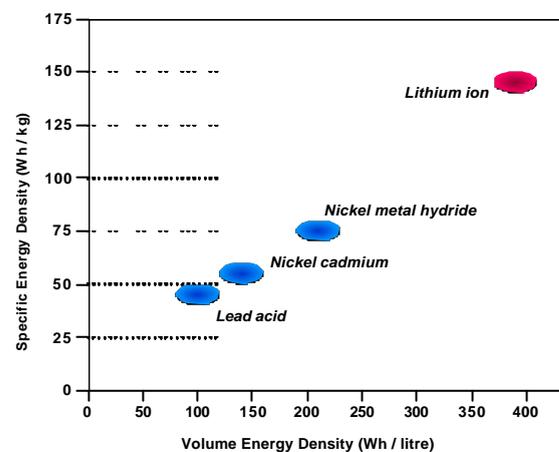


Figure 1 Battery Chemistry Comparisons

The adoption of Lithium-ion decreases operational complexity and can reduce Power Subsystem functionality requirements via:

- The lack of need to recharge. This also helps avoid a potentially hazardous in-orbit operation.
- The lack of need to trickle charge. Simple charge algorithms and simple state of charge measurement.

When discharged to low states of charge, the ageing effects on Lithium-ion cells are negligible.

This makes the long-term storage of cells possible prior to allocation for a mission.

AEA Technology was at the forefront of the development of Lithium-ion technology and, in the 1970's, logged a patent protecting a revolutionary breakthrough in cathode technology. This technology was licensed to SONY and implemented during the 1990's boom in portable electronic equipment. This demand could not be satisfied by SONY so that the technology was sub-licensed to all major Japanese manufacturers. This was a lucrative arrangement for both AEA Technology and SONY and resulted in a very close relationship that still exists today.

Traditionally, the space community takes longer to adopt new technologies than for terrestrial applications. AEA Technology have been active in the space business since the 1960's and were keen to bring this new technology (with its obvious advantages over existing space battery chemistries) to the space market. The unique relationship enjoyed by AEA Technology and SONY offered an opportunity, not just to bring Lithium-ion battery technology to the space market, but also to exploit the benefits of using COTS small cells.

## 2. THE CHOICE OF SMALL CELL

AEA Technology has traditionally used the SONY 18650HC (Hard Carbon) cell for space battery applications. There are several other candidate small cells available that AEA Technology may use in the future to complement or replace the range of batteries offered using the SONY 18650HC cell. Such cells could offer immediate improvements in terms of:

- Increased capacity leading to large increases in battery level energy density reducing battery mass with the benefits explained in section 1.
- The SONY 18650HC cell typically delivers currents up to 1.5A but can satisfy short-term peak loads. This rating is usually expressed as the cell 'C-rate', the ratio of deliverable current over capacity. The SONY 18650HC cell has a capacity of 1.5Ah and so a C-rate of 1. Other cells offer higher C-rates that could be used to support high-power, peaky payloads (such as Synthetic Aperture RADAR).



**Figure 2 The SONY 18650HC Cell**

However, as well as capacity and power, a third cell performance characteristic is crucial in judging suitability for a space mission – ageing. In contrast to terrestrial applications where batteries (and even the powered devices themselves) are replaced within a short lifetime, space applications can undergo thousands of charge/discharge cycles over mission durations of more than five and even ten years. In order to meet battery requirements at End Of Life (EOL), the battery must have low degradation levels in terms of calendar and cycle life.

AEA Technology has invested heavily in characterising the long-term performance characteristics of the SONY 18650HC cell. Ongoing lifetests have recently passed the 40-million cell-hour point at various Depths Of Discharge (DOD), temperatures and undergoing charge/discharge profiles simulating various space mission types (LEO, GEO, Interplanetary...). It is this data that enables AEA Technology to make such accurate future predictions, vital to ensure EOL power requirements are met.

Currently, the SONY 18650HC cell is by far the best candidate commercial cell in terms of calendar and cycle life. To put this superiority into perspective, typical commercial cells are designed for a lifetime of 500 to 1,000 charge/discharge cycles. Low Earth Orbit spacecraft undergo around 5,000 cycles per year and the SONY 18650HC cell has, to date, been selected for LEO missions with target durations of 6.5 years and a GEO mission of 10-year duration. As lifetesting extends the confidence in the lifetime of the cell, AEA Technology expects that mission durations will continue to be extended.

Parameter	Value
SONY Cell Type	18650HC
Dimensions	∅ 18 mm x 65 mm
Mass	42 grams
Maximum Cell Voltage	4.2 V
Minimum Cell Voltage	2.5 V
Nameplate Cell Capacity	1.5 Ah
Nameplate Cell Energy	5.4 Wh

**Figure 3 SONY 18650HC Characteristics**

Important for using commercial products in the long-term space applications is the maturity of the product and also that build standards are not changed. The SONY 18650HC cell has been in production since 1992 and the raw materials, procedures and processes have remained constant since 1996. This consistency is a crucial advantage in employing the SONY 18650HC cell for space use and has two important results:

- 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 further assured by the fact that AEA Technology 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 has been exploited in the AEA Technology space battery product by the decreased cost and complexity of not requiring charge management electronics. Traditionally, differences in cell capacities within space batteries have forced the use of individual charge management for each cell in the battery. Such management systems are complicated requiring cell-level monitoring devices in addition to the charge control functionality itself. Indeed, in a recent large cell battery development, it was revealed the development cost of the charge management system was greater than that of the rest of the battery.

AEA Technology procures SONY 18650HC cells direct from SONY and performs a strict Lot Acceptance Test (LAT) to ensure that the batch is suitable for use for spaceflight. This LAT procedure was developed with ESA using a similar process that is used for employing commercial capacitors for space use. The measured SONY 18650HC cell capacity in a single batch typically follows a normal distribution with a standard deviation of around 6mAh, i.e. less than 0.4%.

The exact details of the LAT procedure is the proprietary information of AEA Technology but as an overview:

- A random subset of cells from the batch is selected for LAT test.
- Electrical properties of all of these cells are measured to ensure performance is within limit.
- A number of the subset is subject to destructive physical analysis. Mechanical and chemical testing of cell components is then performed (DPA).
- The remainder of the subset are split into three groups for endurance, abuse and environmental test.
- Endurance testing ensures that, following accelerated life-test, cell calendar and cycle life is within limit.
- The abuse group of test ensures the correct functionality of the cell protection devices.
- The environmental group performs vibration testing of the cell. 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.



**Figure 4 Cell Destructive Physical Analysis**

It is essential to understand that each test must be passed in order for a successful LAT. The failure of one cell during one of the tests leads to rejection of the entire batch of cells.

Following successful LAT testing, each cell in the batch is individually electrically tested using high precision equipment. The performance of each cell is checked to ensure that performance is within limits. The individual results for each barcoded cell obtained from this Screening process are stored electronically on an AEA Technology database.



**Figure 5 – High-volume cell Screening**

Using this information, when a specific number of cells are required for a particular flight programme, a unique matching algorithm is used to select the group of cells that have the most closely matched performance characteristics. It is this LAT, screening and matching process ensures that flight cells do not require charge management electronics.

AEA Technology has successfully pioneered the use of commercial cells for spaceflight. In the future it is expected that a range of commercial cells will be offered so that the optimal cell (in terms of cycle life, capacity, power capability) can be selected on a mission-by-mission basis. It has now been proved that using commercial cells for spaceflight is no different to other components that have been handled using this approach for many years.

### 3. ALTERNATIVE BATTERY TOPOLOGIES

Traditionally for spacecraft, Nickel Cadmium and Nickel Hydrogen cells were connected in a single series string. This approach is shown in Figure 6 and has three main drawbacks:

**Reliability:** A single point failure within a string of cells leads to a large step loss in capacity (cell short circuit) or loss of the battery (cell open circuit).

**Cost/ Parasitic Mass:** Battery capacity requirements vary from mission to mission so that a fresh, qualified cell design is generally required. The cost of designing and qualifying a new cell design can be considerable. For occasions where qualified cell designs could be used for a new mission, it was found that considerable excess mass had to be flown due to cell oversize.

**Complexity:** To overcome the problem of battery loss following an open circuit cell failure, cell bypass electronics had to be employed. Additionally, small batches of space-qualified cells vary in capacity due to slight manufacturing differences. As a result, charge-balancing electronics must be used to ensure that full

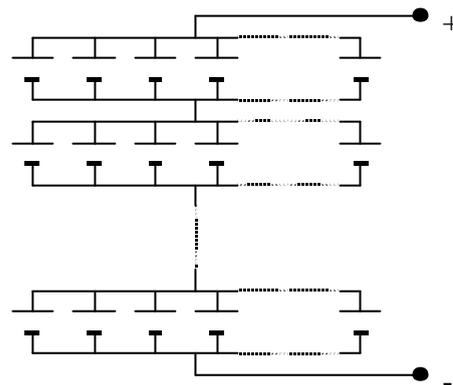
operational capability is used. Cell balancing and bypass electronics add complexity, cost and mass to the overall battery system.



**Figure 6 Single Series String Battery Topology**

AEA Technology alleviated the need for individual cell charge and protection electronics by connecting a large number of highly uniform small cells incorporating protection devices at cell-level. In this way, battery level complexity is reduced by protection functionality being provided at cell level and charge management at battery level only using the terminal voltage for control.

There are two alternative topologies for connecting two-dimensional arrays of cells. These are the p-s topology shown in Figure 7 and the s-p topology shown in Figure 8. In the figures, s and p refer to the number of cells or blocks of cells connected in series or parallel respectively. In both topologies, the number s determines the battery voltage and p determines the battery capacity.



**Figure 7 'p-s' Battery Topology**

Considering the effect of cell failures in the p-s topology:

- In the event of an open-circuit failure, bypass circuitry is required to pass current around the block containing the failed cell to avoid overcharging the other cells in the block.
- In the event of a closed circuit failure, an entire block must be disconnected via a bypass device otherwise the block containing the failed cell will be lost.

Bypass functionality increases the complexity of cell and block connection. Therefore, internal cell protection devices cannot perform the function

Considering the effect of cell failures in the s-p topology:

- In the event of an open-circuit cell failure a string of cells is lost. Importantly, for a small cell, the loss in capacity is relatively small compared to in a large cell battery where the effect is unacceptable.
- In the event of a closed-circuit failure, during charge the other cells in that string become overcharged. If the cells contain an internal protection device causing the cell to fail open-circuit during excessive overcharge then any closed-circuit failure eventually leads to an open-circuit failure and the loss of a single string as before.

It is clear that using a small cell with internal protection devices arranged in the sp topology allows battery protection electronics to be omitted reducing complexity and cost.

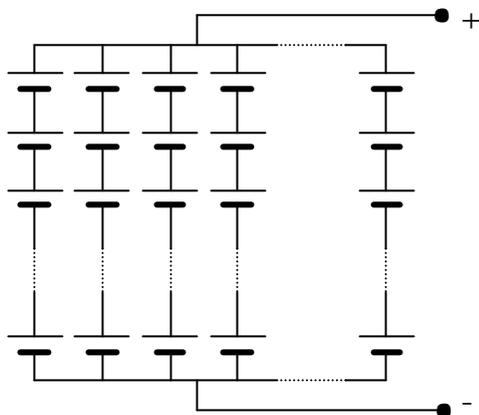


Figure 8 's-p' Battery Topology

#### 4. CELL PROTECTION DEVICES

The SONY 18650HC cell is the safest Lithium-ion cell available due to a number of built-in features that have been included for the consumer market. These features improve battery-level reliability and are essential to allow the cell to be used in the s-p topology without battery-level protection electronics.

The most important benefit of these features for spacecraft applications is that they virtually guarantee that any single cell will fail open circuit. Consequently, as explained in section 3, any credible single-point failures leads to the loss of a series string. Such a loss represents a small loss in overall battery capacity that can be overcome through contingency in the initial battery sizing.



Figure 9 SONY 18650HC Cell (courtesy SONY)

The protection features of the SONY 18650HC cell are shown in Figure 9 and are described in the following paragraphs.

**Over-charge Protection Mechanism** - If the cell is overcharged beyond 4.8 V (approximately 200% SOC) a chemical breakdown within the cell leads to gas generation and an increase in cell internal pressure. The pressure causes an internal disk to bow and physically break an electrical connection within the cell. This disconnect protection mechanism is not reversible and constitutes an open-circuit failure of the cell.

**Shut-down separator** - The separating layer between the anode and cathode is a microporous Polyethylene separator. In the event of a very fast overcharge, or other independent thermal event, where the cell temperature exceeds 0degC, the separator melts and prevents the flow of ions, thereby halting the reaction via an open-circuit cell failure.

**Positive Temperature Coefficient Polyswitch** - The Positive Temperature Coefficient (PTC) polyswitch protects the cell against thermal damage to the cell arising from very long-duration high-current discharges. During an excessive discharge, heat is generated in the PTC switch and this causes its resistance to increase sharply, reducing the current flow to a steady state value of about 1C. The PTC switch cools once the current has returned to normal, and its resistance will return to the normal low-level. The PTC operates on a time scale of one to two seconds, hence the cell's capability in delivering high-currents for duration of less than one second to blow fuses is not impacted.

**Cell Controlled Vent** - A controlled vent is unlikely to occur even under extreme fault conditions in the space environment. This device is required to meet safety requirements for consumer products where such scenarios as controlled venting during fires are required. In such a situation, the cell internal

pressure will rise regardless of the burst-disk operation. If the cell internal pressure reaches 14 bar, the controlled vent operates to alleviate the danger of an explosion. For space applications this feature has only been considered for manned space applications.

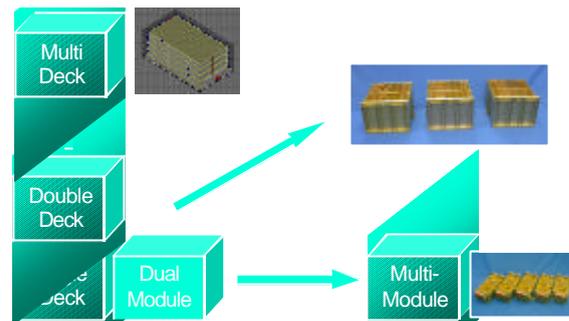
## 5. FLEXIBILITY AND SCALABILITY

The configuration of the  $s-p$  topology means that the number of cells connected in series ( $s$ ) in each string defines the terminal voltage of the battery. The battery End Of Charge (EOC) voltage will therefore be  $4.2V$  times  $s$  and similarly the minimum battery voltage (at 0% state of charge) will be  $2.5V$  times  $s$ . The number of parallel-connected strings ( $p$ ) determines the battery capacity. The nameplate battery capacity is  $1.5Ah$  times  $p$  and the nameplate battery energy is  $5.4Wh$  times  $s$  times  $p$ .

The small increment in capacity as  $p$  is increased or decreased means that battery capacity can be fine-tuned optimising capacity against mass. With the corresponding flexibility in voltage range, the AEA Technology space battery concept is versatile across the spectrum of possible battery requirements. Customers have found the following benefits of scalability

- Optimising the cell configuration minimises battery mass by minimising the amount of unused capacity to a degree equal to the (small) size of an individual cell.
- In the event of mission creep, battery requirements and hence battery size can be adapted with minimal cost and schedule impact.
- Particular missions call for especially stringent reliability requirements. This can be simply met by adding extra strings to allow for a specific number of cell failures during life.

Splitting batteries into a number of identical units instead of a single large module has proved advantageous in the space industry. AEA Technology has taken this 'horizontal' modularity a stage further with 'multi-deck batteries'. Multi deck batteries employ trays of cells stacked vertically to give 'vertical modularity'. The key advantage to customers of multi-decking is that the footprint is reduced compared to single deck batteries.



**Figure 10 – Horizontal and vertical modularity**

AEA Technology has employed both horizontal and/or vertical modularity on different space battery programmes. Adopting modular batteries has given customers the following system level benefits:

- Mission creep can be accommodated by adding modules without the need for any battery design changes. This feature has allowed system level problems to be absorbed at battery level at a low-cost and with the minimum schedule delay.
- Space programmes often choose to procure flight spare units to alleviate schedule risk in the event of handling errors during Assembly, Integration and Test. Modular batteries can offer a low-cost spare solution, as a full suite of modules is not usually required.
- Customers have appreciated the opportunity to mass-balance (especially on spin-stabilised spacecraft) by spreading modules across the spacecraft.
- Spacecraft typically have crowded floor maps so that it is often easier to accommodate a number of small battery modules than a single large entity.
- System level risk analyses are often eased, as anomalies pertaining to a specific area of a spacecraft are less likely to affect battery performance if the battery is not situated in a single area. For example, if a thermal anomaly leaves a portion of the spacecraft unusually hot, only a fraction of the battery may encounter the environment.

The AEA Technology space battery product offers an unrivalled level of flexibility across the full range of possible requirements. The availability of qualified battery designs now means that a range of modular batteries can be produced under low-cost build to print programmes. The satisfaction of AEA Technology is reflected in the way that many have chosen to enter long-term supply agreements.

## 6. BATTERY CONSTRUCTION

Batteries for small satellites have been in the small and medium range in the traditional AEA Technology classification description. The overview of the construction techniques employed in small and medium size batteries is discussed. The emphasis is to demonstrate the maturity and simplicity of the design. For completeness, this section also contains limited information on larger batteries.

### Small Battery Designs

Small spacecraft often require customised designs to fit into irregular cavities. A good example of such a battery was that built for the BEAGLE 2 (carried on the ESA Mars Express spacecraft) Mars lander programme. As shown in Figure 11, the mechanical design of the battery was unique as it had to fit in the crowded confines of the probe. In addition the thermal design was challenging due to the natural warming of the cells during discharge in the Martian night being used to act as a general spacecraft level heater. The BEAGLE 2 battery was 6s9p in configuration and has a mass of 2.6kg.



**Figure 11 – The BEAGLE 2 Battery**

In spite of the typically custom nature of batteries built by AEA Technology for small satellites a general construction has evolved that was first employed on the RoLand (the lander on the ESA Rosetta mission) programme. This design approach has since been developed further on both the NASA ST5 small satellite programme and Nanosat-1 project for INTA. The RoLand, ST5 and Nanosat battery module configurations were 7s2p, 2s6p and 6s2p respectively.



**Figure 12 The RoLand, ST-5 and Nanosat-1 Batteries**

Figure 12 demonstrates how AEA Technology employ a glass fibre reinforced plastic (GFRP-TUFNOL 10G) to isolate the cells and take the structural load. This is an isotropic high-strength electrical isolator that can be procured in sheet stock. This material is machined with counter bored holes into which the cells are bonded. The cells are glued in using REDUX adhesive for a good thermal and structural joint. The tray assembly, comprising the cells and upper and lower GFRP plates is highly rigid; with the GFRP giving a high bending resistance analogous to the outer faces on a honeycomb panel.

Once the cells are glued into the trays, the electrical connections between the cells can be made. Each of the cells is reversed in orientation so that adjacent cells in a string maybe interconnected with a short length of nickel shim stock. The interconnections are pre-formed, to provide stress relief, and welded with a robotic spot welder. Each cell connection has four separate spot welds, for redundancy. Any single spot weld provides an adequate electrical and structural connection.

The mechanical interface is through the lower GFRP tray, and this is directly secured to the battery mounting base-plate either via heli-coiled threaded holes or clearance holes. In a small battery, this simple arrangement is sufficient to ensure that an adequate thermal uniformity is achieved. To provide shear rigidity to the assembled tray, we add cross bracing stamped from thin aluminium sheets. This typically gives the structure a natural frequency of around 800Hz.

The upper GFRP tray provides a good location for a thermofoil heater. This is a feature that AEA Technology include in batteries if thermal analysis indicates the need for active thermal control.

The small battery concept has been further refined following the recognition of three common bus voltages used in small satellites: 28V 14V and 7V nominal. Such bus voltages call for either 2s, 4s or 8s battery designs. AEA Technology has specifically developed a 2s/4s/8s building block for a small satellite modular battery. The block can be configured as a 2s4p, 4s2p or 8s1p and multiple blocks connected to build up a modular battery.



**Figure 13 The NASA Ground Test and Saudisat-1 Batteries**

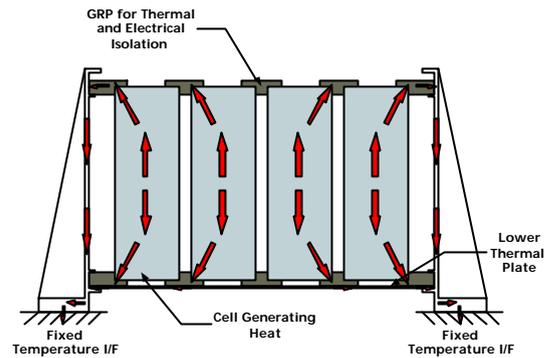
This battery differs from all other AEA Technology battery designs as cells are mounted on their sides instead of upright. In addition the battery is mounted to the spacecraft using bolts driven up through the spacecraft structure into the bottom of the battery. This battery design has a very robust mechanical design with a natural frequency in excess of 2000Hz.

Energy density of small batteries is around 100Wh/kg that is lower than in larger batteries due to parasitic (particularly structural) mass playing a larger proportion of battery mass compared to the cells themselves. NASA has purchased 4s2p versions of this battery for ground test purposes and KACST has purchased 2s4p versions to fly on the Saudisat 1 series of four satellites.

#### Medium Size Batteries Design

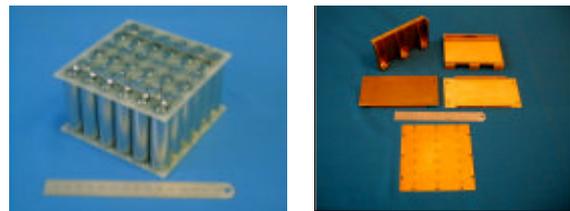
With medium sized batteries, the s-p cell array is much more obvious. The assembly of the trays follows the construction principles described in the last section, but with the cells arranged in a regular rectangular array. In larger modules, more consideration must be given to the thermal design. To achieve the design goals, the cell tray assembly must be housed in a more substantial metallic housing.

The walls that run parallel to the string direction provide the conduction path to the module feet. The heat generated by cells during discharge travels across the strings, hence the centre string is the hottest. The walls that run perpendicular to the strings, and close the box, are thinner and do not have feet. They do not participate in the thermal design but they do provide shear rigidity to the structure. The heat flow is largely one-dimensional across the string direction as shown in Figure 14.



**Figure 14 Battery heatflow**

In our standard product, the strings are connected in parallel via a bus-bar and the power connection is via a single positive and negative terminal or a connector. For the ESA PROBA battery design shown in Figures 15 and 16, the connector is mounted on the sidewalls, above the plane of the battery, as the footprint area is usually at more of a premium than height. The ESA PROBA battery was 6s6p with a mass of 1.9kg.



**Figure 15 – PROBA battery cellblock and piece parts**

The standard medium-size battery product has a specific energy of the order of 110 Wh/kg and natural frequency in excess of 750Hz.



**Figure 16 – The final PROBA battery**

#### Large Battery Design

The largest battery module designed, built and qualified to date is the 8s52p ESA GOCE battery. For such large single-deck modules, the cellblock assembly is split, in the case of the GOCE module, between two 8s16p block and a single 8s20p block.

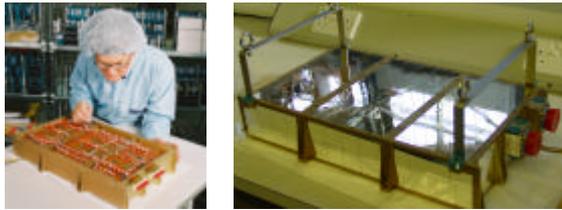


Figure 17 – ESA GOCE Battery

The GOCE battery presented considerable design challenges<sup>2</sup>. Situated on the very front of the spacecraft, and therefore at high risk from LEO orbital debris, a thick protection shield has to be employed. In addition, the battery was housed on the outside of the spacecraft directly over a high Power Distribution Unit (PDU). This aspect complicated the thermal design as, instead of dumping a few watts of heat from the cells, several hundred watts of heat had to be transferred from the PDU through the battery and radiated into space via optical solar radiators.

With large battery designs, as the module size increases, footprint can become very important. For such space applications, AEA Technology has developed multiple tray designs, with trays of cells stacked on top of each other to keep the form factor closer to a cube.

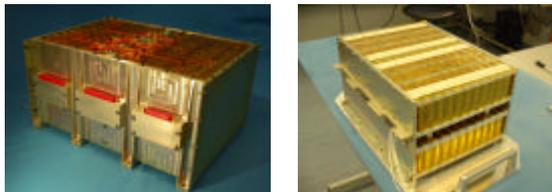


Figure 18 – ESA Cryosat battery

The thermal design principle applied to the medium modules is still applicable to multi-deck designs although the one-dimensional heat flow is now occurring in parallel in multiple trays<sup>3</sup>. The thermal conductance of the sidewalls is high and a thermal plate is situated between double decks to ensure that the average temperature differential between the cell trays is less than a couple of degrees. The ESA Cryosat battery shown in Figure 18 is 8s44p (mass 16.8kg) and will be the first AEA Technology multi-deck battery to fly (in 2004).

In multi-deck designs, the sidewalls also perform a more demanding structural task. Therefore, such batteries carry tapered ribs to increase the resistance to sway under lateral vibration loads. This mode provides the lowest natural frequency and we have measured it to be >500 Hz in our two-tray designs.

## 7. Battery Sizing

AEA Technology employs a battery sizing procedure for space programmes that enjoys an excellent reputation for accuracy, transparency and versatility in the space industry. This process relies on two resources developed by, and uniquely available to, AEA Technology:

- Over 40 million cell-hours of SONY 18650HC cell life-test data for long-term performance prediction.
- The Battery Electrical Analysis Software Tool (**BEAST**) to individually and precisely model Beginning of Life (BOL) and EOL performance for each mission.

AEA Technology realised early in the programme the importance of customer confidence in the long-term performance of our battery product, particularly for the high-reliability demanded by the space industry. It was therefore vital to be able to make accurate long-term Lithium-ion battery performance predictions.

The wealth of AEA Technology performance test data has been used to extend our theoretical knowledge of cell characteristics and to produce our **BEAST** software package<sup>4</sup>. Indeed, ongoing cell characterisation work and new life-test data means that the model is periodically refined. Consequently, the next software iteration **BEAST2004** will be the sixth version since the birth of the programme. The software has proved invaluable in speeding up and reducing costs in the design process as requirement changes can be quickly processed to update the battery size.

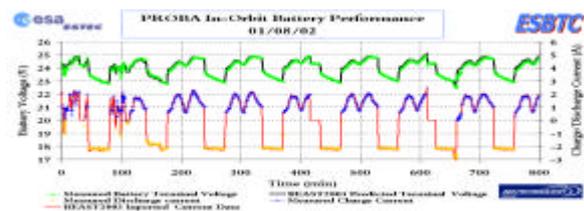


Figure 19 - Comparison of BEAST Simulated and actual in-orbit Battery Performance

One benefit of the strong relationship that AEA Technology has built up with ESA over a number of successful battery programmes is access to in-orbit battery telemetry from the ESA PROBA spacecraft that has been on-orbit for more than 2 years. This data has been used to validate the accuracy of **BEAST** and Figure 19 shows the high level of accuracy achieved by the AEA Technology simulations. The green line is actual terminal voltage telemetry from PROBA whilst the black line shows the predicted terminal voltage from **BEAST**. The accuracy of the software gives

customers a high degree of confidence in the performance of our batteries and allows margin levels to be easily inspected.

The simulations performed using **BEAST** form a cornerstone of battery proposals demonstrating that the proposed battery designs can be safely used for particular applications. AEA Technology encourages customers to utilise **BEAST** themselves in the interests of developing long-term working relationships. Customers have said that two valuable uses of the software are that **BEAST** can be utilised during ground test and in flight in order to check nominal battery performance under mission specific conditions.

AEA Technology has invested heavily in a programme to test the long-term performance of batteries under space mission representative conditions. Batteries undergo charge/discharge cycles indicative of LEO, GEO and interplanetary mission conditions at a range of temperatures. Regular battery capacity and internal resistance measurements are taken to chart natural degradation effects. AEA Technology has now accumulated over 40 million hours of life-test data that allows unparalleled prediction of long-term battery performance.

Capacity fade is a graceful, repeatable and most importantly predictable feature of Lithium-ion battery technology. The life-test pool has been key in the success of the AEA Technology Lithium-ion battery programme as customers can check for themselves that predicted mission End of Life (EOL) battery capacity will be as predicted during sizing analysis.

## 8. Qualified Battery Modules

Small satellite programmes generally carry budget restrictions so that the use of low-cost off the shelf equipment is strongly encouraged. Batteries have traditionally been an item that can demand a significant portion of a programme budget. The vast number of battery designs that AEA Technology now has available, coupled with the ability to use **BEAST** to check that an existing battery configuration can meet the requirements of a new mission, means that off the shelf space qualified Lithium-ion batteries are now available.

Significantly, existing battery designs can be electrically reconfigured with a low amount of non-recurring engineering. For example, the 8s10p battery design qualified for the CNES Microsat programme could easily be reconfigured as a 10s8p or 4s20p module. Taking the versatility further in modular batteries means that standard qualified

designs are either immediately usable or easily adaptable to new missions.

Figure 20 demonstrates the range of available battery designs. To allow for the wiring configuration flexibility, instead of the s-p configuration being given the cell array dimensions are given.

Cell Array	Module Mass (kg)	Number Of decks
4x2	0.4	2
6x2	0.6	1
7x2	0.7	1
6x6	1.9	1
6x4	2.4	1
6x9	2.6	1
6x11	3.3	1
8x10	4	1
6x16	4.7	1
10x30	5.3	1
8x16	6.6	1
6x24	7	1
10x28	14	1
12x24	14.4	2
8x44	16.8	2
8x52	25.4	1

Figure 20 – Qualified Battery Designs

## 9. Acknowledgements

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