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Small Cell Lithium-Ion Batteries: The Responsive Solution for Space Energy Storage

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SMALL CELL LITHIUM-ION BATTERIES: THE RESPONSIVE SOLUTION FOR SPACE ENERGY STORAGE

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ABSTRACT

During a 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 carry heavier and more capable payloads. AEA Technology has pioneered the current state of the art in the space community: 'small-cell' Lithium-ion battery technology. This paper focuses on the direct applicability, and benefits, of this approach to Responsive Space.

Traditionally, space batteries consisted of a single series connected string of 'large cells'. Large cells are sized (in terms of capacity) according to mission requirements, meaning that cell qualification programmes for individual missions are common. The small cell approach involves taking Commercially available Off The Shelf (COTS) Lithium-ion cells, qualifying them for space, and using a strict batch test and screening process to ensure the continued quality of cell batches for space flight. This obviates the need for cell qualification for each programme.

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.

RESPONSIVE SPACE: SPACECRAFT COMPONENT REQUIREMENTS

Encouraged by the Department of Defense, manysections of the United States military space community wish to achieve faster mission response and turnaround, reduced life-cycle mission costs and more streamlined programme execution. Successful achievement of these goals will enable quick-reaction, tailored systems designed to meet the immediate needs of warfighters.

The Responsive Space Conference focuses on the specific challenges that must be overcome to facilitate the "the return of data from space returned within hour of an identified need"[1]. One objective of the 3rd Responsive Space Conference, for which this paper has been produced, is to examine the present responsiveness of space system components in this context.

Launch vehicles require energy storage devices to power on-board systems such as thrust vector control, avionics, pyrotechnics and self-destruct system. The vast majority of spacecraft (except missions powered by radioisotope thermoelectric generators) receive electrical power during periods of solar array shadowing (due to orbital effects) from batteries. Thus, batteries are a mission critical item since their malfunction would lead to failure to reach orbit or the inability to use a spacecraft during eclipse (almost 40% of the time in Low Earth Orbit).

To meet the needs of Responsive Space, spacecraft and launch vehicle batteries must be able to exhibit the following features:

- Reduced unit lead-time. In fact, to meet the end goals of Responsive Space, it must be possible to 'stock-pile' flight batteries for extended periods. Further, the time required to make batteries flight ready must be in the order of only a few hours.

- Continued high reliability whilst reducing non-recurring and recurring engineering costs.
- Batteries must be simple to operate. The importance of this feature should not be overlooked, as rapid pre-launch checkout and minimal on-orbit housekeeping are essential for mission level simplification.

This paper examines the potential of both the 'small-cell' and 'large-cell' Lithium-ion approach to meet the goals of Responsive Space.

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 possible quantity and quality of payload equipment that maintains the general health and safety of spacecraft and launch vehicles must be as light as possible. Batteries make up a significant portion of the dry mass of such systems, leading users to seek ever-lighter energy storage technologies.

This need for reduced mass by the space community has matched a similar demand in terrestrial applications. Good examples are portable items such as mobile phones and laptop computers. To satisfy this demand, alternative and more advanced battery chemistries have been employed. The most common rechargeable battery chemistry utilised is Lithium-ion. Due to the requirement for extreme reliability, the take-up of new battery chemistries takes longer in the space community. In fact, the first spacecraft powered by a rechargeable Lithium-ion battery, PROBA, was not launched until 2001[2].

The reduction in mass and volume corresponding to the progression to new battery chemistries can be seen in Figure 1. This graph demonstrates the two most important benefits of Lithium-ion battery technology for space applications:

- High gravimetric energy density that enables more payload mass to be carried on both launch vehicles and spacecraft
- High volumetric energy density that reduces the amount of floor space that batteries require for accommodation. This allows a greater degree of flexibility for system design and, again, the chance to accommodate increased payload.

Although the operational simplicity of Lithium-ion has been a secondary factor to Lithium-ion in comparison to mass, if the needs of Responsive Space are to be met, a battery technology must be utilised that requires minimal housekeeping.

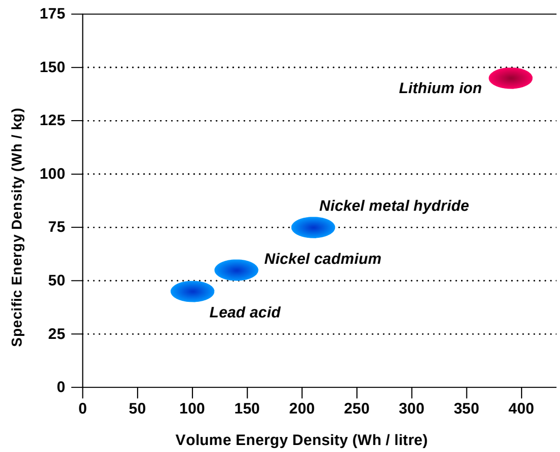

Figure 1 Battery Chemistry Comparisons

Older battery technologies can require a high level of maintenance due to a number of undesirable features:

- Short shelf life leading to high expenditure in the event of launch delays and scrubs. Costs incurred both in battery replacement and maintenance personnel.
- Batteries will naturally self-discharge even when left open-circuit. The rate varies between chemistries but must be countered via a slow 'trickle-charge' to keep batteries at full charge and ready for use. This requirement adds complexity to launch tower and spacecraft power system design.
- Some battery technologies require reconditioning on a regular basis, with units being completely discharged very slowly (over a few days) and then fully recharged.
- Older battery technologies are bigger and heavier and therefore carry an increased overhead cost for storage and lifting during integration.
- Storage orientation can be an issue due to leakage concerns. This can complicate vehicle checkout and reduce flexibility in battery location for system designers.

Spacecraft and launch vehicle designers have already found that the adoption of Lithium-ion batteries can decrease operational complexity and can reduce Power Subsystem functionality requirements. This can be taken a stage further through Responsive Space type missions via increased operational utility for the following reasons:

- When discharged to low states of charge, the ageing effects on Lithium-ion cells at room temperature are negligible. This makes inexpensive, long-term storage of batteries possible prior to allocation for a mission.
- Lithium-ion has a phenomenally low rate of self-discharge so that trickle charge is not required. Spacecraft power system design is simplified, as are launch vehicle umbilical requirements on the launch pad.
- Lithium-ion does not require reconditioning. This enables rapid response to arising operational needs and also avoids a potentially hazardous in-orbit operation.
- Lithium-ion tends to be lighter than the traditional chemistries by a factor of up to 4. AEA Technology have found that, even for the largest spacecraft batteries, only very simple lifting equipment has been required

Lithium-ion is the obvious battery chemistry choice for Rapid Response space missions

THE LARGE CELL APPROACH

Traditionally, for space applications, Nickel Cadmium and Nickel Hydrogen cells were connected in a single series string – the 'large-cell' approach. This approach is shown in Figure 2 and has three main drawbacks:

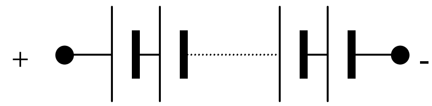

Figure 2 Single Series String Battery Topology

Cost/ Parasitic Mass: Battery capacity requirements vary from mission to mission. For large-cellbatteries, capacity depends on that of each cell. Therefore, to optimise a battery for a given mission, a new cell design must be qualified. The cost and risk of designing and qualifying a new cell can be considerable. For occasions where qualified cell designs can be used for a new mission, it has been found that considerable excess mass has to be flown, due to cell oversize.

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 entire battery (cell open circuit). Furthermore, to ensure continued functionality following a failure, detection and bypass electronics are required to take the failed cell out of service.

Complexity: Bespoke large space cells are produced in small batches using low-volume production techniques. Consequently, large cells exhibit appreciable capacity variation within batches. To ensure that the full capacity of each cell is used and that no cells are overcharged, charge-balancing electronics must be employed on large-cell batteries. Cell balancing and bypass electronics add considerable complexity, cost and mass to the overall battery system.

The large cell approach has been employed on some Lithium-ion space batteries. However, many more spacecraft have employed the AEA Technology small-cell approach.

AEA AND LITHIUM-ION

AEA Technology has remained at the forefront of the development of Lithium-ion technology and, in the 1970's, logged a patent for a revolutionary breakthrough in cathode technology. This technology was licensed to SONY and was utilised to meet the 1990's boom in demand for portable electronic equipment. SONY alone could not satisfy this demand and 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 was 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 Commercial Off The Shelf (COTS) small cells. Taking COTS cells and qualifying them for space applications is at the heart of the ‘small-cell approach’.

THE AEA SMALL CELL APPROACH

AEA Technology removed the need for individual cell charge and protection electronics by connecting together a large number of highly uniform small cells that each contain internal protection devices. In this way, battery level complexity is reduced by the elimination of bypass electronics and cell balancing electronics.

AEA Technology connects small cells in the ‘s-p’ topology shown in Figure 3. ‘s’ signifies the number of cells in each series string and ‘p’ denotes the number of such strings that are connected in parallel. Thus ‘s’ and ‘p’ control the voltage and capacity of the battery respectively.

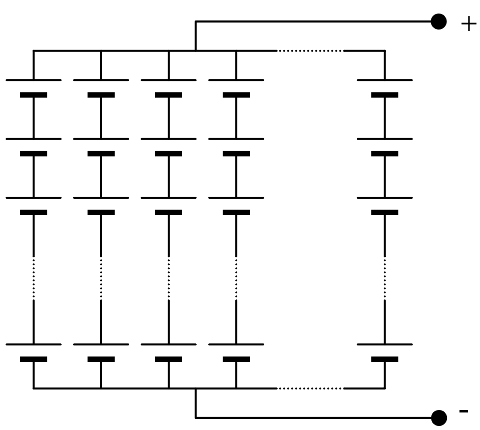

Figure 3 ‘s-p’ Battery Topology

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 battery capacity is relatively small compared to in a large cell battery where the effect is unacceptably large.
- In the event of a short-circuit failure, during charge the remaining cells in that string become overcharged. AEA Technology employs commercial cells that contain an internal protection device causing the cell to fail open-circuit during excessive overcharge. In this way, any short-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 s-p topology, allows battery protection electronics to be omitted reducing complexity and cost. The s-p topology, used in conjunction with small cells with the internal protection devices demanded by the consumer electronics industry, provides a simple yet highly fault-tolerant architecture.

The simplicity of the power, instrumentation and control interface of the small-cell battery is of great value to Rapid Response type missions. Across the entire spectrum of battery configurations, AEA small-cell batteries have the following interface features:

- Positive and negative power connection points.
- Battery level voltage telemetry.
- Battery case or cell-level temperature (typically 1 or 2 points).

There is, therefore, no cost and schedule delay incurred with qualification of battery components (such as bypass devices). This standard interface fits well with the Rapid Response need for components that have the versatility to be interchanged across the different spacecraft bus designs and ground support equipment of the multitude of space vehicle manufacturers.

UTILISING COTS SMALL CELLS FOR SPACE APPLICATIONS

AEA Technology procures large batches of cells (typically 25,000) and performs an initial Lot Acceptance Test (LAT) on a random sample from the batch. This LAT can be thought of as a ‘mini qualification programme’ to ensure that the batch is of the same quality as the original batch that were space qualified. All cells subject to LAT must pass the following groups of tests before any of the batch is accepted for use in space applications:

- 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 (DPA). Mechanical and chemical testing of cell components is then performed.
- 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 are subject to vibration testing. 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.

This LAT procedure was developed with ESA following a similar process to that used for approving commercial capacitors for space use. It is essential to understand that every test must be passed in order for a successful LAT. The failure of even one cell during one of the tests leads to rejection of the entire batch of cells.

Figure 4 Cell Destructive Physical Analysis

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 Ccell 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.

A major benefit for Rapid Response type missions is that a large stock of cells is always available at AEA Technology to ensure security of supply. This can be taken a step further, to minimise battery lead time, by prior allocation of cell lots for particular customers and keeping kits of parts to speed assembly. Of course, the long-term storage characteristics of Lithium-ion allow the ultimate goal of fully assembled and flight-ready battery units being stored until required for use.

AEA Technology has successfully pioneered the use of commercial cells for spaceflight. A range of commercial cells can be offered to meet the needs of different space applications using a common battery-packaging scheme. AEA has now been awarded over thirty space contracts using the small cell approach. It has been shown that using commercial cells for spaceflight is similar to other components, such as solar cells, that have been handled using this philosophy for many years.

SMALL CELL SELECTION

When selecting the appropriate cell for a particular battery application, a trade-off must be made of performance parameters. Normally, an increase in the performance of one parameter results in reduced performance in at other areas. Arguably, the three most important parameters are:

- Long-term performance in terms of cycle and calendar life. For example, launch vehicle batteries require only a low number of cycles for checkout and launch compared to tens of thousands for LEO spacecraft.
- Energy density is the measure of energy stored in a cell per unit of mass. Consequently, higher energy density leads to batteries with a lower mass to meet a given capacity requirement. This is obviously a key factor for space applications.
- Power density is the measure of the maximum power that can be drawn from a cell whilst maintaining a useful voltage level. This parameter can become a driving factor in power profiles that have short-term high current demands. A good example is in launch vehicle thrust vector control systems.

AEA has amassed a huge database of information on candidate small cells. Each has advantages over the others in terms of particular performance characteristics. Armed with this information, AEA is able to choose the optimum cell for each given space application.

AEA utilises commercial standard '18650' cells for space applications – meaning a cylindrical cell of diameter 18mm and 65mm height. Utilising a standard cell size allows qualified battery packaging schemes to be employed with different cells without the need of re-design and qualification. This further reduces cost and lead-time.

For spacecraft applications, AEA Technology has traditionally used the SONY 18650HC (Hard Carbon) cell.

Important for using commercial products in long-term space applications is the maturity of the product and also that build standards do not vary. 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.

Figure 6 The SONY 18650HC Cell

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 charge/discharge profiles simulating various space mission types (LEO, GEO and Interplanetary).

At present, for high-cycle applications, 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.

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 7 SONY 18650HC Characteristics

Due to the reliability standards required by space customers, a conservative approach is often taken and flight heritage is vital. The SONY 18650HC has now powered thirteen separate spacecraft and has clocked up over 900 cell-years in space. This maturity is another reason that the cell is the baseline for spacecraft applications.

AEA small-cell batteries employing the SONY 18650HC cell do not require cell-balancing electronics[3, 4]. The combination of a natural self-balancing mechanism and the high uniformity of cell performance (assured by the strict LAT, screening and matching process) ensure cells remain closely matched following the high number of cycles undergone during flight.

The cost benefit of the elimination of the validation of cell balancing software is highly significant. Furthermore, such validation is a notoriously time-consuming activity. Therefore, this characteristic is of immediate benefit to the needs of Rapid Response type missions.

FLEXIBILITY AND SCALABILITY

Utilising the s-p topology with small cells allows a huge degree in flexibility in battery design. Merely by altering the s-p array dimensions the capacity and voltage range can be modified without the need for fundamental re-design or cell qualification.

The small increment in capacity as p is altered 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.

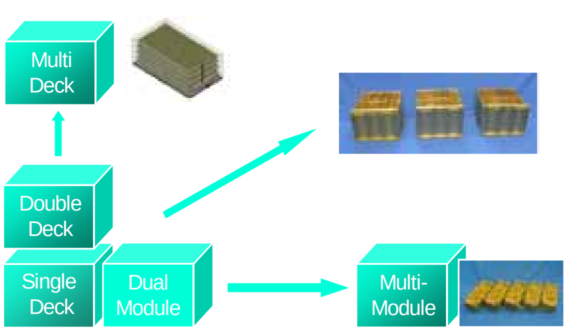

Figure 7 – Horizontal and vertical modularity

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

- Adding modules without the need for any battery design changes can accommodate mission creep. This feature has allowed system level problems to be absorbed at battery level with lowcost 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 means that a range of modular batteries can be produced, under low-cost build to print programmes.

Access to such a large inventory of Off The Shelf (OTS) batteries is revolutionary for the space industry. The availability of equipment to meet a broad spectrum of missions can be immediately brought to use in Rapid Response missions.

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 software packages developed by, and uniquely available to, AEA Technology:

- The Battery Electrical Analysis Software Tool (*BEAST*) that allows prediction of battery performance over a number of orbits under any given load and environmental conditions.
- The *MATRIX* software that enables long-term prediction of capacity fade. Capacity fade is a natural process that affects all Lithium-ion batteries. However, the unique maturity and frozen build standard of the SONY 18650HC cell has allowed AEA to prove the accuracy of *MATRIX* for mission duration predictions.

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[5]. Indeed, ongoing cell characterisation work and new life-test data means that the model is routinely refined. The current version is the sixth since the birth of the programme. The software has proved invaluable in reducing time and costs in the design process, as requirement changes can be quickly processed to update the battery size.

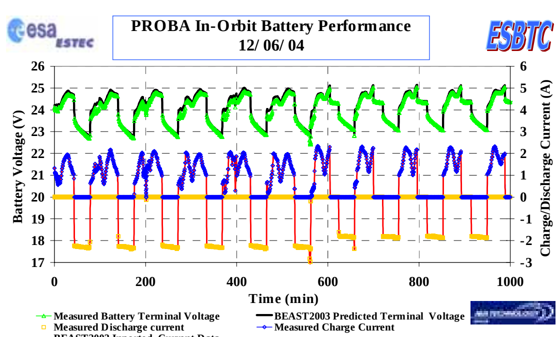

Figure 8 -Comparison of BEAST Simulated and actual in-orbit Battery Performance

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 verify the accuracy of *BEAST* predictions, and Figure 8 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 analysis, demonstrating that the proposed battery designs can be safely used for particular applications. In order for *BEAST* to generate such accurate EOL predictions, the battery capacity fade after long periods of use must be determined. This information is imported from *MATRIX*.

AEA strongly suspects that the MATRIX tool is the only software currently available that has been proven over mission term durations. The Mars Express real-time lifetest has been running for over 4 years with a DOD varying between 5-55% making the capacity fade rate highly varied. Figure 9 shows that, even with this highly unique mission, the MATRIX tool continues to predict capacity fade within 2% throughout the mission.

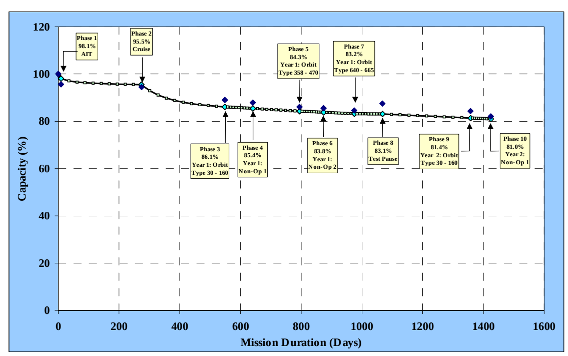

Figure 9 – AEA Predictions of capacity fade have been verified against mission duration test data

The usefulness of BEAST and MATRIX extends much further than a design tool. Two applications are of immediate interest to members of the Rapid Space community: Operational planning and system checkout.

For many payloads, battery performance can impact directly on the level of operational use. Overuse of the payload can result in draining the battery too far and risking the health and safety of the spacecraft. However, being overly conservative will result in a potentially useful operational asset being unnecessarily unused. Only with accurate and simple to use operational planning software will users be able to fully utilise payloads on Rapid Space type missions.

If the goal of Rapid Space is to be achieved, the rapid checkout of multiple spacecraft must be possible. Plug and play modular spacecraft will lead to the desire for components to be interchangeable with software simulation packages so that the non-availability of a single unit will not delay the checkout of the entire system. For Lithium-ion batteries such software has been produced, space-proven and is available now.

SMALL CELL BATTERY CONSTRUCTION

Small-cell batteries have grown larger, from initial application in small spacecraft up to those for large manned applications and launch vehicles as acceptance of the philosophy has spread[6]. The overview of the construction techniques employed in AEA batteries is discussed in this section.

AEA wishes to demonstrate the maturity and simplicity of the design. Indeed, AEA is developing high volume manufacture and test processes and equipment to further decrease lead-time and cost. Such improvements will further benefit the Rapid Response paradigm. The section has been split up to allow small, medium and large batteries to be discussed separately.

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 Mars lander, carried on the ESA Mars Express spacecraft. As shown in Figure 10, 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 use of the natural warming of the cells during discharge in the Martian night to act as a general spacecraft level heater. The BEAGLE 2 battery was 6s9p in configuration and has a mass of 2.6kg.

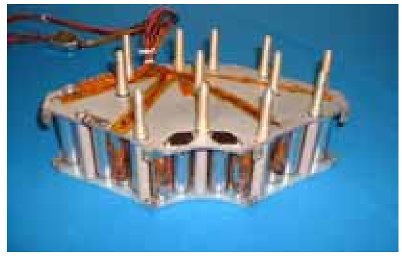

Figure 10 – The BEAGLE 2 Battery

In spite of the 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 the Nanosat-1 project for INTA. The RoLand, ST5 and Nanosat battery module configurations were 7s2p, 2s6p and 6s2p respectively.

Figure 11 The RoLand, ST-5 and Nanosat-1 Batteries

Figure 11 demonstrates how AEA Technology employs 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, 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, cross bracing (stamped from thin aluminium sheets) is added. 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 includes 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 and launch vehicles: 7V 14V and 28V nominal. Such bus voltages call for either 2s, 4s or 8s battery designs. AEA Technology has specifically developed an 8-cell building block that can be utilised in modular batteries. The block can be configured as a 2s4p, 4s2p or 8s1p and multiple blocks can be connected to build a modular battery. This design is of great interest to launch vehicle manufacturers, as well as for small satellites, pyrotechnic and self-destruct applications.

This battery design is shown in Figure 12 and differs from all other AEA Technology designs, with cells mounted on their sides instead of upright. In addition the battery is fixed to the vehicle using bolts driven up through the mounting structure into the bottom of the battery. This battery design has a very robust mechanical design with a natural frequency in excess of 2000Hz.

Figure 12 Eight-cell Battery Building Block

Energy density of small batteries is around 100Wh/kg. This is lower than that which AEA typically achieve in larger batteries, due to the parasitic (particularly structural) mass being 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 (one is already successfully operating in orbit).

<u>Medium Size Battery Design</u>

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.

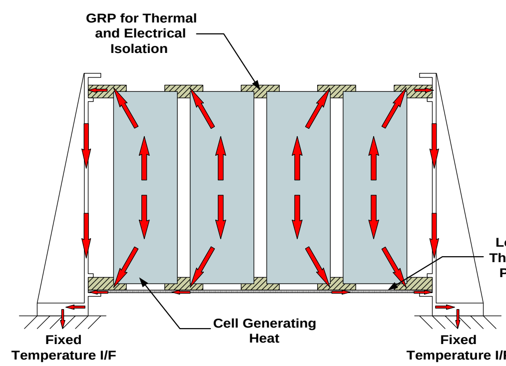

Figure 13 Battery heatflow

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 13.

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 14 and 15, 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 14 – PROBA battery cellblock and piece parts

Figure 15 – The final PROBA battery

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

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 16 – ESA GOCE Battery

The GOCE battery presented considerable design challenges[6]. 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 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, the 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 17 – ESA Cryosat battery

The thermal design principles 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. 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 17 is 8s44p (mass 16.8kg) and will be the first AEA Technology multi-deck battery to fly (in 2005).

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 around 500 Hz in our two-tray designs.

QUALIFIED BATTERY MODULES

As mentioned earlier in this paper, Rapid Space programmes will benefit greatly from OTS hardware. 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* and *MATRIX* to check that an existing battery configuration can meet the requirements of a new mission, means that AEA could build a customer stock of batteries to meet demands for years into the future.

Further flexibility from existing designs is gained by the fact that existing battery designs can be electrically reconfigured with a small 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. This inherent versatility of modular batteries, enables standard qualified designs to be either immediately usable or easily adaptable to new missions.

Figure 18 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	1.3	1
6x9	2.6	1
6x11	3.3	1
8x8	3.5	1
8x10	4	1
9x10	4.4	1
6x16	4.7	1
8x16	6.6	2
6x24	7	1
12x24	14.4	2
10x30	16.2	1
12x28	16.4	2
8x44	16.8	2
8x50	20.2	2
8x52	25.4	1

Figure 18 – Qualified Battery Designs

CONCLUSIONS

The features and benefits of the AEA small-cell battery provide a perfect match to the energy storage needs of Rapid Space programmes, for both launch vehicles and spacecraft. Comparing the needs for Rapid Space, as stated at the beginning of the paper, with the information presented in this document:

- *Reduced unit lead-time.* A multitude of space qualified battery designs are available now. These designs utilise a cell that is stored in large quantities and readily available for use. Battery packs can be stored in a low-cost environment, in bulk, until required and can be activated within hours.
- *High reliability*. The small-cell approach offers a highly robust and fault-tolerant design. Multiple failures can be tolerated if reliability requirements deem this to be necessary, simply by using extra strings of cells.
- *Simple Operation*. No other space battery manufacturer can offer such a simple interface, without bypass and charge balancing electronics. In-orbit and pre-launch maintenance is extremely simple, allowing reduction in battery personnel compared to other technologies.

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