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ESA PPRB EXECUTIVE SUMMARY REPORT

Project Title: Preparation of Enabling Space Technologies and Building Blocks – Passive Propagation Resistant Battery

Project Acronym: PPRB

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Project Phase: 3

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ENABLING ELECTRIFICATION

1 Abbreviation Definitions

Abbreviation	Definition
PPR	Passive propagation resistant
Dummy module 1	All aluminium dummy cells
Dummy module 2	Seven Live cells surrounded by aluminium dummy cells
PPR Sample Module	All live cells with final foam design specification (thickness)
PC-ABS V0	Polycarbonate/Acrylonitrile Butadiene Styrene flame retardant filament meeting UL-94 V0 standard
PPR Foam Sample 1	300mg PPR foam sample for Outgassing test
PPR Foam Sample 2	PPR foam sample for Thermal Vacuum test
Li-ion	Lithium-ion

2 Summary

Battery packs comprising of Lithium-ion (Li-ion) cells are used extensively in Space applications; however, they can fail in some instances and one form of failure is thermal runaway. This form of failure can result in loss of vehicle or satellite and could consequently contribute to the exacerbation of the problem of Space debris. Li-ion cells are known for their limited tolerance to operating outside a pre-set safe operating envelope of temperature range and voltage/current. Any deviations in cell parameters to values outside this window could be potentially detrimental to the cell which results in decreased lifespan; larger deviations could increase the chances of thermal runaway. Additionally, if a cell is punctured by a piece of Space debris the cell can go into thermal runaway.

Thermal Runaway events are initiated by unstoppable chain reactions, characterised by rapid increase in cell temperature, venting of gases, cell rupture/rapid disassembly/explosion accompanied by particle ejection, and uncontrolled fire because the energy content of the Li-ion cell is released over the timespan of a few seconds.

A cell failure can result from mechanical (impact or penetration of a foreign object), electrical, thermal, and manufacturing defects. The failure characteristics of the thermal runaway event will be different for different abuse conditions; consequently, the method used for initiating the event is a critical parameter to consider so that the test results can be acquired to satisfy a specific target.

A failure in one Li-ion cell can rapidly propagate to adjacent cells within a battery pack which presents the potential risk of loss of vehicle/satellite. Xerotech has designed battery packs that incorporate a passive propagation resistant (PPR) foam that effectively insulates adjacent cells from a cell undergoing thermal runaway; thus, resulting in a safer battery pack. Generally, a PPR technology operates in tandem with an active thermal management system. To use the analogy of a bike the active thermal management system is the steering of the bike (battery) keeping it within the confines of a safe bike path, in this case the safe operating temperature range. The PPR technology is the passive helmet that ensures if there is an incident that the cargo is sufficiently protected from the effects, in this case protecting the battery pack and vehicle against thermal runaway of one cell.

The goal of this project was the initial development of a Passive Propagation Resistant Battery (PPRB) that could be flown in a space environment. Critical for this development was the optimisation of a PPR foam, Xerotherm®, that surrounds the Li-ion cells within PPRB.

Once the optimisation stage was complete, we carried out experimental and numerical tests to confirm the effectiveness of the PPR foam in mitigating the effects of thermal runaway of a Li-ion cell within a module. The foam passed all these tests. Lastly, the PPR foam underwent Space qualification testing. Unfortunately, the PPR foam, in its current chemical composition and structure, failed the outgassing test. However, it has shown to be very effective in mitigating the effects of thermal runaway within a Li-ion battery pack. Further work is needed in developing the PPR foam for use in a Space environment.

Overall, the results are a successful first step towards a PPRB that could be flown in a space environment.

3 Project Background

ESA flew the very first Li-ion space battery in Proba 1 back in 2001 & since then Li-ion batteries have entirely supplanted previous battery technologies. The target application is a passive safety enhancement which is applicable to all space battery systems across each mission profile and vehicle type. Xerotech's battery design is an enhancement to typically cylindrical cell-based battery pack designs, particularly those using commercial off-the-shelf (COTS) battery cells.

Li-ion batteries have a failure mode that can result in thermal runaway (progressive self-heating of the battery cell using internal energy). This failure mode can propagate to adjacent battery cells within a battery pack which typically consist of regular repeating arrays of battery cells. This phenomenon is known in the industry as thermal propagation. Propagation resistance (PR) is a technique to inhibit or retard the spread of catastrophic cascading chain-reaction failures of battery systems. PPR is a specific subset of technology that does not require active control or intervention such as active fire suppression systems using fire extinguishing agents.

The PPR technology presented in this project is an ultra-lightweight fire-retardant foam encapsulant that completely fills the void spaces within a battery pack. This prevents propagation of heat, fire, and expelled particulates from failed cells to the wider cell array. When compared to best-in-class PPR solutions used in the automotive industry Xerotech's solution is *85% lighter* than competing silicone-based technologies. This offers tremendous safety and light weighting benefits to aerospace applications. Xerotherm® requires no power, has no moving parts or active controls, and has ancillary benefits of improved shock and vibration resilience. In addition, satellite and orbiting launcher upper stage explosions are a leading source of space debris – with a large proportion of these detonations triggered by the older generation of batteries. Battery degradation due to aging and thermal runaway of Li-ion batteries can thus present challenges to future missions.

PPR is not currently implemented in commercial space batteries, but both PPR and Thermal Management of batteries will be of crucial importance for upcoming missions and become mandatory to meet upcoming regulatory requirements like SMC-S-017 section 4.2.3.8 and JSC20793 section 5.1.5.1. Our PPR foam, Xerotherm®, can greatly contribute to safety and performance of the battery system in programs like:

- Galileo Navigation Constellation

- GPS Navigation Constellation
- International Space Station
- Space Launch System / Orion / Artemis
- On-ground during assembly, integration, and testing phase.

To enable the use of Xerotherm® in these applications this project was undertaken to refine the PPR foaming process, to optimise a typical module design, and to qualify the technology for Space. This is envisioned to demonstrate efficacy and compatibility of this enabling technology building block for Space battery systems and advance its Space-readiness.

3.1 Technical Requirements and Work Packages

The main technical objective was to develop the Xerotherm® PPR battery for Space applications. To achieve this objective there are three separate requirements:

Technical Requirement 1: Optimal foam material and processing parameters

Technical Requirement 2: Determine optimal cell spacing and thermal PPR characterisation

Technical Requirement 3: Evaluation of PPR module space-readiness

These three Technical Requirements were addressed in three Work Packages (WPs) that progressed the technology through from conception to completion with each subsequent WP depending on the previous.

3.1.1 WP 1: Foam Material and Process Study

In this WP the goal was to identify the critical foam specifications and processing parameters that would lead to optimal thermal PPR performance. WP 1 focused on foam material and processing development. Critical foam design characteristics are significantly impacted by the foaming process; therefore, characterisation of the process was completed as a priority to ensure that subsequent design test samples produce reliable and repeatable results. A five-factor process input screening design of experiments (DOE) with 1 repeat was designed, as below, giving 32 trials. This DOE was completed using standard receptacle cups of different base sizes.

Process input variables:

1. Ambient Temperature
2. Part A/B Temperature
3. Mix Ratio
4. Mix Speed
5. Injection Speed

Process manufacturability variables:

1. Expansion rate
2. Expansion ratio
3. Cure time

Design Variables:

1. Flammability
2. Thermal Conductivity
3. Cell spacing

An example of the type of defects that can result from an ineffective foaming process is the honeycomb defect shown in Figure 3-1 which produces large cell sizes in some areas. This would lead to ineffective PPR. Through experimentation and optimisation of the foaming process we completely negated this defect.

FIGURE 3-1: EXAMPLE OF A PPR FOAM DEFECT – HONEYCOMB

At the end of WP 1 we defined the PPR foam design specification as derived from the extensive DOE described above. The final foam specifications were measured from cup and tray samples produced as part of an initial production run using the optimised process settings. These results were then taken forward into WP2 in the design of the Dummy Modules that had one central live cell surrounded by "dummy" aluminium cells with similar thermal transport properties and then, finally brought through to the final live PPR Sample Module.

3.1.2 WP 2: PPR Module Development

For WP 2 we took the optimal foam specifications and processing parameter results from WP 1 and developed a PPR module using COTS cylindrical 18650 Li-ion cells with Nickel Manganese Cobalt (NMC) chemistry.

A typical battery module composes of a staggered array of COTS 18650 Li-ion cells, to develop the PPR module using the Xerotherm® PPR foam the critical parameter for consideration was the cell-to-cell spacing. Thus, we assessed three different cell-to-cell spacings using both experimental (physical) and validated numerical (computer-based prediction) tests to arrive at the optimal value. The validation of the numerical tests was key to using the data generated to reliably predict the response of a PPR module to a thermal runaway event. Numerical tests or simulations are very useful for fairly determining the optimum cell-to-cell spacing because the setup and execution of the simulated thermal runaway is the same in each case but without the real-world uncertainties and complexities. The numerical simulations were complemented by the experimental tests as they provided real-world data and incorporated effects that would be difficult to include in a numerical test.

With the combination of experimental and numerical results an optimum cell-to-cell spacing of 4mm was found.

The optimal PPR Module was then assessed in three separate experiments: thermal abuse test, electrical abuse test and mechanical abuse test, where the critical result was pass/fail on prevention of thermal runaway propagation to adjacent cells from one central cell within the module (the initiation cell). The thermal abuse test was designed to take the PPR module outside the predefined safe operating temperature window, as shown in Figure 3-2. Additionally, the electrical abuse test was designed to also take the initiation cell outside the safe operating window but instead using overcharging the cell to 200% state-of-charge or 8.4V (twice the 4.2V specified for the 18650 cell). Lastly, the mechanical abuse test was designed to guarantee thermal runaway with a nail penetration test that destroys the internal structure of the initiation cell resulting in the expelling of gas and particles.

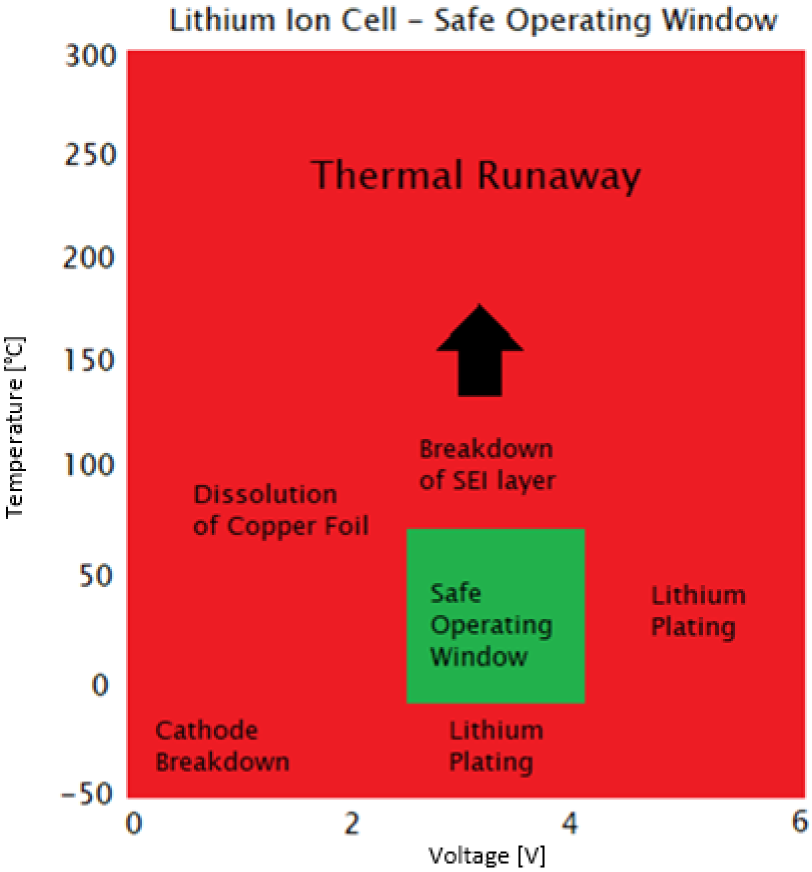

FIGURE 3-2: LI-ION CELL OPERATING WINDOW

The PPR Sample Modules passed all the abuse tests. Interestingly, once the PPR foam was used to completely encapsulate the cells the effects of the mechanical abuse tests were significantly reduced, best illustrated by comparing stills from a test where the PPR foam was only around the sides of the cells (Figure 3-3) and one where the PPR foam was also on the top surface as well where the nail penetrated (Figure 3-4). There was a considerable difference in the resultant maximum temperature measured on the initiation cell (1192.58°C vs 119.29°C), but crucially in both cases the PPR foam successfully insulated the adjacent cells from the heat and prevented them from going into thermal runaway.

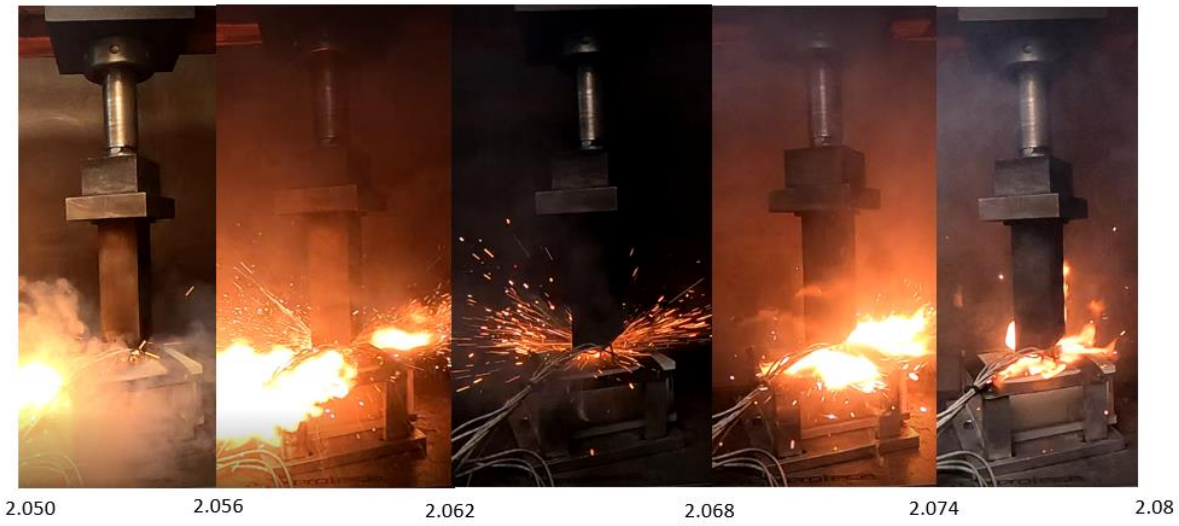

FIGURE 3-3: MECHANICAL ABUSE TEST WITH PPR FOAM AROUND SIDES OF CELLS

FIGURE 3-4: MECHANICAL ABUSE TEST WITH PPR FOAM COMPLETELY SURROUNDING THE CELLS INCLUDING AT NAIL PENETRATION SITE.

3.1.3 WP 3: Space Qualification Testing

To qualify for Space applications there were two separate experiments that the Xerotherm® PPR foam was to be assessed: an outgassing test, which assesses how much gas/volatiles are released by the material when exposed to the vacuum of Space, and a thermal vacuum test, which puts the material through four thermal cycles between a lower temperature of 20°C and a higher temperature of 140°C while in a chamber that is lowered to a pressure of 1×10^{-5}mbar (mimicking the near vacuum of Space). Both experiments are critical for qualifying a material for use in a Space environment as it can not fly if there is a possibility that the material may release gasses or degrade/become ineffective when exposed to the vacuum of Space. Unfortunately, the PPR foam failed the outgassing test with over 45% loss of weight of the samples from outgassing.

4 Conclusions

The result from the outgassing tests shows that the PPR foam in its current form is not suitable for Space applications where the PPRB may experience the vacuum of Space. However, the results of the thermal runaway tests show that the PPR foam is very effective in mitigating the effects of thermal runaway of a cell within a battery pack.

With further refinement of the foaming process, we could arrive at a PPR foam mixture that could withstand the rigours of Space; therefore, this may be the first crucial step on the road to achieving safe PPRBs for Space applications.