KULR One Space

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ABSTRACT

Small spacecraft battery packs are both mass and cost prohibitive if they are to meet the thermal runaway requirements for manned missions. Exploratory Mission 1 (EM-1), also known as Artemis 1 had 13 secondary, intended small spacecraft payloads. Many of these payloads would have exceeded the 80WHr energy threshold, and these would have been required to adhere to thermal runaway standard JSC 20793. All 13 payloads were covered under the EM-1 thermal runaway waiver for secondary payloads; however, EM-2 is not expected to grant such waivers. Further, the EM-2 secondary small spacecraft payloads are growing in size and the battery packs are expected to grow proportionately. Higher energy batteries with low probability of waivers indicates most payloads will be expected to meet JSC 20793 Rev. D – Crewed Space Vehicle Battery Safety Requirements. However, the mass and cost of traditional battery pack technologies will be a major challenge at best – if not completely prohibitive. Marshall Space Flight Center (MSFC), in partnership with KULR Technology Corp, sought to create an advanced manufactured battery architecture to solve the problem. The team developed a prototype 3D-printed enclosure with mesh filters, carbon vents, and a KULR proprietary liquid-filled carbon fiber wrap. The battery design is based on 18650 lithium-ion cells and is adaptable to different form factors. KULR's designs for passive propagation resistance (PPR) had been previously demonstrated to be effective in a prototype 1U CubeSat battery pack but was only built to test the thermal features of the design. The mechanical design required advancement of the system in order to meet vibration requirements for launch to space. Tolerance to vacuum also required investigation and modest design changes. In addition to internal strengthening features, the project's next-gen prototype incorporates advanced 3D-printed materials developed at MSFC. The prototypes contained 8 cells in the slightly larger than ½-U volume, but the design is readily adapted to fewer cells if desired for a particular program. The solution is significantly lower mass and lower cost than prior state-of-the-art technology. Further, the solution can be commercialized into a COTS option for secondary payloads and other applications where battery mass is critical. In addition to cost and weight savings, these designs can likely be adapted, produced, and assembled on a faster timeline than designs built from traditionally machined components.

INTRODUCTION

Lithium-ion batteries (Li-ion) offer lightweight and high-energy density solutions that are crucial for space exploration. However, the practical application of Li-ion technology in human-oriented scenarios is hindered by safety concerns associated with thermal issues.[1] As small spacecraft mission complexity increases so do the associated power requirements. Lithium-ion cells are commonly used in aerospace applications whether or not small spacecraft battery packs exceed the 80WHr energy threshold, defined in JSC20793.

To employ Li-ion technology in any application, it is essential to have a comprehensive grasp of the mechanisms behind thermal runaway and the subsequent release of energy into the environment. This knowledge plays a pivotal role in the development of reliable thermal management systems, which aim to minimize the impact of thermal runaway and prevent the propagation of such incidents between battery cells.[1] Additionally, safe containment of a thermal runaway event in a battery pack will help to reduce space orbital debris if under the energy threshold requirements.

KULR Technology has developed compact and light-weight technology for preventing thermal runaway propagation in Li-ion batteries and NASA-MSFC has developed novel 3D-printed materials to combining stiffness and light weight which will be utilized to create an enclosure for this project. NASA also has experience in mechanical design for space and launch environments. These technologies in combination with NASA's expertise will help to advance the state of the art for small spacecraft batteries that are required to meet crew-rated safety standards. For spacecrafts at or above the energy threshold it will allow more programs the opportunity to submit a secondary payload that contains a competitive gravimetric and volumetric energy density in combination with unparalleled safety to the small sat community. KULR is looking to help more programs.

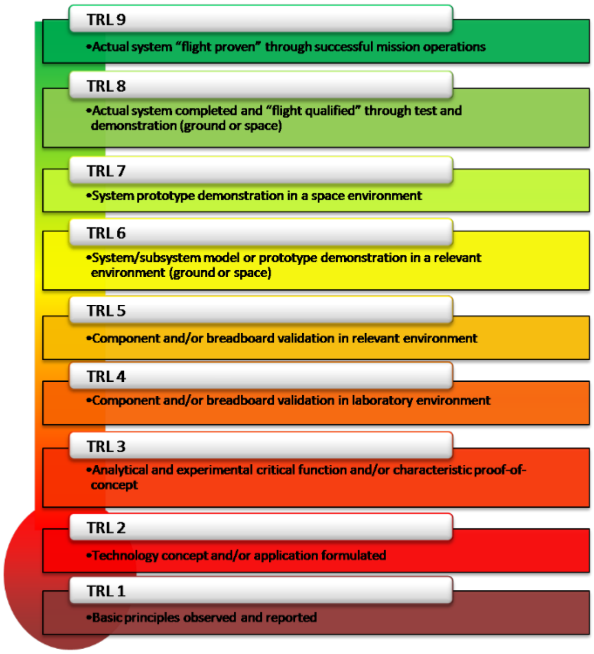
MISSION REQUIREMENTS

The primary mission objective is to create a battery pack that satisfies the requirements of JSC20793 Rev D while low-mass and low-cost. Figure 1 helps to differenciate between the rediness of a particular assembly and the type of testing an assembly has been qualified to. A summary of requirements for the battery pack are shown in table 1.

Table 1: Mission Requirements

Requirement	Description
JSC 20793 Rev D	Battery Packs exceeding 80WHrs
TRL4	Technology Readiness Level

Additional objectives include the ability to test the prototype in vibration and vacuum, and to confirm passive propagation resistence (PPR) requirements.



TRL 9
•Actual system "flight proven" through successful mission operations

TRL 8
•Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 7
•System prototype demonstration in a space environment

TRL 6
•System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
•Component and/or breadboard validation in relevant environment

TRL 4
•Component and/or breadboard validation in laboratory environment

TRL 3
•Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
•Technology concept and/or application formulated

TRL 1
•Basic principles observed and reported

Figure 1: Technology Readiness Level Guide[2]

PROTOTYPE DEVELOPMENT

Multiple generations of battery enclosures were designed and tested, with modifications dictated by fabrication considerations and thermal runaway test results. Thermal runaway tests were largely successful regardless of prototype configuration, with success being defined as the ability to vent thermal runaway gases without ignition of said gases once vented from the pack and also required no propagation between cells.

Generation I

Not furnished to NASA as a demonstration article. The initial design of the 3D-printed ABS battery pack utilized no fasteners for fixturing the major components. Instead, the inner surface of the case was printed with locating features such as ribs. The internal components mated with these features and with one another in such a fashion as to define their positions within the case. Bonding the lid onto the case constrained the internal components from moving out of position. The lid was bonded in place using ABS cement. The following materials were used for PPR:

- Thermal Runaway Shield (TRS), an encapsulated coolant, designed by KULR to open in the temperature range of 100-120 ºC. TRS protects the cells and is the first contact of cell flare.

- Metal screen was used to retain the TRS in a printed tray like component that had been faced with ablative material and bonded in place.

- A coarse filter that helped to act as a heat absorber in line with the flame arrestors.

- Flame arrestor manufactured by KULR used as a final filter.

The prototype was an eight 18650 cell configuration. Cells had additional ablative material sleeves and TRS installed into the pack assembly.

Generation II

Not furnished to NASA as a demonstration article. This prototype was a simplification of the previous iteration. The ejecta barrier tray and metal screen were omitted. The ablative material and TRS were applied directly to the case walls.

Generation III

Iterations were made that resulted in the removal of previously included features. The design features of this iteration were the following:

- One-millimeter case and lid walls

- The flame arrestor assemblies were attached directly to the case walls at the locations of the case wall vent slots.

- The ejecta barrier materials were attached directly to the case walls as in generation 2.

- Ablative material was applied to remaining areas of case walls. Testing of a flare produced from a cell prevented burn through when placed in direct contact.

The cell assembly was fixed in place with threaded fasteners that passed through the case walls. Testing revealed the need for modification to assist in the protection of side wall rupture during a thermal event.

Generation IV

Final design furnished to NASA as a demonstration article. This design offered a simplistic assembly and added protection against breaching of the case wall by high-temperature gas. The significant design features were as follows:

- Two-millimeter case walls and lid. In addition, the lid fit internally into the case opening and was fixed with screws which passed through the case and into heat-set inserts in the lid's lip.

- The entire inner surface of the case (including the lid) was faced with ablative material, except for the positions of the flame arrestor vents.

- TRS was placed directly against the cell holders with a layer of open-cell polyimide foam. No fastening or bonding was required, as the TRS and foam were sized to fit within the cavity formed by the cell holder, case walls, and lid.

All polymeric surfaces were covered. The vent assemblies and ablative materials were closely fitted such that any hot gas generated within the case either exited through the vents or encountered ablative materials. The cell assembly remained the same as with the previous iteration. The mass characteristics of the generation IV prototype were documented since the design was considered deliverable, see table 2.

Table 2: Gen. IV Prototype Mass Characteristics

Battery and PPR Components	Weight
Cell and Tabbing	366g
Housing and Cell Holders	143g
Assembly Fasteners	31g
Ejecta barriers, flame arrestor, TRS, cell tubes	225g
Total Battery Mass (Basics + PPR)	765g

Generation V

Final design enhanced with advanced plated polymer housing. This design is like the previous generation but includes the use of a custom metal alloy plated 3D printed nylon housing material in place of the flame-retardant ABS used previously, see figure 2. Even though the battery survived GEVS +3 dB level vibration with the plain polymer housing, the plated material is intended to provide improved mechanical strength and reduced outgassing from the plastic in a vacuum environment.

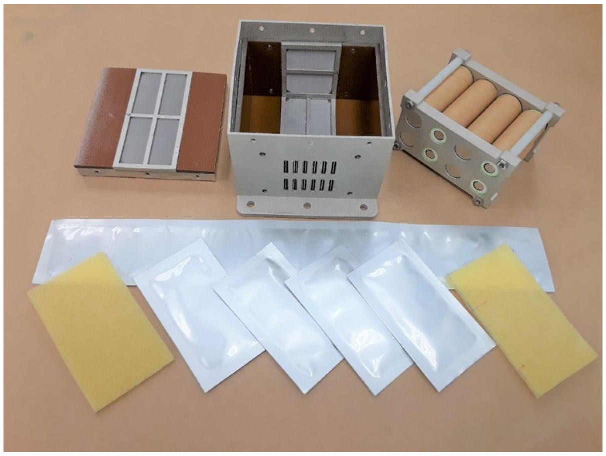


Figure 2: Generation V Final Assembly

The assembly presented in figure 2, from left to right, displays the inside surface of the lid showing the ablative material and flame arresting vent, plated case with additional ablative material, cell holders with sleeved cells. The bottom row shows the longer TRS 1 which is installed into the cell pack, the smaller TRS 2 installed against the cell holder for flare mitigation, and polyimide foam to hold the TRS against the cell holders. The orientation of the TRS in the cell pack is shown in figure 3.

Figure 3: 18650 Cell Pack & TRS

The ends of the TRS are secured in place with a Kapton tape. To prevent cell shorting, the surface of the cell holders were insulated with fiberglass tape prior to spot welding the bussing strips and fuse wires. A final layer of self-adhesive mica is then installed over the bussing. Once the cell pack is prepared, it is installed into the case, see figure 4. A complete assembly is shown thereafter in figure 5.

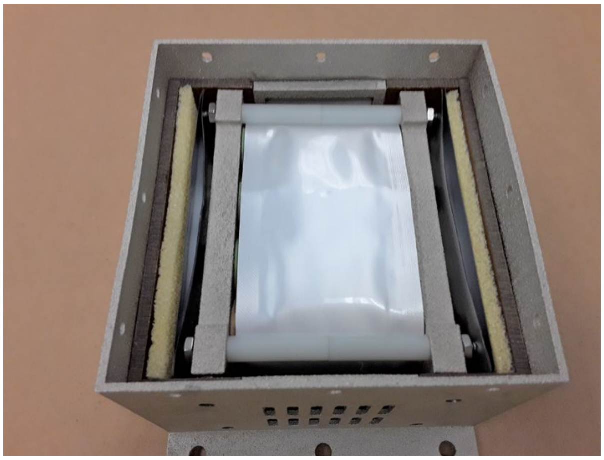


Figure 4: Generation V Prototype Internal View

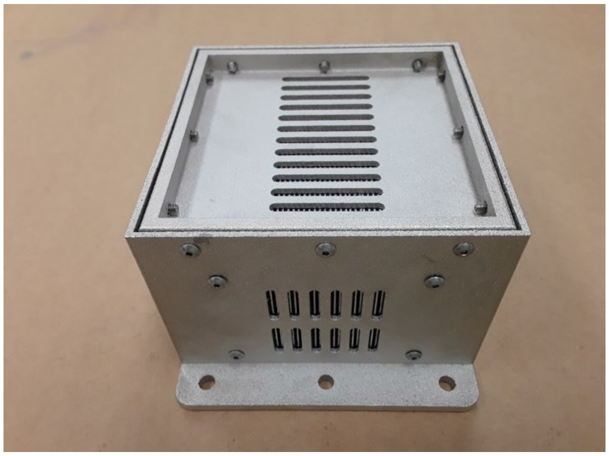


Figure 5: Generation V Final Prototype

PROTOTYPE TESTING

All battery components were supplied by KULR and NASA-MSFC provided environmental expertise, the plated housing components, and design guidance while the batteries were assembled at KULR in San Diego California. Vibrational testing was performed at the MSFC location by MSFC personnel and test levels for the random vibe testing were mutually agreed upon prior to testing by project engineers at MSFC and KULR. PPR testing was performed at KULR technology by KULR personnel. Extensive testing was done independently by KULR to validate the material selected for use in the assembly. Once mechanical design of the 4th generation prototype was completed testing was performed to validate that the prototype could meet the standards set by TRL4.

Testing was performed as specified for PPR as well as random vibration. Random vibe was done in all 3 axes for each of 3 test series. It was decided to use general environmental verification standard (GEVS) qualification levels as a baseline standard for the pack at this point in development. Since durability was uncertain, testing was first run at GEVS minus 3dB. The battery survived without damage and runs were subsequently done at GEVS, and then at GEVS plus 3dB. No significant damage was observed. Individual parts were vibed to screen for potential issues that could cause overall prototype failure, but again no significant damage was observed. These were encouraging results and there was an expectation that incorporation of advanced metal-plated 3D printed housing materials would produce an even stronger battery.

PPR testing also demonstrated successful results. A KULR trigger cell with an embedded internal short circuit (ISC) device was used to initiate thermal runaway in a selected corner cell. Video records showed that no sparks or flame exited the enclosure. Temperature data and physical examination demonstrated that there was no thermal runaway propagation to other cells. Additionally, there was very little deformation to the exterior of the battery enclosure.

Vacuum testing was also completed on the components and the system of the 5th generation prototype to assess the sensitivity of the individual components, as well as system, to a vacuum environment.

Battery Vibration Testing

The purpose of this test was to evaluate the vibration survivability of the KULR 3D printed battery pack. Although cells were present in the system there was no load or voltage monitoring performed on the battery to determine survivability. There was no test of the individual cells or any sort of wiring or connector. After testing the packaging was inspected for the following signs of failure cracks, delamination, screws that had backed out or plastic deformation.

When setting up the prototype for testing the unit was mounted to an adapter plate. The six screws of the mounting plate were torqued to a value of 30 in-lb. The assembly, both prototype and adapter plate, were mounted to the shaker table using a torque value of 75 in-lb. A single axis accelerometer was placed on the battery aligned with the vibration motion for each test. The accelerometer was reoriented for each test to maintain orientation, see figure 6.

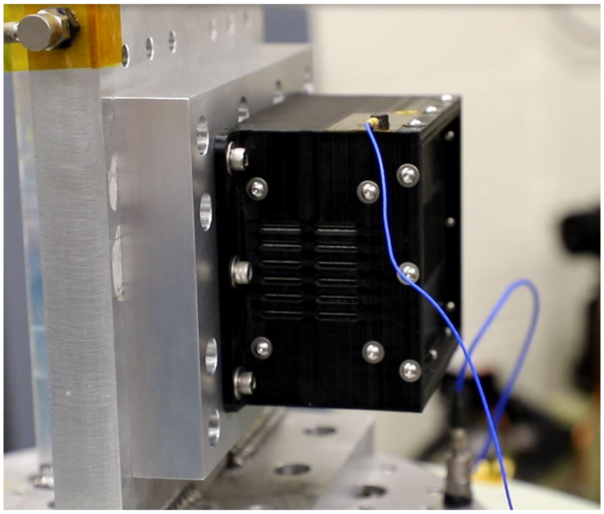
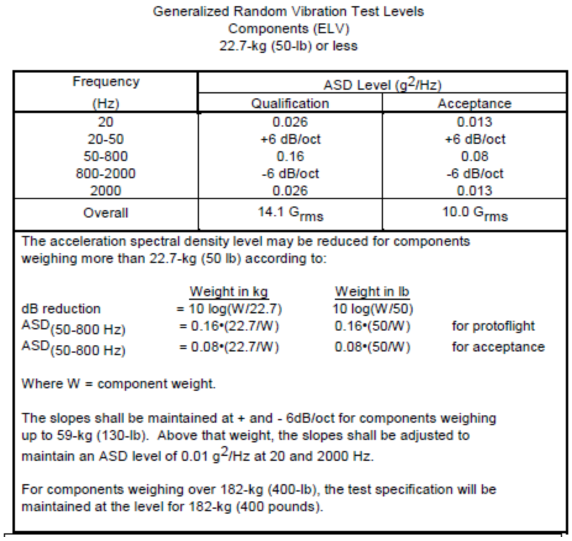


Figure 6: Prototype in Vibration Testing

The battery was tested to GEVS qualification level -3db in the XYZ axis (10 GRMS), then GEVS qualification in the XYZ (14.1 GRMS), then finally GEVS qualification +3db in the XYZ axis (20 GRMS). Qualification test levels are shown below in figure 7. A sine sweep was run before and after each level in each axis to compare before and after mechanical response. Each axis was run at level for 2 minutes. The prototype vibrational performance can be seen below in figures 8 - 10.



Generalized Random Vibration Test Levels
Components (ELV)
22.7-kg (50-lb) or less

Frequency (Hz)	ASD Level (g^2/Hz)	
	Qualification	Acceptance
20	0.026	0.013
20-50	+6 dB/oct	+6 dB/oct
50-800	0.16	0.08
800-2000	-6 dB/oct	-6 dB/oct
2000	0.026	0.013
Overall	14.1 G_{rms}	10.0 G_{rms}

The acceleration spectral density level may be reduced for components weighing more than 22.7-kg (50 lb) according to:

	Weight in kg	Weight in lb	
dB reduction	= 10 log(W/22.7)	10 log(W/50)	
$ASD_{(50\text{-}800 \text{ Hz})}$	= 0.16•(22.7/W)	0.16•(50/W)	for protoflight
$ASD_{(50\text{-}800 \text{ Hz})}$	= 0.08•(22.7/W)	0.08•(50/W)	for acceptance

Where W = component weight.

The slopes shall be maintained at + and - 6dB/oct for components weighing up to 59-kg (130-lb). Above that weight, the slopes shall be adjusted to maintain an ASD level of 0.01 g^2/Hz at 20 and 2000 Hz.

For components weighing over 182-kg (400-lb), the test specification will be maintained at the level for 182-kg (400 pounds).

Figure 7: GEVS Qualification Test Levels

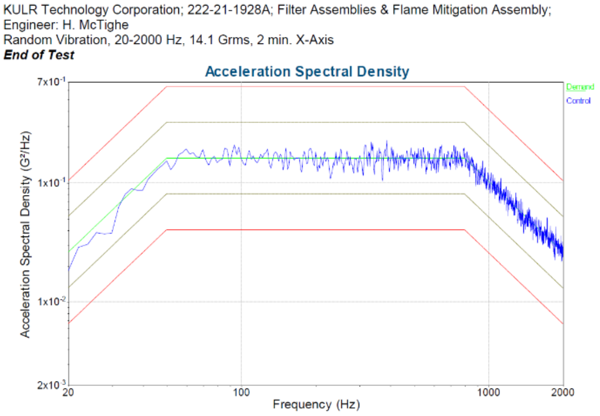


Figure 8: Random Vibration, 20-2000 Hz, 14.1 Grms, 2 min. X-Axis

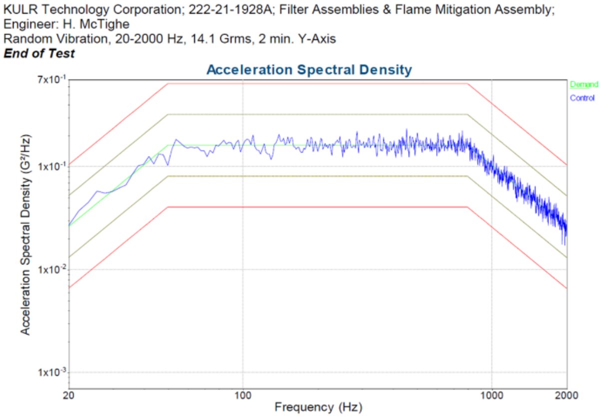


Figure 9: Random Vibration, 20-2000 Hz, 14.1 Grms, 2 min. Y-Axis

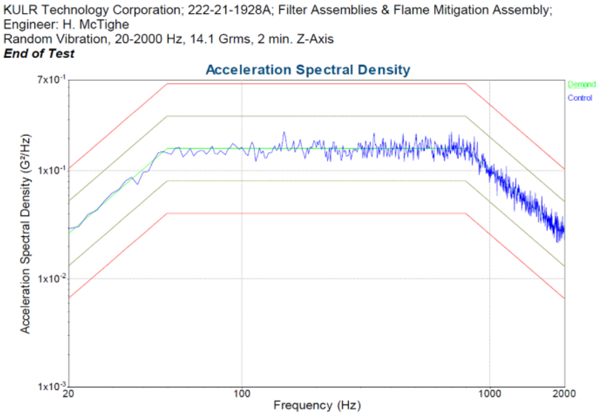


Figure 10: Random Vibration, 20-2000 Hz, 14.1 Grms, 2 min. Z-Axis

The battery was monitored visually to ensure that there were no mechanical failures during vibe testing. The battery pack was disassembled to inspect for the signs of failure previously defined. The prototype was found to be in good condition and no failure was noted upon inspection.

Passive Propagation Resistance Testing

The purpose of this test was to validate the prototype design with fully enforced enclosure walls and to test the pack with all electrical connections.

The test is initiated by heating the trigger cell. Thermocouples are attached to the trigger cell and three other neighboring cells. Additionally, five thermocouples were attached to each exterior surface of the prototype. Cell configuration can be seen in figure 11. The trigger cell starts at the top left of the cell configuration.

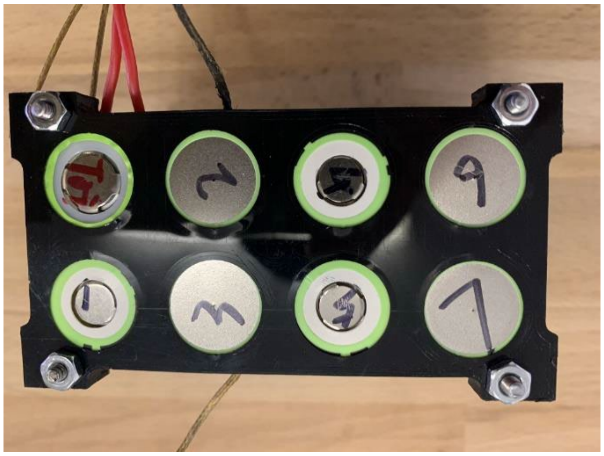


Figure 11: Cell Configuration

The heater power was set to approximately 20W and after 3.7 mins heating the ISC trigger cell reached 62°C and went into thermal runaway. The trigger cell reached 500°C after Thermal runaway (TR) activation. The hottest neighboring cell went up to 107°C. Another neighbor cell went up to 92°C. Other cells stayed below approximately 70°C. Hot gas exited the system at recorded temperatures as high as 150°C, see figure 12.

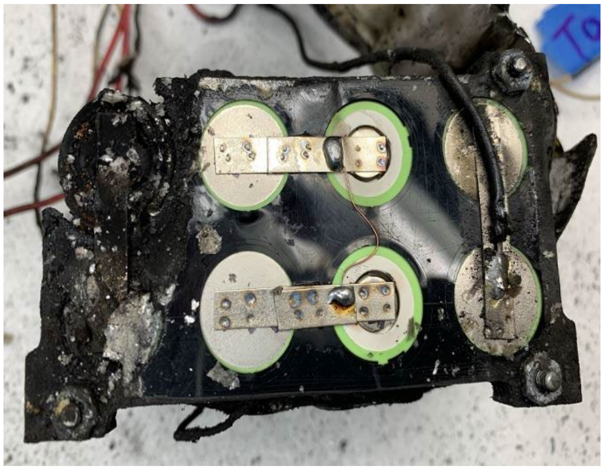


Figure 12: Post PPR Test Cell Pack Condition

After TR initiation, the pack voltage immediately dropped from 16.5V to 0.9V, then oscillated between 0V to 4V, and finally stabilized around 7V, see figure 13. Thermocouple T0, T1, T2, and T3 are the trigger cell and neighboring cell temperatures, respectively.

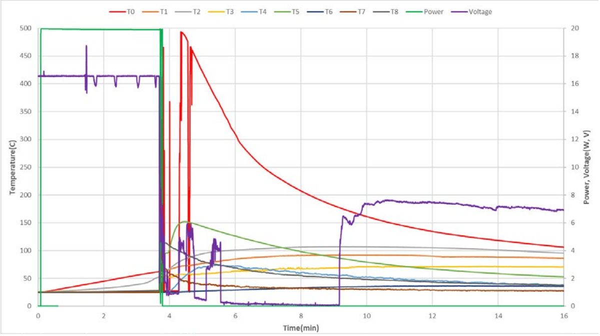


Figure 13: 4th Generation Thermocouple Data

The post-test DPA showed the ISC trigger cell had top vent and spin groove breach in TR. The jellyroll of the trigger cell stayed inside case. The fuse wire between the trigger cell and its parallel cell was blown in TR. Cell two had its current interrupt device (CID) open, see figure 14.

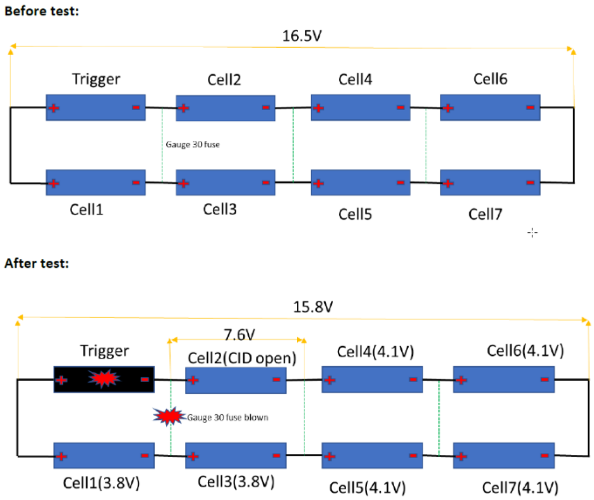


Figure 14: Before & After Cell Diagram

Cell 1 & cell 3 dropped in voltage to approximately 3.8V. All of the cells remained at approximately 4.1V. The side vent showed warping due to hot gasses exiting the flame arrestors, see figure 15.

Figure 15: Thermal Distortion on Side Vent

The pack lip showed a surface deformation most likely due to overheating. No cell-to-cell propagation occurred. No flame or sparks escaped from the pack. Testing was successful.

PPR testing was performed again on the 5th generation prototype post vacuum testing. Results were like the previous generation. The differences between the 4th and 5th generation can be seen in figure 16. The metal alloy plated surface gave an added rigidity and resistance to the TR event.

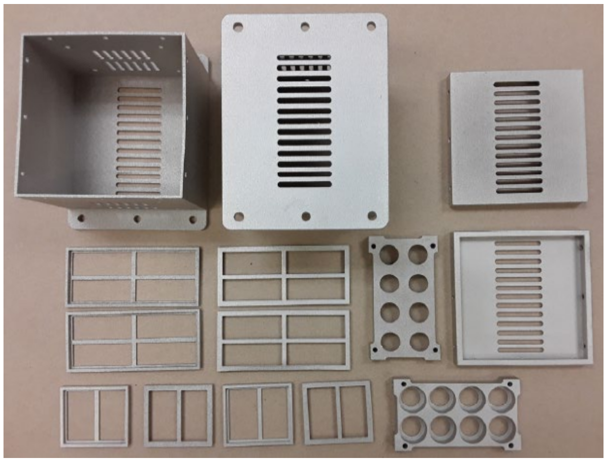


Figure 16: 3D Printed Parts with Specialized Finish

In testing the ISC cell reached a maximum temperature of 680°C after triggering at 73°C. None of the other thermocouples exceeded approximately 100°C. Dense white smoke issued from the vents during the test, but it was not ignited outside of the case. The power axis corresponds to the wattage supplied to the film heater on the trigger cell. In figure 17, the photo on the left shows the cell holder and thermocouple positions prior to insulating the cell holder with fiberglass tape, spotwelding bussing and fuse wires in place, and applying mica sheet over the bussing. The photo on the right illustrates thermocouple locations on the exterior of the case.

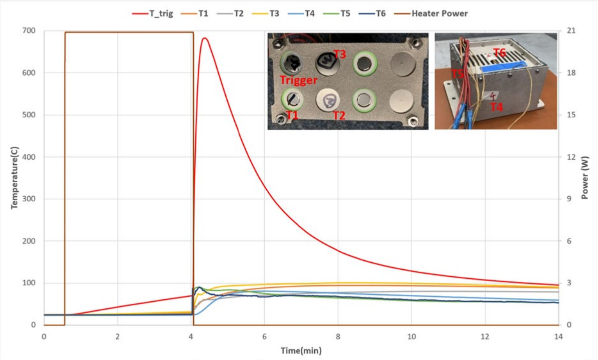


Figure 17: 5th Generation Thermocouple Data

The 5th generation was completely successful in that there was no cell-to-cell propagation, and the prototype did not allow combustion from the TR event. Visuals of the cell pack and complete prototype are shown in figure 18 and figure 19.

Figure 18: Post PPR Test - Cell Pack

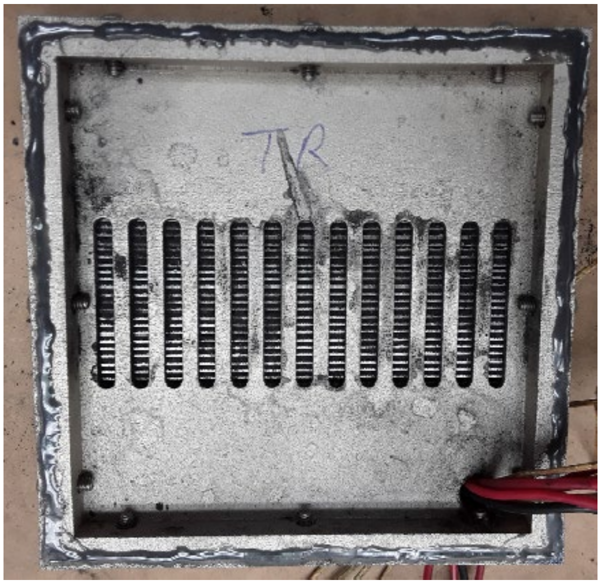


Figure 19: Post PPR Test - 5th Generation Prototype

Vacuum Testing

The purpose of this test would be to look for vulnerabilities. Ultimately, the test articles would be exposed to pressures below 10^{-5} Torr. The Prototype can be seen in the vacuum testing chamber shown in figure 20.

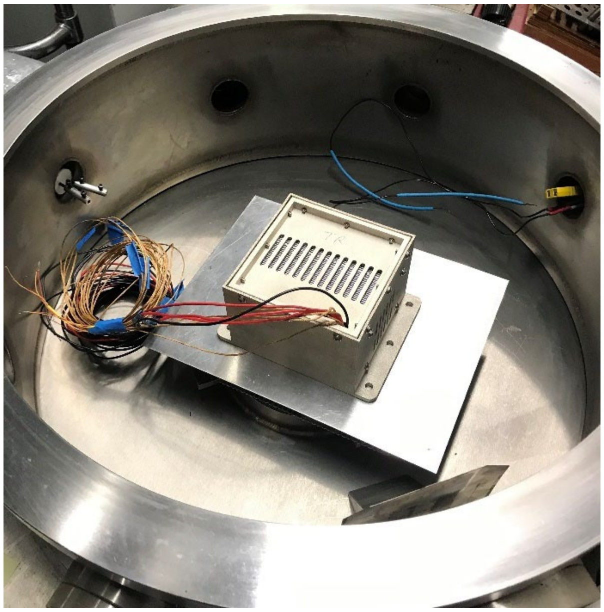


Figure 20: 5th Generation Battery Assembly in Vacuum Chamber

The prototype was placed in a diffusion-pump equipped vacuum system and was exposed to a pressure of 1 x 10^{-5} Torr. After the test, the battery was disassembled to allow inspection of the TRS pouches. No signs of leakage (coolant release or loss in mass) were observed. The battery was reassembled for use in a thermal runaway test. Results were successful.

CONCLUSION

As Li-ion battery systems continue to increase in power due system requirements and mission parameters it is crucial that battery safety and thermal protection become a standard in all designs. The design implementations shared and tested by KULR and MSFC will help to mitigate thermal runaway events of a single cell and allow for the qualification of crewed missions.

Path Forward

The testing performed to the 5th generation small sat battery prototype provides the validation of a technology readiness level of 4 (TRL4). KULR and MSFC have shown that the battery design can contain a single cell thermal event, safely vent the pressure and gas generated during a TR event, maintain structural integrity while subjected to vibrations from its environment, and maintain while under vacuum. KULR is working on reduced volume prototypes that will be commercial-off-the-shelf (COTS) capable for programs in need of a battery systems that meet the JSC 20793 Rev D requirements and/or are looking to reduce orbital debris and create a safer environment.

Acknowledgments

This project and technological advancements were made possible due to the expertise and guidance of Marshall Space Flight Center and all MSFC personnel that assisted in testing, all material processing contributions, and evaluation.

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