Battery A60 Fire Survivability Test 2 Preliminary

Document

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Revision History

Version #	Created By	Approved by	Release Date	Details
1	I Robinson	B Perry	2021-03-28	Initial Release

SPBES

1 Introduction

1.1 Scope of this Document

This document provides the preliminary results for an A60 fire 'survivability' test of the SPBES BBU battery module. The main purpose is to test the effectiveness of the BBU cooling system and verify that the system can withstand a prescribed heat level for a defined period of 60 minutes and remain operable to cool the battery and prevent charged cells from entering thermal runaway. This is the second in our series of testing to demonstrate the safety of the SPBES energy storage system, designed to be continued until we have demonstrated full safety of an entire system. In our first test, we successfully managed Part 1, but had to stop Part 2 when our external cooling circuit failed prematurely. We were only able to cook the battery at temperatures up to 840°C for 22 minutes, and while the results were positive and there was no damage to the cells, it was not a conclusive test.

The objective of this report is to offer a summary of the test results, our actual third-party test results will be available within April 21st for public review. The tests we conducted on March 24th are set out in two parts, as follows:

1. Ensure the cooling system can withstand 215°C for 60 minutes without the cells exceeding 150°C. 215°C being the maximum A60 insulated bulkhead surface temperature. This test will demonstrate that the battery will remain safe from thermal runaway and safe to operate whilst a fire exists on the other side of a battery room bulkhead.
2. Determine how long the cooling system remains functional (with cell temperature below 150°C) while exposed to 950°C. 950°C being the maximum temperature an A60 bulkhead has to withstand for 60 minutes. This test will demonstrate the survivability of the battery core (cells) and cooling system should the battery room experience a direct fire.

2 Results of the A60 215°C Test

Test 1 – 215°C for 60 minutes – A60 bulkhead maximum surface temperature

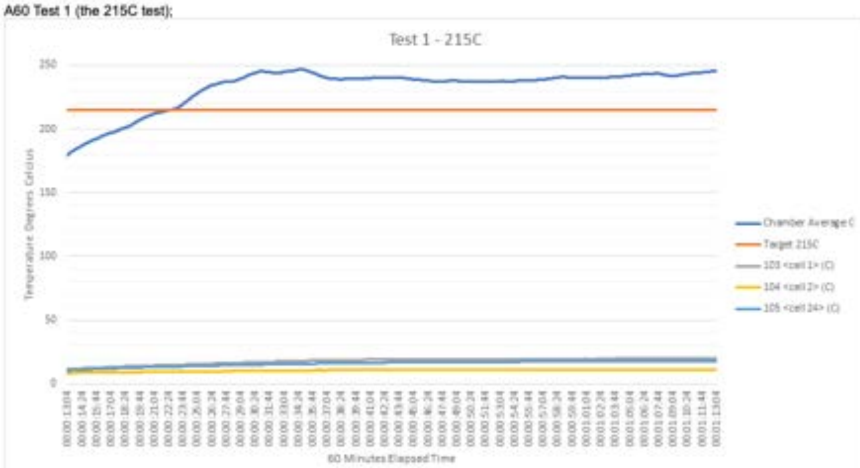
The test was completed without interruption or issue. The battery module withstood the 60-minute heat with no visual degradation externally, no leakage from the cooling system and certainly no thermal event from the cells. Cell temperature during the test never exceeded 19.7°C. Apart from a light covering of soot from the gas burners, the battery was in perfect condition. The heat during the test was brought up to and kept above 215°C over the duration of 60 minutes – it took 9 minutes and 35 seconds to get the temperature over 215°C, it was kept between 230°C and 250°C for the remaining test period. As the battery was in such good condition after Test 1, it was immediately used for the higher temperature Test 2 – the battery was not stripped down between tests.

Test 2 – IMO FTP Code Fire Heat Curve (up to 950°C) – A60 heat survivability

This test was also competed without interruption or issue. The heat rise was controlled to follow the IMO FTP Code heat formula, starting at 20°C and reaching 945°C – at most times the test heat was higher than this, reaching a maximum of 960°C towards the end. The plastic fittings within the battery were melted and destroyed by the heat, but the main battery core containing the cells and the cooling system was completely intact. During the test none of the lithium cells within the battery module went into thermal runaway – cells #1 temperature was recorded up to 154°C, with cell #24 reaching 396°C, however on examination of the cells, we have determined that this was due to melted plastics within the battery module reaching and affecting the thermocouple sensor. Cell #2 recorded a more realistic maximum temperature of 64°C after 60 minutes. We still have to do another test to validate the actual test of the cells with more reliably located sensors, but our conclusion of physical examination is that the temperature of Cell #2 is likely to be a maximum of all of the cells. There is no way the cells would have survived either a 154°C or a 396°C temperature without bloating and failure occurring, and none of the cells on inspection were damaged significantly physically at all. After cooling for 24 hours, the battery was dis-assembled, and the cells closely examined – all were intact with no thermal event evident although pin holes and minor gas release was suspected on cells #1 and #24. Cell #2 still recorded a voltage reading.

Graph of Test 1

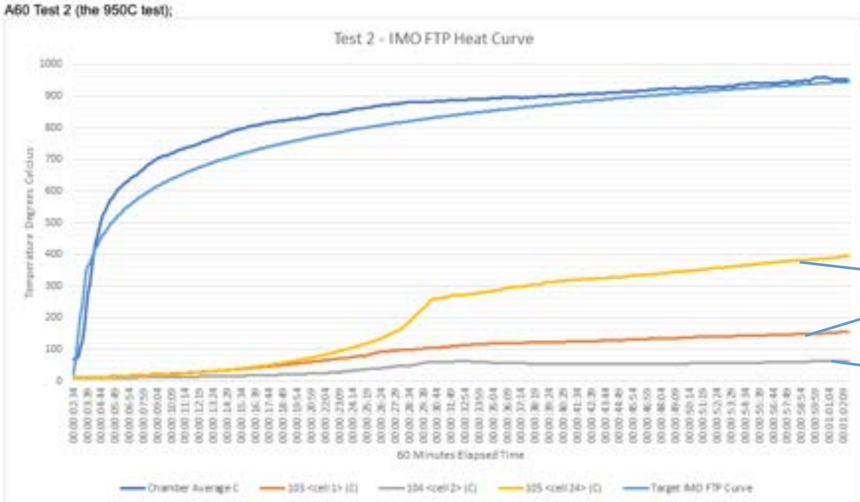
A60 Test 1 (the 215C test);



As there was no notable rise in temperature in the cells and no physical damage to any parts of the battery at all, we will not focus on the results of test 1 as outside of observing no actual physical impact of the battery occurred, we have nothing else to summarize. Another test focussed on this with post op testing of the BMS and all power electronics will be made on A60 Test 3.

Graph of Test 2

A60 Test 2 (the 950C test);



Temperatures due to badly placed temperature sensors- compromised by melting plastics

Expected to be maximum temperature but need to better locate sensors

Anecdotal Comments and Photographs of Testing

Battery in Rack mounted in Oven- Pre-Test

Standard SPBES Module and Racking, including all power electronics. Changes to standard battery for test are as follows:

1. Added fire-rated insulation to plumbing lines.
2. Added second gasket to cooling caps.

Battery on Exit of Chamber, post 950°C

This picture was taken post both A60 test 1 (survive A60 fire in an A60 room) and A60 test 2 (Battery Directly in A60 environment) and shows the impact of the high temperature on the total surfaces, note the drooping power connectors on the front of the battery. Wires are the temperature sensors throughout. All powder coating is effectively destroyed.

Removing Rack

Top plate removed, obvious impact of fire as everything was consumed. First indicator that the cells were intact was no obvious use of rear mounted vent, no indication of off gassing burning. All damage was obviously due to excessive heat.

Insulation added to the plumbing and wiring (test section) and was very effective in protecting components. In test one, December 13, we did not insulate the plumbing, and while it did not fail, it did start to deflect. With the insulation no deflection occurred.

First Look- Visual Results

Cooling cap covers removed, no damage to cooling caps or watertight seals on each cell carrier. No breech of IP67 seal around the top plate.

Power Ports started to melt; all of the power electronics were consumed totally. One thing we could have done better, will look to for design improvement, is to improve temperature rating effect of plastics.

Total Destruction of the Power Electronics & PCB

Better pictures highlighting the incredible effect of high temperature fires. If not insulated, everything is consumed. Cell Carriers were totally intact, no damage at all. These cell carriers were also used in same test in December, so this is the second time they have been through this test, with no visible material damage to the cell carriers or the cooling circuit.

Battery Core Prior to Disassembly

Prior to disassembly following day, the cell carriers were drained of water and then disassembled. No damage to the water seals on the liquid cooling system. No damage to the crimps of the plumbing system. Only slight visible impact to the cooling caps at either end, but no damage. Cooling caps have now been used through 2 A60 Fire tests with no detrimental effect.

Vent not damaged (high temperature seal intact also) and no visual signs of cell failure.

Back Plate Removed

On Removal of back plate, it was obvious that our compressive foam layer had been destroyed totally, but the graphite heat transfer sheet was totally intact, although it became more brittle than when new. The tab isolators were totally melted and probably represented the cause of the bag penetration that was evident in micro spots across the top of the cell. Interesting, the cell showed no real damage physically at all, no bloating, no sign of aggressive off gassing. It was remarkably intact. If we had a ceramic isolating insulation layer here, we think the damage of cell 24 would be the same as cell 1 and 2.

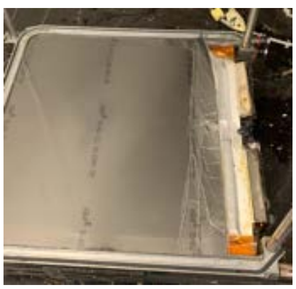
On the lower photo you can see that the temperature sensor was totally engulfed by melting plastic and this was true of cell 1 as well, so we consider the temperature readings of these cells as non-representative given the lack of physical damage to the cells.

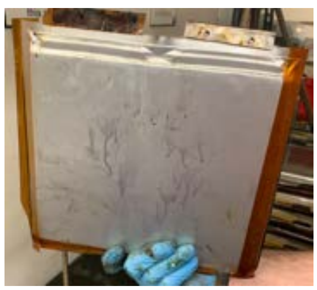
Disassembly of Stack

Both incredible evidence of the damage of a high temperature fire, and the validation of the engineering in our thermal management system.

Note the failed tab isolators, mostly melted on the side exposed to the heat, and the gasket that contains gas that survived fully intact on the outside ring- no damage at all. With the tab isolator removed, this cell carrier can be used again (it was already used in test 1 in December) and again.

Note Cell 2 below- fully intact, graphite sheet is perfectly intact.





Cells in great shape overall. Cell 1 and Cell 24 were both "0" VDC, so totally killed, but cell 2 was holding voltage 24 hours later. We are going to test with an insulating material at the outward faces of Cell 1 and cell 24 to validate we can survive all cells with voltage.

Conclusion

Our thermal management system is capable of protecting our lithium cells from contributing to a fire even directly in a A60 (up to 950°C) environment. The battery would not go into thermal runaway, and if the fire was contained, our batteries will be able to be safely drawn down in temperature for safe management. When we completed the fire testing, we took about 20 minutes with no fire present to bring the cells down to about 25°C again, and after waiting about 24 hours, we were able to safely disassemble the batteries without any danger to workers, with no dangerous gases being emitted. An SPBES Battery has very little chance to be a contributing factor to a fire and will present ships with minimum risk from damage from a fire.

Next Steps

We are very positive on what we have achieved, but all testings will always indicate a way to improve even further. Now that we are confident in our ability to manage thermal runaway effectively, we are now going to take the next steps to improve this risk even further:

1. Design a cooling system circuit that is completely capable of surviving an A60 fire to insure we have the cooling in operation and circulating during a fire. This will involve some discussion around power supply, safe locations and how to manage the plumbing routes, but we are confidant planning and engineering can support a practical solution.
2. It is not yet tested as to what effect would be of the cooling circuit being disconnected during an A60 fire, something that needs to be accounted for to understand the relative importance of keeping the cooling in circulation. We have tested the effect of internal cell failure without cooling and are able to manage an internal cell failure or multiple (up to 24 cells) cells failing without causing thermal runaway, but not as of yet from the perspective of being in an A60 fire.
3. Improve the battery design. The following:
    a. A heat barrier of ceramic insulation, rated at 1200°C or better would greatly improve the effect on cell 1 and cell 24 to prevent any heat impact from the front and back faces from being impacted by the heat.
    b. Add high heat temperature insulation around the main power cables to prevent a dead short from contributing to a thermal runaway event. We did wrap a common point of crossover and it did manage to prevent dead short from occurring, but this is an area of high risk to further validate.
    c. Consider a better way (better materials) to isolate the cell tab connectors from melting into the cell carrier space and prevent any possible failure of the cells at the cause of the melting of the cell tab connector materials.

Test 3 (Scheduled for End April)

Our next test for purposes of final validation of our batteries ability to prevent our lithium cells from contributing to a fire will be towards the end of April, when we will be performing two tests:

1. The A60 test 1 to a constant temperature of 215°C for one hour- with a fully functional module with 24 cells inside. We will perform a full function test prior to the test, and a full function test post the test to see what damage occurs and what functionality remains within the BBU unit under these conditions.
2. The A60 test 2, to a constant temperature of 950°C for one hour- with a fully functional module with 24 cells inside. We will do a post-op of the battery and all components to measure the actual temperature of the cells during the test and video any impact of exposure to the 950°C.

We invite all Type Approval Agencies and Flag authorities to witness this next test. The testing will as always be witnessed by a third party for validation, and the final test results will be reported by a third party for full validation and integrity.