BESAFE - FIRE AND EXPLOSION BEHAVIOR OF LITHIUM-ION BATTERIES

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Introduction

Lithium-ion batteries (LIBs) are essential for energy storage but pose fire and explosion risks. Ensuring the safe design of LIB applications, without compromising their practical use, is essential. This study was conceived to better understand LIB behavior, by investigating the emissions, the battery surface temperatures, the mass loss, the burning behavior, including the explosive atmosphere and the effect of water mist on the explosions. Test specimens were prismatic NMC batteries subjected to heat-induced thermal runaway (TR) at cell (0.17 kWh) and module (three modules, 2.07 kWh/module, 12 cells/module) levels. The tests were conducted in a tailored 12 m³ test compartment.

Methodology

The tests were performed in the DBI MOBAT - mobile battery testing facility, which consisted of a refurbished 20 ft container, divided into a testing compartment and control room for the installed equipment. The MOBAT is instrumented with FTIR gas analyzer and oxygen analyzer, and other instrumentation can be added depending on test requirements, such as: thermocouples, load cells, cameras, semi-conductor gas sensors, electrochemical cells (H_2, CO) and voltmeters. Particle size distribution measurements were also performed during the cell level tests. The configuration of MOBAT slightly changed from the cell to the module level, as presented in Figure 1.

a) **b)**

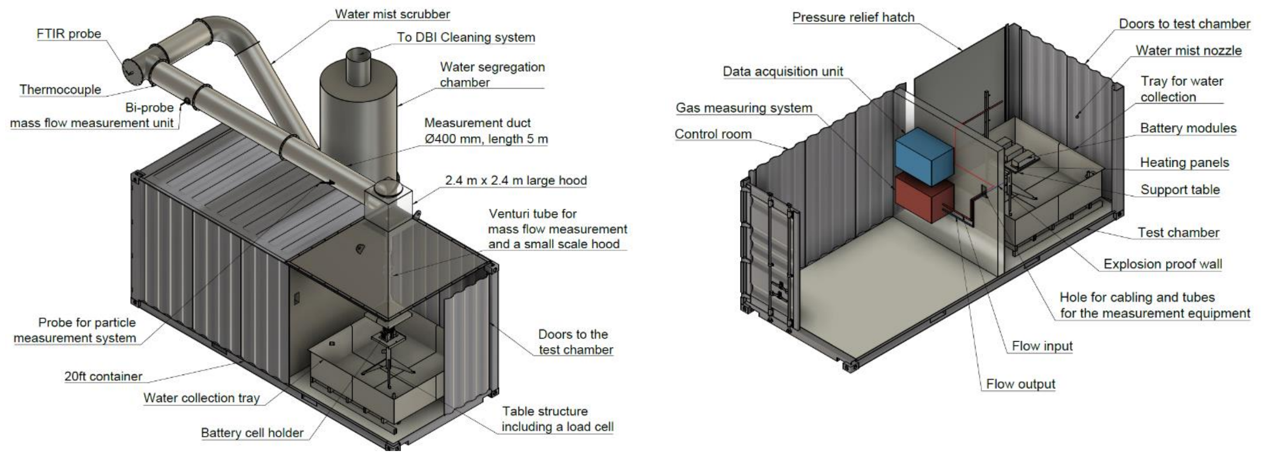

Figure 1. MOBAT configuration at the a) cell level, and b) module level.

Ten cell-level tests at 50% state of charge (SOC) were conducted to examine emissions during battery failure without ignition. In contrast, four module-level tests at 75% SOC aimed to initiate simultaneous thermal runaway (TR) across all 36 parallel-connected cells (three modules), leading to the release of gases and particulates. Explosions were then intentionally triggered using remotely controlled spark igniters. During the breakdown the fire atmosphere was sampled. Figure 2 shows the instrumented cell and modules used in the test. The size of the module was 14 × 6 × 4 1/4 inches, weight 23 lb, and the module’s voltages was the following: max 49.8 V, nominal 44.4 V, min 32.4 V.

In the cell-level tests, the cells were heated on the two long sides, with an average temperature rise of 7.5°C/min, and data was collected for one hour.

In the module-level tests, the modules were heated from below with an average temperature rise of 2.5°C/min.

The module-level tests were designed to increase the likelihood of the burning and explosion of the vented gases. The thermal runaway was initiated, and the contained gases were ignited with spark ignitors. In two of the module tests, water mist was used at two different flow rates (36 L/min and 51 L/min) for at least eight minutes, to observe the effect on the explosions.

a) b)

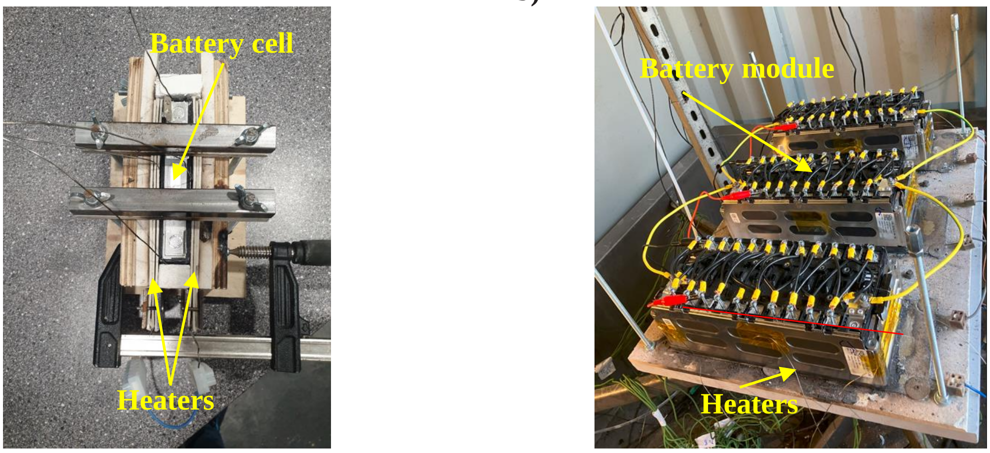

Figure 2. a) Instrumented cell and b) instrumented modules during the tests.

Main findings

The main results are presented in Table 1. The average temperatures given in Table 1 are based on two temperature measurements on the cell level, and six temperature measurements at the module level. All thermocouples were placed at the interface between the heater and the cell/module surface.

Gradual heat-induced battery failure was characterized by two distinct venting events, both releasing effluents. The first venting occurs as built-up gas break the cell safety valve which was detectable by a hissing sound, visual ejection of material, surface temperature drop, particle emission, and a sudden, intense release of small molecule decomposition products, e.g., CO, CH_4, C_2H_4. Once the valve was opened, gases continued to escape the battery cell. By complete failure of the battery cells, the voltage across the electrodes dropped and the surface temperature rose rapidly, which was associated with a second venting detectable by sound and visual ejection of effluents. In all tests, the first and second venting occurred at surface temperatures of 200 – 281˚C and 233 – 294˚C, respectively.

Explosions occurred in three out of four module-level tests, generating sufficient force to open the pressure relief hatches of the MOBAT facility. Figure 3 shows video snapshots during the explosion events captured during these tests.

a) b) c)

Figure 3. Video snapshots during explosion events in module level tests: a) M 1 - view from inside the container; b) M 2 - view from inside the container; c) M 4 - view from outside the container.

Table 1. Summary of the results from cell and module level tests. Average temperatures between heaters and cell/modules are given.

	Test No.	**First venting**[a] *time [min] (temperature [˚C])*	**Second venting**[a] *time [min] (temperature [˚C])*	**Voltage drop** *time [min] (temperature [˚C])*	**Explosion**[a] *time [min] (temperature [˚C])*	**Relative mass loss** *[%]*	**Water mist**[b] *time [min]*
Cell-level tests	1	Ignition at 19 minute was observed.				11.14	-
	2	22 (200)	30 (262)	28 (233)	None	14.85	-
	3	24 (207)	31 (271)	28 (246)	None	Not available	-
	4	22 (214)	29 (261)	27 (246)	None	14.98	-
	5	23 (213)	31 (270)	30 (261)	None	14.08	-
	6	21 (219)	27 (254)	27 (253)	None	12.16	-
	7	Test failed early due to heater power loss				13.85	-
	8	25 (217)	31 (241)	31 (242)	None	14.39	-
	9	23 (215)	Not available[c]	29 (241)	None	12.75	-
	10	24 (220)	Not available[c]	29 (254)	None	12.95	-
Module-level tests	M 1	78 (220)	Not available	94 (249)	101 (557)[d]	24.41	-
	M 2	75 (281)	Not available	83 (280)	77 (286)	Not available	84–92 (36 L/min) & 104–111 (51 L/min)
	M 3	81 (270)	Not available	103 (294)	None[e]	Not available	106–126 (36 /min)
	M 4	65 (221)	Not available	Not measured	99 (271)	Not available	-

[a] Based on visual observations
[b] Based on notes
[c] Result is not available due to technical issues with camera recording
[d] Explosion time was estimated based on visual observations which creates uncertainties in the temperature readings
[e] No explosion was observed, nevertheless a violent, momentum driven flaming was observed starting at around 108 min

Summary and conclusions

In the cell-level tests, the first venting and the voltage drop occurred within a range of 4 minutes. The relative mass loss was in the range of 11% - 15%. It is concluded that the test method provided repeatable results.

During the module-level tests the burning events were observed in all tests while explosions were observed in three out of the four tests. Nevertheless, the capability of the water mist to limit the explosion hazards is still unclear and needs to be further investigated. In these tests the water mist was applied later than usual, because the aim was to reach the second venting and to create explosive atmosphere.

Acknowledgement

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