Nexceris Li-Ion Tamer Testing Summary

Test Report

Prepared For:

Nexceris Inc.
404 Enterprise Dr.
Lewis Center, Ohio 43035

Energy Safety Response Group, LLC
8350 US Highway 23 North
Delaware, OH 43015

www.energyresponsegroup.com
1-833-SAFE-ESS

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PROJECT INFORMATION

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Prepared by:

Nick Warner
Founding Principal
nick.warner@energyresponsegroup.com

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Contents

Executive Summary

The following report contains comparative data from several detection methodologies in lithium-ion battery failure testing. The technologies compared included the following:

- Li-ion Tamer™ (off-gas detection)
- Aspirating Smoke Detection System 1 (ASD-1)
- Aspirating Smoke Detection System 2 (ASD-2)
- CO_2 Gas Detector (ppm)
- CO Gas Detector (ppm)
- H_2 Gas Detector (ppm)
- CH_4 Gas Detector (%v LEL)

The primary goal of this testing was to understand how quickly the monitoring devices detect initial cell venting (i.e. the off-gas event) and thermal runaway events during battery abuse tests.

Summary of Findings

- The earliest indication of battery abuse and imminent failure is provided through off-gas event detection. The Li-ion Tamer sensor provided consistent early warning for the abuse conditions in all tests by an average of 15 minutes and 12 seconds.
- Single gas detectors (such as hydrogen, carbon monoxide, carbon dioxide, and methane lower explosive limit) did not alarm during the off-gas event but did respond to thermal runaway.
    - This is consistent with findings from UL during UL 9540A Installation Level Tests with Outdoor Lithium-ion Energy Storage System Mockups report.[1]
- ASD-1 and ASD-2 alarmed during the thermal runaway in each test but did not respond during the off-gas event.

Technical Background

Lithium-ion batteries

Lithium-ion batteries have many applications, from consumer electronics to electric vehicles (EV) The recent global adoption of EVs has caused a huge demand for lithium-ion batteries, generating cost reductions due to economies of scale in manufacturing, thus enabling more applications. Among these new applications is the utility-scale stationary energy storage market, where utilities worldwide have found many uses for batteries on their grid, including peak shaving, transmission deferral, renewables bolstering, and many more use cases.

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[1] https://ulfirefightersafety.org/docs/UL9540AInstallationDemo_Report_Final_4-12-21.pdf

The utility market is poised for significant growth, increasing from 4.5 GW of installed capacity in 2020, to 10 GW of installed capacity in 2021[2]. However, this has come with a number of safety issues for this nascent industry. The Electric Power Research Institute (EPRI) has reported 42 catastrophic fires in their newly released BESS Failure Event Database[3]. Much of the database contains events occurring after 2018.

Stationary energy storage systems

The utility-scale energy storage market is constantly evolving and with that, it is necessary that the safety systems keep up with this evolution. Energy storage systems (ESS) commonly utilize lithium-ion battery cells as their core component. These cells are arranged into a battery module which has a local battery management system (BMS). The BMS controls the batteries within the module, keeping their charging characteristics within their manufacturer's specifications. Several battery modules are then arranged into a battery rack which has a master controller, sometimes referred to in code as an EMS (energy management system) that controls all the modules. The quantity of battery racks is scaled to meet the needs of a particular application and the battery racks are arranged in a system with balance controls to allow for proper interfacing to utility-grade equipment.

Abuse factors

The root cause of the 42 catastrophic fires is widely debated; however, the industry has landed on three primary methods for forcing a lithium-ion battery to fail. These methods are overheating, overcharging, and nail penetration or other physical damage. These are regarded as thermal abuse, electrical abuse, and mechanical abuse, respectively.

Detection methodologies

There were two detection methodologies studied within the tests described below: smoke detectors and gas detectors. The ASD-1 and ASD-2 are aspirating smoke detectors which detect smoke by light scattering principles to quantify the amount of smoke present. Smoke concentration is measured in percent obscuration per meter. The gas detectors studied include the Li-ion Tamer off-gas monitor, CO_2 gas (ppm) detector, CO gas (ppm) detector, H_2 gas (ppm) detector, and CH_4 equivalent lower explosive limit (LEL) detector (catalytic bead sensor type). The quantitative ranges are summarized in the table below:

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[2] https://pv-magazine-usa.com/2021/02/17/u-s-poised-to-lead-utility-scale-energy-storage-market-in-record-year/#:~:text=The%20global%20utility%2Dscale%20energy,continuing%20to%20lead%20the%20way.&text=%E2%80%9CThe%20global%20market%20for%20energy,2020%20to%2017%20in%202022

[3] https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

Table 1. Quantitative ranges for detection methodologies studied.

Detector	Detection Range
Li-ion Tamer off-gas monitor	Single cell vent detection
ASD-1	0 - 35 % obscuration/m
ASD-2	0 - 35 % obscuration/m
H_2 Gas Detector	0 - 1000 ppm H_2 in air
CO Gas Detector	0 - 300 ppm CO in air
CO_2 Gas Detector	0 - 5000 ppm CO_2 in air
CH_4 LEL Gas Detector	0 - 100%v of CH_4 LEL (0 - 5%v CH_4 in air)

Li-ion Tamer detection methodology

The Li-ion Tamer off-gas monitor works differently than most commercial gas detectors, where there is a pre-programmed detection threshold. The Li-ion Tamer detection methodology is based on a rate of rise principle, where the rate of gas release is used to determine whether the alarm should activate. The detection threshold is based on empirical data from application specific testing, where cells used in industry are failed in representative volumes within representative air flow patterns.

The Li-ion Tamer off-gas monitor emits four voltage states, 0.1 VDC (error), 0.25 VDC (warm up), 0.5 VDC (ready), 3.0 VDC (alarm). The error state and warm up state can be effectively ignored within the context of this report.

Experimental Method

All tests were performed at Energy Safety Response Group' (ESRG) Alternative Energy Research and Training Center. There were six total experiments performed in one of two experimental set ups:

- Setup A was a purpose-built battery failure testing room.
- Setup B was a shipping container that allowed free airflow.

The two smoke aspirating systems were configured to have comparable transport times; the aspirating pipe length varied depending on the experimentation setup. Further details on the configuration of the aspirating units are in Table 2, below.

Table 2. Key settings for smoke aspirating systems.

Device	Fan Speed	Detection Mode	Alarm Sensitivity
ASD-1	4	-	Lowest Setting
ASD-2	High	Ultra-sense	PS1

Setup A

Physical setup

The room where the cells were tested is a purpose-built battery failure testing area that has dimensions of approximately 16’ x 14’ x 12’ (5.3m x 4.5m x 4.0m). Batteries were failed near the middle of the room, approximately 2 feet above the ground. Half of the failure testing location is shown in Figure 1.

Figure 1. Purpose-built battery failure testing area for Setup A.

Obscuration detectors/gas monitors placement

On the vent side of the cell, the aspirating sampling points and standalone Li-ion Tamer off-gas monitor were placed 4 feet (1.2m) horizontally and 7 feet (2.1m) vertically from the cell as shown in Figure 2. The aspirating pipe was 35 feet (10.5m) in length. The aspirating pipe was plumbed outside of the testing room into the data acquisition area shown in Figure 3.

Figure 2. Aspirating sampling points and standalone Li-ion Tamer off-gas monitor. The cell failure location is located at the bottom right, just out of the photo.

Figure 3. Data acquisition area of Setup A.

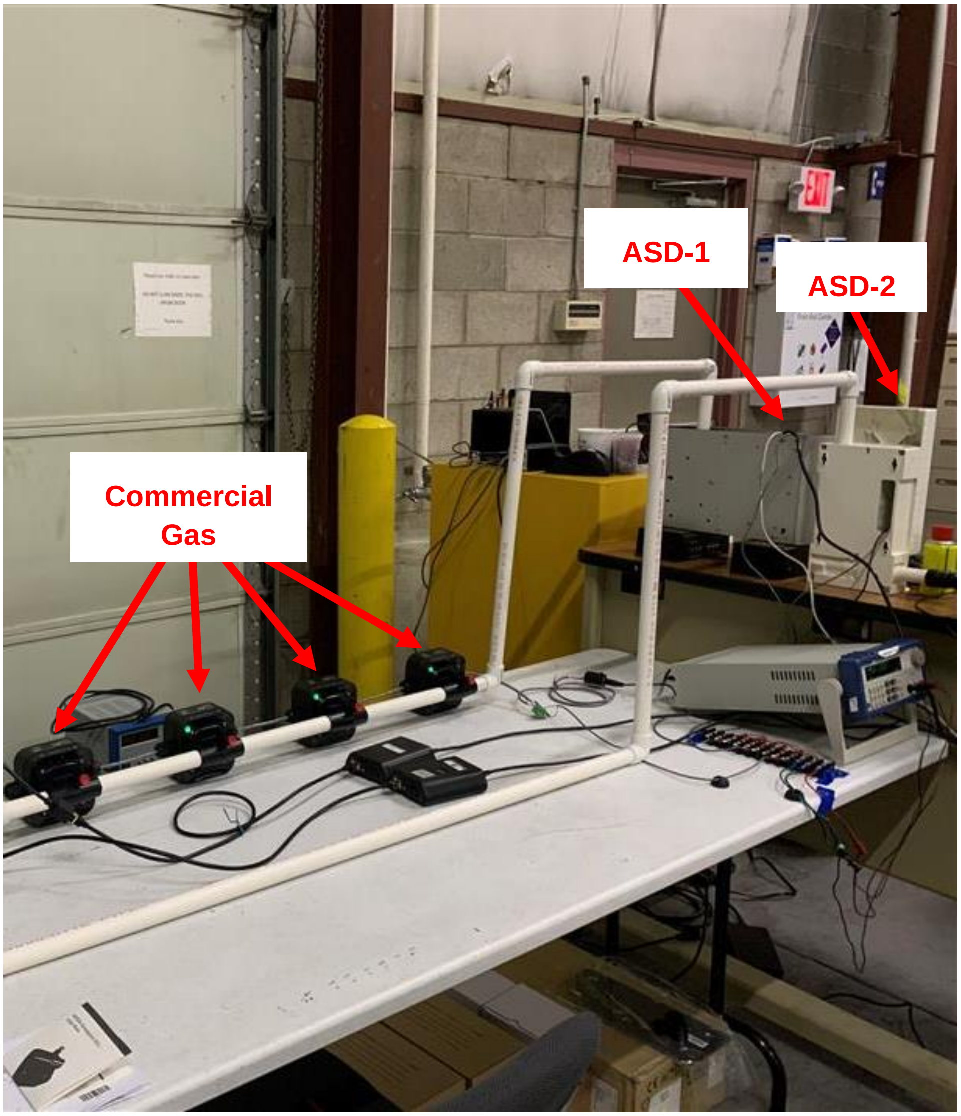

Figure 4. Aspirating pipe with commercial gas detectors, ASD-1, and ASD-2.

All aspirating pipe and sampling points for the gas detectors were implemented as per the manufacturer's specifications, with the setup shown in Figure 4.

Setup B

Physical setup

The room where the cells were tested is a purpose-built battery failure testing area with dimensions of approximately 8' x 8' x 10' (2.4m x 2.4m x 3.0m). Batteries were failed near the middle of the room, three feet from the ground. The failure testing location is shown in Figure 6.

Figure 6. Container testing space for Setup B.

Obscuration detectors/gas monitors placement

On the vent side of the cell, the aspirating sampling points and standalone Li-ion Tamer off-gas monitor were placed 3 feet (0.9m) horizontally and 2 feet (0.6m) vertically from the cell as shown in Figure 7. The aspirating pipe was 16 feet (4.9m) in length. The aspirating pipe was plumbed outside of the testing room into the data acquisition area shown in Figure 8.

Figure 7. Aspirating sampling points and standalone Li-ion Tamer off-gas monitor. The cell failure location is located at the bottom left, on the hanging platform.

Figure 8. Data acquisition area of Setup B.

Test Results

There were seven experiments performed, summarized in the table below.

Table 3. Summary of the testing conditions

Test ID	Cathode chemistry	Form Factor	Capacity	Abuse factor	Abuse severity	Test Setup
1	LFP	Prismatic	280 Ah	Overcharge	0.5C	A
2	LFP	Prismatic	280 Ah	Overcharge	0.5C	A
3	NMC	Pouch	63 Ah	Overcharge	0.5C	A
4	LTO	Pouch	34 Ah	Overcharge	2C	B
5*	LTO	Pouch	34 Ah	Overcharge	2C	B
6*	LFP	Prismatic	280 Ah	Overcharge	0.5C	B

*Indicates experiments where thermal runaway was mitigated by removing the abuse upon off-gas detection by Li-ion Tamer.

Experiments 1 through 5 are presented with three graphs in the following pages. The first graph presents the in-line Li-ion Tamer off-gas monitor and cell temperature. This graph shows when the cell initially vented gas (as detected by the Li-ion Tamer off-gas monitor) and when the cell entered thermal runaway (as demonstrated by a sharp temperature increase shown through the measured cell temperature). The second graph shows the LT off-gas monitor signal and smoke aspirated detectors between 0 and 5% obscuration per meter with thermal runaway notated by a red line. The third graph shows the LT off-gas monitor signal and the commercial gas detectors with thermal runaway notated by a red line.

Experiment 6 is presented in one graph. This graph presents the Li-ion Tamer off-gas monitor and cell temperature. Experiments 5 and 6 demonstrate Li-ion Tamer's ability to prevent thermal runaway by detecting the initial off-gas event. Upon off-gas detection, the abuse was removed. The cell was allowed to cool, showing a prevention of thermal runaway.

Test ID 1 – LFP Prismatic 0.5C Overcharge

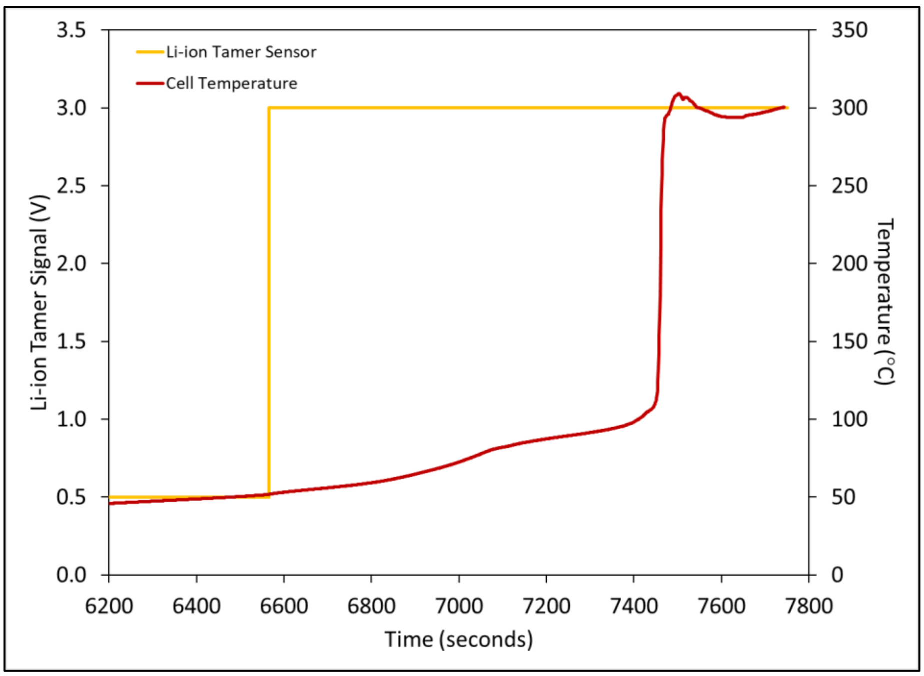

Figure 9. Test ID 1 off-gas event and thermal runaway quantification. The off-gas event occurred at 6566 seconds and thermal runaway occurred at 7453 seconds, 14.8 minutes apart.

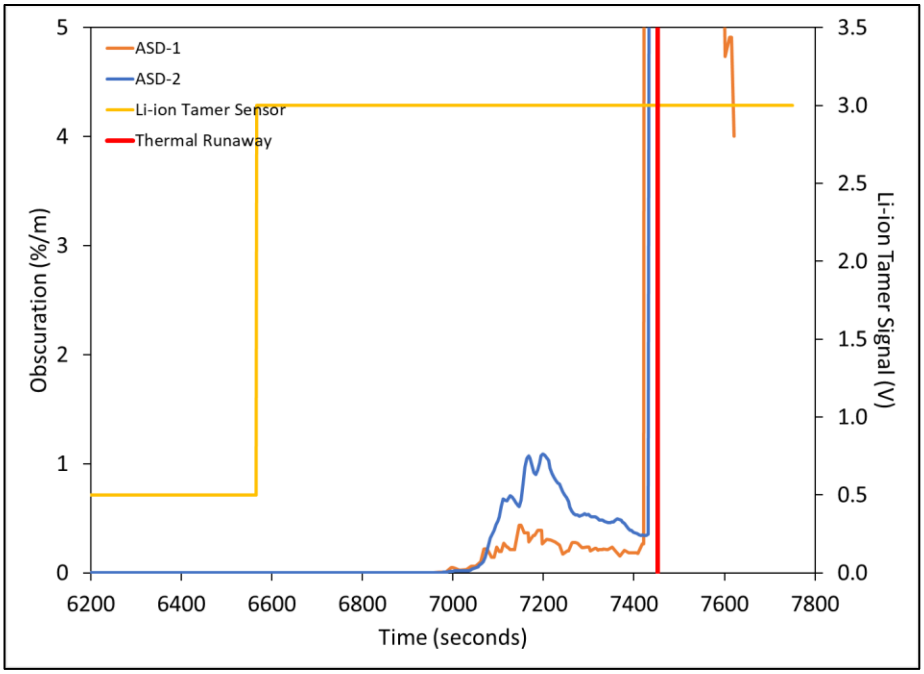

Figure 10. Test ID 1 off-gas monitor and obscuration detector response with thermal runaway noted by a red vertical line.

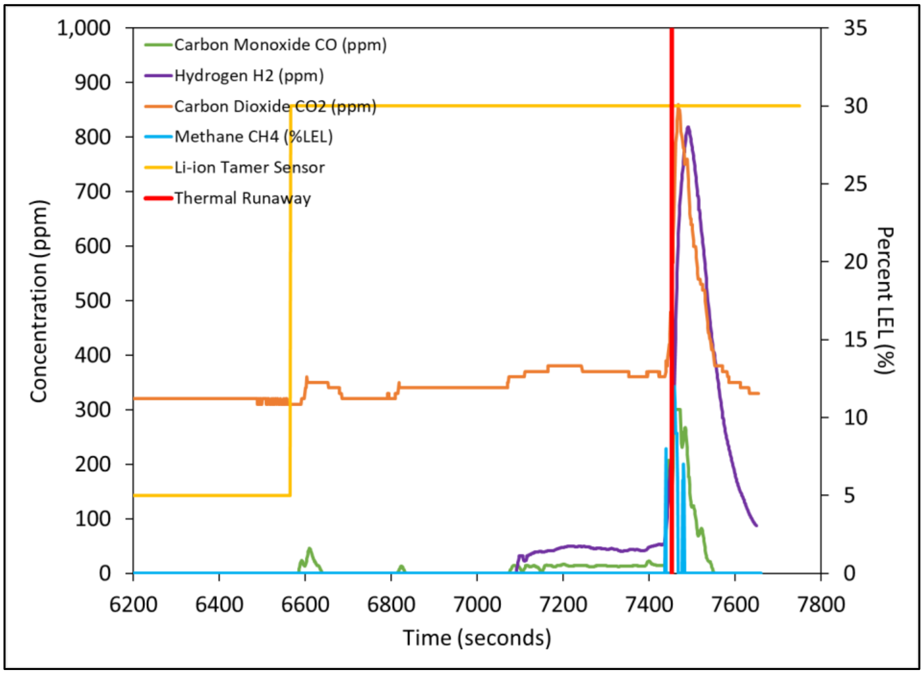

Figure 2. Test ID 1 gas monitor responses with thermal runaway noted by a red vertical line.

Test ID 2 – LFP Prismatic 0.5C Overcharge

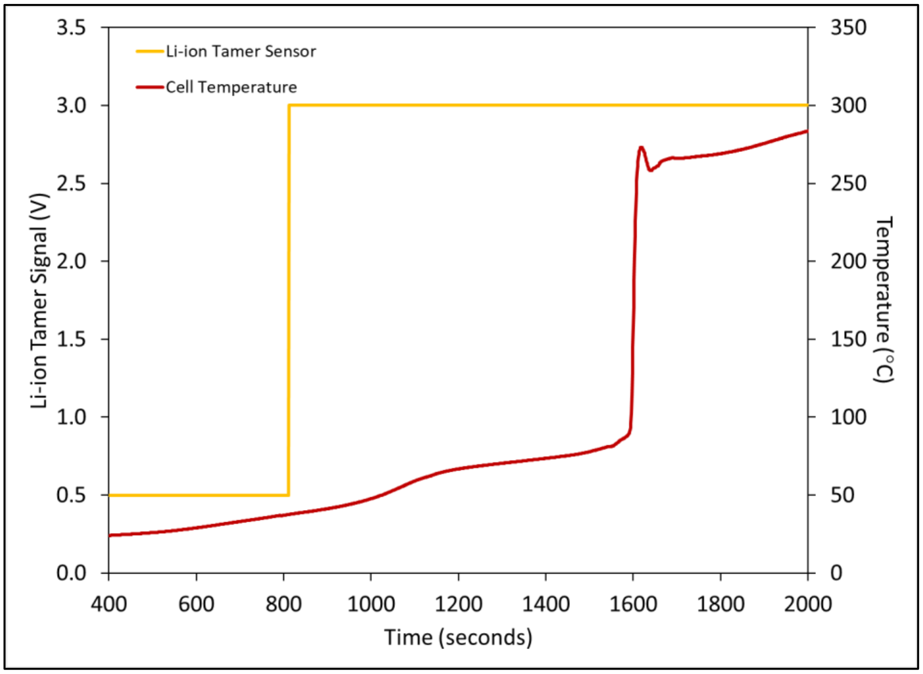

Figure 32. Test ID 2 off-gas event and thermal runaway quantification. The off-gas event occurred at 812 seconds and thermal runaway occurred at 1594 seconds, 13.0 minutes apart.

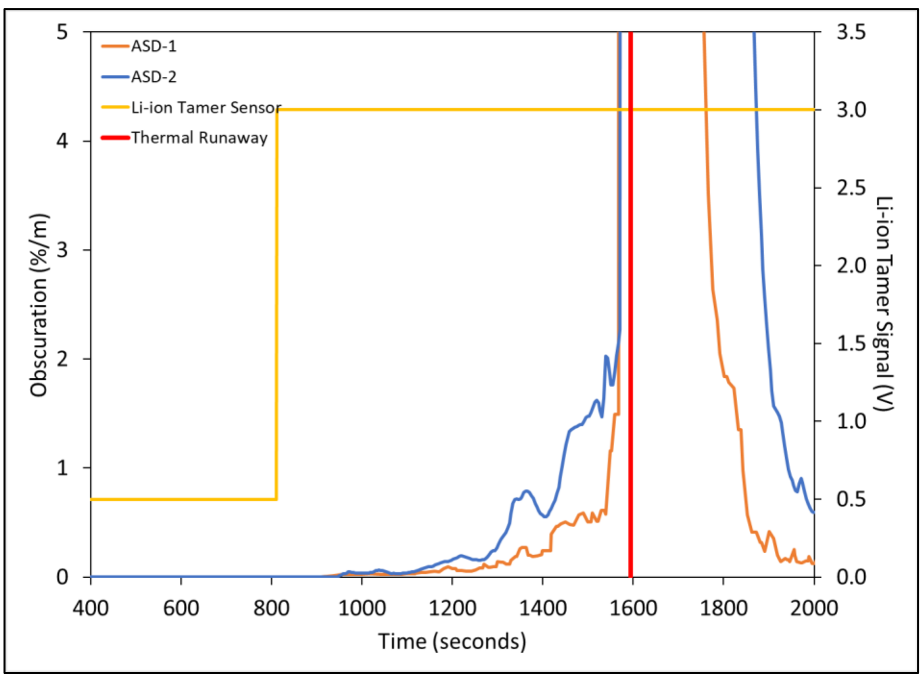

Figure 13. Test ID 2 off-gas monitor and obscuration detector response with thermal runaway noted by a red vertical line.

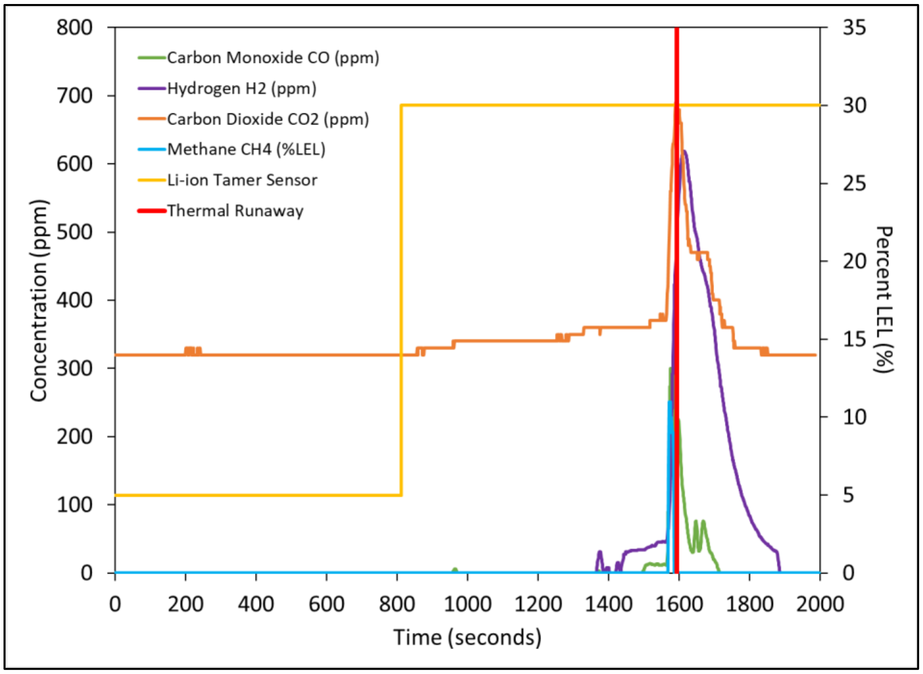

Figure 4. Test ID 2 gas monitor responses with thermal runaway noted by a red vertical line.

Test ID 3 – NMC Pouch 0.5C Overcharge

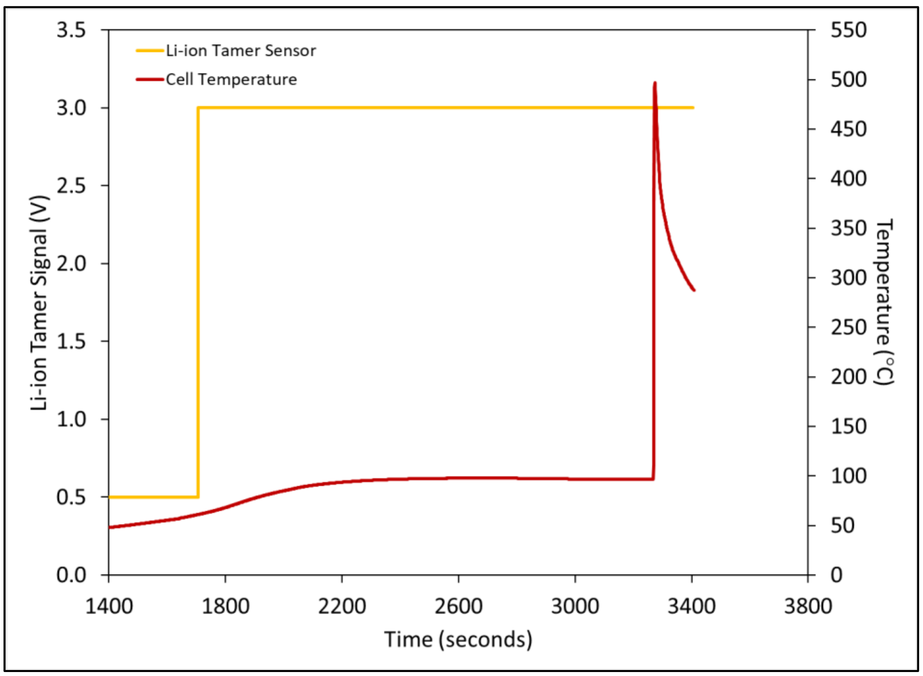

Figure 15. Test ID 3 off-gas event and thermal runaway quantification. The off-gas event occurred at 1706 seconds and thermal runaway occurred at 3270 seconds, 26.0 minutes apart.

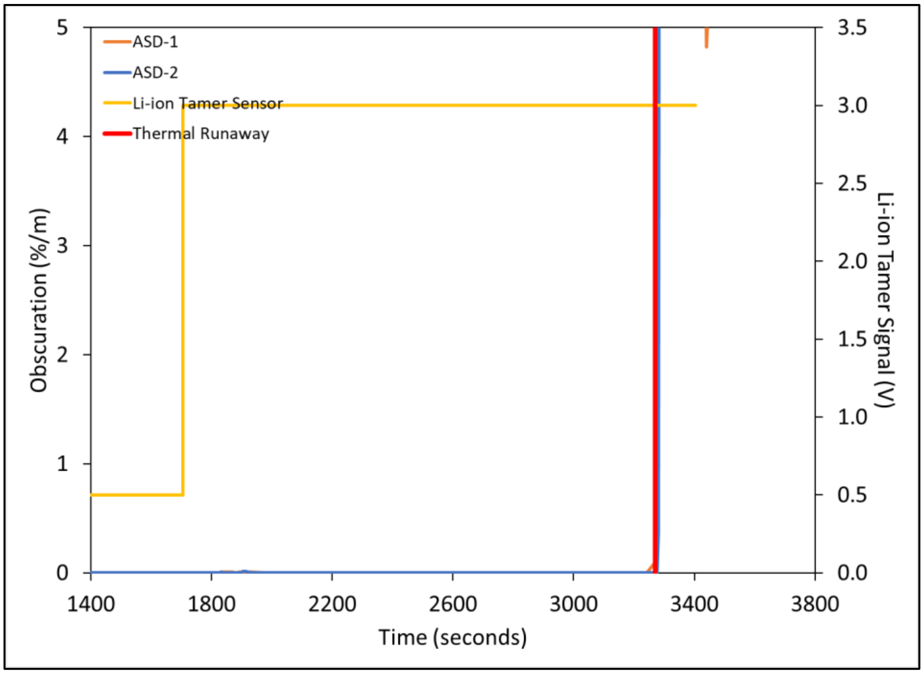

Figure 16. Test ID 3 off-gas monitor and obscuration detector response with thermal runaway noted by a red vertical line.

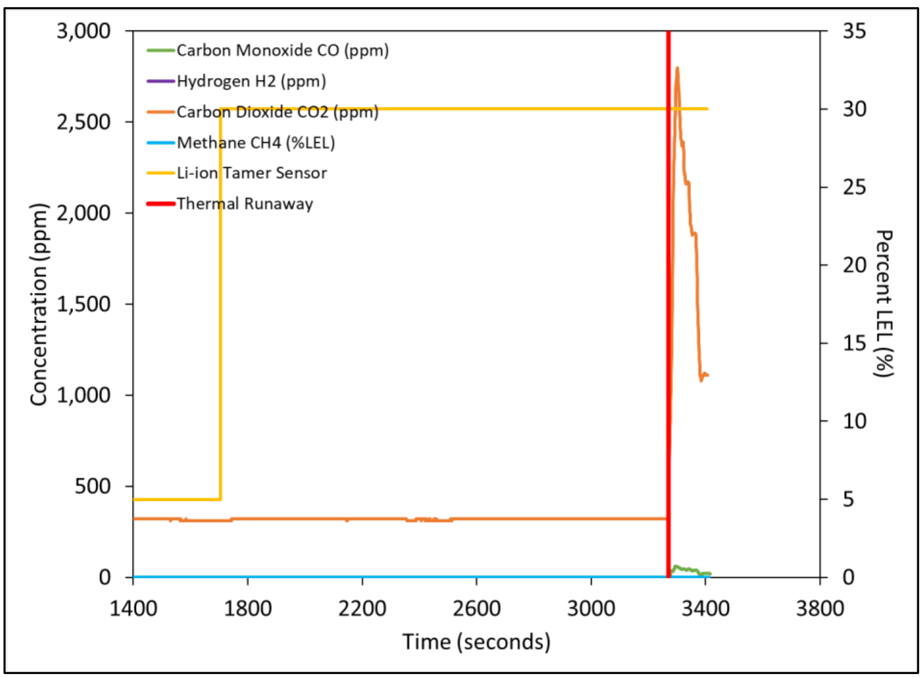

Figure 5. Test ID 3 gas monitor responses with thermal runaway noted by a red vertical line.

Test ID 4 – LTO Pouch 2C Overcharge

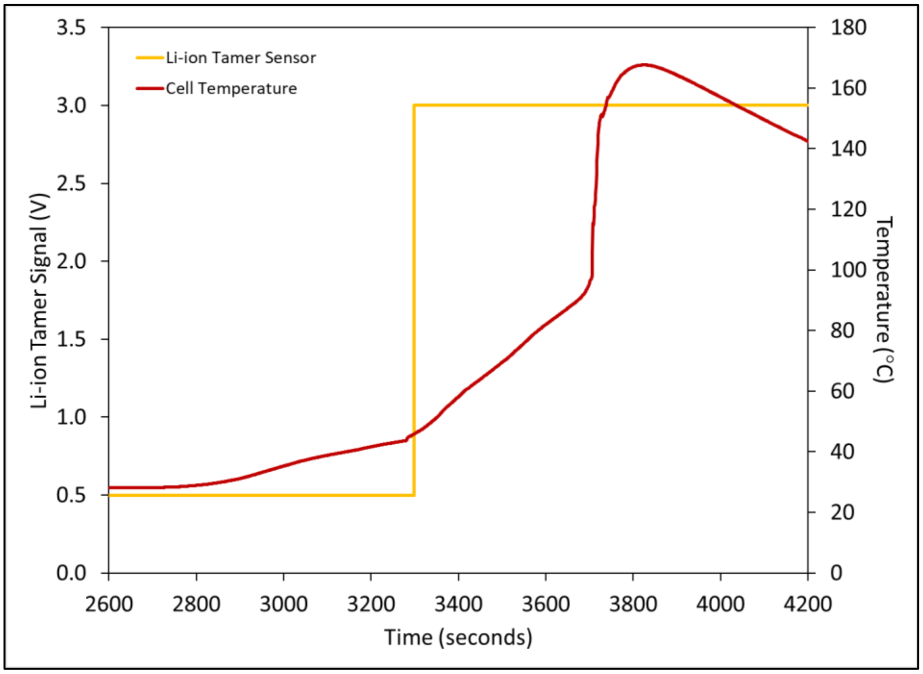

Figure 18. Test ID 4 off-gas event and thermal runaway quantification. The off-gas event occurred at 3292 seconds and thermal runaway occurred at 3705 seconds, 6.9 minutes apart.

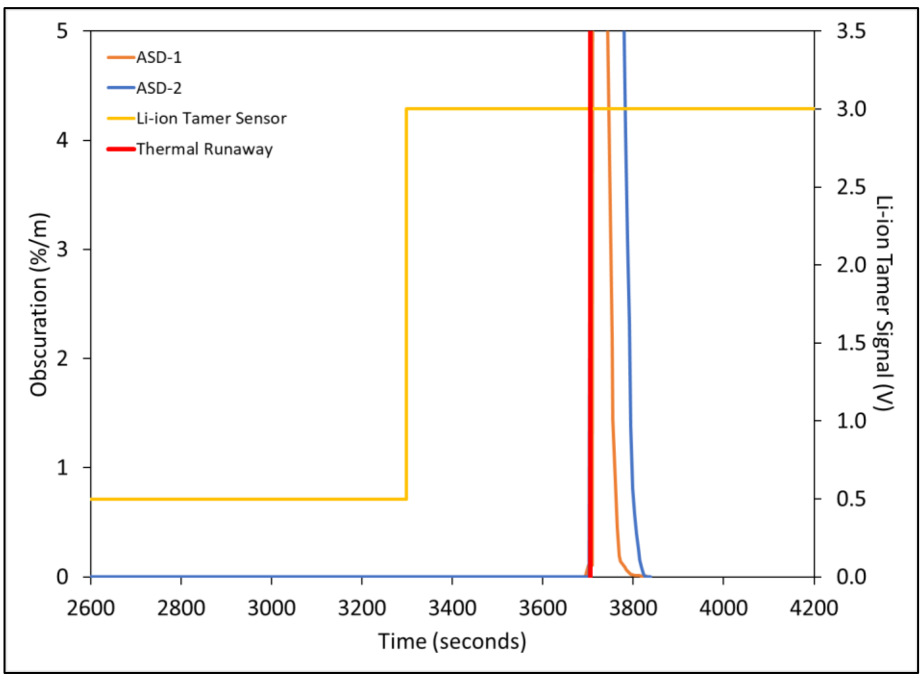

Figure 19. Test ID 4 off-gas monitor and obscuration detector response with thermal runaway noted by a red vertical line.

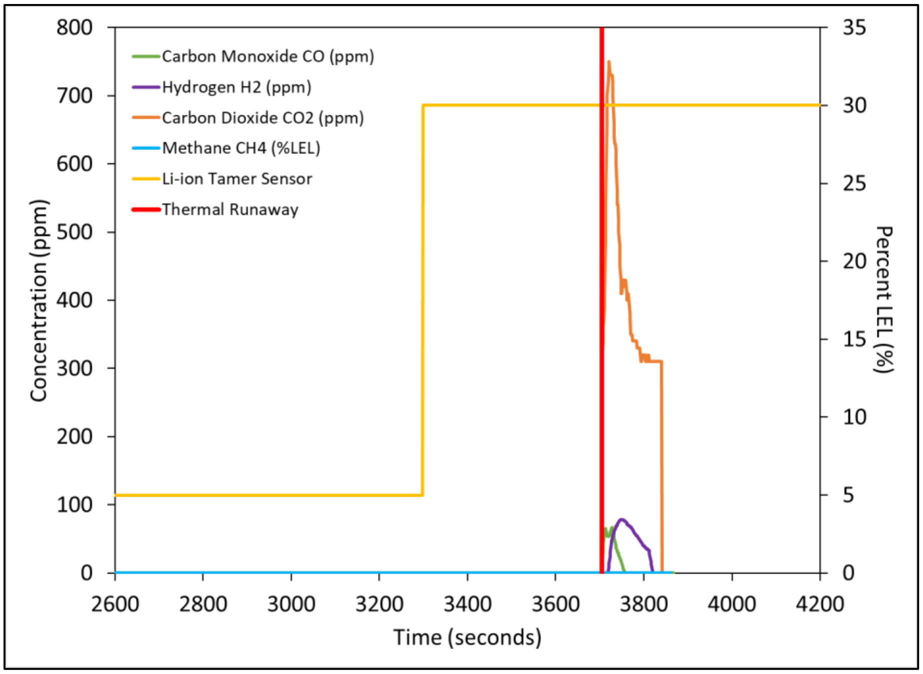

Figure 20. Test ID 4 gas monitor responses with thermal runaway noted by a red vertical line.

Test ID 5 – LTO Pouch 2C Overcharge Failure Prevention

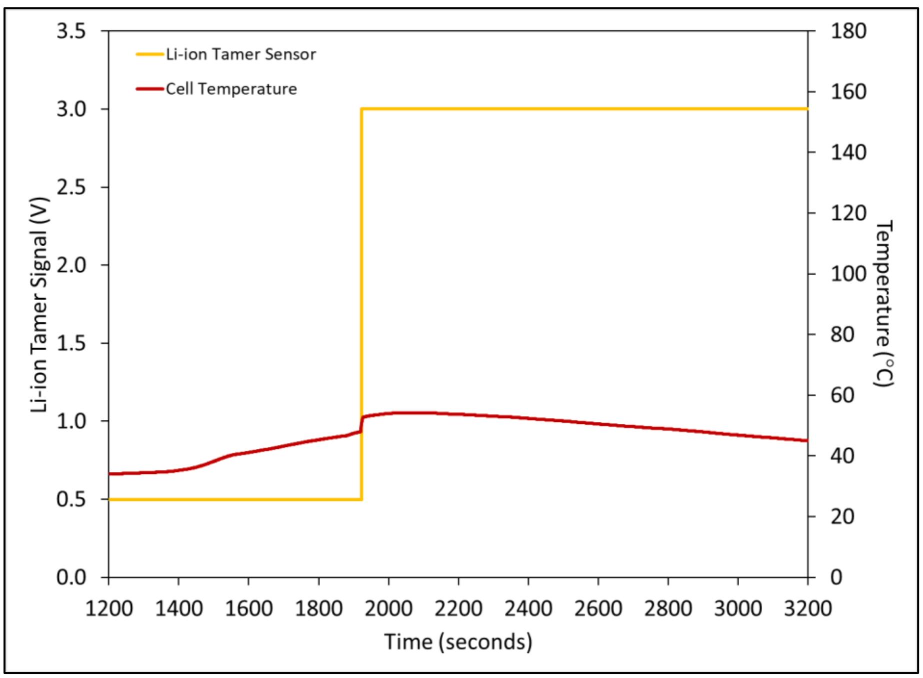

Figure 21. Test ID 5 off-gas event and thermal runaway quantification. The off-gas event occurred at 1900 seconds and thermal runaway was prevented by removing the abuse.

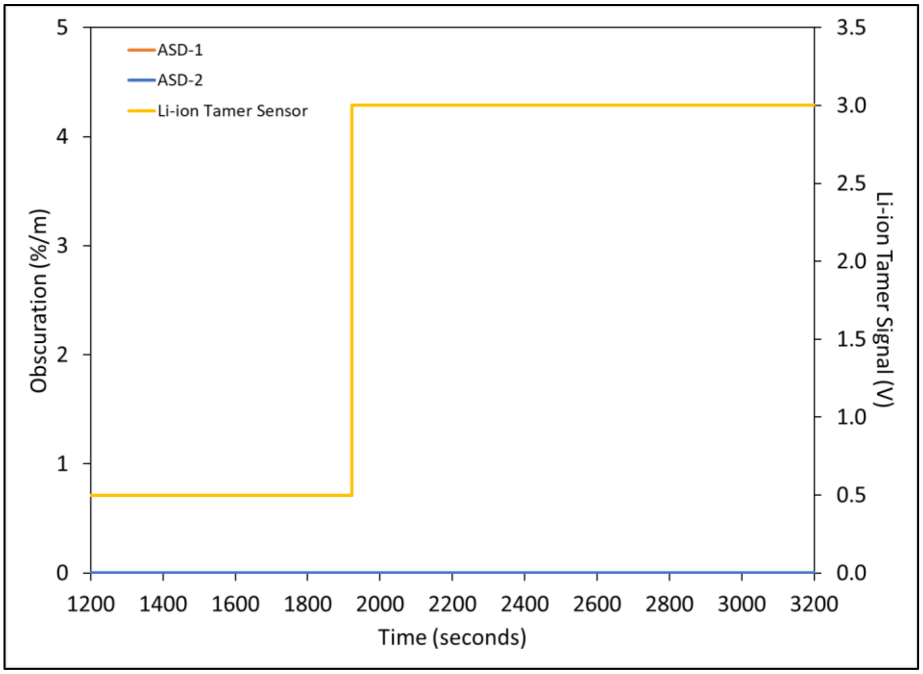

Figure 22. Test ID 5 off-gas monitor and obscuration detector response.

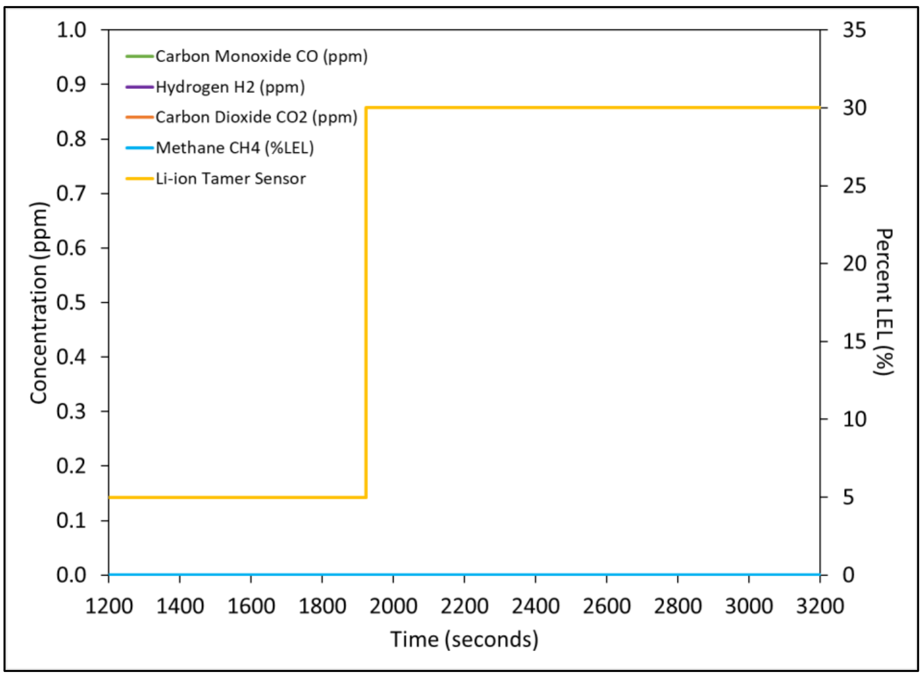

Figure 23. Test ID 5 gas monitor responses.

Test ID 6 – LFP Prismatic 0.5C Overcharge Failure Prevention

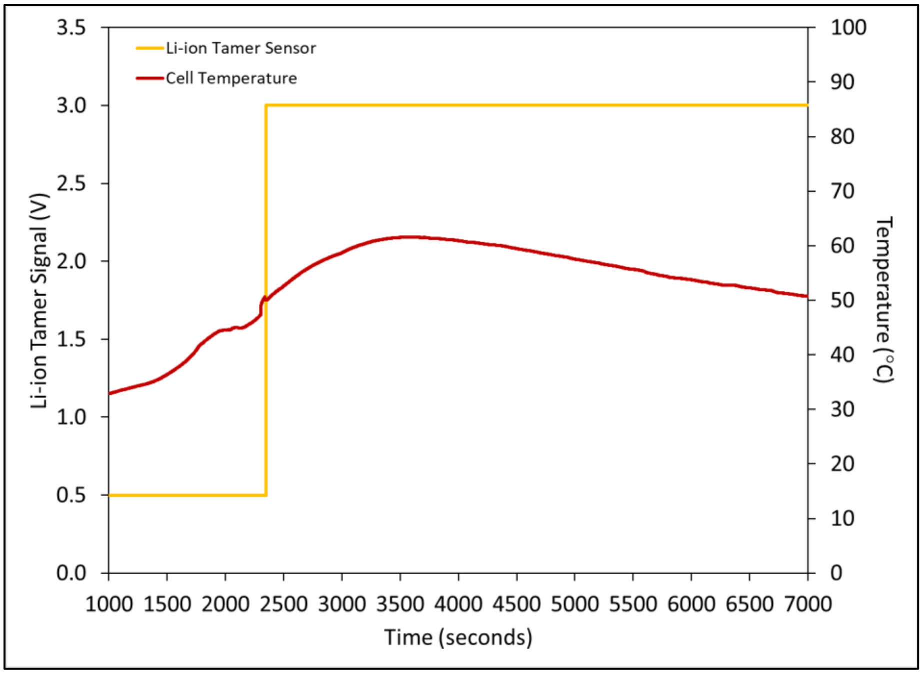

Figure 24. Test ID 6 off-gas event and thermal runaway quantification. The off-gas event occurred at 2347 seconds and thermal runaway was prevented by removing the abuse.

Discussion

Test ID 1 ($t_{off\text{-}gas\ event}$ = 6566 seconds, $t_{thermal\ runaway}$ = 7453 seconds)

The results in this test demonstrate a significant advantage with Li-Ion Tamer compared to the other detection devices. The Li-ion Tamer off-gas monitor responded at 6566 seconds.

The aspirated smoke detectors have the first non-zero response at approximately 7000 seconds, which was prior to thermal runaway at 7453 seconds. The percent obscuration fluctuates above zero after the initial responses at 7000 seconds until thermal runaway, when it exceeds 30% obscuration/meter. Between 7000 seconds and 7453 seconds, the peak response from the ASD-1 was 0.44% obscuration/meter at 7151 seconds. Between 7000 seconds and 7453 seconds, the peak response from the ASD-2 was 1.09% obscuration/meter at 7199 seconds.

The gas detectors follow a similar trend to the aspirated smoke detectors, registering the first non-zero measurement at 7100 seconds-- excluding the methane LEL detector, which does not respond at all until thermal runaway. The carbon monoxide detector experiences a small reading prior to 7100 seconds, where it briefly (< 30 seconds) reads a maximum of 46 ppm CO at 6610 seconds and, similarly, the carbon dioxide detector experiences a small reading prior to 7100 seconds where it reads 360 ppm (ambient is 320 ppm) at 6603 seconds.

Between 7100 seconds and thermal runaway at 7473 seconds, the CO detector reads consistently around 10-15 ppm, the H_2 detector around 40-50 ppm, and the CO_2 detector around

360-380 ppm (ambient is 320 ppm) until thermal runaway. After thermal runaway, the gas detectors all significantly respond, with the CO detector registering 300 ppm (saturation), the H_2 detector 818 ppm, the CO_2 detector 860 ppm, and the methane LEL detector registering 12%v LEL all within 15 seconds of thermal runaway occurring.

Test ID 2 ($t_{off\text{-}gas\ event}$ = 812 seconds, $t_{thermal\ runaway}$ = 1594 seconds)

The results in this test again demonstrate an advantage to Li-Ion Tamer compared to the rest of the detection devices. The Li-ion Tamer off-gas monitor responded at 812 seconds.

The aspirated smoke detectors have the first non-zero response at about 974 seconds, which occurs prior to thermal runaway at 1594 seconds. After 974 seconds, the percent obscuration gradually increases until thermal runaway when, just prior, the maximum measurement is 1.5% obscuration/meter for the ASD-1 and 2.0% obscuration/meter for the ASD-2. Once thermal runaway occurs at 1594 seconds, the aspirated smoke detectors both immediately exceed 30% obscuration/meter.

The response of the gas detectors in this test is again less effective than the obscuration detectors, where the first non-zero H_2 measurement is at 1376 seconds, with a small reading of 31 ppm. This is a short-lived response, lasting less than 10 seconds. The H_2 detector then becomes consistently non-zero at 1450 seconds with 30 ppm H_2 and gradually increases to 45 ppm H_2 until after thermal runaway, where it reaches a maximum value of 618 ppm H_2 at 1616 seconds. The CO detector becomes non-zero at 1509 with 12 ppm measured and remains consistently between 10 and 15 ppm until thermal runaway, where it reaches a maximum value of 300 ppm CO (saturation) at 1585 seconds. The CO_2 detector gradually increases from 320 ppm to 370 ppm between the off-gas event and thermal runaway and reaches a maximum 690 ppm at 1591 seconds. The methane LEL detector does not respond prior to thermal runaway and reaches a maximum of 11%v LEL at 1571 seconds.

Test ID 3 ($t_{off\text{-}gas\ event}$ = 1706 seconds, $t_{thermal\ runaway}$ = 3270 seconds)

The results in this test again show an advantage to Li-ion Tamer performance compared to the rest of the detection devices, with 26 minutes of early warning compared to the other detection methods.

There is no response from any of the aspirated smoke detectors until thermal runaway and both detectors' responses immediately exceed 30% obscuration/meter during thermal runaway.

There is no response from any of the gas detectors during the off-gas event or prior to thermal runaway. The CO_2 and CO detectors all register significant responses during thermal runaway and the H_2 and CH_4 LEL detectors do not respond at all. The CO_2 detector registers 2800 ppm CO_2 at 3301 seconds and the CO detector registers 62 ppm CO at 3295 seconds.

Test ID 4 ($t_{off\text{-}gas\ event}$ = 3292 seconds, $t_{thermal\ runaway}$ = 3705 seconds)

The results in this test again show an advantage to Li-ion Tamer performance compared to the rest of the detection devices, with 6.9 minutes of early warning compared to the other detection methods.

There is no response from any of the aspirated smoke detectors until thermal runaway and both detectors' responses immediately exceed 30% obscuration/meter during thermal runaway.

There is no response from any of the gas detectors during the off-gas event or prior to thermal runaway. The CO_2, CO, and H_2 detectors all register significant responses during thermal runaway and the CH_4 LEL detector did not respond at all. The CO_2 detector registers 750 ppm CO_2 at 3721 seconds, the CO detector registers 67 ppm CO at 3728 seconds, and the H_2 detector registers 78 ppm H_2 at 3747 seconds.

Test ID 5 ($t_{off\text{-}gas\ event}$ = 1900 seconds)

The results in this test demonstrate only Li-Ion Tamer is capable of detecting failure ahead of thermal runaway such that removal of the abuse condition prevents thermal runaway from occurring..

There was no response from any of the aspirated smoke detectors or commercial gas detectors during or after the off-gas event.

Test ID 6 ($t_{off\text{-}gas\ event}$ = 2347 seconds)

The results in this test demonstrate again Li-ion Tamer's sole capability to prevent thermal runaway by providing reliable off-gas detection. Further, this test shows how Li-ion Tamer's detection is agnostic of the lithium-ion battery chemistry (ex. LTO, LFP, NMC), enabling the prevention of thermal runaway across different anode and cathode chemistries.

Conclusion

Overall, the six experiments performed demonstrate Li-ion Tamer's ability to detect pending thermal runaway compared to other common detection devices for lithium-ion batteries. Li-ion Tamer provided reliable warning of ongoing battery abuse with an average of 15.2 minutes early warning prior to thermal runaway. These experiments also further supported UL's 9540A pro forma installation report with the commercial gas detectors providing no off-gas detection, but consistently detecting thermal runaway. Additionally, both aspirating detection technologies were demonstrated to be incapable of detecting the off-gas event, only providing detection of thermal runaway once it occurred.