Detailed Characterization of Emissions from Battery Fires

SOUTHWEST RESEARCH INSTITUTE®

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Outline

- Overview and background
- Project brief
- Experimental methods
- Instrumentation
- Results
  - Physical observations, gaseous and particle emissions
- Summary

Overview

- Significant growth in adoption of electric batteries for a wide array of applications
- Lithium-ion (Li-ion) batteries are commonly used due to high energy density and specific energy capacity
  - These desirable characteristics also make them a safety hazard
- Objectives:
  - To investigate emissions from Li-ion battery fires triggered by thermal runaway
  - Develop a robust process to capture such emissions

Background

- Several battery fire incidents in the last few months
  - Morris Illinois fire resulted in the evacuation of 4000 people (1000 homes)
    - Fire lasted several days
    - 27 different chemistries
- Critically important to understand composition of particulates and gases emitted from such fires
  - To equip first responders with appropriate PPE
  - To understand impact on people living nearby
  - Environmental impact – air and water quality
  - Develop solutions to mitigate such emissions

Morris Illinois (June 2021)

Haverford Pennsylvania (July 2021)

LaSalle, Illinois (July 2021)

Australia (August 2021)

Several e-bike fires (2021)

Project Brief

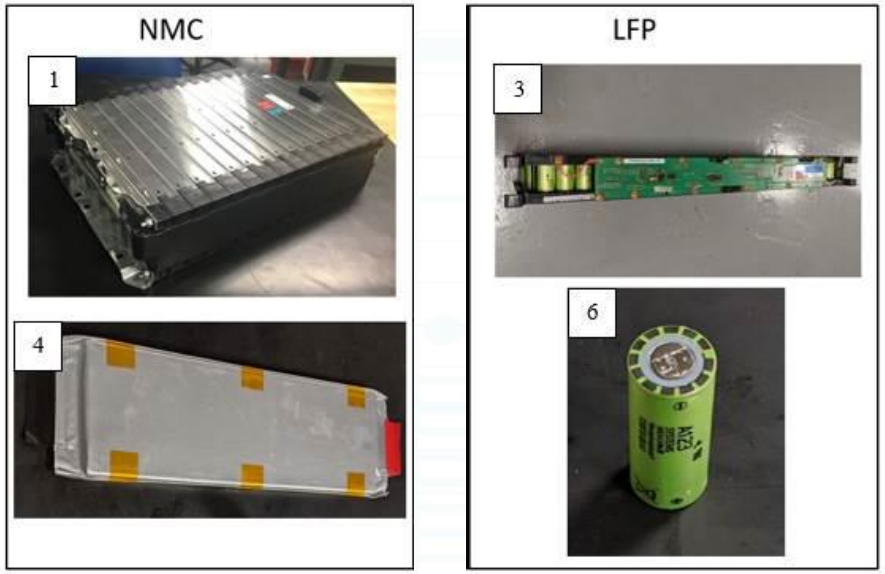
- Conducted detailed characterization of particle emissions from Li-ion battery fires triggered by thermal runaway
- Two different types of Li-ion battery technologies were evaluated - Lithium nickel manganese cobalt (NMC) oxide system and Lithium iron phosphate (LFP) system
- Five tests were conducted to gain information on repeatability, impact of battery chemistry, and initiation mechanism on emissions
  - Test 1 – LFP via nail penetration
  - Test 2 – LFP via nail penetration
  - Test 3 – LFP via overcharging
  - Test 4 – LFP via overcharging
  - Test 5 – NMC via nail penetration

Tests 1–2: Repeatability/Variability
Tests 3–4: Repeatability/Variability
Tests 2–3: Initiation mechanism
Tests 1–5: Battery chemistry

- All modules charged to full SOC

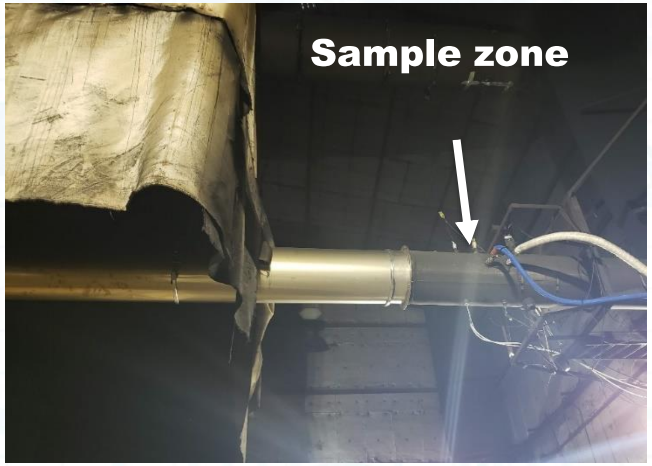
Experimental Methods

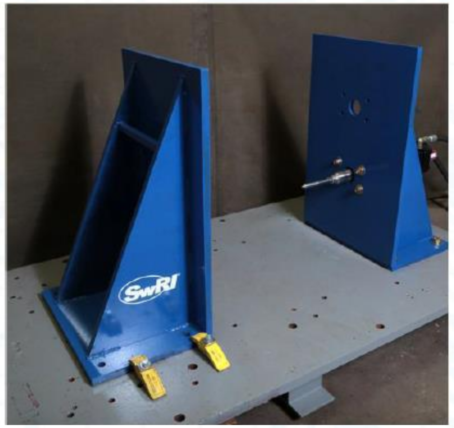
- Test articles include four LFP modules and one NMC module
  - Capacity of NMC module is 7.56 kW-hr, LFP module is 0.864 kW-hr
- Tests were conducted at SwRI's Fire Tech facility that is equipped with a large pollution abatement system

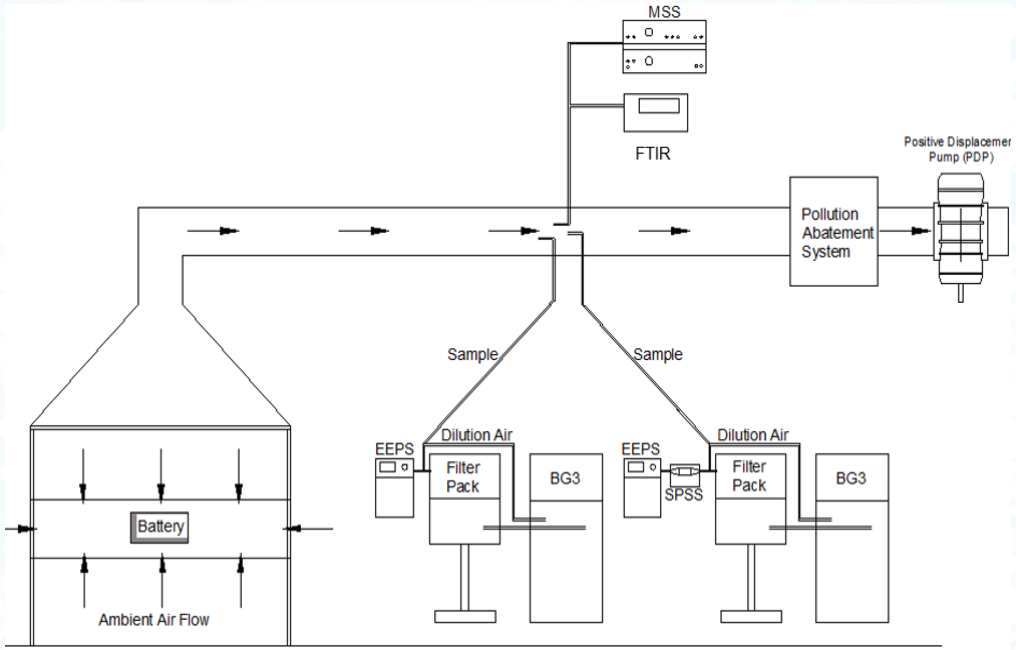


Cell chemistry	**LFP**	**NMC**
Battery type	Cylindrical	Pouch
Capacity, Ah	2.5	60
Cutoff voltage, V	3.6	4.2
Maximum cont. charge rate, A	10	60
Maximum cont. discharge rate, A	60	120
Dimensions, mm	26 φ, 66.5 height	16.5 x 100 x 330
Weight, g	70	820
Module configuration	8P12S	3P10S
Module Energy, kWh	0.864	7.56

Experimental Methods (Cont'd…)







- Test article placed inside the enclosure
- Particle/gaseous emissions sampled from inception to completion – no suppression systems
- Sufficient oxygen was always present to simulate fire incidents occurring at ambient conditions

Emissions Instrumentation

AVL MSS (soot)

Total Particle Sizer – PN/size (volatile + solid)

Solid Particle Sampling System (SPSS)

+

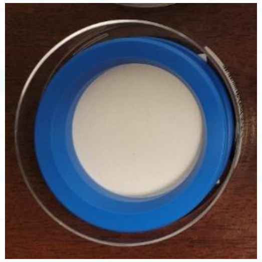
Solid Particle Sizer – PN/size (metallic + soot, no volatiles)

Sierra BG-3

+

Heat-Pak

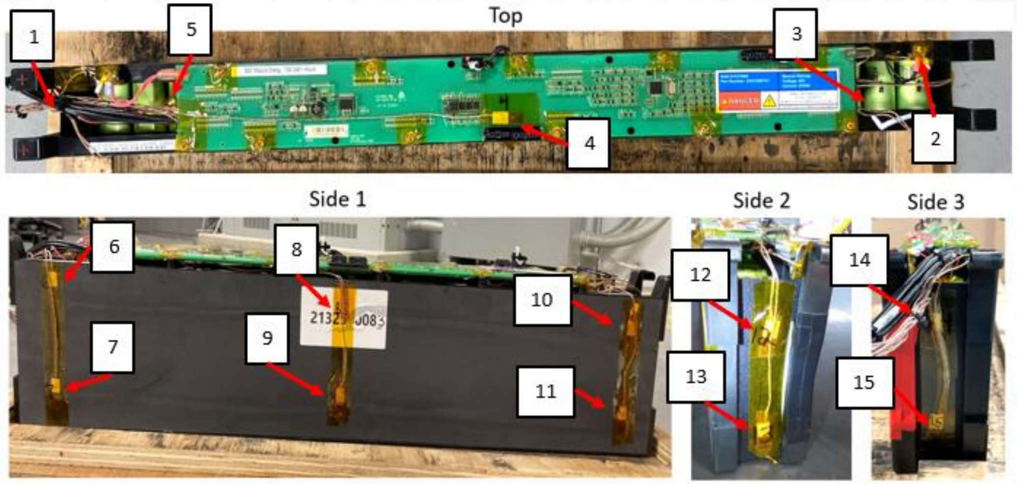
PM filter



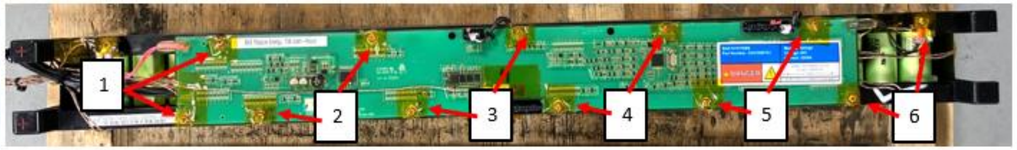
- AVL Micro-Soot Sensor for real-time black (soot) carbon measurement
- TSI Engine exhaust particle sizer (EEPS) for real-time total particle number/size
  - 5.6 nm to 560 nm detection range
- SwRI's SPSS + TSI EEPS for real-time solid particle number/size
  - Includes a catalyst maintained at 350 °C that removes volatile species
  - Helps characterize solid constituents such as metallic and soot particles
- Sierra BG-3 for PM filter measurement
  - Post analysis for volatile organic fraction (VOF) determination
  - Elemental analysis of filters
- FTIR was used to characterize gases
  - CO, CO_2, NO, NO_2, HCN, HCl, HF, CH_2O, CH_4 and C_3H_8

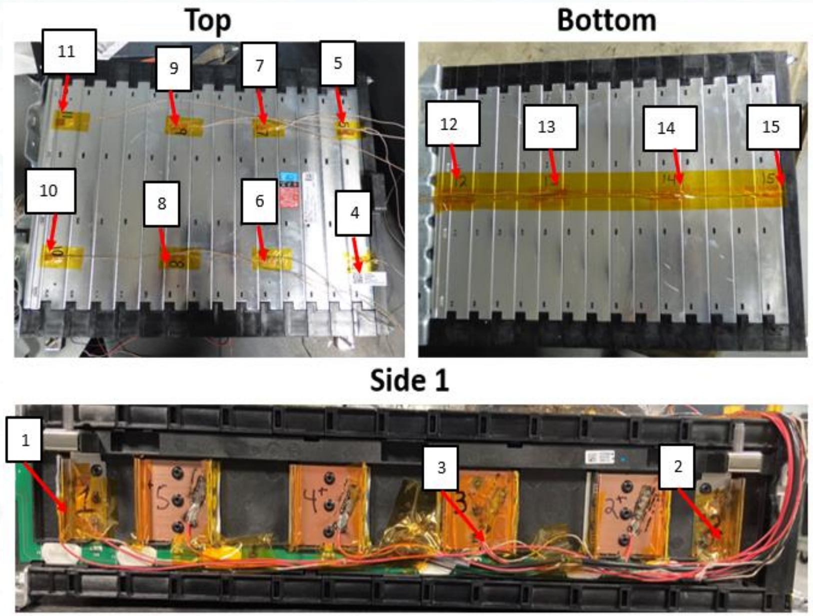
Battery Module Instrumentation

LFP module

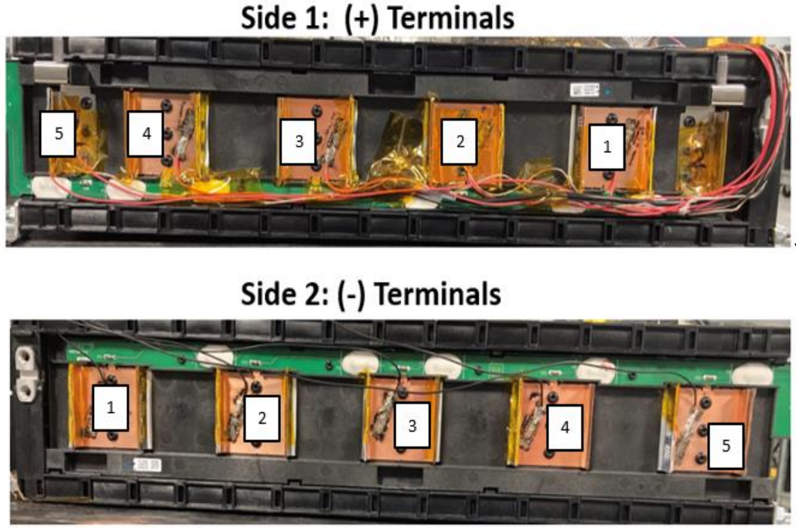


LFP module voltage sensors





NMC module thermocouples

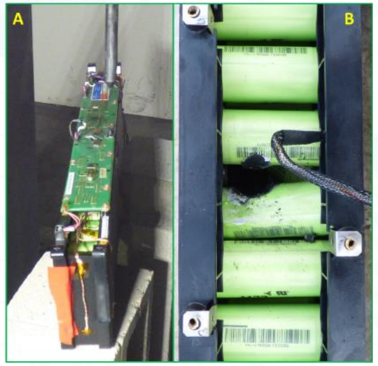


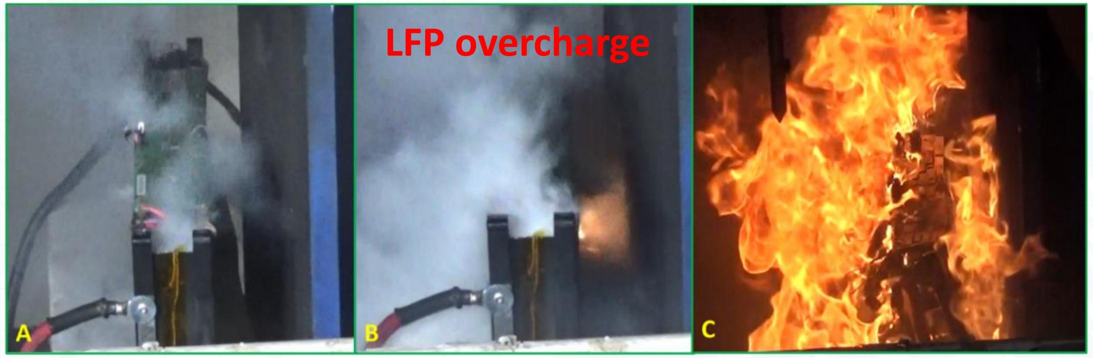
NMC module Voltage sensors

- LFP module was instrumented with 16 thermocouples and 6 voltage sensors
- NMC module was instrumented with 16 thermocouples and 5 voltage sensors

Results-1 Physical Observations

LFP nail penetration





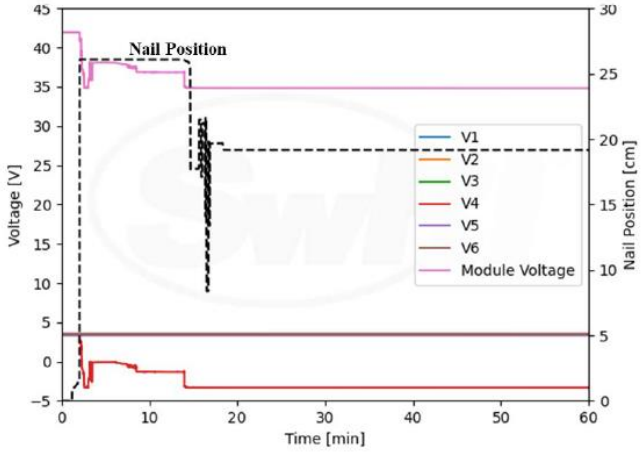
LFP overcharge

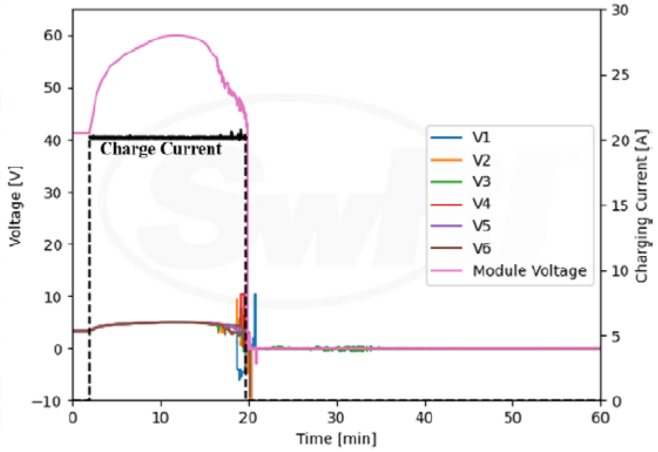
NMC nail penetration

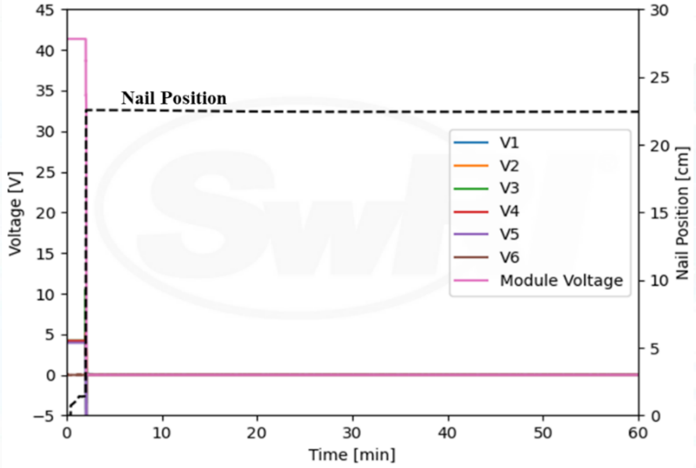
- LFP nail-penetration tests
  - Only cells in the path of the nail experienced thermal runaway
- LFP overcharge tests
  - All cells in the module experienced thermal runaway
  - Significant smoke and fire was observed
- NMC nail-penetration tests
  - All cells in the module experienced thermal runaway
  - Thermal runway propagation was observed cell-to-cell
  - Significant smoke and fire was observed

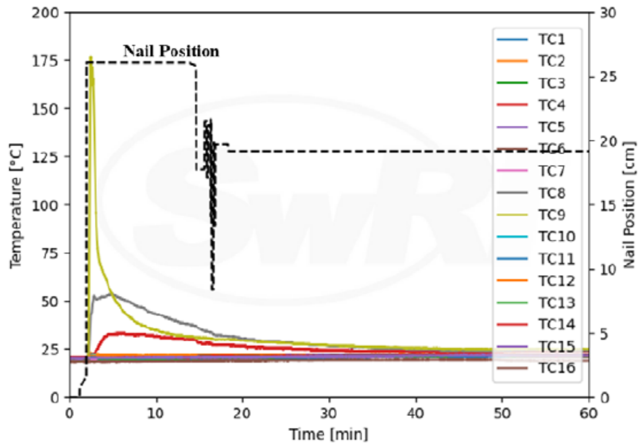
Results-2 Battery Parameters

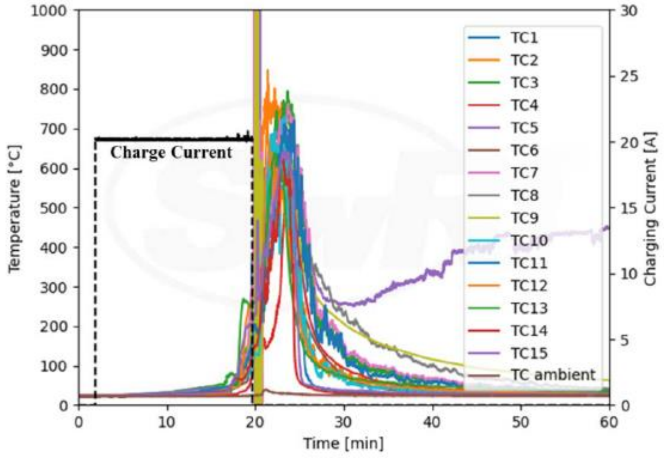
LFP via nail-penetration	LFP via overcharging	NMC via nail-penetration

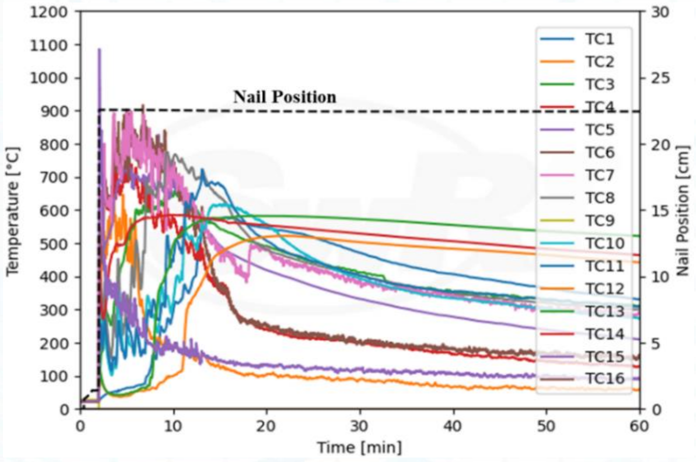








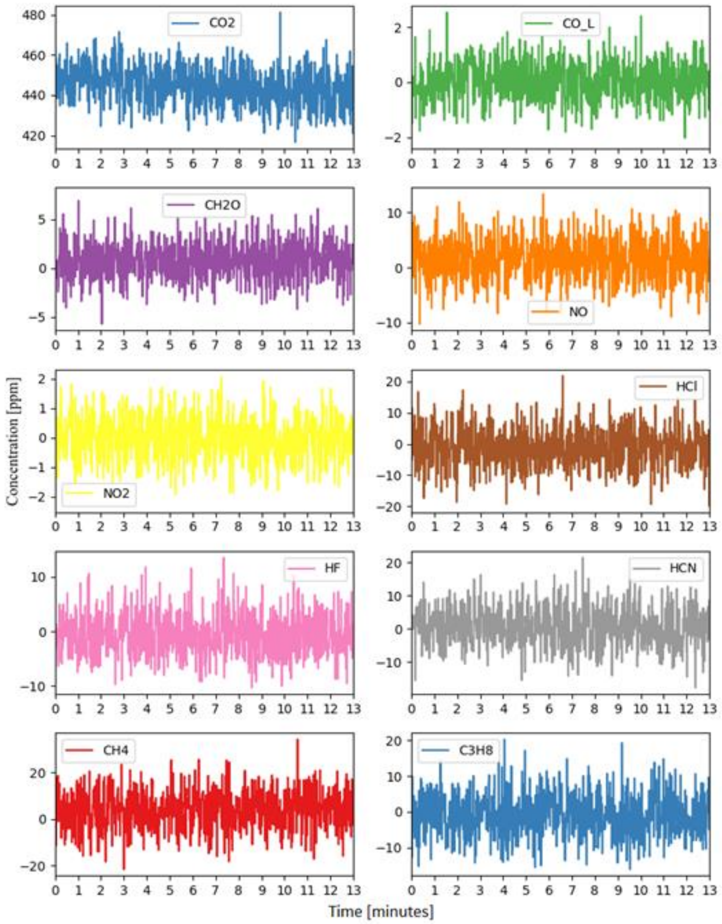




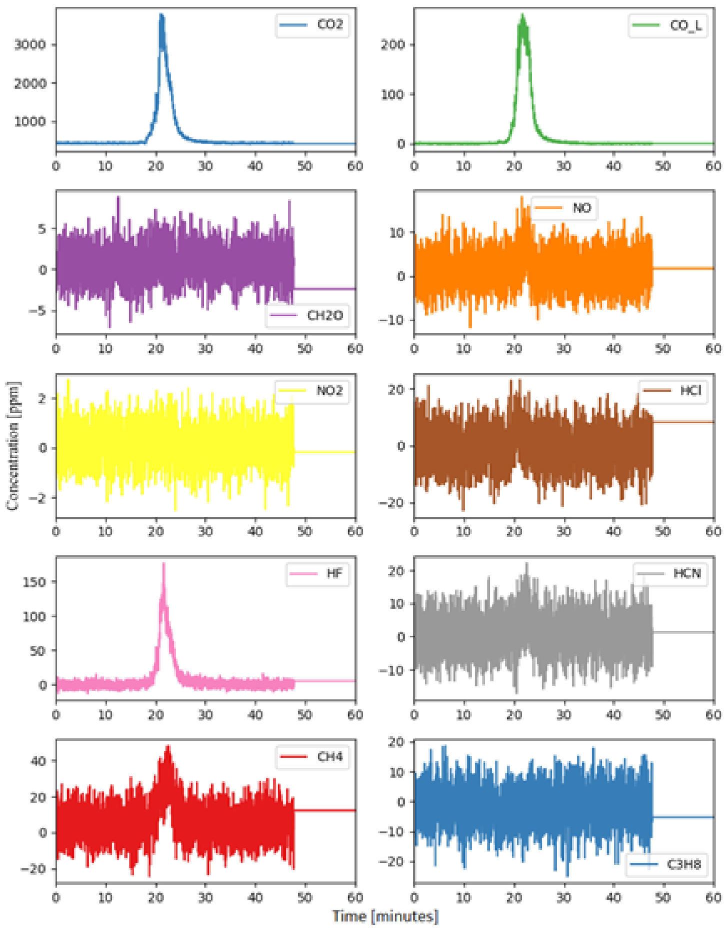
- All modules were charged to full state-of-charge
- LFP modules entered thermal runaway after about 15 minutes of overcharging

Results-3 Gaseous Emissions

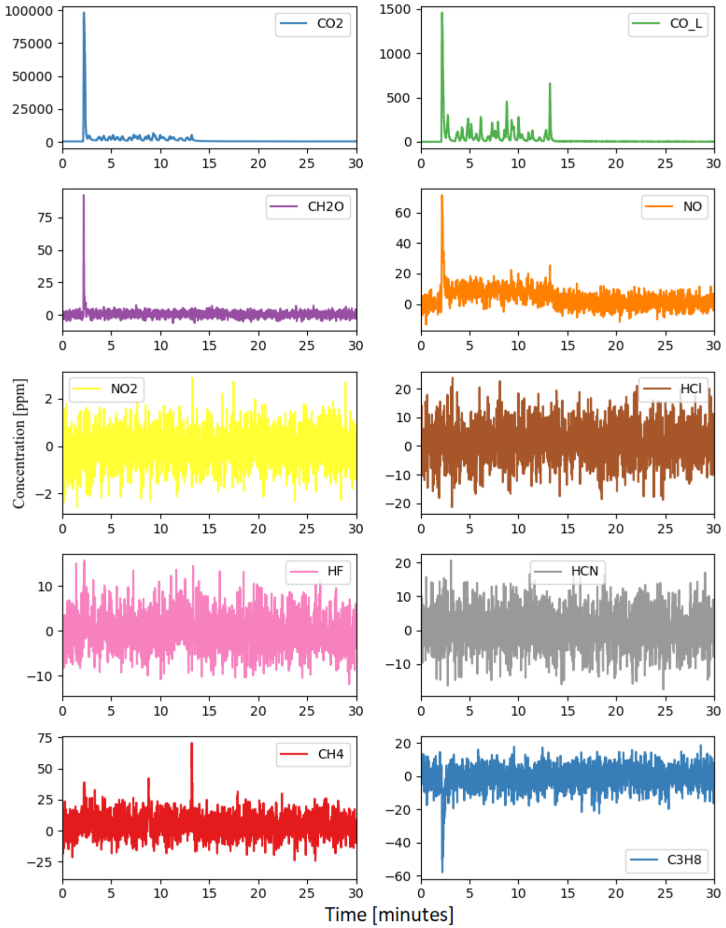
LFP via nail-penetration



LFP via overcharging



NMC via nail-penetration

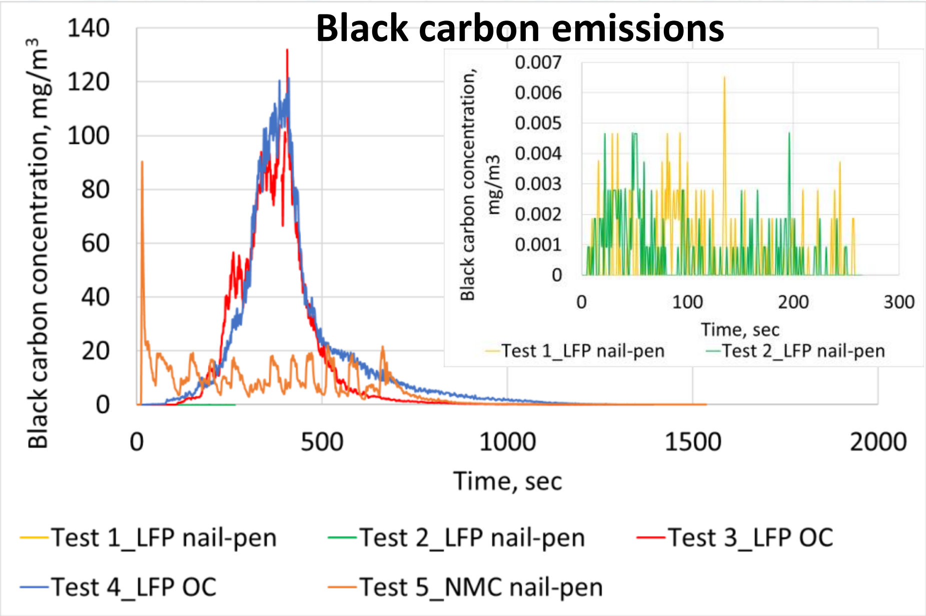


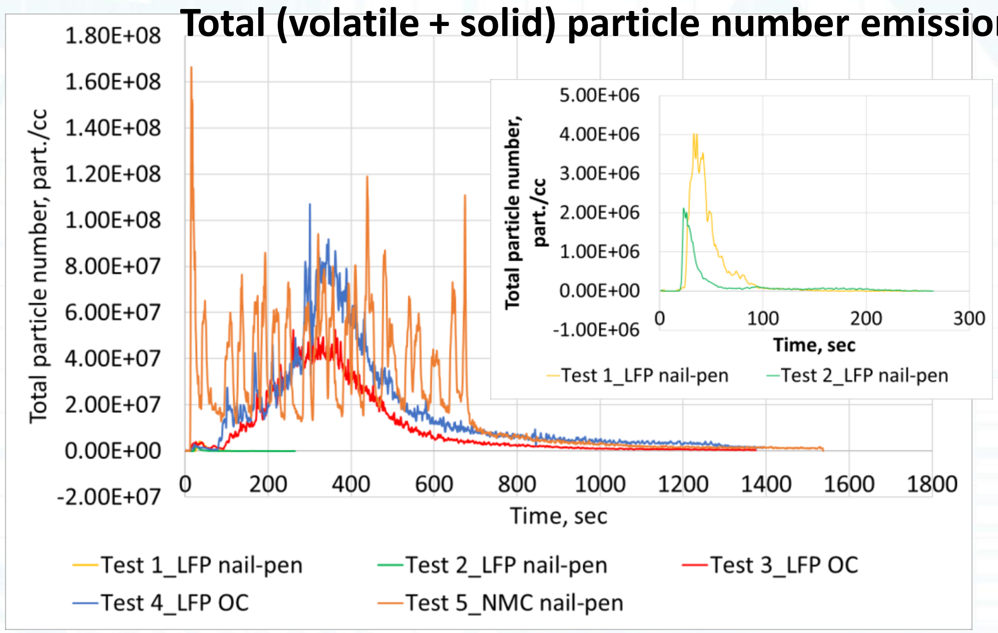
- **LFP via nail-penetration (no significant emissions)**

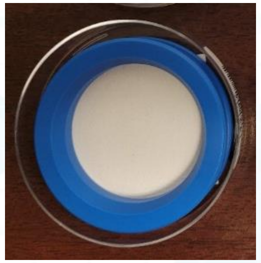
- **High emissions observed for multiple gases**
- **HF exceeded immediately dangerous to life or health (IDLH) limit of 30 ppm**

- **CO_2 peak 20 times higher than LFP**
- **Formaldehyde above IDLH limit of 20 ppm**

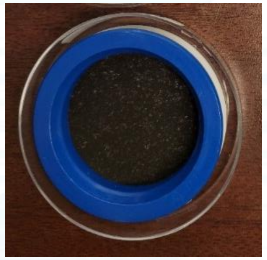
Results-4 Particle Emissions (Real-time)



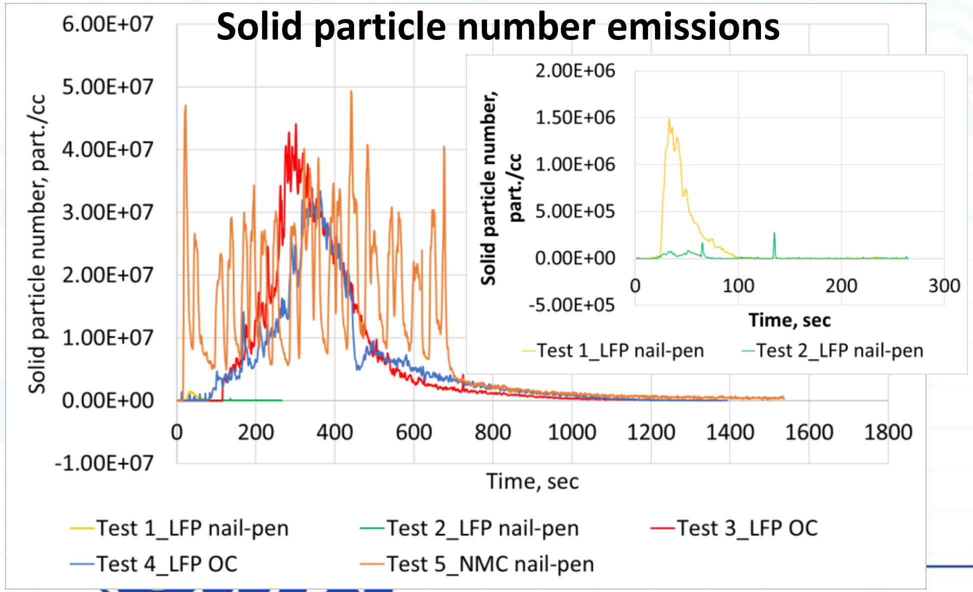




Background PM filter



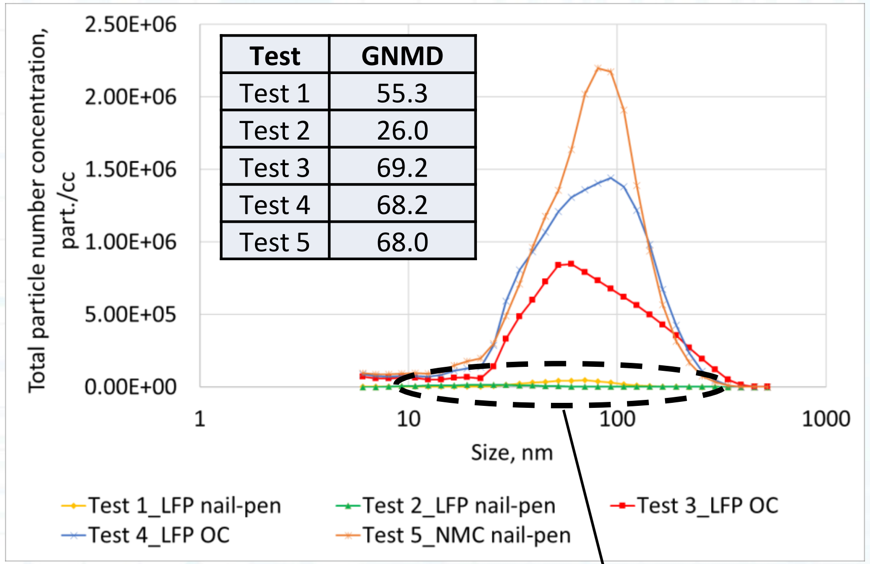
PM Filter for Test 4



Test	Test duration, sec	PM2.5 emissions, g/hr	Black carbon emissions, g/hr	Solid PN emissions, part./hr	Total PN emissions, part./hr
Test 1_LFP nail-pen	260	1.81	0.00	1.56E+15	4.24E+15
Test 2_LFP nail-pen	266	0.00	0.00	1.12E+14	1.61E+15
Test 3_LFP OC	1376	386.09	149.90	8.89E+16	1.13E+17
Test 4_LFP OC	1392	375.97	185.78	6.11E+16	1.83E+17
Test 5_NMC nail-pen	1535	551.03	66.52	1.06E+17	2.08E+17

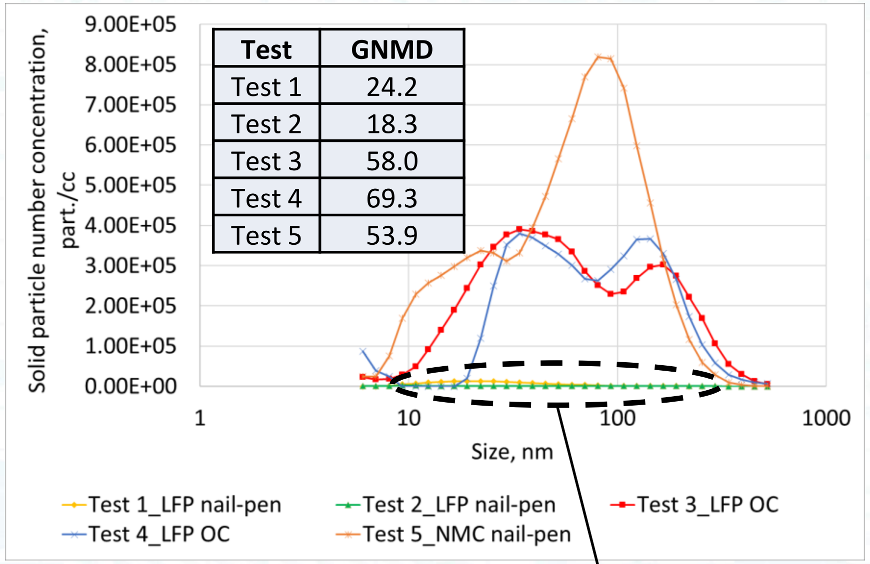
Results-5 Particle Size Distributions

Total particle size distribution

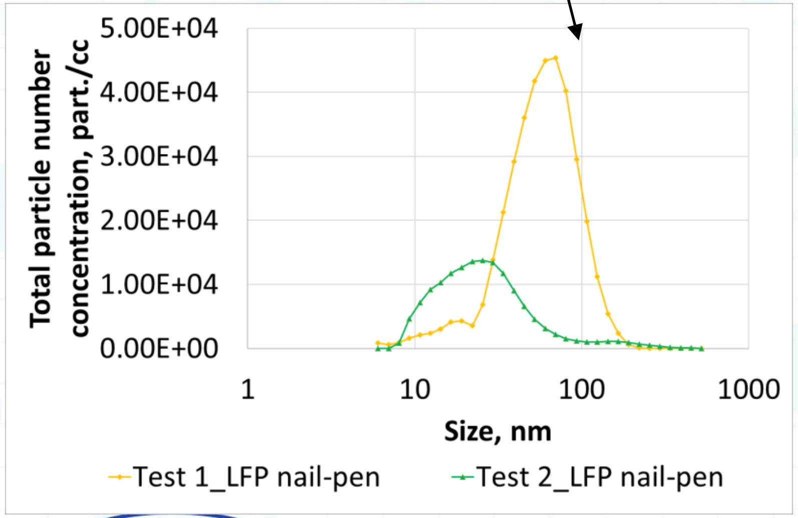


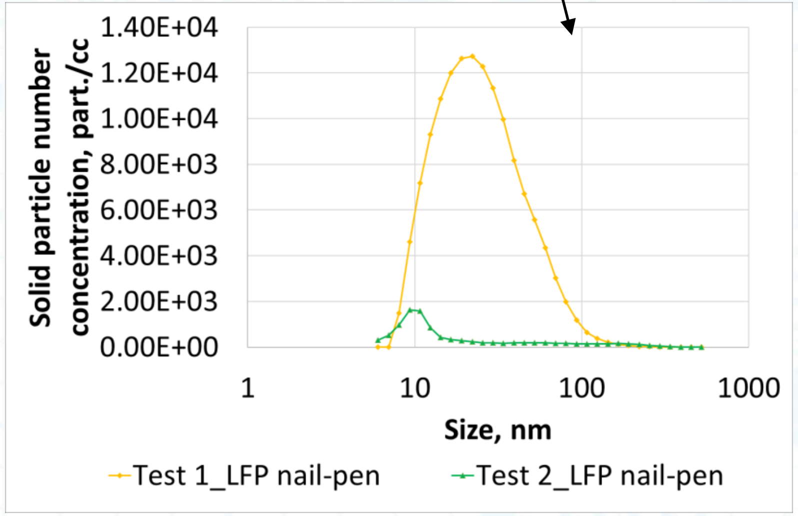
Test	GNMD
Test 1	55.3
Test 2	26.0
Test 3	69.2
Test 4	68.2
Test 5	68.0

Solid particle size distribution



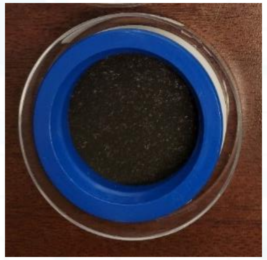
Test	GNMD
Test 1	24.2
Test 2	18.3
Test 3	58.0
Test 4	69.3
Test 5	53.9





- Particles were observed to be in the respirable size range
- All five tests exhibited unique size signatures, both, for solid and total particles
- Tests 1 and 2 showed different size signatures for both, solid and total particles
- Tests 3 and 4 also showed different size signatures

Results-6 PM Analysis



- TX-40 PM filters were analyzed via vacuum oven sublimation
  - Heated at 225 °C over 8 hours under vacuum
- Quartz filters were analyzed for organic carbon/elemental carbon partitioning
  - Using Sunset Lab Carbon Aerosol Analyzer

Test	PM2.5 emissions, g/hr	Volatile weight fraction	OC/TC Ratio
Test 1_LFP nail-pen	1.81	NA	100%
Test 2_LFP nail-pen	0.00	NA	100%
Test 3_LFP OC	386.09	19%	87%
Test 4_LFP OC	375.97	20%	55%
Test 5_NMC nail-pen	551.03	8%	50%

Summary

- Emissions from battery thermal runaway events can result in significant particle emissions
  - 5 to 6 orders of magnitude higher than those typically emitted from exhaust of modern heavy-duty diesel engine
  - Particles are well within the respirable size range
- Battery chemistry coupled with initiation mechanism influences magnitude of emissions, along with release profile
  - Initiation mechanism could play an important role in the scale of the thermal runaway event
  - In a module, there could be localized impact with some cells experiencing thermal runaway without further propagation
- Physical dimensions and arrangement of cells within a module could influence the severity of the runaway event
- Particle emissions from thermal runaway events of identical modules induced into runaway via the same mechanism could be highly variable

Thank you for your attention!

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