The Threat of Cascading Thermal Runaway:

A Case Study into Thermal Runaway within Lithium Ion Batteries and the Development of Fike Blue™

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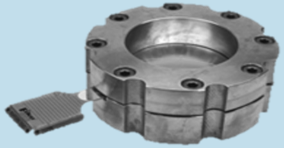
Fike Safety Technology

Fike Corporation

- Engineering Solutions Company focused on Life & Critical Infrastructure Safety
- Established in 1945 (third generation family ownership)
- Headquarters in Blue Springs, Missouri, USA
- Over 1000 staff globally



Pressure Relief

Petro-Chemical
Power Generation
Process Environments
Oil & Gas - Downhole

Engineered Fire Systems

Data Centers
Power Generation
ESS
Manufacturing

Explosion Protection

Food & Beverage
Pulp & Paper
ESS
Metal Manufacturing

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Agenda:

- ESS Overview & The Early Days of Fire Protection Methods
- ESS Case Study
- Conclusions

Energy Storage Systems (ESS) Overview

- Often contain hundreds of lithium ion batteries

- Stores energy generated from:
  - Power Generation Facilities
  - Solar Farms
  - Wind Farms
  - Utility Grid*

  **to be redistributed for later use*

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Early Days ESS Fire Protection

- Not metallic lithium
- Lithium Electrolyte
  - Class B flammable
  - Use Class B concentrations
- Standard Agents Implemented
- Prove results with testing
  - Cell inside a small enclosure

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Early Days ESS Fire Protection

What happened

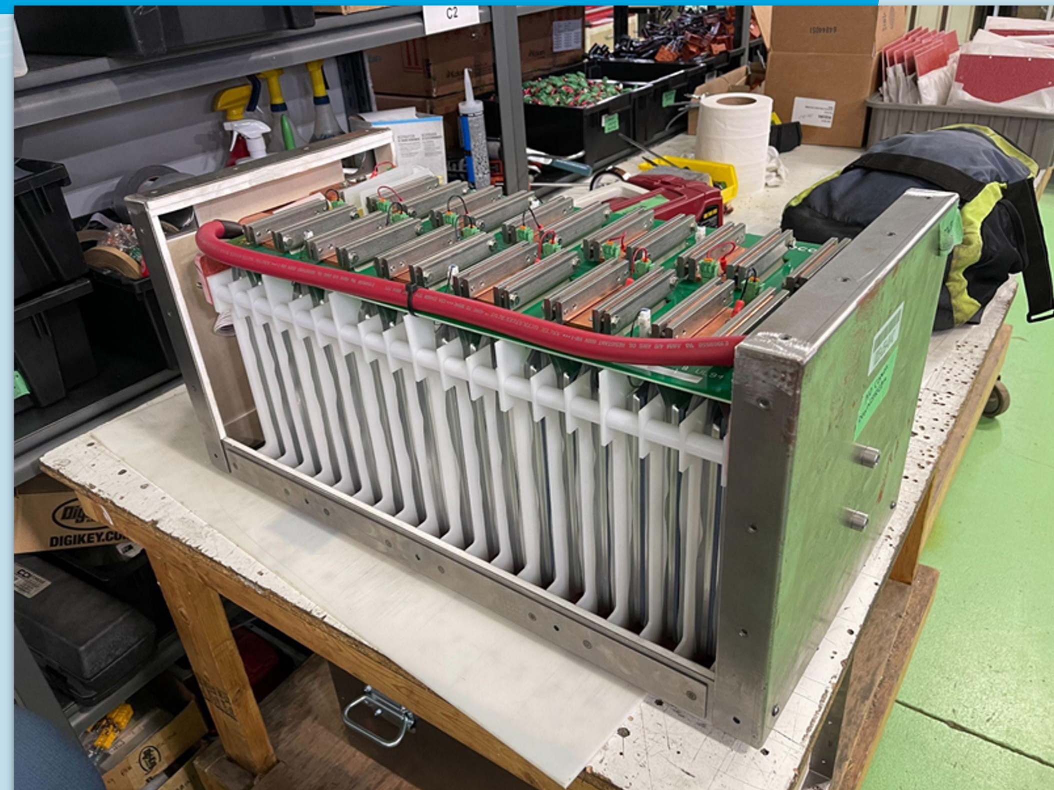
- Location: Surprise, AZ
- Protection System: Novec 1230
- Location: Warwick, New York
- Protection System: Aerosol

Did the system put out the fire?
Arguably, yes. The system likely put out a fire.

Lithium Ion Fire Testing & Case Study

Early Trials

- Quantity of 36 NMC pouch cells (103 Ah)
- 3P-12S configuration (15 kW-h)
- Armored module (containment by design)
- Tested at 100% SoC
- TR initiated by heating a cell in the center of the assembly (4°C per minute)



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Early Trials – Test Development

- Unit/Installation level testing
  - Charge and monitor cells
  - Thermal Runaway induced by heating
  - Internal and External temperatures
  - Heat Flux at target surface(s)
  - UL 9540A without the gas measurement

- Capability to test various battery types at Fike BHA (Battery Hazard Analysis)

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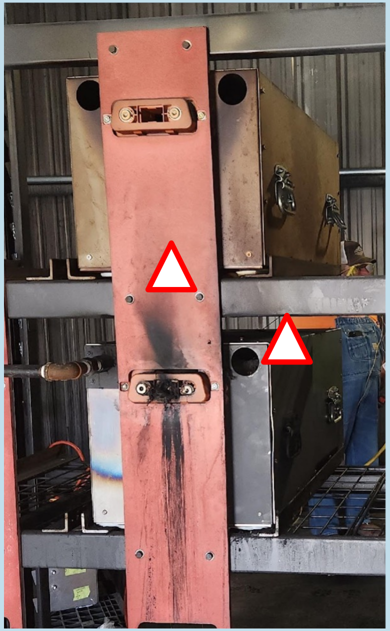
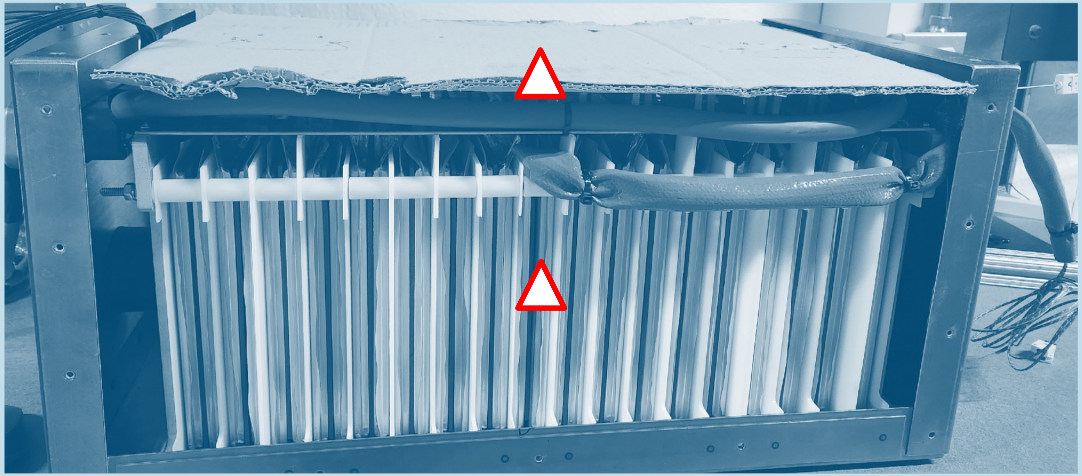
Early Trials – Test Development

Instrumentation Setup

- "Core" temperature
- Internal Vapor Temperature (Vented Gases)
- External Case Surface Temperature
- "Target" Heat flux (kw/m^2) and temperature

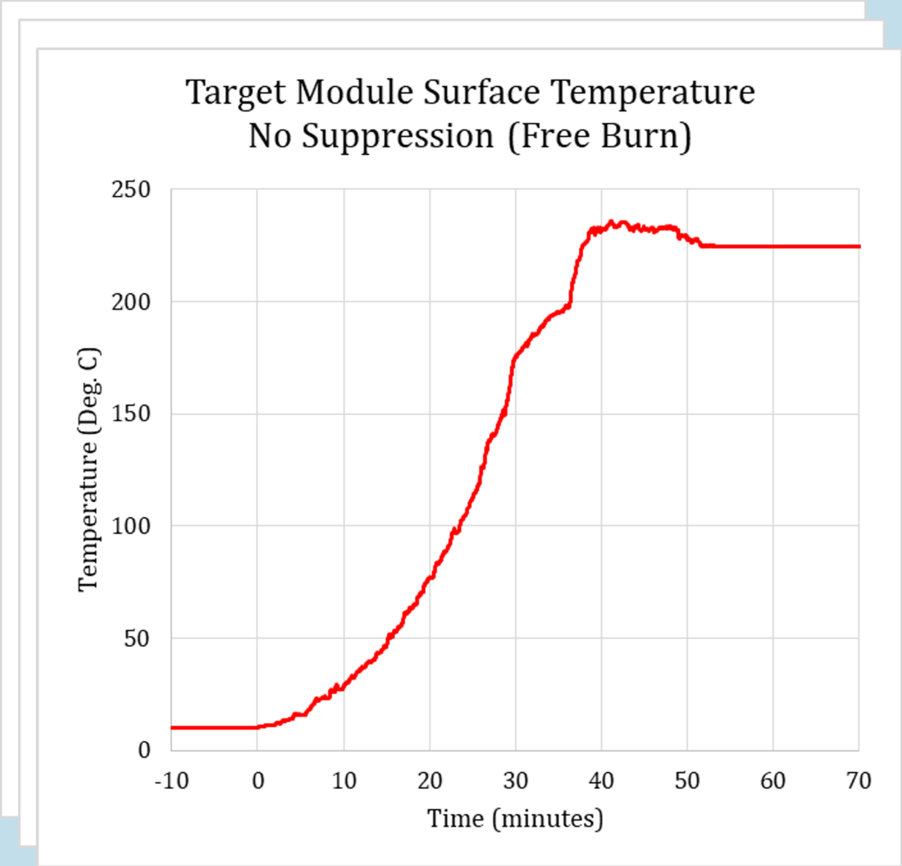




Early Trials – Baseline Testing

Test #1 – Free Burn

- Baseline Hazard Assessment
- Battery in As-Received Condition
- No agent applied
- All 36 cells burned
- Extreme smoke production
- Very high internal and external temperatures
- High impact on nearby (target) module



Early Trials – Testing Currently Available Agents

- Multiple agents
  - NOVEC 1230
  - Inert Gas (Various)
  - FM200
  - Ecaro25
- Poor initial results
  - In most cases fire was extinguished
  - Significant heat generation & Cascading Thermal Runaway continued until all cells consumed

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Understanding The Problem: Thermal Runaway

Thermal Runaway

An extremely dangerous and unpredictable exothermic chemical reaction within a Lithium Ion cell.

Caused by a malfunction or damage to the cell that creates an internal short across the separator layer.

- Generates a high amount of heat
- Heat generated accelerates the reaction
- Toxic and Flammable gasses build up
- Cell Ruptures

Once the reaction starts within a single cell **it cannot be stopped**

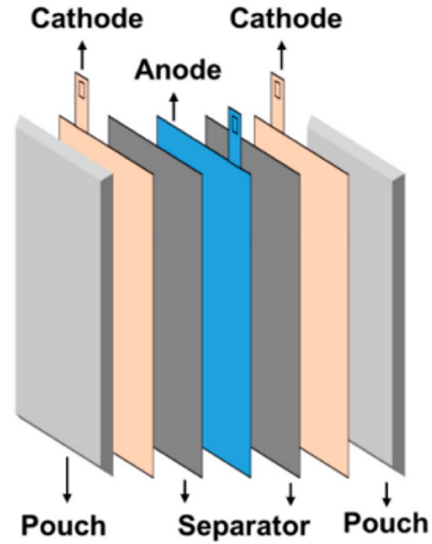

Figure 1: Li-Ion Battery

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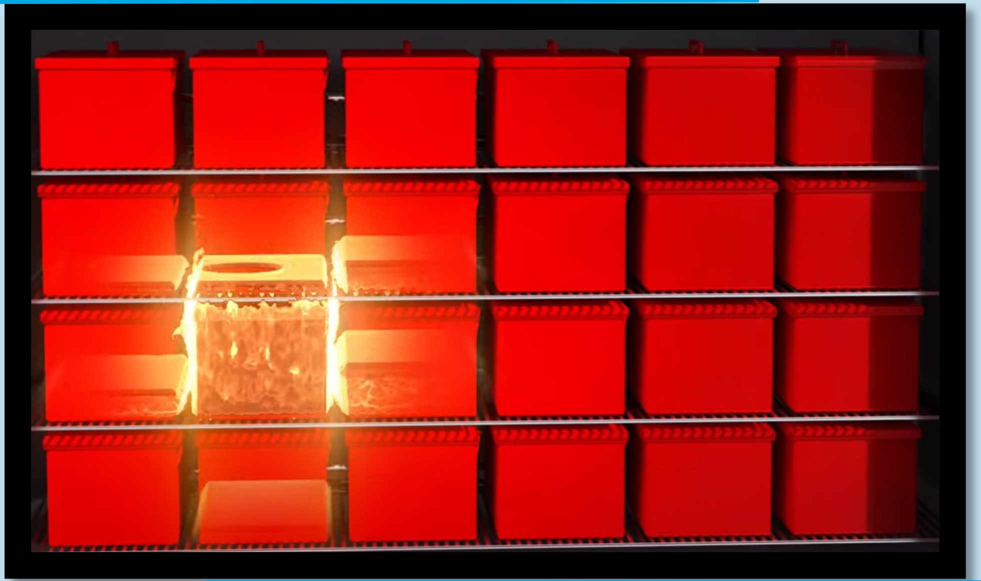
Understanding The Problem: Cascading Thermal Runaway

Cascading Thermal Runaway

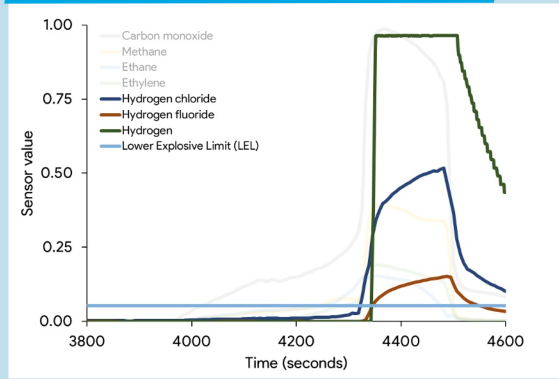
When a cell in Thermal Runaway heats the adjacent cells to a point where they too enter thermal runaway, starting a chain reaction that if left unchecked will eventually consume all cells within the module or container.



Understanding The Problem: Off Gassing & Lithium Ion Fires

Off Gassing

The Toxic and highly flammable gasses that are produced when a cell or cells enter Thermal Runaway. Generated at a very early stage in the reaction, these gasses contain a high concentration of Hydrogen as well as other flammable gasses.



Lithium Ion Fire

When the Off Gasses or other flammable materials are ignited due to the high temperatures created through the Thermal Runaway process

The REAL Problem: Cascading Thermal Runaway

The ***fire*** itself can be suppressed with:

- Chemical Agents, Inert Agents, Aerosols
- Water, Water with Additives & Watermist

Yet the threat persists:

- Heat management/thermal problem
- Thermal Runaway and Off Gassing continues after extinguishing of flames
- Re-ignition after suppression exhausted

INTRODUCING

...

blue

A Solution to Stop Lithium Battery Fires

AND Cascading Thermal Runaway

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The Solution:
Create a Fluid with High Heat Absorption & Dissipation Properties

- High Heat Capacity Without Breaking Down
- Non Toxic
- Non Electrically Conductive

Fike Blue^{TM} is a non-toxic, non-conductive, water based solution that has a boiling point in excess of 400 ^{o}C allowing for rapid cooling of the affected cells.

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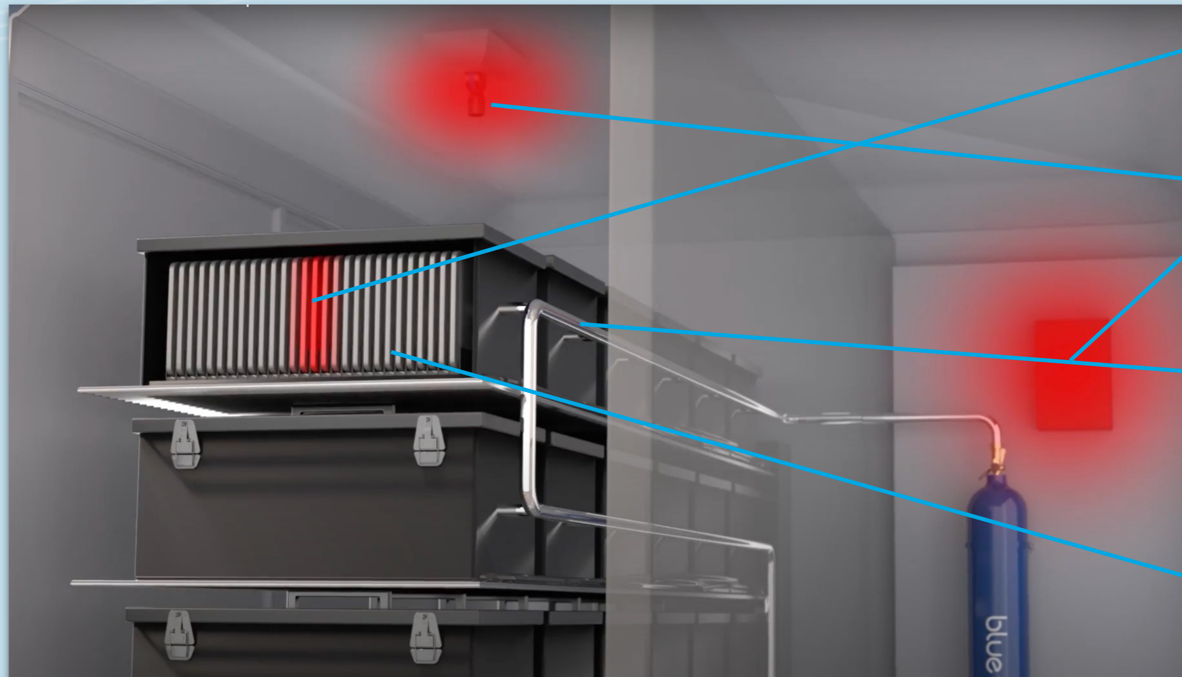
The Delivery Method



Cells begin to overheat.

Detection system identifies rising temp, releases Fike Blue.

Fike Blue fills pipes and releases into the overheated module.

Fike Blue submerses module, absorbing cells heat, preventing further thermal runaway.

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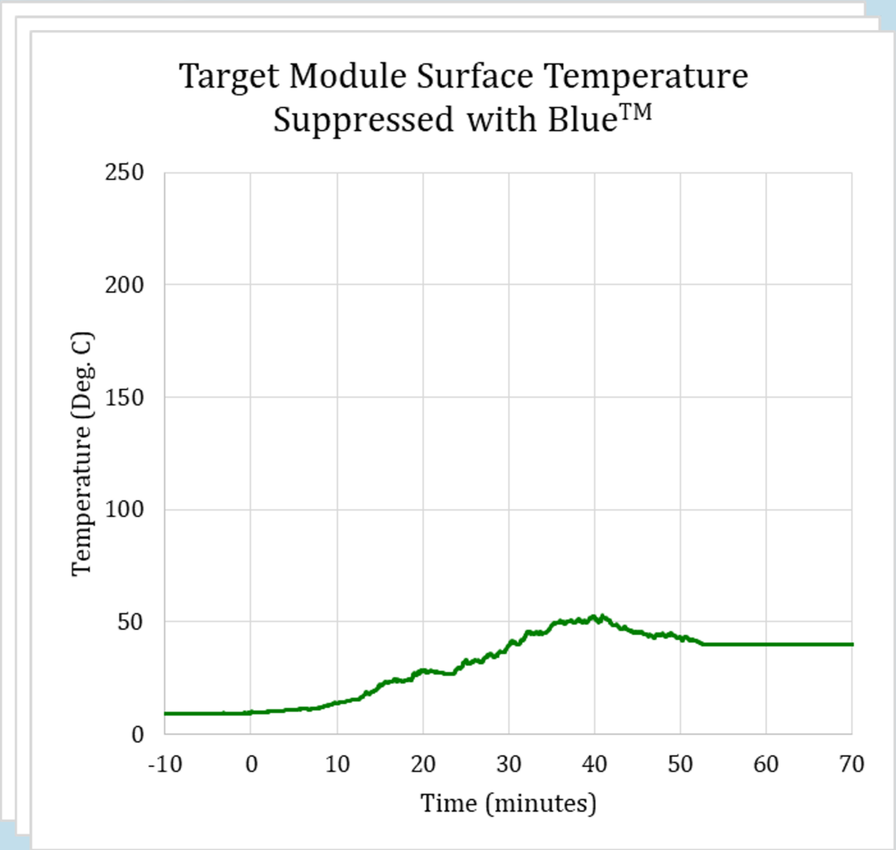
Testing the Solution

Test #2 – Blue™ agent applied

- Battery in As-Received Condition
- Direct injection method
- Sprinkler nozzle for activation

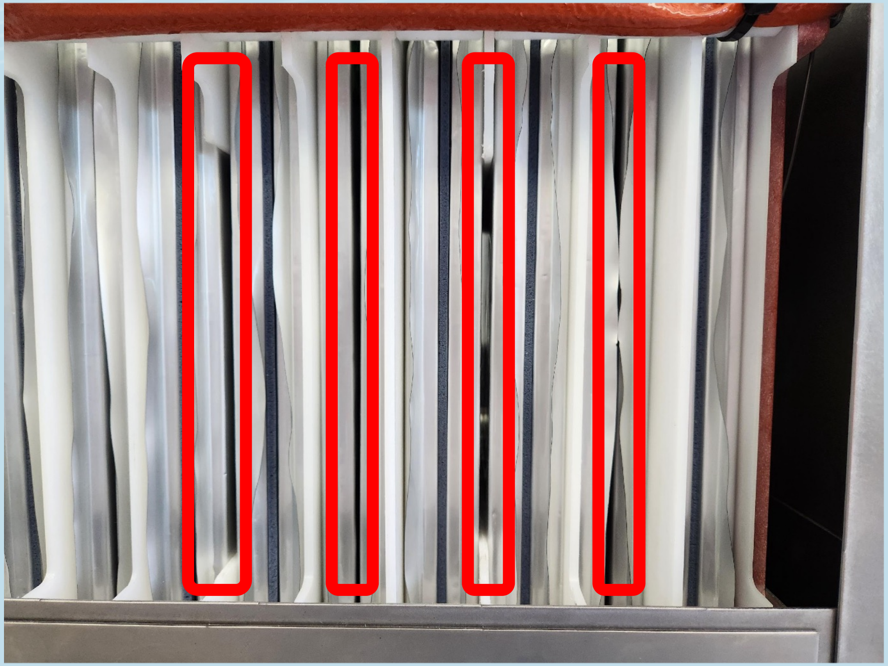
- Reduced sustained internal and external temperatures
- Reduced thermal loading on target module (above)



Testing the Solution

Test #3 – Blue™ agent applied; "Fire Breaks" added

- Removed thermal isolators between parallel groups of cells
- 2mm "channel" for Blue™
- All other test conditions unchanged from Test #2



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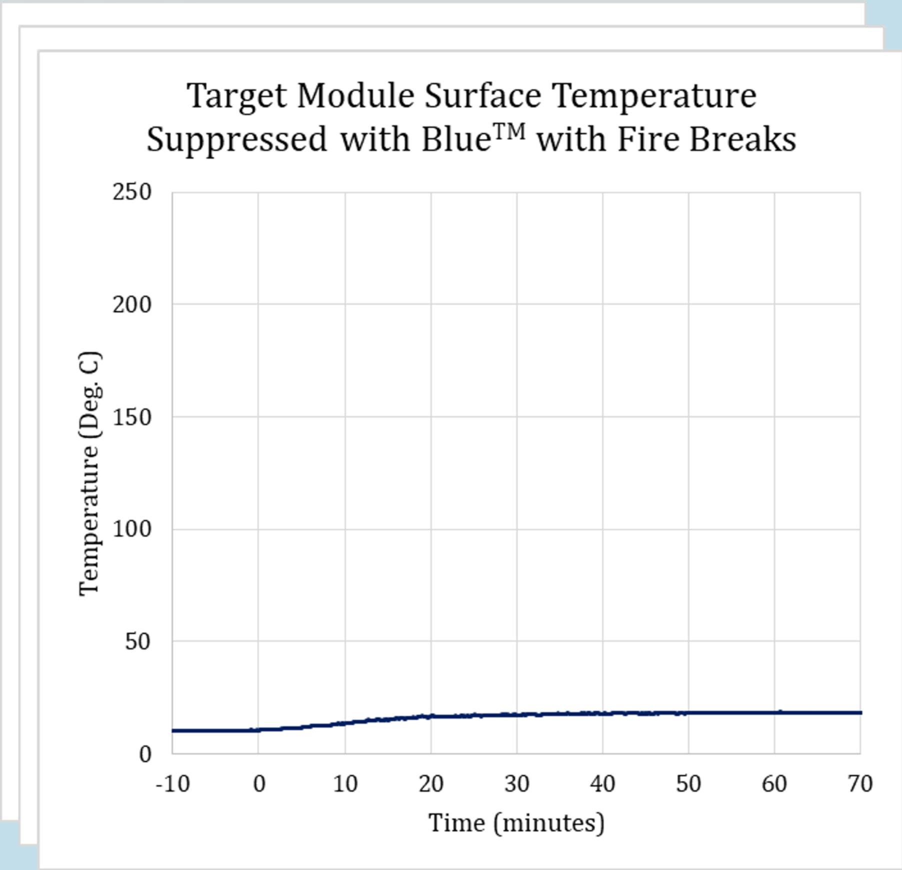
Testing the Solution

Test #3 – Blue™ agent applied; "Fire Breaks" added

- Further reduction in internal and external temperatures
- Drastically reduced thermal loading on target module (above)

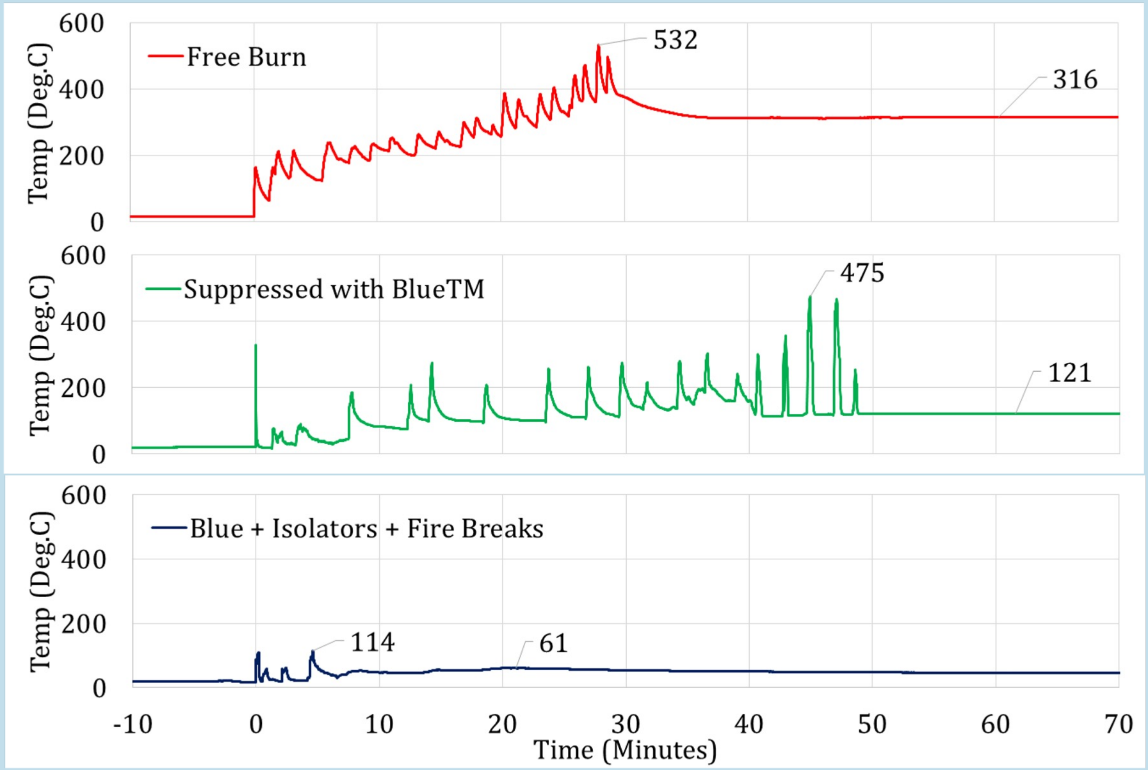


Testing the Solution

Performance Summary

- Blue™ halted cascading thermal runaway within the module
- Drastic reduction in internal vapor temperatures

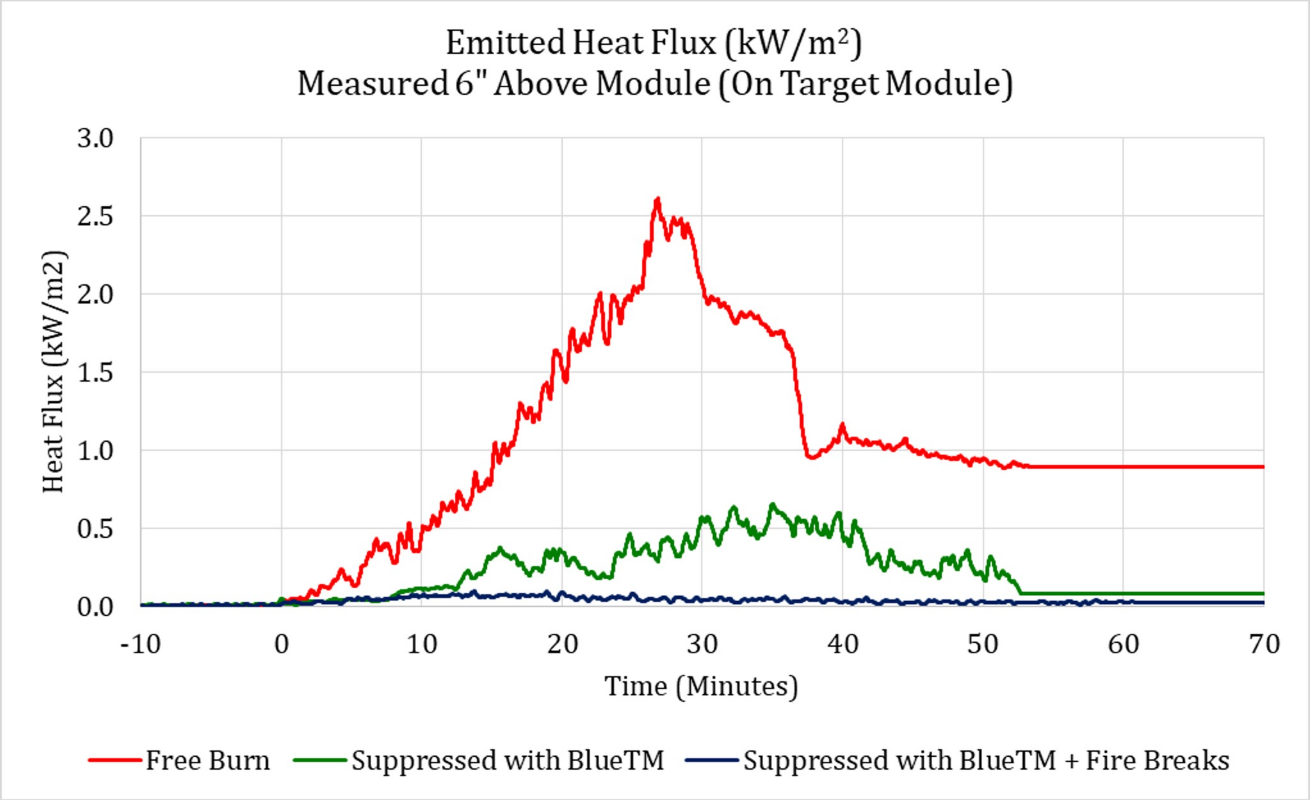
Internal Vapor Temperatures



Testing the Solution

Performance Summary

- Drastic reduction in peak emitted heat flux



Performance Comparison

Metric	Free Burn	Suppressed with Blue™	Suppressed with Blue™ + Fire Breaks
Cells Burned	36	21 (42% Reduction)	6 (83% Reduction)
Duration (minutes)	30	49	6
Peak Vapor Temperature (°C)	532	475	114
Settled Vapor Temperature (°C)	316	121	61
Peak Heat Flux (kW/m^2)	2.61	0.66 (75% Reduction)	0.09 (96% Reduction)
Peak Target Module Surface Temperature (°C)	236	53	19

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Further Testing at NRTL

CSA Testing to UL9540A

- 16 fully charged modules totaling 768 v and 200 kw of power
- Used minimum spacing found in the field (rack to rack and rack to wall)
- Temperature and heat flux measured at target walls and target modules
- Temperatures of the target BESS and walls were never close to the UL9540a limits

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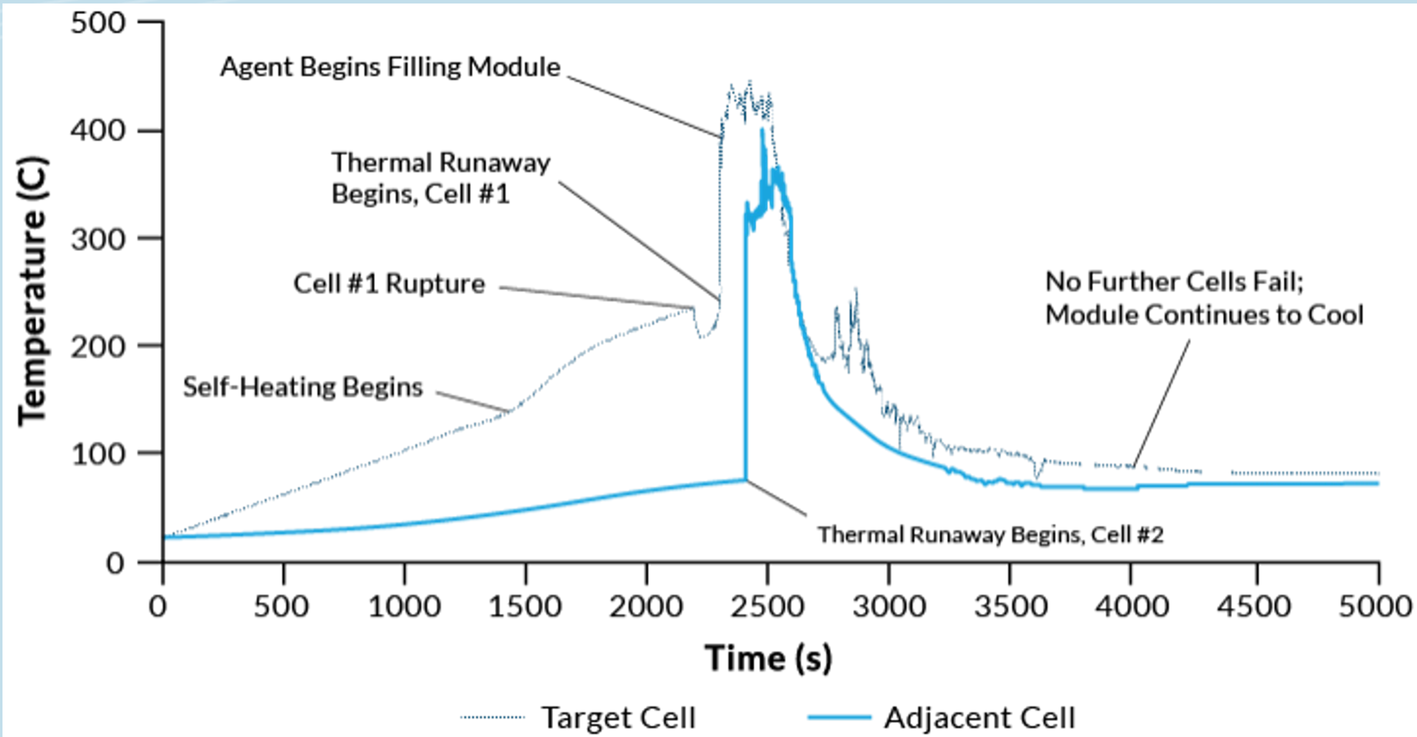
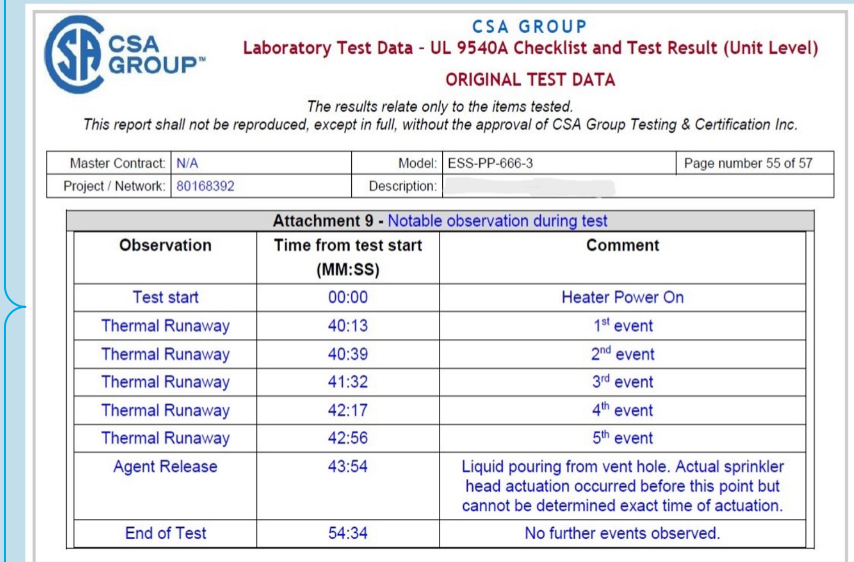
Further Testing at NRTL

- Fike Blue™ Performance – Proven at scale



Further Testing at NRTL

Observation	Time (MM:SS)	Comment
Test Start	00:00	Heater Power On
Thermal Runaway	40:13	1st Event
Thermal Runaway	40:39-42:56	2nd-5th Event
Agent Release	43:54	Liquid pouring from vent hole. Sprinkler actuation occurred sooner, but exact time indeterminable
End of Test	54:34	No further events observed



CSA GROUP

Laboratory Test Data - UL 9540A Checklist and Test Result (Unit Level)

ORIGINAL TEST DATA

The results relate only to the items tested.
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Master Contract:	N/A	Model:	ESS-PP-666-3	Page number 55 of 57
Project / Network:	80168392	Description:		

Attachment 9 - Notable observation during test

Observation	Time from test start (MM:SS)	Comment
Test start	00:00	Heater Power On
Thermal Runaway	40:13	1st event
Thermal Runaway	40:39	2nd event
Thermal Runaway	41:32	3rd event
Thermal Runaway	42:17	4th event
Thermal Runaway	42:56	5th event
Agent Release	43:54	Liquid pouring from vent hole. Actual sprinkler head actuation occurred before this point but cannot be determined exact time of actuation.
End of Test	54:34	No further events observed.

Conclusions

Conclusions

- **Understand the Risk**

  Understand the stages of Thermal Runaway and don't assume that because the fire is out that the problem is contained.

  Not all Lithium Ion batteries are created equal, there are many different chemistries and cell/module constructions available, each of these is critical to the way the cell reacts when entering Thermal Runaway.

- **Performance Based Design**

  Each ESS configuration has its own challenges and the protection solutions will need to vary accordingly. The globalization in supply chain for ESS manufacturers also requires multiple approval and response strategy requirements for each destination.

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Conclusions

- **Robust Testing**

  Testing is only valid if it has been performed with the same battery chemistry AND mechanical layout of the cell/module. Assuming that a battery with the same chemistry alone will react in the same way is incorrect.

  It should also be noted that the Abuse Factor used to initiate the reaction and the current condition of the battery can also have an effect the results, therefore multiple tests using multiple Abuse Factors and battery states should be performed.

  With this in mind, a full BHA (Battery Hazard Analysis) is critical in proving the performance of a system