Energy storage systems
Stored energy and the firefighter's response

Sean DeCrane, manager, Industry Relations, UL

Empowering Trust®

Hoverboards

Hoverboard incidents — Nashville

Culprit

Remains

UL’s hoverboard test

UL 2272

Underwriters Laboratories Inc.
Standard For Safety For Electrical Systems for Personal E-Mobility Devices, UL 2272

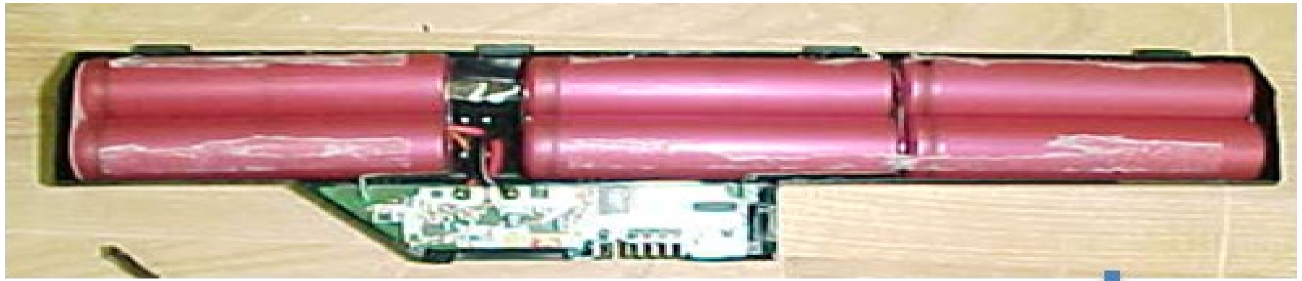
STP 2272 Membership

Name	Representing	Interest Category*	Region
Bigler, Robert	Hoverboard Technologies	Producer	USA
Brueckner, Shawn	National Research Council Canada	Government	CANADA
Byczek, Rich*	Intertek	Testing and Standards	USA
Cassidy, Tim	Best Buy	Supply Chain	USA
Chenyu, Lu	China Electrical Equipment Industry	General	CHINA
Crosby, Patrick	PTX Performance Products USA	Supply Chain	USA
Dabydeen, Andy	Canadian Tire Corp	Supply Chain	CANADA
Dick, David*	Bureau Veritas CPS	Testing and Standards	USA
Doughty, Daniel	Battery Safety Consulting Inc.	General	USA
Florence, Laurie*	UL LLC	Testing and Standards	USA
Greiner, Michael*	MGA Research	Testing and Standards	USA
Jolivette, Joalene	Inventist	Producer	USA
Lambaz, Sadeddin	Littelfuse Inc.	Supply Chain	USA
Leber, Jody*	SGS	Testing and Standards	USA
Lee, Douglas	U.S. Consumer Product Safety Commission	Non-voting	USA
Lu, Janet	Hangzhou Chic Intelligent	Producer	CHINA
McLean, Ryan	Razor USA	Producer	USA
Monahan, Charles	Panasonic	Supply Chain	USA
Morrissey, Len	ASTM International	Non-voting	USA
Nam, Dae Ho	LG Chem, Ltd.	Supply Chain	KOREA
Phillips, Stephen	Segway Inc.	Producer	USA
Pollack-Nelson, Carol	Independent Safety Consulting	General	USA
Prince, Deborah	Underwriters Laboratories Inc.	STP Chair - Non-voting	USA
Reddy, Thomas	Self	General	USA
Schapiro, Steven	Orbitboards LLC	Producer	USA
Sepper, Megan	Underwriters Laboratories Inc.	STP Project Manager - Non-voting	USA
Seregelyi, Joe	Health Canada	Government	CANADA
Wood, Daniel	Focus Designs Inc.	Producer	USA

Li-ion battery designs and challenges

Thermal gradient and safety are major challenges.

Low voltage/low capacity



High voltage/high capacity

Lithium-ion battery background

Legacy stationary battery systems

Location

- Telecom central offices (dedicated use)
- Internet data centers
- Incidental use areas in occupied buildings

Legacy stationary battery systems

Lead-acid system hazards

- Hydrogen gas produced during charging
- Corrosive liquid spills
- Large quantities of electrical energy

Energy storage systems (ESS)

Expanding energy storage infrastructure

- Grid balancing and resiliency
- Mitigating renewable energy intermittency
- Reliable UPS

Utility, commercial and residential applications

Modern battery technologies

Energy density and cost drive new battery technologies

Stationary battery technologies include:

- Flow batteries
- Sodium-sulfur batteries
- Lithium-ion (li-ion) batteries
- Other technologies on the way

Lithium-ion batteries

- Excellent energy density
- The current battery of choice
- Batteries and systems are readily available
- Majority of ESS market is Li-ion

2015 IFC battery systems requirements

- Since 1997, (lead-acid) battery systems allowed in incidental use areas
- 1- or 2-hour fire-rated separations
- Hazmat requirements exempted
- Spill control, ventilation and smoke detection
- Battery quantities unlimited
- Location in building not regulated
- Standby and emergency power, UPS use

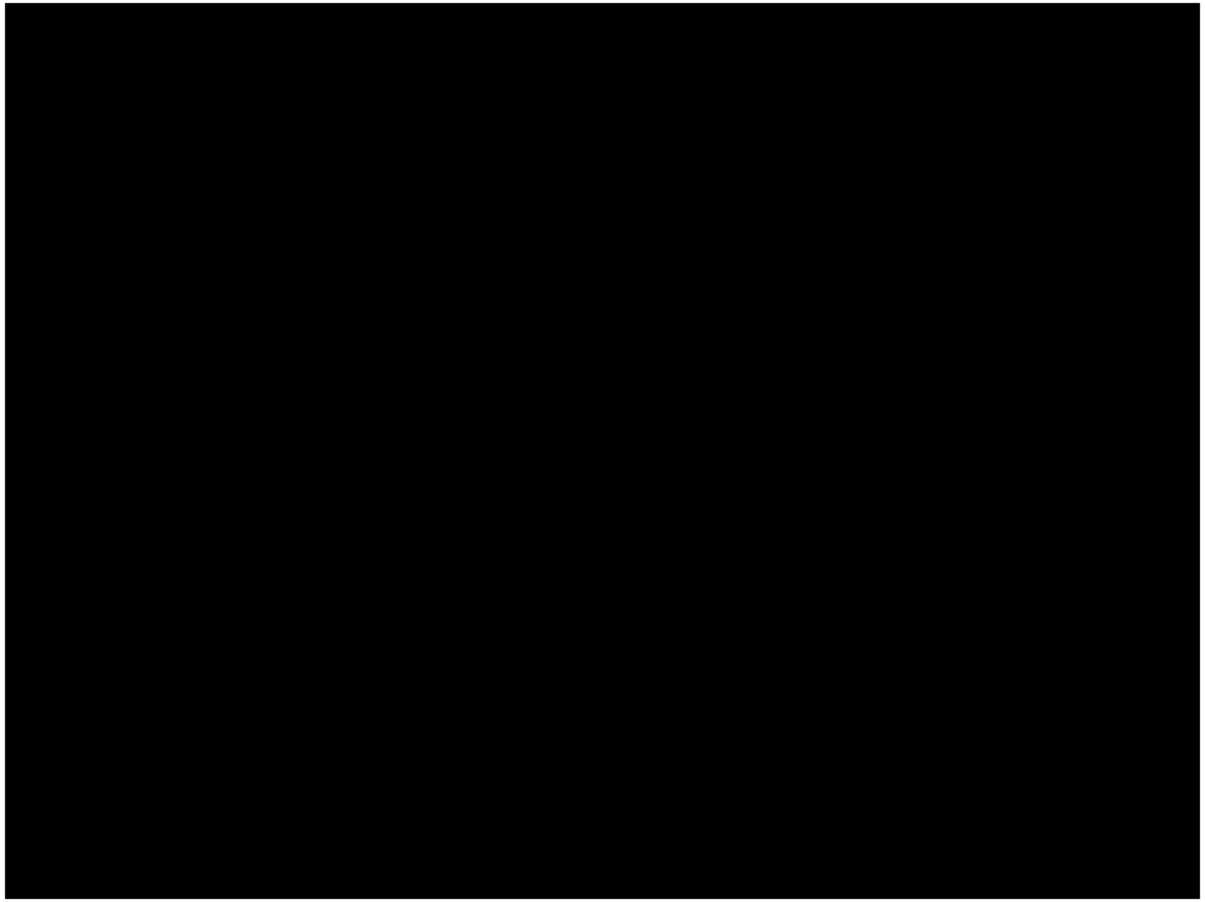
2015 fire codes do not adequately protect newer battery technologies

Li-ion battery cell reactions

- Overheating and cell rupture is possible from:
  - Overcharging
  - Overheating
  - Short circuits
  - Manufacturing defects
  - Mishandling
- Overheated cells can vent flammable gas
- Ignition source creates fire/explosion

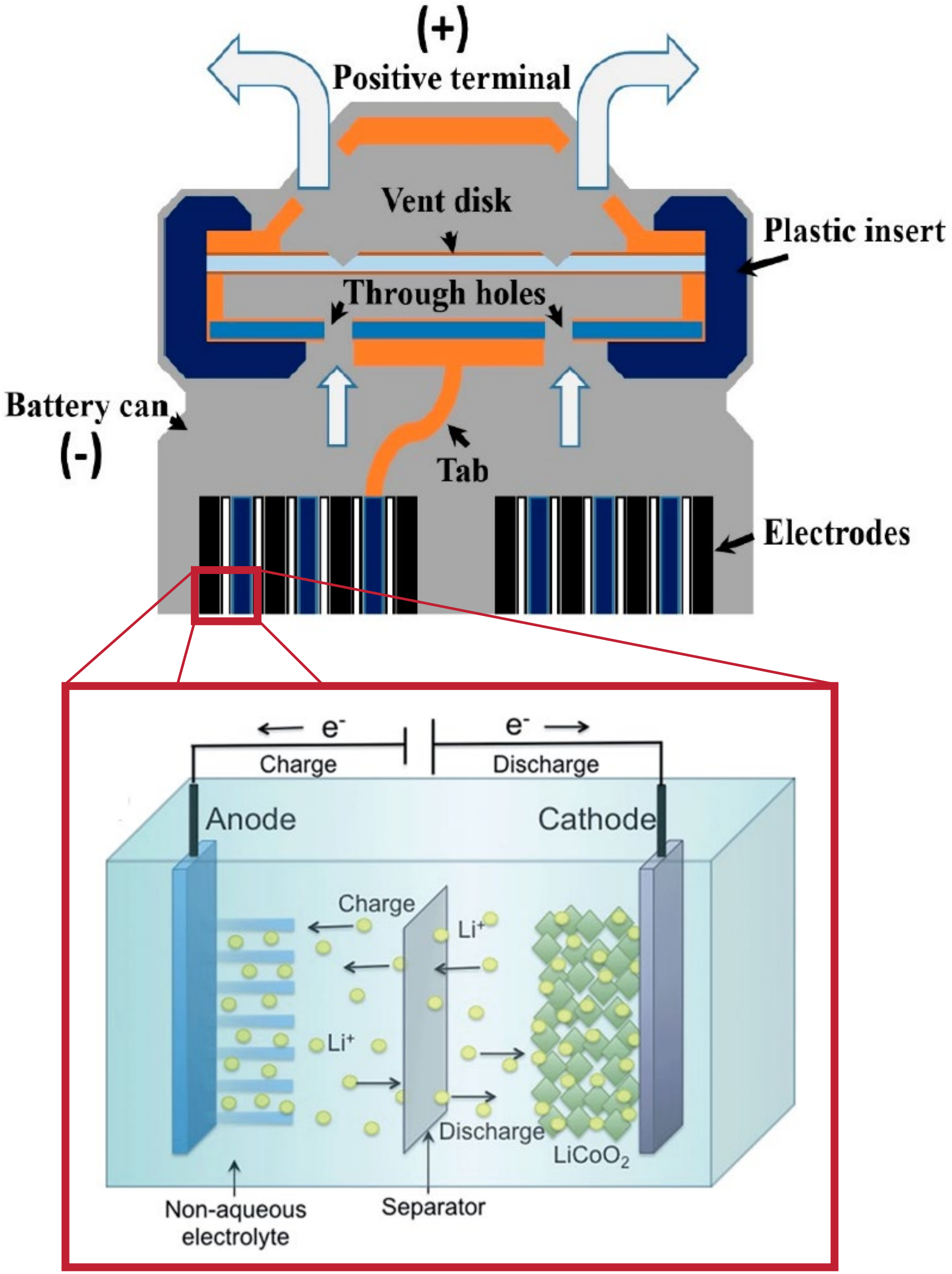
Thermal runaway in one battery will readily spread to adjacent cells

Li-ion batteries — abnormal charging



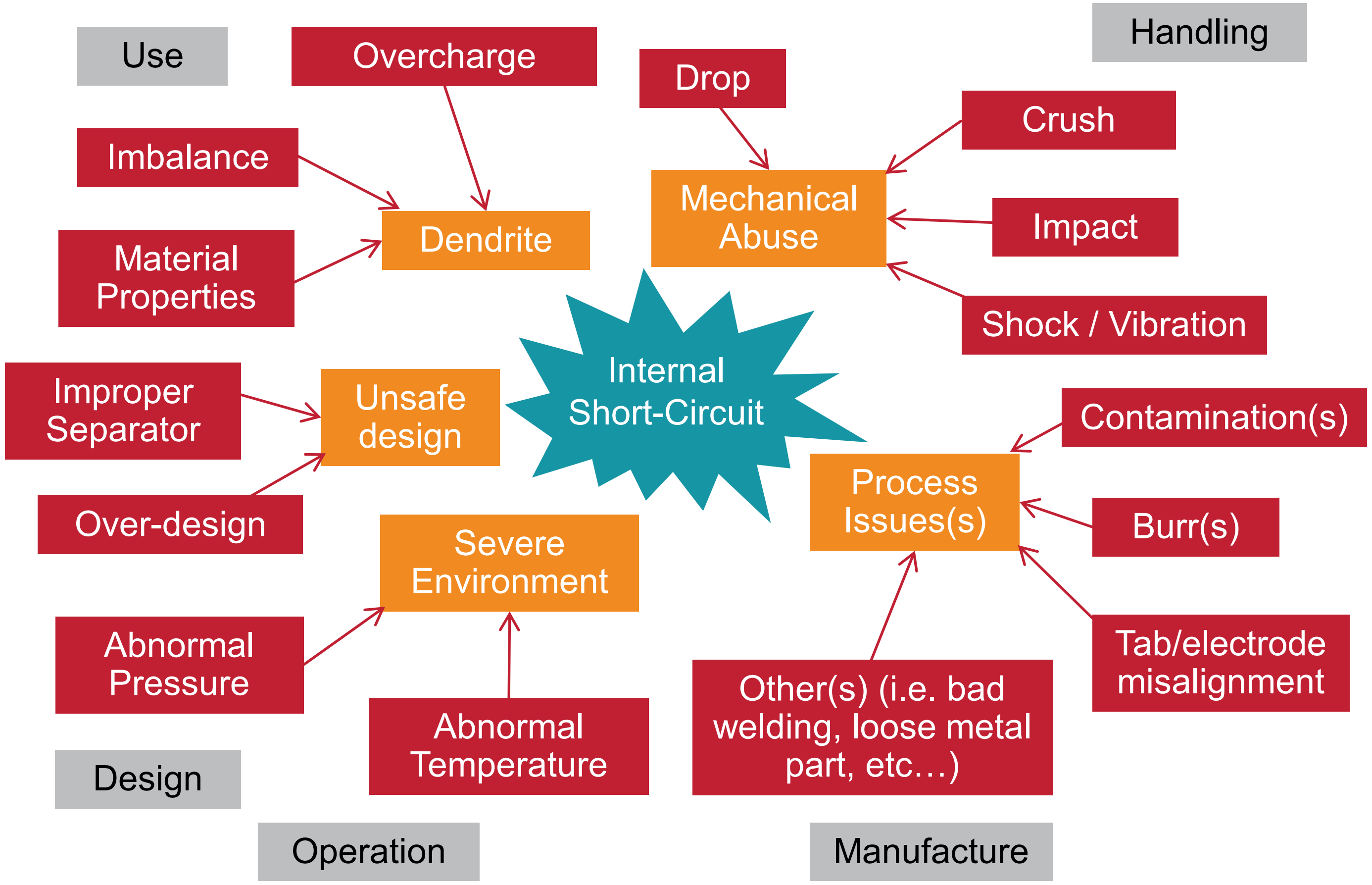
Components

- **Anode** – Typically, a graphite matrix deposited on copper foil
- **Cathode** – Crystalline structure comprised of lithium compounds typically containing a mixture of metal oxides (nickel, cobalt, manganese, phosphorus, iron, etc.)
- **Electrolyte** – Typically, a lithium salt dissolved in a polymeric solvent
- **Separator** – Typically, one or more layers of polyethylene



Courtesy of FSRI

Causes of cell thermal runaway (TR)



Note: UL 9540A, the Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems, is conducted with thermal runaway induced in an energy storage system (ESS) module.

Thermal runaway — 25 lithium-ion cells

Fire safety approach

Evolution of ESS fire/explosion protection: timeline

Pre-2016

ESS fire and explosion hazards not yet reflected in Codes and Standards.

Feb 2016

ESS fire hazards demonstrated in first public report.

Aug 2017

Fire and explosion hazards reflected in 2018 International Fire Code, Section 1206.

Nov 17–Jun 18

UL 9540A first edition to third edition.

UL 9540A enables path to meet code exemptions via large-scale test safety performance.

Aug 2019

Reference to UL 9540A, 25% of LFL condition added, NFPA 855 and IFC 2021 draft.

Nov 2019

ANSI/CAN UL 9540A fourth edition.

Methodology added to develop input data for NFPA 68, 69 calculations.

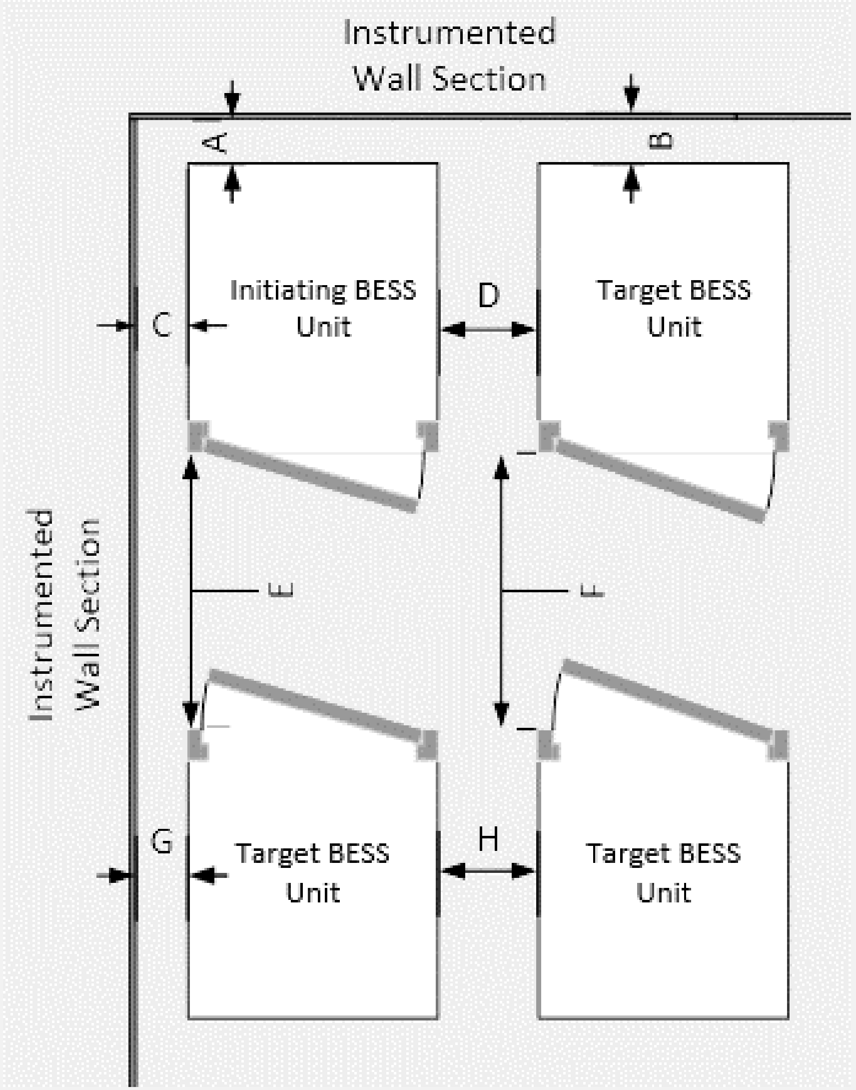
Present

Future ESS fire and explosion testing approaches.

International Fire Code (IFC) constraints

Testing is required when one of the following requirements from the IFC is not met:

- Max. 50 kWh each
- Max. 250 kWh each for listed systems
- Min. 3-foot spacing from other arrays and from walls
- Other arrangements/quantities as approved by code authority based on large-scale fire testing (UL 9540A)



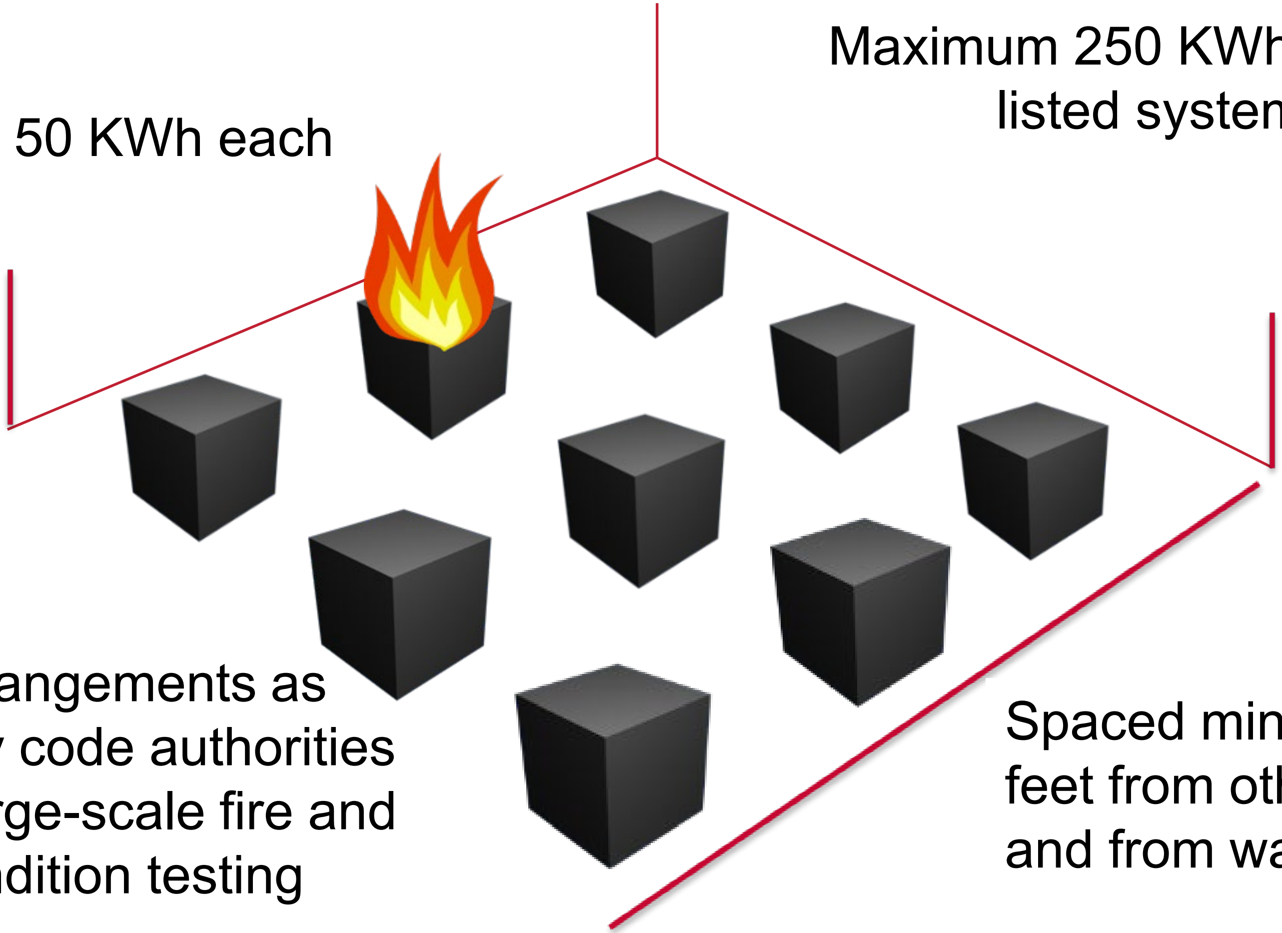
Thermal runaway — 25 lithium-ion cells

- An 18650 Li-ion cell is ~10 Wh
- 25 cells is ~250 Wh
- A 50 kWh ESS (max. unit without UL 9540A testing) has 200 times more energy capacity

2018 IFC Size, Separation, MAQ

Maximum 50 KWh each

Maximum 250 KWh each for listed systems



Other arrangements as approved by code authorities based on large-scale fire and fault condition testing

Spaced minimum three feet from other arrays and from walls

MAQ 600 KWh (lead acid battery exception)

UL 9540A test Standard

Scope

Evaluate fire characteristics of a battery energy storage system (BESS) that undergoes thermal runaway. Data generated will be used to determine the fire and explosion protection required for an installation of a battery energy storage system.

Match fire protection of installation to performance of BESS

UL 9540 is a system standard

Systems are constructed either as one unitary complete piece of equipment or as matched assemblies.

- UL 9540 evaluates the compatibility and safety of the various components integrated into a system.

Individual parts (e.g. power conversion system, battery system, etc.) of an energy storage system are not considered an energy storage system on their own.

- While each component may be evaluated to their respective component standard, there is a need to ensure the relationship of those components used together, maintain that same high level of safety.

UL 9540A large-scale fire testing

The code authority can approve the following installations based on UL 9540A large-scale fire testing:

- Increased unit size
- Reduced spacing to adjacent units and/or walls
- Increased MAQ/MRE in a fire area
- Alternate fire suppression systems
- Outdoor ESS clearance to exposures

UL 9540A is also used to generate gas production data design explosion control systems.

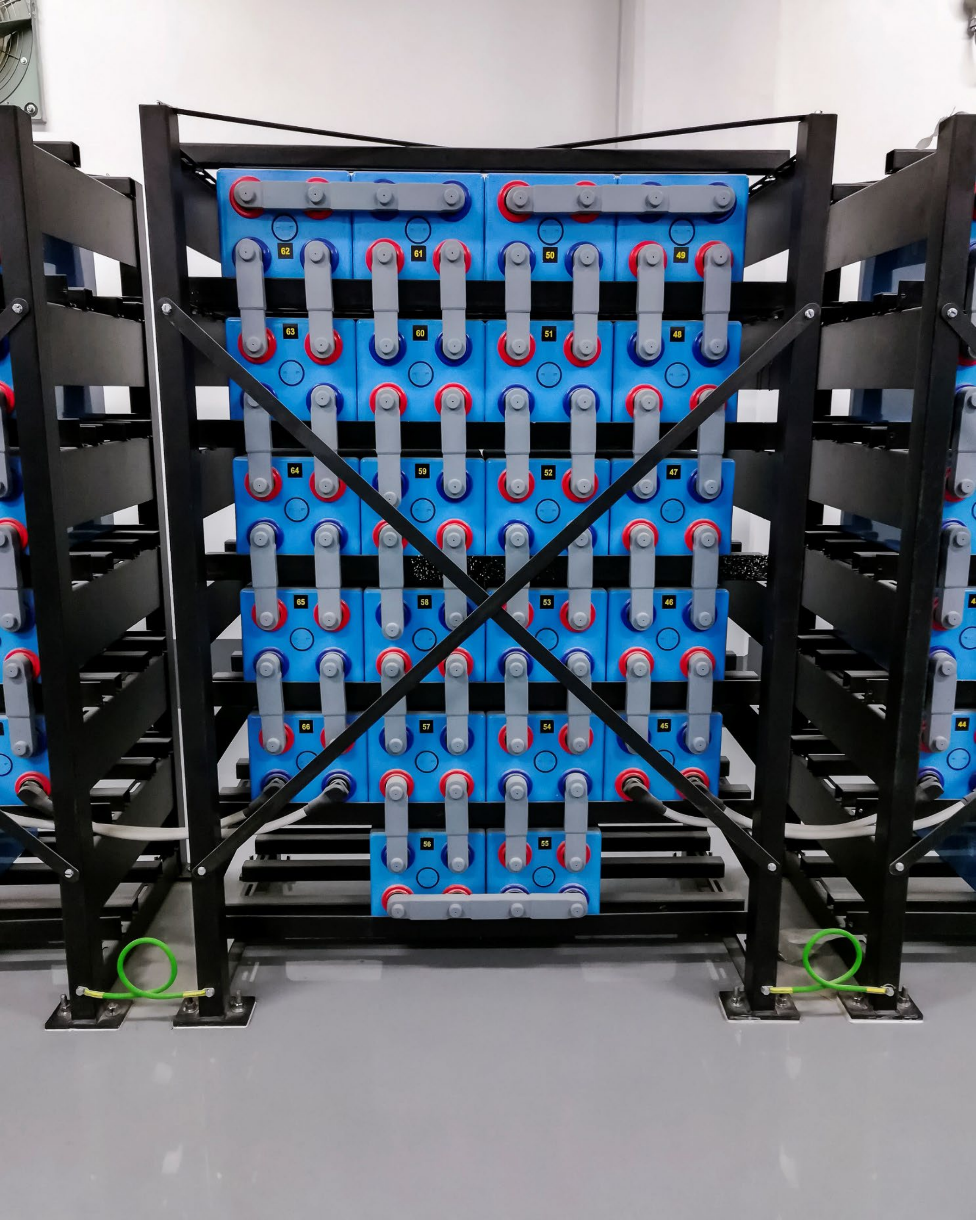
Scope and applications

A UL 9540 certification can include:

- ESS walk-in systems
- Mobile ESS
- Indoor ESS
- Outdoor ESS
- Residential ESS
- Wall-mounted ESS

Applications that utilize UL 9540:

- Telecom
- UPS
- Electric vehicle supply equipment
- Voltage support and regulation
- Frequency support and regulation
- Capacity reserve
- Energy shifting
- Other utility-grid support services



UL 9540A General Info

There are four levels of tests within the test method that build upon one another:

- Cell level
- Module level
- Unit level
- Installation level

A report is provided as a result of the testing. There is no certification to UL 9540A, however, certification to UL 9540 requires UL 9540A if indicated in the codes.

UL 9540A test methodology

Cell Level — x1

- Whether cell can exhibit thermal runaway
- Thermal runaway characteristics
- Gas composition

Module level — x4

- Propensity for propagation of thermal runaway
- Heat and gas release rates
- Deflagration hazards

Unit level — x16

- Evaluation of fire spread
- Heat and gas release rates (severity/duration)
- Deflagration hazards
- Reignition hazards

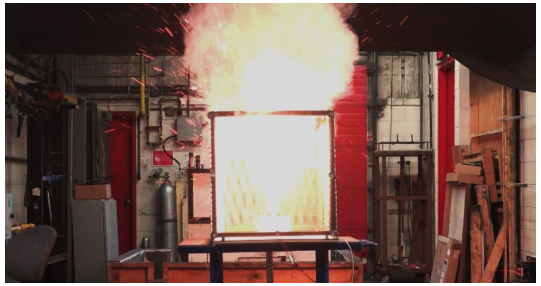
Installation level

- Effectiveness of fire protection system(s) to mitigate fire propagation
- Deflagration hazards
- Reignition hazards

Current UL 9540A approach for ESS fire/explosion hazard testing

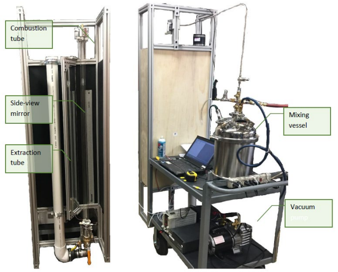
Cell Level Test

Thermal runaway T_{vent} T_{TR}



Gas composition

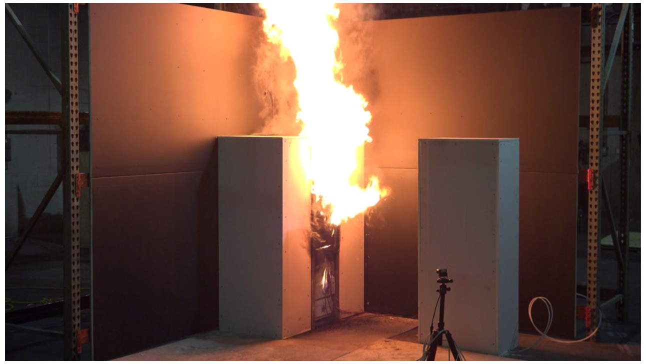
Burning velocity



P_{max}, LFL

Module Level Test

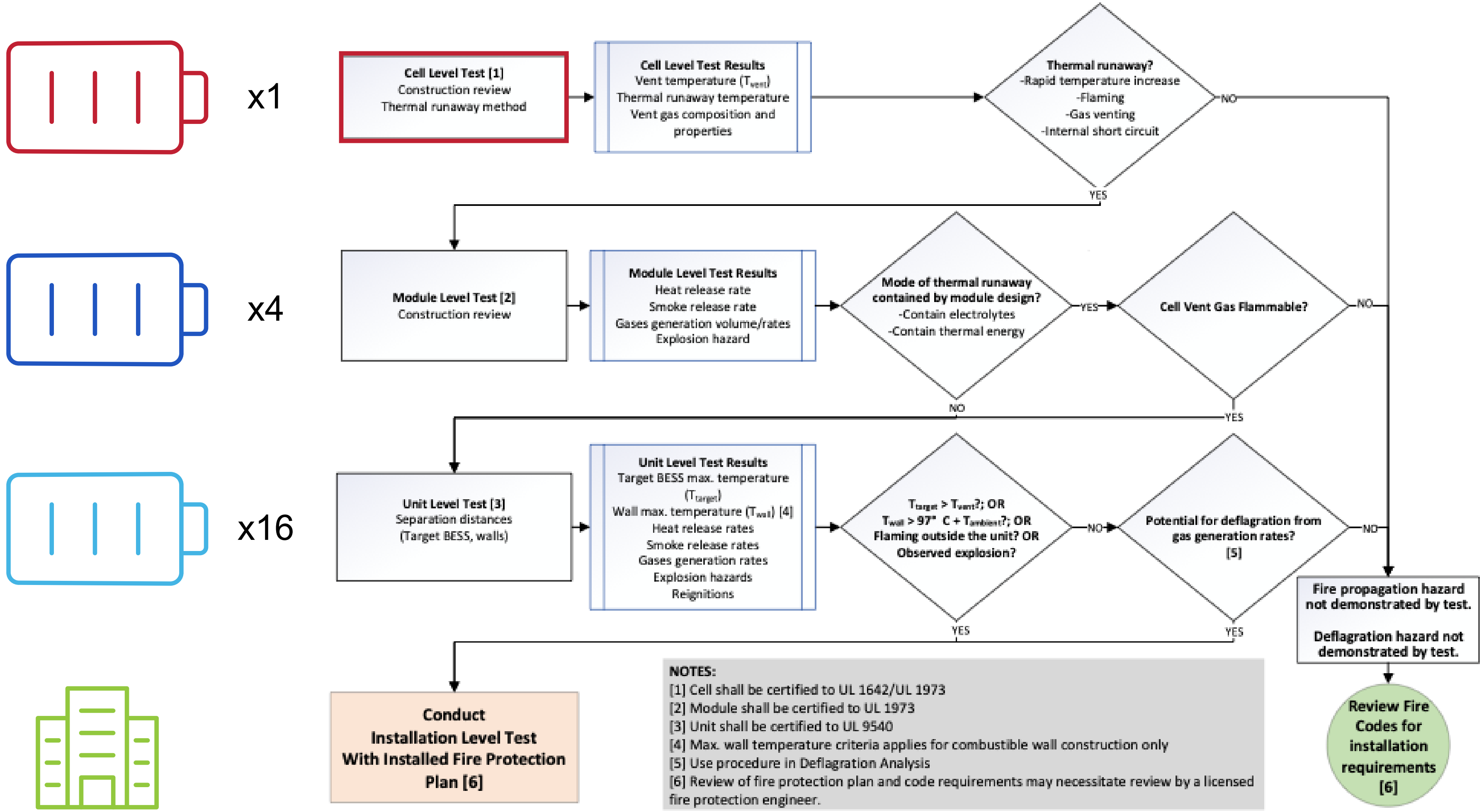
Unit Level Test



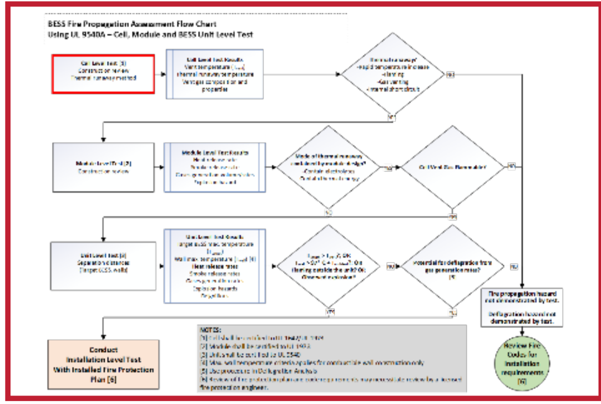
Installation Level Test

Overview of UL 9540A test levels – cell, module, unit, and installation

BESS fire propagation assessment process



Cell construction review/test initiation

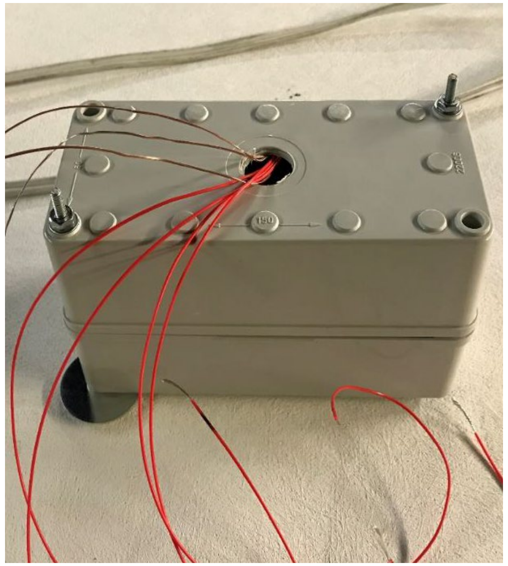


Property	Value
Manufacturer	UL
Model	6-706
Chemistry	Li-ion ($LiNiCoAlO_2$)
Form factor	Prismatic
Electrical capacity	100 Ah
Nominal voltage	3.6 V
Weight	1.7 kg
Separator material	PE/PP
Dimensions	6 3/4" x 3 3/4" x 3 3/4"

Thermal runaway methodology tests:

Determine abuse condition based on construction review:

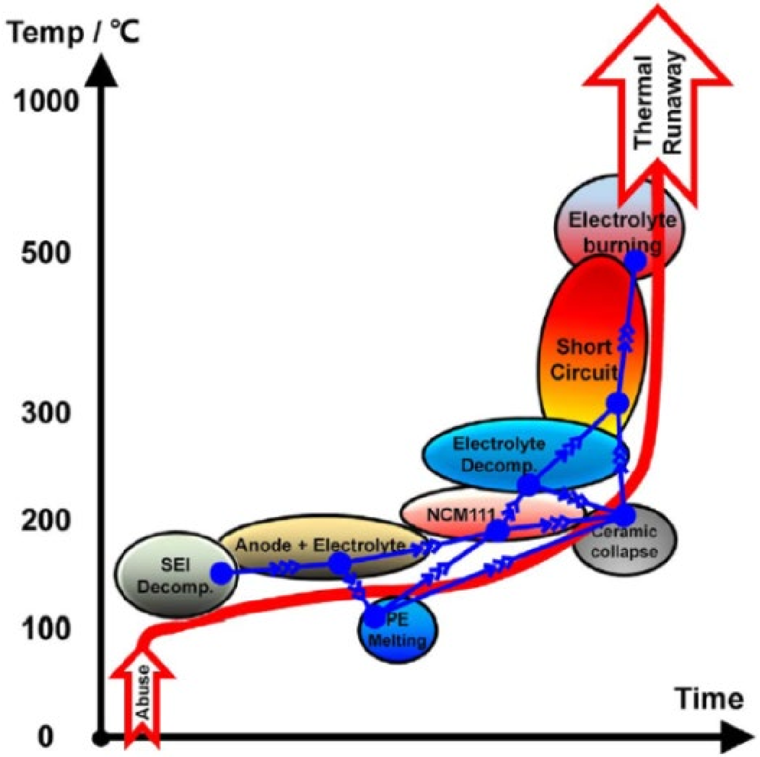
- Heat – first choice (e.g., flexible film heater, furnace, hold temperature)
- Electrical (e.g., overcharge, external short)
- Mechanical (e.g., nail penetration, crush)



Cell level testing

Purpose:

- Cell thermal runaway methodology, instrumentation
- Thermal runaway test parameters
- Cell surface temp at venting and thermal runaway
- Gas generation/composition; characterize gas flammability hazards (LFL)



Cell level testing apparatus

Important data

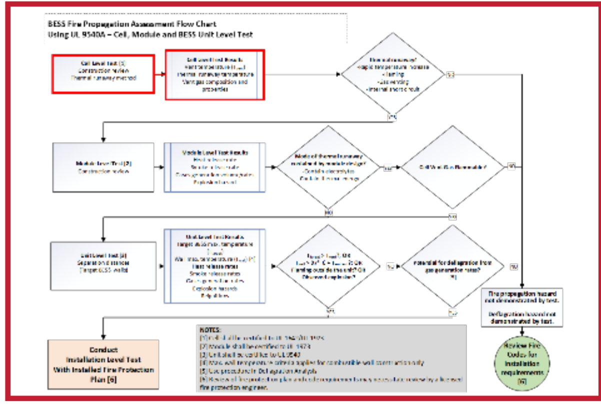
- Thermal runaway method and parameters
- Temperature at venting
- Temperature at thermal runaway initiation
- Cell vent gas measurements:
  - Composition
  - Volume
  - Lower flammability limit
  - Burning velocity
  - P_{max}

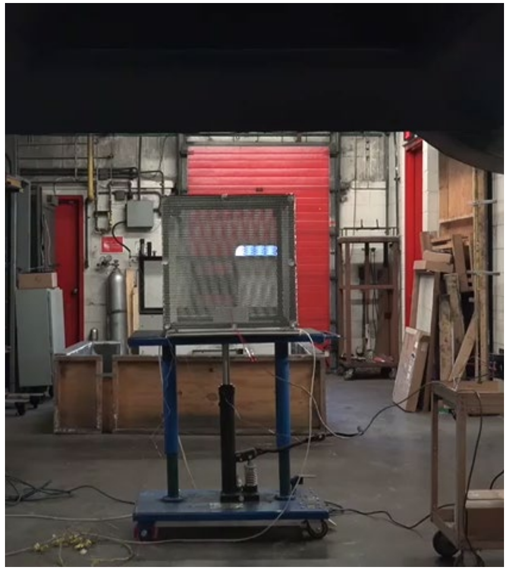
Cell level test results

Property	Value
Vent temperature #1	133 C
Vent temperature #2 (repeat #1)	129 C
Vent temperature #3 (repeat #2)	133 C
Vent temperature #4 (repeat #3)	132 C
Average vent temperature	132 C
Thermal runaway temperature #1	190 C
Thermal runaway temperature #2 (repeat #1)	210 C
Thermal runaway temperature #3 (repeat #2)	190 C
Thermal runaway temperature #4 (repeat #3)	200 C
Average TR temperature	198 C

Thermal runaway temperature confirms that this technology is susceptible to thermal runaway.

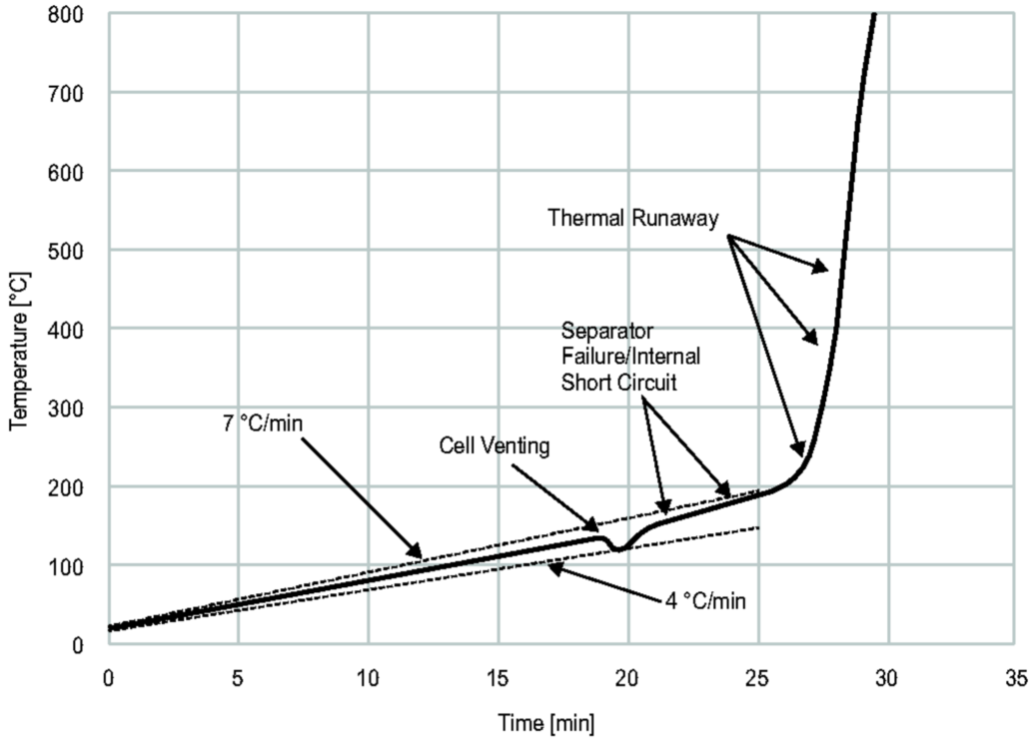
Cell vent temperature is averaged from repeat tests. Cell vent temperature is a critical metric for unit and installation level test performance assessment.





Cell level mock-up test

Example of generic Li-ion cell heated to thermal runaway;
cell venting and thermal runaway temperature are documented.



Gas	Composition (Vol. %)
CO	36.2
CO_2	22.1
H_2	31.7
Hydrocarbons	~10%

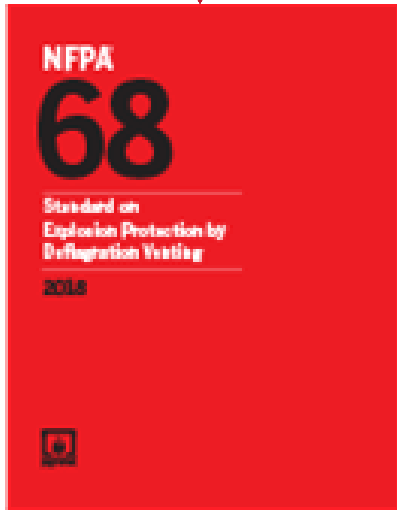
Lower flammability limit: ~8.5%

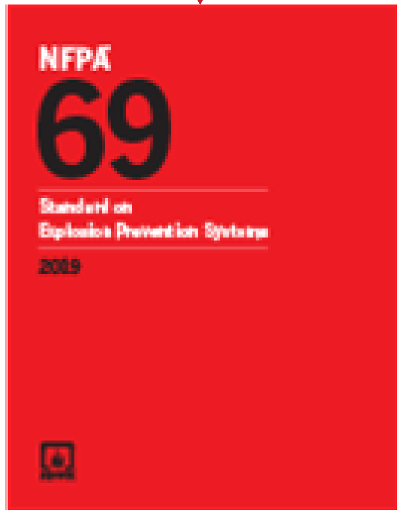
Burning velocity: 35 cm/sec

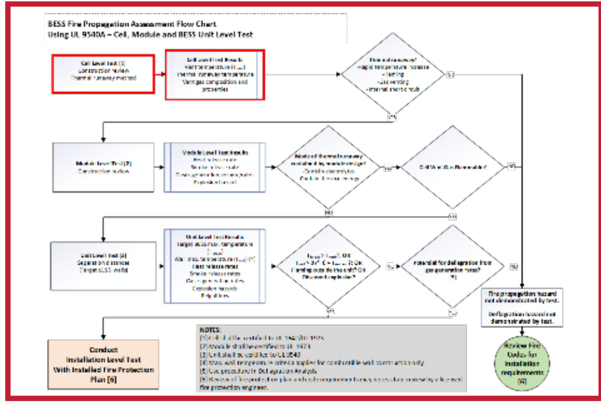
Cell level test results

Gases	Vol. %
Carbon monoxide (CO)	36.2
Carbon dioxide	22.3
Hydrogen (H_2)	31.7
Methane (CH_4)	7.4
Propylene (C_3H_6)	0.2
Ethylene (C_2H_4)	0.9
Ethane (C_2H_6)	0.6
Butane (C_4H_{10})	0.1
Benzene (C_6H_6)	0.2
Dimethyl carbonate ($C_3H_6O_3$)	0.4
Total	**100**

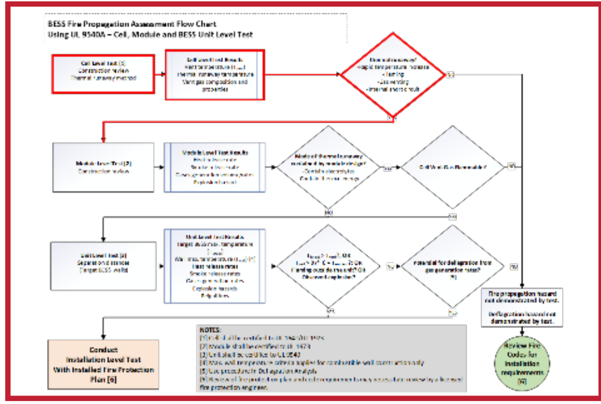
Measurement	Value
Lower flammability limit (LFL)	8.5 %/vol
Burning velocity (Su)	35 cm/sec
Maximum deflagration pressure (Pmax)	93 psig
Volume (V)	70 L







Review of cell test results



Does the cell demonstrate susceptibility for thermal runaway?

Yes – by heating:

- Thermal runaway temperature – 198 C
- Vent temperature – 132 C

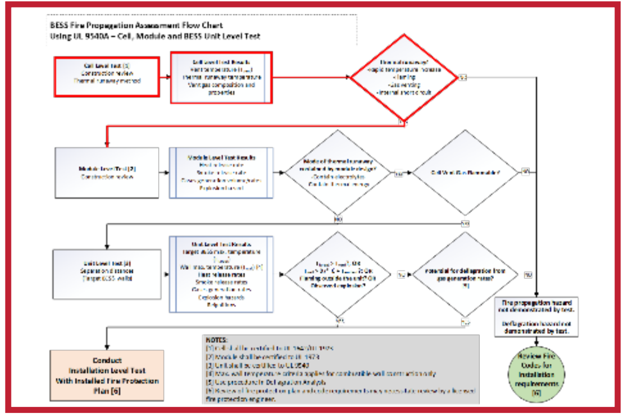
Does the cell release flammable gas as a result of thermal runaway?

Yes:

- LFL – 8.5%/volume
- S_u – 35 cm/seconds
- P_{max}: – 93 psig
- Volume – 70 L

Proceed to module level test

Results as seen in a UL 9540A report



UL 9540A Report
Unit Report

Ed.4
2020-04-21

UNIT TEST REPORT
UL 9540A
Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (AACD)

Project Number.......................:	12345678
Date of issue.........................:	July 1, 2020
Total number of pages ....:	43
UL Report Office ....:	UL LLC, Northbrook, IL 60062 USA
Applicant's name ....:	ACME Energy Storage
Address....................................:	Anywhere USA
Test specification:	4th Edition, Section 7, November 12, 2019
Standard.................................:	UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Test procedure ....:	9.1 – 9.8
Non-standard test method ....:	N/A

General disclaimer:

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UL LLC did not select the sample(s), determine whether the sample(s) was representative of production samples, witness the production of the test sample(s), nor were we provided with information relative to the formulation or identification of component materials used in the test sample(s).

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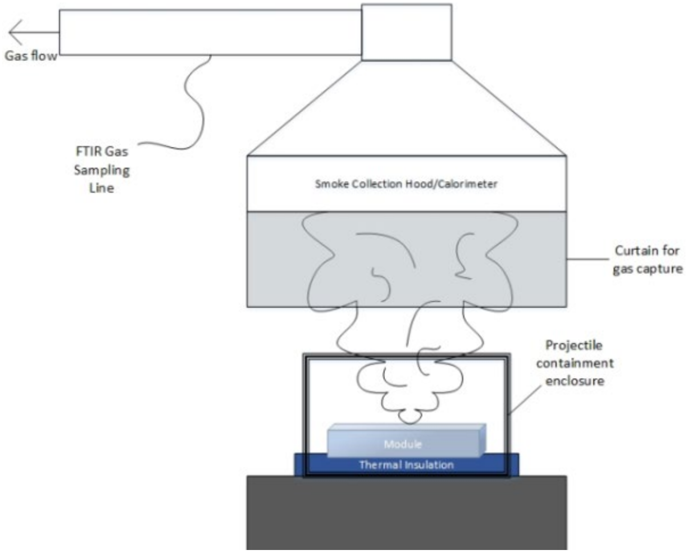
This is a sample report to demonstrate the content provided in a UL 9540A unit level test report. This sample report contains real measurements taken from UL 9540A testing of a non-proprietary example product fabricated by UL for the purposes of creating demonstration data. This report has been created for the purposes of demonstrating a minimum level of information and data that should be provided for a UL 9540A unit level test report.

Module level testing

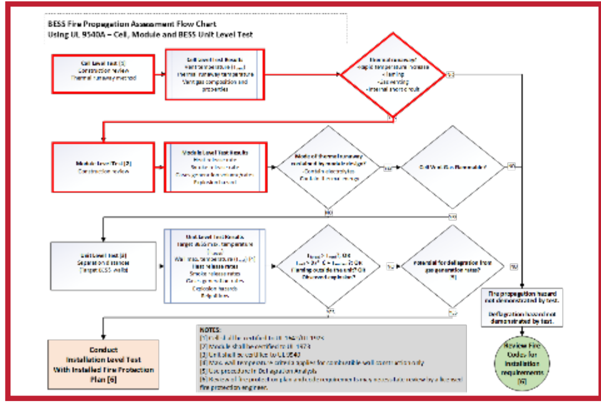
Purpose:

- Demonstrate the propensity for cascading thermal runaway propagation within a module
- Develop data on heat release rate and cell vent gas composition
- Document fire and deflagration hazards



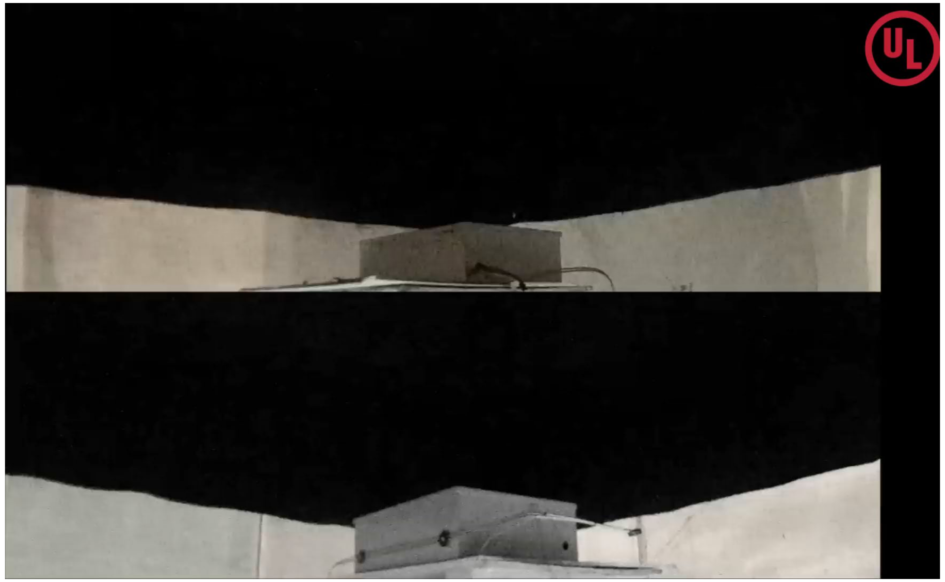
Important data:

- Thermal runaway propagation
- Heat release rate
- Deflagration hazards
- Cell vent gas measurements, composition and volumes:
- Hydrocarbons, H2, THC, CO/CO2, O2, Halogens, etc.



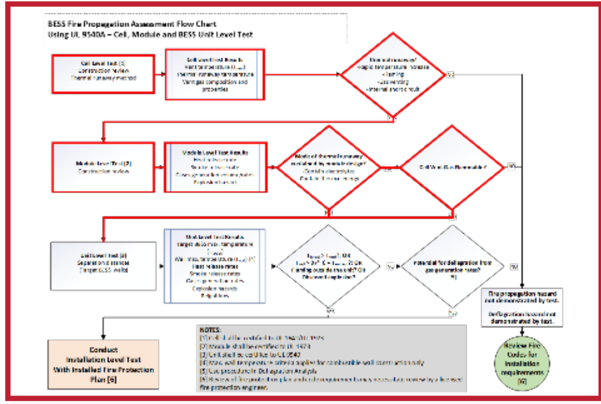
Module level construction review/test

Property	Value
Manufacturer	UL
Model number	1-8026
Electrical ratings	100 Ah @ 32.4 V
Electrical config.	9S1P
Weight	27.2 kg
Description	Steel enclosure, front and rear cooling vents, no fan.
Dimensions	20”x16”x6 ¾”



Module level mock-up test

Review of module test results



Does the module design contain thermal runaway and prevent propagation of thermal runaway to the next module?

No:

- Vent gases from cells ignited — flaming jet extended 3 ft. to 4 ft. from a cooling vent
- Gases burning around the module seams
- Extremely hot module surface temperature (not shown)

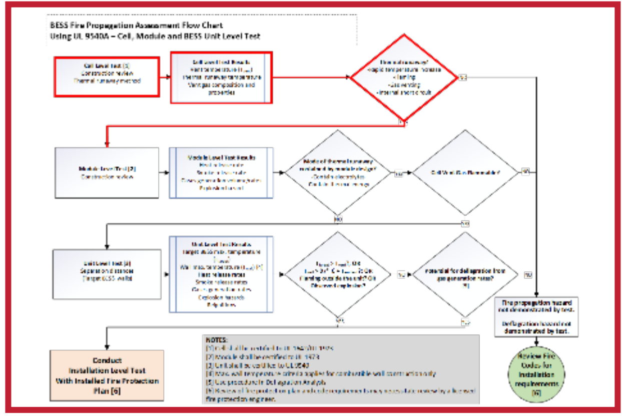
Does the module release flammable gas as a result of thermal runaway?

Yes:

276 L of unburned hydrocarbons released

Proceed to unit level test

Results as seen in a UL 9540A report



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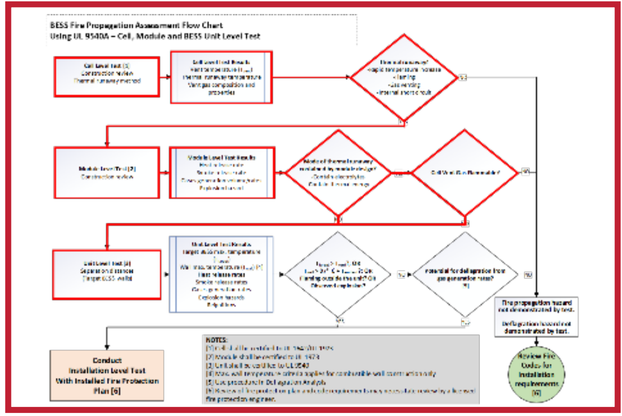
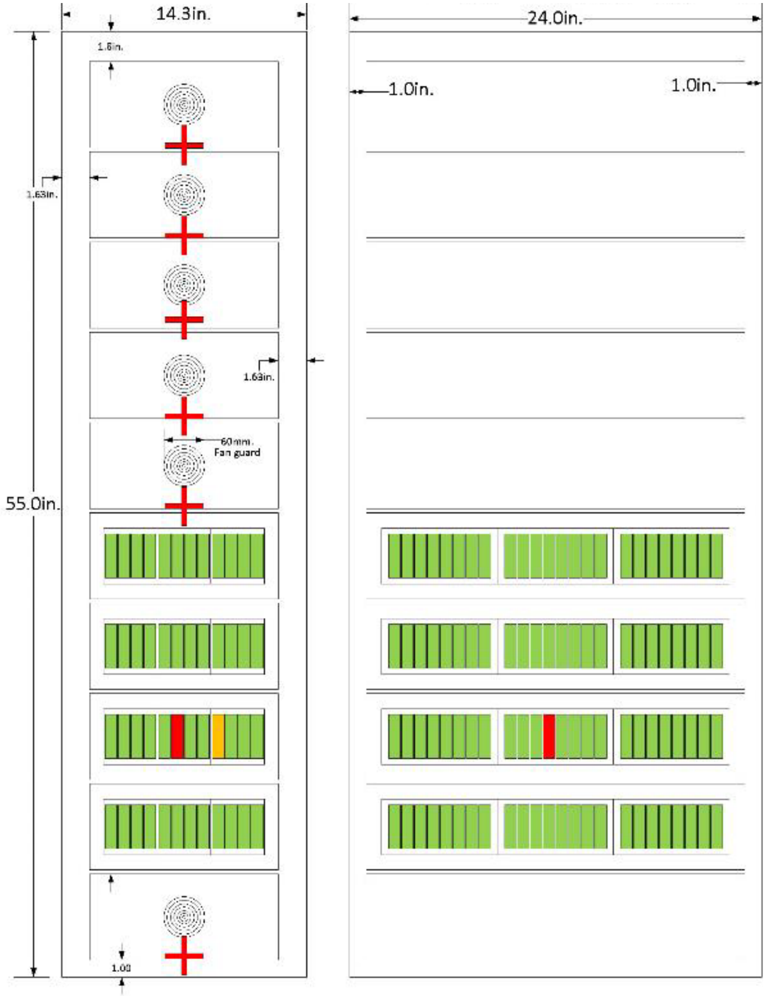
Unit level construction review



Physical and electrical specifications

Property	Value
Manufacturer	UL
Model number	3-1415
Electrical ratings	900 Ah @ 32.4 V (29.2 kWh)
Electrical config.	1S9P
Weight	281 kg
Description	Steel rack and shelving, enclosed sides, nine modules in vertical array, BMS on top
Dimensions	55” x 14.3” x 24”

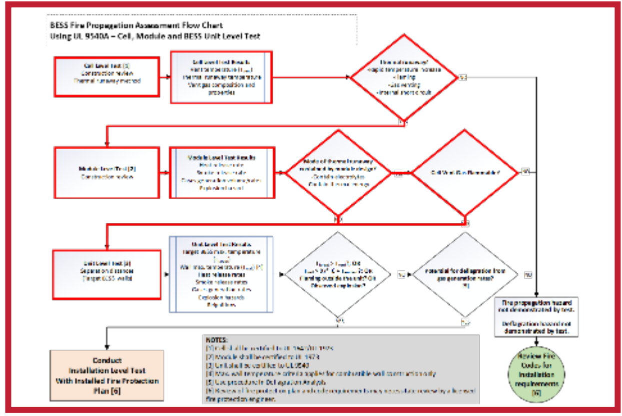


Unit level test

Test configurations include:

- Indoor floor mounted non-residential use
- Indoor floor mounted residential use
- Outdoor ground mounted non-residential use
- Outdoor ground mounted residential use
- Indoor wall mounted non-residential use
- Indoor wall mounted residential use
- Outdoor wall mounted non-residential use
- Outdoor wall mounted residential use BESS
- Rooftop and open garage non-residential use

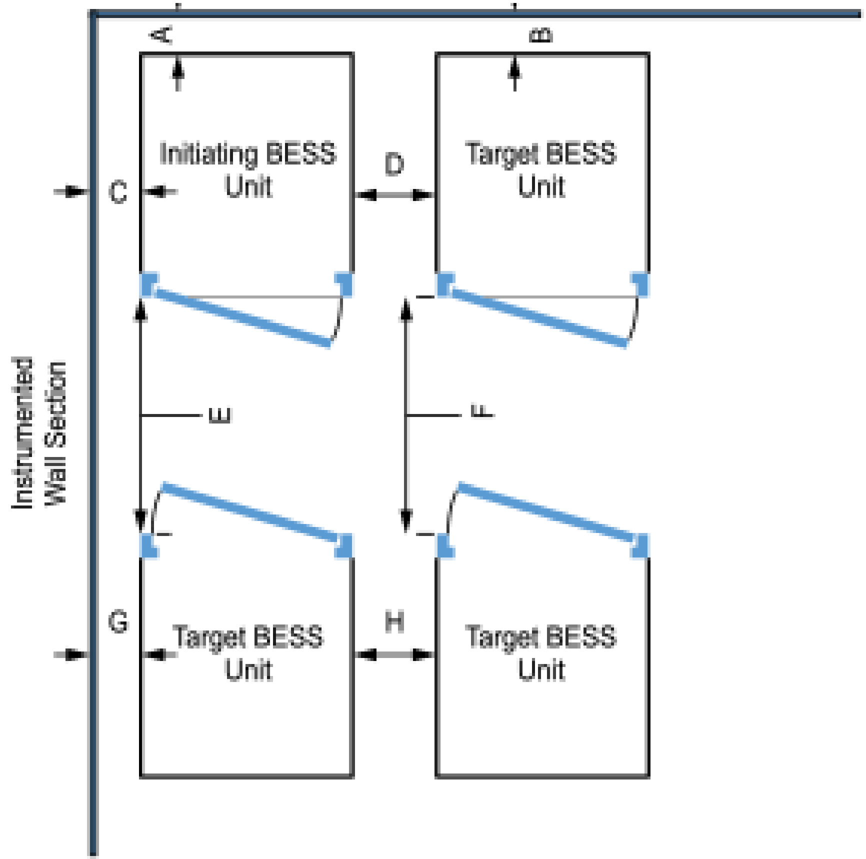
Initiating BESS is populated with all components and cells. Target BESS are installed per the installation and do not contain cells



Unit level construction review

Equipment spacing specified by test sponsor

UL 9540A spacing example

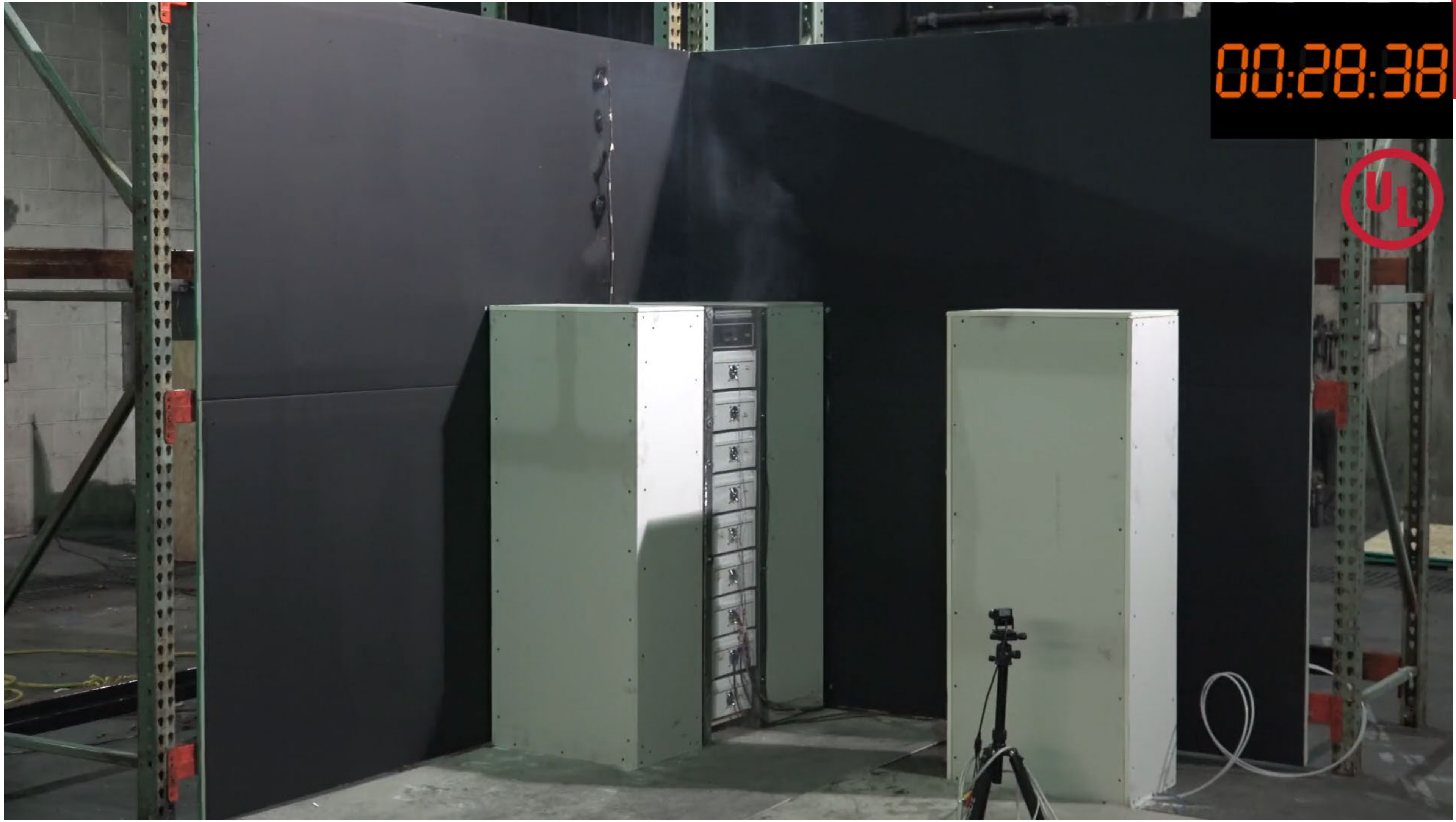


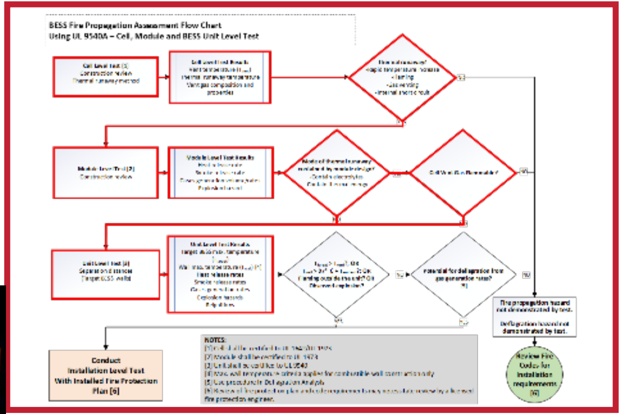
Installed

Spacing details

Dimension	Value
A	0”
B	0”
C	0”
D	0”
E	36”
F	--
G	14.3”
H	--

Unit level test

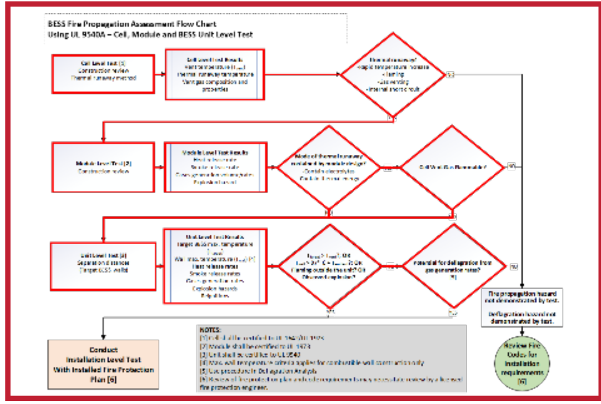




Unit level test

Performance level criteria – non residential	
Indoor floor mounted, indoor wall mounted, outdoor wall mounted	• Flaming outside the initiating BESS unit is not observed; • Surface temperatures of modules in target BESS adjacent to initiating BESS ≤ venting occurs • For BESS intended for installation with combustible constructions, wall surfaces ≤ 97°C (175°F) rise above ambient • Explosion hazards are not observed, including deflagration, detonation or accumulation of battery vent gases • Heat flux in the center of means of egress ≤ 1.3 kW/m2.
Outdoor ground mounted, roof top and open garage	Same as Indoor except: • If flaming outside of the unit is observed, separation distances to exposures shall be determined by greatest flame extension observed

Review of unit test results



Did temperature measurements in target units exceed the vent temperature measured in cell level testing? (T_{vent})

Yes: All locations measured >132 C.

Did target wall temperature measurements exceed 97 C + $T_{ambient}$?

Yes: T_{wall} >117 C in all measured locations

Was there flaming outside the initiating unit?

Yes

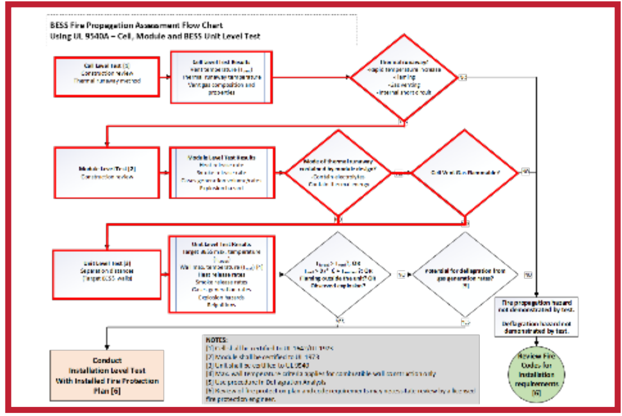
Were there any explosions or flying debris observed?

Yes:

- Flying debris – holes were found in the unit enclosure through which cells were ejected
- Explosions – no explosions observed

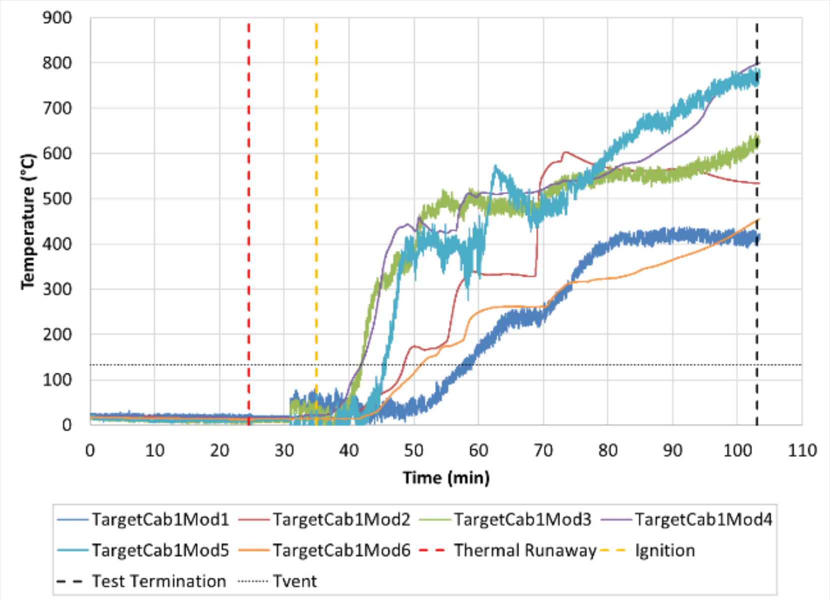
Proceed to installation level test

Unit level test results — target temps

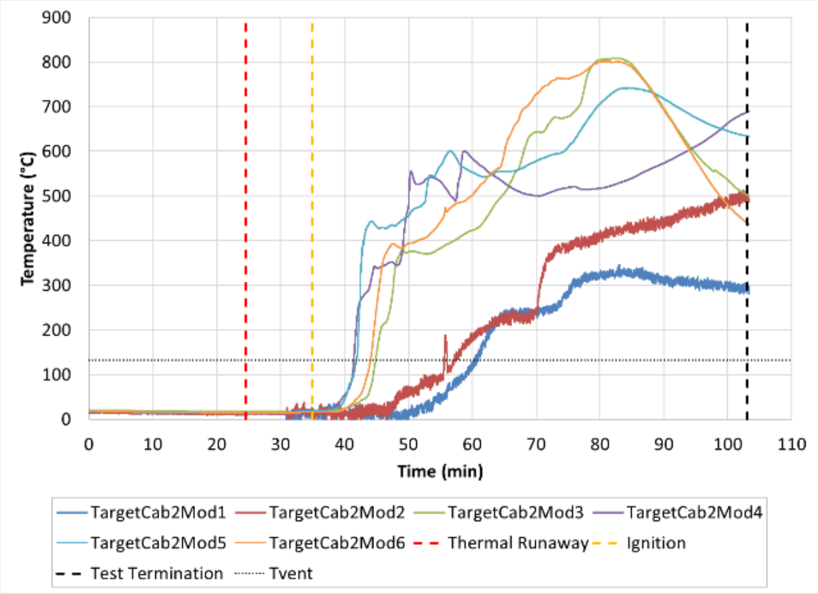


$T_{target} > T_{vent}$ in all three target units

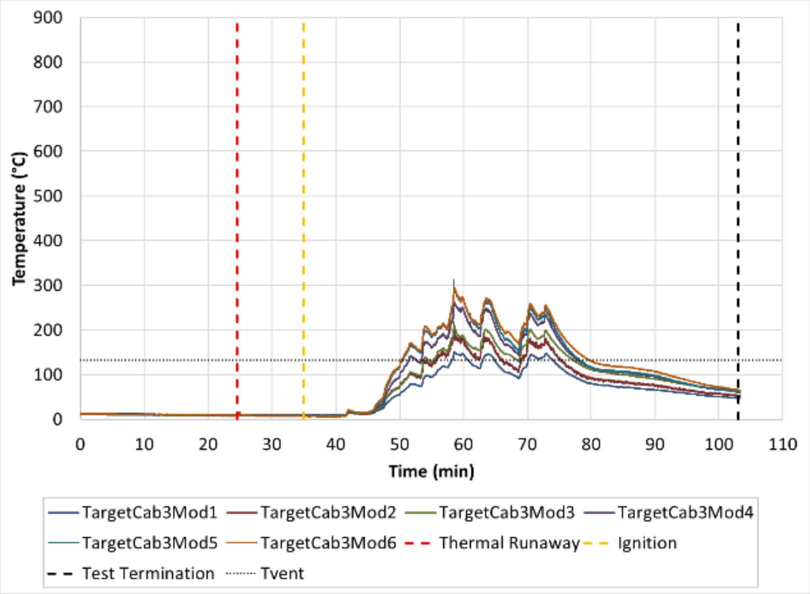
Target 1 (left)



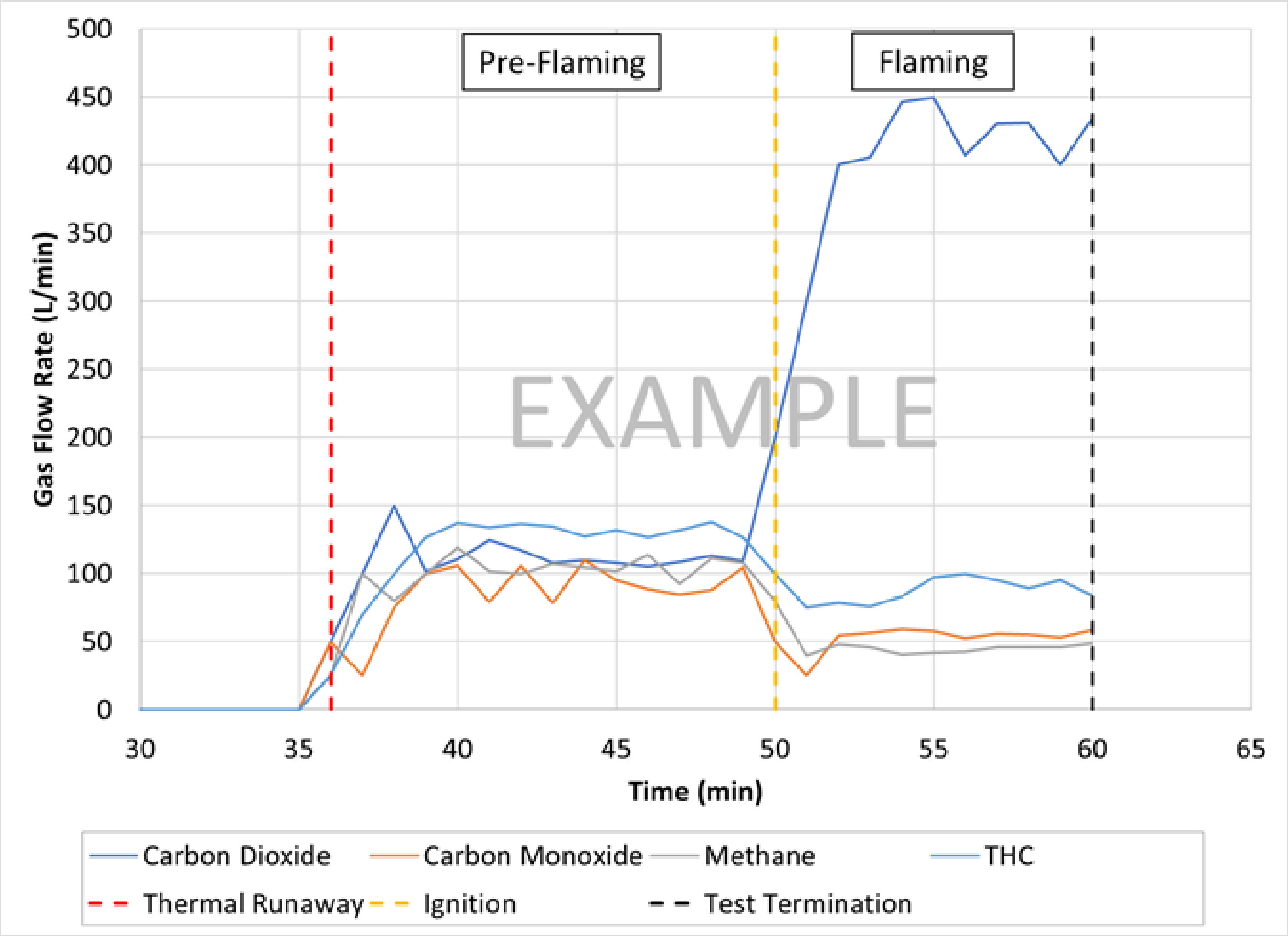
Target 2 (right)

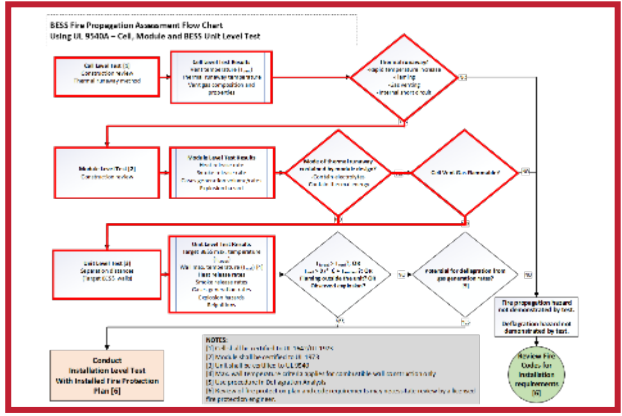


Target 3 (across aisle)



Unit level test results — gas release

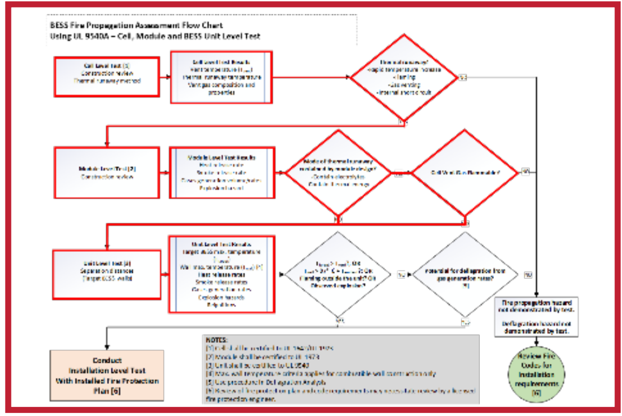


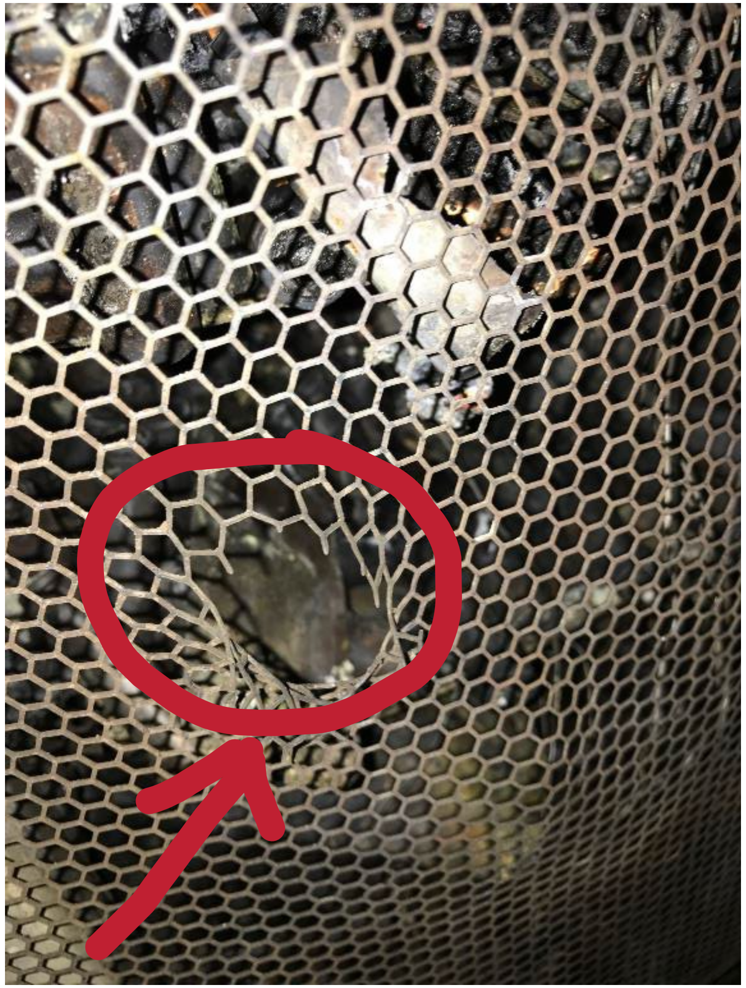


Gas component	Gas type	Pre-flaming (L)	Flaming (L)
Carbon dioxide	Carbon containing	##	##
Carbon monoxide	Carbon containing	##	##
Ethylene	Hydrocarbons	##	##
Methane	Hydrocarbons	##	##

*Gas measurements were not possible during unit level test demo.

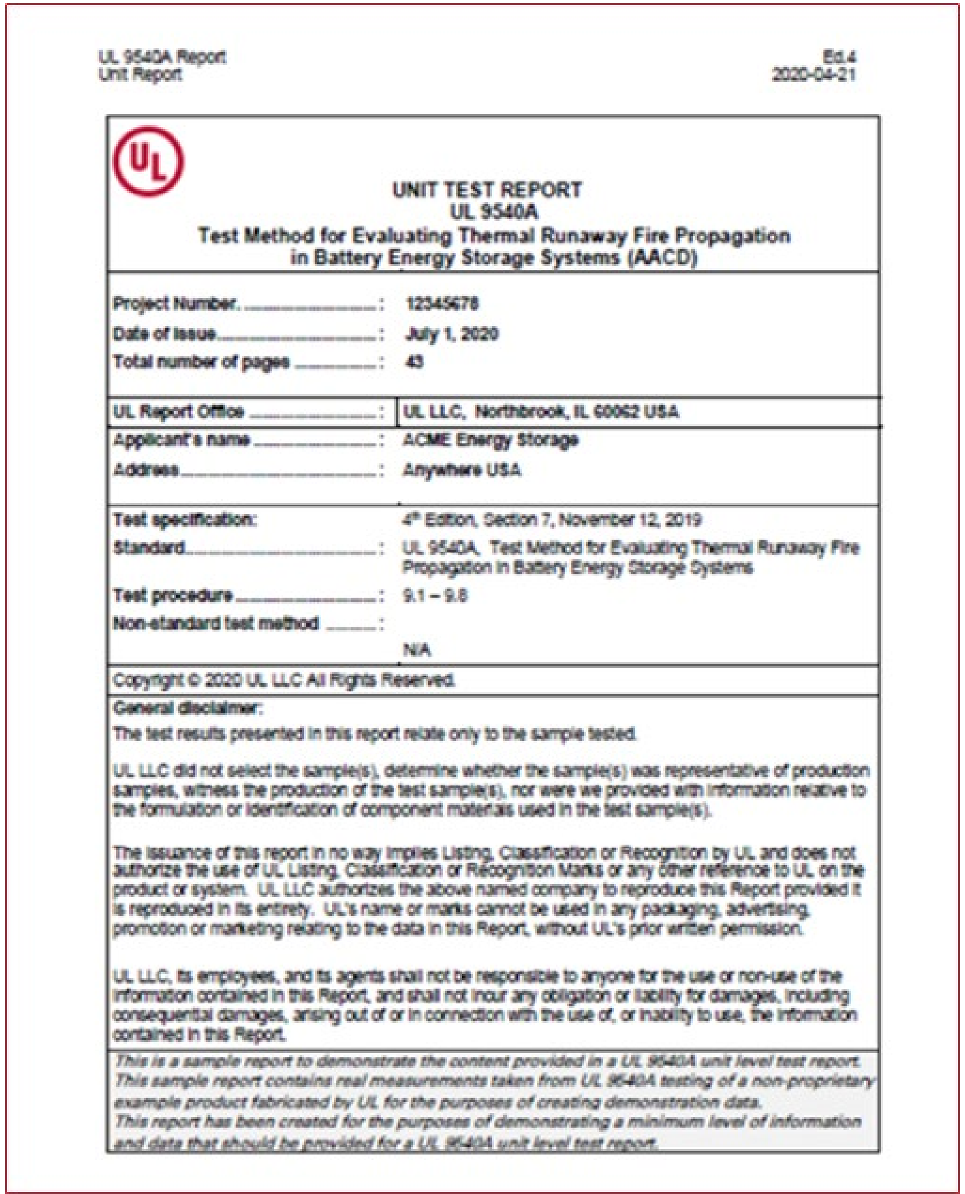
Unit level test results — explosion hazard





- Cells ejected outside unit enclosure
- Hole punched through vented front door

Results as seen in a UL 9540A report


UL 9540A Report
Unit Report

Ed.4
2020-04-21

UNIT TEST REPORT
UL 9540A
Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (AACD)

Project Number:	12345678
Date of issue:	July 1, 2020
Total number of pages:	43
UL Report Office:	UL LLC, Northbrook, IL 60062 USA
Applicant's name:	ACME Energy Storage
Address:	Anywhere USA
Test specification:	4th Edition, Section 7, November 12, 2019
Standard:	UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
Test procedure:	9.1 – 9.8
Non-standard test method:	N/A

General disclaimer:

The test results presented in this report relate only to the sample tested.

UL LLC did not select the sample(s), determine whether the sample(s) was representative of production samples, witness the production of the test sample(s), nor were we provided with information relative to the formulation or identification of component materials used in the test sample(s).

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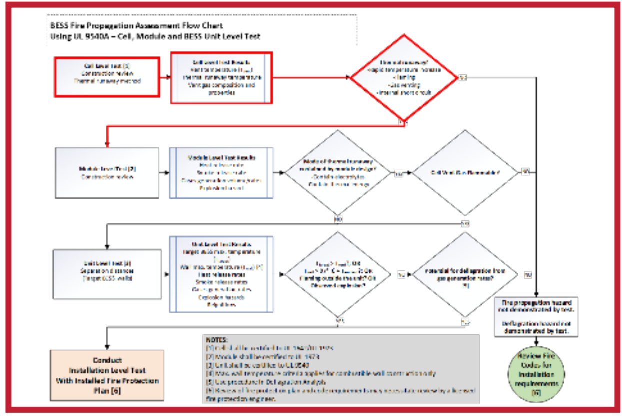
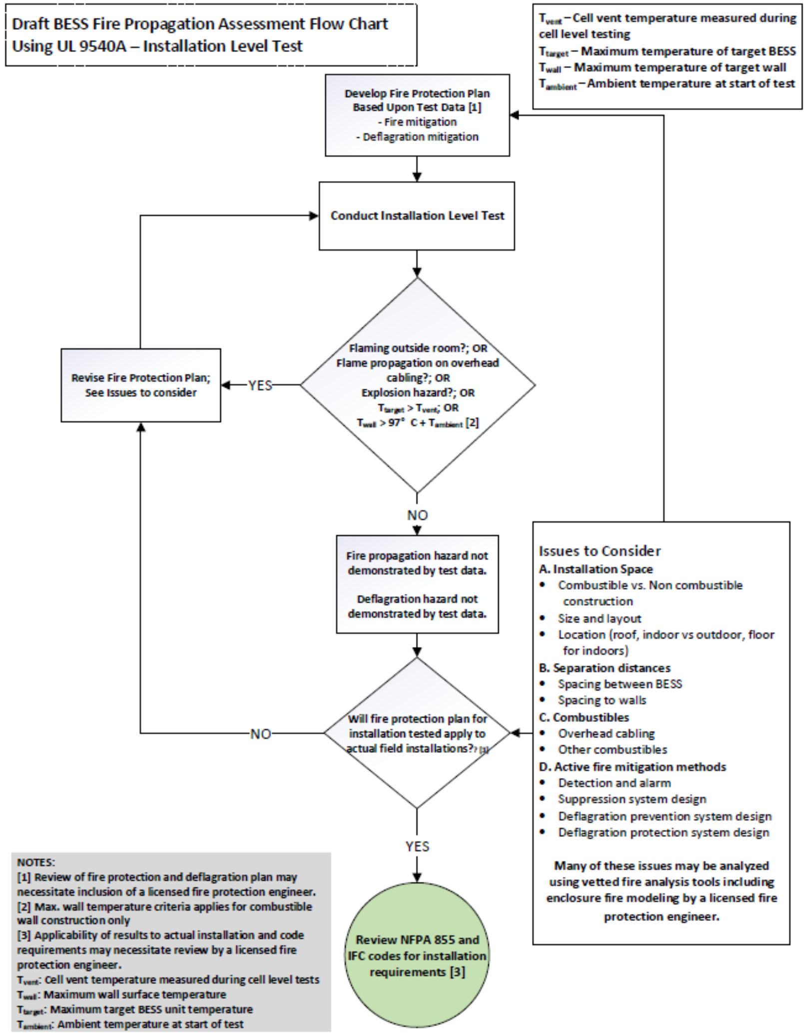
This is a sample report to demonstrate the content provided in a UL 9540A unit level test report. This sample report contains real measurements taken from UL 9540A testing of a non-proprietary example product fabricated by UL for the purposes of creating demonstration data. This report has been created for the purposes of demonstrating a minimum level of information and data that should be provided for a UL 9540A unit level test report.



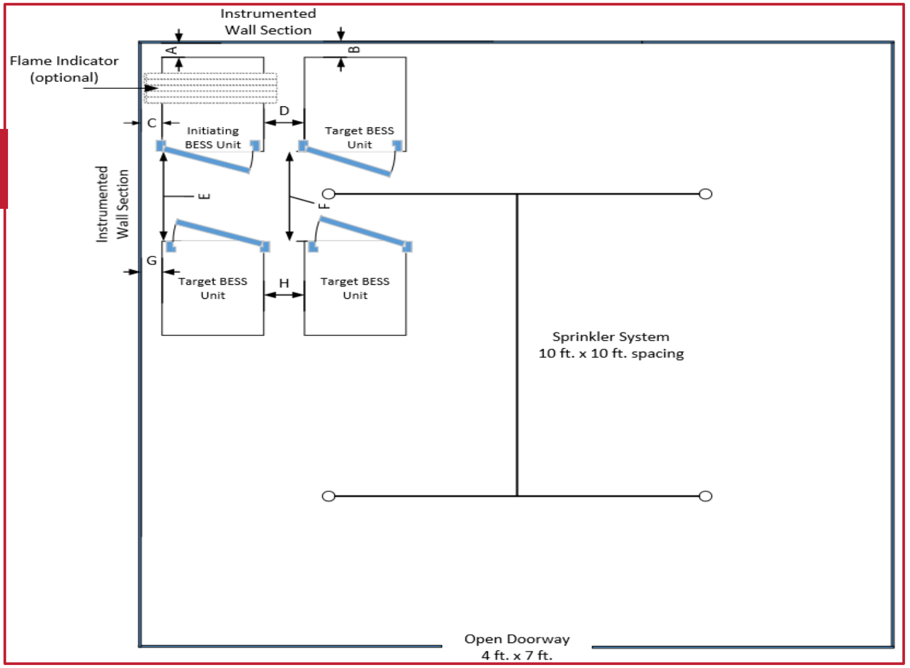
Installation test process

1. Unit level test and fire protection system (designed by client)
2. Representative of all installations?
3. Representative of the installation under review?
4. Loop for redesign



Installation level test

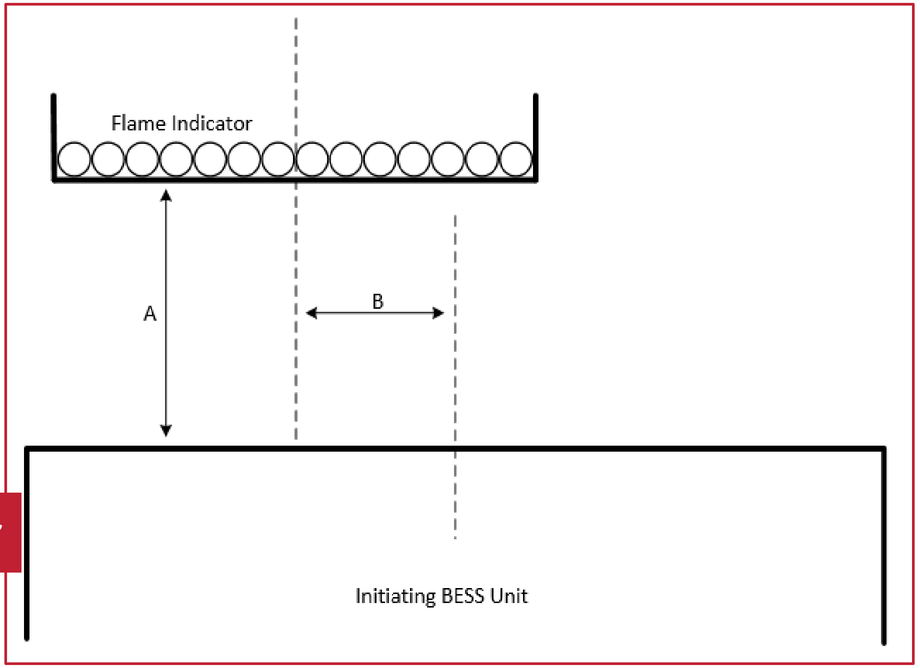
Installation Setup



Method 1: Effectiveness of sprinklers – evaluate the effectiveness of sprinkler fire protection and explosion mitigation methods

- Type of sprinkler (make/model, activation temperature, Response Time Index)
- Design water density for sprinklers
- Test may include overhead cabling that is used in installation of units

Flame indicator



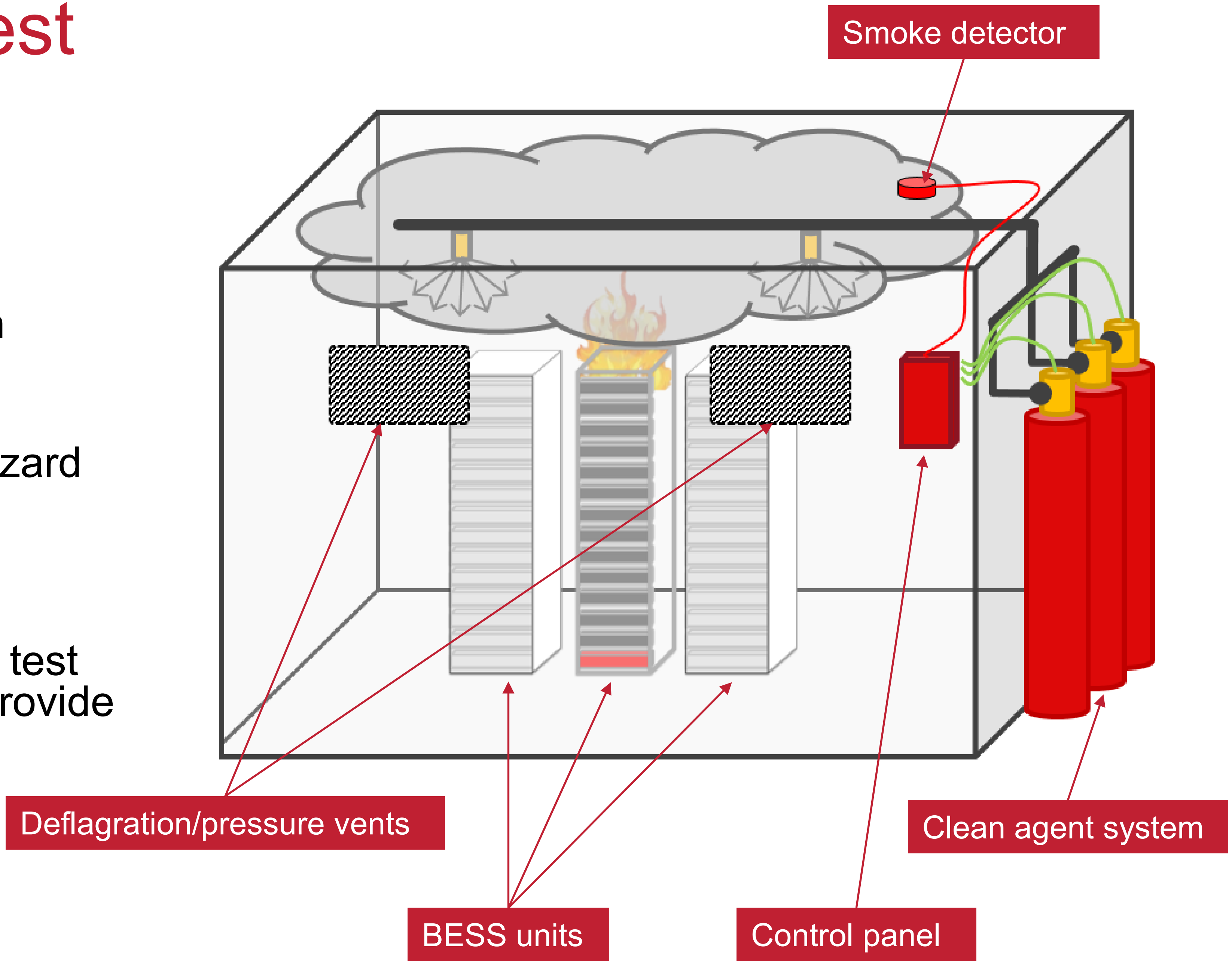
Installation level test

Method 2: Effectiveness of fire protection plan

Objectives:

- Effectiveness of suppression (gaseous and/ or water)
- Thermal exposure to walls
- Characterize deflagration hazard
  - Gases generated
  - Deflagration events

Deflagration vents shown in the test room diagram are intended to provide safe testing conditions only.



Evolution of ESS fire/explosion protection: testing

Prescriptive safety requirements:

- Unit size
- Unit separation
- Clearance to exposures (combustibles, egress)
- Max allowable quantity (e-capacity)
- Fire suppression system – sprinklers
- Explosion control (NFPA 68, 69)

Installation can adhere to prescriptive requirements or pursue exceptions with UL 9540A test results that “show that **a fire involving one ESS will not propagate to an adjacent ESS** and … **will be contained within the room, enclosed area or walk-in unit**”

UL 9540A measurement data:

Fire hazards:

- T_{vent}
- $T_{thermal\ runaway}$
- Module, unit HRRs
- Thermal exposure to second items
- Integrated FP systems

Explosion hazards:

- Battery Gas:
  - Composition
  - LFL, burning velocity, P_{max}
  - Release volumes
  - Vol. rates
- Observed explosion hazards

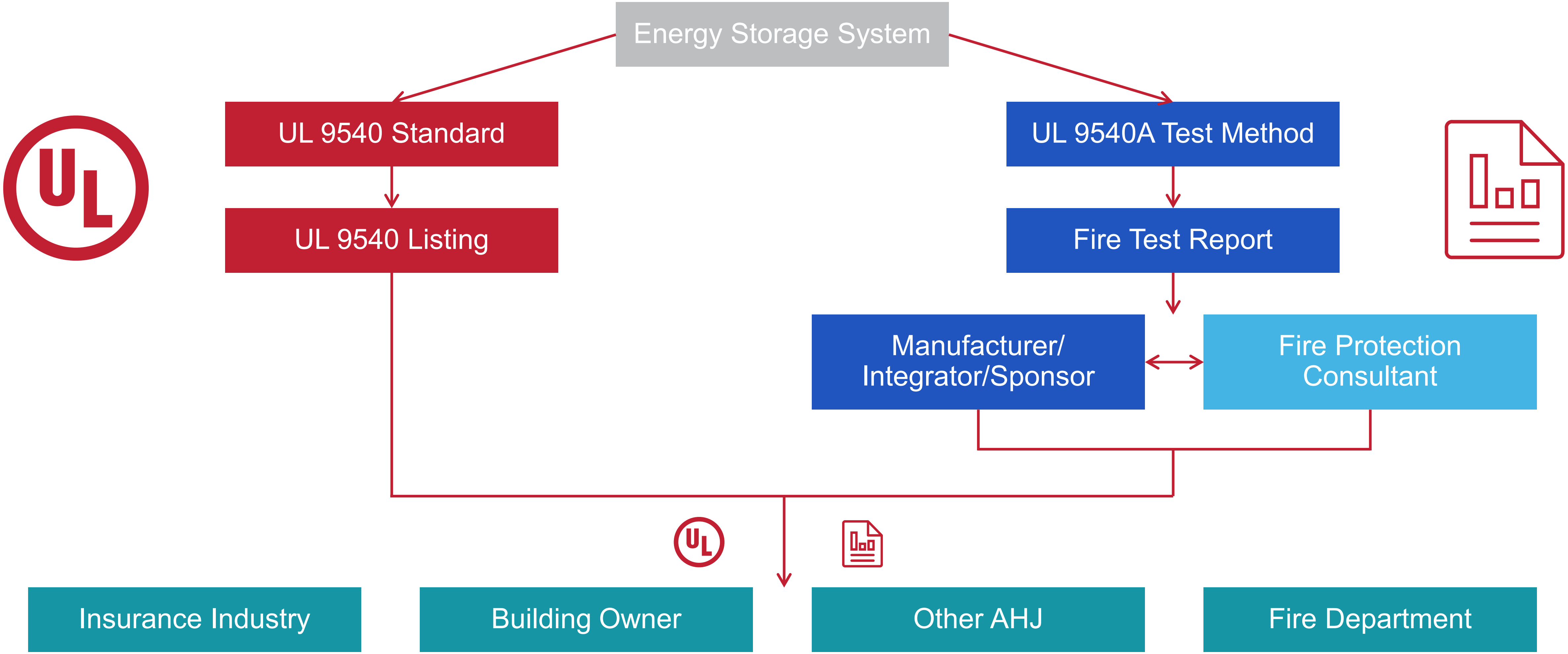
Installation level test

Performance Criteria for Installation Test

- For installation in locations with combustible construction, surface temperature measurements on wall surfaces shall ≤ a temperature rise of 97°C (175°F) above ambient.
- The temperatures of modules within target BESS adjacent to initiating BESS ≤ cell vent temperature
- The fire spread on the cables in the flame indicator shall not extend horizontally beyond the initiating BESS enclosure dimensions
- There shall be no flaming outside the test room.
- There is no observation of detonation. There is no observation of deflagration unless mitigated by an engineered deflagration protection system.
- Heat flux in the center of the accessible means of egress ≤ 1.3 kW/m2
- No observation of re-ignition within the initiating BESS after test was concluded and the sprinkler operation/fire suppression was discontinued.

An installation level test that does not meet the applicable performance criteria noted above is considered noncompliant and would need to be revised and retested.

UL 9540A use in industry



UL 9540A 4th Edition
Unit Level AHJ Checklist

Laboratory Checks:

Yes No

1. The lab is ISO 17025 accredited.
2. The unit construction details and specifications were provided.
3. The number of cells and location of cells failed at the unit level was the same as what was used at the module level.
4. The thermal runaway method used to initiate propagation was the same as the method used at the cell level and module level test.
5. Mitigation devices that are not part of the module/system construction were not introduced during the test to impact the outcome. (*Example: external barriers introduced around the external heater on the cell.)*
6. Critical information on any fire mitigation means employed in the system was provided and is consistent with the intended installation.
7. Testing was done at an indoor facility unless the ESS was for outdoor installations only.

Test Setup:

Yes No

8. A summary of the critical data from the cell test is provided (vent temperature, thermal runaway temperature, and gas data is available).
9. A summary of the critical data from the module test is provided (thermal runaway temperature, propagation occurrence, peak heat release rate, convective heat release rate, peak smoke release rate, gas data).
10. Test walls and test rooms were built using 5/8 inch drywall and painted flat black except for outdoor ground mounted residential applications or outdoor wall mounted residential applications which need to be tested with 3/4 plywood.
11. The test layout matched the intended installation layout with regard to separation distances from walls and other units.
12. The system was at maximum operating state of charge, which was checked prior to initiation of the test.

Test Method:

Yes No

8. Test outcome did not rely upon operation of integral electrical devices such as the BMS, fans or coolant pumps.
9. Temperatures were measured on walls and did not exceed 97°C of temperature rise above ambient unless intended for only noncombustible installations.
10. Temperatures measured on target units did not exceed the onset of cell venting temperature measured during the cell test.
11. Heat flux measured on walls and target units were measured and recorded.
12. The report indicated whether there was evidence of explosions, flying debris during the test or reignitions after the test.
13. For residential systems except for the outdoor ground mount installations, the report noted whether the cheesecloth indicator was charred as a result of flame during testing.
14. The report indicated whether or not the performance criteria of the unit level test were met.

UL 9540A 4th Edition
Unit Level AHJ Checklist

Gas Measurements:

Yes No

1. The total hydrocarbon (THC) gas volume was measured and recorded for both the pre-flaming period and after start of flaming during the test using flame ionization detection (FID).
2. The total volume of carbon monoxide (CO) and carbon dioxide (CO2) gases were measured using non-dispersive infrared spectroscopy (NDIR) and recorded for both the pre-flaming period and after initiation of flaming during the test.
3. The volume of hydrogen (H2) was measured using a solid state hydrogen sensor during the pre-flaming period and after initiation of flaming during the test.
4. Smoke release rate measured with white light source and photo detector for the duration of the test was provided.

Supporting Documentation:

Yes No

8. Profiles showing the temperatures of initiating cells and nearby cells within the initiating module, modules in the initiating unit are provided.
9. Profiles showing that temperatures on target units do not exceed the cell vent temperature are provided.
10. Profiles showing heat flux measurements are provided showing that they do not exceed 1.3 kW/m2 at the egress path for non-residential applications and outdoor ground mounted residential applications.
11. Profile showing the heat release rate (Chemical & Convective heat release rate) versus time data for non-residential applications was provided.
12. The report provided photos taken during the test to show the progress of the initiating thermal runaway as well as diagrams and photos to show the test layout.

UL Resources:

Access additional information online at the below links:

UL 9540A test method: https://www.ul.com/offerings/ul-9540a-test-method

Energy storage testing and certification: https://www.ul.com/offerings/energy-storage-system-testing-and-certification

UL Field Evaluations (FE): https://www.ul.com/offerings/field-evaluations

Code authority resources: https://code-authorities.ul.com/about/technical-resources/application-guides/

Empowering Trust®

Residential storage battery systems

- Lithium-ion with BMS
- One manufacturer has 6.4 KWh unit ~ $3000
- Will provide power for a typical home overnight, but probably not A/C
- Increase capacity by providing multiple systems

Residential storage battery systems

Unit level test

Performance level criteria – residential	
Indoor floor mounted and indoor wall mounted	• Flaming outside the initiating BESS unit is not observed as demonstrated by no flaming or charring of the cheesecloth indicator; • Surface temperatures of modules in target BESS adjacent to initiating BESS ≤ temperature when cell venting occurs • For BESS intended for installation with combustible constructions, wall surfaces ≤ 97°C (175°F) rise above ambient • Explosion hazards are not observed, including deflagration, detonation or accumulation of battery vent gases • The concentration of flammable gas ≤ 25% LFL in air for the smallest specified room installation size.
Outdoor ground mounted	Same as Indoor except: • If flaming outside of the unit is observed, separation distances to exposures shall be determined by greatest flame extension observed • Heat flux in the center of the accessible means of egress shall not exceed 1.3 kW/m^2.
Outdoor wall mounted	Same as Indoor wall mounted except: • ~~The concentration of flammable gas ≤ 25% LFL in air for the smallest specified room installation size.~~

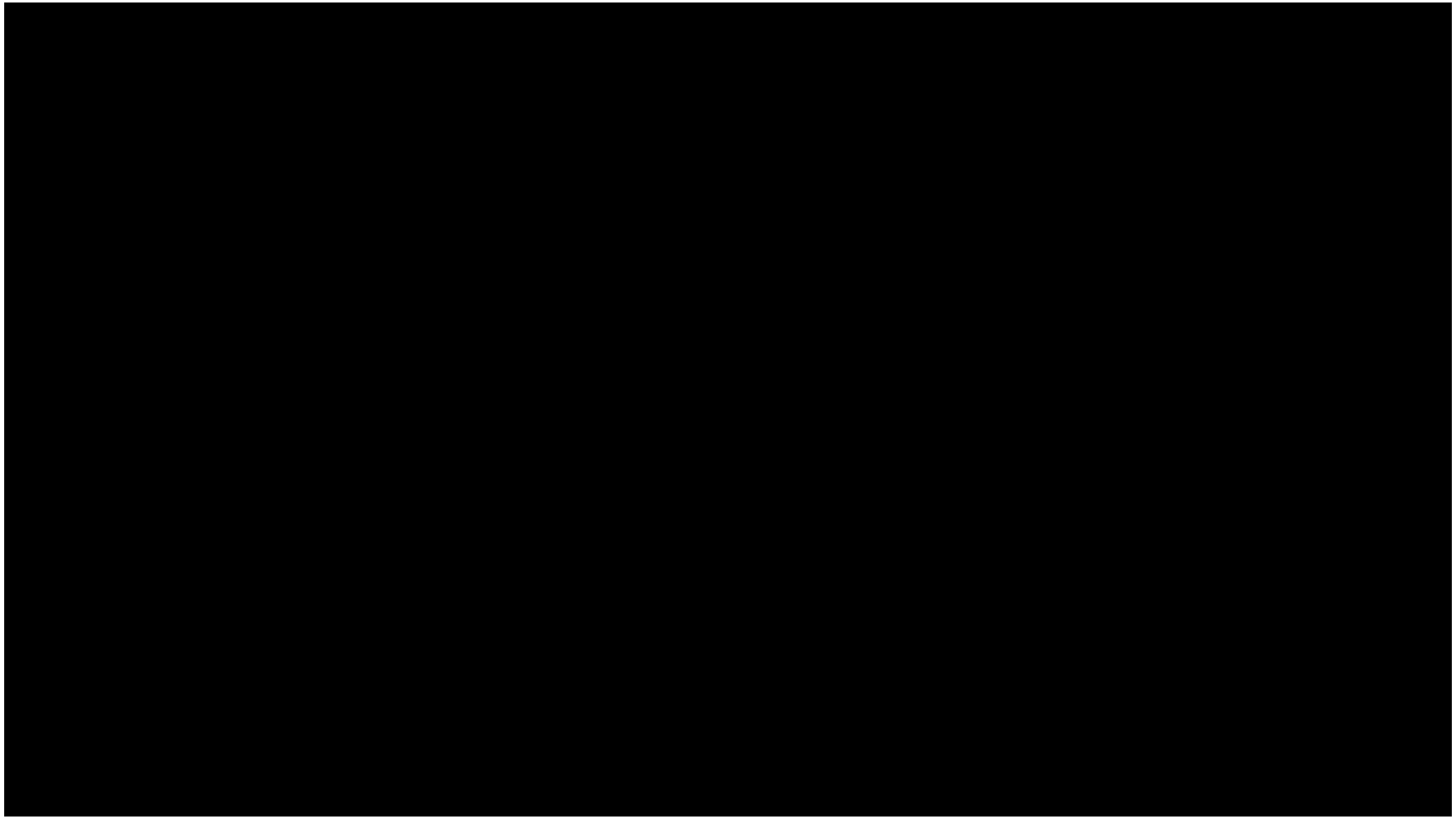
Reignition hazards

Hilden recycling plant battery fire

Near-miss research
Surprise, Arizona, ESS incident

Fire Safety Research Institute (FSRI) is dedicated to addressing the world’s unresolved fire safety risks and emerging dangers.

FSRI promotional video



FEMA-funded Assistance to Firefighters Grant project focused on studying firefighter (FF) line-of-duty injuries and near misses

- The goal of this project is to enhance the safety and situational awareness of the fire service with high-quality interactive training materials developed by applying fire dynamics research results to significant near-miss or line-of-duty-injury fire incidents.
- The National Institute for Occupational Safety and Health's (NIOSH) Firefighter Fatality Investigation and Prevention Program investigates line-of-duty deaths but lacks the resources for near misses.
- There are voluntary programs to share near misses, but in-depth investigations are rarely conducted.

Background

2 MW/2.16 MWh lithium-ion battery ESS

- Average home in Arizona consumes 1 MWh/month
- ESS owned by local electric utility (APS)
- Batteries manufactured by LG Chem
- ESS designed by the integrator (Fluence)
- ESS maintained by contractors to the integrator (Sturgeon)

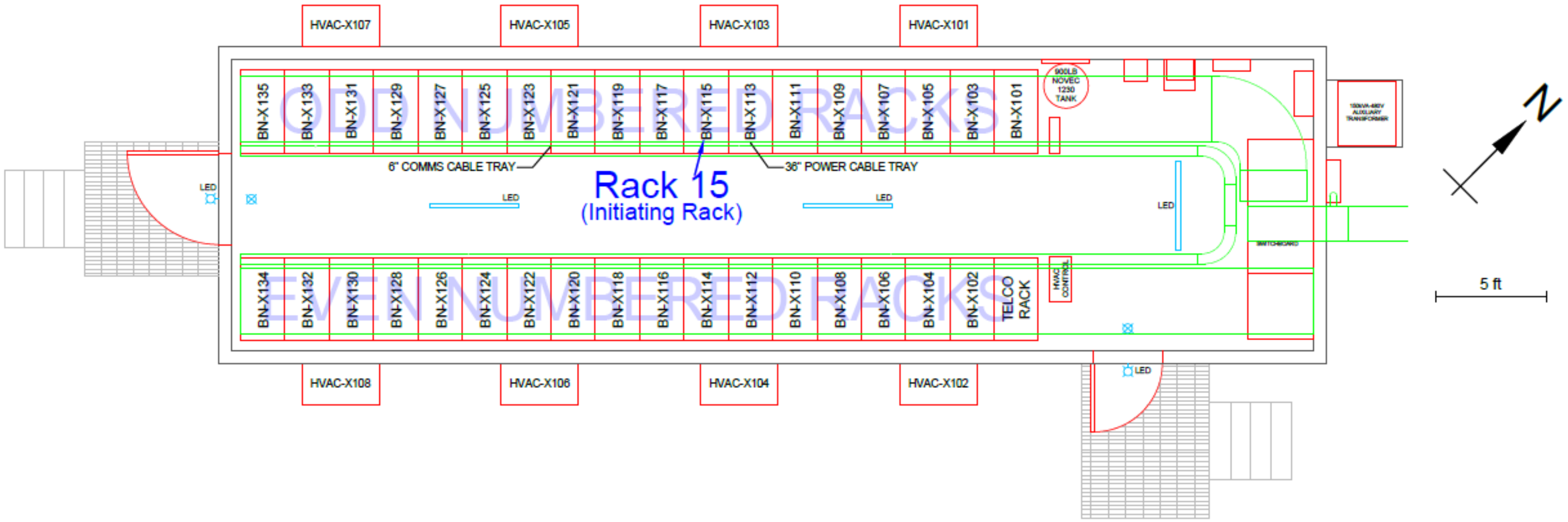
Four firefighters (Peoria HAZMAT team) seriously injured

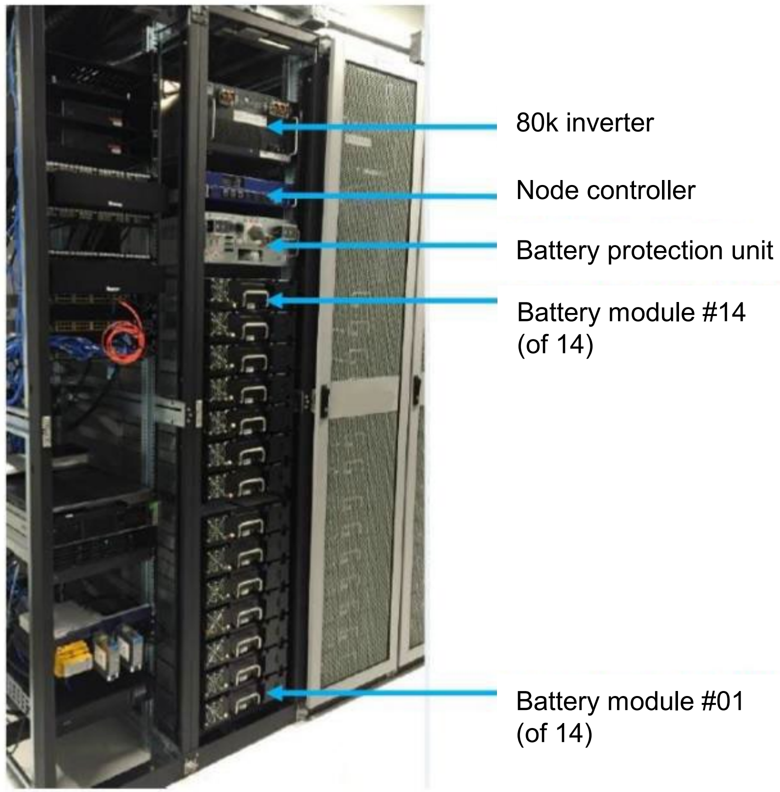
Four firefighters (Surprise E304) held overnight for suspected exposure to HCN

Courtesy of APS

Energy storage system

- 27 racks of battery modules
- 14 modules per rack
- 28 lithium-ion NMC pouch cells per module (2P14S)
- 10,584 cells total
- 8 HVAC units (75 °F ± 5 °F)
- Very Early Smoke Detection Apparatus (VESDA) smoke detector system
- Novec 1230 total flooding clean agent suppression





Timeline

16:54:30 — Minimum battery cell voltage in Rack 15 began to decrease.

16:54:44 — Air temperature measurements started to rapidly increase.

16:55:20 — VESDA smoke detector registered an alarm condition; all breakers and contactors opened.

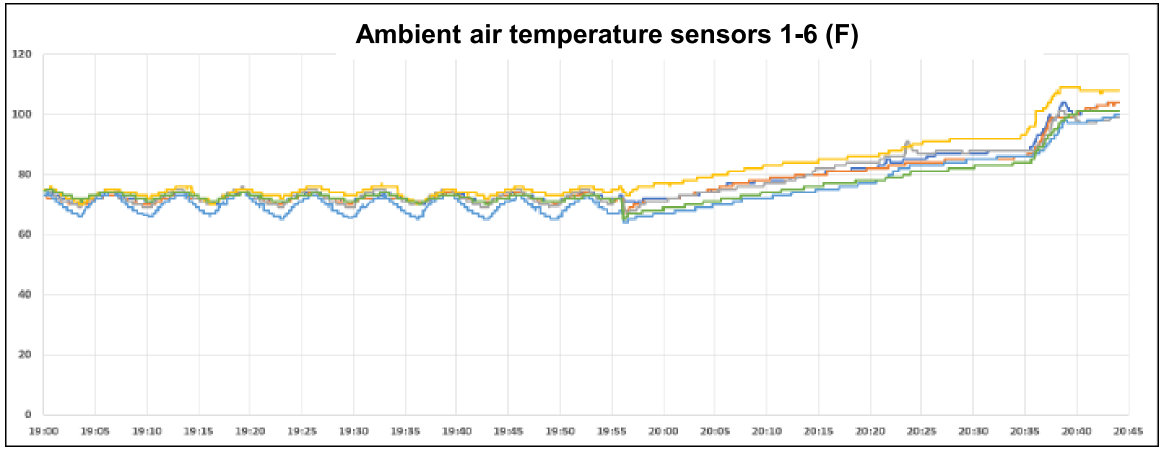
16:55:38 — Air temperature measurements peaked at 121.6 F.

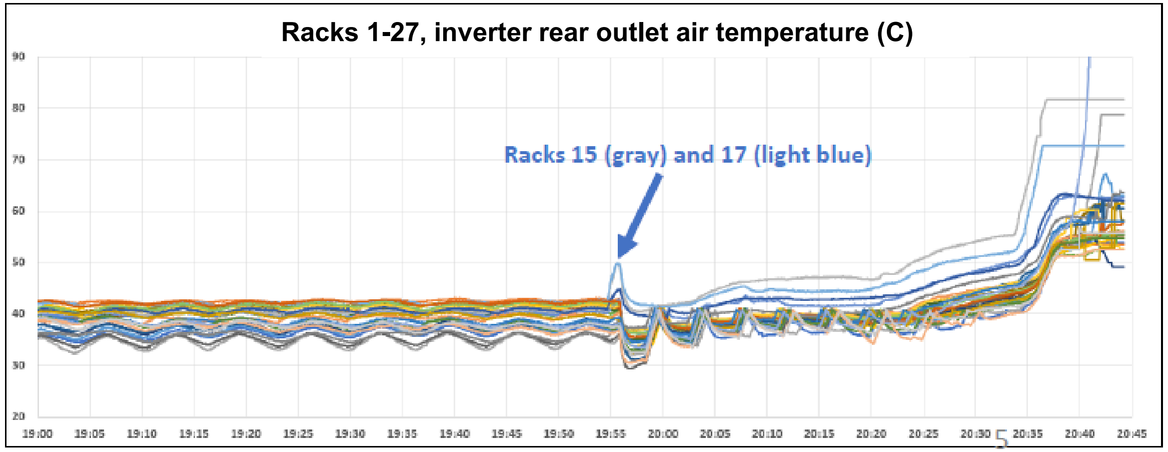
16:55:50 — Suppression system discharged.

Timeline

17:41:54 — Phoenix Metro dispatch received a call for smoke and a bad smell near an electric substation, and Surprise Fire Department (FD) E304, BR304 and T304 were dispatched.

17:44:08 — All communication from the ESS was lost.
Air and module temperatures reported prior to 17:44:08.





Timeline

17:48:52-17:49:12 — Surprise Fire Department E304, BR304 and T304 arrived on the scene.

18:04:21 — E304 Capt. elevated to HAZMAT operation; Peoria FD E193 HAZMAT.

Google Earth

Courtesy of FSRI

Timeline

17:48:52–17:49:12 — Surprise FD E304, BR304 and T304 arrived on the scene.

18:04:21 — E304 Capt. elevated to HAZMAT operation; Peoria FD E193 HAZMAT team dispatched to call.

Photos courtesy of Peoria Fire Department

Timeline

18:18:30 — Surprise battalion chief (BC) 301 arrived on the scene.

18:28:21 — Peoria FD E193 and HM193 arrived on the scene.

Photos courtesy of Peoria Fire Department

Timeline

18:37:00 — HAZMAT team conducted 360-degree size-up and defined a hot zone.

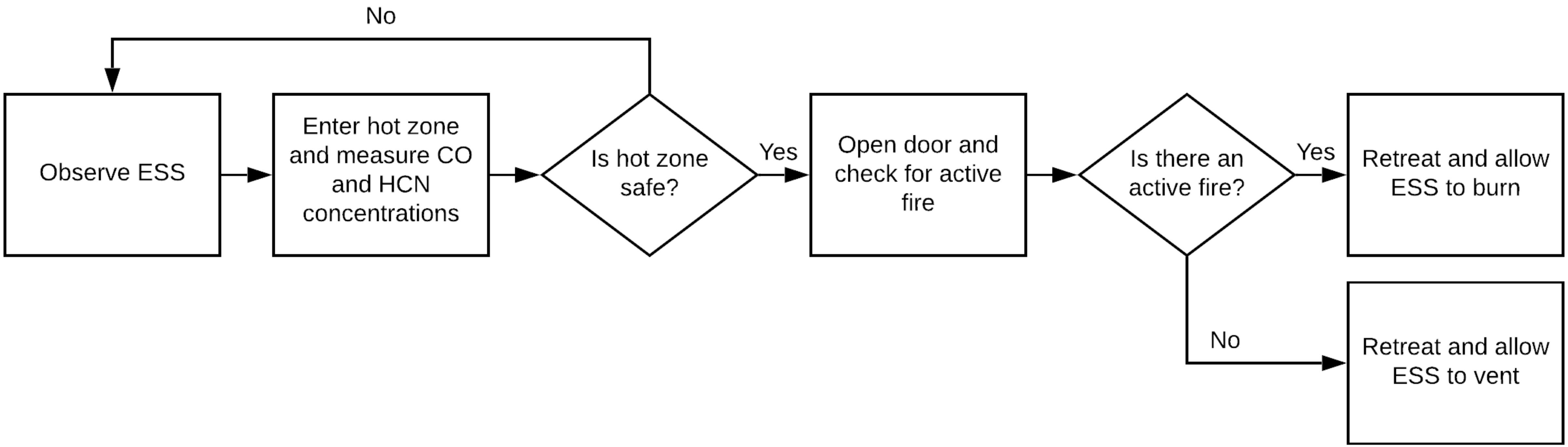
18:51:21 — HAZMAT team made second entry into hot zone.

19:10:00 — HAZMAT team made third entry into hot zone.

Photos courtesy of Peoria Fire Department

Timeline

19:15-19:50 — HAZMAT team conferenced with senior fire department officers and developed a plan to render the ESS and hot zone safe.



Timeline

19:50 — The visible gas/vapor mixture was no longer leaking out of the ESS.

19:52:24 — HAZMAT team made final entry into the fenced area around the ESS.

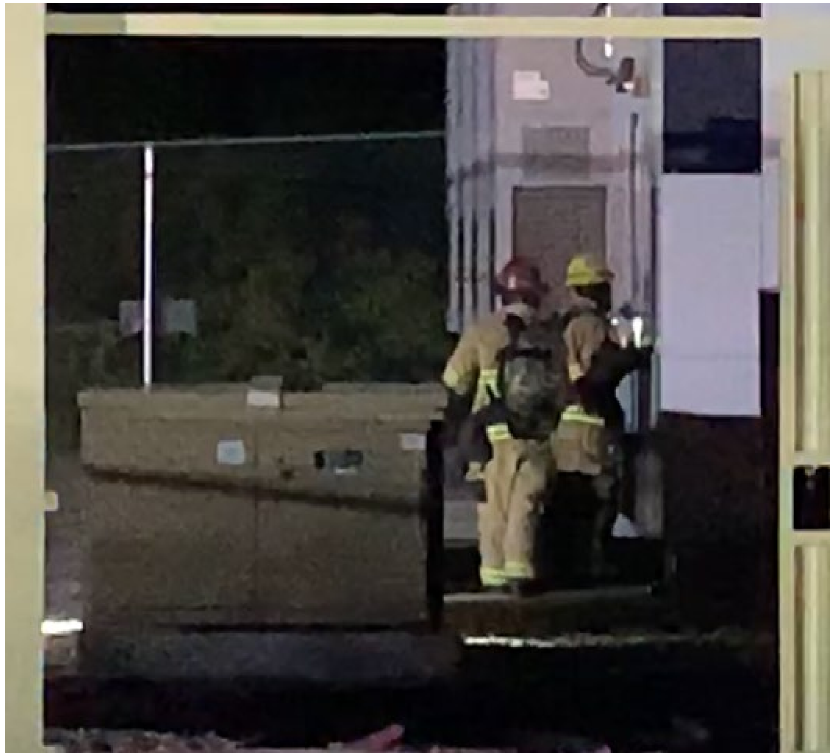
19:58:03 — HAZMAT team pulled hoseline to ESS to prepare to open door.

Photos courtesy of APS

Timeline

20:00:54 — HAZMAT team opened the door to the ESS.

20:03:49 — Mayday call



Photos courtesy of APS

Photos courtesy of Peoria Fire Department

Contributing factors

- Core HAZMAT training curricula for first responder and technician levels do not yet cover basic ESS hazards.
- Extra-curricular ESS-specific training opportunities do not comprehensively address ESS hazards.

Recommendations

- Basic firefighter, officer and HAZMAT training should emphasize ESS safety, the potential explosion hazard from lithium-ion batteries, vapor cloud formation and dispersion and the dynamics of deflagrations.
- Research that includes full-scale testing should be conducted to understand the most effective and safest tactics for the fire service in response to lithium-ion battery ESS incidents.
- Until definitive tactics can be established, it is recommended that fire service personnel define a conservative blast radius to remain outside of while treating the gas/vapor mixture in the ESS as if it is above the LEL until proven otherwise.
- An online education tool should be developed to proliferate the appropriate base knowledge about lithium-ion battery ESS hazards and fire service tactical considerations

Contributing factors

- The ESS did not include sensors that provided information about the presence of flammable gases.
- There was no way for the HAZMAT team to monitor toxic gas concentrations, LEL or any other conditions inside the ESS from a physically secure location.

Recommendations

- Lithium-ion ESSs should incorporate gas monitoring that may be accessed remotely.
- Research that includes multi-scale testing should be conducted to evaluate the effectiveness and limitations of stationary gas monitoring systems for lithium-ion battery ESSs.

Contributing factors

The ESS's communication system failed early in the incident.

Recommendations

ESS communications systems should be more robust to ensure that communication remains uninterrupted through a conservative estimate of the duration of a thermal runaway incident.

Contributing factors

- The emergency plan was not provided to the responding fire service personnel prior to the incident.
- The emergency response plan that was provided was inadequate.

Recommendations

- Owners and operators of ESSs should develop an emergency operations plan in conjunction with local fire service personnel and the code authorities and command a comprehensive understanding of the hazards associated with lithium-ion battery technology.
- Signage that identifies the contents of an ESS should be required on all ESS installations to alert fire responders to the potential hazards associated with the installation.

Contributing factors

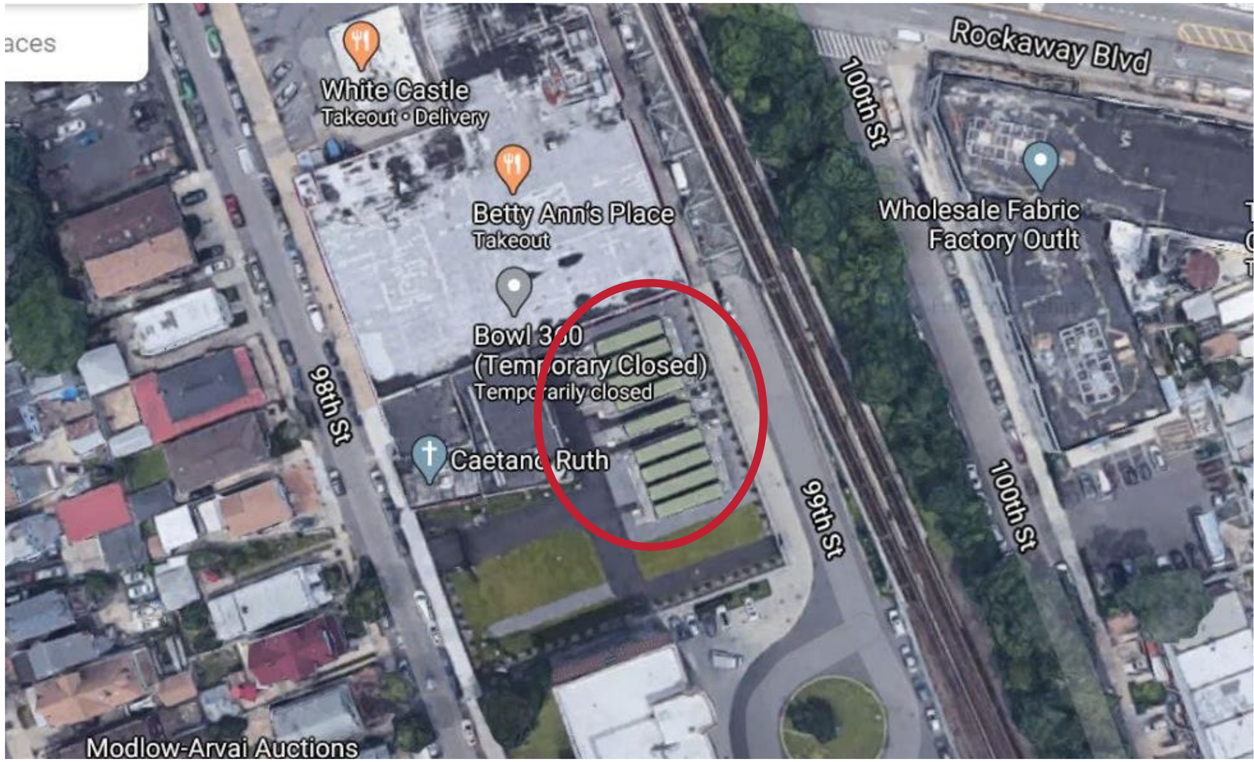
- The ESS did not have deflagration venting panels (NFPA 68) or adequate ventilation to prevent the accumulation of flammable gases (NFPA 69).
- The total flooding clean agent suppression system likely contributed to the deflagration.

Recommendations

- Lithium-ion battery ESSs should incorporate adequate explosion prevention protection as required by consensus standards in coordination with the emergency operations plan.
- Research that includes full-scale testing should be conducted to determine the most effective fire suppression and explosion prevention systems for lithium-ion battery ESSs.

Additional recommendation

Conduct research focused on emergency decommissioning best practices and the fire service's role in an emergency situation.



Google Earth photos

Fire service considerations with Li-ion battery ESS

A new online training module
for the fire service is available from FSRI.

training.fsri.org

Battery installation scenarios

- Outdoor remote structures
- Dedicated ESS buildings
- Outdoor trailers near buildings
- Rooftop installations
- Mixed occupancy buildings

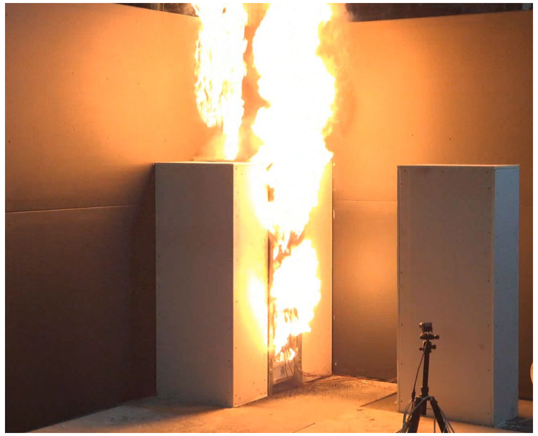
Recent lithium-ion battery incidents

Over the last few years, there have been several major lithium-ion battery ESS incidents:

- Sept. 15, 2020 – Liverpool, England (20 MW)
- Dec. 1, 2020 – France
- April 6, 2021 – South Korea
- April 16, 2021 – Beijing, China (25 MWh)*
- Currently in Progress – Chandler, AZ

*Two firefighters died in suppression efforts.

Hazard scenarios demonstrated by incidents and tests

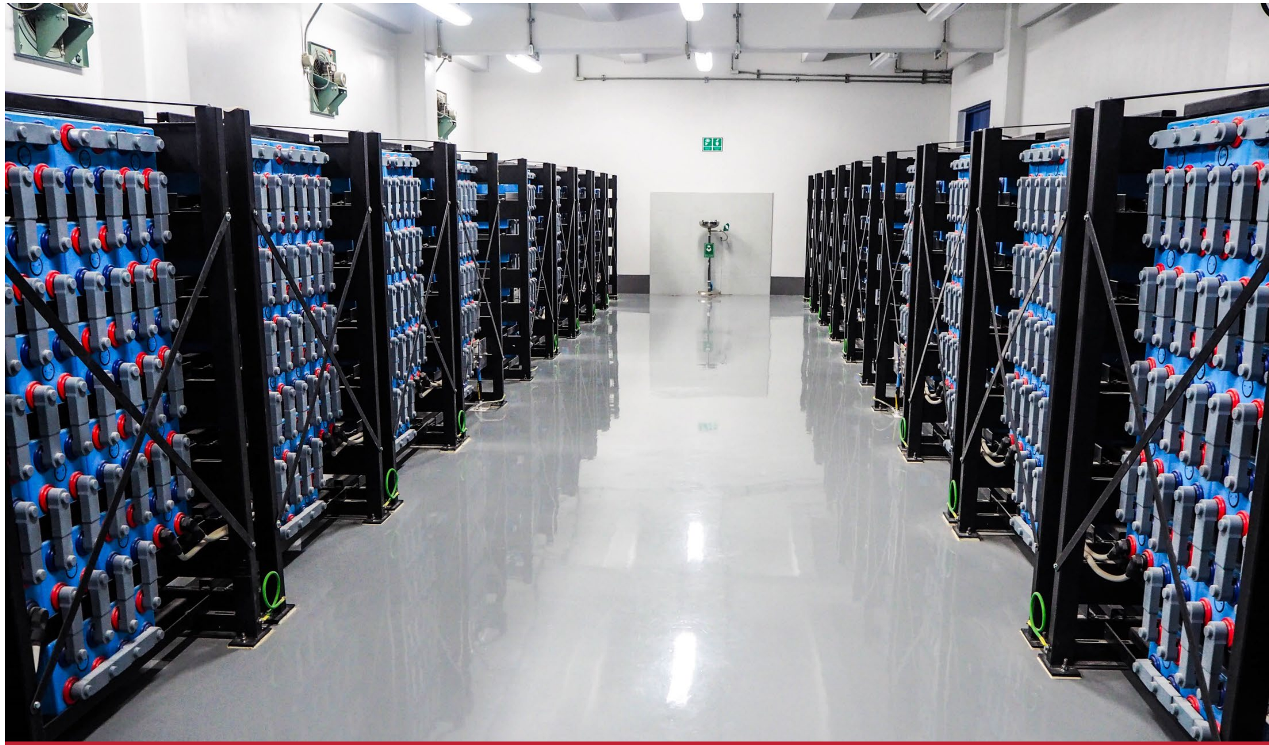
	Immediate ignition	Delayed ignition in unit enclosure	Delayed ignition in installation
Incident	 South Korea ESS fire (April 2021)	 Telco cabinets w/ Li-ion backup (mid-2000s)	 Surprise, AZ (April 2019)
Test	 UL 9540A unit test	 UL 9540A unit test	 UL 9540A installation test
	Flaming present without deflagration	**Flaming after deflagration typical**	**Flaming after deflagration possible**

UL 9540A test Standard

Scope:

Evaluate fire characteristics of a battery energy storage system that undergoes thermal runaway.

Data generated will be used to determine the fire and explosion protection required for an installation of a battery energy storage system.



Match fire protection of installation to performance of BESS

Hazard scenarios demonstrated by incidents and tests

Thermal runaway propagation in an ESS Unit

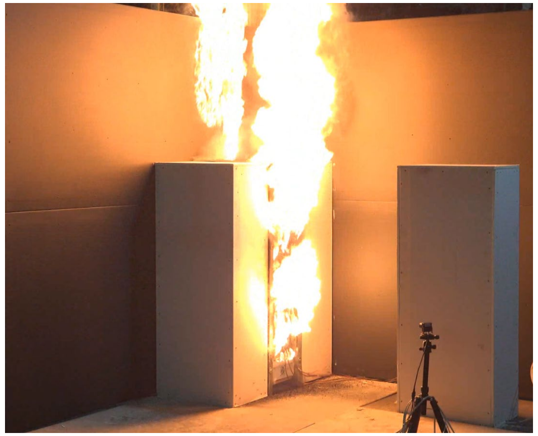
Fire hazards

Explosion hazards, then fire hazards

Immediate/ Delayed Ignition?

Immediate Ignition

<u>Hazard Scenario:</u>
Flaming, array-array propagation, loss of containment



Delayed Ignition

Ignition inside/ outside unit enclosure?

Outside

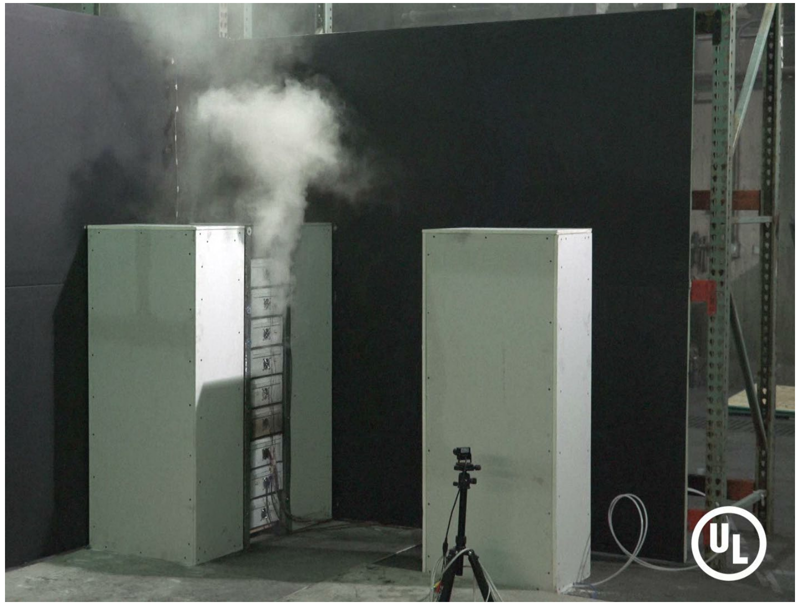
<u>Hazard Scenario:</u>
Occupiable Volume Deflagration Hazard

Inside

<u>Hazard Scenario:</u>
Non-occupiable Volume Explosion Hazard

Not currently covered by NFPA 855 OR 2021 International Fire Code

Hazard scenarios – immediate ignition



Fire hazards

Thermal runaway propagation in an ESS Unit

Immediate/ Delayed Ignition?

Immediate Ignition

Delayed Ignition

Measurements:

ESS unit enclosure fire containment & HRR
+
Thermal exposure to adjacent surfaces

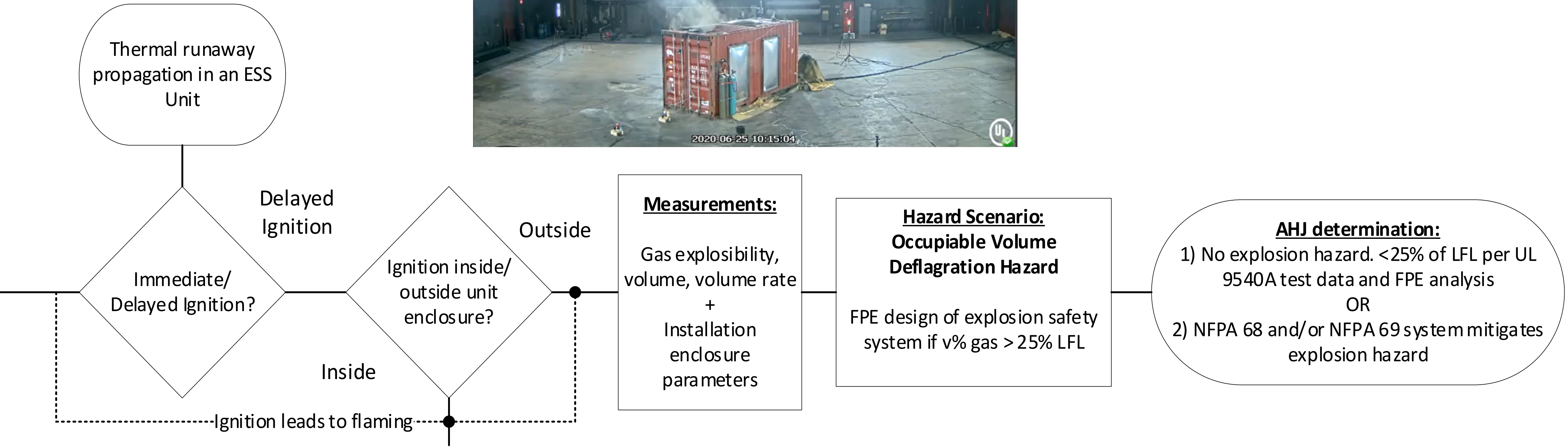
Hazard Scenario: Flaming ESS Unit

Either performance is nonhazardous or installation test is run with fire protection system(s)

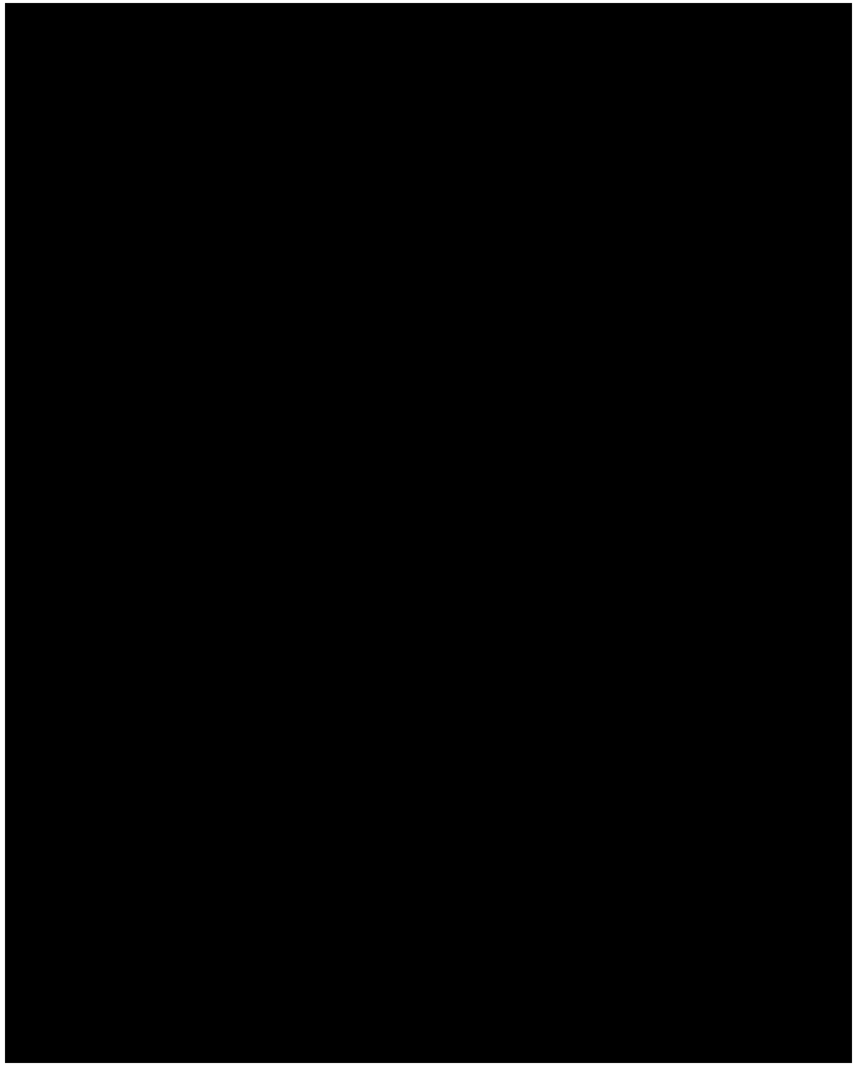
AHJ determination:
1) No array-array fire hazard
2) No loss of fire containment
OR
3) UL 9540A Installation test data demonstrates fire protection system(s) provide conditions 1 and 2

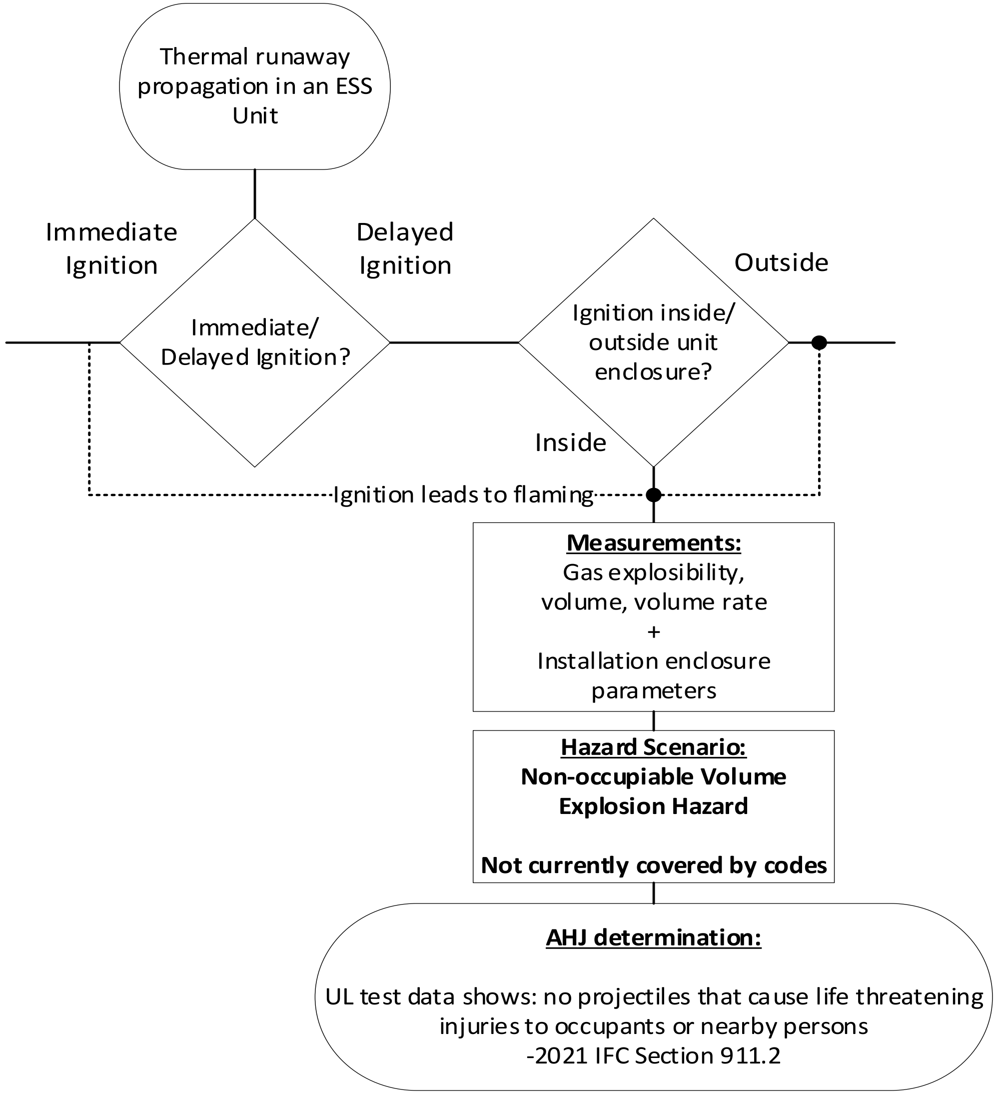
UL 9540A performance criteria provided to aid analysis

Hazard scenarios – delayed ignition in installation

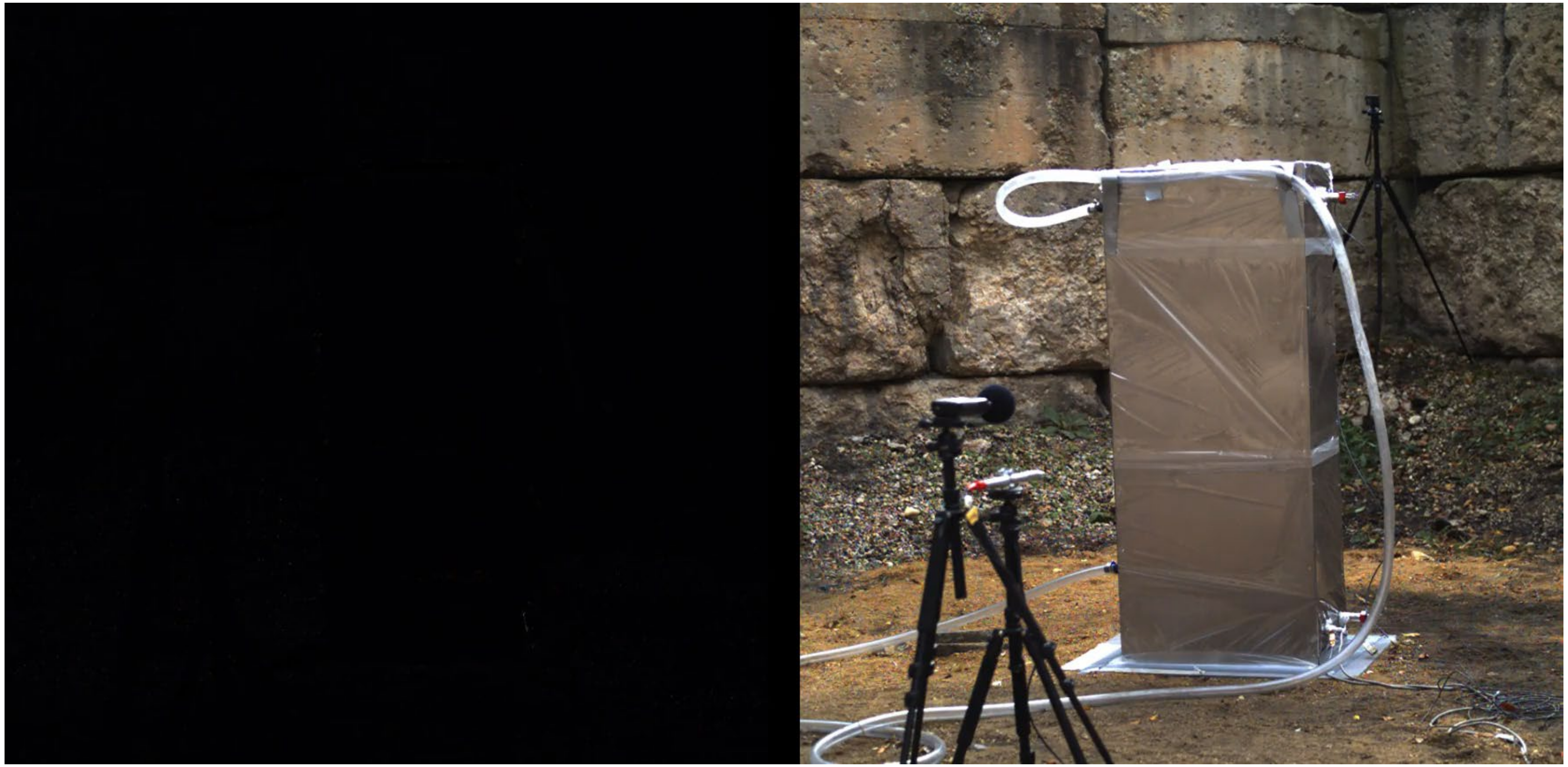


Hazard scenarios – delayed ignition in unit enclosure





Hazard scenarios – delayed ignition in unit enclosure



- Deflagration venting systems cannot be evaluated unless a deflagration occurs during test.
- Deflagration severity during a UL 9540A test is dependent on gas conditions at the time of ignition.

Continued evolution of ESS fire and explosion protection

- Prescriptive safety requirements are improved as understanding of hazards improve, based on both research and field incidents.
- UL 9540A tests provide data where the safety performance of an ESS would otherwise be unknown:
  - Fire hazards can be evaluated using UL 9540A based on thermal exposure measurements and HRR.
  - Explosion hazards can be evaluated for installation enclosure from gas explosibility properties, release volume and installation parameters.
- Unit enclosure explosion evaluation method needed

Further cabinet testing

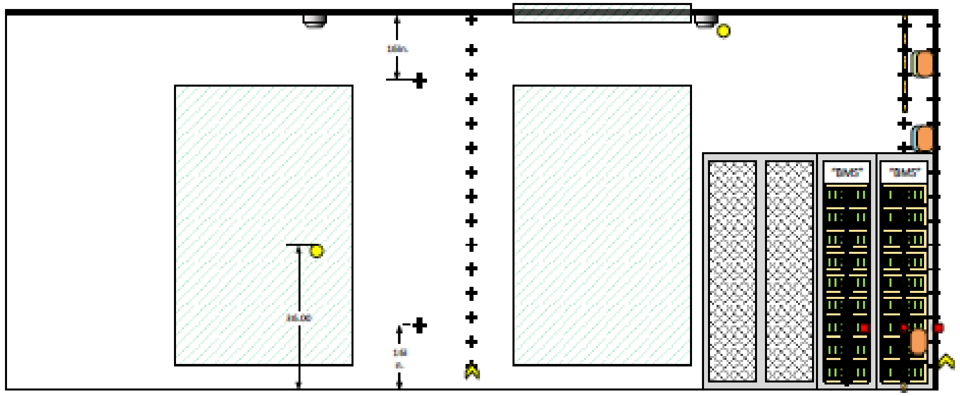
UL 9540A test demonstration

UL 9540A installation level demonstration

Objectives

- Develop non-proprietary UL 9540A installation level data with representative Li-ion chemistry batteries with and without active fire protection systems.

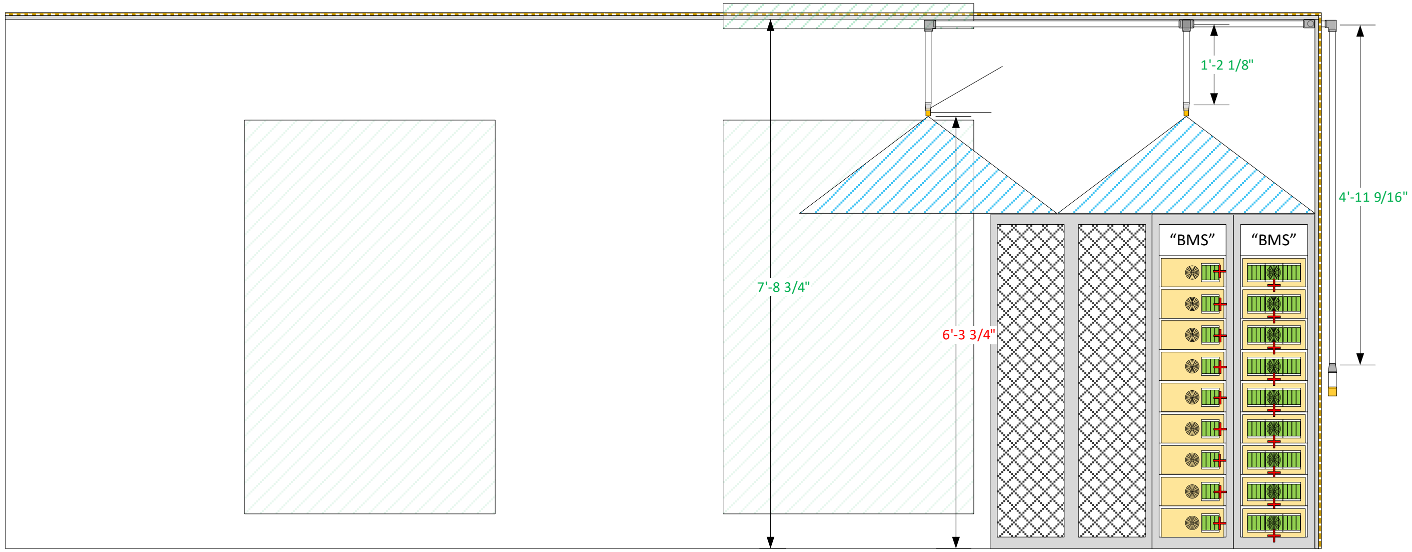
- Develop a fire service size-up and operational and tactical considerations.



Test setup

Test setup — UL 9540A installation level test

- Test 1 –Without any provision for fire protection
- Test 2 – With Novec 1230 total flooding clean agent system (8 v% concentration)
- Test 3 – With 0.5 gpm/ft^2 (20.4 lpm/m^2) density water spray system (from ceiling)



Operation pressure 0.5 psig (3.4 kPa); vent area calculation based on NFPA 68, Standard on Explosion Protection by Deflagration Venting

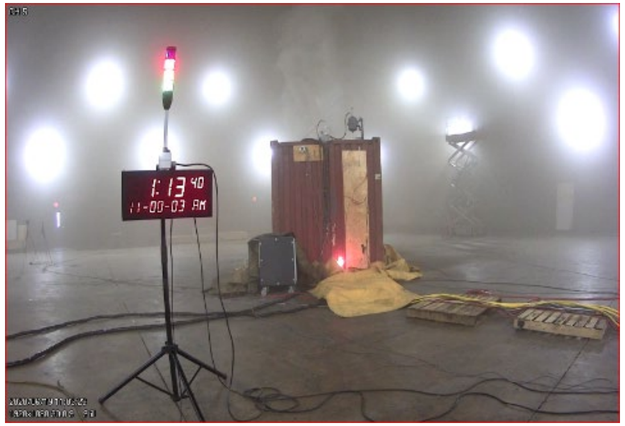
Test results

Results — Test 1, timeline of major events

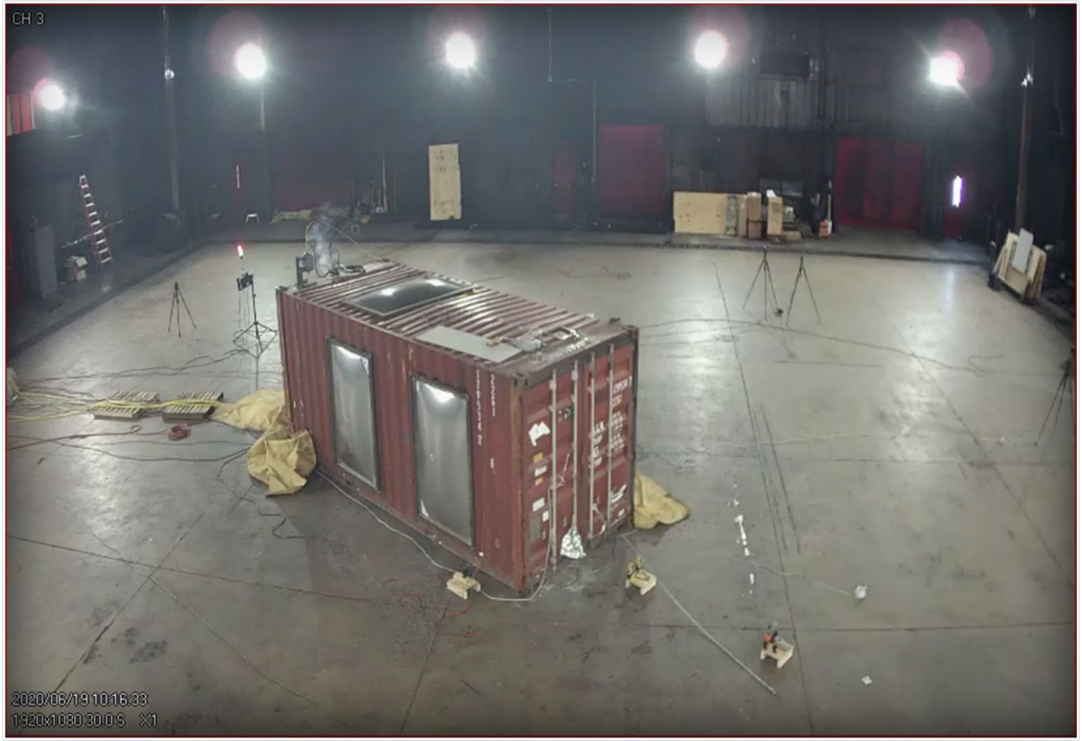
Smoke accumulation
[TR + 00:00:31]

Ignition
[TR + 00:00:31]

TR propagation for 3 hours
[TR + 00:11:54]



Flaming outside container
[TR + 00:47:18]



Partial volume deflagration
[TR + 00:00:31]

TR notes the time of the first cell thermal runaway.

Results — Test 2, timeline of major events

Novec 1230 discharge
[TR + 00:00:58]

Smoke stratification before
ignition [TR + 00:26:51]

Ignition
[TR + 00:28:32]

Flashover conditions and
flaming from open door
[TR + 02:09:48]

Deflagration
[TR + 00:44:39]

TR notes the time of the first cell thermal runaway.

Results — Test 3, timeline of major events

Ignition, sustained flaming
[TR + 00:08:49]

Waterflow @ 0.5 gpm/ft^2
[TR + 00:10:13]

TR propagation after water flow off
[TR + 01:13:05]

TR propagation continues after
water flow restart [TR + 01:49:54]

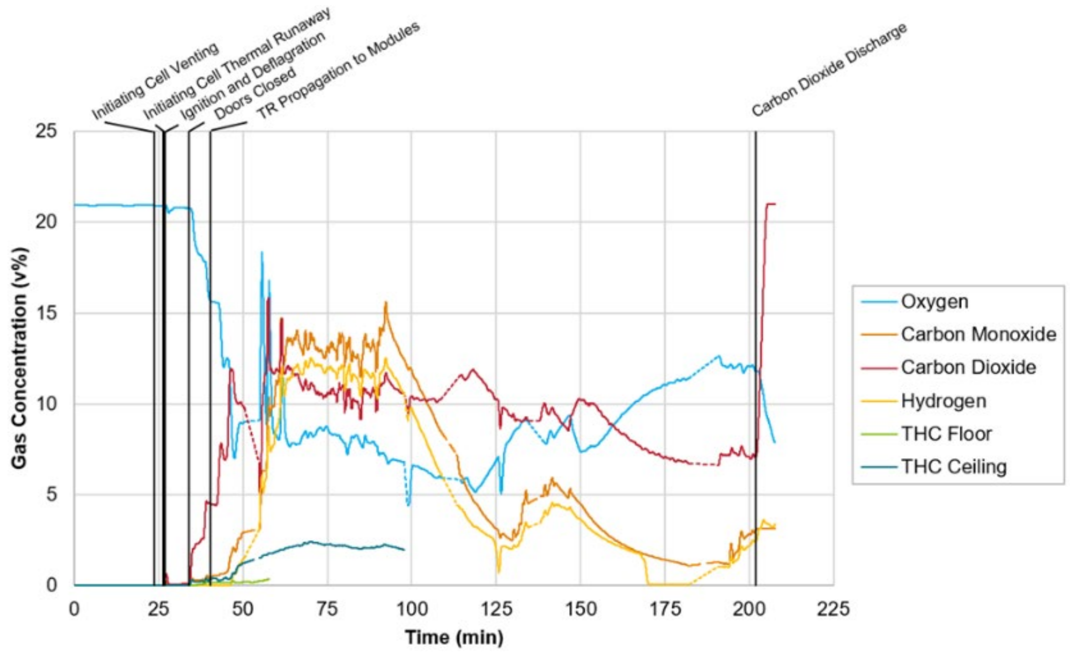
Deflagration
[TR + 00:42:02]

TR notes the time of the first cell thermal runaway.

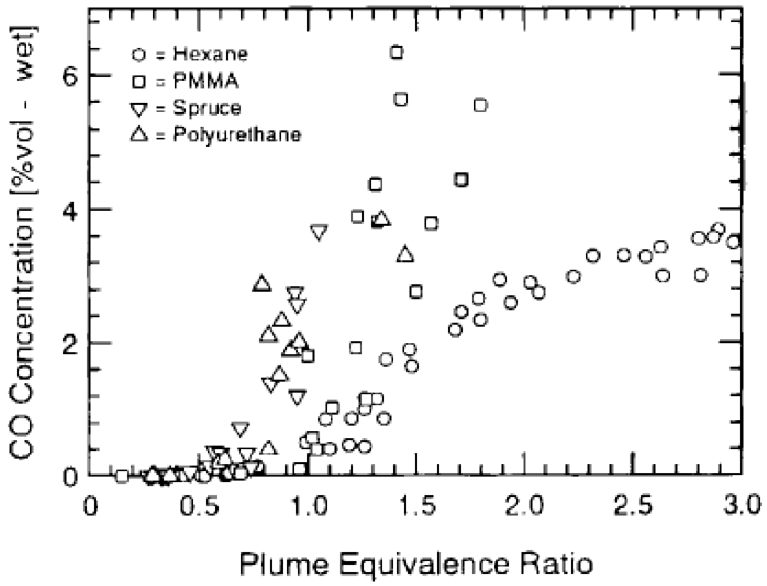
Key findings

Key findings: comparison to room and content fires

Propagating thermal runaway events generate more severe flammability and toxicity hazards than typical room and content fires.



- H_2: > 10 v%
- CO: 12 v% - 15 v%
- CO_2: ~10%



- H_2 = 0 v%
- CO: ~6 v%
- CO_2: ~10%

D. Gottuk, et al. J. of Fire Prot Eng. 4, 4, 1992

Key findings: gas detection

Common combustible gas, carbon monoxide and hydrogen detectors were:

Effective for thermal runaway gas detection

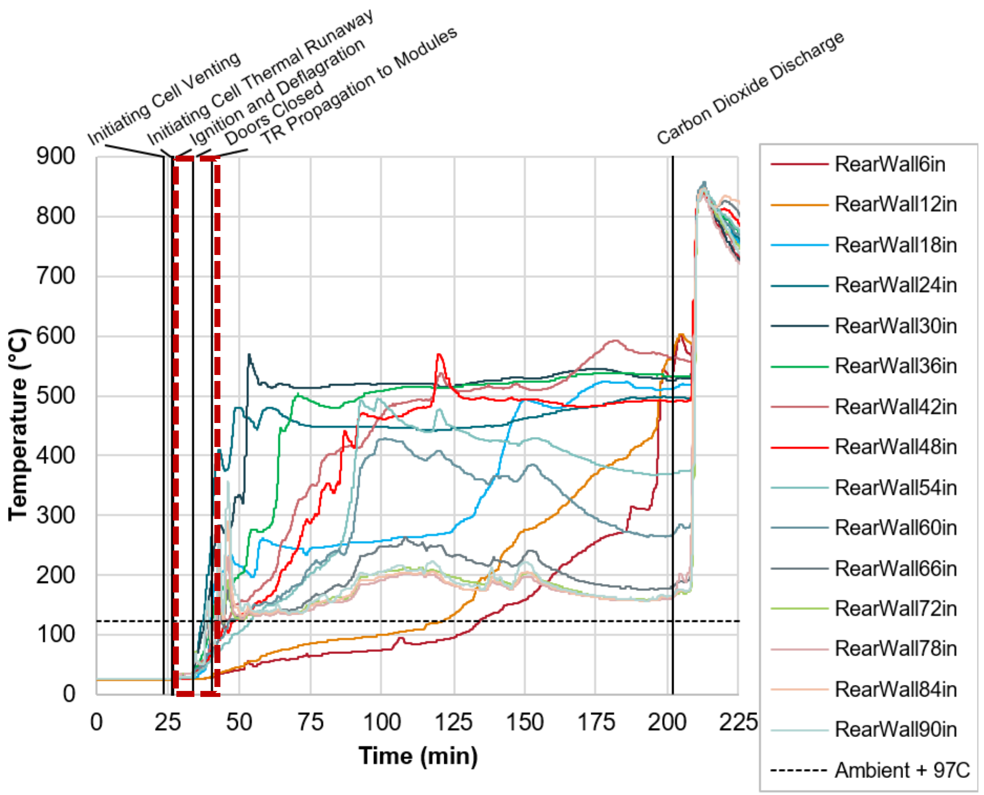
- All detectors responded in <5 seconds when exposed to gas.
- Nuisance sources are unlikely, given measurands (H_2, CO, LEL).
- Proximity to ESS units is critical for detection time.

Not reliable for ongoing hazard assessment

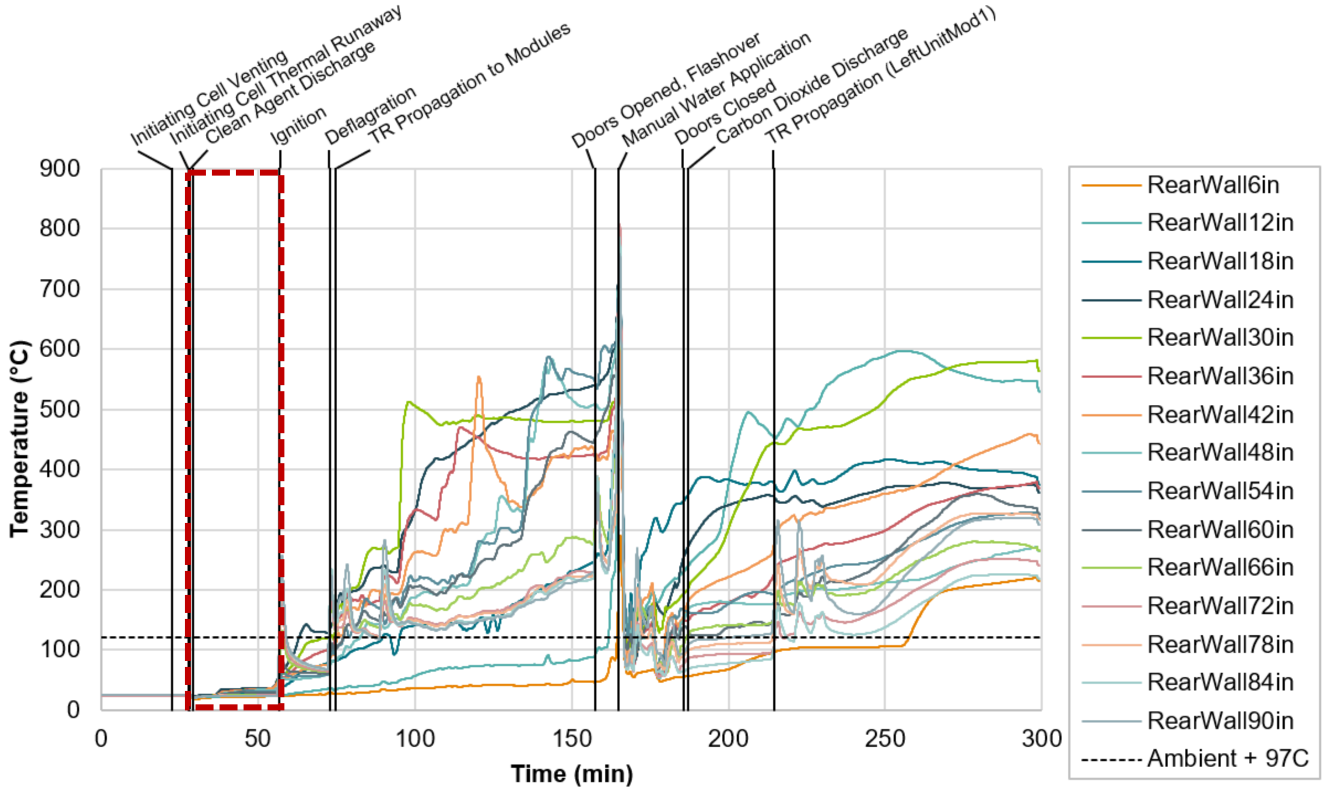
- Cross-sensitivity diminishes sensor accuracy.
- Thermal, chemical and particulate stresses damage sensors.

Key findings: Novec 1230 total flooding system

The simulated Novec 1230 system did not prevent propagation of thermal runaway or mitigate thermal exposure to its surroundings.*



Rear wall — baseline without Novec 1230

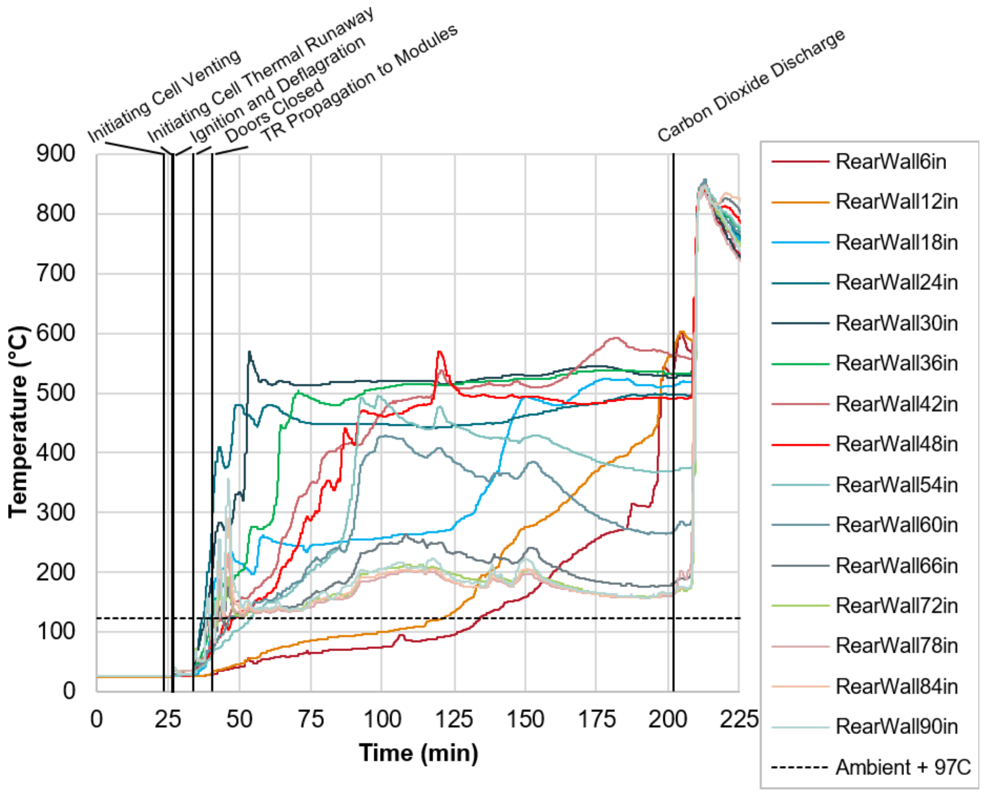


Rear wall — with Novec 1230

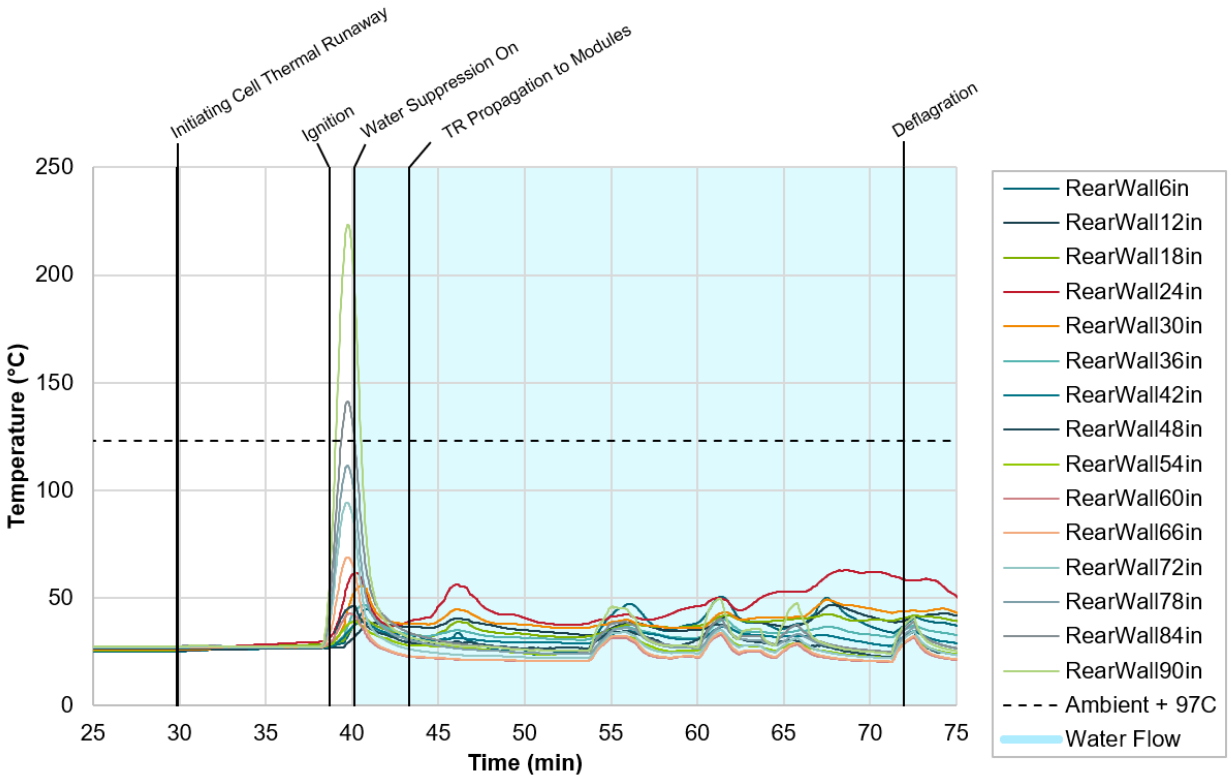
*3M makes clear the limitations and appropriate use of Novec 1230 for battery applications in the product datasheet.

Key findings: water spray suppression system

The water spray suppression system prevented unit-to-unit propagation and cooled wall surfaces adjacent to the initiating ESS unit; limited effectiveness to prevent module-to-module thermal runaway propagation.



Rear wall — without water spray

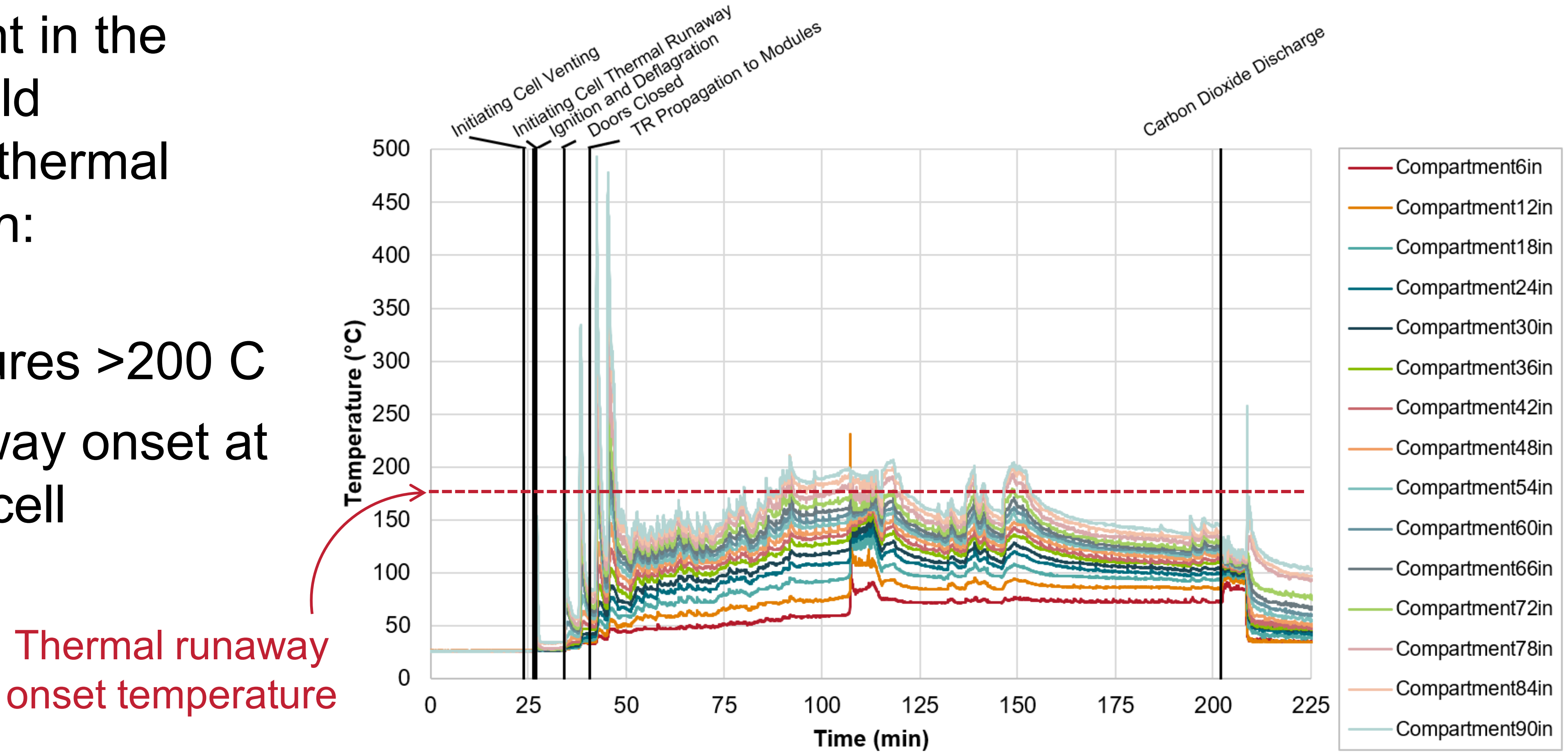


Rear wall — with water spray

Key findings: gas environment temperature

The gas environment in the BESS container could increase the rate of thermal runaway propagation:

- Gas temperatures >200 C
- Thermal runaway onset at 180 C for this cell



Key findings: deflagration protection system

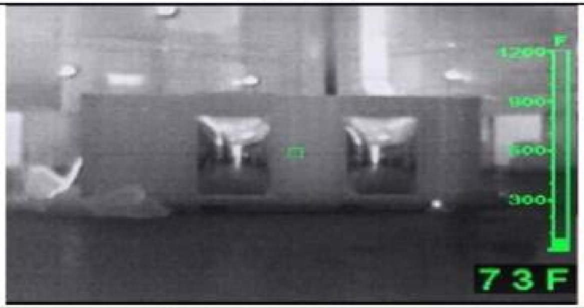
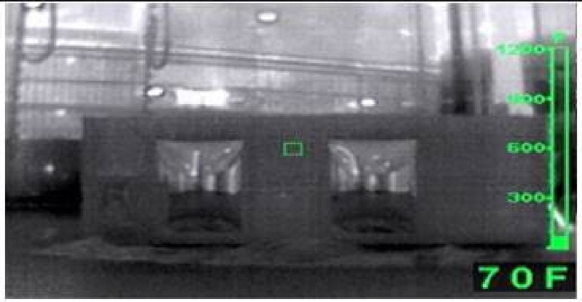
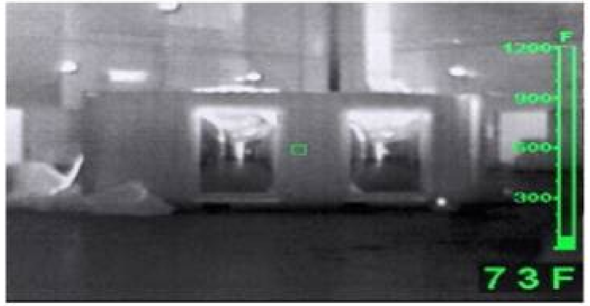
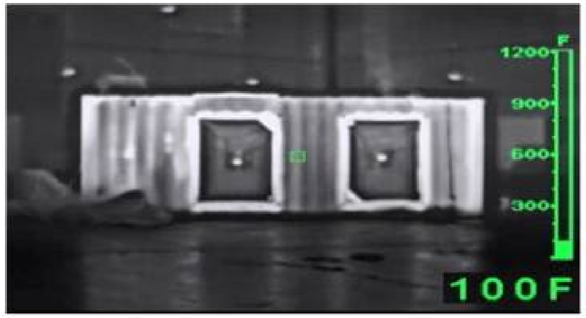
- Deflagrations occurred in all three tests.
- The deflagrations were all mitigated with an engineered deflagration protection system designed per NFPA 68.
- Deflagration intensity varied based on the gas conditions at the time of ignition.



Fire service tactical considerations

Tactical consideration: thermal imager use

- Thermal imaging cameras (TIC) do not enable evaluation of the number or location of ESS units in thermal runaway.
- TICs provide a limited ability to determine whether a suppression system has operated or is operating.
- TICs are not a viable tool for determining the nature of visible vapors (e.g., battery gas, steam, Novec 1230).

	Side B	Side D
Thermal Runaway – Initiating Module		
Thermal Runaway – Additional Modules		
120 minutes after test start		

Tactical consideration: size-up and gas monitoring

- Using portable gas meters to evaluate interior conditions or the gases/vapors leaking from an ESS places firefighters in an explosion hazard area.
- Portable gas meter measurement of battery gas is likely to be compromised by clogging and cross-sensitivity to battery gas mixture species.

UL's tests

Surprise, Arizona

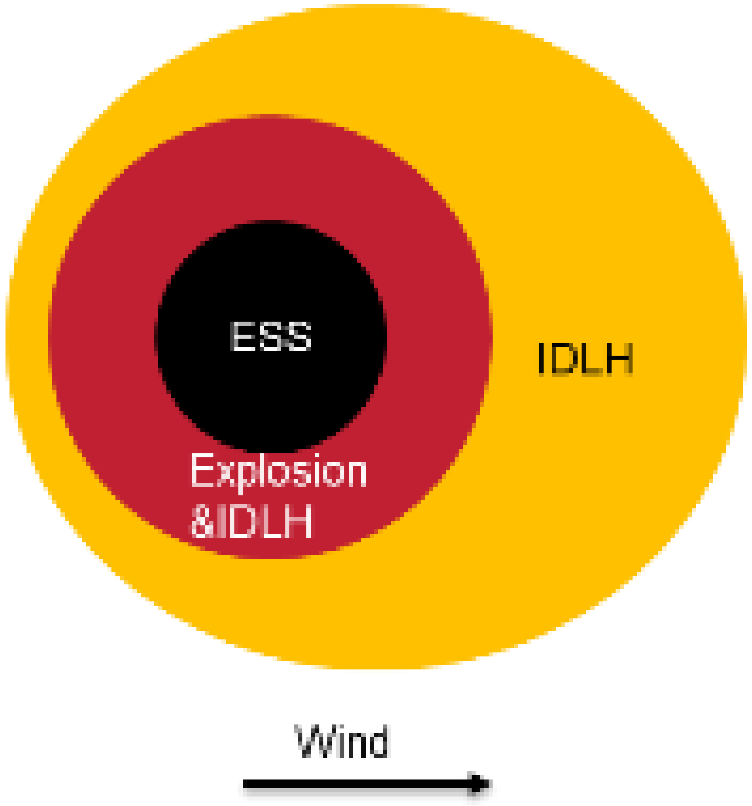
Figure 4.9: Photograph of the ESS scene taken by E193 FE upon the arrival of E193 [6].

*M. B. McKinnon, S. DeCrane and S. Kerber, "Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion - Arizona," UL's Firefighter Safety Research Institute, Columbia, Maryland, 2020.

Tactical consideration: size-up and gas monitoring

A deflagration event is hard to predict, even with good-quality gas concentration data.

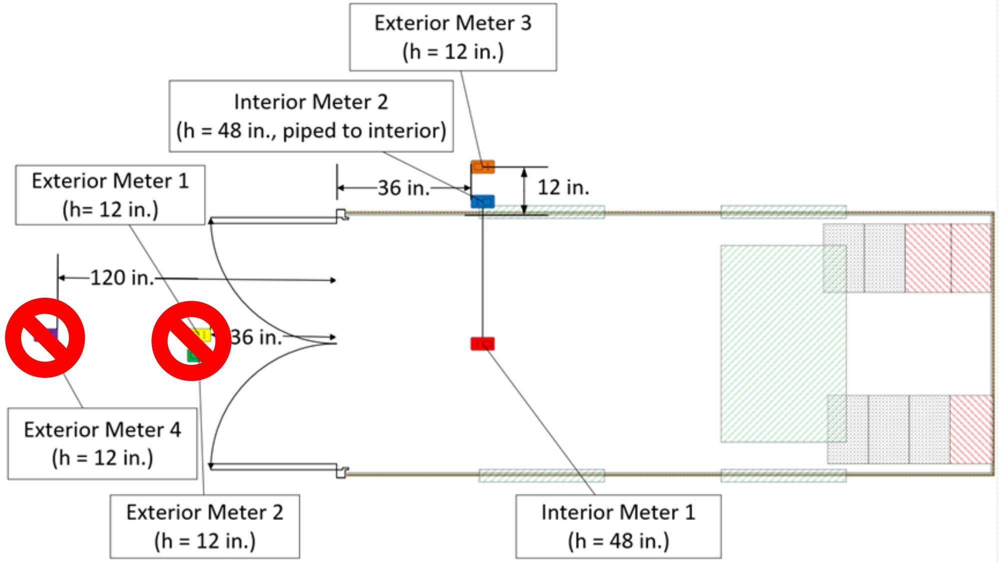
Responding firefighters should consider using portable gas meters and visual observations to define an exclusion zone while wearing full structural PPE (Level D Ensemble) with full SCBA.



Tactical consideration: portable gas meters

Portable gas meters have limited effectiveness to evaluate the potential for explosive atmosphere within the ESS container.

- Deflagration may occur before flammable gas is detectable at the exterior of the container for measurement.
- Flammable gas only detected/measured one foot from container – FF may be dangerously close to the container before an explosion hazard via LEL measurement is identified.
- Exterior gas concentrations approximately equal to interior gas concentrations – Remotely monitored gas meters may safely provide insight into continued or halted thermal runaway activity but are subject to factors like wind, terrain, etc.



Tactical consideration: ventilation

Ventilation of an ESS installation may result in a deflagration or rapid transition to flashover.

UL's tests — flashover

$\Delta t = 21$ sec

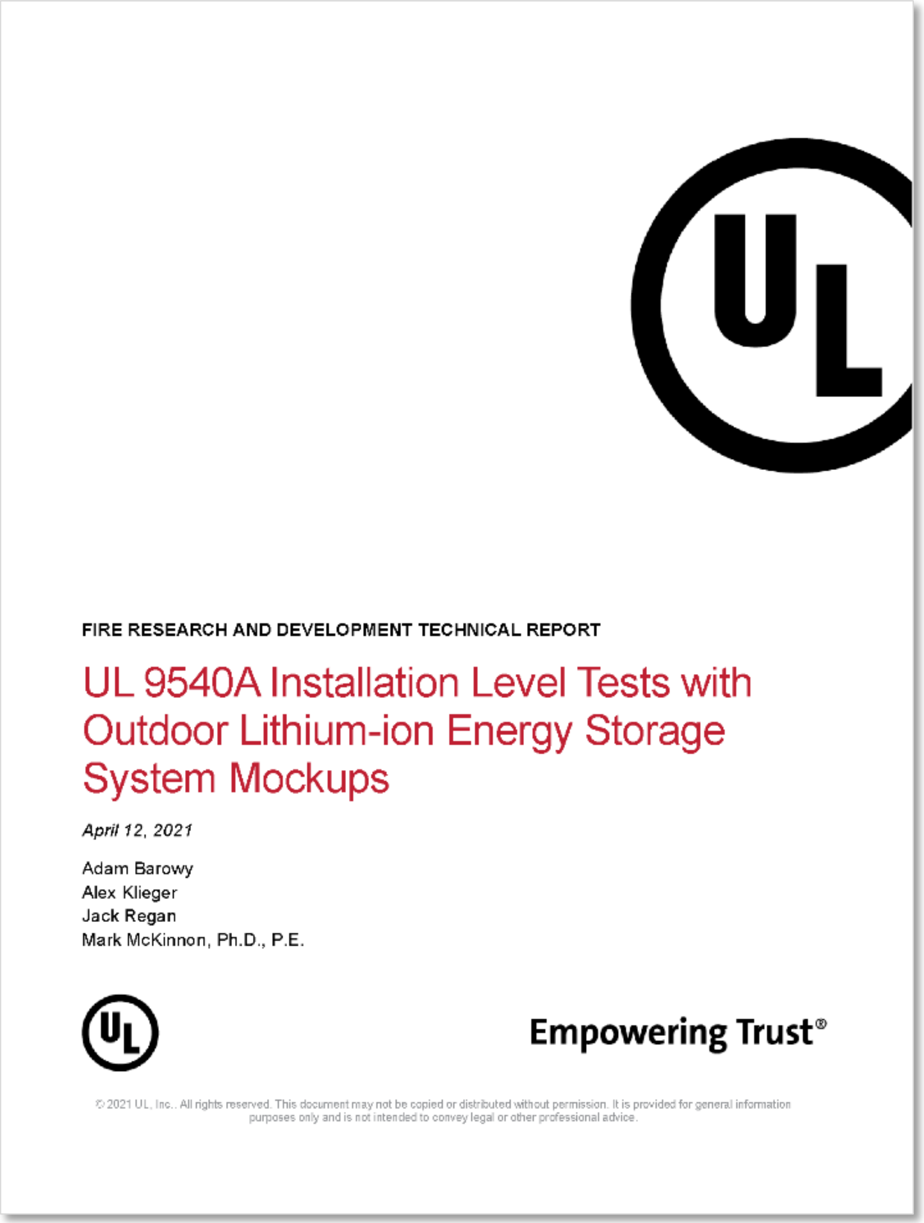
Surprise, Arizona — deflagration

$\Delta t \approx 3$ min

*M. B. McKinnon, S. DeCrane and S. Kerber, "Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion - Arizona," UL's Firefighter Safety Research Institute, Columbia, Maryland, 2020.

Technical report available

- UL 9540A Installation Level Tests with Outdoor Lithium-ion Energy Storage System Mockups
- Published April 12, 2021
- Available for download at:
  - ULFirefighterSafety.org/Research-Projects/Firefighter-Line-of-Duty-Injuries-and-Near-Misses.html
  - UL.com/services/UL-9540A-Test-Method


FIRE RESEARCH AND DEVELOPMENT TECHNICAL REPORT

UL 9540A Installation Level Tests with Outdoor Lithium-ion Energy Storage System Mockups

April 12, 2021

Adam Barowy
Alex Klieger
Jack Regan
Mark McKinnon, Ph.D., P.E.

Empowering Trust®

Moving forward

Residential ESS Project Introduction

U.S. DEPARTMENT OF ENERGY

- The International Association of Fire Fighters (IAFF) and UL LLC, have partnered with the US Department of Energy
- Conduct large-scale burn experiments involving renewable energy components
- Residential Battery Energy Storage Systems (BESS) and ~~Exterior Building Technologies~~ and benefit from previous research developed by UL LLC and the UL Firefighter Safety Research Institute (UL FSRI)
- Experiment design coordinated by a Project Advisory Panel: fire fighters, UL fire protection engineers, industry representatives and subject matter experts.

Residential ESS Project Objectives

- Size-up Considerations:
  - What does a responding fire company look for as indicators of onsite energy generation & storage?
  - Are there indicators that batteries are involved the fire (e.g., white vapor, detectable gases, etc.)?
  - Can an explosion hazard be identified?

- Tactical Considerations:
  - Does battery involvement in the fire develop explosion hazards?
  - How does energy storage impact fire behavior (e.g., response to manual ventilation)?

International Residential Code – Locations

R328.4 Locations. ESS shall be installed only in the following locations:

1. Detached garages and detached accessory structures
2. Attached garages separated from the dwelling unit living space in accordance with Section R302.6.
3. Outdoors or on the exterior side walls located not less than 3 feet from doors and windows directly entering the dwelling unit.
4. Enclosed utility closets, basements, storage or utility spaces within dwelling units with finished or noncombustible walls and ceilings. Walls and ceilings of unfurnished wood-framed construction shall be provided with not less than 5/8-inch Type X gypsum wallboard.

ESS shall not be installed in sleeping rooms, or closets or spaces opening directly into sleeping rooms.

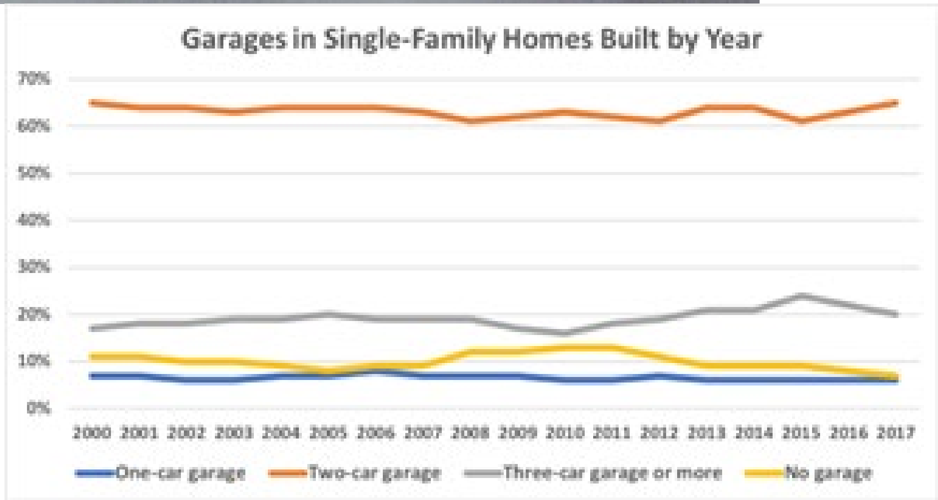
International Residential Code – Energy Ratings

R328.5 Energy Ratings. Individual ESS units shall have a maximum rating of 20 kWh. The aggregate rating of the ESS shall not exceed:

1. 40 kWh within utility closets, basements and storage or utility spaces.
2. 80 kWh in attached or detached garages and detached accessory structures.
3. 80 kWh on exterior walls.
4. 80 kWh outdoors on the ground.

ESS installations exceeding the permitted individual or aggregate ratings shall be installed in accordance with Section 1207 of the International Fire Code.

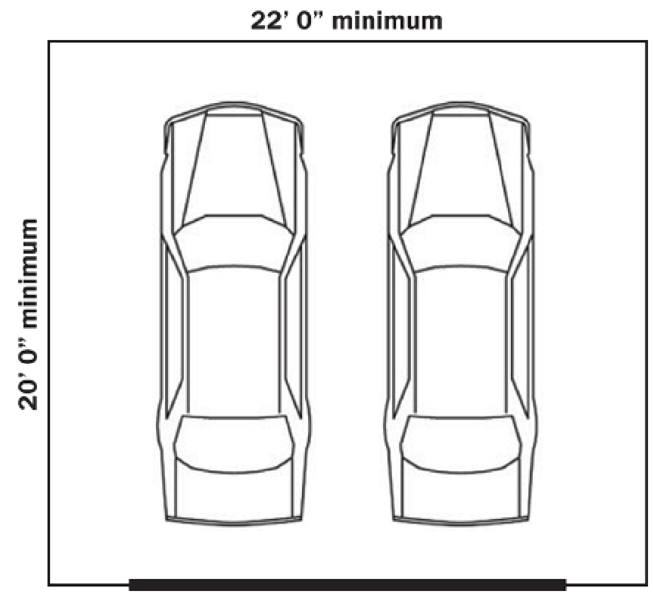
Survey of Residential ESS Products

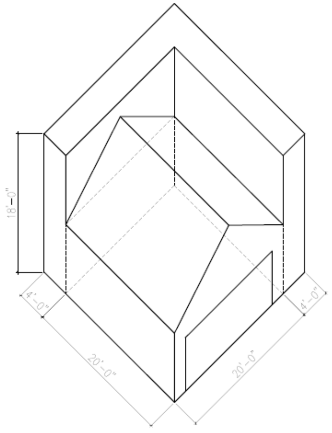


Majority of garages in single family homes are 2-car

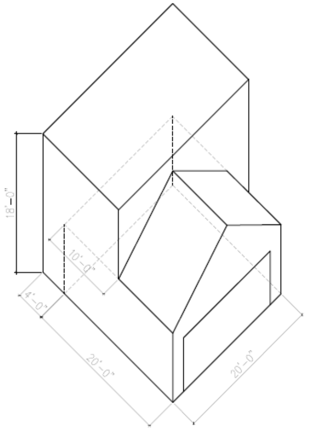
Proposed Garage Size and Structure

- Attached.
- 2 cars garage.
- 20 ft x 22 ft x 9.5 ft.
- Shed roof style.

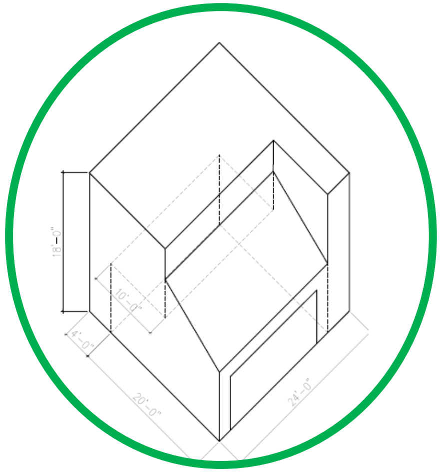




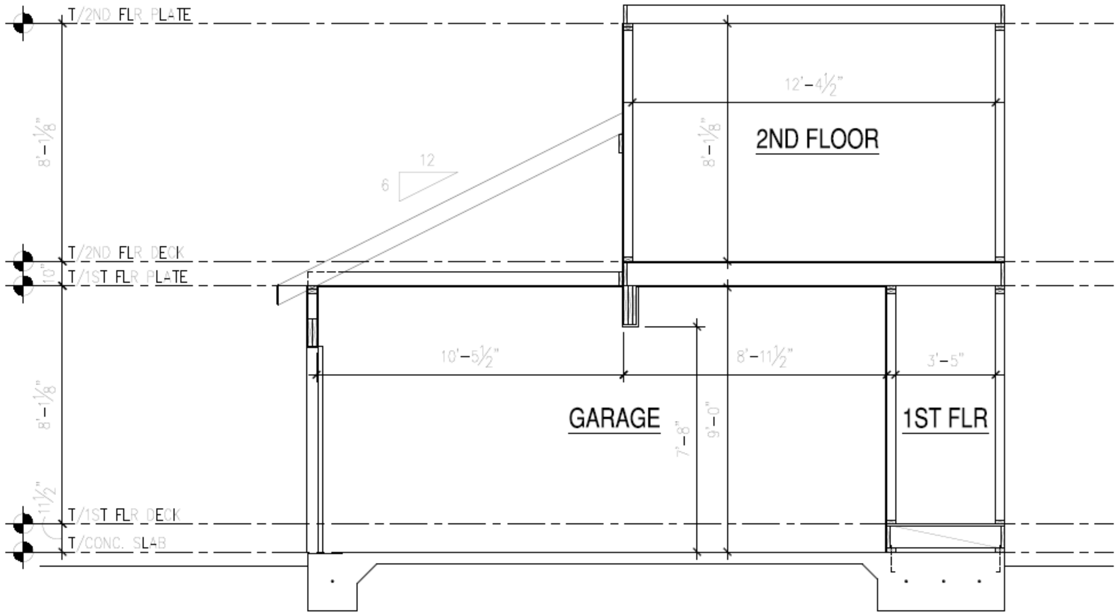
Garage
Front Facing Gable - Generic Walls



Garage
Front Facing Gable - 2nd Floor Abv.



Garage
Shed Roof - 2nd Floor Abv.



Project Scope

- Test location: Building 11 Large scale fire lab in UL Northbrook
- Hazards: Fire, explosion, particulate/gas exposure
- Equipment: Residential ESS units (Li-Co-O_2)
- Structure: Attached garage, shed roof and 2-car size
- Installation: RESS mounted on wall closest to main electrical panel
- Thermal runaway scenarios:
    1. Batteries as 1st item ignited (no control over battery gas ignition timing)

    OR

    2. Batteries as 2nd item ignited (forced flaming ignition of battery gas)

Questions or comments

Sean DeCrane
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Thank you!

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