Battery Safety Science Webinar Series

Advancing safer energy storage through science

May 24, 2021

Fire Service Considerations – Investigation of AZ Li-ion ESS Incident

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Fire Service Considerations

Investigation of AZ Li-Ion ESS Incident

Mark McKinnon & Steve Kerber

UL Firefighter Safety Research Institute

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UL FSRI is dedicated to increasing firefighter knowledge to reduce injuries and deaths in the fire service and in the communities they serve.

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

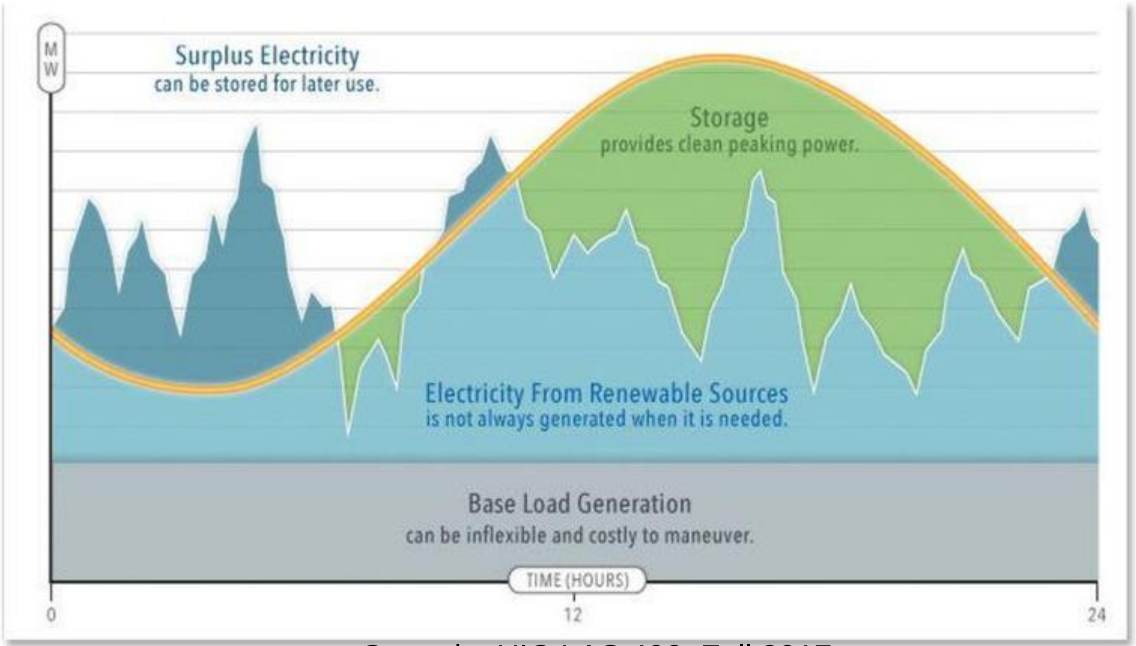
- The goal of this project is to enhance the safety and situational awareness of the fire service with high quality interactive training materials developed from applying fire dynamics research results to significant near miss or line of duty injury fire incidents.
- NIOSH's Fire Fighter Fatality Investigation 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.

ELECTRICAL GRID ISSUES

- Aging infrastructure and demand growth outpacing supply
- Electrical grids not designed for peak demand
- Renewable energy sources produce electricity intermittently

WHY ENERGY STORAGE?

- ESS are a reliable source of energy during peak usage
- Mitigate the variability in renewable energy sources
- Low cost alternative to increasing base load generation capacity

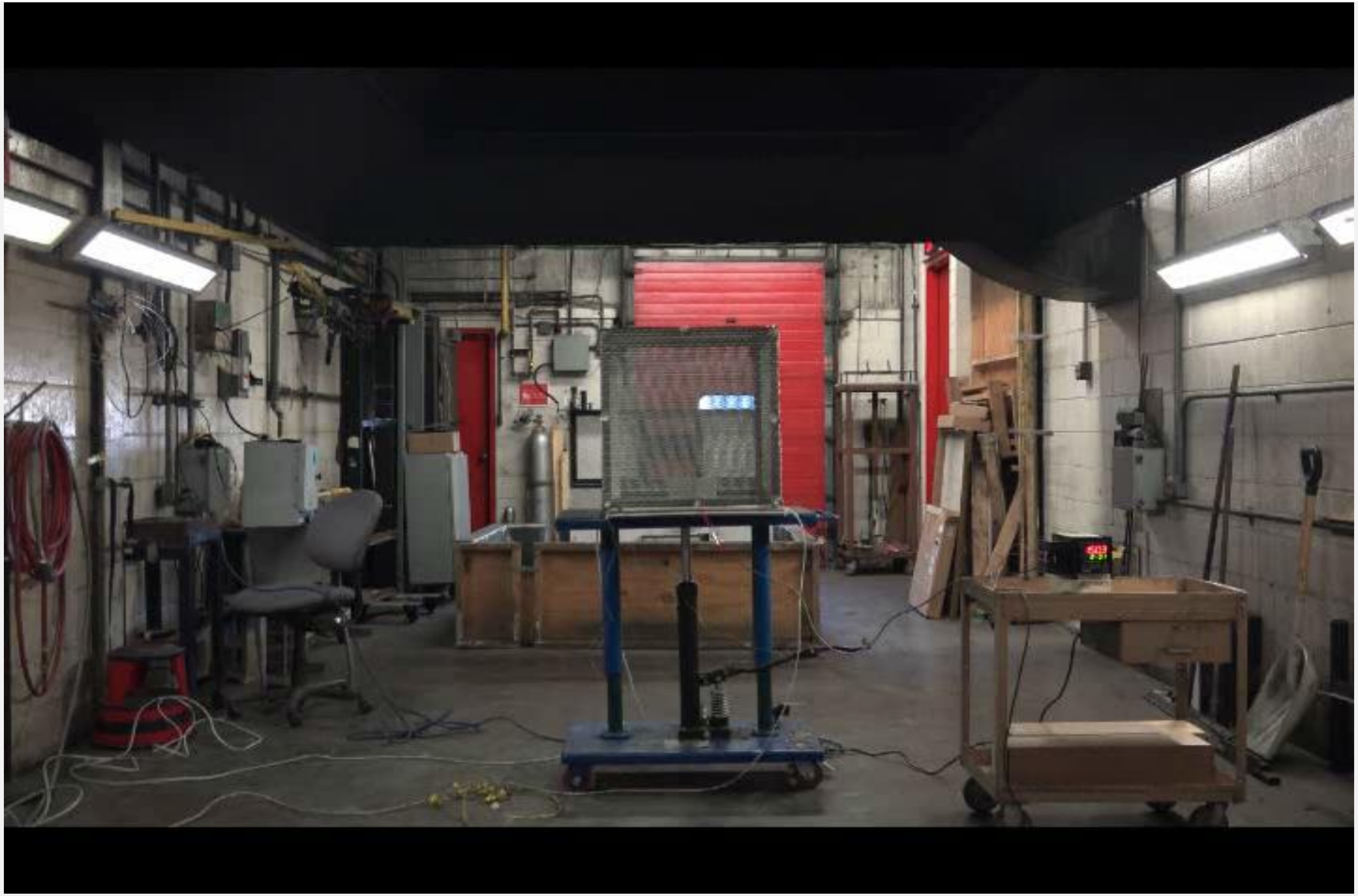


Gapasin. UIC LAS 493. Fall 2017.

LITHIUM-ION BATTERIES

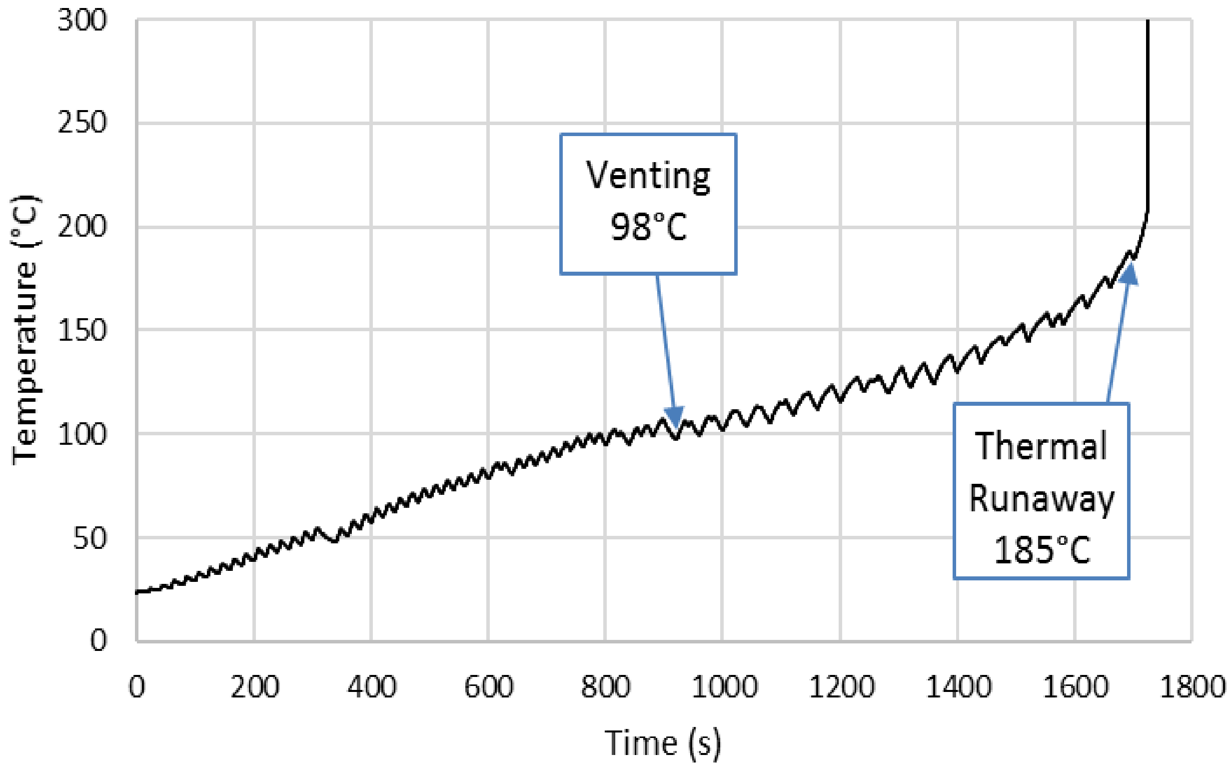
- Excellent Energy Density
- The Current Battery of Choice
- Batteries and Systems are Readily Available
- Majority of ESS Market is Li-ion

CELL LEVEL MOCKUP TEST



CELL LEVEL MOCKUP 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

RECENT LITHIUM-ION BATTERY INCIDENTS

Over the last year, there have been several major Lithium-Ion Battery ESS incidents.

- September 15, 2020 – Liverpool (20 MW)
- December 1, 2020 – France
- April 6, 2021 - South Korea
- April 16, 2021 – Beijing (25 MWh)

  - 2 firefighters died in suppression efforts

Hongseong, S.K.

Perles et Castelet, France

Liverpool, UK

Surprise, AZ ESS Incident

Background

2 MW/2.16 MWh Lithium-Ion Battery ESS

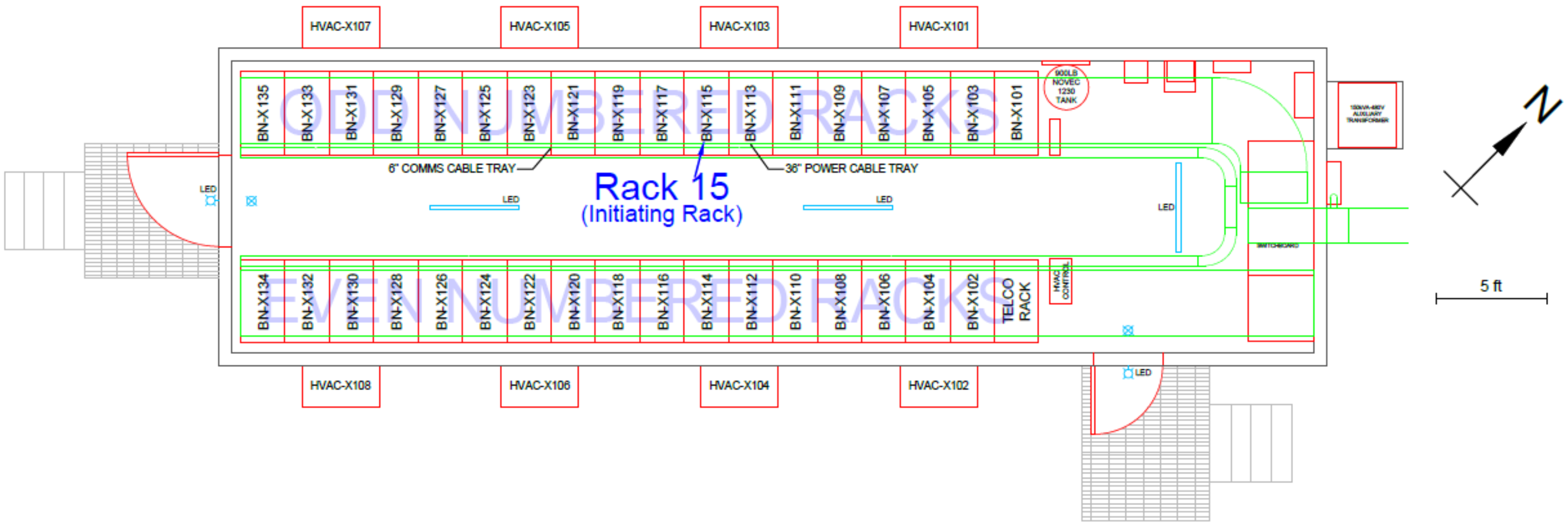
- Capacity to power 60 average AZ homes for a full day
- ESS owned by local electric utility (APS)
- Batteries manufactured by LG Chem
- ESS designed by integrator (Fluence)
- ESS maintained by contractors to the integrator (Sturgeon)

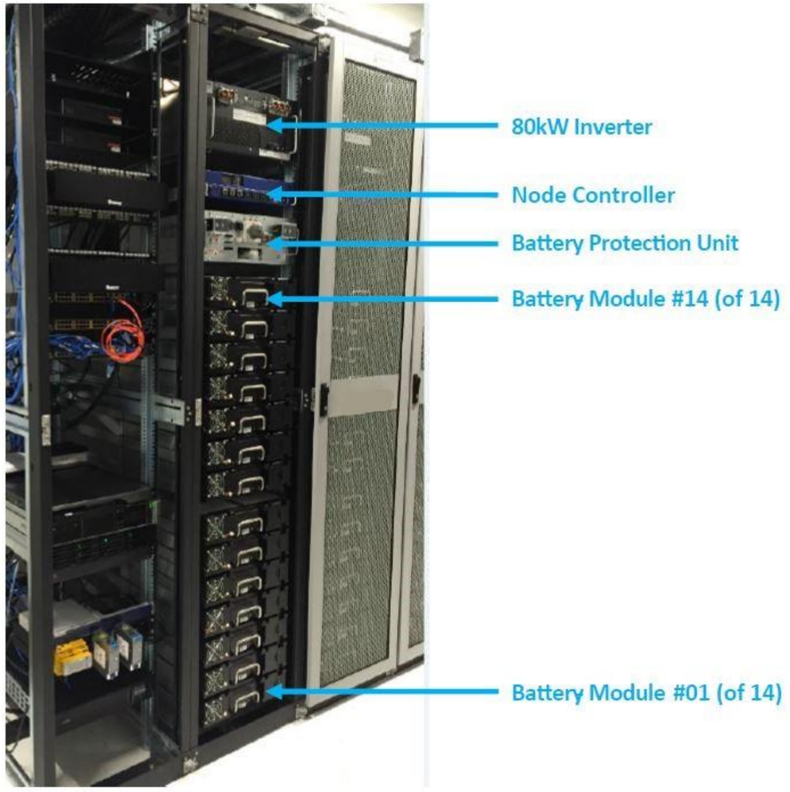
Four firefighters (Peoria HAZMAT team) seriously injured

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

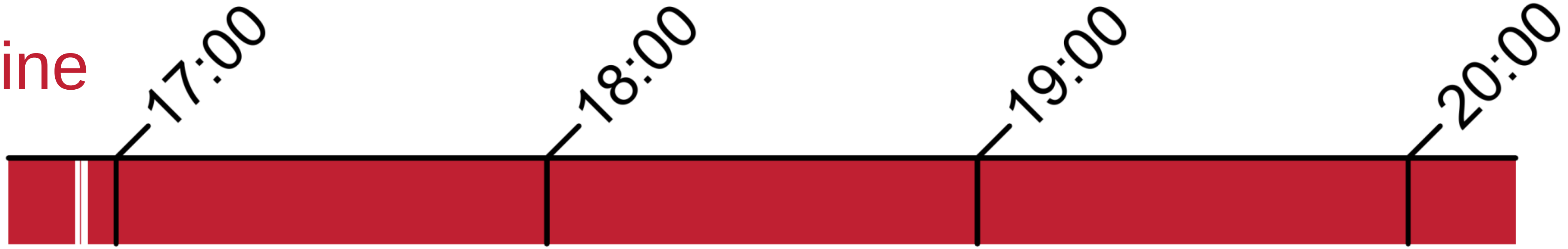
Energy Storage System

- 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)
- 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

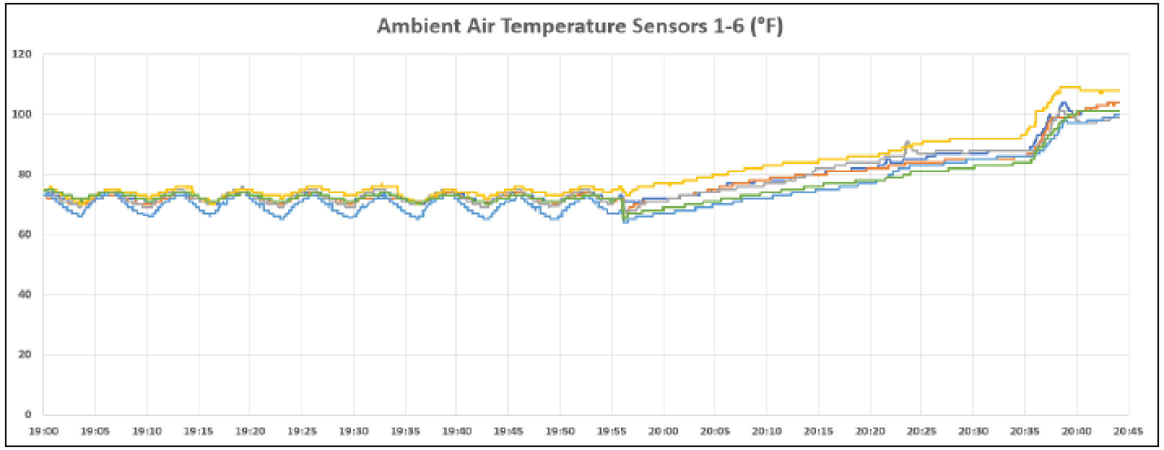
16:55:50 – Suppression system discharged

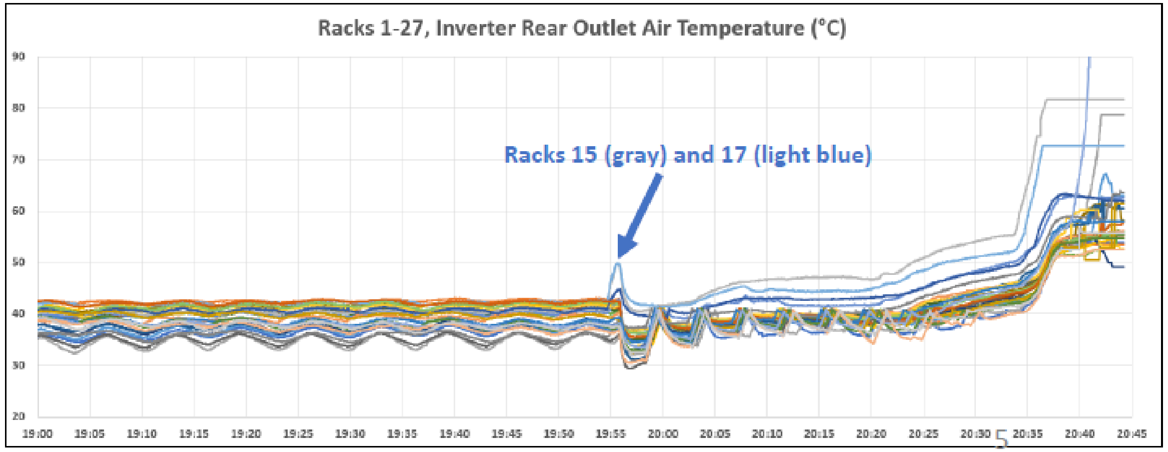
Timeline

17:41:54 – Phoenix Metro dispatch received a call for smoke and a bad smell near an electric substation and Surprise 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 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.

Timeline

18:18:30 – Surprise BC 301 arrived on the scene

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

Timeline

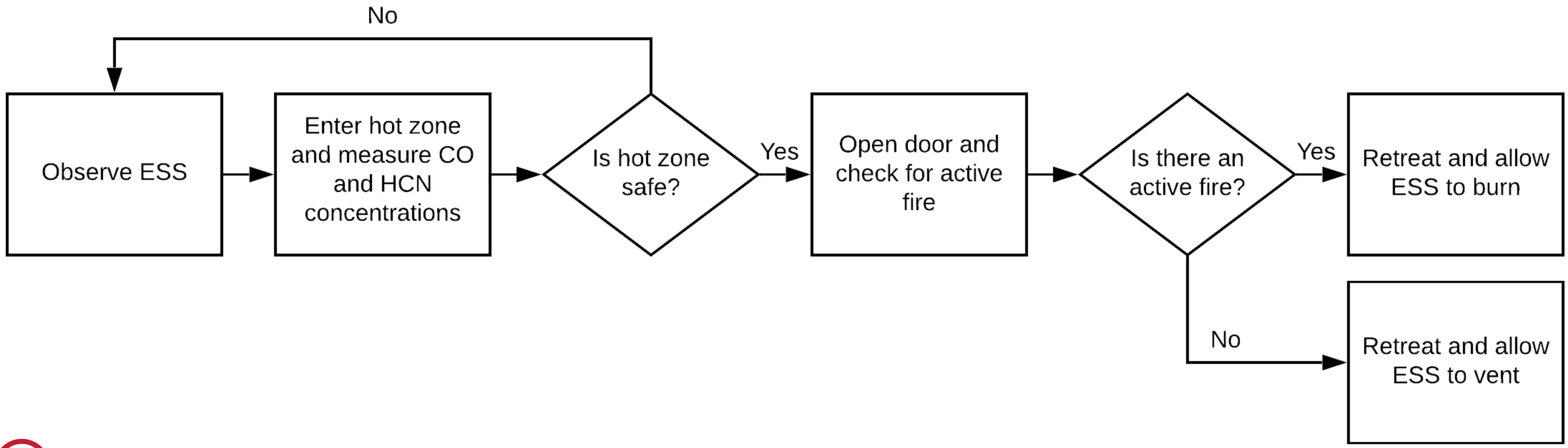
18:37:00 – HAZMAT team conducted 360-degree size-up and defined hot zone

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

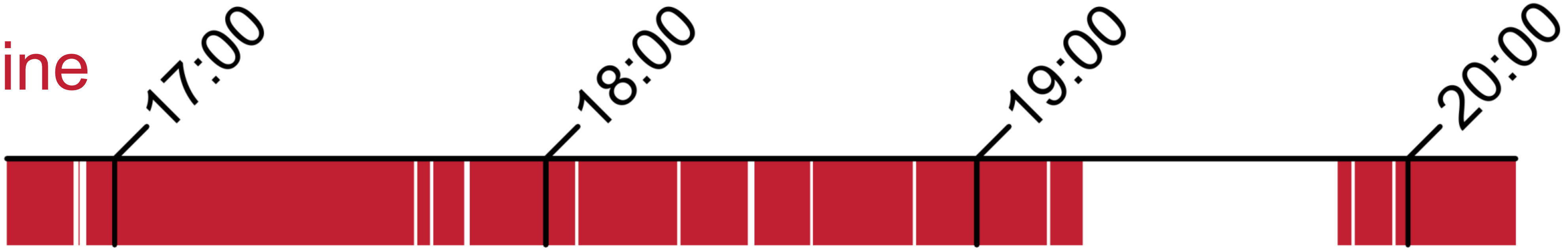
19:10:00 – HAZMAT team made third entry into hot zone

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

Timeline

20:00:54 – HAZMAT team opened the door to the ESS

20:03:49 – Mayday call

Contributing Factors and Recommendations

Contributing Factors

- Core HAZMAT training curricula for First Responder and Technician Level 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 Factor

- The ESS communication system failed early in the incident.

Recommendation

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

Contributing Factors

- The emergency response 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 ESS should developed an emergency operations plan in conjunction with local fire service personnel and the AHJ and hold 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

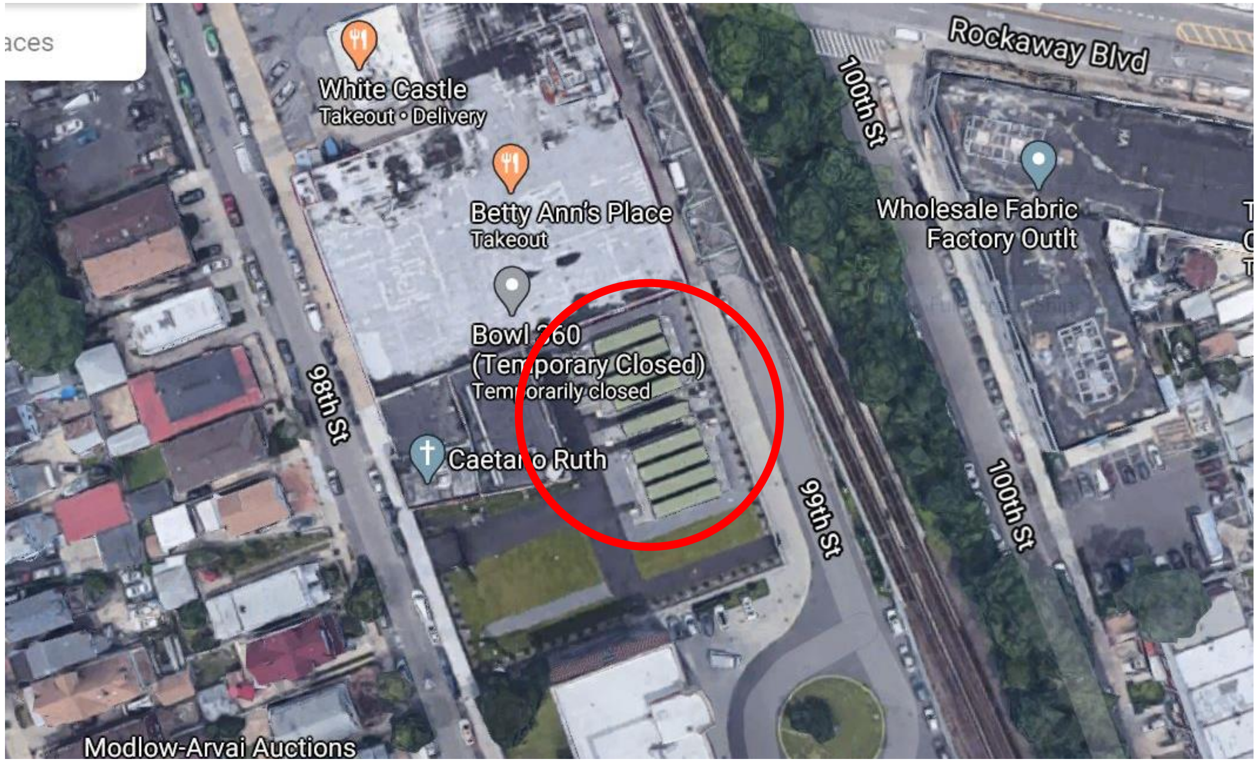
- The ESS did not have deflagration venting panels (NFPA 68) or adequate ventilation to prevent accumulation of flammable gases (NFPA 69).
- The total flooding clean agent suppression system likely contributed to the deflagration.

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

- Research focused on emergency decommissioning best practices and the role of the fire service in an emergency situation should be conducted.



UL9540A Test Method

Codes, Standards, and Test Methods for ESS

Model Codes: Building and Life Safety	■ NFPA 1 (Chapter 52) — 2018 Fire Code[32] ■ NFPA 70 (Article 706), National Electrical Code, 2017[33] ■ International Fire Code (IFC, Section 1206), 2018[34] ■ International Residential Code (IRC, Section R327), 2018[35] ■ IEEE C2, National Electric Safety Code, 2017[36]
ESS Installation Standards	■ NFPA 855, Standard for the Installation of Stationary Energy Storage Systems[30] ■ UL 9540A, Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems*[37]
ESS Design	■ UL 9540, Energy Storage Systems and Equipment[38] ■ ASME TES-1, Safety Standard for Thermal Energy Storage Systems (DRAFT)[39]
ESS Components	■ UL 1973, Batteries for Use in Light Electric Rail and Stationary Applications[40] ■ UL 1974, Evaluation for Repurposing Batteries[41] ■ UL 810A, Electrochemical Capacitors[42] ■ UL 1741, Standard for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources[43]

Updated Since Surprise, AZ Incident

- IFC 2021, Section 1207
- NFPA 855 (2020)
- UL 9540 - 2nd Edition (2020)
- UL 9540A 4th Edition (2019)

Barowy, A. 'True Grid: Standards for Fire, Explosion, and Electrical Safety of Battery Energy Storage Systems'. Fire Protection Engineering. 84. 2019.

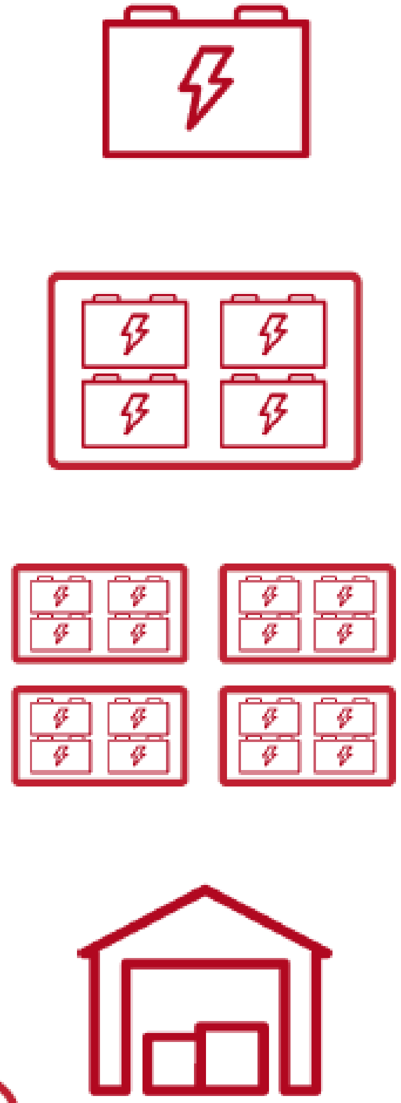
UL 9540A Test Method

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

Structure of UL 9540A and Deflagration Hazard Characterization



Cell Level Test

- Whether cell can exhibit thermal runaway
- Gas composition
- Explosibility parameters of gas mixture (LFL, P_{max}, Burning Velocity)

↓

Module Level Test

- Gas release rates and total volumes

↓

Unit Level Test

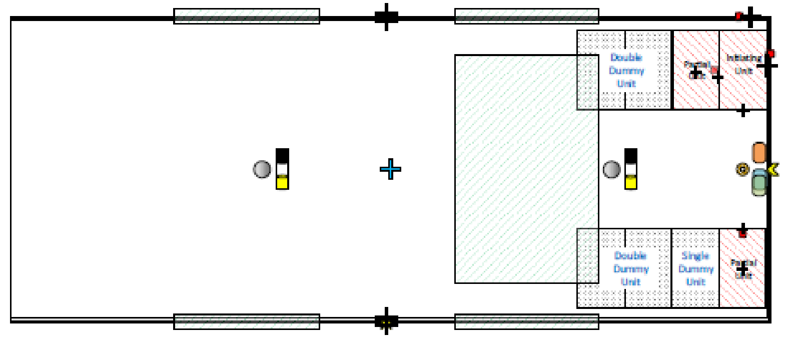
- Gas release rates and total volumes
- Deflagration hazards resulting from confinement

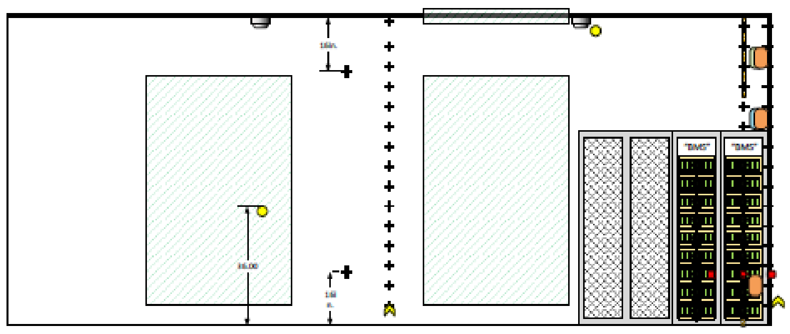
↓

Installation Level Test

- Effectiveness of fire protection system(s)
- Gas release rates or accumulated gas composition
- Deflagration hazards resulting from confinement

UL 9540A Installation Level Demonstration





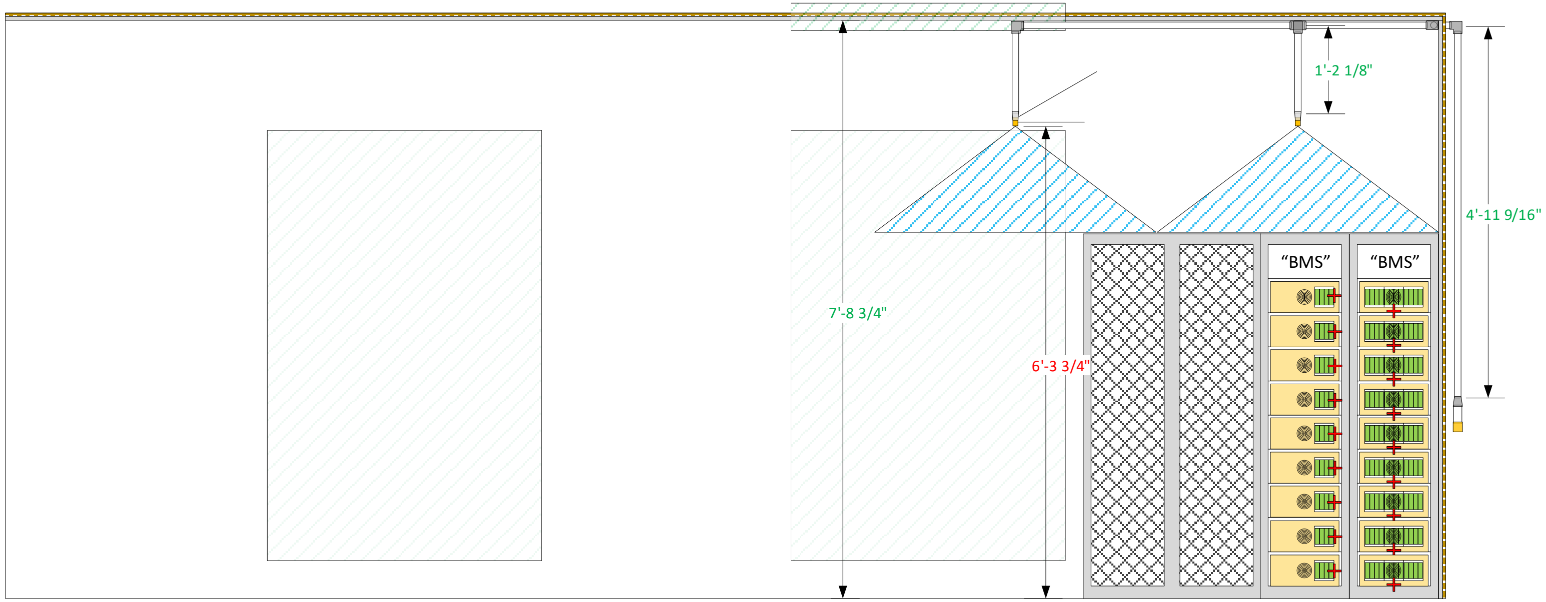
Objectives

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

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

Test Setup - Installation Level Test Configurations

- 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 density water spray system (from ceiling).



Operation pressure 0.5 psig; vent area calculation based on NFPA 68, *Standard on Explosion Protection by Deflagration Venting*

UL 9540A Installation Level Demonstration

Smoke accumulation at second smoke detector activation [TR + 00:00:55]

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

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

Ignition [TR + 00:28:32]

Partial volume deflagration [TR + 00:44:39]

Continued thermal runaway propagation [TR + 00:46:26]

Smoke plume from open door [TR + 02:09:27]

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

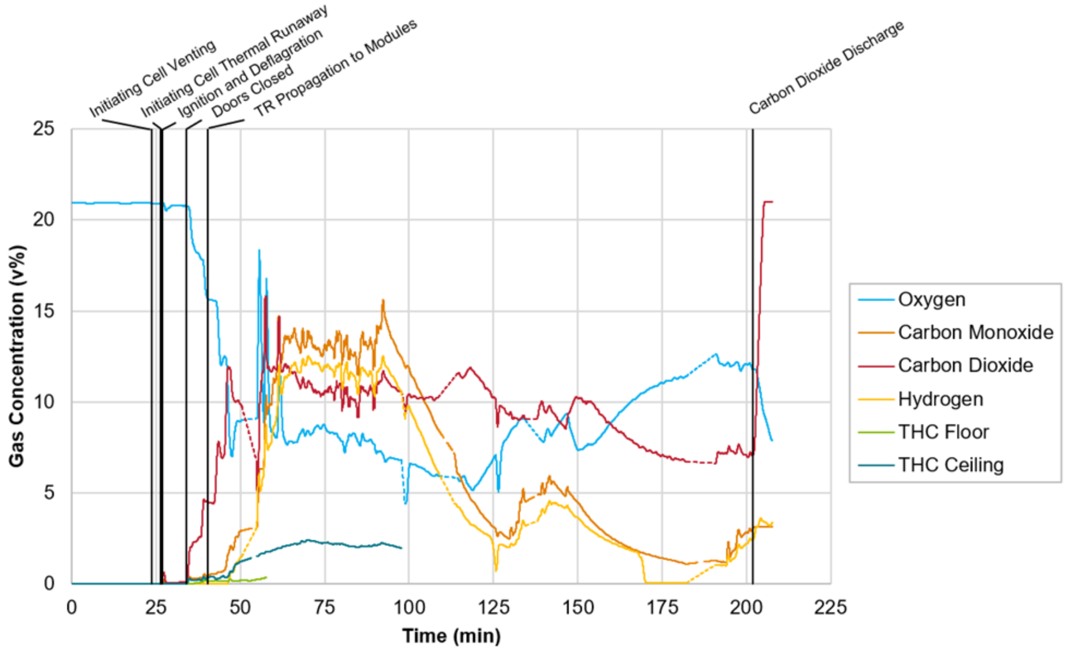
Reports Available: https://ulfirefightersafety.org/research-projects/firefighter-line-of-duty-injuries-and-near-misses.html

UL9540A Test Method

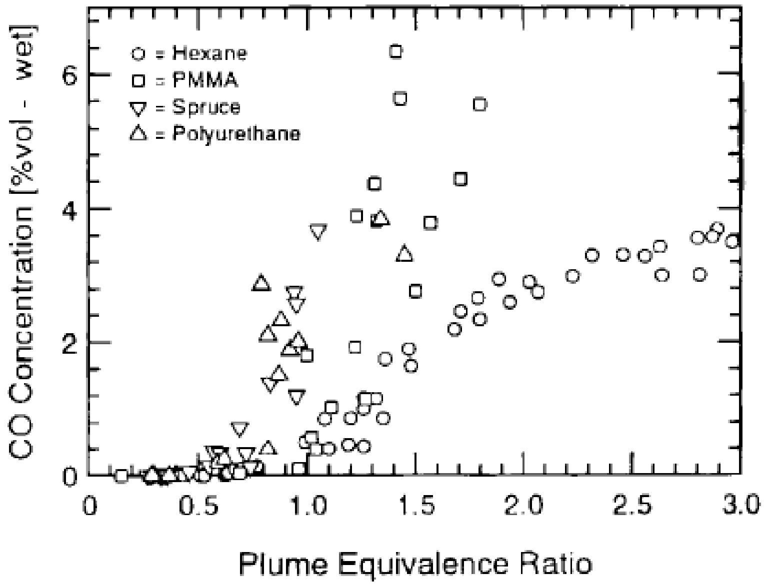
Key Findings

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.



- THC: ~3 v%
- 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/hydrogen detectors:

1) **Effective for detecting that thermal runaway has occurred.**
2) **Not reliable for ongoing hazard assessment.**

Advantages:

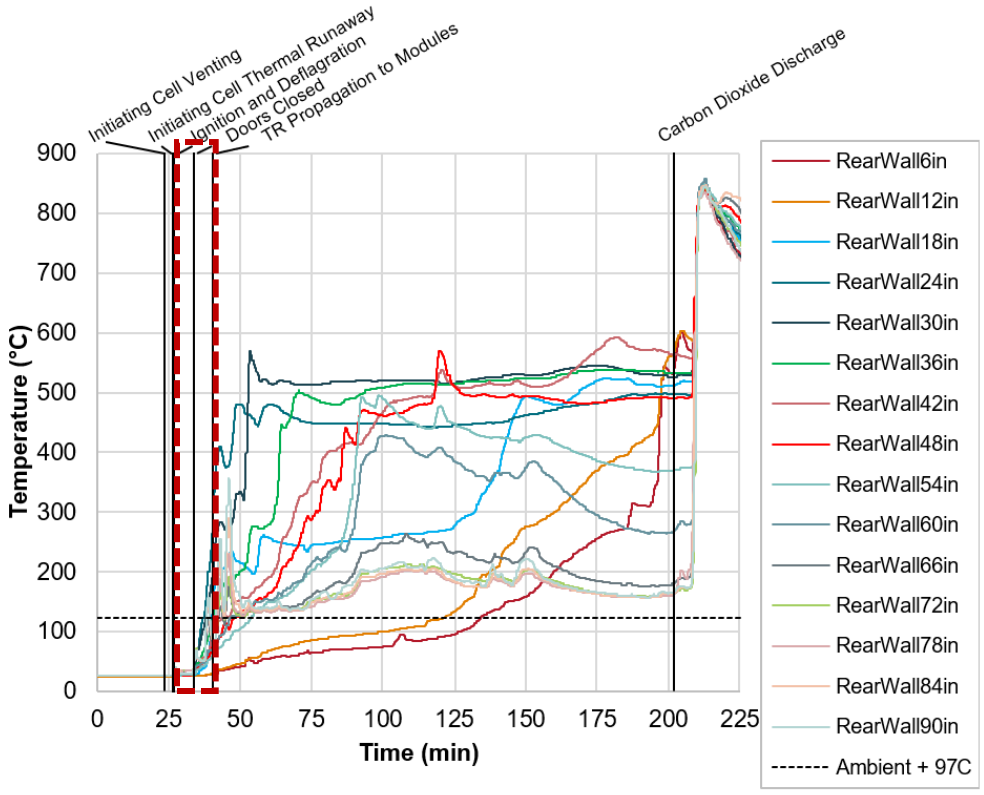
- All detectors responded within seconds when exposed to battery gas.
- Nuisance activation unlikely given measurands (e.g., H_2, CO, LEL).

Limitations:

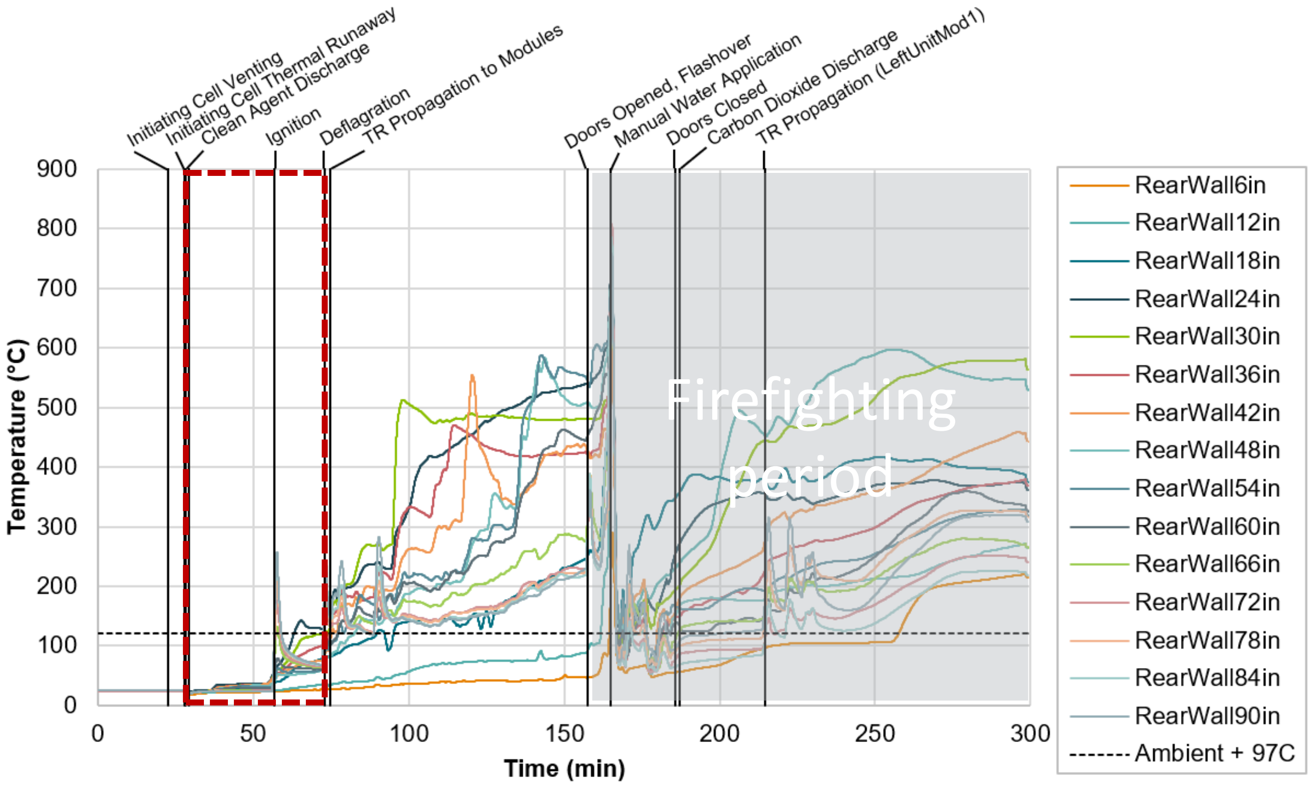
- Detection time dependent on positioning. These tests did not seek to determine optimal locations.
- Cross sensitivity diminishes electrochemical sensor accuracy
- Catalytic bead:
  - Imprecise measurements of flammable gas mixtures,
  - Requires > 10% O_2 for proper operation,
  - “Poisoned” by halogen exposure.

Key Findings – Novec 1230 Total Flooding System

When simulating a total flooding system approach, Novec 1230 did not deliver sufficient cooling to prevent propagation of thermal runaway or to prevent thermal exposure to combustible construction materials.



Rear Wall – No Novec 1230

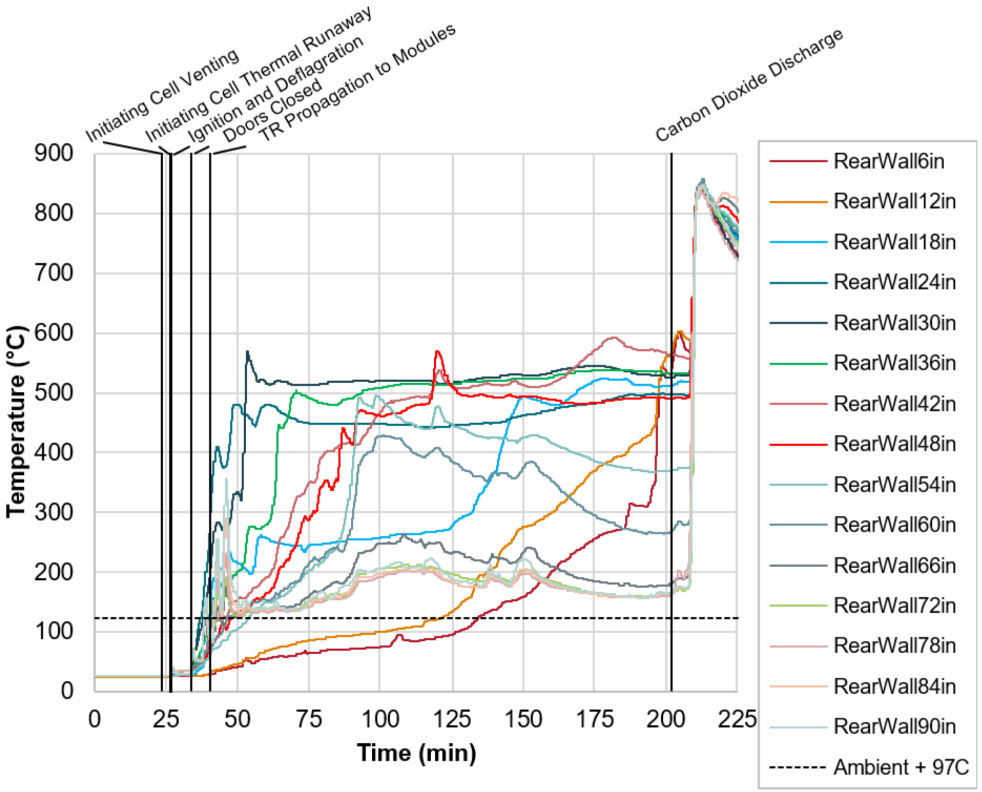


Rear Wall – w/ Novec 1230

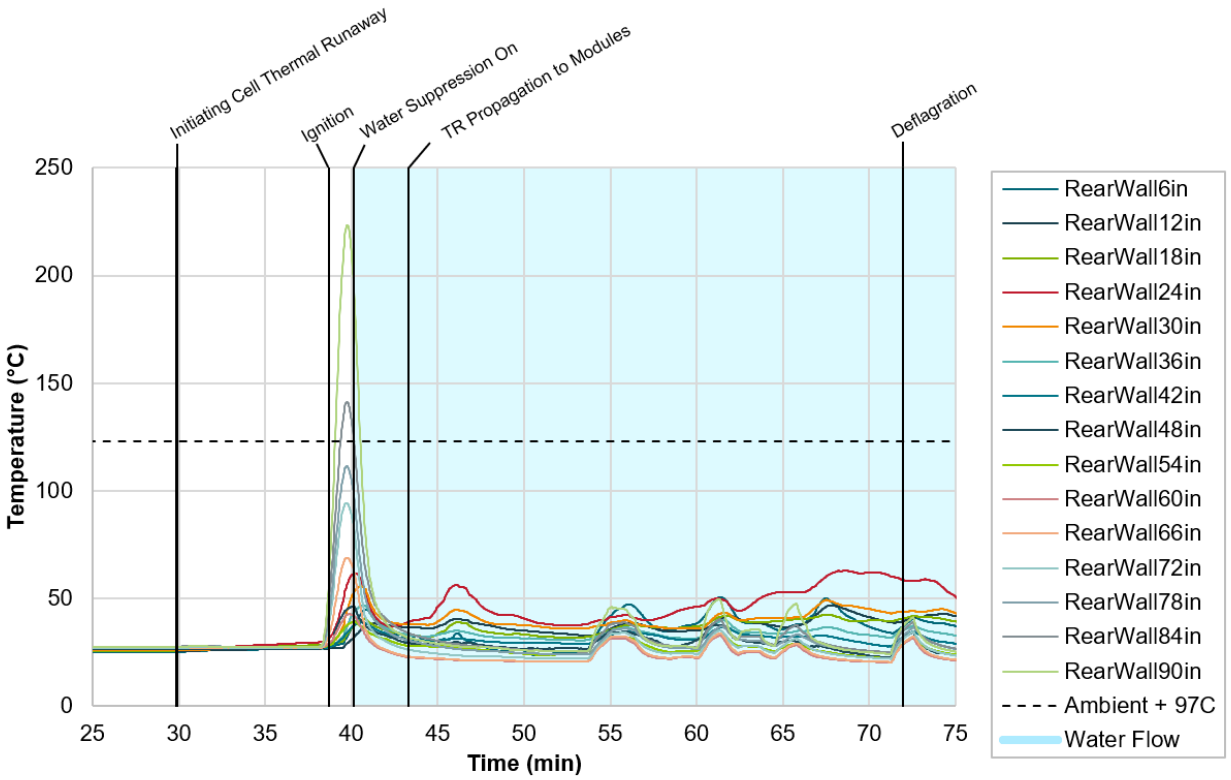
Key Findings – Water Spray Suppression System

Ceiling-based water spray suppression system prevented unit-to-unit propagation and cooled surfaces adjacent to initiating ESS unit.

Demonstrated limited effectiveness to prevent module-to-module thermal runaway propagation within initiating unit.



Rear Wall – No Water



Rear Wall – w/ Water

Key Findings – Deflagration Protection System

The generation and accumulation of battery gases created an explosion hazard and was mitigated with an engineered deflagration protection system.

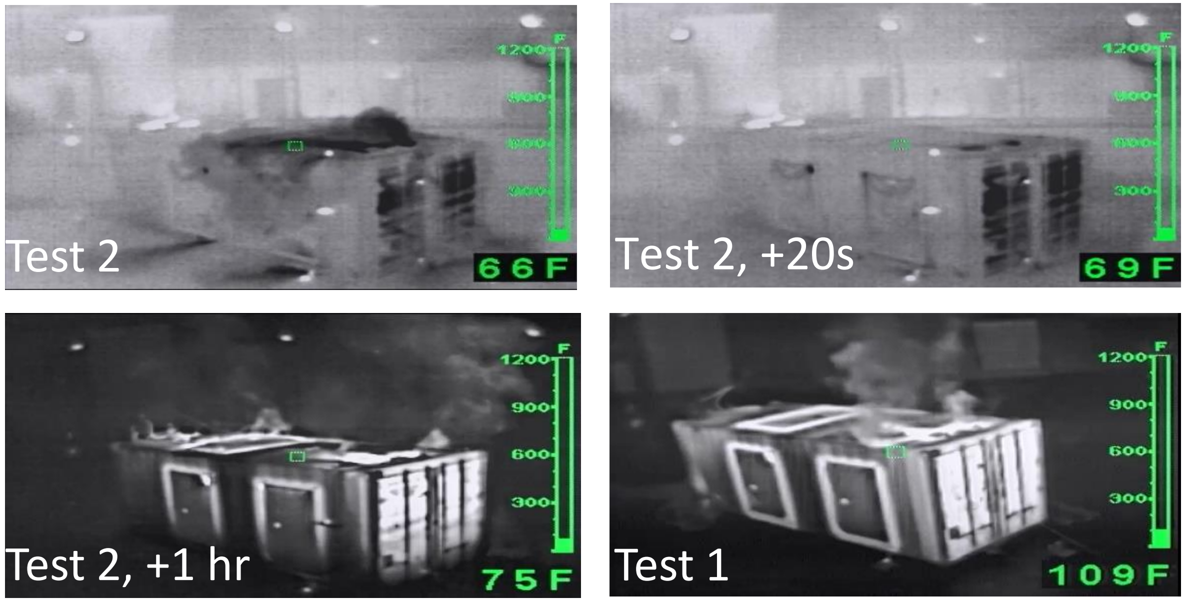
UL9540A Test Method

Tactical Considerations

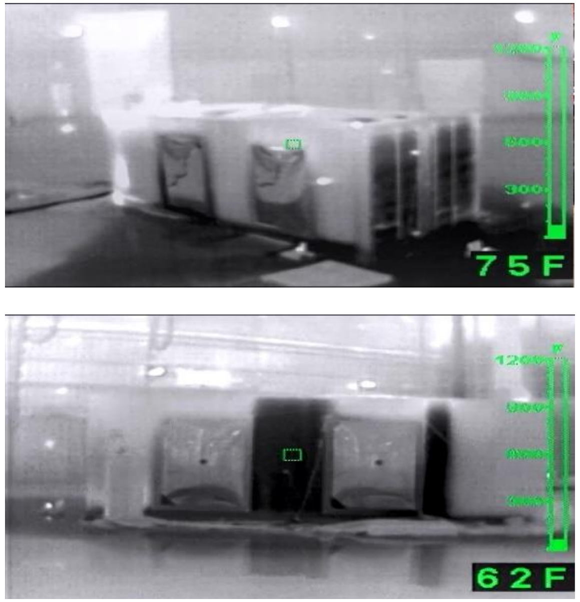
Tactical Consideration – Thermal Imaging Cameras

Thermal imaging cameras enable a limited ability to determine whether a suppression system has operated or is operating.

Thermal Imaging Cameras are not a viable tool for determining the nature of visible vapors (e.g. battery gas, steam, Novec 1230).



Novec discharge evident for short time, likely prior to FD arrival.

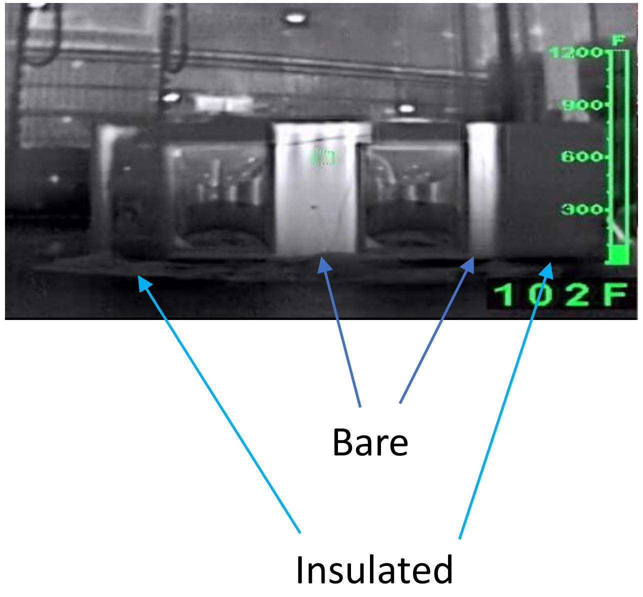


Sprinkler operation visible while water flowing.

Tactical Consideration – Thermal Imaging Cameras

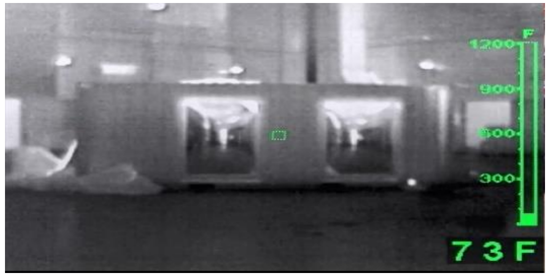
Thermal imaging cameras do not enable evaluation of the number or location of ESS units in thermal runaway.

Wall construction influenced thermal image.



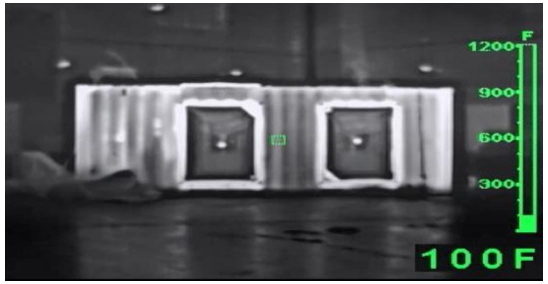
Heat sources not identifiable.

Built up/insulated wall



t= 15 min

Built up/insulated wall



t= 95 min

Bare/insulated wall

t= 95 min

Tactical Consideration – Continuous Gas Monitoring

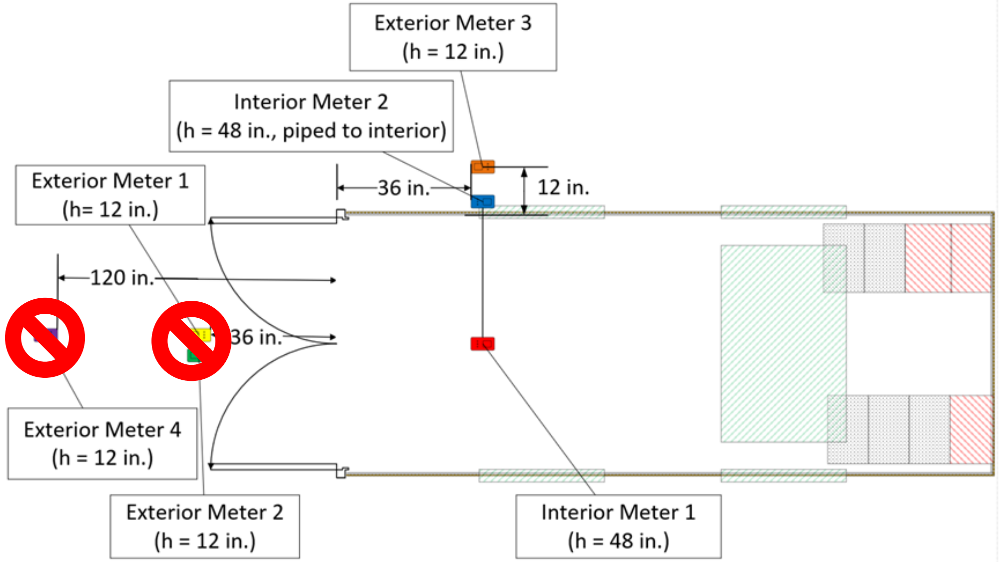
First responders should consider the practicality of continuous monitoring of the interior and exterior gas environment near the ESS.

- Firefighters may need to create an opening into container to insert gas meter probe – proximate to potential explosion hazard.
- Soot accumulation clogged pump style meter shortly after the onset of thermal runaway in all three tests.
- CO and H_2 v% measured was often several orders of magnitude higher than the upper measurement limit of the portable gas meters.

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 detectable at exterior of the container for measurement.
- Flammable gas only detected/measured 1 ft from container:
  - FF may be dangerously close to the container before an explosion hazard via “LEL” measurement is identified.
- Exterior gas concentrations were approximately equal to interior gas concentrations:
  - Remotely monitored gas meters may safely provide insight into continued or halted thermal runaway activity, but subject to factors like wind, terrain, etc.



Tactical Consideration – Portable Gas Meters

Fire service portable gas meters have limitations in a battery gas environment.

Electrochemical sensor cross-sensitivity

RAE Systems				
Cross-Sensitivity %	Gas			
Sensor	CO	H_2S	HCN	H_2
CO	100%	0%	N/A	40%
CO-H_2 Compensated	100%	N/A	N/A	1%
H_2S	1%	100%	N/A	N/A
HCN	5%	600%	100%	N/A
H_2	20%	20%	30%	100%
MSA				
Cross-Sensitivity %	Gas			
Sensor	CO	H_2S	HCN	H_2
CO	100%	0%	-5%	48%
H_2S	1%	100%	-3%	0%
HCN	0%	400%	100%	0%
Ventis				
Cross-Sensitivity %	Gas			
Sensor	CO	H_2S	HCN	H_2
CO	100%	5%	15%	22%
H_2S	1%	100%	-1%	0%
HCN	0%	10%	100%	0%

Catalytic bead sensitivity

Compound	LEL Relative Sensitivity[1]	LEL CF
Acetone	45	2.2
Ammonia	125	0.8
Benzene	40	2.5
Carbon monoxide	83	1.2
Cyclohexane	40	2.5
Ethanol	59	1.7
Ethyl acetate	45	2.2
Hydrogen	83	1.2
Isobutylene	67	1.5
Isopropanol	38	2.6
Leaded gasoline	42	2.4
Methane	100	1
Methanol	67	1.5
Methyl ethyl ketone	38	2.6
n-Butane	63	1.6
n-Heptane	37	2.7
n-Hexane	40	2.5
n-Octane	34	2.9
n-Pentane	50	2
Phosphine	385	0.26
Propane	63	1.6
Propene	59	1.7
Toluene	33	3
Turpentine	34	2.9

Note: Interior measurements peaked at 80% LEL, despite several deflagrations.

Tactical Consideration – Ventilation

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

UL Tests - Flashover

$\Delta t = 21$ s

Surprise, AZ - Deflagration

$\Delta t \approx 3$ min

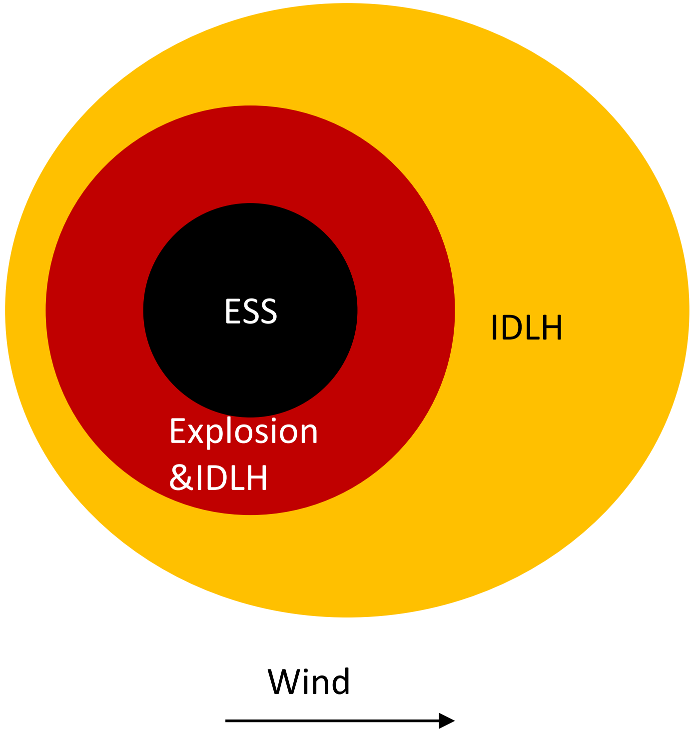
Tactical Consideration – Personal Protective Equipment

Gas meters and visual observations should be utilized for defining the "hot zone" or "exclusion zone" at ESS incidents.

Full structural PPE (Level D Ensemble) with full SCBA should be donned before performing size-up or operating within the hot zone.

Hazards during size-up:

1. CO concentrations above IDLH - SCBA
2. Deflagration, flash fire, flashover hazard – Level D



www.ulfirefightersafety.org

Questions?

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Thank you for your time.

The following information is provided if you would like to contact the speakers.

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Learn more about our battery safety science research and initiatives at:

Web: ul.org/focus-areas/battery-safety
Email: NFP.BatterySafety@ul.org

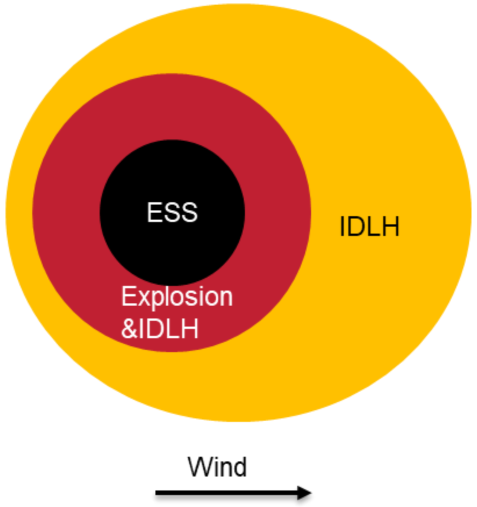
Tactical Considerations

1. **Using portable gas meters to evaluate interior conditions or the gases/vapors leaking from an ESS places firefighters in an explosion hazard area.**
2. **Portable gas meter measurement of battery gas is likely to be compromised by clogging and cross-sensitivity to battery gas mixture species.**
3. **A deflagration event is hard to predict, even with good quality gas concentration data.**
4. **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.**
5. **Additional tactical considerations and detail available in the full report:**

   https://ulfirefightersafety.org/research-projects/firefighter-line-of-duty-injuries-and-near-misses.html

Future Needs:

1. **Better understanding and ID of ESS deflagration precursors are needed for incident size-up.**
2. **Responding firefighters need access to ESS instrumentation data, particularly gas measurement, through a remote monitoring panel and to personnel who can aid in interpretation.**



International Fire Code (IFC)

IFC 2018 Section 1206

- Capacity and Spacing requirements for Battery Arrays
  - Exception when experimental testing indicates a fire involving one array will not propagate and will remain contained
- Listed in accordance with UL 1973 and/or UL 9540
- Established fire extinguishing and detection system requirements

Surprise, AZ has enacted local amendments to IFC 2018

International Fire Code (IFC)

IFC 2021 Section 1207

- Commissioning, decommissioning, operation and maintenance
- Commissioning required for new ESS, retrofit ESS, or ESS returning to service
- Approved commissioning plan required that includes a decommissioning plan
- Large scale fire test
- Shall be conducted in accordance with UL 9540A

NFPA 855

Effective August 25, 2019

- ESS Listed in accordance with UL 9540
- Requires Explosion Control Protection (NFPA 68 or NFPA 69)
- Requires Thermal Runaway Protection
- Requires Commissioning and Decommissioning Plan
- Annex C includes Fire Fighting Operations Considerations
  - Research is necessary for Additional Guidance

UL 9540 – Energy Storage Systems and Equipment

- Consensus Safety Standard for Energy Storage System (not individual components)
  - System includes an energy storage mechanism, power conversion equipment, and balance of plant equipment
- UL 9540A tests are required if battery arrays exceed 50 kWh

ESS Early Warning Communication Systems Task Group formed in April 2021