Lithium Ion Battery Energy Storage System Fires

March 2, 2016
Andrew Blum, P.E., CFEI, CVFI
R. Thomas Long Jr., P.E., CFEI
Overview

• Introduction
• Project History
• Lithium Ion Battery Background
• ESS Background
• ESS Fire Tests
• Key Findings
• Recommendations for Future Work
• Acknowledgements
Introduction
Energy storage is emerging as an integral component to a resilient and efficient electrical grid

In recent years, there has been a marked increase in the deployment of lithium ion (Li-ion) batteries in Energy Storage Systems (ESSs)

ESSs are being deployed in both high-rise structures and single- and multi-family residences

Local authorities having jurisdiction (AHJs) along with ESS integrators and installers are challenged by the lack of clear direction regarding the hazards of these installations
Public Concerns for Li-ion

• How are Li-ion ESSs different from other battery systems?
• Do Li-ion ESSs pose a greater fire hazard than traditional battery systems (i.e., lead acid, VRLA, etc.)?
• How can Li-ion fires be suppressed?
  – Water?
  – Dry chemical?
  – Clean agent?
• Can sprinkler systems control a Li-ion fire?
  – What are the sprinkler design criteria?
Public Concerns for Li-ion

• What are the best practices for firefighters to suppress Li-ion ESS fires?
  – Additional equipment necessary?
  – Different tactics/strategies required?
• Do Li-ion battery ESSs pose additional hazards, such as respiratory or electric shock to first responders compared to traditional fires?
• What are the cleanup/overhaul hazards?
Public Concerns for Li-ion

• What are the best practices for fire fighters to suppress Li-ion ESS fires?
  – Additional equipment necessary?
  – Different tactics/strategies required?
• Do Li-ion battery ESSs pose additional hazards, such as respiratory or electric shock to first responders compared to traditional fires?
• What are the cleanup/overhaul hazards?

A fire hazard assessment of Li-ion ESSs will provide a first step towards developing the technical basis necessary for the safe installation, protection, and emergency response to Li-ion ESS fires
Project History

• Partnership between:
  – NFPA
  – OEM

• Partnership goal:
  – This project is the first phase of an overall initiative with the goal to develop safe installation practices, fire protection guidance, and appropriate emergency response tactics for ESSs
The objective of this first phase project was to create a publically available technical document focusing on ESS fire safety through a preliminary fire hazard assessment of a Li-ion battery ESS.
Project Objective

- The objective of this first phase project was to create a publically available technical document focusing on ESS fire safety through a preliminary fire hazard assessment of a Li-ion battery ESS.

This project did not include an analysis or testing of fire detection systems, fire suppression systems, emergency response tactics, or overhaul operations related to Li-ion battery ESS fire scenarios.
Project Scope

• The scope of work included four primary tasks:

1. A literature review and gap analysis related to Li-ion battery ESSs
2. Development of a detailed full-scale fire testing plan to perform a preliminary assessment of Li-ion battery ESS fire hazards
3. Witnessing the implementation of the fire test plan through full-scale fire testing
4. A report of final results and a preliminary hazard assessment
Presentation Scope

• The scope of work included four primary tasks:

  1. A literature review and gap analysis related to Li-ion battery ESSs
  2. Development of a detailed full-scale fire testing plan to perform a preliminary assessment of Li-ion battery ESS fire hazards
  3. Witnessing the implementation of the fire test plan through full-scale fire testing
  4. A report of final results and a preliminary hazard assessment
Li-ion Battery Background
How do Li-ion Batteries Work?

- Charge / discharge through numerous cycles
- Positive ions transport across separator; electrons move externally across load
- Charging: lithium ions move from + to –
- Discharging: lithium ions move from – to +
How do Li-ion Batteries Work?

Electrolyte is commonly a non-aqueous organic solvent - Flammable
ESS Background
What is an Energy Storage System?

- An ESS stores energy for later use to supply the utility grid or local grids.
- The system collects from the grid, a solar installation, wind installation, or other source during a low demand time - typically during the day.
What is an Energy Storage System?

• The ESS uses the stored energy during peak hours - typically in the mornings and evenings

• An ESS allows for utilities, homeowners, or building owners to balance the supply and demand of electrical energy
Batteries Deployed in ESSs

- Li-ion beginning to dominant the market
- Other chemistries still being deployed

![Pie chart showing total megawatt percentage with Lithium ion at 41.79%, Lead acid at 28.20%, Sodium sulfur at 8.17%, Flow at 2.62%, and Other at 14.38%.]
Batteries Deployed in ESSs

- Variety of battery chemistries increases the complexity of developing a one size fits all safety protocol for ESSs
- This work focuses on a Li-ion battery ESS designed by a single manufacturer
ESSs in the Codes

- Codes that discuss ESSs or stationary battery systems include:
  - NFPA 70
  - NFPA 1
  - IBC
  - IFC
  - IRC
ESS Design

• Two ESSs generously donated from a manufacturer
• ESS is a 100 kWh unit designed for commercial installation
• ESS is modular, can be expanded to include multiple 100 kWh units to increase capacity
• Outdoor installations typically placed on a concrete pad
• Can be remote from the building or abutting
ESS Design
ESS Design
ESS Design

- Each pod has a low voltage - approximately 50-volt output
- Low voltage is converted to a 400-volt output by the ESS’s power electronic system
- Each pod is encased in a steel enclosure
Energy Storage Pod

- Each pod has a low voltage - approximately 50-volt output
- Low voltage is converted to a 400-volt output by the ESS’s power electronic system
- Each pod is encased in a steel enclosure
Energy Storage Pod
Battery Cells

- 3.6-volt, 2.4-amp hour cylindrical 18650 cells
- Approximately 450 cells per module
- Two modules per pod - 900 battery cells per pod
- Approximately 14,400 battery cells within ESS
Thermal Management System

• Front door houses equipment for the thermal management system to cool the pods
  – Coolant pumps
  – Reservoirs
  – Fans
  – Radiator
• 50% water / 50% ethylene glycol mixture pumped to each pod
• A refrigerant system using 400 grams of R134a further cools the ethylene glycol
Thermal Management System
Exhaust Manifold

• Energy pods connect to an exhaust manifold in the rear of the ESS that vents at the top
ESS Safety Features

• Listed to UL 1741 and IEC 62109 for converters used in power systems
• Listed to UL 1973 and for stationary battery systems
• UL 1973 requires:
  1. ESS cannot be an explosion hazard when attacked by an external fire source
  2. A single cell failure within an ESS battery pack will not result in a cascading thermal runaway of cells
ESS Specific Safety Features

• Because of the design of this ESS:
  – During charging or discharging, the battery cells are not at a high voltage and there is no electrical pathway from the live battery voltage to the exterior of a pod
  – Battery cells are encased in a steel enclosure of the pod and inside a steel cabinet
  – Pods are cooled by a thermal system
  – Exhaust manifold directs runaway gas out the top of ESS in the unlikely event of cell thermal runaway
ESS Specific Safety Features

- Clearances to combustibles include:
  - Six feet from the front of the ESS
  - Six inches from the sides and back of the ESS
  - Five feet from the top of the ESS
ESS Fire Test Setup
Fire Test Overview

• Location: Outdoors in open air
• Batteries at 100% State-of-Charge (SOC)
• Number of Tests: 2
  – 1 external ignition test and 1 internal ignition test
• Data Collected:
  – ESS cabinet pressures
  – Gas sampling of select products of combustion
  – Temperatures – inside ESS cabinet and external of ESS
  – Heat fluxes at various standoff distances from the ESS
  – Weather conditions, photography and HD videos
• Suppression: None – free burn
Fire Test Overview

- Location: Outdoors in open air
- Batteries at 100% State-of-Charge (SOC)
- Number of Tests: 2
  - 1 external ignition test and 1 internal ignition test
- Data Collected:
  - ESS cabinet pressures
  - Gas sampling of select products of combustion
  - Temperatures – inside ESS cabinet and external of ESS
  - Heat fluxes at various standoff distances from the ESS
  - Weather conditions, photography and HD videos
- Suppression: None – free burn
External Test: Instrumentation
External Test: Instrumentation

- Heat flux gauges at 6 feet, 3 feet, and 6 inches
External Test: Instrumentation

- Heat flux gauges at 6 feet, 3 feet and 6 inches
- Weather station
External Test: Instrumentation

- Heat flux gauges at 6 feet, 3 feet and 6 inches
- Weather station
- HD video cameras
- Still photography
External Test: Instrumentation

- Heat flux gauges at 6 feet, 3 feet and 6 inches
- Weather station
- HD video cameras
- Still photography
- Thermocouples on the exterior of the ESS cabinet
External Test: Instrumentation

- Heat flux gauges at 6 feet, 3 feet and 6 inches
- Weather station
- HD video cameras
- Still photography
- Thermocouples on the exterior of the ESS cabinet
- Thermocouples and pressure transducers inside the ESS cabinet
External Test: Instrumentation

- Heat flux gauges at 6 feet, 3 feet and 6 inches
- Weather station
- HD video cameras
- Still photography
- Thermocouples on the exterior of the ESS cabinet
- Thermocouples and pressure transducers inside the ESS cabinet
External Test: Instrumentation

- Heat flux gauges at 6 feet, 3 feet and 6 inches
- Weather station
- HD video cameras
- Still photography
- Thermocouples on the exterior of the ESS cabinet
- Thermocouples and pressure transducers inside the ESS cabinet
- Gas sampling at ESS exhaust vent
External Test: Instrumentation

• Heat flux gauges at 6 feet, 3 feet and 6 inches
• Weather station
• HD video cameras
• Still photography
• Thermocouples on the exterior of the ESS cabinet
• Thermocouples and pressure transducers inside the ESS cabinet
• Gas sampling at ESS exhaust vent
External Test: Instrumentation

- Heat flux gauges at 6 feet, 3 feet and 6 inches
- Weather station
- HD video cameras
- Still photography
- Thermocouples on the exterior of the ESS cabinet
- Thermocouples and pressure transducers inside the ESS cabinet
- Gas sampling at ESS exhaust vent
- Burner
External Test: Burner Arrangement

- Three tube burners
- All connected to burner gas train
- Produced approximately 400 kW
- Positioned to the side of the ESS
External Test: Burner Arrangement
Burner Arrangement
External Test: Protocol

- Turn on instrumentation
- Ignite burner
- Monitor until approximately 20 thermal runaways audibly confirmed
- Turn off burners; allow ESS to burn freely
- Monitor until the fire burns itself out or self-extinguishes
External Test Video

00:00:21.98
External Test Result Summary

- 400 kW burner impinging directly on the outside of the ESS cabinet can induce thermal runaway of the cells inside
- 35 minutes to smoke
- 45 minutes to first audible thermal runaway
- 47 minutes to first flames
- Flames observed at exhaust vent and out ESS front door
- Temperatures inside high – greater than 2,000 °F
- External surface temperatures much lower – 150-450 °F
- HF (excess of 100 ppm) and CO (50 ppm) detected
- CH₄ and CL₂ not detected
- No violent projectiles, explosions, or bursts observed
- Post test: all 16 pods and the internal electronics damaged
Internal Test: Instrumentation
Internal Test: Instrumentation

- Weather station
- HD video cameras
- Still photography
- Thermocouples on the exterior of the ESS cabinet
- Thermocouples and pressure transducers inside the ESS cabinet
- Gas sampling at ESS exhaust vent
- Heater cartridges
Internal Test: Heater Arrangement

- Six (6) 1/8-inch diameter 25-watt cartridge heaters
- Installed in Pod 6 between battery cells
Internal Test: Protocol

- Turn on instrumentation
- Power up heater cartridges
- Monitor until approximately 20 thermal runaways audibly confirmed
- Turn off heaters; allow ESS to progress freely
- Monitor until the event is over
Internal Test Video
Internal Test Result Summary

- 6 heater cartridges inside a pod can induce thermal runaway of the cells adjacent to the heaters
- Thermal runaway did not spread outside the initiator pod
- 13 minutes to first audible thermal runaway
- 15 minutes to smoke
- No flames, violent projectiles, explosions, or bursts observed
- Temperatures inside initiator pod high – greater than 2,000 °F
- Temperatures at other pods lower - 80-180 °F
- External surface temperatures much lower – 60-70 °F
- HF (peak 26 ppm), CO (excess of 2,000 ppm), and CH₄ detected, CL₂ not detected
- Post test: initiator pod damaged, remaining pods functional
Key Findings
Key Findings

- Based on the results of these two tests:
  - Large (400 kW) external fire impinging directly on the ESS for 60 minutes required to achieve self-sustaining thermal runaway
  - Multiple (6) heater cartridges heating adjacent cells simultaneously did not result in thermal runaway of the ESS outside of the initiator pod
  - In the external fire exposure, flames were observed from the exhaust vent and front door – clearance distances to nearby combustibles should be evaluated at install
  - Flame spread hazards from an internal failure are negligible, not withstanding a wide spread system failure
Key Findings

- Based on the results of these two tests:
  - HF detected at levels greater than OSHA permitted levels in both tests – recommend first responders don typical SCBA when responding to an ESS fire
  - CO and CH$_4$ detected in significant quantities in the internal failure scenario – if the ESS is to be installed indoors, additional ventilation of the ESS of the room may be required
Recommendations
Recommendations for Future Work

- Research studying first responder tactics and suppression for Li-ion ESS fires
- Research studying post fire incident response and recovery (i.e., overhaul) procedures
- Heat release rate testing of ESSs
- Testing to study what effect, if any, severe wind conditions may have on the spread of flames from one ESS to another or to other nearby combustibles
- Testing to study what effect, if any, an array of ESSs installed within close proximity to one another would have on the spread of flames from one ESS to another or to other nearby combustibles
Recommendations for Future Work

• Testing of ESSs inside a compartment to study what effect, if any, a room will have on the fire behavior and potential toxic gas hazards within an enclosure
• Testing to study different ESS manufacturers’ products, battery chemistries, and/or sizes under similar conditions to verify the performance of other ESSs under these fire conditions
Acknowledgements
Acknowledgements

• Our thanks to:
  – Kathleen Almand, Executive Director, FPRF
  – Daniel Gorham, Research Project Manager, FPRF
  – FPRF panel
  – Exponent team

• Special thanks to the manufacturer who generously donated the ESSs, the test facility and their time – we could not have made this happen without you!
Questions?

Andrew Blum, P.E., CFEI, CVFI
Managing Engineer
Thermal Sciences
Exponent, Inc.
678-412-4816
ablum@exponent.com

R. Thomas Long Jr., P.E., CFEI
Principal Engineer
Thermal Sciences
Exponent, Inc.
301-291-2501
longrt@exponent.com