AGENDA

1 Protecting Against Failure Events
2 Fire Safety Approach
3 UL 9540A
   › Objectives of 9450A – What does it do?
   › Cell Level Testing
   › Module Level Testing
   › Unit Level Testing
   › Installation Level Testing
PROTECTING AGAINST FAILURE EVENTS

- Mitsubishi Materials Corporation (Japan 2011)
  – 2 MW Sodium Sulfur system, thermal runaway

- Kahuku Wind farm (USA, 2012)
  – 15 MW, Advanced lead acid battery

- The Landing Mall (USA, 2013)
  – 50 kW Li-ion ESS system in a shopping mall, thermal runaway

- Boeing 787 Dreamliner (USA, 2013)
  – Li-ion battery, thermal runaway

- Engie Electrabel (Belgium, 2017)
  – 20 MW Li-ion facility, thermal runaway
FIRE SAFETY APPROACH

**Installation Codes**
- **NEC**: National Electric Code (NFPA 70)
- **NFPA 855**: Standard for the Installation of Stationary Energy Storage Systems
- **ICC**: The International Fire Code, International Residential Code

**Battery Safety Certification**
- **UL 1642**: Lithium Batteries
- **UL 1973**: Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications
- **UL 9540**: Energy Storage Systems and Equipment

**Testing for Performance**
LAYERS OF FIRE PROTECTION

Prevention

Layers of Protection → Preventative Measures

Mitigation

Fire Growth Control

Life Safety and Property Protection

Fire Mitigation

Mitigation Methods →

• Tested and certified components

• Integrated fire protection system
• Smoke and fire detection

• Automatic sprinklers
• Fire containment
• Fire resistance
• Designed safe zones

• Evacuation
• Emergency service response

Precipitating Hazard

- Internal short circuit
- Mechanical abuse
- External fire

Internal Heating

Separator Failure
- Chemical Reactions
  - Cathode
  - Anode
  - Electrolyte

Cell Failure

Thermal Runaway

Hazard Propagation

- Other ESS units in proximity
- Cabling other ESS components
- Additional combustible materials

Hazard Containment

- Fire spread to adjoining rooms
- Deflagration, detonation

Fire Impact

- Re-ignition
- Injuries/fatalities
- Property loss

Preventive measures

- Tested and certified components

Prevention

Layers of Protection

- Thermal runaway

Mitigation

- Hazard propagation

Life Safety and Property Protection

- Hazard containment

Fire Mitigation

- Fire impact

Evacuation

Emergency service response

Other ESS units in proximity

Cabling, other ESS components

Additional combustible materials

Fire spread to adjoining rooms

Deflagration, detonation

Re-ignition

Injuries/fatalities

Property loss

Evacuation

Emergency service response
**LAYERS OF FIRE PROTECTION**

**Prevention**
- **Layers of Protection** → Preventative Measures
  - Internal Heating
    - Separator Failure
    - Chemical Reactions
      - Cathode
      - Anode
      - Electrolyte
  - Cell Failure

**Mitigation**
- **Fire Growth Control**
- **Life Safety and Property Protection**
- **Fire Mitigation**

**Mitigation Methods**
- Tested and certified components
- Integrated fire protection system
- Automatic sprinklers
- Evacuation

**Precipitating Hazard**
- Internal short circuit
- Mechanical abuse
- External fire

**Enabling Hazard**
- Re-ignition
- Injuries/fatalities
- Property loss
LAYERS OF FIRE PROTECTION

Prevention

Layers of Protection → Preventative Measures

Internal Heating
- Precipitating Hazard
  - Internal short circuit
  - Mechanical abuse
  - External fire
- Chemical reactions
  - Cathode
  - Anode
  - Electrolyte
- Cell Failure
- Mitigation Methods
  - Tested and certified components

Mitigation

Fire Growth Control
- Hazard Propagation
  - Other ESS units in proximity
  - Cabling other ESS components
  - Additional combustible materials
- Hazard Containment
  - Fire spread to adjoining rooms
  - Deflagration, detonation
- Fire Impact
  - Re-ignition
  - Injuries/fatalities
  - Property loss

Life Safety and Property Protection
- Automatic sprinklers
- Fire containment
- Fire resistance
- Designed safe zones
- Evacuation
- Emergency service response

Evacuation
- Other ESS units in proximity
- Cabling, other ESS components
- Additional combustible materials
- Fire spread to adjoining rooms
- Deflagration, detonation
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
UL 9540A ADDRESSES KEY FIRE SAFETY CONCERNS

BESS Installation Parameters
• Enables determination of separation distances between units to minimize unit-to-unit fire propagation
• Enables determination of separation distances between units and enclosure walls
• Enables determination of potential of fire spread to overhead cabling

Installation Ventilation Requirements
• Quantifies deflagration potential
• Quantifies heat generation

Fire Protection (Integral or External)
• Enables the development of fire protection strategies based on measurement data
  • Fire hazards
  • Explosion hazards
  • Tenability hazards

Fire Service Strategy and Tactics
• Characterizes magnitude of potential fire event
• Documents re-ignitions within a BESS unit under test
• Documents gases generated
• Whether cell can exhibit thermal runaway
• Thermal runaway characteristics
• Gas composition (flammability)

• Propensity for propagation of thermal runaway
• Heat and gas release rates (severity/duration)
• Flaming/deflagration hazards

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

• Effectiveness of fire protection system(s)
• Heat and gas release rates (severity/duration)
• Deflagration hazards
• Re-ignition hazards
UL 9540A – USE IN INDUSTRY

Energy Storage System

UL 9540A Test Method

Fire Test Report

Manufacturer/Integrator/Sponsor

Fire Protection Consultant

Insurance Industry  Building Owner  Other AHJ  Fire Department
CELL LEVEL TESTING

Purpose:
1. Cell thermal runaway methodology, instrumentation
2. Thermal runaway test parameters
3. Cell surface temp at venting and thermal runaway
4. Gas generation/composition; characterize gas flammability hazards (LFL)
CELL LEVEL MOCKUP TEST

Cell Level Testing Apparatus

<table>
<thead>
<tr>
<th>Gas</th>
<th>Composition (Vol %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>36.2</td>
</tr>
<tr>
<td>CO₂</td>
<td>22.1</td>
</tr>
<tr>
<td>H₂</td>
<td>31.7</td>
</tr>
<tr>
<td>Hydrocarbons</td>
<td>~10%</td>
</tr>
</tbody>
</table>

Lower Flammability Limit (LFL) = 8.5%
Burning Velocity ($S_u$): 35 cm/sec
Volume = 70 L
$P_{max}$ = 91 psig
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:
  • Gas composition and volumes
    • Hydrocarbons, $\text{H}_2$, THC, $\text{CO}/\text{CO}_2$, $\text{O}_2$, Halogens, etc.
Example of generic li-ion propagation of thermal runaway.
<table>
<thead>
<tr>
<th>Gas Component</th>
<th>Gas Type</th>
<th>Volume Released Pre-Flaming (Liters)</th>
<th>Volume Released Flaming (Liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene</td>
<td>Hydrocarbons</td>
<td>3.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Ethylene</td>
<td>Hydrocarbons</td>
<td>39.4</td>
<td>10.5</td>
</tr>
<tr>
<td>Methane</td>
<td>Hydrocarbons</td>
<td>72.4</td>
<td>48.7</td>
</tr>
<tr>
<td>Methanol</td>
<td>Hydrocarbons</td>
<td>1.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Propane</td>
<td>Hydrocarbons</td>
<td>39.2</td>
<td>21.3</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>Hydrocarbons</td>
<td>2.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Total Hydrocarbons (% Propane)</td>
<td>Hydrocarbons</td>
<td>276.4</td>
<td>82.3</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>Carbon Containing</td>
<td>197.4</td>
<td>2312.0</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>Carbon Containing</td>
<td>513.6</td>
<td>254.8</td>
</tr>
<tr>
<td>Hydrogen Bromide</td>
<td>Hydrogen Halides</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>Hydrogen Chloride</td>
<td>Hydrogen Halides</td>
<td>0.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Hydrogen Fluoride</td>
<td>Hydrogen Halides</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Ammonia</td>
<td>Nitrogen Containing</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Hydrogen Cyanide</td>
<td>Nitrogen Containing</td>
<td>1.3</td>
<td>2.6</td>
</tr>
</tbody>
</table>
UNIT LEVEL TESTING

Purpose:
1. Document thermal runaway progression within a BESS unit;
2. Document if flaming occurs outside the BESS unit;
3. Measure heat and gas generation rates;
4. Measure surface temperatures and heat fluxes in target BESS units; and
5. Measure surface temperatures and heat fluxes on surrounding walls.

Important Data
- Module to module thermal runaway propagation in Initiating BESS
- Heat release rate
- Gas composition and volume
- Wall temperatures and heat fluxes
- Target BESS temperatures and heat fluxes
- Deflagration hazards
- Re-ignition (on-going thermal runaway)
UNIT LEVEL MOCKUP TEST
UNIT LEVEL MOCKUP TEST – Heat Release Rate

![Heat Release Rate Graph](image-url)
INSTALLATION LEVEL TESTING (IF REQUIRED)

Methods:
1. Ceiling mounted automatic sprinklers; or
2. Designed Fire Protection Plan (open to manufacturer’s design).
UNIT/INSTALLATION LEVEL PERFORMANCE ASSESSMENT

IFC and NFPA 855 Large Scale Test Requirements

1. No fire spread to surrounding equipment
2. No array to array propagation
3. No fire spread through fire resistance rated barrier
4. Explosions are contained
5. Explosions cannot injure occupants/first responders
6. Toxic gases shall not exceed IDLH
7. Gas released will not exceed 25% of LFL in installation

UL 9540A Performance Data

(1,2) Observations of flaming outside the initiating BESS unit (if flaming observed, proceed with installation level test);
(2) Report whether maximum temperatures in target BESS units are less than the vent temperature measured in the cell level test;
(1,3) With regard to combustible wall construction, report whether surface wall temperature rise above ambient is more than 97 °C (175 °F); (UL 103, UL 1978, UL 8782)
(3, 4, 5) Observations with regard to explosion hazard(s);
(6) Gas generation and composition data;
(1) Observation of fire spread in the flame indicator; (Installation Level);
(3, 7) Observation of flaming outside the test room (Installation Level)
BESS FIRE PROPAGATION ASSESSMENT PROCESS

Cell Level Test [1]
- Construction review
- Thermal runaway method

Module Level Test [2]
- Construction review

Unit Level Test [3]
- Separation distances (Target BESS, walls)

Thermal runaway?
- Rapid temperature increase
  - Flaming
  - Gas venting
- Internal short circuit

Cell Vent Gas Flammable?
- NO

Cell Vent Gas Flammable?
- YES

Module Level Test Results
- Heat release rate
- Smoke release rate
- Gases generation volume/rates
- Explosion hazard

Mode of thermal runaway contained by module design?
- YES
- NO

Unit Level Test Results
- Target BESS max. temperature ($T_{\text{target}}$)
- Wall max. temperature ($T_{\text{wall}}$)
- Heat release rates
- Smoke release rates
- Gases generation rates
- Explosion hazards
- Reignitions

Target BESS $T_{\text{target}}$ > Wall $T_{\text{wall}}$ OR
- Wall $T_{\text{wall}}$ > 95°C + $T_{\text{ambient}}$
- OR
- Flaming outside the unit? OR
- Observed explosion?

Fire propagation hazard not demonstrated by test.
Deflagration hazard not demonstrated by test.

NOTES:
[1] Cell shall be certified to UL 1642/UL 1973
[2] Module shall be certified to UL 1973
[3] Unit shall be certified to UL 9540
[4] Max. wall temperature criteria applies for combustible wall construction only
[5] Use procedure in Deflagration Analysis
[6] Review of fire protection plan and code requirements may necessitate review by a licensed fire protection engineer.

Conduct Installation Level Test
With Installed Fire Protection Plan [6]
BESS FIRE PROPAGATION ASSESSMENT PROCESS

Draft BESS Fire Propagation Assessment Flow Chart Using UL 9540A – Installation Level Test

Conduct Installation Level Test

- Flaming outside room?; OR
- Flame propagation on overhead cabling?; OR
- Explosion hazard?; OR
- Target > Vent
- Wall > 97°C + Ambient [2]

Develop Fire Protection Plan Based Upon Test Data [1]
- Fire mitigation
- Deflagration mitigation

Issues to Consider
A. Installation Space
   - Combustible vs. Non combustible construction
   - Size and layout
   - Location (roof, indoor vs outdoor, floor for indoors)
B. Separation distances
   - Spacing between BESS
   - Spacing to walls
C. Combustibles
   - Overhead cabling
   - Other combustibles
D. Active fire mitigation systems
   - Detection and alarm
   - Suppression system design
   - Deflagration prevention system design
   - Deflagration protection system design

Many of these issues may be analyzed using vetted fire analysis tools including enclosure fire modeling by a licensed fire protection engineer.

Notes:
[1] Review of fire protection and deflagration plan may necessitate inclusion of a licensed fire protection engineer.
[3] Applicability of results to actual installation and code requirements may necessitate review by a licensed fire protection engineer.

Review NFPA 855 and IFC codes for installation requirements [3]

WILL Fire Protection Plan for this BESS system apply to actual installations [3]

NO

Review Fire Protection Plan; See issues to consider

YES

Develop Fire Protection Plan

Fire propagation hazard not demonstrated by test data.
Deflagration hazard not demonstrated by test data.

WILL Fire Protection Plan for this BESS system apply to actual installations [3]

NO

Review Fire Protection Plan; See issues to consider

YES

Will Fire Protection Plan for this BESS system apply to actual installations [3]
BESS FIRE PROPAGATION ASSESSMENT PROCESS

Definitions:
- $V_{\text{flam}}$: Volume or volume flow rate of flammable gas
- $V_{\text{enc}}$: Volume of enclosure or ventilation rate of enclosure
- $X_{\text{pv}}$: Flammable mix partial volume fraction
- LFL: Lower flammability limit
- $P_{\text{pv}}$: Partial volume pressure
- $P_{\text{dam}}$: Maximum allowable pressure

Use flammable gas mixture from UL 9540A Cell/Module/Unit Test Data on
- Composition and Volume
- LFL
- Stoichiometric concentrations
- Laminar burning velocity
- $P_{\text{max}}$

1. Calculate $V_{\text{flam}}/V_{\text{enc}}$ and $X_{\text{pv}}$ for stoichiometric mixture
2. Determine enclosure damage threshold pressure, $P_{\text{dam}}$
3. Increase in ventilation rate to reduce flammable gas accumulation

BESS enclosure volume and ventilation rate

If $V_{\text{flam}}/V_{\text{enc}} < 0.25 \times \text{LFL}$
- Satisfies NFPA 855
- Perform hazard analysis to determine if deflagration hazard is still present

Is $P_{\text{pv}} < P_{\text{dam}}$?
- Yes
- Deflagration suppression system or another method such as enclosure inerting per NFPA 69
- Deflagration Venting Acceptable per NFPA 68
- No explosion hazard per fundamental approach

Choose deflagration protection method

NOTES
[1] $V_{\text{flam}}$ and $V_{\text{enc}}$ can be either volumes or volumetric flow rates
[2] $P_{\text{dam}}$ depends upon enclosure construction and may require structure engineering analysis
CONTACT US

Technical Questions
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