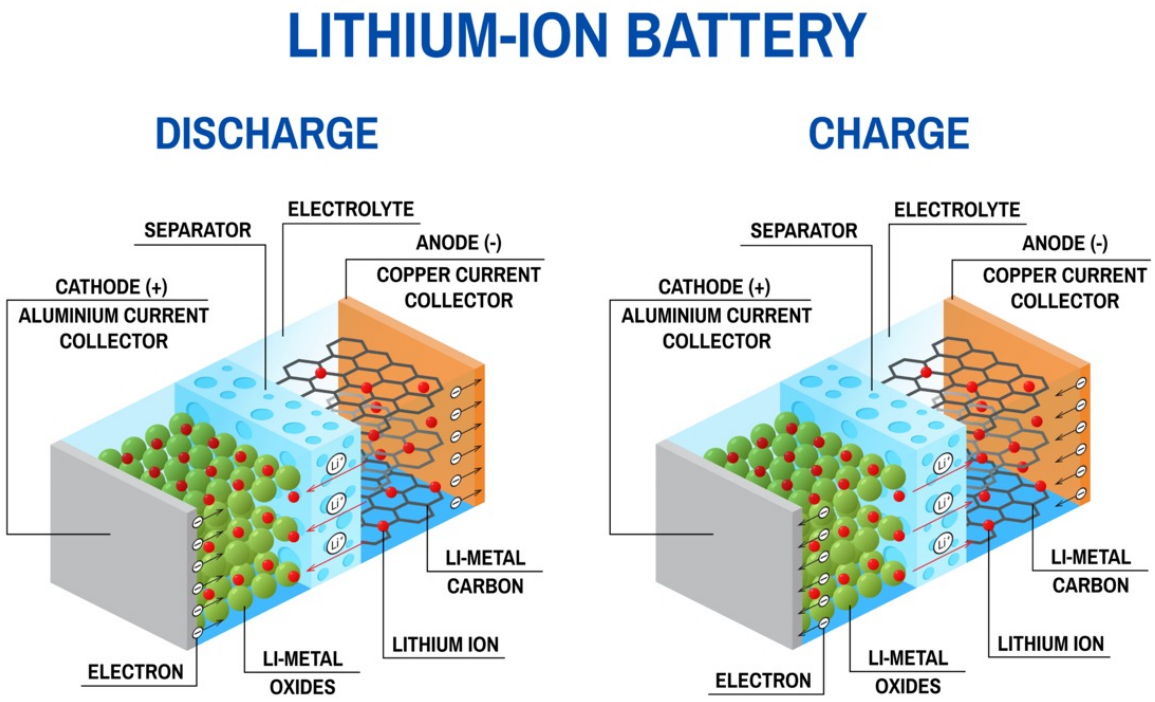
HOW DO LITHIUM-ION BATTERIES WORK?



FIRE RESEARCH AND DEVELOPMENT TECHNICAL REPORT

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

April 12, 2021

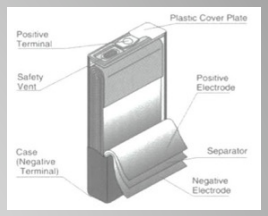
Adam Barowy
Alex Klieger
Jack Regan
Mark McKinnon, Ph.D., P.E.

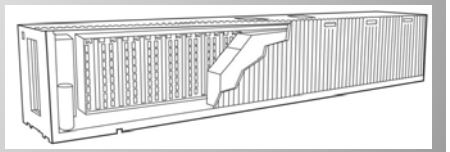
Figure 85 – Deflagration images from Test 2.

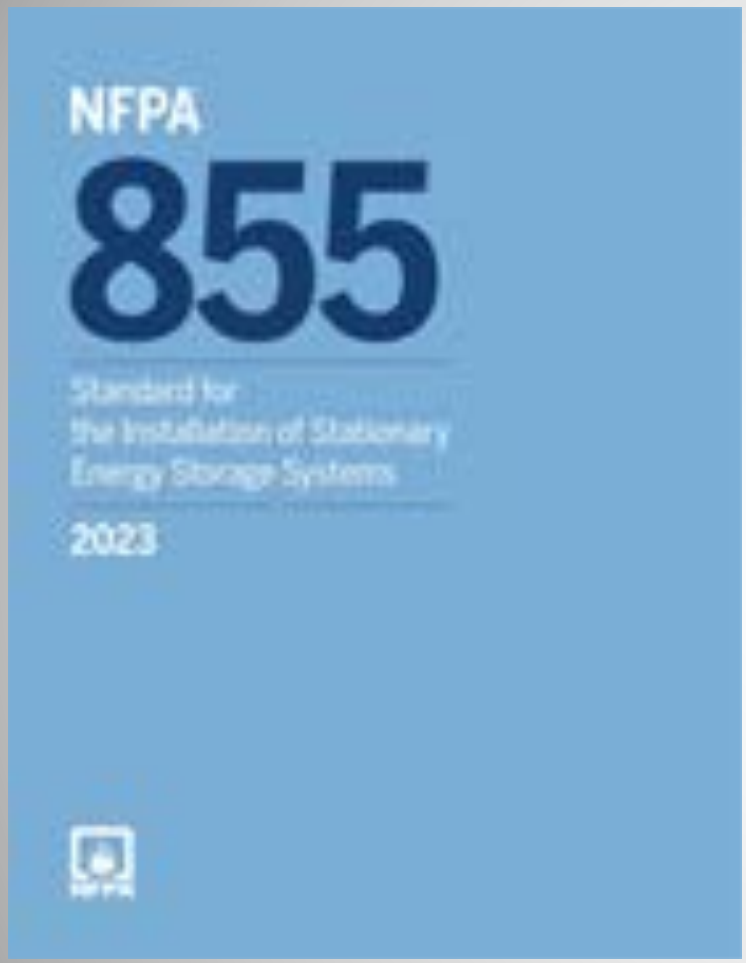
Table E1 – Test Levels in UL 9540A (4th Edition).

Test level	Data developed
Cell	a. Methodology required to initiate thermal runaway for testing. b. Cell surface temperature at onset of gas venting and thermal runaway. c. Gas composition, volume, and explosibility parameters.
Module	a. Number of initiating cells required for propagation of thermal runaway. b. Heat, smoke, and flammable gas release rates and total release quantity. c. Observations of external flame extension. d. Observations of deflagration and debris hazards.
Unit	a. Extent of thermal runaway propagation. b. Heat, smoke, and flammable gas release rates and total release quantity. c. Observations of external flame extension, deflagration, and debris hazards, and re-ignition hazards. d. Thermal exposure (temperature on adjacent walls, and target units; heat flux to adjacent walls, target units, and egress pathways)
Installation	a. Evaluation of fire protection method. b. Fire growth control. c. Extent of thermal runaway propagation. d. Design features related to containment of thermal runaway gases and heat that create an explosion hazard. e. Deflagration protection system. f. Egress protection. g. Thermal exposure to adjacent surfaces. h. Observations of flaming outside the installation i. Observations of reignition. j. Deflagration and debris.

This report presents the results of three installation level tests conducted between June 19 and July 9







1.1* Scope.

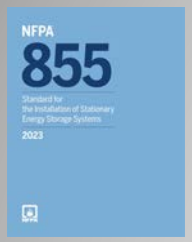
This standard applies to the design, construction, installation, commissioning, operation, maintenance, and decommissioning of stationary energy storage systems (ESS), including mobile and portable ESS installed in a stationary situation and the storage of lithium metal or lithium-ion batteries.

1.3* Application.

This standard shall apply to ESS installations exceeding the values shown in **Table 1.3** and the storage of lithium metal or lithium-ion batteries.

Table 1.3 Threshold Quantities per Each Fire Area or Outdoor Installation

ESS Technology	Aggregate Capacity[a] kWh	MJ
Battery ESS		
Lead-acid, all types	70	252
Ni-Cad, Ni-MH, and Ni-Zn	70	252
Lithium-ion, all types	20	72
Sodium nickel chloride	20 (70[b])	72 (252[b])
Flow batteries[c]	20	72
Other battery technologies	10	36
Batteries in one- and two-family dwellings and townhouse units	1	3.6
Capacitor ESS		
Electrochemical double layer capacitors[d]	3	10.8
Other ESS		
All other ESS	70	252
Flywheel ESS (FESS)	0.5	1.8



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4.3 Emergency Planning and Training.

4.4 Hazard Mitigation Analysis (HMA).

4.5 Combustible Storage.

4.6 Equipment.

4.7 Installation.

4.8 Smoke and Fire Detection.

4.9 Fire Control and Suppression.

4.10 Mobile ESS Equipment and Operations.

4.2 Construction Documents.

4.2.1.3

The following test data, evaluation information, and calculations shall be provided in addition to the plans and specifications in **4.2.1.1** where required elsewhere in this standard:

(1) Fire and explosion testing data in accordance with **9.1.5**

(2) Hazard mitigation analysis (HMA) in accordance with Section **4.4**

(3) Calculations or modeling data to determine compliance with NFPA 68 and NFPA 69 in accordance with **9.6.5.6.3**

(4) Other test data, evaluation information, or calculations as required elsewhere in this standard

4.2.1.4

If modeling data is provided, validation of the modeling results shall also be included.

4.3 Emergency Planning and Training.

Δ **4.3.1* General.**

For ESS installations that exceed the maximum stored energy limits of **Table 9.4.1**, emergency planning and training shall be provided by the owner of the ESS or their authorized representative so that ESS facility operations and maintenance personnel and emergency responders can address foreseeable hazards associated with the on-site systems.

4.3.2 Facility Staff Planning and Training.

For ESS installations that exceed the maximum stored energy limits of **Table 9.4.1**, an emergency operations plan and associated training shall be established, maintained, and conducted by ESS facility operations and maintenance personnel.

N

Table 9.4.1 Maximum Stored Energy

ESS Type	Maximum Stored Energy[a] (kWh)
Lead-acid batteries, all types	Unlimited
Nickel batteries[b]	Unlimited
Lithium-ion batteries, all types	600
Sodium nickel chloride batteries	600
Flow batteries[c]	600
Other battery technologies	200
Storage capacitors	20

[a]For ratings in amp-hrs, kWh should equal maximum rated voltage multiplied by amp-hr rating divided by 1000.

[b]Nickel battery technologies include nickel cadmium (Ni-Cad), nickel metal hydride (Ni-MH), and nickel zinc (Ni-Zn).

[c]Includes vanadium, zinc-bromine, polysulfide, bromide, and other flowing electrolyte-type technologies.

4.3.2.1.4

The emergency operations plan shall include the following:

(1) Procedures for safe shutdown, de-energizing, or isolation of equipment and systems under emergency conditions to reduce the risk of fire, electric shock, and personal injuries, and for safe start-up following cessation of emergency conditions

(2) Procedures for inspection and testing of associated alarms, interlocks, and controls

(3)* Procedures to be followed in response to notifications of system alarms or out-of-range conditions that could signify potentially dangerous conditions, including shutting down equipment, summoning service or repair personnel, and providing agreed-upon notification to fire department personnel, if required

(4)* Emergency procedures to be followed in case of fire, explosion, release of liquids or vapors, damage to critical moving parts, or other potentially dangerous conditions

(5) Response considerations similar to a safety data sheet (SDS) that will address response safety concerns and extinguishment when an SDS is not required

(6) Procedures for dealing with ESS equipment damaged in a fire or other emergency event, including contact information for personnel qualified to safely remove damaged ESS equipment from the facility

(7) Other procedures as determined necessary by the AHJ to provide for the safety of occupants and emergency responders

(8) Procedures and schedules for conducting drills of these procedures

Annex G — Guide for Suppression and Safety of Lithium-Ion Battery (LIB) Energy Storage Systems (ESS)

This annex is not a part of the requirements of this NFPA document but is included for informational purposes only.

G.1 General.

G.2 Fundamentals of Hazards Associated with LIB-Based ESS.

G.3 Hazards and Risks Posed by ESS with Hazard Mitigation Analysis (HMA) and Fire Risk Assessment (FRA).

G.4 Known Failure Modes and Their Associated Consequences and Mitigation Approaches (Bowtie Analysis).

G.5 Application of LIB-Based ESS and How Location Within a Building Impacts the Hazard Analysis. (Reserved)

G.6 Fire Protections Systems and Mitigation Strategies, Including System Goal, Water Duration, and Water Application Strategies.

G.7 Fire and Flammable Gas Detection, Including the Location, Type, and Purpose for Available Technologies.

G.8 Flammable Gas, Deflagration Hazard Studies, and Use of NFPA 68 and NFPA 69 for Lithium-Ion Batteries. (Reserved)

G.9 LIB Construction and Installation Guidance.

G.10 Guidance on Inspection and Maintenance for Installed LIB Fire Protection Systems.

G.11 Guidance on Developing a First Responder Plan for LIB-Based ESS Installations.

4.4 Hazard Mitigation Analysis (HMA).

Δ **4.4.1***

A hazard mitigation analysis shall be provided to the AHJ for review and approval where any of the following conditions are present:

(1) Technologies not specifically addressed in **Table 1.3** are provided

(2) More than one ESS technology is provided in a single fire area where adverse interaction between the technologies is possible

(3) Where allowed as a basis for increasing maximum stored energy as specified in **9.4.1.1** and **9.4.1.2**

(4) Where required by the AHJ to address a potential hazard with an ESS installation that is not addressed by existing requirements

(5) Where required for existing lithium-ion ESS systems that are not UL 9540 listed in accordance with **9.2.2.1**

(6) Where required for outdoor lithium-ion battery ESS systems in accordance with **9.5.2.1**

Chapter 9 — Electrochemical Energy Storage Systems

N 9.5 Location and Applications.

N **9.5.2 Outdoor Installations.**

N **9.5.2.1 HMA.**

A HMA shall be required for lithium-ion ESS that exceed 600 kWh (2,160 MJ) for outdoor ESS installations, ESS installations in open parking garages and on rooftops of buildings, and mobile ESS equipment.

Δ **4.4.2 Failure Modes.**

N **4.4.2.1***

The hazard mitigation analysis shall evaluate the consequences of the following failure modes and others deemed necessary by the AHJ:

(1) A thermal runaway or mechanical failure condition in a single ESS unit

(2) Failure of an energy storage management system or protection system that is not covered by the product listing failure modes and effects analysis (FMEA)

(3) Failure of a required protection system including, but not limited to, ventilation (HVAC), exhaust ventilation, smoke detection, fire detection, fire suppression, or gas detection

4.4.2.2

Only single failure modes shall be considered for each mode given in **4.4.2.1**.

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G.11 Guidance on Developing a First Responder Plan for LIB-Based ESS Installations.

N **9.1.5 Fire and Explosion Testing.**

N **9.1.5.1***

Where required elsewhere in this standard, fire and explosion testing in accordance with **9.1.5** shall be conducted on a representative ESS in accordance with UL 9540A or equivalent test standard.

Δ A.9.1.5.1

A UL 9540A test or equivalent test should evaluate the fire characteristics of the composition of gases generated at cell level, module level, and unit and installation levels for an indoor installation of an ESS that undergoes thermal runaway, such as what might occur due to a fault, physical damage, or exposure hazard. The evaluation of the fire characteristics during fire vent testing at the unit level and indoor installation level testing should document whether the fire event propagates to the neighboring ESS units and include radiant heat flux measurements at enclosing wall surfaces and at various distances from the ESS being tested at the unit level. The data generated by the fire and explosion testing is intended to be used by manufacturers, system designers, and AHJs to determine the need for fire and explosion protection required for an ESS installation.

N **9.1.5.2* Test Reports.**

N **9.1.5.2.1**

The complete test report and its supporting data shall be provided to the AHJ for review and approval.

N **9.1.5.2.2**

The test report shall be accompanied by a supplemental report prepared by a registered design professional with expertise in fire protection engineering that provides interpretation of the test data in relation to the installation requirements for the ESS.