

Guidelines for Failure Mode Testing of Battery Energy Storage Systems

Full-Scale Test Method for Evaluation of Fire Propagation and Deflagration Mitigation in Single and Multi-Level Systems

Revision 0B

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List of Acronyms

AHJ	Authority Having Jurisdiction
BESS	Battery Energy Storage System
BMS	Battery Management System
DH	Deflagration Hazard
DT	Deflagration Testing
DUT	Device Under Test
EODV	End of Discharge Voltage
FID	Flame Ionization Detector
FPT	Flaming Propagation Testing
GB	Gas Buildup
HFG	Heat Flux Gauge
HRR	Heat Release Rate
HVAC	Heating, Ventilation, and Air Conditioning
LEL	Lower Explosive Limit
LFL	Lower Flammability Limit
LFP	Lithium Iron Phosphate
NDIR	Non-Dispersive Infrared
NMC	Nickel Manganese Cobalt
PCS	Power Conditioning System
SOC	State-of-Charge
VT	Ventilation Testing
WCFMT	Worst-Case Failure Mode Testing

1 Introduction/Motivation

All battery energy storage systems (BESS) present fire and explosion hazards associated with their failures. Standardized test methodologies, principally UL 9540A [1], exist in an attempt to assess these hazards. UL 9540A is designed to evaluate BESS safety at several levels of system construction: specifically at the individual cell level, module level (groupings of cells), unit level (groupings of modules), and installation level (grouping of units paired with installed mitigation systems).

At the unit level, UL 9540A testing involves initiating thermal runaway in one or more cells and observing the resulting effects. In some cases, there is limited cell-to-cell propagation. In other cases, flaming combustion is observed, and entire units are consumed. BESS system design plays a role in which outcome is observed, but randomness does as well; manufacturers may repeatedly test the same BESS design to UL 9540A methods, and achieve significantly different results each time.

These UL 9540A results inform the decisions of designers, developers, and Authorities Having Jurisdiction (AHJs) on BESS products and installations. It is clear that UL 9540A test methods do not consistently produce worst-case failures in systems under test, and therefore may not fully capture the hazard associated with BESS product designs or provide sufficient detail to make decisions regarding site layout. As a result, there is a need for a method which is able to consistently evaluate worst-case BESS hazards, so that designers, developers, and AHJs can make better-informed decisions.

This document describes such a method, developed and informed by extensive large-scale BESS testing experience. The methodology, which consists of a variety of large-scale gas dispersion, deflagration, and fire tests, is able to consistently induce worst-case failure modes - both deflagration and flaming propagation - in systems under test. As a result, this approach can provide increased confidence that the hazards associated with tested systems are more completely characterized.

The purpose of this document is to describe the overall methodology and provide general guidance on the tests contained within. The method is intended to supplement UL 9540A or equivalent standards. UL 9540A methods are valuable for evaluating the potential hazard associated with typical/usual failures, while this method expands the understanding of hazards to ensure that potential impacts can be appropriately accounted for to personnel and property.

2 Approach

The method, herein referred to as Worst-Case Failure Mode Testing (WCFMT), is based on a full exploration of two separate failure modes: (1) gas buildup/deflagration and (2) flaming propagation. By investigating each separately, a more complete understanding of the hazards associated with a BESS design can be established. When a BESS unit fails, one of two conditions is true: either flaming combustion is present, or it is not. Different hazards are presented in each case, both of which are important to understand. As indicated previously, it is not clear which scenario will occur during a failure, and thus both possibilities need to be investigated.

When there is no flaming combustion during a unit failure, or when flaming combustion is delayed, a deflagration (subsonic explosion) hazard is present. Since released gas is not being consumed by combustion, it can build up within an enclosure until a combustible gas-air mixture is created. A deflagration will occur if ignition is triggered by electrical arcing or other means. This can result in the development of significant overpressure resulting in damage to the BESS enclosure and the potential creation of flying debris/shrapnel.

When there is flaming combustion during a unit failure, a flaming propagation hazard is present. Flaming combustion can lead to rapid propagation both internally within a unit (from module to module) and between units themselves. Both of these hazards present a potential risk to first-responder safety and property.

The methods designed to investigate the hazards associated with each failure mode are detailed below, beginning with gas buildup/deflagration hazards followed by flaming propagation hazards.

2.1 Gas Buildup/Deflagration Hazard

To protect the units from explosive gas buildup, BESS manufacturers typically employ one of two methods of mitigation:

- **Ventilation:** Fans are installed to exhaust battery gas from within a BESS unit and replace it with ambient air drawn from outside the unit. Alternatively, roof panels are installed, which open automatically to allow battery gas to escape upwards. In both cases, the system is triggered by alarm signals generated by gas sensors located within the unit.
- **Pressure Relief:** Panels are designed to break away (completely or swing open) from a BESS unit at relatively low internal pressures, which reduces the maximum over-pressure observed within the unit during a deflagration event. This design feature is sometimes paired with spark igniters designed to ignite pockets of flammable gas prior to the entire unit being filled with flammable gas.

The Gas Buildup/Deflagration Hazard (GB/DH) portion of the testing is designed to evaluate the effectiveness of these mitigation systems as installed in a BESS design. In a non-flaming gas release scenario, mitigation system effectiveness will determine the presented deflagration hazard. GB/DH testing is comprised of two main test methods: one to evaluate BESS units which use active ventilation systems (**Ventilation Testing, VT**), and another to evaluate BESS units which use pressure relief systems (**Deflagration Testing, DT**). There is also a third optional test (**Gas Dispersion Testing**) designed to inform manufacturers on the optimal placement of the gas sensors and spark igniters. If the **Gas Dispersion Testing** is performed as part of the design, it is recommended that this testing (see Section 3.3) is performed first prior to the other two tests: VT (Section 3.1) and DT (Section 3.2). A graphical depiction of the method is shown in Figure 2.1. A description of the test methods follows in the subsequent subsections.

2.1.1 Ventilation Testing

Ventilation Testing (VT) should be performed for any BESS unit which employs ventilation-based mitigation strategies. It is designed to evaluate the ability of a BESS unit's ventilation system to manage a

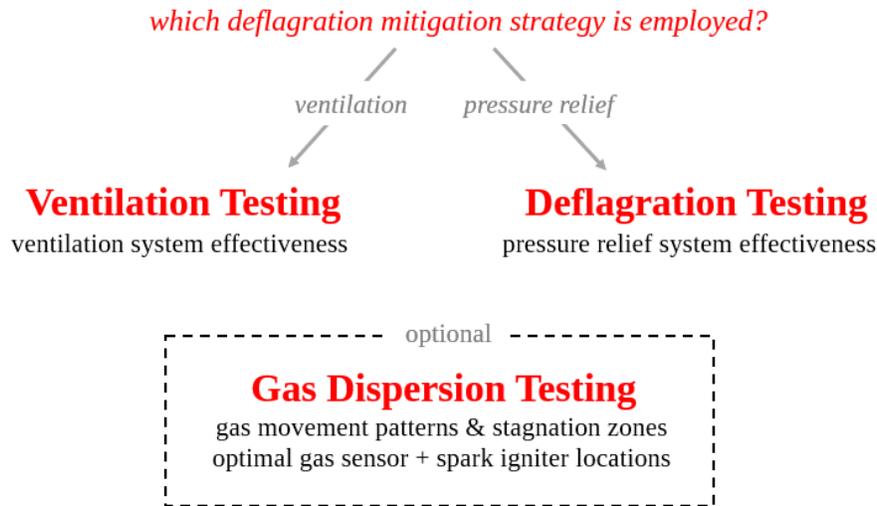


Figure 2.1: GB/DH Test Method

worst-case gas release event.

A gas blend, representative of cell gas produced and analyzed through UL 9540A cell testing, is injected into a BESS unit. If multiple cell designs are considered as part of the BESS design, each gas blend shall be tested unless certain blends are determined to provide more conservative results. Thus, the blends resulting in less conservative scenarios can be eliminated from the test matrix.

The rate of injection should match the gas production rate observed in UL 9540A cell and module level testing, as monitored by calibrated mass flow controllers. The system should be tested under the least-favorable conditions. Therefore, gas should be released from a point within the unit which results in the slowest activation of the ventilation system - typically the point furthest away from manufacturer-integrated gas sensors. The ventilation system is allowed to activate once triggered by manufacturer-integrated sensors at the manufacturer alarm or activation LEL. The unit is thoroughly instrumented with a network of test-installed gas sensors; by this method, gas concentrations throughout the unit are known. The ventilation system is evaluated on its ability to maintain sufficiently low gas concentrations throughout the unit for the duration of the gas release such that no, or low pressure, deflagration occurs. The acceptable gas concentration limits might vary between different designs. Low pressure deflagration refers to ignition that do not challenge the integrity of the BESS unit and its components.

2.1.2 Deflagration Testing

Deflagration Testing (DT) should be performed for any BESS unit which employs pressure-relief-based mitigation strategies. It is designed to evaluate the ability of a BESS unit's pressure relief system to manage deflagrations of varying intensity.

Similar to VT testing in Section 2.1.1, a gas blend, representative of cell gas produced and analyzed through UL 9540A cell testing, is injected into a BESS unit. Also, just as for the VT testing, if multiple cell designs are considered as part of the BESS design, each gas blend shall be tested unless certain blends are determined to provide more conservative results. Thus, the blends resulting in less conservative scenarios can be eliminated from the test matrix.

The rate of injection should match the gas production rate observed in UL 9540A cell and module level

testing, as monitored by calibrated mass flow controllers. The unit is thoroughly instrumented with test-installed gas sensors. Gas is injected until the average concentration within the unit reaches 100% LEL. 100% LEL is equal to the volume percent of the gas blend in air at the LEL. As an example, 100% LEL for methane is equal to 5% by volume of methane in air. The LEL varies between different combustible gases and gas blends. The UL 9540A cell level testing evaluates the gas blend's LEL.

A deflagration is initiated by the activation of spark igniters. Resulting pressure effects are measured by high-speed camera video recordings and dynamic pressure measurements at acquisition rates of at least 1 kHz. If the BESS unit is in a sufficiently good condition following a deflagration event (structural integrity is maintained), new pressure relief panels are installed, as necessary, and the test is repeated. The gas concentration at ignition should be increased by 25% LEL, or $0.25 \times \text{LEL}$ expressed in fuel volume percentage in air, for each subsequent test until a stoichiometric concentration is tested. (Refer to the example below for methane for more clarity.) A stoichiometric concentration is expected to result in the highest overpressure event following ignition, since the amount of fuel and air is balanced such that all fuel and oxygen is consumed during the event. In other words, the mixture is neither fuel lean or rich. If the BESS unit's mitigation design incorporates spark igniters, they are allowed to activate once triggered by manufacturer-integrated sensors.

A 25% LEL increase is exemplified for a methane in air mixture. LEL for methane is 5% by volume of methane in air, which corresponds to 100% LEL. 25% LEL is equal to $0.25 \times 5 = 1.25\%$ by volume of methane in air. Thus, an increase by 25% LEL from 100% LEL to 125% LEL corresponds to an increase in the amount of methane in air from 5% to 6.25% by volume.

2.1.3 Gas Dispersion Testing

Gas Dispersion Testing (GDT) is an optional test designed to inform manufacturers of the optimal locations for gas sensors and/or spark igniters within a BESS unit.

Similar to VT and DT testing in Sections 2.1.1 and 2.1.2, respectively, a gas blend, representative of cell gas produced and analyzed in UL 9540A cell testing, is injected into a BESS unit. Also, just as for the VT and DT testing, if multiple cell designs are considered as part of the BESS design, each gas blend shall be tested unless certain blends are determined to provide more conservative results. Thus, the blends resulting in less conservative scenarios can be eliminated from the test matrix.

The rate of injection should match the gas production rate observed in UL 9540A cell and module level testing, as monitored by calibrated mass flow controllers. The unit is thoroughly instrumented with test-installed gas sensors. The test is repeated by varying the gas injection locations. Gas movement patterns and stagnation zones are identified for each release location. Readings are recorded from both test-installed and manufacturer-integrated sensors.

2.2 Flaming Propagation Hazard

The methods designed to explore non-flaming hazards have been described in Section 2.1. This section focuses on methods to investigate flaming propagation hazards.

Flaming Propagation Testing (FPT) is designed to evaluate the dynamics of and hazards presented by intra-unit (module-to-module) and inter-unit (unit-to-unit) flaming propagation.

Worst-case BESS flaming propagation is characterized by the following scenario: a module within a BESS unit is exposed to a flame, either by ignition of vent gas from a cell within a module, or by an external flame source. The exposed module is located near the bottom of the unit, as flame spread will occur more readily in the upward vertical direction rather than laterally or vertically downward. A significant path for oxygen

ingress is present during the test via a penetration in the unit exterior, opening of the unit door(s), or other causes.

FPT aims to reproduce the above described scenario, quantify aspects of the resulting heat release and heat exposure, and empirically evaluate whether or not unit-to-unit propagation will occur in the planned unit installation configuration. Computational fire modeling is often an integral part of assessing the flaming propagation hazard associated with a BESS installation. Thus, FPT also aims to generate high quality information for use as inputs in these models, as well as a method to validate unit-to-unit spread modeling results.

The method is comprised of three tests: (1) evaluate intra-unit propagation (**Single Unit FPT**), (2) investigate lateral unit-to-unit propagation (**Multi-Unit FPT**), and (3) investigate vertical unit-to-unit propagation (**Stacked FPT**).

A graphical depiction of the method is shown in Figure 2.2. A description of the test methods is presented in the following subsections.

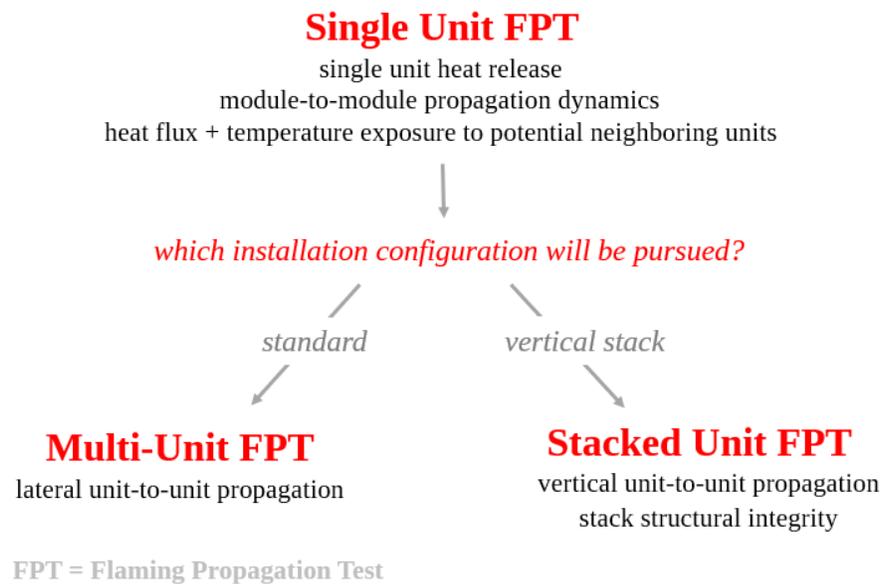


Figure 2.2: Flaming Propagation Hazard Method

2.2.1 Single Unit Flaming Propagation Test

Single Unit FPT is intended to evaluate intra-unit module-to-module flame propagation, as well as provide quality inputs for use in computational fire models.

Single Unit FPT involves exposing a module within a fully populated BESS unit to a flame, e.g. a pre-mixed jet burner, and evaluating the resulting propagation. A significant path for oxygen ingress is created into the unit, either by making penetrations in the unit exterior or by opening the unit door(s). The inside of the unit is thoroughly instrumented with thermocouples and gas sensors. Also, heat flux gauges and thermocouple trees are placed around the unit's exterior. Internal instrumentation provides information about module-to-module propagation, while external instrumentation provides information about boundary conditions experienced by potential neighboring units. An opportunity exists to perform the test under a calorimetry hood setup where heat release rate and gas concentration could be measured, since only a single

unit with a relatively small footprint is involved in the test. The heat release rate is another valuable input to the fire models.

2.2.2 Multi-Unit Flaming Propagation Test

Multi-Unit FPT should be performed on BESS units which are intended to be installed side-by-side with neighboring units. It is intended to provide empirical observations and measurements of lateral unit-to-unit propagation.

Multi-Unit FPT involves exposing a fully populated initiating BESS unit to a flame by the same method described for Single Unit FPT in Section 2.2.1. The initiating unit is surrounded on all sides by partially-populated target BESS units. The resulting unit-to-unit propagation (or non-propagation) is investigated as part of the test. Initiating and target units are thoroughly instrumented with thermocouples, gas sensors, and heat flux gauges.

2.2.3 Stacked Unit Flaming Propagation Test

Stacked Unit FPT should be performed on BESS units which are intended to be installed in a vertically-stacked configuration with neighboring units. It is intended to provide empirical observations and measurements of flaming propagation between BESS units stacked in a vertical configuration. BESS manufacturers are increasingly pursuing vertically stacked configurations in footprint-limited areas, and thus the associated hazard is important to understand.

Stacked FPT involves exposing a fully populated initiating BESS unit to a flame by the same methods utilized in Single and Multi-Unit FPT in Sections 2.2.1 and 2.2.2, respectively. A target unit is installed in a vertically stacked configuration above the initiating unit. The resulting unit-to-unit propagation (or non-propagation) is investigated as part of the test. Initiating and target units are thoroughly instrumented with thermocouples, gas sensors, and heat flux gauges.

3 Gas Buildup/Deflagration Hazard Test Methods

This section details the three test methods designed to evaluate BESS unit gas buildup/deflagration hazards.

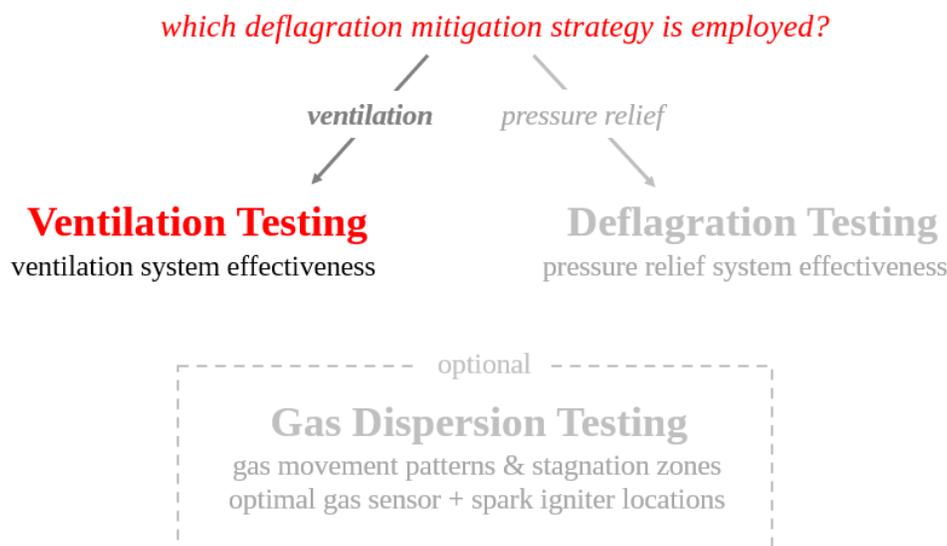
3.1 Ventilation Testing

Device Under Test (DUT): Single BESS unit, fully populated with dummy modules, active ventilation systems enabled.

3.1.1 Overview

Ventilation Testing is designed to evaluate the ability of a BESS's active ventilation system(s) to mitigate a worst-case gas release event.

A gas blend, or blends if multiple cell designs are considered, representative of the cell level vent gas analyzed as part of UL 9540A testing, is injected into the DUT. Gas dispersion is tracked by a network of sensors that measure various gas concentrations. Active ventilation systems, which are initially off, are turned on when gas is detected by the corresponding manufacturer-integrated sensors. The ventilation system is evaluated with respect to its ability to keep the global gas concentrations within the DUT below a critical threshold. A critical threshold could be defined as a gas mixture that remains below the LEL. The test is repeated where the injection location is varied to study the gas movement as a function of the release location.



3.1.2 Setup/Instrumentation

Ventilation testing requires proper selection of three elements: (1) the gas blend injected into the DUT, (2) the location and method by which the gas is injected, and (3) the location and type of sensors used to detect the gas. The following should be considered for each:

1. Gas Blend(s)
 - Composition: The composition of the gas blend injected into the DUT should be representative of the gas composition determined through UL 9540A cell level testing.

- Multiple Blends: If multiple blends need to be considered, each blend shall be tested unless certain blends are determined to provide more conservative results. Thus, the blends resulting in less conservative scenarios can be eliminated from the test matrix.

2. Gas Delivery

- Plumbing: The gas injection system should be plumbed such that the DUT can be fully closed/sealed during each test.
- Injection Location: The gas should be injected at locations furthest from the manufacturer-integrated gas sensors. Locations that might result in local high gas concentration pockets and/or inhibit gas dispersion should also be considered.
- Rate & Volume: The gas delivery rate should represent the gas production rate observed in UL 9540A cell and module level testing. Gas flow should be controlled and monitored via calibrated mass flow controllers. The gas mixture should be well mixed prior to injection through, for example, a manifold.

3. Gas Sensors

- Species: Sensors should be selected to detect gas species which are predominant in the composition of the injected gas blend.
- Measurement Range: The sensors should be selected such that they are able to measure twice the highest concentration of each gas expected within the DUT based on the estimations of free and injected gas volumes. Similarly, the sensors should be selected such that each sensor's minimum detectable limit is low enough to measure meaningful concentrations of each gas, rather than the data suggesting that no gas is present. If necessary, various sensors for the same gas species might be necessary to detect both low and high concentrations during the test.
- Response Time: The sensors should have a t_{90} response time of 10 seconds or less.
- Location: The sensors should be placed within the DUT such that the measured data provides sufficient spatial resolution across the entire volume under consideration. Figure 3.4 provides an example for a thorough sensor placement.

3.1.3 Procedure

The general procedure for VT is as follows:

1. Instrument the DUT with gas sensors and the gas delivery system. Ensure that the ventilation system(s) is enabled, but initially off.
2. Initiate data acquisition from the gas sensors (including manufacturer-integrated sensors, if applicable) in accordance with Section 5.
3. Begin flowing the gas blend/mixture into the DUT at a rate consistent with the production rate observed in UL 9540A cell and module level testing. The gas volume delivery should be monitored using calibrated mass flow controllers, and the flow rates integrated over time to indicate the total volume of gas injected into the DUT.
4. Continue injecting the gas mixture, monitor the gas concentrations inside the DUT, and stop the gas injection if any one of the conditions are reached:
 - (a) the gas concentrations have reached steady-state concentrations for a minimum of 5 minutes, or
 - (b) all functioning and installed sensors are reading concentrations 50% LEL or higher, or
 - (c) any one of the sensors is reading a concentration of 75% LEL or higher, or
 - (d) the total gas released into the unit corresponds to a 75% LEL mixture in the DUT's free volume.
5. Purge the DUT with ambient air until sensor readings return to background ambient measurements.
6. Repeat Steps 1 to 5 until all worst-case release locations and gas blends, if applicable, are studied.

3.2 Deflagration Testing

DUT: Single BESS unit, fully populated with dummy modules, automatic deflagration mitigation systems enabled.

3.2.1 Overview

Deflagration Testing is designed to evaluate the ability of a BESS's pressure relief system(s) to mitigate deflagration events of varying intensity.

A gas blend, or blends if multiple cell designs are considered, representative of the cell level vent gas analyzed as part of UL 9540A testing, is injected into the DUT. Gas dispersion is tracked by a network of sensors that measure various gas concentrations. Spark igniters are activated once a volume of gas corresponding to a 100% LEL mixture has been injected. 100% LEL is measured based on the total free volume of the DUT. Resulting pressure effects are captured by high speed video and pressure transducers specifically designed to measure dynamic pressure. Additionally, manufacturer-integrated ignition systems are allowed to activate once triggered by manufacturer-integrated gas sensors.

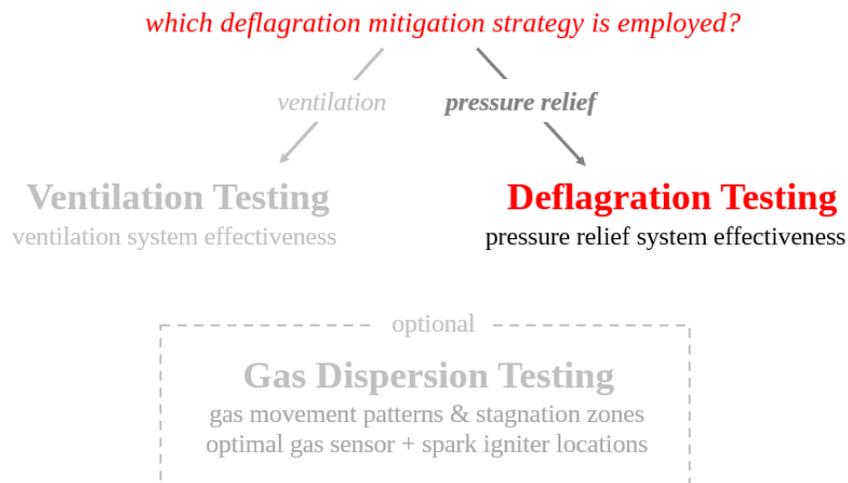


Figure 3.2: DH DT Method

3.2.2 Setup/Instrumentation

Deflagration Testing requires proper selection of several elements related to the gas delivery and instrumentation. The following considerations should be made:

1. Gas Blend(s)
 - **Composition:** The composition of the gas blend injected into the DUT should be representative of the gas composition determined through UL 9540A cell level testing.
 - **Multiple Blends:** If multiple blends need to be considered, each blend shall be tested unless certain blends are determined to provide more conservative results. Thus, the blends resulting in less conservative scenarios can be eliminated from the test matrix.
2. Gas Delivery
 - **Plumbing:** The gas injection system should be plumbed such that the DUT can be fully closed/sealed during each test.

- **Injection Location:** If manufacturer-integrated gas sensors and spark igniters are part of the DUT design, the gas should be injected at locations furthest from these devices to conservatively delay the detection of gas and the activation of the spark igniters. Otherwise, injection should occur at locations furthest from the pressure relief panels, such that the effectiveness of the panels is reduced should ignition occur at the locations furthest away from the panels.
- **Rate & Volume:** The gas delivery rate should represent the gas production rate observed in UL 9540A cell and module level testing. Gas flow should be controlled and monitored via calibrated mass flow controllers. The gas mixture should be well mixed prior to injection through, for example, a manifold.

3. Gas Ignition System

- **Location:** If manufacturer-integrated gas sensors and spark igniters are part of the DUT design, those will be installed per the system design. If additional spark igniters will be installed as part of the test, those will be installed such that the distance between the spark igniters and pressure relief panels is maximized.

4. Gas Sensors

- **Species:** Sensors should be selected to detect gas species which are predominant in the composition of the injected gas blend.
- **Measurement Range:** The sensors should be selected such that they are able to measure twice the highest concentration of each gas expected within the DUT based on the estimates of free and injected gas volumes. Similarly, the sensors should be selected such that each sensor's minimum detectable limit is low enough to measure meaningful concentrations of each gas, rather than the data suggesting that no gas is present. If necessary, various sensors for the same gas species might be necessary to detect both low and high concentrations during the test.
- **Response Time:** The sensors should have a t_{90} response time of 10 seconds or less.
- **Location:** The sensors should be placed within the DUT such that the measured data provides sufficient spatial resolution across the entire volume under consideration. Figure 3.4 provides an example for a thorough sensor placement.

5. Pressure Transducers

- **Type:** Pressure transducers specifically designed to measure dynamic pressure, e.g. piezoelectric, should be used to measure the pressure pulsation events at a rate no less than 1,000 Hz. Additionally, it is recommended that standard pressure transducers are also included as part of the pressure measurement setup, programmed to the same acquisition rate, to capture pressure pulsation events that are not dynamic enough to result in meaningful measurements using the dynamic pressure transducers. In other words, using both sets of transducers will allow for better measurement of the pressure pulsation events regardless if the deflagration is acoustic or inertial. The standard transducers should be protected with snubber fittings.
- **Location:** The sensors should be installed such that sufficient spatial resolution is obtained across the entire DUT volume. Additionally, transducers should be installed near the pressure relief panel(s), if available, to demonstrate the pressure at which the panels opened (if such an event was observed).
- **Installation:** It is imperative that the dynamic pressure transducers be installed flush with the inside of the DUT wall to accurately measure the dynamic pressure. If the sensor is not flush, e.g. is sticking into the DUT free volume, or there is a cavity between the inside of the wall and the tip of the transducer, then the pressure measurement will not be correct. An incorrect installation will modify the pressure wave as it traverses the space near the transducer. The standard pressure transducers utilized for inertial pressure pulsation events do not require such consideration during installation.

6. High-Speed Video

- Acquisition Rate: The video should be recorded at a minimum of 240 frames per second.
- Location: The cameras should record, at minimum, the pressure relief panels, unit doors, and at least two different angles of the DUT exterior.
- Lighting: The lighting for high-speed cameras is more challenging than regular recording devices. Thus, for example, if testing is conducted at night or in a poorly illuminated enclosure, proper lighting is required, e.g. high intensity and frequency. Improper lighting will result in footage that appears black.

3.2.3 Procedure

The general procedure for DT is as follows:

1. Instrument the DUT with gas sensors, gas delivery system, ignition system, and pressure transducers. If automatic manufacturer-installed spark igniters are part of the mitigation system design, ensure that they are enabled but initially off.
2. Initiate data acquisition from the gas sensors (including manufacturer-integrated sensors), pressure transducers, and spark igniters (if applicable) in accordance with Section 5. Begin high-speed video recordings, ideally synchronized with the start of the data acquisition.
3. Begin flowing the gas blend/mixture into the DUT at a rate consistent with the production rate observed in UL 9540A cell and module level testing. The release location should promote mixing/diffusion. Terminate the gas flow when the volume of the injected gas mixture corresponds to a 100% LEL mixture in the DUT's free volume. The gas volume delivery should be monitored using calibrated mass flow controllers.
4. Activate the spark igniters no later than 10 seconds following the gas mixture injection termination.
5. Proceed to one of the two steps below:
 - Deflagration: Turn off the spark igniters and purge the DUT with ambient air. Monitor the gas concentrations within the DUT and continue purging until all surviving sensors are reading concentrations below 10% LEL before approaching and opening the DUT. If there are no surviving sensors, purge the DUT until the free volume is turned over with ambient air, at minimum, 10 times.
 - No deflagration: Continue to activate the spark igniters intermittently (at least once every 10 seconds) for 60 minutes following the initial activation. If no deflagration has occurred after 60 minutes, turn off the spark igniters and purge the DUT with ambient air. Monitor the gas concentrations within the DUT and continue purging until all sensors are reading concentrations below 10% LEL before approaching and opening the DUT.
6. Repeat Steps 1 to 5 with varying concentrations of injected gas, as well as different gas blends, if applicable, as required per the objective of the study.

3.3 Gas Dispersion Testing

DUT: Single BESS unit, fully populated with dummy modules, active ventilation systems disabled.

3.3.1 Overview

Gas Dispersion Testing is designed to identify gas movement patterns within BESS units to inform manufacturers for the optimal placement of different equipment, such as the gas sensors, smoke detectors, ventilation systems, deflagration panels, and spark igniters.

A gas blend, or blends if multiple cell designs are considered, representative of the cell level vent gas analyzed as part of UL 9540A testing, is injected into the DUT. Gas dispersion and movement is tracked by a network of sensors that measure various gas concentrations. Automatic mitigation systems are disabled to allow for complete and unmitigated gas transport throughout the DUT. The test is repeated for several injection locations.

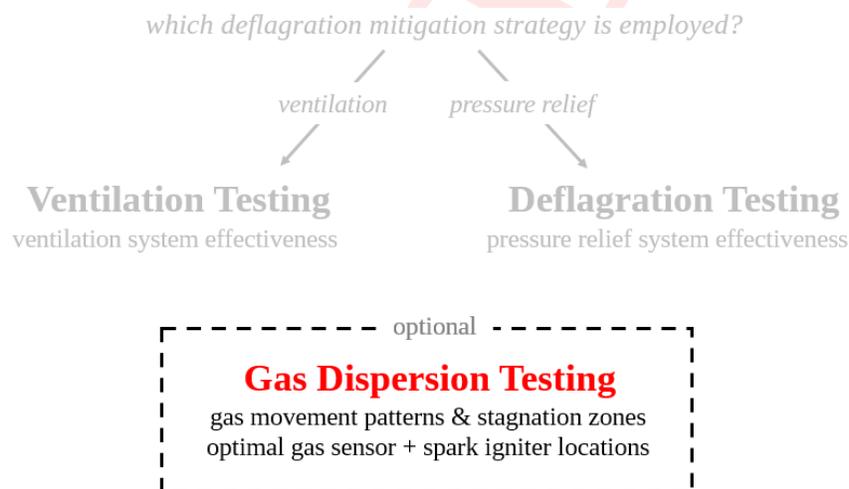


Figure 3.3: Gas Dispersion Test Method

3.3.2 Setup/Instrumentation

Gas dispersion testing requires proper selection of three elements: (1) the gas blend injected into the DUT, (2) the location and method by which the gas is injected, and (3) the location and type of sensors used to detect the gas. The following should be considered for each:

1. Gas Blend(s)
 - **Composition:** The composition of the gas blend injected into the DUT should be representative of the gas composition determined through UL 9540A cell level testing.
 - **Multiple Blends:** If multiple blends need to be considered, each blend shall be tested unless certain blends are determined to provide more conservative results. Thus, the blends resulting in less conservative scenarios can be eliminated from the test matrix.
2. Gas Delivery
 - **Plumbing:** The gas injection system should be plumbed such that the DUT can be fully closed/sealed during each test.

- **Injection Location:** The release location should be varied between each test.
- **Rate & Volume:** The gas delivery rate should represent the gas production rate observed in UL 9540A cell and module level testing. Gas flow should be controlled and monitored via calibrated mass flow controllers. The gas mixture should be well mixed prior to injection through, for example, a manifold.

3. Gas Sensors

- **Species:** Sensors should be selected to detect gas species which are predominant in the composition of the injected gas blend.
- **Measurement Range:** The sensors should be selected such that they are able to measure twice the highest concentration of each gas expected within the DUT based on the estimates of free and injected gas volumes. Similarly, the sensors should be selected such that each sensor's minimum detectable limit is low enough to measure meaningful concentrations of each gas, rather than the data suggesting that no gas is present. If necessary, various sensors for the same gas species might be necessary to detect both low and high concentrations during the test.
- **Response Time:** The sensors should have a t_{90} response time of 10 seconds or less.
- **Location:** The sensors should be placed within the DUT such that the measured data provides sufficient spatial resolution across the entire volume under consideration. Figure 3.4 provides an example for a thorough sensor placement.

3.3.3 Procedure

The general procedure is as follows:

1. Instrument the DUT with gas sensors and gas delivery system. Ensure that the automatic ventilation system(s) is disabled for the duration of the test.
2. Initiate data acquisition from the gas sensors (including manufacturer-integrated sensors, if applicable) in accordance with Section 5.
3. Begin flowing the gas blend/mixture into the DUT at a rate consistent with the production rate observed in UL 9540A cell and module level testing. The gas volume delivery should be monitored using calibrated mass flow controllers, and the flow rates integrated over time to indicate the total volume of gas injected into the DUT.
4. Stop the injection of gas when the total gas released into the unit corresponds to a 50% LEL mixture in the DUT's free volume.
5. Monitor the gas concentrations inside the DUT until the gas concentrations have reached steady-state concentrations for a minimum of 20 minutes.
6. Purge the DUT with ambient air until sensor readings return to background ambient measurements.
7. Repeat Steps 1 to 6 with varying gas mixture release locations, as well as different gas blends, if applicable.

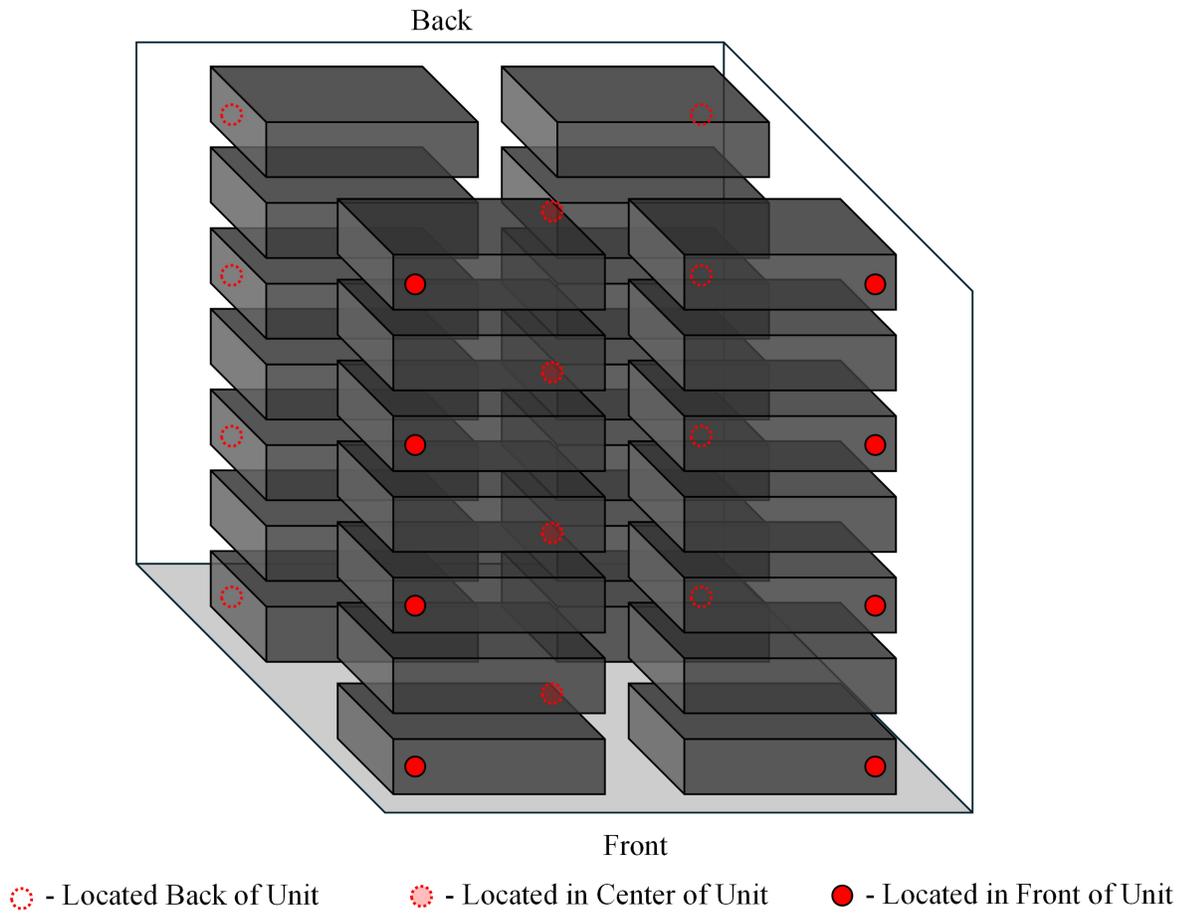


Figure 3.4: Example sensor placement for GB/DH tests

4 Flaming Propagation Test Methods

This section details the three test methods designed to evaluate BESS unit flaming propagation testing hazards.

4.1 Single Unit FPT

DUT: Single BESS unit fully populated with 100% SOC modules.

4.1.1 Overview

Single Unit FPT is designed to evaluate the dynamics of module-to-module flaming propagation within a single BESS unit, as well as to provide quality inputs for use in computational fire models.

A module within the DUT is exposed to constant direct flame impingement by a premixed fuel-air gas burner(s). Flame impingement is applied until the initiating module maintains flaming combustion without the burner(s). Resulting fire propagation is observed throughout the DUT. Unit doors are opened for the duration of testing to provide a significant path for oxygen ingress. The DUT, and modules contained within, are thoroughly instrumented with thermocouples, both internally and externally, as applicable. The DUT is surrounded on all sides by wall sections instrumented with arrays of thermocouples and heat flux gauges as exemplified in Figure 4.2. Internal instrumentation provides information about module-to-module spread dynamics and conditions within the unit. External instrumentation provides information about conditions experienced by potential neighboring units. The test should be performed under a ventilation hood/system with oxygen-consumption calorimetry capabilities so that heat-release rate measurements can be taken.

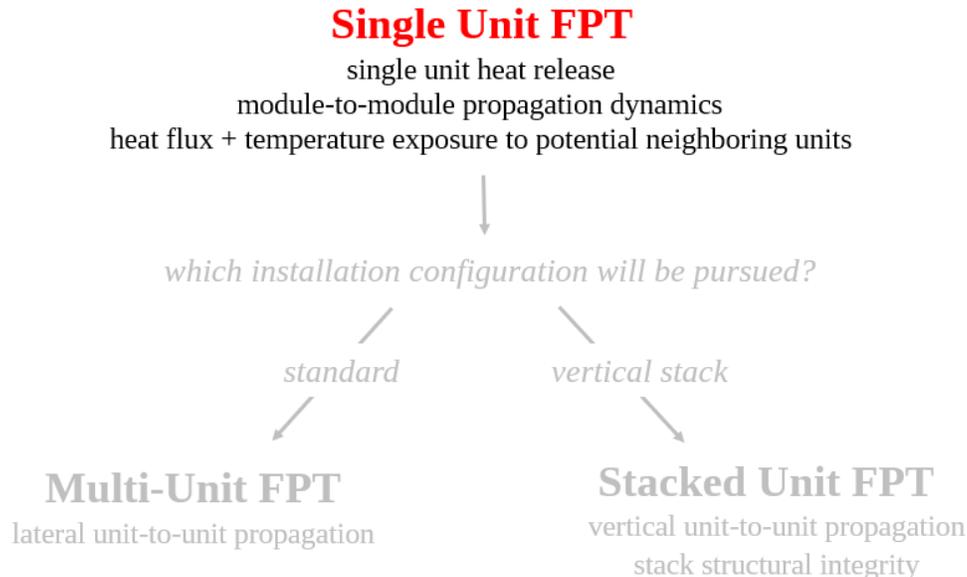


Figure 4.1: Single Unit FPT

4.1.2 Setup/Instrumentation

Single Unit FPT requires proper selection of several elements related to gas delivery and instrumentation. The following considerations should be made:

1. Premixed Fuel-Air Burner(s)

- Location: The burner(s) should be installed such that its flame impinges on the bottom of the initiating module. The initiating module should be chosen from the second-from-the-bottom row within the DUT. This location promotes upward propagation, while also allowing for the investigation of downward propagation.
- Fuel: A stoichiometric air-methane (or equivalent fuel, e.g. propane) mixture should be supplied to the burner. Air and methane should be plumbed separately and mixed as they enter the burner. Air and methane delivery should be controlled and monitored via calibrated mass flow controllers.

2. Instrumented Wall Sections

- Position: Instrumented wall sections should represent potential neighboring units. The distance between the DUT exterior and each target wall should be representative of the separation distance between the units as installed in the field.

3. Thermocouples

- Type: Type K thermocouples should be utilized for the testing.
- Location: The following thermocouples should be installed, at minimum:
 - (primary option) on each cell within the initiating module or (secondary option) on enough cells to clearly indicate propagation through the initiating module,
 - (primary option) on each cell within the module above the initiating module or (secondary option) on enough cells to clearly indicate propagation through the module, and
 - the exterior faces of each module within the DUT.

4. Heat Flux Gauges

- Type: All heat flux gauges should be water-cooled Schmidt-Boelter gauges.
- Location: The heat flux gauges should be installed within each instrumented wall section at several heights and mounted such that the sensing surface is flush with the wall section facing the DUT.
- Range: The range should be selected based on the data application. For example, if the heat flux data will be used for life safety assessments, then a lower range heat flux gauge might be better suited for the test, e.g. 0-15 kW/m². Conversely, if the measured heat flux is meant to assess the integrity of the neighboring units, the allowable range for these units is likely significantly higher than the life safety limits, and thus a higher range heat flux gauge should be chosen for that application. It is anticipated that the range of those heat flux gauges will be determined prior to testing through computational analyses, but it is expected that the upper limit of the range will be around 50 kW/m².
- Cooling: The heat flux gauges should be cooled with recirculated water, such that the temperature at each gauge remains constant. The cooling temperature during the test should be equal to the cooling temperature during calibration of each heat flux gauge. If the temperature between the test and calibration is not equal, then the measurement must be corrected due to the temperature difference. Ideally, the temperature of the cooling water should be measured at the inlet and outlet of each heat flux gauge.

5. Gas Sensors

- Species: Sensors should be selected to detect gas species that are expected during the test based on the gas composition determined through UL 9540A cell level testing. Consideration should also be taken when selecting appropriate sensors that flaming combustion is likely during the test, instead of only gas venting due to cells thermal runaways.

- **Measurement Range:** The sensors should be selected such that they are able to measure twice the highest concentration of each gas expected within the DUT based on the estimates of free and vented gas volumes. Similarly, the sensors should be selected such that each sensor's minimum detectable limit is low enough to measure meaningful concentrations of each gas, rather than the data suggesting that no gas is present. If necessary, various sensors for the same gas species might be necessary to detect both low and high concentrations during the test.
- **Response Time:** The sensors should have a t_{90} response time of 10 seconds or less.
- **Location:** The sensors should be placed, at minimum, in each corner of the DUT.

4.1.3 Procedure

The general procedure is as follows:

1. Instrument the DUT with thermocouples, heat flux gauges, and gas sensors.
2. Install the burner system in the desired location within the initiating DUT. Ensure that the initiating unit doors are open, and remain open, for the duration of the test.
3. Initiate data acquisition from all the instruments (thermocouples, heat flux gauges, and gas sensors) in accordance with Section 5.
4. Activate the burner system by initiating the flow of fuel and air and igniting the mixture. Continuously apply the burner flame to the initiating module until self-sustaining combustion is observed on the module.
5. Stop the burner gas supply and allow the module-to-module flaming to self-propagate.
6. Terminate the test when both conditions are met:
 - (a) flaming combustion is no longer observed visually or through temperature measurements, and
 - (b) all the thermocouple measurements within the DUT indicate temperatures decreasing below the cells' thermal runaway temperature as determined through UL 9540A cell level testing.

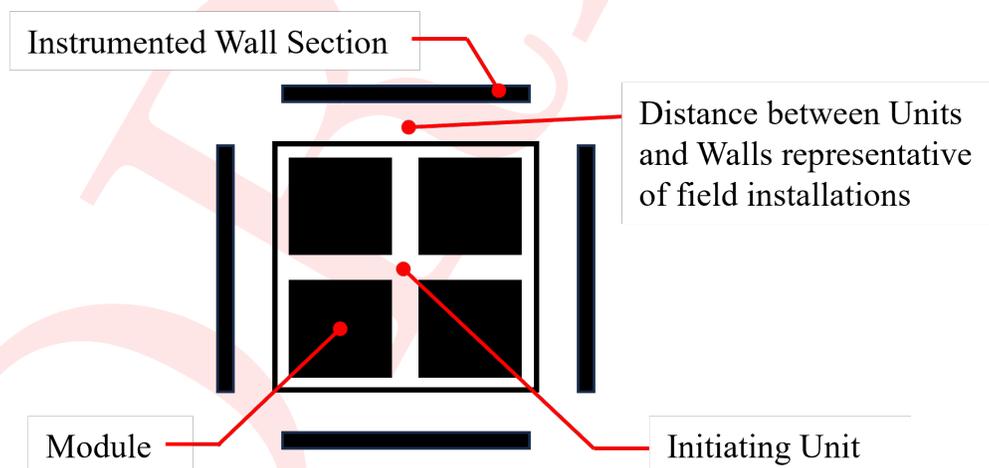


Figure 4.2: Single Unit FPT Layout (top view)

4.2 Multi-Unit FPT

DUTs:

- Initiating BESS unit - fully populated with modules at 100% SOC.
- Target BESS units - surround the initiating BESS unit, partially populated with modules at 100% SOC.

4.2.1 Overview

Multi-Unit FPT is designed to evaluate the potential for unit-to-unit flame propagation between BESS units installed in a lateral (side-by-side) configuration.

A fully populated BESS unit (initiating DUT) is surrounded on all sides by partially populated units (target DUTs). Target DUTs are only partially populated with modules installed closest to the initiating DUT. Figure 4.4 provides more details and a diagram of the setup. A module within the initiating DUT is exposed to constant direct flame impingement by a premixed fuel-air gas burner(s). Flame impingement is applied until the initiating module maintains flaming combustion without the burner(s). Resulting fire propagation is observed throughout the initiating DUT, as well as target DUTs. Initiating DUT doors are opened for the duration of the testing to provide a significant path for oxygen ingress. Not all doors need to be open, but only enough doors to prevent oxygen starvation within the DUT. If not all doors will be open during the test, then the open door(s) should be the one/those furthest removed from the target DUTs. All DUTs, and modules contained within, are thoroughly instrumented with thermocouples, both internally and externally, as applicable. Additionally, all DUTs are also thoroughly instrumented with gas sensors on the inside of the units.

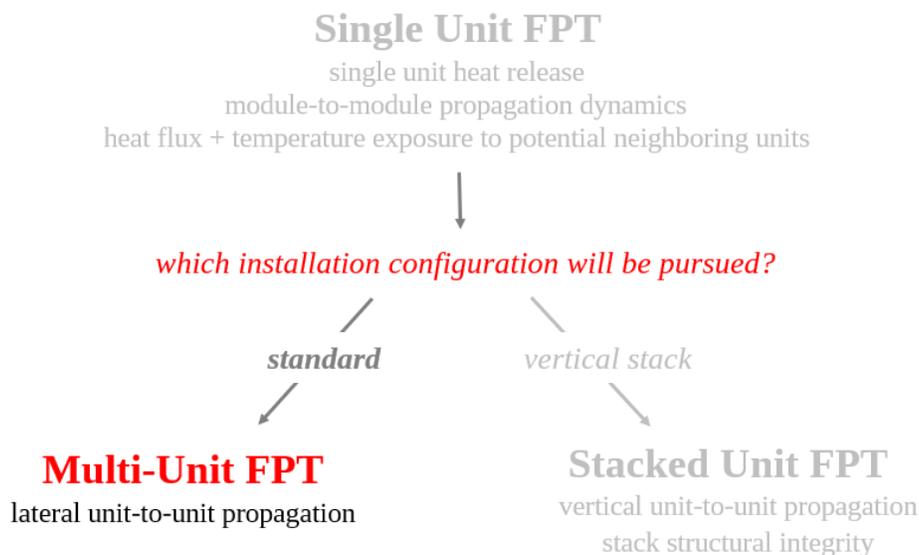


Figure 4.3: Multi-Unit FPT

4.2.2 Setup/Instrumentation

1. Premixed Fuel-Air Burner(s)

- Location: The burner(s) should be installed such that its flame impinges on the bottom of the initiating module. The initiating module should be chosen from the second-from-the-bottom row

within the initiating DUT. This location promotes upward propagation, while also allowing for the investigation of downward propagation.

- Fuel: A stoichiometric air-methane (or equivalent fuel, e.g. propane) mixture should be supplied to the burner. Air and methane should be plumbed separately and mixed as they enter the burner. Air and methane delivery should be controlled and monitored via calibrated mass flow controllers.

2. Thermocouples

- Type: Type K thermocouples should be utilized for the testing.
- Location: The following thermocouples should be installed, at minimum:
 - (primary option) on each cell within the initiating module or (secondary option) on enough cells to clearly indicate propagation through the initiating module, and
 - the exterior faces of each target module.

3. Heat Flux Gauges

- Type: All heat flux gauges should be water-cooled Schmidt-Boelter gauges.
- Location: The heat flux gauges should be installed in the anticipated first-responder pathways to gauge potential exposure to personnel.
- Range: The range should be selected based on the data application. For example, if the heat flux data will be used for life safety assessments, then a lower range heat flux gauge might be better suited for the test, e.g. 0-15 kW/m². Conversely, if the measured heat flux is meant to assess the integrity of the neighboring units, the allowable range for these units is likely significantly higher than the life safety limits, and thus a higher range heat flux gauge should be chosen for that application. It is anticipated that the range of those heat flux gauges will be determined prior to testing through computational analyses, but it is expected that the upper limit of the range will be around 50 kW/m².
- Cooling: The heat flux gauges should be cooled with recirculated water, such that the temperature at each gauge remains constant. The cooling temperature during the test should be equal to the cooling temperature during calibration of each heat flux gauge. If the temperature between the test and calibration is not equal, then the measurement must be corrected due to the temperature difference. Ideally, the temperature of the cooling water should be measured at the inlet and outlet of each heat flux gauge.

4. Gas Sensors

- Species: Sensors should be selected to detect gas species that are expected during the test based on the gas composition determined through UL 9540A cell level testing. Consideration should also be taken when selecting appropriate sensors that flaming combustion is likely during the test, instead of only gas venting due to cells thermal runaways.
- Measurement Range: The sensors should be selected such that they are able to measure twice the highest concentration of each gas expected within the DUT based on the estimates of free and vented gas volumes. Similarly, the sensors should be selected such that each sensor's minimum detectable limit is low enough to measure meaningful concentrations of each gas, rather than the data suggesting that no gas is present. If necessary, various sensors for the same gas species might be necessary to detect both low and high concentrations during the test.
- Response Time: The sensors should have a t_{90} response time of 10 seconds or less.
- Location: The sensors should be placed, at minimum, in each corner of all the DUTs.

4.2.3 Procedure

The general procedure is as follows:

1. Instrument all the DUTs with thermocouples, heat flux gauges, and gas sensors.
2. Install the burner system in the desired location within the initiating DUT. Ensure that the unit doors are open, and remain open, for the duration of the test.
3. Initiate data acquisition from all the instruments (thermocouples, heat flux gauges, and gas sensors) in accordance with Section 5.
4. Activate the burner system by initiating the flow of fuel and air and igniting the mixture. Continuously apply the burner flame to the initiating module until self-sustaining combustion is observed on the module.
5. Stop the burner gas supply and allow the flaming to self-propagate, both intra-initiating DUT, as well as initiating DUT to target DUTs. Note that propagation between DUTs might occur without direct flame impingement, and simply by heat transfer to target cells that undergo thermal runaway.
6. Terminate the test when both conditions are met:
 - (a) flaming combustion is no longer observed visually or through temperature measurements, and
 - (b) all the thermocouple measurements within all DUTs indicate temperatures decreasing below the cells' thermal runaway temperature as determined through UL 9540A cell level testing.

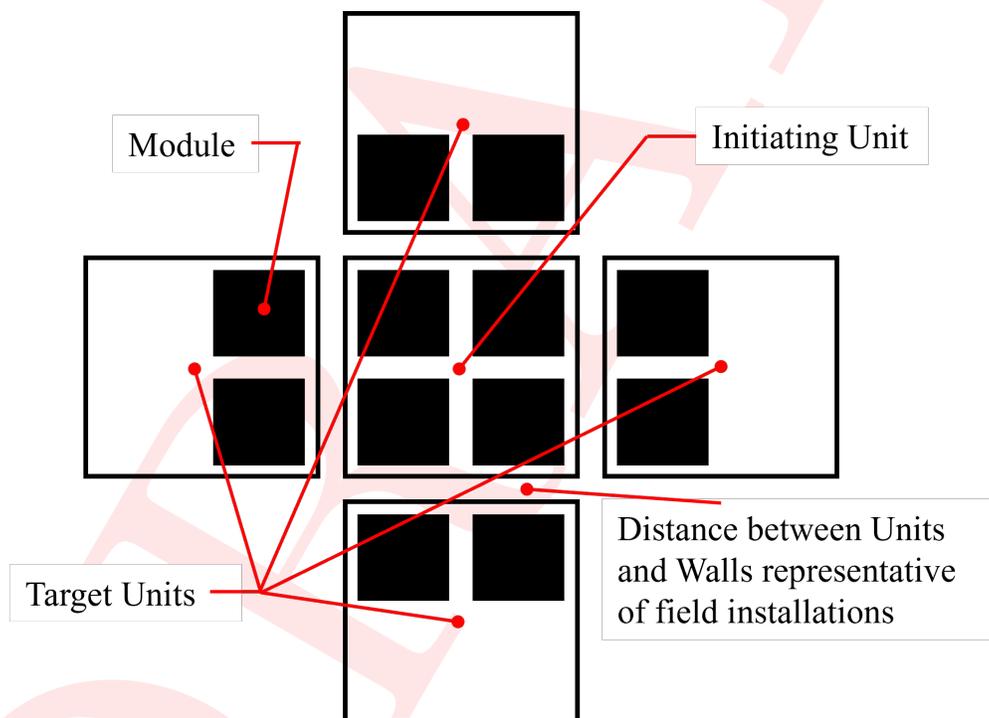


Figure 4.4: Multi-Unit FPT Layout (top view)

4.3 Stacked Unit FPT

DUTs:

- Initiating BESS unit - fully populated with modules at 100% SOC.
- Target BESS unit - mounted vertically above the initiating BESS unit, fully populated with modules at 100% SOC.

4.3.1 Overview

Stacked Unit FPT is designed to evaluate (1) the potential for unit-to-unit flame propagation between BESS units installed in a vertically-stacked configuration, and (2) the impact of a fire scenario on the integrity of the stacked structure.

A fully populated BESS unit (initiating DUT) is installed at ground level. A second fully populated BESS unit (target DUT) is mounted above the initiating DUT using the same mechanism/hardware representative of the field installation. Figure 4.6 provides more details and a diagram of the setup. A module within the initiating DUT is exposed to constant direct flame impingement by a premixed fuel-air gas burner(s). Flame impingement is applied until the initiating module maintains flaming combustion without the burner(s). Resulting fire propagation is observed throughout the initiating DUT, as well as target DUT. Initiating DUT doors are opened for the duration of the testing to provide a significant path for oxygen ingress. Not all doors need to be open, but only enough to prevent oxygen starvation within the DUT. If not all doors will be open during the test, then the open door(s) should be the one/those furthest removed from the stacked DUT. All DUTs, and modules contained within, are thoroughly instrumented with thermocouples, both internally and externally, as applicable. Additionally, all DUTs are also thoroughly instrumented with gas sensors on the inside of the units. The exterior of the initiating DUT is also instrumented with strain gauges to monitor the unit's potential stresses and deformation.

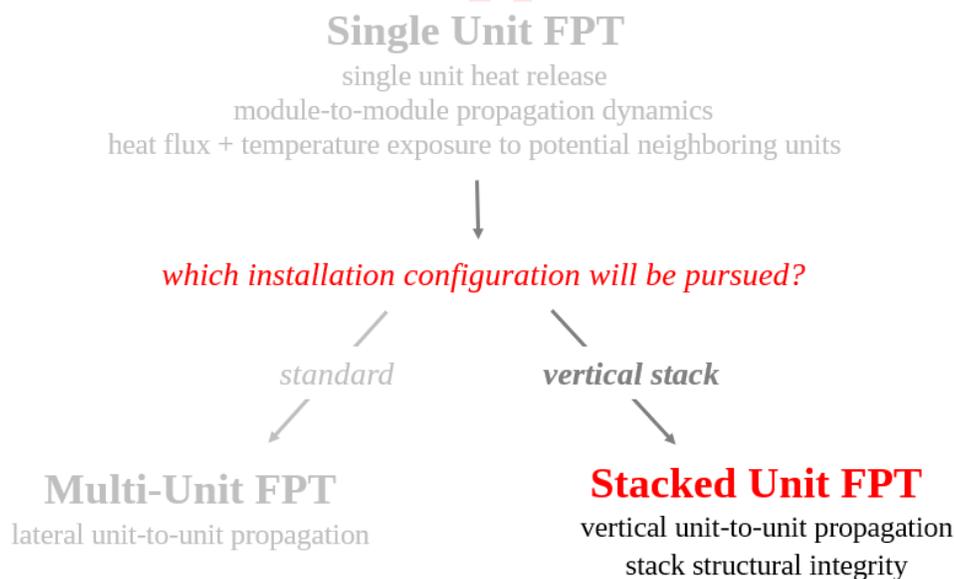


Figure 4.5: Stacked Unit FPT

4.3.2 Setup/Instrumentation

1. Premixed Fuel-Air Burner(s)

- Location: The burner(s) should be installed such that its flame impinges on the bottom of the initiating module. The initiating module should be chosen from the second-from-the-bottom row within the initiating DUT. This location promotes upward propagation, while also allowing for the investigation of downward propagation.
- Fuel: A stoichiometric air-methane (or equivalent fuel, e.g. propane) mixture should be supplied to the burner. Air and methane should be plumbed separately and mixed as they enter the burner. Air and methane delivery should be controlled and monitored via calibrated mass flow controllers.

2. Thermocouples

- Type: Type K thermocouples should be utilized for the testing.
- Location: The following thermocouples should be installed, at minimum:
 - (primary option) on each cell within the initiating module or (secondary option) on enough cells to clearly indicate propagation through the initiating module, and
 - the exterior faces of each target module.

3. Heat Flux Gauges

- Type: All heat flux gauges should be water-cooled Schmidt-Boelter gauges.
- Location: The heat flux gauges should be installed in the anticipated first-responder pathways to gauge potential exposure to personnel.
- Range: The range should be selected based on the data application. For example, if the heat flux data will be used for life safety assessments, then a lower range heat flux gauge might be better suited for the test, e.g. 0-15 kW/m². Conversely, if the measured heat flux is meant to assess the integrity of the neighboring units, the allowable range for these units is likely significantly higher than the life safety limits, and thus a higher range heat flux gauge should be chosen for that application. It is anticipated that the range of those heat flux gauges will be determined prior to testing through computational analyses, but it is expected that the upper limit of the range will be around 50 kW/m².
- Cooling: The heat flux gauges should be cooled with recirculated water, such that the temperature at each gauge remains constant. The cooling temperature during the test should be equal to the cooling temperature during calibration of each heat flux gauge. If the temperature between the test and calibration is not equal, then the measurement must be corrected due to the temperature difference. Ideally, the temperature of the cooling water should be measured at the inlet and outlet of each heat flux gauge.

4. Strain Gauges

- Type: TBD.
- Location: The gauges should be installed on all primary or secondary structural members. The measurements are intended to assess the structural integrity of the system, if the members experience plastic/permanent deformation, and if the stresses indicate a total collapse of the structure (which might be observed during the test).

5. Gas Sensors

- Species: Sensors should be selected to detect gas species that are expected during the test based on the gas composition determined through UL 9540A cell level testing. Consideration should also be taken when selecting appropriate sensors that flaming combustion is likely during the test, instead of only gas venting due to cells thermal runaways.
- Measurement Range: The sensors should be selected such that they are able to measure twice the highest concentration of each gas expected within the DUT based on the estimates of free and vented gas volumes. Similarly, the sensors should be selected such that each sensor's minimum detectable limit is low enough to measure meaningful concentrations of each gas, rather than the data suggesting that no gas is present. If necessary, various sensors for the same gas species might be necessary to detect both low and high concentrations during the test.

- Response Time: The sensors should have a t_{90} response time of 10 seconds or less.
- Location: The sensors should be placed, at minimum, in each corner of all the DUTs.

4.3.3 Procedure

The general procedure is as follows:

1. Instrument all the DUTs with thermocouples, heat flux gauges, strain gauges, and gas sensors.
2. Install the burner system in the desired location within the initiating DUT. Ensure that the unit doors are open, and remain open, for the duration of the test.
3. Initiate data acquisition from all the instruments (thermocouples, heat flux gauges, strain gauges, and gas sensors) in accordance with Section 5.
4. Activate the burner system by initiating the flow of fuel and air and igniting the mixture. Continuously apply the burner flame to the initiating module until self-sustaining combustion is observed on the module.
5. Stop the burner gas supply and allow the flaming to self-propagate, both intra-initiating DUT, as well as initiating DUT to target DUT. Note that propagation between DUTs might occur without direct flame impingement, and simply by heat transfer to target cells that undergo thermal runaway.
6. Terminate the test when both conditions are met:
 - (a) flaming combustion is no longer observed visually or through temperature measurements, and
 - (b) all the thermocouple measurements within all DUTs indicate temperatures decreasing below the cells' thermal runaway temperature as determined through UL 9540A cell level testing.

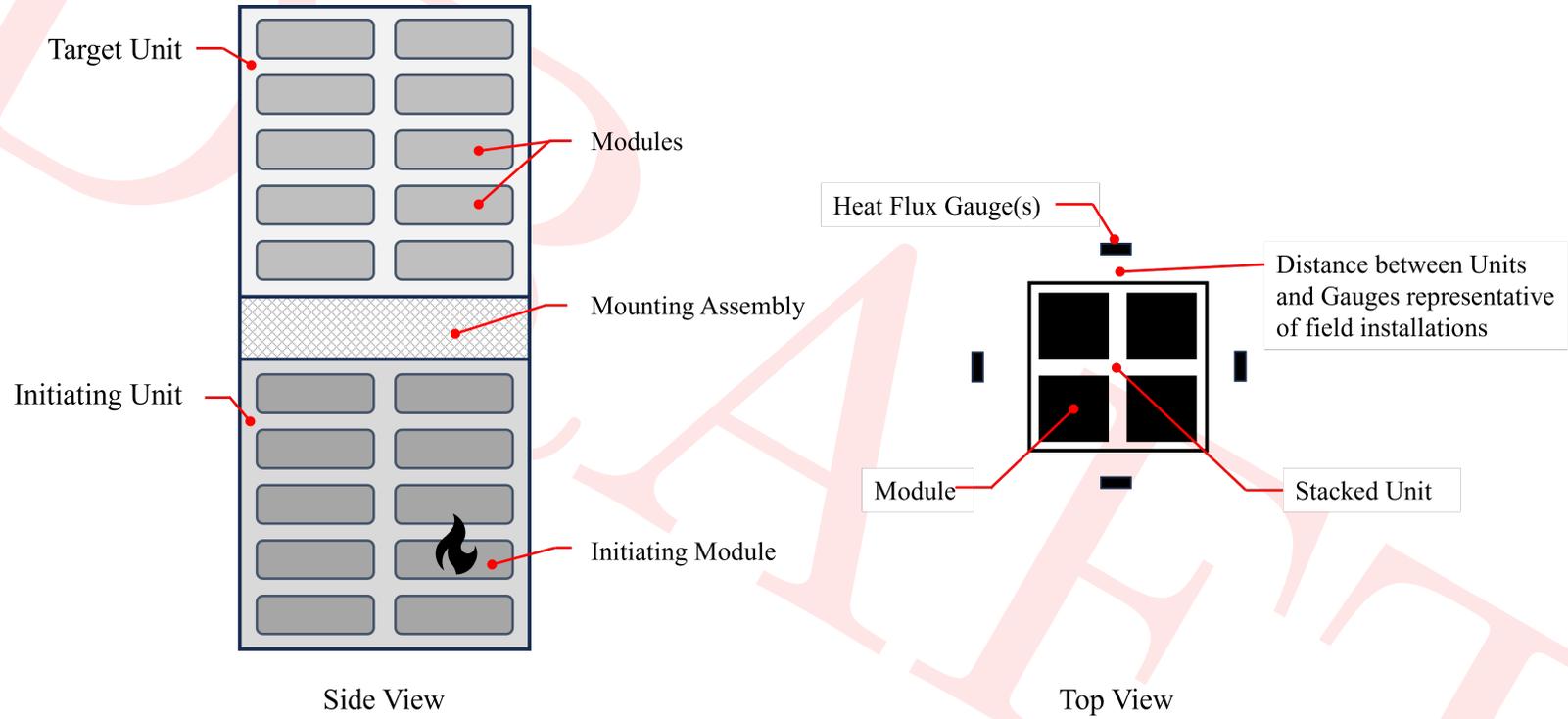


Figure 4.6: Stacked Unit FPT Layout

5 Standard Practices

The following practices should be implemented in all the tests described in this document:

- A safety brief should be conducted prior to the start of any test and the following, at minimum, aspects should be discussed/considered:
 - risks associated with the test,
 - availability of safety equipment, e.g. respirators,
 - buddy system,
 - meeting location should evacuation be necessary, and
 - firefighter intervention.
- At least 5 minutes of baseline/background data should be collected before test initiation.
- Relative humidity and temperature of the ambient test environment should be recorded using calibrated sensors for the duration of the test. Outdoor tests should also measure wind speed and direction.
- Video of the test should be recorded from multiple angles using standard video recording equipment. High-speed cameras should also be utilized if deflagration is anticipated during the test. The high-speed cameras should record at or above 240 frames per second.
- The test site layout and instrumentation should be well documented by photographs and schematics. The DUT should be photographed extensively before and after testing.
- Data should be acquired at a minimum of 2 Hz. Dynamic pressure measurements for deflagration events shall be acquired at a minimum of 1 kHz.
- Gas analyzers employed for the purposes of HRR (heat release rate) calculations should adhere to the measurement methods and ranges specified in Table 5.1. All sensors should be evaluated to ensure their applicability for the test. Consideration should be given to sensor response time, temperature and humidity effects, as well as cross-sensitivity to ensure accurate and timely data is collected.

Table 5.1: Gas measurement methodologies applied to unit test exhaust characterization.

Gases Measured	Chemical Formula	Measurement Method	Measurement Range
Oxygen	O ₂	Paramagnetic analyzer	0 - 25 %vol
Carbon Monoxide	CO	NDIR analyzer	0 - 1 %vol
Carbon Dioxide	CO ₂	NDIR analyzer	0 - 20 %vol
Hydrogen	H ₂	Palladium-nickel thin film solid state sensor	0.4 - 5 %vol
Hydrogen	H ₂	Catalytic sensor	0 - 4 %vol
Total Hydrocarbons	CH ₄	FID	0 - 3 %vol

5.1 Glossary

The following definitions apply to this document:

- **BATTERY ENERGY STORAGE SYSTEM (BESS)** – Stationary equipment that receives electrical energy and utilizes batteries to store that energy for future use. A BESS, at a minimum, consists of one or more modules, a battery management system (BMS), and balance of plant components.
 - **INITIATING BESS UNIT (INITIATING BESS)** – A BESS unit which has been equipped with resistance heaters or burner(s) to create the internal thermal runaway and/or fire condition necessary for the installation level test.
 - **TARGET BESS UNIT (TARGET BESS)** – The enclosure and/or rack hardware that physically supports and/or contains the components that comprise a BESS that may be exposed to an initiating BESS.
- **CELL** – The basic functional electrochemical unit containing an assembly of electrodes, electrolyte, separators, container, and terminals. It is a source of electrical energy by direct conversion of chemical energy.
- **DEFLAGRATION** - Combustion which propagates through a gas at subsonic speeds, driven by the transfer of heat.
- **DEFLAGRATION PROTECTION SYSTEM** - Deflagration protection systems either vent flammable gases prior to exceeding a flammable limit or the combustion gases following a deflagration event. These systems may also protect against over-pressure events. The mitigation strategies are designed such that damage is prevented or minimized to the enclosure.
- **DETONATION** - Combustion which propagates through a gas at supersonic speeds, driven by the transfer of heat.
- **DUT** – Device under test.
- **ELECTRICAL RESISTANCE HEATERS** – Devices that convert electrical energy into thermal energy.
- **END OF DISCHARGE VOLTAGE (EODV)** – The manufacturer’s specified minimum voltage level during discharge.
- **FLEXIBLE FILM HEATERS** – Electrical resistance heaters of a film, tape or otherwise thin sheet-like construction that easily conform to the surface of cell.
- **LOWER EXPLOSIVE LIMIT (LEL)** - The lowest concentration of a flammable gas in air that will produce a flash or fire when an ignition source is present. The fuel-air mixture is too lean to ignite or burn below this limit.
- **MAXIMUM SURFACE TEMPERATURE END-POINT** – The final hold temperature measured on the cell case after conducting the thermal ramp when using the external heater method to achieve thermal runaway of the cell.
- **MODULE** – A sub-assembly that is a component of a BESS that consists of a group of cells or electrochemical capacitors connected together in a series and/or parallel configuration (sometimes referred to as a block) with or without protective devices and monitoring circuitry.
- **STACKED** - A configuration of BESS units in which a unit is placed directly above another unit. Structural support may be provided by the units themselves or via external/supplemental structural supports.
- **STATE-OF-CHARGE (SOC)** – The available capacity in a BESS, pack, module or cell expressed as a percentage of rated capacity.
- **T₉₀** – The time required for a sensor to reach 90% of the final measurement value.

- **THERMAL RUNAWAY** – An incident when the cell’s temperature increases at an exponential rate due to self-heating of the cell’s components/chemicals. The thermal runaway progresses when the cell’s heat generation is higher than heat dissipation to the surroundings. A thermal runaway may lead to fire, explosion, and/or gas and smoke evolution.
- **UNIT** – A frame, rack or enclosure that consists of a functional BESS, which includes components and sub-assemblies such as cells, modules, BMS, ventilation devices, and other ancillary equipment.

DRAFT

References

- [1] “Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems,” Standard ANSI/CAN/UL 9540A:2019, Underwriters Laboratories Inc., Northbrook, Illinois, 2019.

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