IAFF SAFETY ADVISORY

RESPONDING TO RESIDENTIAL ENERGY STORAGE SYSTEMS • FEBRUARY 2025

This safety advisory is a summary of the UL Fire Safety Research Institute report: "Considerations for Fire Service Response to Residential Battery Energy Storage System Incidents."

As the installation of residential energy storage systems increase, the frequency of fire incidents involving these products will increase. In response to this new and evolving hazard for the fire service, the IAFF partnered with UL Solutions and UL Fire Safety Research Institute to conduct a series of large-scale tests sponsored by the U.S. Department of Energy.

This test series was designed to characterize the challenges for fire fighters responding to fires involving residential ESS with a focus on developing size-up and tactical considerations to support the fire service in navigating the modern fireground.

The project included four large-scale tests, including one baseline test and three tests utilizing a mockup of a residential lithium-ion ESS installed in a representative two-car garage. The ESS was constructed with three units with equivalent energy capacity of 17 kWh per unit.

The testing demonstrated the impact of lithium-ion (li-ion) battery involvement on fire growth rate. For the fire fighter, this means incipient fires, well-developed fires, and explosion hazards followed by fires, and rapid-fire growth should all be included in their mental models considered when responding to li-ion battery-initiated incidents.

Unburned battery gas, if present in a ventilation limited fire, will increase the flammability of the smoke and can contribute to increased risk of backdraft, as demonstrated in Tests 3 and 4. This reinforces the potential impact of ventilation that could result in deflagration or a rapid transition to flashover. Deflagration scenarios in a residential garage are considered in three cases: partial volume deflagration, full volume deflagration, and backdraft.

Lithium-ion battery thermal runaway without active fire may be recognizable by distinct white/gray battery gas leaking from the structure and forming low-hanging clouds. Should thermal runaways occur after fire fighters enter, thermal runaway can be indicated by a two-layer accumulation of whitish/gray lighter gases near the ceiling and heavier gases and vapors along the floor. However, there are no reliable visual, thermal imaging, or portable gas meter indicators to confirm battery involvement in a room and contents fire. Additional indicators for battery involvement should be considered beyond smoke appearance. Other common detection methods (e.g., smoke alarms, CO alarms, heat alarms) may be able to detect thermal runaway but may not be viable to detect all thermal runaway scenarios and may be susceptible to nuisance.

The timing and severity of a battery gas explosion is unpredictable. An explosion hazard begins when the instant batteries undergo thermal runaway and release gas without burning. A significant explosion hazard can develop before any exterior indicators (visual or measurable) are shown. Additionally, unburned battery gas ignites readily and can increase the flammability of the smoke in a ventilation-limited fire.

Fire fighters are at greatest risk for explosion hazards in the driveway and at doors, windows, and other vent points. The command post and fire apparatus should not be parked in front of the garage door to avoid this hazard.

Portable gas meters are not effective for determining whether a garage fire involves li-ion batteries. The structure should not be approached or entered to take gas meter measurements if there is a suspected case of batteries in thermal runaway and there are no indicators of a concurrent fire. Full structural PPE (Level D ensemble) with full SCBA should be donned before performing size-up. In all cases when li-ion thermal runaways are suspected, hose lines should be pre-deployed, charged, and ready for operations before ventilation or entry.

An additional 21 large-scale outdoor tests, conducted utilizing a constructed two-car garage outdoors, led to the development of the following tactical considerations for fire fighters responding to a fire potentially involving a residential ESS in an attached two-car garage with the overhead door closed.

The IAFF is seeking additional funding to continue research into the application of various ventilation and suppression tactics. An online educational program will be posted to the IAFF website in the near future.

The following tactical considerations are designed to be incorporated during the initial and continuous size-up.

TACTICAL CONSIDERATIONS

1. **When lithium-ion batteries undergo thermal runway without burning, an explosion hazard begins to develop. The timing of a battery gas explosion is unpredictable. The severity of a battery gas explosion is dependent on gas quantity.**

   If thermal runaway occurs and releases unburned battery gas, an explosion hazard from a partial volume deflagration begins to develop. The severity of the potential explosion hazard increases as thermal runaway propagation continues without flaming.


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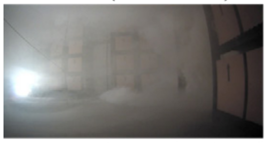
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2. **A significant explosion hazard can develop before any exterior indicators (visual or measurable) are shown.**

   The explosion incident in Erie, CO, as described in Section 2 of the report, is an example that a significant explosion hazard can develop and even occur without any prior exterior indicators. At that incident, it was known that the garage was filled with smoke, but due to the visual similarity between ordinary smoke and unburned battery gas, the explosion hazard was not recognized. When the explosion occurred, the garage door was thrown from its opening and contacted the helmet of the incident commander as it traveled down the driveway. Given the condition of the garage at the time of arrival, hazard could also occur during size-up with no prior indication.

Pictures captured seconds prior to the deflagration. No exterior indicator of failure.

3. **Unburned battery gas ignites readily and can increase the flammability of the smoke in a ventilation-limited fire.**

   Although unburned battery gas has distinct visual and olfactory characteristics, it can appear similar to, and potentially be mistaken for, smoke from a room and contents fire. It is important to be aware that sparking hand tools and powered saws for cutting ventilation holes can create ignition sources for unburned battery gas. No intentional ignition sources were introduced into Test 2, which demonstrated that even ignition sources provided by thermal runaway itself can ignite unburned battery gas unpredictably.

Enough batteries had gone into thermal runaway during the vent-limited phase of the fire in Test 3 to increase the flammability of the smoke inside the garage. When rotary rescue saw cuts were simulated with a gerb, the smoke ignited immediately upon contact with the sparks, and flames spread around the perimeter of the garage door from which smoke was venting.

4. **Without active fire, lithium-ion battery thermal runaways may be recognizable by white/gray battery gas leaking from the structure and forming low-hanging vapor clouds.**

White/gray gas and vapor was first observed leaking out from around the garage door after it had first accumulated inside the structure for several minutes of thermal runaway propagation in Test 2. White/gray gases and/or vapors are only produced from the batteries when they experienced thermal runaways without burning, so continued leakage of these from a structure may indicate ongoing thermal runaways and that the batteries have not yet ignited. It is critical to recognize that this smoke appearance and related potential deflagration hazard is contrary to previous size-up guidance that implies "lazy" or non-turbulent white smoke is an incipient fire and does not cover this potential deflagration risk.

It should be considered that environmental conditions such as wind velocity and direction, terrain, and lighting conditions may impair the ability to identify the distinct battery thermal runaway effluent. Structural factors include the tightness of the seal around the garage door and any penetrations through the exterior walls. The figures below show an example of the conditions observed in Test 2, in outdoor UL experiment in 2020, and at the scene of the explosion in Surprise, AZ.

5. **With or without active fire, stratification of smoke at the ceiling and at the floor indicates the thermal runaway of li-ion batteries.**

The components of battery gas stratify near the ceiling and the floor in a room where batteries are experiencing propagating thermal runways. This tends to leave a characteristic visible region between a smoky layer at the floor and a smoky layer at the ceiling. As thermal runaways do not release as much thermal energy as a flaming fire, there is not as much thermally driven gas movement. As such, the gases may appear stagnant or slow-moving. This distinctive two-layer accumulation of lighter gases near the ceiling and heavier gases and vapors along the floor was clearly present in Test 2. It is important to recognize that this can represent an immediate flash fire or deflagration hazard.

Test 4 demonstrated that even after a transition to flaming (including a possible deflagration), the layer of battery gas near the floor may still be recognizable and unique to a post-thermal runaway condition. Figure 186 provides two different viewing angles from Test 4 demonstrating this phenomenon.

6. **With an active fire, there are no reliable visual or thermal imaging indicators to confirm battery involvement from the exterior of the structure.**

   Despite battery gas from thermal runaways being distinct on its own, the indication of batteries in thermal runaway was obscured by heat and smoke when the room and contents were involved in fire, as demonstrated with Test 3 and Test 4. Soot created from the combustion of ordinary combustible materials will likely obscure the whitish/gray appearance of the battery gases and a significant rise from the fire will result in buoyancy driven movement. Some behavior of smoke "puffing" out from seams around the garage door was observed, but the behavior was very short lived and may not be noticed or could be mistaken for wind driven behavior. Infrared views did not provide any additional detail that was not visible to the naked eye, and the "puffing" behavior was less observable in IR. Should this "puffing" behavior be observed, firefighters should be aware that battery-gas influenced fire dynamics, including backdraft hazards, are possible.

7. **Portable gas meters are not effective for determining whether a garage fire involves li-ion batteries.**

   There was no clear indication whether batteries were involved in the garage fire when portable gas meters were used to measure the gas concentrations near the garage door. The peak gas concentrations observed from the fire with no batteries (Test 1) was similar to the peak gas concentrations when many batteries (12 or more modules) entered thermal runaway during a fire (Test 4).

8. **During initial and continuous size-up, additional indicators for residential energy storage system installation should be considered beyond smoke appearance.**

   During size-up, additional indicators beyond the appearance of any battery gas from thermal runaway should be considered to assess the likelihood of battery involvement. Potential indicators that suggest a residence may have an energy storage system installed include:

   i. The presence of a photovoltaic system.
   ii. An additional connection at the electric meter, or an electric vehicle.
   iii. These pieces of equipment may also be identified by their labeling if mounted on the exterior of the structure.
   iv. If present, the homeowner or resident may also be interviewed to identify the presence or specific location of an energy storage system.
   v. Roofing should be closely scrutinized, as it may be challenging to recognize building-integrated photovoltaic panels (i.e., solar shingles).
   vi. Therefore, fire fighters should be additionally observant about the introduction of energy storage systems (ESS) in their residential response coverage areas. This may be accomplished through coordination with other city divisions responsible for permitting them to identify installation locations. During other responsibilities fire fighters should be alert for indications of ESS.

vii. Fire departments should consider updating their dispatch cards to include questions that develop pertinent information regarding batteries and photovoltaic systems on the property.

Sounds and smells may also indicate the presence of lithium-ion batteries in thermal runaway. In a Federal Aviation Administration database full of hundreds of li-ion battery incidents, the sound of thermal runaway is described as "popping," "clapping," "banging," and "hissing." The smells of thermal runaways are repeatedly described as "electrical" and "plastic."

Improvements to battery awareness are also possible before an incident occurs. It may be possible to review permits for the installation of ESS, PV, and EV chargers, but this capability will vary from jurisdiction to jurisdiction. An additional possibility is to incorporate questions about whether batteries are installed in a residence or believed to be involved in the fire.

9. **Fire fighters are at greatest risk for explosion hazards in the driveway and at doors, windows, and other vent points. Do not park fire apparatus or stage crews in front of garage door.**

Notice the location of the door after the deflagration.

As observed by the forceful gas ejection and garage door damage in Test 2, a deflagration of accumulated battery gas can risk harm to fire fighters in the driveway or other potential vent locations, including windows or doors. The peak pressure is not known for Test 2, but a partial volume deflagration involving approximately 2% (or 0.4 kWh) of the cells in the initiating ESS unit in Test 4 demonstrated that a small volume of battery gas (~213 L) can generate pressures high enough (1–4 kPa) to shatter windows.

Larger battery gas release volumes than what was observed in Test 4 can create higher explosion pressures, detach garage doors, and potentially cause structural damage. Detailed damage information is not available, but two electric vehicle battery thermal runaway incidents that resulted in garage explosions ejected the garage doors tens of feet from the residences. Further data is needed to improve the understanding of the relationship between the amount of gas released from a battery versus explosion hazard severity in residential structures, including a better understanding of whether the structure will be damaged by the explosion (e.g., creating additional areas of hazards to fire fighters) or if the garage door provides adequate pressure relief capacity.

10. **Do not approach or enter to take portable gas meter measurements if there is a suspected case of batteries in thermal runaway and there are no indicators of an active fire.**

Measurements from this test series demonstrated that portable gas meter measurements taken from the exterior of the garage cannot provide a reliable indication of an explosion hazard within. The LEL % measurement, which might be anticipated to be most relevant to determining whether an explosion hazard is present, was zero at the garage door location in all tests. Carbon monoxide, and to a lesser extent VOC concentrations, were elevated when cells were in active thermal runaway propagation, but the concentrations were not appreciably different from the baseline in Test 1 when no batteries were involved.

To get to the locations where these measurements were taken an entry team would have to get close to the garage, exposing them to blast wave, flame, and projectile hazards. In a previous set of tests run in 2020, deflagrations were observed as early as 30 seconds after the start of thermal runaway, prior to any of the interior or exterior portable gas meters indicating an increase in flammable gas concentrations and prior to the development of a visible vapor cloud.

An explosion is most likely to occur during active thermal runaways, which adds both further unburned gas

and potential ignition sources to the garage. For example, in Test 2, an explosion occurred without any otherwise recognizable warning that an explosion was about to occur. Use of a portable gas meter near the door in this case could have caused serious injury or even death to the user. Distance away from the garage (as demonstrated) and wind will diminish or prevent any potentially useful gas concentration measurements. These same observations were made in a series of walk-in containerized lithium-ion battery experiments conducted by UL in 2020.

The deflagration event in Tests 2 occurred after a vapor cloud had started to form on the exterior of the garage, and exterior portable gas meters measured flammable gas concentrations higher than zero.

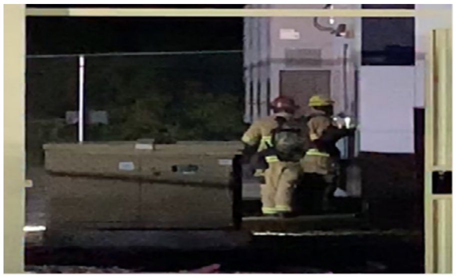
Two real-world incidents also demonstrate this point. At an ESS explosion in Surprise, Arizona, the battery gas concentration exterior to a structure with batteries in thermal runaway reduced below levels associated with HazMat and explosion hazards. Approximately three minutes after the door was opened, outside air had mixed with battery gases to create a flammable mixture and a severe explosion injured four fire fighters near the door from which gas concentrations were being measured. More recently, an explosion occurred due to an electric battery thermal runaway in a garage in Erie, Colorado. It is not known if there were any gas measurements collected, but the scene was sized-up with "nothing showing." The explosion caused the garage door to become a projectile, which narrowly missed a fire fighter standing nearby.

11. **Because conditions can change rapidly, full structural PPE with SCBA should be donned before performing size-up. PPE should also be worn in the vicinity of heat impacted batteries until removed from the scene.**

This test series demonstrated that it will likely be difficult to recognize any indications that li-ion batteries have generated an explosion hazard or are significantly involved in a room and contents fire. Tests 2 and 4 made clear that conditions can change quickly during a deflagration or rapid increase in fire growth.

Test 2 demonstrated that following deflagration, the driveway can become an area of high risk for respiratory hazards during size-up or preparation for entry by ejecting accumulated smoke and battery gas tens of feet from the structure. High concentrations of toxic gases built up emphasize the need for breathing protection at the level of SCBA. The speed of the hazard development precludes donning protective equipment after the fact. In deflagration, projectiles and thermal hazards may be hazards as well. Structural PPE is not intended for protection from projectile hazards but may reduce thermal hazards sufficiently. Test 4 demonstrated that adding ventilation to a li-ion battery involved fire may create rapid fire growth conditions which preclude donning protective equipment.

It is critical that fire fighters wear adequate PPE when working around heat-impacted batteries during suppression, overhaul, and any protracted scene examination. Any time a lithium-ion battery is heat-impacted, fire fighters should anticipate the potential for sudden and unpredictable thermal runaways. Thermal exposure may damage the delicate internal structure of a battery and cause the battery to re-ignite at unpredictable times. The development of smoke and fire from a heat-impacted battery may create life-threatening exposures faster than proper PPE can be donned; therefore, it is critical to wear appropriate PPE before handling or working near heat-impacted batteries.



12. **Because conditions can change rapidly, hose lines should be pre-deployed, charged, and ready for operations before ventilation or entry when li-ion thermal runaways are suspected. Hose lines should remain available to manage reignition/thermal runaway of heat impacted batteries until removed from the scene.**

Venting a garage fire that involves a significant quantity of li-ion batteries in thermal runaway can result in exceptionally fast fire growth and/or a backdraft. Fire fighters should confirm all residents have evacuated from the structure prior to making entry into the home. When fire fighters are conducting search operations, fire fighters need to be aware that pressure due to a backdraft may damage the fire-resistant barrier between the garage and living space, enabling fire spread from the garage into the home. This could occur behind their operations.

The results of these tests emphasize the need to treat manual ventilation of a fire that may involve ESS with additional caution. Flammable gas accumulation hazards can exist whether there is visible evidence of thermal runaways or no clear indication of thermal runaways.

Fire fighters should anticipate the potential for ignition of accumulated thermal runaway effluent gases and rapid transition to flashover and/or a backdraft following changes in ventilation when the involvement of a residential ESS unit in a garage fire is suspected. Both a rapid increase in flaming (Test 3) and a backdraft (Test 4) were observed in this test series as a result of changing ventilation.

Test 3 demonstrated enhanced flammability of the smoke when it ignited during simulated saw operation. Once flaming started, any increase in the vent area immediately resulted in an increase in the size of the fire venting through the garage door. Battery gas can increase the flammability of smoke from ventilation limited fires.

Test 4 demonstrated that introducing air into a ventilation limited garage fire involving an ESS unit may result in a backdraft. These findings are consistent with the findings published by UL in 2020 regarding containerized ESS installations.

Reignitions were not observed in this testing because the batteries were managed with extreme safety conservatism. Test termination procedures included immediately flooding the battery unit enclosures prior to initiating room fire suppression. While water may cause shorting, which could lead to thermal runaways later, this hazard was managed by immediately disconnecting the units from the structure and expediently moving the affected units to an electrolyte-enhanced water bath for managing thermal runaways and dissipating stranded energy. Extreme caution should be exercised in real incidents to consider reignitions of heat impacted batteries that have not been removed from the structure and fire fighters must not put themselves in a position where a heat-impacted battery is in their path of egress during a reignition.

Fire departments should also consider the potential longevity of resource deployment during incidents involving li-ion batteries in structures. The potential for re-ignitions may create extended timelines in which resources must remain committed to post incident standby and are not available for use in other responses.