Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion - Arizona

Mark B. McKinnon
Sean DeCrane
Stephen Kerber

UL Firefighter Safety Research Institute
Columbia, MD 20145

UNDERWRITERS
LABORATORIES™

Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion - Arizona

Mark B. McKinnon
Sean DeCrane
Stephen Kerber

UL Firefighter Safety Research Institute
Columbia, MD 21045

July 28, 2020

UNDERWRITERS
LABORATORIES™

Underwriters Laboratories Inc.
Terrence Brady, President

UL Firefighter Safety Research Institute
Stephen Kerber, Director

Contents

List of Figures

List of Abbreviations

UL	Underwriters Laboratories
UL FSRI	UL Firefighter Safety Research Institute
AC	Alternating Current
AHJ	Authority Having Jurisdiction
ALS	Advanced Life Support
BMS	Battery Management System
DC	Direct Current
EMS	Emergency Medical Services
ESMS	Energy Storage Management System
ESS	Energy Storage System
EV	Electric Vehicle
HAZMAT	Hazardous Materials
HVAC	Heating Ventilation & Air Conditioning
IAP	Incident Action Plan
IFC	International Fire Code
ISO	Insurance Services Office
JPR	Job Performance Requirement
LEL	Lower Explosive Limit
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
PASS	Personal Alert Safety System
PPE	Personal Protective Equipment
SCBA	Self-Contained Breathing Apparatus
SDS	Safety Data Sheet
SME	Subject Matter Expert
SOC	State of Charge
TIC	Thermal Imaging Camera
UEL	Upper Explosive Limit
VESDA	Very Early Smoke Detection Apparatus
WMD	Weapons of Mass Destruction

Acknowledgments

This review was funded through a grant from the Department of Homeland Security (DHS) Federal Emergency Management Agency's (FEMA) Assistance to Firefighters Grant (AFG) Program as a Fire Prevention and Safety Grant: (EMW-2018-FP-00476). This critical fire service project would not be possible without this funding and continued support. The Surprise Fire-Medical Department, Peoria Fire-Medical Department, and Arizona Public Service (APS) supplied requested information and made the personnel who had knowledge pertinent to the incident available for interviews and conversations. Representatives from the International Association of Fire Fighters (IAFF) Local 0493 were present at the meetings with the fire department personnel held to review the incident. Adam Barowy of UL LLC provided guidance on lithium-ion battery thermal runaway and reviewed this report. This report would not have been possible without aid and cooperation from these groups and individuals.

1 Executive Summary

On April 19, 2019, one male career Fire Captain, one male career Fire Engineer, and two male career Firefighters received serious injuries as a result of cascading thermal runaway within a 2.16 MWh lithium-ion battery energy storage system (ESS) that led to a deflagration event.

The smoke detector in the ESS signaled an alarm condition at approximately 16:55 hours and discharged a total flooding clean agent suppressant (Novec 1230). The injured firefighters were members of a hazardous materials (HAZMAT) team that arrived on the scene at approximately 18:28 hours. The HAZMAT team noted low-lying white clouds of a gas/vapor mixture issuing from the structure and nearby components and drifting through the desert. The team defined a hot zone and made several entries into the hot zone to conduct 360-degree size-ups around the ESS using multi-gas meters, colorimetric tubes, and thermal imaging cameras (TICs). The team detected dangerously elevated levels of hydrogen cyanide (HCN) and carbon monoxide (CO) during each entry. The team continued to monitor the ESS and noted the white gas/vapor mixture stopped flowing out of the container at approximately 19:50 hours.

The HAZMAT leadership developed an incident action plan with input from a group of senior fire officers and information about the ESS provided by representatives from the companies that owned, designed, and maintained the ESS. The HAZMAT team made a final entry into the hot zone and found that HCN and CO concentrations in the vicinity of the ESS were below an acceptable threshold. In following with the incident action plan, the team opened the door to the ESS at approximately 20:01 hours. A deflagration event was observed by the firefighters outside the hot zone at approximately 20:04 hours. All HAZMAT team members received serious injuries in the deflagration and were quickly transported to nearby hospitals. Note: The lithium-ion battery ESS involved in this incident was commissioned prior to release of a first draft of the current consensus standard on ESS installations, NFPA 855 [1]; the design of the ESS complied with the pertinent codes and standards active at the time of its commissioning.

1.1 Contributing Factors

- Despite all responding firefighters being current with HAZMAT competencies from First Responder to Technician level, core HAZMAT training curricula for these competencies do not yet cover basic ESS hazards. Extra-curricular ESS-specific training opportunities do not yet comprehensively address ESS hazards.
- The fire and smoke detection systems did not include, and were not required to include, sensors that provided information about the presence of flammable gases. There were no means for the HAZMAT team to monitor toxic gas concentrations, LEL, or the conditions inside the ESS from a physically secure location.

- The ESS communication system failed before the HAZMAT team arrived at the incident. Personnel who maintained the ESS and the fire department were unable to use the system to understand the conditions inside the installation.
- The emergency response plan was not provided to the responding fire service personnel prior to this incident. Advanced disclosure of the emergency response plan was not required by the applicable codes or standards at the time of the incident.
- The emergency response plan that was provided to fire service personnel on the scene, although compliant with the applicable codes and standards at the time of the incident, did not provide adequate guidance for mitigating thermal runaway, fire, and explosion hazards generated by the ESS.
- The design of the ESS did not include deflagration venting per NFPA 68 or adequate mechanical ventilation per NFPA 69 to prevent accumulation of flammable gases above an explosive concentration. Construction to these standards was not required by applicable codes at the time the ESS was commissioned.
- The total flooding clean agent suppression system prevented flaming during the early phase of the incident, but was not designed for and did not provide explosion protection.

1.2 Key Recommendations

The following items are recommendations that should be considered as requirements in the appropriate standards, codes, research programs, and curricula to ensure the safety of the fire service and maintenance personnel who work with lithium-ion battery ESS:

- Basic Firefighter, Officer, and HAZMAT training should emphasize ESS safety; the potentially explosive nature of the gases and vapors released during lithium-ion battery thermal runaway, vapor cloud formation and dispersion; and the dynamics of deflagrations and blast wave propagation.
- Research that includes full-scale testing should be conducted to understand the most effective and safest tactics for the fire service in response to lithium-ion battery ESS incidents.
- Until definitive tactics and guidance can be established through full-scale experiments, it is recommended that fire service personnel define a conservative potential blast radius and remain outside of it, while treating the lithium-ion ESS as if the gas mixture in the enclosure is above the LEL until proven otherwise.
- An online educational tool should be developed to proliferate the appropriate base knowledge about lithium-ion battery ESS hazards and fire service tactical considerations.
- Lithium-ion battery ESSs should incorporate gas monitoring that can be accessed remotely.

- Research that includes multi-scale testing should to be conducted to evaluate the effectiveness and limitations of stationary gas monitoring systems for lithium-ion battery ESSs.
- Lithium-ion battery ESSs should incorporate robust communications systems to ensure remote access to data from the BMS, sensors throughout the ESS, and the fire alarm control panel remains uninterrupted.
- Owners and operators of ESS should develop an emergency operations plan in conjunction with local fire service personnel and the AHJ, and hold a comprehensive understanding of the hazards associated with lithium-ion battery technology.
- Signage that identifies the contents of an ESS should be required on all ESS installations to alert first responders to the potential hazards associated with the installation.
- Lithium-ion battery ESSs should incorporate adequate explosion prevention protection as required in NFPA 855 or International Fire Code Chapter 12, where applicable, in coordination with the emergency operations plan.
- Research that includes full-scale testing should be conducted to determine the most effective fire suppression and explosion prevention systems for lithium-ion battery ESSs.
- Research focused on emergency decommissioning best practices and the role of the fire service in an emergency situation should be conducted.

2 Introduction

On April 19, 2019, one male career Fire Captain, one male career Fire Engineer, and two male career Firefighters received serious injuries as a result of a catastrophic failure within a 2.16 MWh lithium-ion battery energy storage system (ESS) that led to a deflagration event. In the same event, one male career Fire Captain and three male career Firefighters, as well as one male police officer, required overnight observation at a local hospital.

On October 28 and October 29, 2019, a Research Engineer, a Research Director, and an Advisory Board Member from the UL Firefighter Safety Research Institute (FSRI) traveled to Arizona to conduct a review of the incident. The UL FSRI team met with the Fire Chiefs of the two automatic-aid departments that responded to the ESS fire (Surprise Fire-Medical Department and Peoria Fire-Medical Department), the Assistant Fire Chief and Fire Marshal of the Surprise Fire-Medical Department, and a representative of the IAFF local union. The UL FSRI investigators visited and inspected the incident site and took photographs while questions were answered by a Program Manager and Engineer from the company that owned the ESS. The investigators interviewed all members of the Surprise Fire-Medical Department crew that initially responded to the incident as well as three of the four members of the Peoria Fire-Medical Department Hazardous Materials (HAZMAT) team who were injured in the incident.

3 Fire Department Overview

3.1 Surprise Fire-Medical Department

Surprise Fire-Medical Department is a mid-sized, all-hazard fire department with a total of 171 employees. The department has seven stations with six engines and one ladder truck and employs 127 uniformed Firefighters. The department has three Battalion Chiefs, three Battalion Safety Officers (Captains), 27 Captains, 28 Engineers, 57 firefighters, and 30 civilian staff. Of these personnel, 25 are HAZMAT technicians, 64 are medics, 12 are certified wildland firefighters, and 26 are safety officer certified. The department is managed by the Fire Chief with the aid of administrative staff that includes one Assistant Chief, a Training Division Chief, a Drill Officer, and one EMS Medical Officer. In addition, they have a dedicated training division within their administration department. Along with having their own training facility, this division is responsible for firefighter recruit training, monthly training, EMS training, driver training, HAZMAT training, career development, required OSHA training, and wildland training [2].

All units in the Surprise Fire-Medical Department are advanced life support (ALS) units. The department operates a three-platoon shift assignment that consists of 48 consecutive hours on, followed by 96 consecutive hours off. The department provides emergency medical services (EMS) and gives ALS (transporting) care. With a geographical area of 107.82 square miles, their protected population is approximately 131,161 (as of 2018). The department responded to 14,713 calls in 2018 and holds an Insurance Services Office (ISO) Class 1 rating [2].

3.2 Peoria Fire-Medical Department

Peoria Fire-Medical Department is a mid-sized department with a total of 190 sworn firefighters that has a protected population of 172,259 (as of 2018) and covers 179.10 square miles. The department has a total of six Battalion Chiefs, 40 Captains, 33 Engineers, and 106 firefighters. The department is comprised of four divisions that include operations/training, administrative, medical services, and prevention/emergency management, each of which is managed by a Deputy Chief. The department operates a three-platoon shift assignment that consists of 48 consecutive hours on, followed by 96 consecutive hours off [3].

The department provides EMS and gives ALS (transporting) care. In addition, Peoria Fire-Medical Department is comprised of several tactical teams that include two technical rescue teams, trained wildland firefighters, paramedic bike teams, a HAZMAT team, and a fire boat with rescue swimmers. The department has eight stations with eight engines, two ladder trucks, four ambulances, and several other specialty vehicles (a brushfire truck, a low acuity truck, a HAZMAT support truck, a technical rescue team support truck, a fire boat, and a 6x6 UTV off-road rescue vehicle).

The HAZMAT operations team is housed at one of the fire stations that has an engine and a HAZMAT support truck. This team is dispatched to respond to chemical spills, carbon monoxide calls, and gas leaks, as well as any other situation where dangerous materials come into contact with the environment [3].

3.3 Automatic Aid

Surprise Fire-Medical Department and Peoria Fire-Medical Department are members of the Phoenix Regional Automatic Aid Dispatch System, a consortium of governmental fire departments wherein the participants agree to act as a single entity in the interest of providing the best care to the residents of the region. In the case of an emergency, firefighters in the Phoenix Metropolitan Area closest to an emergency respond regardless of jurisdictional boundaries. The Phoenix Fire Department Regional Dispatch Center provides fire and emergency medical dispatching for 26 jurisdictions directly and three entities indirectly, covering a service area over 2,000 square miles. The ESS involved in this incident was in the city of Surprise, but when the call was elevated to a HAZMAT operation after the initial size-up, and with the Surprise Fire-Medical Department HAZMAT team previously dispatched to a separate call, the Peoria Fire-Medical Department HAZMAT team responded to the incident and assisted the Surprise Fire-Medical Department.

3.4 Training and Experience

In Arizona, the Fire Training Recruit Academy involves a 14-week training program. This training program achieves the training requirements designated as Firefighter I and Firefighter II as defined in the National Fire Protection Association (NFPA) 1001 *Standard for Fire Fighter Professional Qualifications* [4], as well as the HAZMAT First Responder designation. Graduates of the academy training hired by Peoria Fire-Medical Department advance to the rank of Probationary Firefighter and are placed in the field for 12 months for ongoing training with monthly evaluations.

Promotions to higher ranks follow the guidelines and requirements of NFPA 1021 *Standard for Fire Fighter Professional Qualifications* [5]. Additionally, advancement to Fire Engineer requires 3.5 years at the rank of Firefighter. Promotion to Fire Captain requires at least seven years of experience. Battalion Chief requires one year of service as a Fire Captain. All promotions require a written test and practical exercise.

The HAZMAT First Responder designation is achieved after a 40-hour course aimed at educating first responders on awareness and operations of hazardous materials. The objectives of the course are stated as the following:

- Analyze the incident to identify the problem and the behavior of HAZMAT/Weapons of Mass Destruction (WMDs) and structures present.

- Plan an initial response, develop an incident action plan and communicate that plan in accordance with standard operating procedures/guidelines and available equipment and personnel.
- Implement the planned response while observing operations and outcomes.
- Use personal protective equipment (PPE) at HAZMAT/WMD incidents.
- Defensively control products at HAZMAT/WMD incidents.
- Evaluate the progress to assess the effectiveness of the actions taken to stabilize the incident, and protect people, property, and the environment.

The HAZMAT technician designation is achieved after a 200-hour course aimed at providing additional education to those who have already achieved the designation of HAZMAT First Responder. The objectives of the courses are stated as the following:

- Analyze the incident to determine the complexity of the problem and potential outcomes.
- Plan a response including developing response objectives, identifying potential response options, selecting PPE required and a technical decontamination process, and developing an incident action plan (IAP).
- Implement the planned response consistent with local emergency response plans and/or standard operating procedures by performing the duties of the HAZMAT branch, donning, doffing, and working in PPE, and performing control functions and decontamination.
- Evaluate progress to determine the effectiveness of control and decontamination functions identified in the IAP.

The Fire Captain of the Surprise Fire-Medical Department crew that initially responded to the ESS fire scene was a HAZMAT technician and the rest of the crew were HAZMAT First Responders [6]. In addition, three of the four Surprise Fire-Medical Department crew members were trained as medics [7]. Three of the four members of the Peoria Fire-Medical Department HAZMAT team that responded to the ESS fire were HAZMAT technicians, and the fourth was a certified HAZMAT First Responder [6].

The Peoria Fire-Medical Department HAZMAT training involved an initial six week course with weekly continued education [3]. The Fire Captain who led the Peoria Fire-Medical Department HAZMAT team attended NFPA ESS Awareness Training that was focused on solar panels, but the training did not expound on the hazards associated with lithium-ion battery storage systems. He sought out additional training and education and attended several additional local training opportunities that focused on solar panels. He responded to a fire in an electric vehicle (EV) repair facility that involved lithium-ion batteries in May 2017 and made several entries into the facility during the fire. He attended a HAZMAT class that was informed by the 2017 incident in the EV facility and provided more emphasis on the hazards of lithium-ion batteries. He attended a HAZMAT class on cell tower battery storage that was not specific to lithium-ion battery technology. This training and these experiences made the Peoria Fire Captain aware of the most up-to-date information and operating procedures concerning lithium-ion batteries available to the fire service.

3.5 Equipment and Personnel

A call for smoke in the area of an electric substation came into Phoenix dispatch on April 19, 2019, at 17:41:54 hours [8]. The following apparatus and personnel were dispatched from the Surprise Fire-Medical Department:

Engine 304 (E304)
Captain (E304 Capt)
Firefighter (E304 FF) (Acting Fire Engineer)

Brush 304 (BR304)
Firefighter (BR304 FF)

Tanker 304 (T304)
Firefighter (T304 FF)

The incident was elevated to a HAZMAT operation at approximately 18:04 hours at the request of the E304 Capt. The following apparatus and personnel were dispatched from the Surprise Fire-Medical Department at that time:

Battalion Command 301 (BC301)
Battalion Chief (BC301 BC)
Battalion Safety Officer (BC301 BSO)

The Surprise Fire-Medical Department HAZMAT unit was previously dispatched to a call, so the following Peoria Fire-Medical Department personnel were dispatched at 18:04 hours due to the automatic aid response plan:

Engine 193 (E193)
Captain (E193 Capt - Injured)
Fire Engineer (E193 FE - Injured)

Hazardous Materials Support 193 (HM193)
Two Firefighters (HM193 FF1 - Injured, HM193 FF2 - Injured)

The Hazardous Materials Support unit carried all of the equipment required for a HAZMAT operation more serious than a gas leak. The equipment from the Hazardous Materials Support unit used during the ESS fire included a gas detector (Bascom-Turner Instruments Gas-Ranger), five-gas meter (RAE Systems MultiRAE Lite (PGM-6208)), colorimetric tubes (Dräger), and a thermal imaging camera (TIC). The gases of interest whose concentrations were measured near the ESS were carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), volatile organic compounds (VOCs), hydrogen cyanide (HCN), ammonia (NH_3), chlorine (Cl_2), and hydrogen sulfide (H_2S). The MultiRAE gas meter was manufactured in 2010 and was last calibrated prior to the incident on April 1, 2019 [9].

Car 957 North and South are Phoenix Fire Department Safety Officers specializing in HAZMAT and Technical Rescue. Car 957 North and South were not dispatched to the scene, but the HAZMAT team consulted with Car 957 North and South prior to the HAZMAT team making the final entry into the hot zone.

3.6 Contributing Factors

A review of the fire department organization, training, experience, and resources highlights one factor that existed before this incident that contributed to its ultimate outcome:

- Despite all responding firefighters being current with HAZMAT competencies from First Responder to Technician level, core HAZMAT training curricula for these competencies do not yet cover basic ESS hazards. Extra-curricular ESS-specific training opportunities do not yet comprehensively address ESS hazards.

4 Incident Overview

4.1 Weather

At 18:58 hours, weather data collected at Luke Air Force Base (approximately 11 miles south of the ESS) indicated the temperature was 91°F. The dew point was 32°F with a humidity of 12%. The wind speed was 6 miles per hour to the northwest and there were 0 inches of precipitation throughout the day [10].

4.2 Building Construction

The lithium-ion battery ESS was housed within a steel structure with approximate exterior dimensions 50 ft x 14.25 ft x 13 ft. An aerial image of the building site is provided in Figure 4.1, with the facility highlighted with a red outline. The building was oriented such that the side with the longer dimension ran from the southwest to the northeast. The structure had a steel door on the northeast side of the southeast-facing wall as well as a steel door in the center of the southwest-facing wall. These steel doors included transparent vision panels that allowed optical access to the interior of the building. The interior of the building was lined with insulation of unknown material and thickness [11]. The installation was put into service in March 2017. The building fire code at the time of construction was IFC 2012. This version of the fire code did not dictate specific thermal runaway management or ventilation for lithium-ion battery ESS, but set forth requirements for signage, seismic protection, and smoke detection. Note that the date the ESS was commissioned was prior to release of a first draft of the current consensus standard on ESS installations, NFPA 855 [1].

Photographs of the ESS and fence collected after overhaul of the scene are provided in the following figures. Figure 4.2 displays the solid wall and gate that isolated the structure from the frontage road. Figure 4.3 displays the southeast side of the ESS, Figure 4.4 displays the northeast side of the ESS, Figure 4.5 displays the northwest side of the ESS, and Figure 4.6 displays the southwest side of the ESS. Each of these photographs have been modified to remove brand names and logos to protect the anonymity of the owner and designer of the ESS. Note that both doors were removed and destroyed in the deflagration, and those that appear in the following images were installed to retain control of entry and protect the structure from weather.

The facility was equipped with a very early smoke detection apparatus (VESDA) aspirated smoke detector system that constantly drew air samples to monitor the conditions within the facility. The facility was protected by an automatic clean agent suppression system designed to discharge 30 seconds after the smoke detection system registered an alarm condition. The suppression system was designed to completely discharge 713 lbs. of Novec 1230 within 10 s (note that the design

Figure 4.1: Aerial photo of lithium-ion battery ESS site with the facility outlined in red. (modified from [12])

Figure 4.2: Photograph of the solid wall and gate to the northeast of the ESS [13].

Figure 4.3: Photograph of the ESS after the incident from the southeast [13].

Figure 4.4: Photograph of the ESS after the incident from the northeast [13].

concentration for the ESS was 10%) [14]. A performance requirement of clean agent suppression systems defined in NFPA 2001 is that the concentration of the extinguishing agent must remain greater than 85% of the design concentration at the highest elevation of the protected content within the hazard area for 10 minutes after discharge or for sufficient time to enable action by trained personnel. The system installed in the ESS was designed for a hold time of 10 minutes

Figure 4.5: Photograph of the ESS after the incident from the northwest [13].

with a predicted hold time in the range of 5.4–7.6 minutes based on the leakage rate measured in two enclosure integrity tests [14].

The ESS had a total of eight HVAC units, four on both the southeast and northwest sides of the structure. The HVAC system was set to maintain a temperature of 75°F ± 5°F [11]. Dampers within the systems were designed to seal when the suppression agent was discharged to prevent venting that could decrease the effectiveness of the clean agent suppressant.

Figure 4.6: Photograph of the ESS after the incident from the southwest [13].

4.3 Energy Storage System

The ESS was owned by the local electric company and consisted of a lithium-ion battery array that had a capacity of 2 MW AC/2.16 MWh. The primary function of this system was to integrate solar energy resources in an area with high rooftop solar penetration and grid services, including voltage regulation and power quality [11]. The array was comprised of 27 racks that each housed 14 battery modules. Each of the modules contained 28 lithium-ion NMC battery cells, which means the cathode material was a lithium-metal oxide that contained nickel, manganese, and cobalt ($LiNiMnCoO_2$).

A schematic of the ESS is provided in Figure 4.7. A photo of a typical battery rack installed in the system is displayed in Figure 4.8. The racks also housed a battery protection unit, a node controller, and an inverter. At the time the ESS communication system first indicated an anomaly, all of the batteries in the system were charged to 90% state-of-charge (SOC). The ESS was monitored remotely via wireless communication, which was lost approximately 50 minutes after the initial anomaly [11].

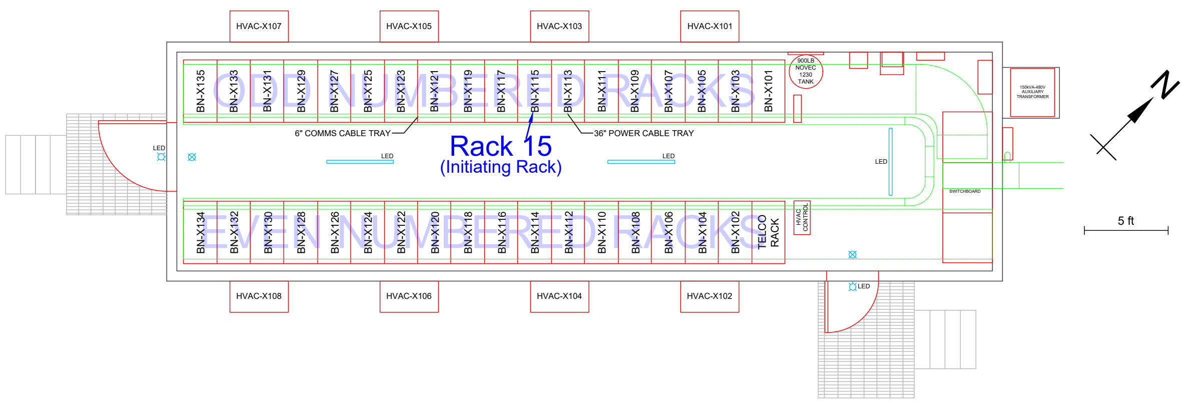

Figure 4.7: Schematic of the ESS (adapted from [15]).

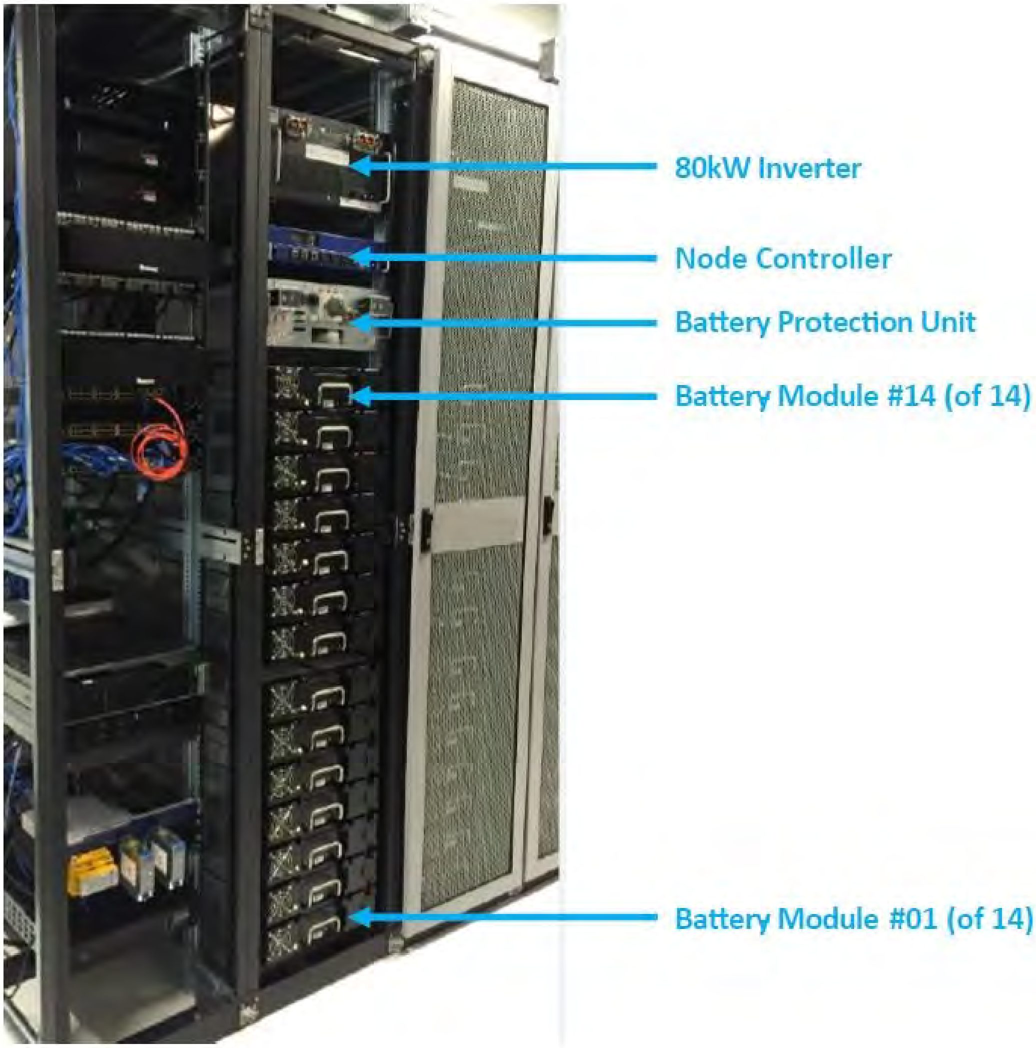

Figure 4.8: Photo of an example battery rack in an ESS [15].

4.4 PPE

The crew of E304, BR304, and T304 expected a brush fire when they were initially dispatched, and they were dressed in PPE adequate to respond to a brush fire. When they arrived on the scene and it was evident the call involved a structure, the crew donned full turnout gear and self-contained breathing apparatuses (SCBAs) to conduct a 360-degree size-up and deploy a hoseline to the southeast-facing door. E304 Capt defined a tentative hot zone just prior to elevating the call to a HAZMAT operation and instructed the rest of the crew to remain outside the hot zone. The crew dressed down and removed SCBAs during operations in which they were outside the hot zone.

The HAZMAT team wore full turnout gear with SCBAs to perform an initial size-up that involved defining the extent of the hot zone and assessing the hazards present. The HAZMAT team made several more entries into the hot zone and wore full turnout gear and SCBAs during all entries. In the rescue operations after the deflagration event and the subsequent mayday call, the helmets and masks of all members of the HAZMAT team and E193 Capt's SCBA tank and gloves were found to have been removed by the force of the deflagration.

4.5 Timeline

An approximate timeline summarizing the salient events in this incident up to the time of the mayday is listed below. The times are approximate and were obtained from data sent from the ESS to the company that maintained the ESS, available dispatch channel records, witness statements, and fire department records. This timeline is not intended to be used as, nor should it be used as, a formal record of events. Only those dispatch channel communications related to the fire service personnel actions and the resulting injuries are included.

- **16:54:30 Hours**

  The minimum battery cell voltage in Module 2 of Rack 15 begins to rapidly decrease. [15].

- **16:54:44 Hours**

  Air temperature measurements within the inverters at the top of Racks 15 and 17 begin to rapidly increase from approximately 104°F (40°C) to a peak of 121.6°F (49.8°C) over 54 s [15].

- **16:55:20 Hours**

  Smoke detection system registered an alarm condition causing all DC circuit breakers, AC inverter contactors, and the main AC breaker to open [15].

- **16:55:38 Hours**

  Air temperature measurements within the inverters at the top of Racks 15 and 17 reach a peak temperature of 121.6°F (49.8°C) [15].

- **16:55:50 Hours**

  Suppression system discharged [15].

- **17:41:54 Hours**

  Dispatch received a call reporting smoke in the area of an electric substation accompanied by a bad smell [8].

  Engine 304 (E304), Brushfire 304 (BR304), and Truck 304 (T304) were dispatched [8].

- **17:44:08 Hours**

  All communication from the ESS was lost [15].

- **17:48:52–17:49:12 Hours**

  E304, BR304, and T304 arrive on scene [8].

- **18:04:21 Hours**

  E304 Capt elevated call to a HAZMAT operation and requested a Battalion Chief be dispatched [8].

  Engine 193 (E193), HAZMAT Support Truck 193 (HM193), and Battalion Command Vehicle 301 (BC301) were dispatched [8].

- **18:18:30 Hours**

  BC301 arrives on scene [8].

- **18:28:21–18:28:50 Hours**

  E193 and HM193 arrive on scene [8].

- **18:37 Hours (approximate)**

  HAZMAT team donned full turnout gear and SCBAs and made their first entry into the fenced area to conduct a 360-degree size-up around the ESS and define a hot zone [8, 9].

- **18:51:21 Hours**

  HAZMAT team made second entry into hot zone to conduct 360-degree size-up and monitor gas concentrations [8, 9].

- **19:10 Hours (approximate)**

  HAZMAT team made a third entry into the hot zone to conduct a 360-degree size-up and monitor gas concentrations [8, 9].

- **19:15–19:50 Hours (approximate)**

  The HAZMAT team held a conference with E304 Capt, BC301 BC, and Car 957 North and South establishing that the HCN and CO concentrations in the hot zone external to the ESS were trending toward safe levels, and developed a plan to proceed that would involve opening the door to the ESS [6].

- **19:50 Hours (approximate)**

  The visible gas/vapor mixture was no longer observed to be issuing from the ESS [6].

- **19:52:24 Hours**

  HAZMAT team made final entry into the fenced area to measure the HCN and CO concentrations in the hot zone [8, 9].

- **19:58:03 Hours**

  HM193 FF2 pulled a hoseline forward to the entry door to prepare to open the door of the ESS [8].

- **20:00:54 Hours**

  HAZMAT team opened door to the ESS [6].

Shortly after opening the door, E193 Capt put right foot over the door threshold to gain optical access to the line of racks using the TIC. E193 Capt declared a maximum temperature of 104°F with no active fire or visible arcing [6, 8].

- **20:03:49 Hours**

  Mayday call [8].

4.6 Detailed Incident Narrative

At 17:41 hours on April 19, 2019, Surprise Fire-Medical Department Engine 304 was dispatched for a report of smoke in the area of a major highway. The Fire Captain of Engine 304 acknowledged it was brushfire season and expected the smoke to be related to a brushfire in the desert surrounding the highway. He had his crew dress in brushfire gear and respond with the fire engine (E304), the brush truck (BR304), and the tanker truck (T304). All three vehicles arrived on the scene by approximately 17:49 hours.

Upon arrival, the crew identified a structure protected by a chain-link fence on three sides and a block wall with an operable gate on one side. A visible gas/vapor mixture was observed issuing from the structure and adjacent external equipment. The crew was met by a man who identified himself as a contractor employed by the company that maintained the ESS. The contractor asked E304 Capt to cut the lock to the gate so that he could enter and fix the problem. The contractor stated that the building was used to store lithium-ion batteries and that the data from the system indicated a component in the system had overheated [16]. E304 Capt directed the contractor away from the gate and proceeded to cut the lock to gain entry to the fenced area to conduct a 360-degree size-up. At the same time, the other members of the crew pulled a hoseline off the engine and up to the southeast-facing door of the ESS. While the fire department personnel conducted a size-up, the contractor hit the emergency shutoff switch next to the door on the southeast side of the ESS and put a key in the lock on the door. The function of the emergency shutoff switch is unknown.

As E304 Capt was finishing the size-up, an employee from the company that owned the ESS arrived on the scene. The contractor from the company that maintained the ESS and the employee from the company that owned the ESS communicated to E304 Capt that the ESS building was a "sealed system." These representatives recommended that the door not be opened at that time, and that the fire department personnel should, "let it sit for a little bit," but deferred to E304 Capt's expertise to manage the incident [14]. E304 Capt identified the need to elevate the call to a HAZMAT operation due to his knowledge of the possibility of hazardous gases produced during thermal runaway of lithium-ion batteries. E304 Capt decided a temporary 300 ft radius hot zone was necessary and directed the crew to disconnect the hoseline to move E304 to lay an extended hoseline. E304 Capt also directed that BR304 and T304 be moved from the northwest side of the gate to the southeast side to make room for other responding vehicles.

E304 Capt radioed dispatch at approximately 18:03 hours requesting a Battalion Chief and HAZMAT unit be dispatched to the scene. This resulted in BC301 being dispatched with a Battalion

Chief and Battalion Safety Officer. The Surprise Fire-Medical Department HAZMAT unit was already dispatched to a separate call, which resulted in the Peoria Fire-Medical Department HAZMAT team (E193 and HM193) automatically being dispatched as the nearest available HAZMAT unit. BC301 arrived on the scene at approximately 18:18 hours, at which point BC301 BC took command of the fire ground. BC301 BC asked the contractor to sit in BC301 until the HAZMAT unit arrived so that he could relate all of the information he had to the HAZMAT team prior to formulating a plan.

When E193 was dispatched to the call, E193 Capt immediately had his team start to conduct research on the potential hazards associated with battery fires while they were en route to the scene. E193 and HM193 arrived at the scene and E193 Capt met with E304 Capt, BC301 BC, the contractor, and at least one employee from the company that owned the ESS. Upon arrival, the HAZMAT team observed a diffuse cloud of a white/gray gas/vapor mixture ranging from the ground to an elevation approximately 2–3 ft above the ground. The visible gas/vapor mixture appeared to be denser than the ambient air and was observed issuing from the ESS and from the distribution box and transformer to the east and north of the structure. E193 Capt described the smell in the vicinity of the ESS as nasty and acrid. Photographs of the scene taken by E193 FE upon arrival are presented in Figure 4.9.

Figure 4.9: Photographs of the ESS scene taken by E193 FE upon the arrival of E193 [6].

E193 Capt met with E304 Capt, BC301 BC, the contractor, and personnel from the company that owned the ESS to establish the history of the incident and the appropriate next steps [6]. The HAZMAT team donned full turnout gear and SCBAs and started measuring gas concentrations in the vicinity of the fenced area. Hazardous HCN and CO gas concentrations were detected at the gate to the fenced area (above 50 ppm and 500 ppm, respectively). The team walked through the desert outside the fenced area to define the extent of the hot zone and found hazardous conditions at all locations where the gas/vapor cloud was visible. The HAZMAT team inspected the outer surface of the structure using a TIC to determine if an active fire was present in the ESS. A relatively small hot spot (~6 in. x 24 in.) with a maximum temperature of approximately 130°F was identified on the northwest side of the ESS at the approximate location of the Rack 15 inverter [6, 9]. The HAZMAT team reported back gas levels and TIC temperatures to BC301 BC, who had set up the command vehicle (BC301) north of the gate on the frontage road. A diagram of the approximate locations of each vehicle relative to the ESS is provided in Figure 4.10.

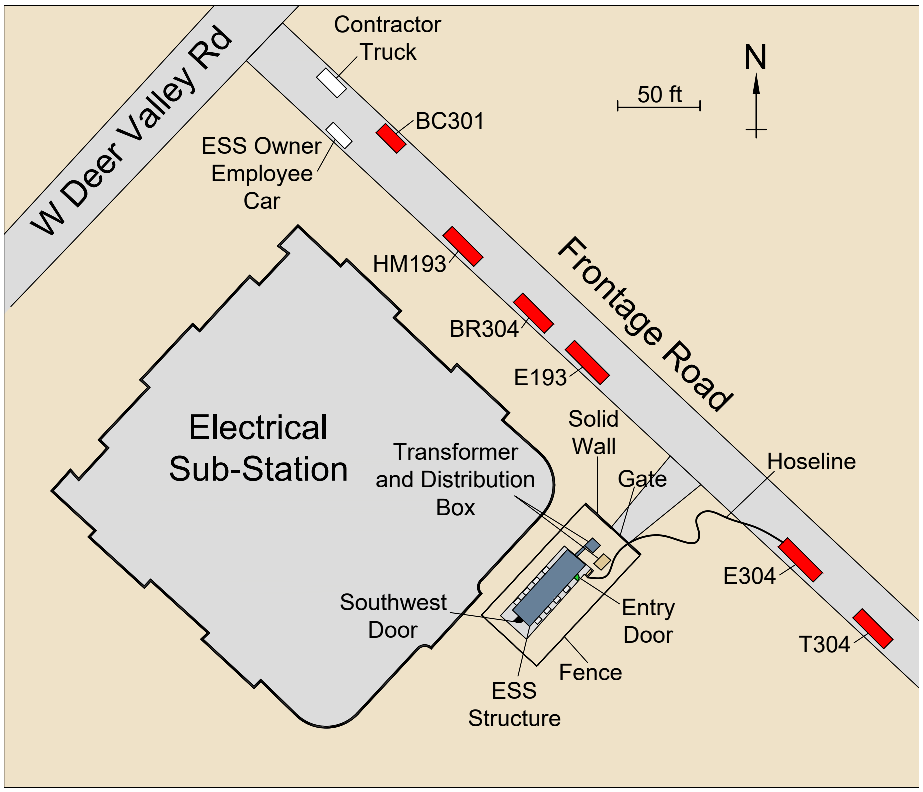

Figure 4.10: Diagram representing approximate locations of vehicles relative to the ESS [6, 7]

The HAZMAT team defined the hot zone as the area enclosed by the fence and returned to the command vehicle. The member of the HAZMAT team temporarily removed their turnout gear and SCBAs to cool off and conduct additional research after their first rotation into the hot zone. E193 Capt, E304 Capt, BC301 BC, the contractor, and representatives of the company that owned the ESS conferenced to discuss the situation. This conference included a person on the phone who identified himself as an engineer from the company that designed the ESS system. The engineer from the company that designed the ESS system stated that the ESS was a sealed system, that there was no way to remotely vent it, and that the suppression system had discharged. E193 Capt was most concerned with the elevated levels of HCN in the white gas/vapor clouds.

The representatives from the companies that designed and maintained the ESS provided an emergency response plan to fire department personnel on the scene in electronic form. The produced document had the stated purpose, "…to provide First Responders with awareness of typical but not exhaustive Risks & Hazards related to Energy Storage Systems during potential failure scenarios" [14]. This document did not provide guidance to first responders related to interacting with the ESS during a cascading thermal runaway event or fire, or information about the potential for an explosion hazard associated with thermal runaway. The personnel from the companies that owned, designed, and maintained the ESS were unable to provide guidance beyond that included in the produced emergency response plan [6, 7].

The HAZMAT team made two more entries into the hot zone and noted that the volume of the gas/vapor mixture leaking from the ESS was decreasing over time, although the concentrations of HCN and CO were measured at levels above the alarm concentration in the visible gas/vapor clouds (OSHA defines the permissible exposure level (PEL) of HCN at 10 ppm and for CO as 50 ppm [17]; NIOSH defines the concentration of HCN that is immediately dangerous to life or health (IDLH) as 50 ppm, and for CO as 1200 ppm [18]; standard operating procedure for the HAZMAT team was to define the perimeter of the hot zone as the location where the hazardous gas concentration was measured as a predetermined percentage of the IDLH concentration (5 ppm for HCN and 60 ppm for CO)). The HAZMAT team also monitored the hot spot on the northwest side of the ESS and noted the temperature decreased and the hot spot grew geometrically smaller as the incident progressed. The HAZMAT team informed BC301 BC that the hot zone was trending toward a safer state [6].

A conference was held with the HAZMAT team, E304 Capt, BC301 BC, and Car 957 North and South in which a plan was formulated to render the ESS safe and pass possession of the site back to the owner of the ESS. The HAZMAT team would enter the hot zone and conduct a 360-degree size-up to measure gas levels throughout the hot zone. If the measured levels were deemed safe, the HAZMAT team would open a door to the ESS and assess whether an active fire was present. To protect the members of the HAZMAT team, a hoseline, manned by HM193 FF2, would be positioned near the entry door. If the structure flashed when the door was opened, HM193 FF2 would not directly attack the fire in the ESS, but would flow water to protect the HAZMAT team as they retreated out of the hot zone to take a defensive position, and allow the ESS to burn. If there was no fire present, the HAZMAT team would leave the door open and allow the hazardous gas/vapor mixture to vent out of the ESS while periodically monitoring the gas concentrations. All fire department personnel agreed on the plan and the two possible courses of action [6].

The HAZMAT team made a final entry into the hot zone and reported back to BC301 BC that the HCN and CO concentrations measured outside the ESS were at a safe level. E193 Capt determined that opening the southwest-facing door rather than the southeast-facing door would minimize potential exposure to the fire department personnel and civilians gathered outside the hot zone to the north of the ESS. E193 Capt removed the key from the southeast-facing door and attempted to open the southwest-facing door but found that the key did not unlock the southwest-facing door. The HAZMAT team returned to the southeast-facing side of the ESS and prepared to open the door.

E193 Capt directed E193 FE to open the door and E193 Capt measured the temperature inside the container with the TIC. A visible white gas/vapor mixture immediately poured out of the open door while the HAZMAT team measured gas concentrations and continued to monitor the ESS. Images extracted from a video recorded on the scene as the door was opened are displayed here. Figure 4.11 displays E193 Capt (red helmet) and E193 FE (yellow helmet) just prior to E193 FE opening the door to the ESS. The hoseline that the HAZMAT team had brought into the hot zone in preparation of opening the door can be seen at the bottom of the image at the entrance gate. Figure 4.12 displays E193 Capt, E193 FE, and HM193 FF1 (far left of image) approximately 5 s after the door was opened. Dense gases and vapors can be seen in the image in Figure 4.12 flowing out of the ESS through the door.

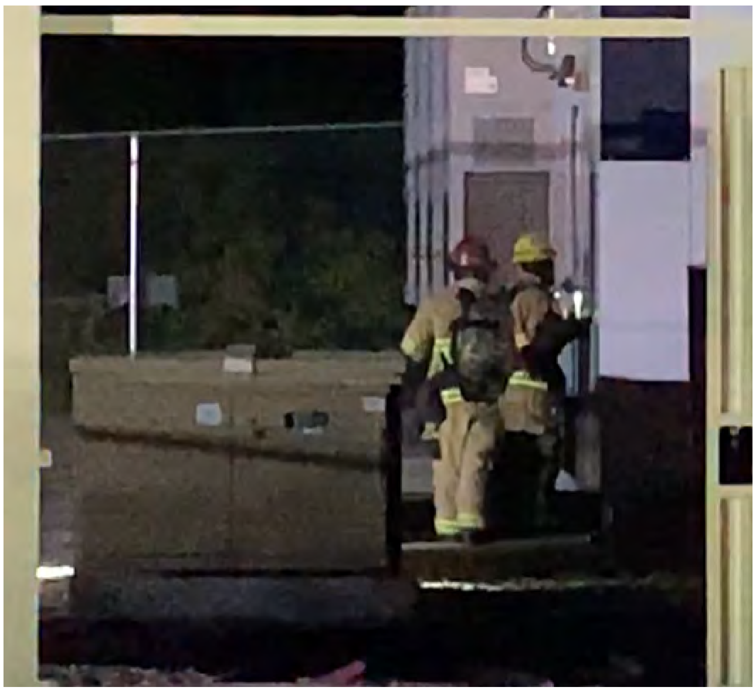

Figure 4.11: Image of the HAZMAT team just prior to door opening [14].

Figure 4.13 displays E193 Capt, E193 FE, and HM193 FF1 approximately 22 s after the door was opened. E193 Capt is shown using a TIC to monitor temperatures inside the ESS. Apparent in the image is an increased flow of high-density gases and vapors out the door as well as increased coverage of the ground in the vicinity of the ESS by the gas/vapor mixture. Figure 4.14 shows E193 FE holding the door open and E193 stepping away from the ESS to retrieve a gas meter approximately 33 s after the door was opened. The high-density gas/vapor mixture can be seen flowing from the door from high elevation to low elevation.

E193 Capt retrieved the gas meter that had been placed on the distribution box just southeast of the door and returned to the doorway. He placed one foot inside the ESS to allow for optical access to the battery racks using the TIC while monitoring gas concentrations. HM193 FF1 made gas concentration measurements in and around the open door (note that the conditions in and around the doorway were rapidly changing and the handheld gas meters used by the HAZMAT crew included estimated time delays of approximately 30–60 seconds before steady, accurate measurements could be displayed). E193 Capt radioed to BC301 BC that the maximum temperature was 104°F with no

Figure 4.12: Image of the HAZMAT team 5 s after opening the door [14].

Figure 4.13: Image of HAZMAT team 22 s after opening the door [14].

active fire or visible arcing, and he scanned back toward the suppression system storage tank with the TIC.

E193 Capt saw a round-topped object with the TIC and he asked HM193 FF1 what he thought

Figure 4.14: Image of the HAZMAT team 33 s after opening the door [14].

it was. HM193 FF1 advised that he could see the top of the round object without the TIC as the gas/vapor mixture flowed out of the doorway but he did not know what it was [6]. This indicates that prior to the deflagration event, visibility was such that the back wall of the ESS was visible, the gas/vapor mixture was flowing out of the doorway from high elevation, and the level of the gas/vapor mixture in the ESS had descended to approximately 5 ft above the floor. A photograph facing into the ESS taken from the entry door after decommissioning is presented in Figure 4.15. This image shows the red suppression agent storage tank, which is the object the HAZMAT team was able to see just prior to the deflagration event.

The approximate locations of the members of the HAZMAT team are displayed in Figure 4.16, in which positions just prior to the deflagration are displayed in blue and approximate positions after the deflagration are displayed in red. E193 Capt was at the door, E193 FE was back and to the left at a 45-degree angle from the door, HM193 FF1 was to the right of the door with a multi-gas meter, and HM193 FF2 manned the hoseline at a 45-degree angle back and to the right of the door [6].

At the moment of the deflagration event, the firefighters outside the hot zone described hearing a loud noise and seeing a jet of flame that extended at least 75 ft outward and an estimated 20 ft vertically from the southeast-facing door [7]. In the event, E193 Capt and E193 FE were ballistically propelled against and under the chain-link fence that surrounded the ESS. E193 Capt came to rest approximately 73 ft from the opened door beneath a bush that had ignited in the event. E193 FE came to rest approximately 30 ft from the opened door. HM193 FF1 was projected toward the transformer and distribution box to the east of the ESS and remained within the fenced area. The entire HAZMAT team lost consciousness in the deflagration event. The event also dislodged or removed the SCBA face pieces and helmets from all of the HAZMAT team members.

Figure 4.15: Photograph of view into the ESS from the entry door [13].

The following figures display the scene surrounding the ESS the day after the incident with as little equipment and debris removed from the scene as possible. Figure 4.17 shows the deformed fence as well as a harness and a hood that were removed from the firefighters during the deflagration. Figure 4.18 shows the hoseline used in the fire service intervention, two firefighter helmets removed during the deflagration, and the entry door that had been torn off the ESS during the deflagration. Figure 4.19 shows fire debris spread out in the desert surrounding the ESS as well as E193 Capt's helmet and an SCBA tank that had been removed during the deflagration. Figure 4.20 provides a view of the fire debris in the desert as well as the overall damage to the ESS. Figure 4.20 displays the deformation of the walls of the ESS as well the remains of both entry doors.

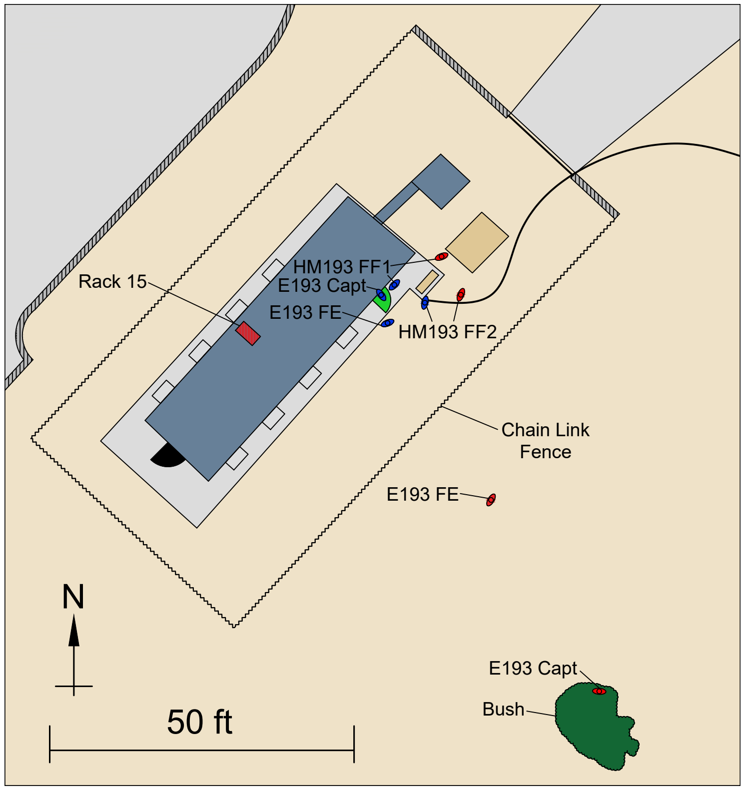

Figure 4.16: Diagram representing the locations of firefighters just before the deflagration event. Approximate positions prior to the deflagration event are displayed in blue, and approximate positions after the deflagration event are displayed in red [6].

Figure 4.17: Photograph of firefighter equipment removed by the fence during the deflagration [6].

Figure 4.18: Photograph of firefighter helmets and the door to ESS removed during the deflagration [6].

Figure 4.19: Photograph of burned bush, E193 Capt's helmet, and SCBA tank removed during the deflagration [6].

Figure 4.20: Photograph of fire debris and SCBA tank removed during the deflagration [6].

After the deflagration event, there was no visible fire in the ESS, but flames were visible in the desert to the southeast of the ESS. HM193 FF2 applied water to the flames in the desert, including to the bush under which E193 Capt had come to rest, which is pictured in Figure 4.19. After applying water to the active fire in the desert, HM193 FF2 retreated out of the hot zone. At no point in the incident was water flowed into the ESS. Shortly after HM193 FF2 emerged from the hot zone, HM193 FF1 also regained consciousness and emerged from the hot zone.

BC301 BC immediately called for a mayday and ordered the crew of E304, BR304, and T304 to conduct rescue operations. The crew of E304, BR304, and T304 commenced rescue and emergency response operations to retrieve the incapacitated members of the HAZMAT team. During rescue operations, it was evident the personal alert safety system (PASS) devices on each of the incapacitated firefighters had activated. E193 Capt was found outside the fence approximately 73 ft from the door and E193 FE was found outside the fence approximately 30 ft from the door. E193 Capt and E193 FE were retrieved and evacuated to the frontage road, but a column of smoke emanating from the southwest of the ESS forced the rescue crew to move the injured further from the hot zone toward BC301.

The rescue crew attempted to intubate both E193 Capt and E193 FE. Neither initially accepted the breathing tube, with E193 Capt regaining consciousness during transport, and E193 FE eventually accepting intubation on the scene. The crew of E304, BR304, and T304 were relieved of ALS duties, which were passed off to the crews E302, E303, and E306. E193 Capt and E193 FE were transported to the Maricopa Integrated Health System Trauma Center via helicopter and HM193 FF1 and HM193 FF2 were transported to a nearby hospital via ambulance. The crew of E304, BR304, and T304 were transported to a nearby hospital for HCN decontamination and to be monitored overnight. The response involved extrication of two firefighters from the hot zone, medical intervention, and evacuation via helicopter staffed with medical personnel.

4.7 Analysis

The scope of this review includes all actions of the fire department personnel from the time of the 911 call to the rescue operations following the mayday call. Parallel investigations have been conducted by various other stakeholders that focused on the origin and cause of the thermal runaway event, the origin and cause of the deflagration event, the overall effect of the total flooding suppression agent, and other aspects of the incident. The results of those investigations were not available and/or were not reviewed in preparation of this report. All analyses presented in this report rely on conservative assumptions and the observations of the firefighters and HAZMAT personnel for the sole purpose of providing recommendations to stakeholders to prevent future incidents like this one.

The available evidence indicates the actions of the fire department and HAZMAT personnel were in accordance with the best practices for interacting with incidents in ESS that had been established by research groups and professional associations at that time. The actions of E304 Capt to get a situation report from a contractor from the company that maintained the ESS that was at the site, conduct an initial size-up, recognize the potential hazardous material threat, and elevate the call to include a HAZMAT team contributed to limiting exposure of the public and first responders to the hazardous gases and vapors emitted by the ESS.

E193 Capt had been trained as a HAZMAT technician, had attended all available training pertaining to ESS, and had experience with a fire involving lithium-ion batteries at an EV repair facility. This training and these experiences likely made E193 Capt one of the most prepared individuals in the Phoenix Metropolitan Area to manage this lithium-ion battery ESS incident. The HAZMAT team monitored the conditions in the vicinity of the ESS and maintained the perimeter of the defined hot zone to ensure fire department personnel and civilians were not exposed to hazardous gases and vapors. The team conducted research and maintained communication with employees of the companies that owned, designed, and maintained the ESS throughout the time they were at the scene to get the best understanding of the potential hazards.

Throughout these conversations, it was made clear that there was no way to remotely track the conditions inside the ESS or remotely vent the ESS. The HAZMAT team monitored the concentrations of harmful gases in the hot zone as well as the rate of emission of the gas/vapor mixture from the ESS and surrounding equipment throughout the time the team was at the scene. The HAZMAT team noted that the rate of emission of the visible gas/vapor mixture from the ESS and equipment appeared to generally decrease over time.

Prior to the final entry into the hot zone, the gas/vapor mixture no longer appeared to be actively flowing out of the ESS. The HAZMAT team understood the ESS was still filled with toxic gases and vapors, and that these and other gases and vapors produced during lithium-ion battery thermal runaway may have been flammable. It was unknown whether the batteries were still offgassing to produce additional toxic and flammable gases and vapors. Furthermore, it was also unknown whether the gas/vapor mixture would resume flowing out of the ESS, which would effectively indicate a change in the conditions inside the structure.

E193 Capt and the rest of the fire department personnel acknowledged that the fire department could not hold the ESS indefinitely or transfer it back to the owner in that condition. At that point in the incident, the HAZMAT team reached the extent of knowledge and advice available from training courses and were required to formulate a plan to return the ESS to a safe condition. It was concluded that to quickly and effectively change the conditions inside the ESS, the door to the ESS should be opened. All fire department personnel agreed this was a reasonable plan.

Although determination of the origin and cause of the thermal runaway and resulting deflagration are outside the scope of this review, the events that transpired leading up to opening the door of the ESS and immediately after the HAZMAT team opened the door lead to some basic conclusions about the reason the deflagration occurred when the HAZMAT team was adjacent to the ESS and not prior. Air temperature measurements and the VESDA smoke detection system detected the onset of abnormal conditions within approximately 1 minute of each other. Given the nature of lithium-ion battery thermal runaway to produce soot and particulates [19] and the high sensitivity of VESDA smoke detection, it is likely that thermal runaway of the first cell was detected shortly after it began.

The smoke detection system activated an alarm condition, which initiated discharge of the Novec 1230 after a 30 s delay, as designed. The clean agent system discharge lasted approximately 10 s, per NFPA 2001. Consequently, an environment intended to inert the ESS installation against flaming fires was likely in place shortly after the initial thermal runaway event. Complete thermal runaway through all the modules in Rack 15 indicates the extinguishing agent did not prevent cascading thermal runaway from the initiating cell to adjacent cells, from cell to cell, or from module to module within the rack. The timeline of the progression of thermal runaway through Rack 15 is unknown.

Though it is not known whether flaming accompanied the initial thermal runaway event, it is likely the Novec 1230 prevented flaming after the minimum extinguishing concentration was achieved, and continued to prevent flaming combustion while the extinguishing concentration was maintained. Many of the gases and vapors emitted from lithium-ion cells during thermal runaway are flammable, and they can create an explosion hazard if they are allowed to accumulate in a confined volume without burning [20]. Therefore, the Novec 1230 likely created an environment in which flammable gases and vapors emitted during cascading thermal runaway accumulated in the ESS in the absence of a fire.

Figure 4.9 indicates the ESS was actively leaking gases and vapors when the HAZMAT team arrived and performed a size-up approximately 100 minutes after the Novec 1230 was discharged. Based on a conservative estimate of the apparent area and depth of the vapor cloud in the photographs (100 ft x 60 ft, and a depth of 3 ft), as well as the estimated internal volume of the ESS, a volume of gas/vapor mixture sufficient for at least two complete volume changes had likely occurred. The continual leakage of a mixture of air, gases and vapors produced during thermal runaway, and Novec 1230 over time caused the concentration of the clean agent to fall below the design concentration. It is unlikely the concentration of Novec 1230 remaining in the ESS at the time the door was opened provided meaningful protection against the ignition of flammable gases and vapors that had accumulated in the ESS.

Part of the difficulty in predicting the composition of the gas atmosphere in the ESS at the time the door was opened is related to variation in the composition, total volume, and timeline of gases and vapors released during cascading thermal runaway, which is dependent on battery chemistry, manufacturer, state of charge, failure mode, and several other variables [20, 21]. The HAZMAT personnel observed a decrease in the rate of leakage of gases and vapors from the ESS over the course of the response. This may have given the appearance from outside the ESS that thermal runaway and the release of flammable battery gas and vapor had subsided, although it is unknown if thermal runaway had actually stopped. The exact state of the gas/vapor mixture and the battery modules inside the ESS prior to the HAZMAT team opening the door is unknown, although gases and vapors had visibly leaked from the compartment for approximately 180 minutes leading up to the opening of the door.

Many potential ignition sources exist in an ESS installation, especially during cascading thermal runaway (see Appendix A). The most conspicuous ignition source present is molten electrode material ejected at high temperature during thermal runaway [22]. Arcing between charged terminals caused by the reduced dielectric strength of the mixture of gases and vapors present in the ESS compared to ordinary air, and surfaces heated above the autoignition temperature of the gas/vapor mixture due to the exothermic reactions associated with thermal runaway, were also possible competent ignition sources.

Due to the flammability of the gases released during thermal runaway, the assumption that the concentration of Novec 1230 decreased over time, and the possible ignition sources in the ESS, it is possible that some flaming combustion occurred within the ESS between the time the concentration of Novec 1230 decreased below the minimum extinguishing concentration and the door was opened. If flaming combustion occurred in the ESS in this time period, with relatively small leakage paths for fresh air to flow into the ESS, it is likely the oxygen concentration within the structure decreased below a level that could support further combustion or a deflagration. Decreasing the oxygen concentration in a gas mixture effectively increases the lower explosive limit (LEL) and decreases the upper explosive limit (UEL). If the oxygen concentration in a mixture is reduced far enough, there is no concentration of gases and vapors in the mixture that will be flammable.

The exact composition of the gas mixture in the ESS prior to the HAZMAT personnel opening the door is outside the scope of this review, and is ultimately not important for any of the major conclusions drawn from the review. When the door to the ESS was opened, the flammable gas and vapor mixture visibly flowed out the door, and outside air flowed into the ESS. This exchange introduced a significant volume of fresh air to the mixture and likely also facilitated mixing. These mechanisms changed the concentration of the gas mixture, locally in proximity to an ignition source, such that it was within the explosive limits for the amount of available oxygen; i.e. above the LEL and below the UEL.

If the gas/vapor mixture within the ESS was above the LEL for the oxygen level in ambient air prior to opening the door, and there was no way to remotely vent the ESS, then there was no safe method to transfer the ESS back to the owner without opening the door to vent the structure. Thermal runaway events and reignition of lithium-ion batteries have been observed to take place over several days [22–24]. If the ESS was allowed to sit, undisturbed, the gas/vapor mixture inside the ESS would have naturally vented and mixed through chemical diffusion and changes in air pressure inside the structure as it heated and cooled with changes in ambient temperature. This means the ESS may have also undergone a deflagration after the initial anomaly without opening the door. Although this type of event has not been observed in a lithium-ion battery ESS installation, the conservative analysis presented here supports the possibility of such an event.

At the time the HAZMAT team opened the door, E193 Capt was aware of the possibility of flammable gases accumulated inside the ESS and the potential explosion hazard they posed. The toxicity of the gas/vapor mixture leaking from the ESS was deemed immediately dangerous to the fire department personnel and civilians who had gathered in relatively close proximity to the ESS, and, with the possibility of a change in wind or weather conditions, it had the potential to affect a nearby major roadway as well. It was unclear how the situation would progress if the ESS was allowed to sit, undisturbed. It was determined that opening the door to the ESS was the most practical method to ensure a rapid decrease in the concentration of toxic and flammable gases and vapors in the structure. By this logic, the actions of the HAZMAT team were reasonable, with the information and technology available, to return the ESS to a safe state.

4.8 Contributing Factors

A review of the weather, building construction, energy storage system, PPE, incident narrative, and fire and deflagration dynamics identifies six factors that contributed to the ultimate outcome of this incident:

- The fire and smoke detection systems were not required by code to include, and did not include, sensors that provided information about the presence of flammable gases. There were no means for the HAZMAT team to monitor toxic gas concentrations, LEL, or the conditions inside the ESS from a physically secure location.
- The ESS communication system failed before the HAZMAT team arrived at the incident. Personnel who maintained the ESS and the fire department were unable to use the system to understand the conditions inside the installation.
- The emergency response plan was not provided to the responding fire service personnel prior to this incident. Advanced disclosure of the emergency response plan was not required by the applicable codes or standards at the time of the incident.
- The emergency response plan that was provided to fire service personnel on the scene, although compliant with the applicable codes and standards at the time of the incident, did not provide adequate guidance for mitigating thermal runaway, fire, and explosion hazards generated by the ESS.
- The design of the ESS did not include deflagration venting per NFPA 68 or adequate mechanical ventilation per NFPA 69 to prevent accumulation of flammable gases above an explosive concentration. Construction to these standards was not required by applicable codes at the time the ESS was commissioned.
- The total flooding clean agent suppression system prevented flaming during the early phase of the incident, but was not designed for and did not provide explosion protection.

5 Description of Injuries

Two members of the Peoria Fire-Medical Department HAZMAT team (E193 Capt and E193 FE) were flown via helicopter to the Maricopa Integrated Health System Trauma Center for treatment. The other two members of the HAZMAT team (HM193 FF1 and HM193 FF2) were sent to the Abrazo West Campus hospital by ground ambulance [6].

E193 Capt suffered a traumatic brain injury, an eye injury, spine damage, broken ribs, a broken scapula, thermal and chemical burns, internal bleeding, two broken ankles, and a broken foot.

E193 FE suffered a traumatic brain injury, a collapsed lung, broken ribs, a broken leg, a separated shoulder, laceration of the liver, thermal and chemical burns, a missing tooth, and facial lacerations.

HM193 FF1 suffered an injured Achilles tendon, a fractured patella, a broken leg, nerve damage in his leg, spine damage, thermal burns, tooth damage, and facial lacerations.

HM193 FF2 suffered facial lacerations.

Surprise Fire-Medical Department E304 Capt, E304 FF, BR304 FF, and T304 FF, as well as one officer from the Surprise Police Department, were transported to the Banner Del E Webb Medical Center and observed overnight for exposure to HCN. These individuals were released from the hospital the following morning with no noticeable lasting effects from HCN exposure [7].

6 Contributing Factors

A review of the fire departments that responded to this incident identified one factor that contributed to its outcome. A review of the incident identified six factors that contributed to its outcome. All contributing factors have been combined below to facilitate development of an ordered list of recommendations which address each contributing factor directly:

- Despite all responding firefighters being current with HAZMAT competencies from First Responder to Technician level, core HAZMAT training curricula for these competencies do not yet cover basic ESS hazards. Extra-curricular ESS-specific training opportunities do not yet comprehensively address ESS hazards.
- The fire and smoke detection systems did not include, and were not required to include, sensors that provided information about the presence of flammable gases. There were no means for the HAZMAT team to monitor toxic gas concentrations, LEL, or the conditions inside the ESS from a physically secure location.
- The ESS communication system failed before the HAZMAT team arrived at the incident. Personnel who maintained the ESS and the fire department were unable to use the system to understand the conditions inside the installation.
- The emergency response plan was not provided to the responding fire service personnel prior to this incident. Advanced disclosure of the emergency response plan was not required by the applicable codes or standards at the time of the incident.
- The emergency response plan that was provided to fire service personnel on the scene, although compliant with the applicable codes and standards at the time of the incident, did not provide adequate guidance for mitigating thermal runaway, fire, and explosion hazards generated by the ESS.
- The design of the ESS did not include deflagration venting per NFPA 68 or adequate mechanical ventilation per NFPA 69 to prevent accumulation of flammable gases above an explosive concentration. Construction to these standards was not required by applicable codes at the time the ESS was commissioned.
- The total flooding clean agent suppression system prevented flaming during the early phase of the incident, but was not designed for and did not provide explosion protection.

7 Recommendations

Recommendation #1-1: Basic Firefighter, Officer, and HAZMAT training should emphasize ESS safety; the potentially explosive nature of the gases and vapors released during lithium-ion battery thermal runaway, vapor cloud formation and dispersion; and the dynamics of deflagrations and blast wave propagation.

Discussion: Basic Firefighter training generally complies with the job performance requirements (JPRs) outlined in NFPA 1001 *Standard for Fire Fighter Professional Qualifications* [4]. One such JPR is defined in §4.3.3 of NFPA 1001 (2019):

> **§4.3.3** Establish and operate in work areas at emergency scenes, given protective equipment, traffic and scene control devices, structure fire and roadway emergency scenes, traffic hazards and downed electrical wires, photovoltaic power systems, battery storage systems, an assignment, and SOPs, so that procedures are followed, protective equipment is worn, protected work areas are established as directed using traffic and scene control devices, and the firefighter performs assigned tasks only in established, protected work areas.

This JPR for the Firefighter I designation includes the ability to operate near battery storage systems, which requires topical knowledge of the hazards associated with the various types of battery storage systems.

Fire Officer training generally complies with the job performance requirements (JPRs) outlined in NFPA 1021 *Standard for Fire Officer Professional Qualifications* [4]. JPRs are defined for each Fire Officer level that require the development of an incident action plan given the available information on the incident in NFPA 1021 (2019). An example JPR for Fire Officer is provided in §4.6.1:

> **§4.6.1** Develop an initial action plan, given size-up information for an incident and assigned emergency response resources, so that resources are deployed to control the emergency.

This JPR and the analogous JPRs defined for the other Fire Officer levels require understanding of all possible hazards present in lithium-ion battery ESSs and the potential outcomes resulting from tactical decisions when responding to ESS incidents. The latest edition of three publications written to educate firefighters per NFPA 1001 (i.e., Fire Engineering's Handbook for Firefighter I and II, 2019 Edition [25], Fundamentals of Fire Fighter Skills and Hazardous Materials Response, Fourth Edition [26], and IFSTA Essentials of Fire Fighting, 7th Edition [27]) do not provide any content on ESSs or lithium-ion batteries. With the projected growth of this technology and these installations [28], it is imperative the fire service is educated about these potential hazards and the recommended standard operating procedures to ensure safety of all personnel in the vicinity of a lithium-ion battery ESS.

A review of NFPA 1001 also identified the absence of requirements to educate firefighters on gas and vapor cloud formation and dispersion, fire dynamics, or the physics of blast wave propagation.

None of the JPRs in NFPA 1001 address the physics of combustion and deflagrations, or the hazards associated with gas and vapor clouds. Education on these topics at the level of Firefighter I would provide a basic understanding to all members of the fire service about the most destructive hazards present in lithium-ion battery ESSs and inform the strategy and tactics used by the fire service when responding to lithium-ion battery ESS incidents. It should be noted that despite a requirement to include these topics in educational materials for firefighters, basic knowledge on the dynamics of explosions is included in the latest edition of the IFSTA handbook [27], and information on vapor dispersion is included in the latest edition of the IFSTA handbook and the Fundamentals of Firefighter Skills and Hazardous Materials Response [26, 27]

HAZMAT training complies with the JPRs outlined in NFPA 1072 *Standard for Hazardous Materials/Weapons of Mass Destruction Emergency Response Personnel Professional Requirements* [29]. Chapters 4 and 5 of NFPA 1072 define JPRs for basic HAZMAT Awareness and Operations, with the following sections specifically directed toward identifying potential hazards associated with HAZMAT incidents, where weapons of mass destruction are abbreviated as WMD:

> **§4.2.1** Recognize and identify the hazardous materials/WMD and hazards involved in the hazardous materials/WMD incident, given a hazardous materials/WMD incident, and approved reference sources, so that the presence of hazardous materials/WMD is recognized and the materials and their hazards are identified.
>
> **(A) Requisite Knowledge.** What hazardous materials and WMD are; basic hazards associated with classes and divisional indicators to the presence of hazardous materials including container shapes, NFPA 704 markings, globally harmonized systems (GHS) markings, placards, labels, pipeline markings, other transportation markings, shipping papers with emergency response information, and other indicators; accessing information from the Emergency Response Guidebook (ERG) using name of the materials, UN/NA identification number, placard applied, or container identification charts; and types of hazard information available from the ERG, safety data sheets (SDS), shipping papers with emergency response information, and other approved reference sources.
>
> **§5.2.1** Identify the scope of the problem at a hazardous materials/WMD incident, given a hazardous materials/WMD incident, an assignment, policies and procedures, and approved reference sources, so that container types, materials, locations of any release, and surrounding conditions are identified, hazard information is collected, the potential behavior of a material and its container is identified, and the potential hazards, harm, and outcomes associated with that behavior are identified.

The JPRs defined for the HAZMAT Awareness and Operations level require the firefighter to be capable of recognizing hazardous materials and identifying the hazards present at an incident. The latest edition of the three previously mentioned publications written to educate firefighters to this level [25–27] do not specifically provide any content on ESSs or lithium-ion batteries. By including information about all of the potential hazards associated with lithium-ion battery thermal runaway (e.g., the production of toxic gases, the potential for a flammable or explosive mixture, the production of competent ignition sources, etc.) in publications used for basic firefighter and

HAZMAT operations training, firefighters will be in a better position to safely respond to ESSs immediately after basic firefighter training.

Chapter 7 of NFPA 1072 defines the JPRs for the HAZMAT Technician. The following two sections define JPRs concerned with predicting the potential hazards due to a HAZMAT incident and estimating the possible outcomes due to hazards present at the incident:

> **§7.2.4 Predicting Behavior.** Predict the behavior of hazardous materials/WMD involved in a hazardous materials/WMD incident, given an incident involving multiple hazardous materials/WMD; an assignment in an IAP; policies and procedures; physical and chemical properties of the materials involved; results of detection, monitoring, and sampling; condition of the container (damage and stress); surrounding conditions; and approved reference sources, so that the behavior of each hazardous materials/WMD container and it contents is identified, the reactivity issues and hazards of the combined materials are identified, and a description of the likely behavior of the hazards is communicated.
>
> **§7.2.5 Estimating Outcomes.** Estimate the potential outcomes at a hazardous materials/WMD incident, given a hazardous materials/WMD incident, an assignment in an IAP, policies and procedures, the likely behavior of the container and its contents, and approved resources and equipment, so that the concentrations of materials within the endangered area are measured or predicted; physical, health, and safety hazards within the endangered area are identified; areas of potential harm in the endangered area are identified; potential outcomes within the endangered area are identified; and potential outcomes are communicated.

All of the aforementioned JPRs require the firefighter to have working knowledge of all the potential hazards associated with the materials present at a HAZMAT incident. The actions of the HAZMAT team at the ESS in this incident showed an emphasis on the potential toxic gas hazard from the gases and vapors leaking out of the structure because these could be readily measured, with less of an emphasis on the possible explosion hazard. This is understandable because the IDLH concentration of the gases being monitored was significantly lower than the LEL of the gases that were monitored and other gases expected to be produced during thermal runaway of lithium-ion batteries.

Assuming the training that the firefighters involved in this incident underwent complied with the pertinent NFPA codes, it would appear that the training did not emphasize all of the hazards associated with lithium-ion batteries. Basic firefighter and HAZMAT training content should be reviewed and additional information on all of the potential hazards associated with lithium-ion battery ESSs installations must be included. Additionally, as this technology is in continuous development and growth, training programs should be reviewed at least bi-annually to ensure the most updated information is included and requirements should be put in place to ensure firefighters are also constantly exposed to the latest available information.

Recommendation #1-2: Research that includes full-scale testing should be conducted to understand the most effective and safest tactics for the fire service in response to lithium-ion battery ESS incidents.

Discussion: The HAZMAT team involved in this incident formulated and executed a plan according to the best practices defined at the time for managing a lithium-ion battery ESS fire that were informed by the most up-to-date information available on this type of incident. This incident has illuminated a need to determine the appropriate fire response tactics to minimize exposure of the public and fire service to hazards due to lithium-ion battery ESSs and to proliferate these tactics to all fire service personnel. Several questions that have arisen due to this incident and several other similar incidents that have taken place in lithium-ion battery ESSs can only be answered through exploratory research that includes full-scale testing conducted by qualified researchers according to the scientific method.

Of particular interest in the context of this review are the fire service tactics and response procedures when interacting with a lithium-ion battery ESS. Appendix C of NFPA 855 [1] provides limited guidance to the fire service on operational considerations. Note that NFPA 855 was first issued almost four months after this incident on August 5, 2019, so the operational considerations in NFPA 855 were not available to the firefighters and HAZMAT team that responded to this incident. Large-scale experiments that incorporate and test the best practices proposed for fire service response to lithium-ion battery ESS incidents as well as the operations recommendations provided in NFPA 855 Appendix C will provide research-backed guidance to firefighters when responding to lithium-ion battery ESSs in the future as the number of similar facilities increases.

An important safety consideration that must be investigated in this research is the minimum safe distance fire service personnel should remain from the ESS enclosure throughout the incident. This research should also investigate the equipment fire department personnel use when monitoring the ESS, and should provide recommendations to the fire service. Appendix C of NFPA 855 notes the importance of air monitoring for the fire service during ESS incidents:

> **C.6 Air Monitoring** Air monitoring should be a priority for responders during and after any ESS emergency. Though the ESS might include an air-monitoring system, it is recommended that the responding fire companies use 4-meter or other gas detection equipment to determine toxic gas levels. Many fire departments carry single gas carbon monoxide meters that can be used to offer limited data on the condition of the ESS environment.
>
> When testing the involved areas, responders should be aware that hydrogen can give an erroneous reading on the carbon monoxide meter because there is a cross-sensitivity with hydrogen. Full PPE and SCBA should always be used during a fire and post-fire event.
>
> The battery room or building might employ a fixed inert gas or other oxygen-displacing fire suppression system. When activated, these agents will displace oxygen from the environment in an effort to control flame. This impact on oxygen levels can impact the lower explosive limit (LEL). Begin metering in areas outside the affected BESS room to establish baseline readings. These areas should include floors above and below the BESS, corners, low-lying areas, and areas out of the path of smoke/gas travel, including near ventilation points.

This excerpt from NFPA 855 indicates the importance of monitoring gas concentrations when interacting with lithium-ion battery ESSs, which emphasizes the need for first responders to fully understand gas detection technology as well as the gases expected to be released by lithium-ion batteries during thermal runaway. It also indicates issues with cross-sensitivity when measuring carbon monoxide levels in the presence of hydrogen gas, which emphasizes the need to fully understand the cross-sensitivities of gas monitoring equipment, which should be addressed in the proposed research. This incident has illuminated the importance of gas detection by firefighters and also the shortcomings of the gas meters typically used by firefighters and HAZMAT teams. Research should address the equipment used for gas detection as well as the techniques firefighters should use when scanning in the vicinity of a lithium-ion battery ESS and generally interacting with the ESS.

Recommendation #1-3: Until definitive tactics and guidance can be established through full-scale experiments, it is recommended that fire service personnel define a conservative potential blast radius and remain outside of it, while treating the lithium-ion ESS as if the gas mixture in the enclosure is above the LEL until proven otherwise.

Discussion: Although the actions taken by the fire service and HAZMAT personnel at the incident were consistent with the best practices defined at the time for managing a HAZMAT situation and a lithium-ion battery ESS fire, the HAZMAT crew still sustained serious injuries during the response. This indicates research is required to improve the state of knowledge and define safer best practices when interacting with lithium-ion battery ESSs. Until that research is completed and its results are validated and published with new tactics and operational recommendations for firefighters and HAZMAT personnel, it is important that the recognized best practices for these situations be modified on an interim basis to ensure the safety of these first responders.

The gas and vapor mixture generated during thermal runaway of a lithium-ion battery ESSs may be toxic and flammable. It is important that certain precautions are taken to ensure the safety of firefighters and HAZMAT personnel when they conduct operations to ensure the public safety in similar ESS incidents. This incident has emphasized that the explosive hazard associated with an ESS may develop or transition on many different timelines. These timelines are dependent on factors that include, but are not limited to, the suppression technology in the ESS, ventilation conditions, the contents of the ESS, the presence or absence of localized flames, and the presence or absence of active battery venting.

This incident has demonstrated the difficulty a HAZMAT crew may experience in attempting to identify and characterize each of these factors and the effect each has on the concentration of gases and vapors in the ESS. Because of these difficulties, it is recommended that whenever possible for the public safety, fire service personnel define a conservative potential blast and hot zone radius and remain outside of it. Fire department personnel should exercise caution with the ESS as if the gas and vapor mixture in the structure is above the LEL. When intervention is necessary, it is recommended that fire service personnel plan operations to limit exposure of personnel to the possible rapid development of explosive conditions. If possible, it is recommended that operations that may involve gas sampling and ventilation of the ESS are conducted remotely.

Recommendation #1-4: An online educational tool should be developed to proliferate the appropriate base knowledge about lithium-ion battery ESS hazards and fire service tactical considerations.

Discussion: Prior to the incident, E193 Capt had been exposed to the latest and most updated information about ESSs, and he followed the guidelines and recommendations outlined in the available training courses while on the scene. However, the HAZMAT team was still confronted with the deflagration and resulting injuries. This review has identified the need for improvements to the base knowledge and firefighter tactics associated with lithium-ion battery ESSs. The fire service will benefit from an easily accessible educational tool that expounds on all of hazards potentially present in a lithium-ion battery ESS incident. This educational tool must also present the results of the research available in the literature, including full-scale testing results, conclusions, and the recommendations for fire service tactical considerations that result from the research. Ease of access to this educational tool is imperative and can be guaranteed if the course is available in a web-based format at no cost to the student.

Recommendation #2-1: Lithium-ion battery ESSs should incorporate gas monitoring that can be accessed remotely.

Discussion: NFPA 855 *Standard for the Installation of Stationary Energy Storage Systems* [1] provides the "minimum requirements for mitigating the hazards associated with ESS." In §4.9, the standard includes a requirement for a continuous gas detection system for ESS enclosures to control ventilation such that the flammable gas concentration in the ESS enclosure does not exceed 25% of the LEL. This requirement is intended to detect and vent gases and vapors produced during normal charging and discharging and not during thermal runaway. Additionally, the requirement does not apply to lithium-ion battery ESSs.

One of the factors that contributed to the injuries sustained in this incident was the lack of information about the contents of the ESS. Information that may have informed the response includes data on the state and concentration of gases and vapors that had accumulated within the ESS leading up to the time the entry door was opened. The lithium-ion battery ESS involved in this incident was built to comply with all pertinent standards at the time of its construction, which did not require a gas composition measurement or monitoring system connected to the fire alarm control panel. Such a system may have provided information to the HAZMAT team about toxic gases and vapors and the composition of the gas mixture relative to the explosive limits, which would have informed the decisions made and may have prevented the injuries that occurred.

A monitoring system capable of measuring concentrations of toxic and caustic gases as well as flammable gases may be complicated for a lithium-ion battery ESS that is known to emit a myriad of flammable and nonflammable gases during thermal runaway. The available technology should be evaluated and implemented to develop monitoring systems that can indicate to first responders if a potentially explosive mixture is present. With the data available to ESS manufacturers, designers, and testers, a robust gas monitoring system tailored to the gases expected to accumulate in an ESS in a thermal runaway and fire scenario can be designed.

Recommendation #2-2: Research that includes multi-scale testing should to be conducted to evaluate the effectiveness and limitations of stationary gas monitoring systems for lithium-ion battery ESSs.

Discussion: It is recommended that stationary gas monitoring capabilities be incorporated into the design of lithium-ion battery ESS that can be remotely accessed by ESS owner personnel as well as the fire service. Gas monitoring within a lithium-ion battery ESSs enclosure may be complicated by a variety of potential factors:

- Sensor position relative to the location of the battery gas vent
- Cross-sensitivity of the sensor to the wide range of gases released during thermal runaway
- Interference of extinguishing agents with correct operation of the gas sensors
- The highly sooty environment of battery fires causing interference or fouling sensors
- Compartment volume
- Compartment geometry
- Confinement of flammable gases within ESS equipment
- Air movement due to HVAC and ESS cooling equipment
- Stratification of gases due to the range of densities expected from thermal runaway (ranging from hydrogen to high-density vapors that are heavier than air)

Because of the wide range of gases that may be produced in an incident and the range of techniques required to detect and measure the concentrations of these gases, research is required to determine the best methods to do so. Additionally, these gases and suppression agents have a wide range of densities, which may result in stratification over time that may render single-point gas monitoring systems obsolete over the course of an incident. Research should also address the effectiveness of single-point static gas detection systems compared to multi-point systems. It is worthwhile to study methods for monitoring the gas composition in the enclosure not only to achieve a better understanding of the typical gas composition caused by thermal runaway on the ESS scale, but also the best method for measuring or constantly monitoring the gas composition to effectively alert ESS maintenance personnel and first responders to the hazards present in the ESS facility.

Recommendation #3: Lithium-ion battery ESSs should incorporate robust communications systems to ensure remote access to data from the batteries, BMS, sensors throughout the ESS, and the fire alarm control panel remains uninterrupted.

Discussion: One of the factors that contributed to the injuries sustained in this incident was the lack of information about the contents of the ESS. Knowledge of the air temperatures throughout the ESS, the status of the battery modules, and the composition of the gases that had accumulated in the ESS at the time the entry door was opened would have informed the strategy employed by the HAZMAT team on the scene and may have prevented the injuries sustained in the incident. This lack of information may be partially attributed to the lack of robustness of the communications system, which failed to externally communicate data from the ESS prior to arrival of the HAZMAT crew.

NFPA 855 includes the provision that the gas detection system central station and smoke and fire detection systems in ESSs comply with NFPA 72 *National Fire Alarm and Signaling Code* [30]:

> **§4.9.3.2 (4)** Failure of the gas detection system shall annunciate a trouble signal at an approved central station, proprietary, or remote station service in accordance with NFPA 72 or at an approved, constantly attended location.
>
> **§4.10.1** All fire areas containing ESS systems located within buildings or structures shall be provided with a smoke detection system in accordance with NFPA 72.

NFPA 72 requires systems to be designed to withstand temperatures up to 120°F:

> **§10.3.5** Equipment shall be designed so that it is capable of performing its intended functions under the following conditions:
>
> (1) At 85 percent and at 110 percent of the nameplate primary (main) and secondary (standby) input voltage(s)
> (2) At ambient temperatures of 32°F (0°C) and 120°F (49°C)
> (3) At a relative humidity of 85 percent and an ambient temperature of 86°F (30°C)

NFPA 855 also includes a requirement for a communication system connected to the ESS without providing additional guidance:

> **§5.4 Communication Systems.** ESS shall have communication interconnections between ESS components and site-located systems necessary for safe operation of the system and in accordance with the product listing, manufacturer's installation instructions, and this document.

The temperature measurements collected from the ESS during this incident exceeded 120°F at a single inverter measurement location within two minutes of the initial anomaly. The ambient air temperature was never measured higher than 110°F at the time communication from the ESS was lost. In future ESS installations, communications systems attached to the fire alarm control panel and ESS components should be protected from the thermal environment that can be expected in an ESS undergoing thermal runaway or involved in a fire, or placed securely outside the ESS such that they will survive elevated temperatures due to fire conditions.

The BMS in ESSs are often powered directly by the batteries managed by the BMS. This practice implies that the BMS may not be a reliable source of information throughout the entire emergency response, but also raises the question of how sensors, data acquisition systems, and communications systems are powered during thermal runaway or an emergency event. ESS communications systems should be designed with robust primary and backup power sources to ensure data collected from the ESS components and fire alarm control panel may be remotely accessed for a duration that conservatively accounts for the entire emergency response.

Recommendation #4-1: Owners and operators of ESSs should develop an emergency operations plan in conjunction with local fire service personnel and the AHJ, and hold a comprehensive un-

derstanding of the hazards associated with lithium-ion battery technology.

Discussion: Because of the breadth of potential hazards that firefighters and specifically HAZMAT personnel are expected to encounter, fire service personnel often rely on subject matter experts (SMEs) from utilities and owners of facilities to provide guidance and advise on the hazards present in an incident. At the time the incident occurred, the state of knowledge about fires in lithium-ion battery ESSs and firefighter response tactics was inadequate to maintain the safety of first responders, and as such, there were no SMEs available from the companies that owned, designed, and maintained the ESS. The accounts from the firefighters indicate the emergency operations plan did not provide adequate guidance for the incident, and that the employees of the companies that owned, designed, and maintained the ESS were unable to provide supplemental guidance for responding to the incident.

The emergency response plan produced at the scene had the stated purpose, "...to provide First Responders with awareness of typical but not exhaustive Risks & Hazards related to Energy Storage Systems during potential failure scenarios." [14]. The document provided a description of the site and all components of the ESS, the designated foot path to gain entry to the ESS, the locations of emergency shut offs and emergency fire agent release levers, details of the suppression system, and a table with a list of potential hazards and the recommended action to mitigate the hazard. Mitigation actions recommended for fire hazards included an ABC extinguisher, the BESS fire suppression system, carbon dioxide, water, and foam + Purple K. The mitigating actions recommended for chemical hazards (i.e., hazardous smoke created by fire and battery leaks creating hazardous vapor) included evacuating the area, donning SCBA, and ventilating the structure.

As the stated purpose suggested, the emergency response plan did not provide information related to thermal runaway, the flammability of the gases and vapors produced during cascading thermal runaway, and the potential explosion hazard generated if gases produced during thermal runaway were allowed to accumulate in the ESS. The emergency response plan did not provide guidance for first responders for interacting with the ESS because this guidance had not been developed and little data was (and currently is) available on ESSs from which tactical considerations for first responders may be developed. NFPA 855 *Standard for the Installation of Stationary Energy Storage Systems* [1] requires the owner of an ESS to develop an emergency operations plan and associated training:

> **§4.1.3.1 General.** 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 effectively address foreseeable hazards associated with the on-site systems.
>
> **§4.1.3.2.1.4** The emergency operations plan shall include the following:
>
> > (3) Procedures to be followed in response to notifications from energy storage management system (ESMS), when provided, that could signify potentially dangerous conditions, including shutting down equipment, summoning service and repair personnel, and providing agreed upon notification to fire department personnel for off-normal potentially hazardous conditions

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

The owner of the ESS in this incident was an electric utility, and language in NFPA 855 is such that had the ESS been commissioned after publication of NFPA 855 and had been compliant with NFPA 855, the owner would have been exempt from the requirement to develop an emergency operations plan:

> **§4.1.3.2.1.5** The emergency operations plan in 4.1.3.2.1 shall not be required for electric utility facilities under the exclusive control of the electric utility located outdoors or in building spaces used exclusively for such installations.

The requirement in NFPA 855 pertaining to the development and implementation of an emergency operations plan should be required universally for all lithium-ion battery ESSs to ensure all reasonable steps are taken to minimize the potential for a similar incident and resulting injuries to take place. The emergency operations plan should be developed with input from the emergency personnel from the fire department that would be expected to respond to an incident in the ESS. The plan should incorporate tactical considerations based on the most up-to-date research pertaining to lithium-ion battery ESSs and should be reviewed by the AHJ periodically to ensure tactics are consistent with the latest recommendations.

Recommendation #4-2: Signage that identifies the contents of an ESS should be required on all ESS installations to alert first responders to the potential hazards associated with the installation.

The Surprise Fire-Medical crew that first arrived on the scene noted that upon arrival, they observed signs identifying the owner of the facility and identifying the facility as associated with electricity, but there were no signs or placards on or near that ESS that identified the use of lithium-ion batteries or hazards specifically associated with an ESS or lithium-ion battery technology. The Surprise Fire-Medical Department personnel were met by a contractor employed by the company that maintained the ESS system, and that contractor identified the structure as a lithium-ion battery storage facility and stated that the clean agent suppression system inside the structure had discharged. This information, in conjunction with a 360-degree size-up, prompted E304 Capt to elevate the call to a working HAZMAT incident. If the contractor employed by company that maintained the ESS was not at the scene to inform the Surprise Fire-Medical personnel about the contents of the structure, the crew may have acted differently, which would have potentially resulted in a different, and possibly worse, outcome.

NFPA 855 *Standard for the Installation of Stationary Energy Storage Systems* [1] includes the following requirements for signage:

> **§4.3.5.1** Approved signage shall be provided in the following locations:

(1) On the front of doors to rooms or areas containing ESS or in approved locations near entrances to ESS rooms
(2) On the front of doors to outdoor occupiable ESS containers
(3) In approved locations on outdoor ESS that are not enclosed in occupiable containers or otherwise enclosed

§4.3.5.2 The signage required in 4.3.5.1 shall be in compliance with ANSI Z535 and include the following information:

(1) "Energy Storage Systems" with symbol of lightning bolt in a triangle
(2) Type of technology associated with the ESS
(3) Special hazards associated with the ESS
(4) Type of suppression system installed in the area of the ESS
(5) Emergency contact information

NFPA 855 also includes an exemption of retroactivity of the signage requirements for installations commissioned prior to the effective date of the standard:

§4.3.5.4 Existing ESS shall be permitted to retain the signage required at installation except as modified by 4.3.5.5.

§4.3.5.5 Existing ESS signage shall be updated to comply with the requirements for new ESS installations when the system is retrofitted or existing signs need to be replaced.

Effective signage can alert emergency responders to the hazards associated with incidents in the ESS installation and help inform the precautions and operations emergency responders should take while interacting with the ESS. Although NFPA 855 does not require signage to be installed retroactively, it is recommended that signage compliant with NFPA 855 §4.3.5 be provided for all lithium-ion battery ESSs, regardless of commissioning date.

A conversation with the members of the Surprise Fire-Medical Department crew that initially responded to the incident indicated that none of the firefighters were aware of the ESS installed in their coverage area prior to arriving on the call. Knowledge of the locations of lithium-ion battery ESS installations will allow local fire departments to educate their personnel and train to respond to ESS incidents. The Department of Energy maintains a web-based database that tracks the ESSs installed all over the world [31].

Recommendation #5: Lithium-ion battery ESSs should incorporate adequate explosion prevention protection as required in NFPA 855 or International Fire Code Chapter 12, where applicable, in coordination with the emergency operations plan.

Discussion: The potential for deflagration events in lithium-ion battery ESSs is evident. As the technology matures, the industry is likely approaching a situation in which lithium-ion battery ESS facilities will be constructed in high-population areas and designed into large, mixed-use buildings in the United States and globally. NFPA 855 *Standard for the Installation of Stationary Energy Storage Systems* [1] requires explosion prevention or deflagration venting designed in accordance with NFPA 69 *Standard on Explosion Prevention Systems* [32] or NFPA 68 *Standard on Explosion Protection by Deflagration Venting* [32], respectively:

> **§4.12.1** ESS installed within a room, building, or walk-in unit shall be provided with one of the following:
>
> (1) Explosion prevention systems designed, installed, operated, maintained, and tested in accordance with NFPA 69
> (2) Deflagration venting installed and maintained in accordance with NFPA 68

The scope and goal of NFPA 69 are defined as follows:

> **§1.1 Scope.** This standard applies to the design, installation, operation, maintenance, and testing of systems for the prevention of explosions by means of the following methods:
>
> (1) Control of oxidant concentration
> (2) Control of combustible concentration
> (3) Predeflagration detection and control of ignition sources
> (4) Explosion suppression
> (5) Active Isolation
> (6) Passive Isolation
> (7) Deflagration pressure containment
> (8) Passive explosion suppression
>
> **§4.1 Goal.** The goal of this standard shall be to provide effective deflagration prevention and control for enclosures where there is the potential for a deflagration.

The scope and goal of NFPA 68 are defined as follows:

> **§1.1 Scope.** This standard applies to the design, location, installation, maintenance, and use of devices and systems that vent the combustion gases and pressures resulting from a deflagration within an enclosure so that structural and mechanical damage is minimized.
>
> **§4.1 Goal.** The goal of this standard shall be to provide effective deflagration venting for enclosures where there is the potential for a deflagration.

It is also important that the strategy to prevent explosions or mitigate the consequences of deflagrations coordinate with the emergency operations plan. Because the deflagration was an apparent direct result of the responders opening the entry door in this incident, deflagration venting installed in the ESS would have been rendered ineffective when the door was opened. When the gas mixture ignited and pressures in the ESS increased, the open entry door acted as the flow path of least resistance for the blast waves, most likely negating the potential effect of deflagration vents to direct blast waves away from the HAZMAT team if they had been installed. This incident emphasizes the importance of ensuring the procedures for emergency responders outlined in the emergency response plan are consistent with the explosion protection strategies; that is if deflagration vents are installed to mitigate the consequences of a deflagration, responders should not decrease the effectiveness of the vents by opening the entry door.

If one of the methods or a combination of methods outlined in NFPA 68 and NFPA 69 were installed in the ESS in this incident, that may have prevented the deflagration event and/or the resulting injuries. It is recommended that AHJs enforce the requirements of NFPA 855 retroactively to lithium-ion battery ESSs constructed prior to the effective date of NFPA 855, and specifically the sections pertaining to an emergency operations plan and explosion protection.

Recommendation #6: Research that includes full-scale testing should be conducted to determine the most effective fire suppression and explosion prevention systems for lithium-ion battery ESSs.

Discussion: There are two distinct phases that require suppression in lithium-ion battery ESSs. The first phenomenon is the initial thermal runaway that may cascade to additional cells, modules, or racks. Explanatory material from § A.4.11.1 of NFPA 855 [1] states the following:

> *Thermal Runaway.* While non-water-based fire suppression has been shown to be effective at suppressing Class B and Class C fires in ESS enclosures, current suppression agents, both water based and non-water based, are probably not going to be able to stop thermal runaway. No published case studies, test reports, or data generated to date indicate otherwise. The current protection concepts in this standard, including size and separation, maximum rated energy, and elevation, are designed to try and keep a thermal runaway event from propagating from one ESS unit to another, contain a fire within a room or outdoor walk-in unit, and not allow it to compromise exposures.

Table 9.2 of NFPA 855 requires thermal runaway protection for lithium-ion battery ESSs and permits this protection to be part of a battery management system that has been evaluated with the battery according to UL 1973 *Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications* or UL 9540 *Standard for Energy Storage Systems and Equipment*. UL 9540A *Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems* presents a test methodology that incorporates testing at the cell, module, and battery scales to characterize thermal runaway and the fire response. By designing a lithium-ion battery ESS tested according to one of these standards, it is expected that the extent of cascading failure due to thermal runaway will be minimized.

Some element in the design of the ESS involved in this incident (separation, suppression, rack design, etc.) was able to limit the thermal runaway to a single rack, although it is unclear which design element or combination of elements contributed. Clean agent suppression systems are known to arrest flaming combustion, but have been ineffective at stopping thermal runaway. In this case, the lack of open flames due to the clean agent and the spacing between the racks may have prevented propagation to neighboring racks because all damage was isolated to Rack 15. Research should be conducted to investigate the effectiveness of various suppressants or prevention technology on limiting or arresting thermal runaway and the spread of thermal runaway through a lithium-ion battery ESS.

The second phenomenon that requires suppression is the potential explosion hazard that results if thermal runaway is unmitigated and explosive gases are allowed to collect in an enclosure. The agent deployed in the ESS in this incident most likely extinguished any flames that may have been produced in the initial thermal runaway, but in arresting flaming combustion, the suppression system facilitated the accumulation of flammable and toxic gases and vapors inside the ESS. The total effect of the clean agent suppression system did not contribute to making the ESS safe for the firefighters and others in the vicinity of the ESS in terms of explosive limits and the toxicity hazard. There are many explosion prevention and deflagration consequence mitigation strategies that must be investigated to determine the most effective method to contain or mitigate an explosion hazard for a lithium-ion battery ESS.

Recommendation #7: Research focused on emergency decommissioning best practices and the role of the fire service in an emergency situation should be conducted.

Discussion: As the lithium-ion battery ESS industry grows and the demand for load shifting, peak shaving, and electrical grid support increases, it is likely that ESS facilities will be constructed in high-population areas and designed into large, mixed-use buildings. This incident has illuminated some of the hazards possible in incidents involving lithium-ion battery ESSs as well as the complications well-trained fire service personnel encountered when the ESS was located in an unpopulated area. As this type of installation is constructed in closer proximity to densely populated areas, the number of civilians who may be affected by a fire or deflagration incident will increase. When considering a scenario in which an ESS facility is constructed on a high elevation level of a high-rise building in the center of a metropolitan area, the total impact and the high number of potential victims in the event of a fire or deflagration event becomes staggering.

Requirements for decommissioning appear in Chapter 8 of NFPA 855 and considerations for a decommissioning plan provided by the North American Electric Reliability Corporation (NERC) and the Federal Energy Regulatory Commission (FERC) are included in § A.8.1.3. The considerations in NFPA 855 provide a good overview of every action a decommissioning plan must include, but also belie the urgency required for the previously described scenario in an emergency situation in a high-rise building or similarly densely populated area. The decommissioning process developed for the ESS involved in this incident (see section 8) commenced several weeks after the incident to ensure thermal runaway had ceased and there was no possibility of reignition. The decommissioning process also required almost two months to completely dismantle the system and discharge all of the battery modules. Such a process would not be feasible for an ESS in a high population area that poses an imminent threat to buildings and people in the immediate surroundings.

When fires occur in ESS installations that threaten surrounding people and property, emergency decommissioning may be a viable option to mitigate damage and casualties. This type of emergency decommissioning is likely to deviate from the preplanned decommissioning process that must be established prior to commissioning per NFPA 855, and fire service and first responders are likely to have a role in such emergency decommissioning situations. Similar questions have been raised pertaining to safely addressing stranded energy in EV incidents. Research should be conducted to determine guidelines and recommendations for fire service personnel in emergency decommissioning situations.

8 Decommissioning the ESS

The off-grid energy storage industry is in the midst of significant growth in the United States, and the number of installations similar to the ESS involved in this incident is projected to increase in the near future [28]. Growing interest in installing lithium-ion battery ESSs in densely populated areas has necessitated the complete understanding of battery cell, module, battery management system, and large-scale ESS failure mechanisms and consequences. To this end, and to safely and effectively discharge the stranded energy remaining in the ESS after the deflagration event, a decommissioning procedure was created that facilitated complete inspection of all electrical components and battery modules left intact in the ESS, the collection of all evidence, and an investigation into the cause of the thermal runaway. It should be noted that NFPA 855 requires a full decommissioning procedure to be developed and approved by an AHJ prior to approval and commissioning of an ESS [1].

After the fire department transferred the ESS site in this incident back to the owner, personnel from the company that owned the ESS first investigated the site with a drone to provide optical access to the interior of the ESS while not exposing humans to potentially hazardous materials. A tent and a temporary fence were constructed around the ESS site to protect the structure and all equipment required for decommissioning from possible adverse weather and intruders. A map of the site during decommissioning is provided in Figure 8.1. The decommissioning process involved progressing from rack to rack inside the structure, disconnecting all electrical connections and cables, and transferring each individual module from inside the ESS to an inspection and discharge station outside the structure. At each station, the battery was connected to a battery management system as well as a thermal load bank and allowed to discharge to approximately 2% SOC. The battery modules were stored on rack shelves in one of two structures, with the differentiating criterion between the two structures being batteries that exhibited issues while discharging, and those that did not exhibit issues while discharging. Ultimately, all battery modules outside of Rack 15 showed no internal damage to any of the battery cells and discharged with minimal issues. The entirety of Rack 15 was sent to a forensic laboratory to attempt to determine the root cause of the thermal runaway event [11].

All technicians involved in the decommissioning process wore PPE, and fire safety and first aid equipment was readily available on the site. With three inspection and discharge stations available, the entire decommissioning process required almost two months to safely discharge, inspect, and store all of the battery modules. This process ensured that none of the battery cells would undergo thermal runaway while in storage, isolated the origin, and confirmed all damage was confined to the modules in Rack 15.

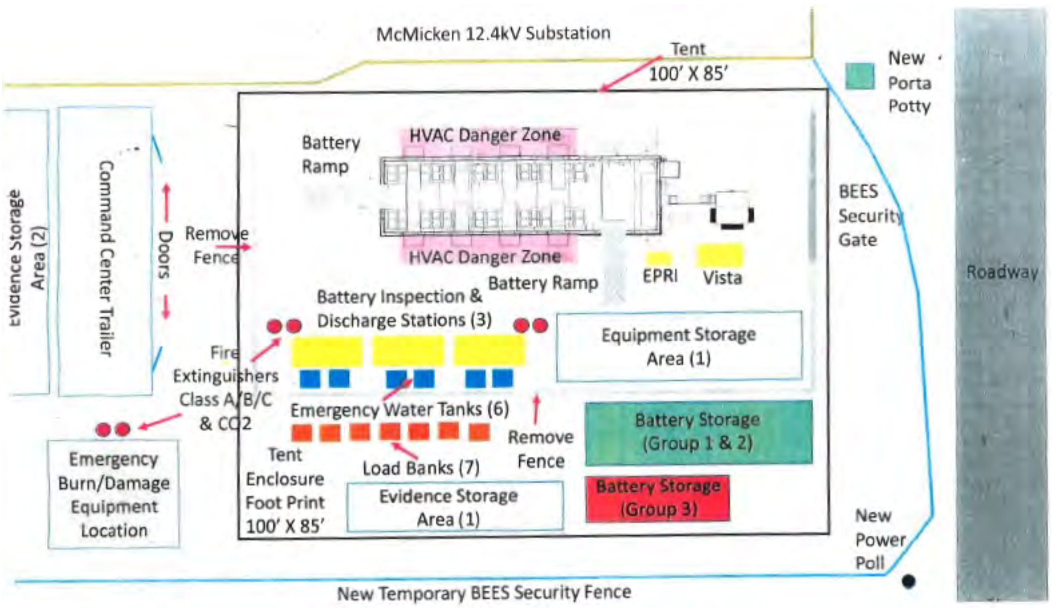

Figure 8.1: Map of decommissioning operation surrounding the ESS [11].

References

[1] NFPA 855: 2020. Standard for the Installation of Stationary Energy Storage Systems. 2020 Edition. Standard, National Fire Protection Association, Quincy, MA, 2020.

[2] City of Surprise, AZ. Surprise Fire-Medical Department. Available at https://www.surpriseaz.gov/8/Fire-Medical-Department. (Accessed December 1, 2019).

[3] City of Peoria, AZ. Peoria Fire-Medical Department. Available at https://www.peoriaaz.gov/government/departments/fire-medical. (Accessed December 1, 2019).

[4] NFPA 1001: 2019. Standard for Fire Fighter Professional Qualifications. 2019 Edition. Standard, National Fire Protection Association, Quincy, MA, 2019.

[5] NFPA 1021: 2020. Standard for Fire Officer Professional Qualifications. 2020 Edition. Standard, National Fire Protection Association, Quincy, MA, 2020.

[6] Peoria Fire-Medical Department Engine 193 Crew. Interview, October 29, 2019.

[7] Surprise Fire-Medical Department Engine 304 Crew. Interview, October 28, 2019.

[8] Phoenix Fire Department. Dispatch History for #F19147615. Transcript from April 19, 2019.

[9] Peoria Fire-Medical Department. 5-Gas Meter Datalog. MultiRAE Lite (PGM-6208). SN:M01CA09594. April 19, 2019.

[10] Weather Underground. Weather history for Luke Air Force Base, April 19, 2019. Glendale, AZ: The Weather Channel Interactive, Inc. Available at https://www.wunderground.com/history/daily/KLUF/date/2019-4-19?req_city=Surprise&req_state=AZ&req_statename=Arizona&reqdb.zip=85374&reqdb.magic=1&reqdb.wmo=99999. (Accessed November 10, 2019).

[11] Company that Owned the ESS. Private Communication, September 3, 2019.

[12] Google Maps. Satellite Imagery from Surprise, AZ. 2019: Maxar Technologies, U.S. Geological Survey. Available at https://www.google.com/maps/place/Surprise,+AZ/@33.6942415,-112.4239504,168m/data=!3m1!1e3!4m5!3m4!1s0x872b50449c4f72a3:0x3d108204ce52db2!8m2!3d33.6292337!4d-112.3679279. (Accessed November 10, 2019).

[13] UL FSRI. Visit to Site of Incident, October 28, 2019.

[14] Company that Owned the ESS. Private Communication, June 25, 2020.

[15] Company that Designed the ESS. Private Communication, September 3, 2019.

[16] Surprise Fire-Medical Department. Internal Incident Review, May 6, 2019.

[17] 29 C.F.R. 1910.1000. Limits for Air Contaminants. Regulation, Occupational Safety and Health Administration, Washington, D.C., 2020.

[18] H Ludwig, S Cairelli, J Whalen. Documentation for Immediately Dangerous to Life or Health Concentrations (IDLHs). Technical report, U.S. Department of Health and Human Services, 1994.

[19] A Blum, RT Long. Hazard Assessment of Lithium Ion Battery Energy Storage Systems. Final Report, Fire Protection Research Foundation, Quincy, MA, 2016.

[20] A Baird, E Archibald, K Marr, O Ezekoye. Explosion hazards from lithium-ion battery vent gas. *Journal of Power Sources*, 446, 2020.

[21] T. Maloney. Lithium Battery Thermal Runaway Vent Gas Analysis. Technical Report DOT/FAA/TC-15/59, U.S. Department of Transportation, 2016.

[22] C Mikolajczak, M Kahn, K White, RT Long. Lithium-Ion Batteries Hazard and Use Assessment. Final Report, Fire Protection Research Foundation, Quincy, MA, 2011.

[23] RT Long, A Blum, T Bress, B Cotts. Best Practices for Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results. Final Report, Fire Protection Research Foundation, Quincy, MA, 2013.

[24] B Ditch, D Zeng. Development of Sprinkler Protection Guidance for Lithium Ion Based Energy Storage Systems. Research Technical Report, FM Global, Norwood, MA, 2019.

[25] G Corbett, editor. *Handbook for Firefighter I and II*. Fire Engineering, New York, 2019.

[26] NFPA and the International Association of Fire Chiefs. *Fundamentals of Fire Fighter Skills and Hazardous Materials Response*. Jones & Bartlett Learning, Burlington, MA, 4th edition, 2019.

[27] International Fire Service Training Association. *Essentials of Fire Fighting*. Fire Protection Publications, Oklahoma State University, 7th edition, 2018.

[28] A Barowy. True Grid: Standards for Fire, Explosion, and Electrical Safety of Battery Energy Storage Systems. *Fire Protection Engineering*, 4, 2019.

[29] NFPA 1072: 2017. Standard for Hazardous Materials/Weapons of Mass Destruction Emergency Response Personnel Professional Qualifications. 2017 Edition. Standard, National Fire Protection Association, Quincy, MA, 2017.

[30] NFPA 72: 2019. National Fire Alarm and Signaling Code. 2019 Edition. Standard, National Fire Protection Association, Quincy, MA, 2019.

[31] U.S. Department of Energy. DOE Global Energy Storage Database. Available at https://energystorageexchange.org/projects.

[32] NFPA 69: 2019. Standard on Explosion Prevention Systems. 2019 Edition. Standard, National Fire Protection Association, Quincy, MA, 2019.

[33] V Somandepalli, K Marr, Q Horn. Quantification of Combustion Hazards of Thermal Runaway Failures in Lithium-Ion Batteries. *SAE Int. J. Alt. Power.*, 3, 2014.

[34] V Babrauskas. *The Ignition Handbook*. Fire Science Publishers, Issaquah, WA, 2003.

[35] International Labour Organization and World Health Organization. Carbon Monoxide. Available at: http://www.inchem.org/documents/icsc/icsc/eics0023.htm (Accessed January 27, 2020), 2017.

[36] DP Nolan. *Chapter 14 - Control of Ignition Sources*. Gulf Professional Publishing, 4th edition, 2019.

[37] Society of Fire Protection Engineers. *Handbook of Fire Protection Engineering*. Springer, Bethesda, MD, 5th edition, 2016.

Appendix A

Ignition of Gases Produced During Thermal Runaway

Several research efforts have attempted to quantify the composition of the gas mixture released from lithium-ion batteries during thermal runaway. A recent article compiled many of these studies and presented the relative amounts of hydrogen, carbon monoxide, carbon dioxide, and total hydrocarbons released from a range of cell chemistries during thermal runaway. In general, the vent gas from lithium-ion cells at 50% SOC and higher was composed of approximately 15–30% hydrogen, 5–50% carbon monoxide, 10–30% hydrocarbons, and 10–70% carbon dioxide [20, 33]. Table A.1 presents the minimum ignition energy and autoignition temperature for hydrogen, carbon monoxide, and several hydrocarbons to support discussion of potential ignition sources in an ESS facility capable of igniting the gas mixture produced during thermal runaway. Without complete knowledge of the composition of the gas mixture in the ESS, it is impossible to accurately assign a minimum ignition energy, but it may be conservatively assumed that the minimum ignition energy for the gas mixture was approximately 1 mJ.

Table A.1: Minimum ignition energy and autoignition temperatures for hydrogen, carbon monoxide, and common hydrocarbons (adapted from [34]).

Substance	Energy (mJ)	Autoignition Temperature in Air (°F)
Hydrogen	0.03	970
Carbon monoxide	0.3 [35]	1,130
Acetylene	0.03	580
Butane	0.26	760
Cyclohexane	2.65	475
Ethane	0.42	960
Ethylene	0.11	915
Heptane	1.15	435
Hexane	0.29	435
Methane	0.71	1,005
Pentane	0.82	500
Propane	0.5	840
Propylene	0.42	860
p-Xylene	0.2	985

A wide range of regularly encountered potential ignition sources are common in electrical installations like the ESS involved in this incident. Potential ignition sources regularly encountered in ESSs include arcing due to the opening and closing of relays, contactors, switches, breakers, and electric fans. These regularly encountered potential ignition sources were absent from the ESS involved in this incident because each node was electrically isolated via the opening of circuit breakers and contactors, and because the HVAC fans were shut off after the smoke detection system registered an alarm condition.

Sparks resulting from the discharge of static electricity, electrical shorts, and stray current may produce enough energy to ignite a flammable gas mixture. The dielectric strength of a gas may be described as the critical voltage across a gap, divided by the gap distance, that results in electrical breakdown of the gas. Electrical breakdown of a gas changes the gas from an insulator to a conductor and allows electricity to flow across the gap, which appears as a spark or arc and can generate high temperatures that may ignite flammable gas mixtures [36].

The static electric charging rate is usually accelerated by increased movement of gases contaminated with particles, dust, or fibers. It is likely that the highly sooty environment in the ESS installation undergoing thermal runaway increased the static electric charging rate, particularly in the high temperature and low humidity environment where the ESS was installed [36]. It is also likely that thermal runaway generated conditions in the ESS that made sparking and arcing more probable. The dielectric strength of the gas mixture in the ESS is unknown, but it has been noted that hot, ionized gas has a lower dielectric strength than air [37], so it is likely that the dielectric strength of the gas mixture was lower than air. Note that a medium with a dielectric strength lower than that of air would facilitate spark formation at lower voltages.

Table A.2 provides values for the minimum voltage and minimum current required to sustain an arc in air between electrodes composed of the materials presented. The values listed correspond to an infinitesimal gap size, and larger gap sizes would require higher minimum voltages and currents. The values should also be understood as the minimum of each quantity, and not as a combination of quantities, meaning that an arc with current near the minimum value would require a voltage significantly higher than the minimum value presented in the table [34]. Notable in Table A.2 is the low minimum current required for carbon electrodes to sustain an arc. The soot deposition on electric switches, relays, contacts, and other similar devices that occurs during thermal runaway may have decreased the critical current required to initiate sparking and sustain arcing in the ESS involved in this incident.

Table A.2: Minimum voltage and current needed to sustain an arc in air (adapted from [34]).

Electrode Material	Min. Voltage (V)	Min. current (A)
Aluminum	12	0.40
Carbon	20	0.01
Copper	13	0.45
Iron oxide	14	0.70
Nickel	8–14	0.5
Steel (Stainless)	15	0.5

The total energy (in J) in a spark or arc across a gap over its duration is equal to the voltage (in V) multiplied by the current (in A) multiplied by the duration (in s). Assuming the minimum current traveling across the gap between two aluminum components over a duration of 0.1 ms, the minimum voltage difference between the two components would need to be 25 V to achieve a minimum energy of 1 mJ. It is estimated that the total voltage of each module was greater than 50 V, and there were likely many locations throughout the ESS with approximate voltage differences of

25 V. This is a simple, first-order calculation that neglects many complicating factors, but it helps to illustrate that many sparks and arcs of sufficient energy to ignite the battery gas mixture were possible in the ESS after the initiation of thermal runaway.

In addition to these typical potential ignition sources that are regularly encountered, there were also likely additional ignition sources that resulted from the thermal runaway. These potential ignition sources included hot surfaces and the ejection of incandescent metal particles.

A photograph of the floor in front of Rack 15 taken during decommissioning is provided in Figure A.1. The photograph shows solidified pools of molten aluminum that apparently flowed down along the sides of the front of the rack during the incident. The melting temperature of aluminum is 1,220°F [22]. Studies conducted by the American Petroleum Institute suggest that a surface temperature approximately 360°F above the autoignition temperature is required to facilitate ignition [36]. Hydrogen as well as most hydrocarbons, which are major components of the gas mixture expected to be released from lithium-ion batteries undergoing thermal runaway, have autoignition temperatures below 860°F [37]. It has also been observed that the exothermic reactions that are a key contributor to propagation of the thermal runaway process produce temperatures that are capable of causing hot surface ignition of flammable mixtures [22].

Figure A.1: Photograph taken during decommissioning of the ESS shows a pool of solidified aluminum on the floor in front of Rack 15 [11].

Lithium-ion battery cells have been observed to eject molten metal during thermal runaway [19, 22]. These metal droplets are likely to be at a sufficient temperature to act as a competent ignition source for a flammable gas and vapor mixture.