

Final Report

Considerations for ESS Fire Safety

Consolidated Edison and NYSERDA
New York, NY

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Consolidated Edison
 Considerations for ESS Fire Safety

Project Name:	Considerations for ESS Fire Safety	DET NORSKE VERITAS (U.S.A.), INC. (DNV GL)
Customer:	Consolidated Edison and NYSEERDA	Materials & Corrosion Technology Center
Contact Person:	Britt Reichborn-Kjennerud	O&G Materials Compatibility / Energy
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Organization Unit:	O&G Corrosion Control/Energy	United States
Report No.:	OAPUS301WIKO(PP151894), Rev. 4	Tel: (614) 761-1214
		Fax: (614) 761-1633
		www.dnvgl.com

Task and Objective:

Please see Executive Summary.

Prepared by

Verified by

Approved by



Davion Hill, Ph.D.
 Energy Storage Leader, Americas



Nick Warner, M.S.
 Engineer, EAA Laboratories



William Kovacs III, P.E.
 Senior Engineer

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Reference to part of this report, which may lead to misinterpretation, is not permissible.

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Executive Summary

This report summarizes the main findings and recommendations from extensive fire and extinguisher testing program that evaluated a broad range of battery chemistries¹. The testing was conducted through much of 2016 on behalf of the New York State Energy Research & Development Authority (NYSERDA) and Consolidated Edison, as they engaged the New York City Fire Department (FDNY) and the New York City Department of Buildings (NY DOB) to address code and training updates required to accommodate deployment of energy storage in New York City. This executive summary can be read as a standalone summary of the main project findings and recommendations.

The main conclusion from the program is that installation of battery systems into buildings introduces risks, though these are manageable within existing building codes and fire fighting methods when appropriate conditions are met. This statement comes with caveats. There is a need to clarify a universal finding in this program: in the case of heating by fire or thermal abuse all batteries tested emitted toxic gases. It should also be noted that the average emissions rates of equivalent masses of plastics exceed those of batteries. Every battery tested emitted toxic gases (Table 3 on page 29); however, this can be expected from most fires.

The toxicity of the battery fires was found to be mitigated with ventilation rates common to many occupied spaces. While it was found that all batteries tested emitted toxic fumes, the toxicity is similar to a plastics fire and therefore a precedent exists. The batteries exhibited complex fire behaviors that led to abundant water use; however, it was found that the extinguishing requirements for batteries need not be excessive if an intelligent, system-level approach is taken that includes external fire ratings, permits direct water contact, and implements internal cascading protections. The general outcome of the work is that fire safety considerations are applicable to all the batteries tested in this program, even though vanadium redox and lead acid electrolytes were not observed to be flammable. The data presented in this report supports these findings.

All energy systems carry with them a risk in their deployment; however, the risks identified in this study are manageable within the limits of today's engineering controls for safety when appropriate conditions are met. The resulting requirements in codes, if implemented, are within the boundaries of the typical built environment.

The batteries tested in this program are as follows:

1. Li-ion NCM (4 vendors)
2. Li-ion LiFePO₄ (2 vendors)
3. Li-ion LTO
4. Lead Acid
5. Vanadium Redox
6. An additional Li-ion chemistry described as BM-LMP

¹ Chemistries are listed in the Appendix on page 107

In addition, at the request of FDNY the following extinguishing agents were tested:

1. Water
2. Pyrocool
3. F-500
4. FireIce
5. An aerosol agent

Greater detail is found within the report. It is suggested the reader use cross references provided in the report to see where technical information can be found that supports these findings. This report extensively uses cross references so that the reader can begin reading at any point in the document and quickly find relevant supporting information in other sections of the document, similar to a handbook.

Sections Directly Informing Code Development and Training

1. Locations (see Locations and Ventilation on page 48)
2. Ventilation rate (see Locations and Ventilation on page 48, as well as the Appendix, page 65)
3. Enclosures, fire rating (see Fire Rating, page 40)
4. Capacity limitation dependent on space (see Room Capacity Limitations on page 56)
5. Clearances (see Clearances page 55)
6. Monitoring, Detection, and Alarms (see page 55)
7. Fire suppression and Water Requirements (see Extinguishing, page 45 as well as the Appendix, page 68)
8. Emergency Response (see Guidance for First Responders on page 34 and Frequently Asked Questions, page 8)

Table of Contents

1.0	ACKNOWLEDGEMENTS.....	1
2.0	ACRONYMS.....	2
3.0	HOW TO USE THIS DOCUMENT	3
4.0	TESTING METHODOLOGY	4
4.1	Cell Testing	4
4.2	Module Testing	5
5.0	CONSIDERATIONS FOR SYSTEM TYPES AND LOCATIONS	6
5.1	Large versus Small Systems	6
5.2	Occupied versus Non-Occupied Spaces	7
5.3	Challenges with Proposed Codes	8
6.0	NEW FINDINGS AND ANSWERS TO FREQUENTLY ASKED QUESTIONS IN BATTERY SAFETY	8
7.0	PRESENT DAY INDUSTRY-ACCEPTED SAFETY PRACTICES FOR ENERGY STORAGE PROJECTS	31
8.0	GUIDANCE FOR FIRST RESPONDERS	34
8.1	Considerations for Permitting and Siting.....	34
8.2	Considerations for Operations at the Scene	35
8.3	Guidance for Isolation and Overhaul	38
9.0	FINDINGS RELATED TO CODES AND TRAINING	40
9.1	Fire Rating	40
9.2	Extinguishing.....	45
9.2.1	Class D and Deep Seated Fires.....	45
9.2.2	Cooling and Collateral Damage	45
9.3	Locations and Ventilation	48
9.3.1	Outdoor Locations	48
9.3.2	Indoor Locations (Penthouse or Dedicated Room).....	48
9.3.3	GPM and CFM Requirement.....	50
9.4	Inspection and Monitoring	55
9.5	Clearances	55
9.6	Room Capacity Limitations	56

9.7	Project Development Considerations for Interaction with First Responders and AHJs	57
9.8	Considerations for Battery Chemistries that are not Li-ion	58
10.0	SUMMARY OF MAIN FINDINGS AND RECOMMENDATIONS	59
10.1	Conclusions	61
11.0	REFERENCES	62
12.0	APPENDIX 1: REFERENCED DATA	65
12.1	Assumptions for Air Changes per Hour (ACH) Calculations	65
12.2	Water Mass Requirement Calculation	68
12.2.1	Sizing the Water Requirement to Peak HRR	69
12.2.2	Alternative Strategy for Sizing the Water Requirement: Preventing the Peak HRR Altogether	69
12.2.3	Additional Consideration: Heat of Vaporization	70
12.2.4	Summary of Water Extinguishing Calculations.....	73
12.3	Why Bowtie Models?	74
12.4	Heat Load from Li-ion Battery Failures	76
13.0	APPENDIX 3: TESTING PLAN AND APPROACH	76
13.1	Design of Experiments	77
13.2	Combustion Gas and Particulate Matter Analysis	77
13.3	Heat Release Rate	78
13.4	Procedure.....	78
13.4.1	Testing Procedure: Lithium Battery Gas Sampling, No Extinguishing	79
13.4.2	Testing Procedure: Lithium Battery Gas Sampling With Extinguishing	79
13.4.3	Testing Procedure: Flow and Lead Acid Battery Electrolyte (liquid)	80
13.4.4	Testing Procedure: Lead Acid Battery Lead (solid)	81
13.5	Large Scale Burns	84

List of Tables

Table 1 Statistics on cell failure rates for the entire test program including all Li-ion variants.	21
Table 2 Average release rate for battery materials over a 30 minute time period.	23
Table 3 Inventory of Toxic and Flammable Hazards found in this Study.....	29
Table 4 Non-battery related codes for energy systems in buildings.	43
Table 5 Battery specific codes for battery systems in buildings, existing and proposed.....	44
Table 6 Immediately Dangerous to Life and Health (IDLH) for the emphasized toxic gases identified in the testing work.	49
Table 7 Example calculation to determine the minimum water requirement per kg of burning cell.	51
Table 8 Benchmarks for airflow and water flow for typical structures.	51
Table 9 Values derived from probabilistic analysis of water flow rates (GPM) and air flow rates (CFM) per system energy (kWh) or mass (kg).	52
Table 10 Example implications based on extrapolated findings from testing. It can be seen that the calculated water requirement is within the bounds of what was described for libraries, pharmacies, warehouses, and laboratories; similarly the air flow requirements can be at or below unless the room volume is too small.	53
Table 11 Air change rates based on HCl emissions as a function of room size and quantity of failing cells.	65
Table 12 Air change rates based on HCN emissions as a function of room size and quantity of failing cells.	66
Table 13 Air change rates based on CO emissions as a function of room size and quantity of failing cells.	66
Table 14 Air change rates based on HF emissions as a function of room size and quantity of failing cells.	66
Table 15 Conversions from ACH to CFM based on the example room volumes for energy storage systems.	67
Table 16 Aggregation of data regarding battery fires, extinguishing, emissions rates, and extinguishing. Distributions in the column labeled "Dist" are triangular; the mean is shown.	68

Table 17 Summary of methodologies and results of the water requirement calculation.....	74
Table 18 Battery burn tests without extinguishing, combustible batteries only	82
Table 19 Battery burn or heat tests with extinguishing.....	83

List of Figures

Figure 1 Diagram of the abuse chamber used for fire testing of batteries in the BESS program.	4
Figure 2 Configuration of module burn site.	6
Figure 3 A proactive, system level approach to extinguishing need not prescribe excessive levels of water if the system also contains a high external fire rating as well as internal barriers to prevent cascading.	8
Figure 4 Peak ppm per kg (in a 0.44 m³ volume) for all batteries tested as compared to plastics.	10
Figure 5 Average emissions per kg per minute of test mass for plastics vs. batteries.	11
Figure 6 Emission of HCl was observed from the vanadium redox flow electrolyte.	12
Figure 7 Heating of Pb acid electrolytes yielded SO₂.	12
Figure 8 Heating of Pb acid electrolytes also yielded HCl.	13
Figure 9 Observation of delayed cascading during extinguishing in a module without cascading protections.	14
Figure 10 Internal temperatures between two sandwiched pouch cells remained 300°C higher than external faces after aerosol extinguishing.	15
Figure 11 Some battery modules still had residual voltage after fire testing.	16
Figure 12 Progression toward lower water requirements as testing progressed.	17
Figure 13 Residue analysis from a coupon hung in the headspace of the vanadium redox boiling test.	19
Figure 14 Percent of mass loss as a function of cell form factor.	20
Figure 15 Relationship of heat release rate (kW) per gram of mass lost.	22
Figure 16 Estimated ventilation rates (air changes per hour) as a function of room volume and mass of battery undergoing failure for HCl.	23

Figure 17 **Estimated air changeover rate (air changes per hour) as a function of room volume and battery mass undergoing failure for HCN.** 23

Figure 18 **Estimated air change over rate (air changes per hour) as a function of room volume and battery mass undergoing failure for CO. Because the IDLH of CO is much higher, there is little dependency on battery masses at these scales.** 24

Figure 19 **Estimated air change rate (ACH) as a function of room volume and battery mass during failure for HF.**..... 24

Figure 20 **Representative emissions histogram from a Li-ion battery.** 25

Figure 21 **The combined LEL and autoignition temperature of mixed gases emitted from Li-ion batteries may be as low as 3,000 ppm and less than 400°C, as flammable gases were ignited and burned off above this temperature.**..... 26

Figure 22 **For Li-ion batteries, the mass loss is directly proportional to the state of charge prior to failure.** 27

Figure 23 **It is generally true that LiFePO₄, LTO, and BM-LMP batteries demonstrate lower than average temperatures during failure. The temperatures indicated for Pb acid and vanadium redox batteries is the peak heating temperature, as these electrolytes did not demonstrate flammable or exothermic properties as they were tested.**..... 28

Figure 24 **Smoke plume rising through door gaps and out of top vents in the burn container.** 31

Figure 25 **Project development timeline and the implementation of FMEA or other safety review for the site.**..... 33

Figure 26 **Submerging batteries in water resulted in cooler temperatures, but slow shorting and persistent CO generation (bubbles).** 39

Figure 27 **Simplified diagram of fire impinging on the external wall of a battery energy storage system.** 41

Figure 28 **Direct fire exposure model to a steel wall with a 1/16" thickness and 1" air gap between the wall and battery modules.** 42

Figure 29 **Performance of water compared to other agents as water additives, top temperature of battery cell.** 46

Figure 30 **Cooling performance of water compared to other extinguisher types, bottom temperature of cell.**..... 46

Figure 31	Distribution of gallons per minute for a 1 MWh battery, calculated from cell testing and extrapolating with the latent heat value, which demonstrates that the 0.1 GPM/kg estimation is highly conservative.	54
Figure 32	Example of the air flow requirement for a 1 MWh Li-ion system, demonstrating that the distribution of values is strongly skewed leftward.	54
Figure 33	The FDNY Building Information Card (actual example) contains emergency contact information for fire safety and building engineers.	58
Figure 34	A reactive cooling approach requires an oversized water flow requirement; whereas a system-level proactive approach enables a reduced water requirement.	72
Figure 35	Regression coefficients of the ventilation requirement.	72
Figure 36	Regression coefficients for the water flow rate in GPM/kg demonstrate that the duration of the event and the water contact efficiency are the strongest drivers in reducing the water requirement.	73
Figure 37	BowTie analysis permits the visualization of threats to a top event, such as loss of battery control, and ties these threats to consequences.	75
Figure 38	Battery weight and the peak room temperature are positively correlated.	76
Figure 39	Large abuse test chamber design for battery fire and extinguishing testing.	78

FINAL REPORT: NYSERDA / Consolidated Edison BESS Program Considerations for ESS Fire Safety



Work conducted by:



Consolidated Edison and NYSERDA Disclaimer

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1.0 ACKNOWLEDGEMENTS

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NCM 1: LG Chem
NCM 2HE and NCM 2HP: Samsung SDI
NCM 3: Kokam (donated by Sunverge)
NCM 4: Electrovaya
LFP 1: BYD
LFP 2: XO Genesis
T 1: Toshiba
BM-LMP: C4V
VR 1: UET
PBA 1: EnerSys
Aerosol agent: Fireaway Inc. (product Stat-X)

2.0 ACRONYMS

ACH – Air Changes per Hour
AHJ – Authority Having Jurisdiction
BESS – Battery Energy Storage Safety
BIC – Building Information Card
BMS – battery management system
BM-LMP – Bio-mineralized Lithium Mix-Metal Phosphate
BSCAT – Barrier-Based Systematic Cause Analysis Technique
BTM – Behind the Meter
CFM – Cubic Feet per Minute
CFR – Code of Federal Regulations
CHP – Combined Heat and Power
CID – Current Interrupt Device
CO – Carbon Monoxide
COF – Certificate of Fitness
C-rate – charge rate
DCE – Duty Cycle Eccentricity
DMC – Dimethyl Carbonate
DOB – New York City Department of Buildings
DOD – depth of discharge
EC – Ethylene Carbonate
EDS – energy dispersive spectroscopy
ERPG – Emergency Response Planning Guidelines
ESS – Energy Storage System
FAQ – Frequently Asked Questions
FID – Flame Ionization Detector
FDNY – New York City Fire Department
FEA – Finite Element Analysis
FMEA – Failure Mode Effects Analysis (sometimes FMECA to include “Criticality”)
FTA – Fault Tree Analysis
FTIR – Fourier Transform Infrared Spectroscopy
GPM – Gallons Per Minute
HAZID – Hazard Identification
HCl – Hydrochloric Acid
HRR – Heat Release Rate
HCN – Hydrogen Cyanide
HF – Hydrofluoric Acid
HVAC – Heating, Ventilation, and Air Conditioning
IDLH – Immediately Dangerous to Life and Health
IE – Independent Engineer(ing)
IEC – International Electrotechnical Commission
IFC – International Fire Code
IPP – Independent Power Producer
LEL – Lower Explosion Limit
LMO – Lithium Manganese Oxide
LTO – Lithium Titanium Oxide
NYSERDA – New York State Energy Research and Development Authority
NAVSEA – Naval Sea Systems Command
NCA – Nickel Cobalt Aluminum
NCM – Nickel Cobalt Manganese

NIOSH – National Institutes for Occupational Safety and Health
NFPA – National Fire Protection Association
NHTSA – National Highway and Traffic Safety Administration
NRTL – Nationally Recognized Test Laborator
PBA – Lead Acid
PC – Polypropylene Carbonate
PID – Photo Ionization Detector
PPE – Personal Protective Equipment
PVC – Polyvinyl Chloride
SCBA – self contained breathing apparatus
SEI – Solid Electrolyte Layer
SOC – State of Charge
SOP – Standard Operating Procedures
SME – Subject Matter Expert
UL – Underwriter’s Laboratories
UN – United Nations
UPS – Uninterruptible Power Supply
VOC – Volatile Organic Compounds
VRLA – Valve Regulated Lead Acid

3.0 HOW TO USE THIS DOCUMENT

This document is designed to inform codes writing procedures and first responder training. It can be considered a reference and handbook for this purpose. To that end, the document is structured around key ingredients to codes as determined by a survey of building and fire codes for energy-related machinery and devices.

Executive Summary: This section can be considered the consolidated list of findings and recommendations from the NYSERDA/Con Edison Battery Energy Storage System (BESS) Program.

Frequently Asked Questions (FAQ): This may be considered the main guide of the document, cross referencing to relevant sections of the report, and also serving as an introduction to the topic.

Recommendations: This is the main deliverable of the document. Essential data is provided to support recommendations, detail is left to the appendix. Recommendations and main findings are within the document text in **bold**.

Appendix: Supplementary reference data needed to communicate the recommendations, but as useful reference for detailed background. The Appendix begins on page 65. The appendix is separated in two parts that represent supporting information: a literature review on past fire incidents and data, and a confidential appendix which can be omitted for the public version of the report.

Literature References: Whenever possible, literature references are provided for independent confirmation of facts, figures, or assertions. Literature references are found in “References” on page 62.

Cross references: Whenever possible, cited data or key conclusions that are relevant to other sections of the report are cross referenced by section title and page number.

4.0 TESTING METHODOLOGY

Four different lithium chemistries (LTO, LFP, NCM, BM-LMP), lead acid, and vanadium redox batteries represented by nine unique battery types from eight different manufacturers were tested. For the Li-ion batteries, these included prismatic cells as well as pouch cells, but no cylindrical cells. For the lead acid and vanadium redox batteries, testing was largely focused on the battery electrolytes. Modules were also provided for large scale burn testing. A more explicit description of the test plan is included in the Appendix.

4.1 Cell Testing

The cells tested ranged from 1.2 to 200 Ah with an average of 52 Ah, excluding the electrolytes from vanadium redox and Pb acid cells that were tested separately. All cells were heated with 4 kW of radiant electric heat in DNV GL's Large Battery Destructive Testing Chamber (see Figure 1). All cells were placed inside the chamber and exposed to heat until they vented. Upon venting, some cells self ignited. For those that did not, hot point ignitors were placed in the upper half of the chamber and were activated once lower explosive limit (LEL) reached 50% to prevent an explosion. Many cells vented enough gas to lead to a flashover in the chamber upon activation of ignitors. In addition to heaters and ignitors, the chamber also contained ambient and inlet air temperature thermocouples, two thermocouples on each cell (top and bottom) and eight thermocouples in a cube shape around the cell to act as a thermopile for Heat Release Rate (HRR) calculations; four were level with the cell while four more were eight inches above the cell. There was one additional thermocouple in the center exhaust stack of the abuse chamber. In addition, swatches of Morning Pride personal protective equipment (PPE) material were placed in the unit above the cell to assess the effect of the fire and offgas on firefighter PPE. Cells were tested at 25, 50, 75 and 100% state of charge (SOC).

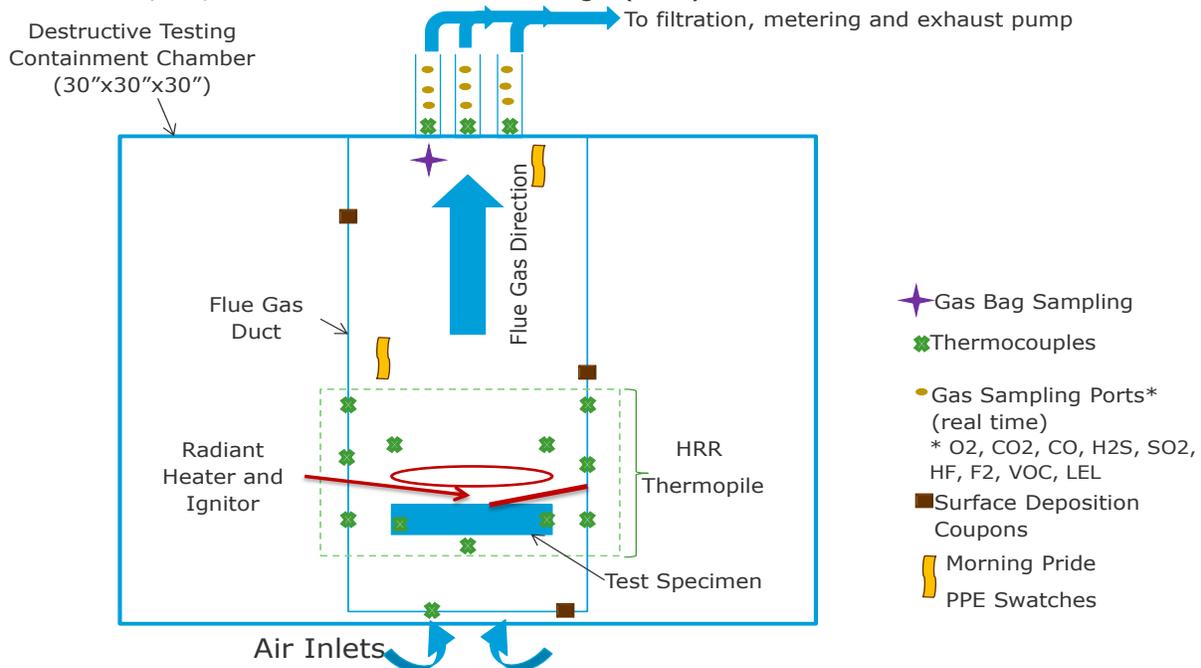


Figure 1 **Diagram of the abuse chamber used for fire testing of batteries in the BESS program.**

Finally, gas sampling was performed by a Gasetm DX4000 Fourier transform infrared spectroscopy (FTIR) gas analyzer. This analyzer monitored HCl, HF, HCN, CO, CO₂, O₂, SO₂, NO, NO₂, and a range of hydrocarbons including methane, ethane, ethylene, benzene, toluene, and others. In line with the FTIR analyzer were MSA Ultima sensors for O₂ (redundant measurement), H₂, and F₂/Cl₂. A final MSA sensor was placed directly off the chamber for flammability measurements. The sensor was of the catalytic bead type and was factory calibrated to non-specific gas for total LEL measurement. This was deemed suitable as a range of flammable gases were expected and calibration to one may show improper bias. In addition to the gas sensors, gas capture bags were set up off of the exhaust stacks. Select gas bag samples were taken periodically and were used to verify the FTIR measurement.

For extinguishing, the abuse chamber was fitted with a 2.5-gallon water can with an extinguishing trigger. The can was pressurized and engaged by a temperature trigger, with an in-line electronic solenoid valve for actuation. Once a single temperature exceeded 350°C, the solenoid was opened and the extinguisher released. The can was typically filled with 1 gallon of liquid and the entirety of the can was emptied. In one test, an 8-second pulse of water was used and the solenoid reclosed. The extinguisher nozzle was fixed approximately 10 inches from the battery, to the side and about 3 inches above. The nozzle was a fogging mist nozzle, and because of proximity, tank pressure was reduced to 75 psi to allow better saturation. All cells for extinguisher testing were tested at 90% SOC.

For large scale testing, a purpose built propane torch was constructed by Fire Force Inc, a builder of aircraft fire simulators. This torch was used to apply a direct propane flame to battery modules which were placed in a walled off shipping container shown in Figure 2 and Figure 24. The "room" was approximately 10 feet into the trailer, with one end being the trailer door and having a man door installed into a double sheeted drywall wall on the interior wall. A series of ventilation ports were cut into the room to allow for ventilation testing (two high, two low, one roof) and positive and negative ventilation were tested. In addition, two sprinklers were piped into the room for suppression testing. Most tests were conducted with doors open; however, two tests were conducted with the container closed to test ventilation. In addition to the sprinklers, hose suppression was used at times as well to assess effectiveness.

4.2 Module Testing

DNV GL and Rescue methods constructed a partially enclosed outdoor burn facility for module testing for all Li-ion battery types where modules were provided. The module sizes ranged from 7.5 to 55 kWh. Burns were conducted directly with a propane torch. A steel grate was hung from the ceiling of the burn enclosure at a height of approximately 4 feet. Below the grate a pan was constructed to catch water runoff from extinguishing. Two sprinkler heads were installed above the burn location and were fed with a 2.5-inch line reduced to a ½-inch pipe from a hydrant and pumper truck at the burn site.

Venting ports were constructed above and below the burn platform to control ventilation and also provide sampling locations. The doors to the burn chamber could be opened or closed to test the effect on oxygen, toxicity, and heat release of the fire (Figure 2).

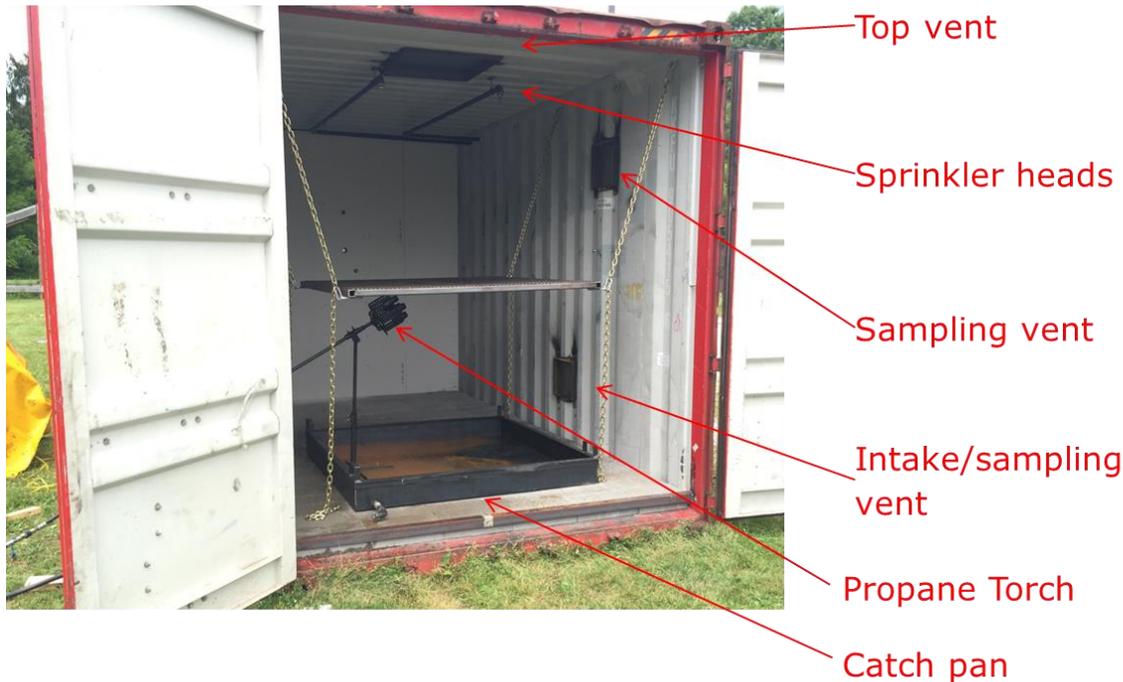


Figure 2 **Configuration of module burn site.**

5.0 CONSIDERATIONS FOR SYSTEM TYPES AND LOCATIONS

As of 2016, energy storage systems to be deployed in the near-term market will have differentiating characteristics dependent on size and location.

5.1 Large versus Small Systems

The testing results have been translated to scalable metrics for ventilation and fire suppression such as cubic feet per minute of air flow per kilogram of battery mass (CFM/kg), and gallons per minute of water flow per kilogram of battery mass (GPM/kg).

The reasons for this are several:

- Large systems and small systems should have an intelligent means of addressing ventilation and fire suppression with a scalable metric that correlates to size or mass is preferable to meet this challenge, rather than an arbitrary kW, kg, or kWh number as what is proposed in some codes as shown in Table 5.
- Energy and power densities for systems are perpetually evolving and improving. Arbitrarily prescribing a kW, kWh, or kg number to limit system installation threatens the value proposition of energy storage as energy density increases in the future
- With an energy density metric, it is possible to translate CFM/kg or GPM/kg to CFM/kWh or GPM/kWh with a single calculation. The same can be done for power density such as CFM/kW or GPM/kW. Lastly, it is possible to translate these numbers to CFM/ft³ or GPM/ft³ as is used by the fire service. All of these metrics are scalable and can be calculated depending on context. Because battery mass and energy

density will continue to evolve, these metrics will capture that evolution as codes follow the market.

- Many small systems are dependent on the ventilation and fire suppression in the space, and there should be a means to check if the host-infrastructure is adequate.
- Large systems may have standalone ventilation and fire suppression equipment.
- One of the main stakeholders of this report is the New York Fire Department (FDNY) and consequently most United States (US) fire departments, and they are familiar with GPM and CFM units of measure for firefighting and codes.

5.2 Occupied versus Non-Occupied Spaces

As discussed, the proposed codes in many standards organizations shown in Table 5 become increasingly prescriptive as energy equipment becomes installed in occupied spaces. Non-occupied spaces (such as outdoor energy storage containerized systems, for example) may have less restrictive codes for ventilation or clearance.

The water flow calculations presented in this document are addressing a key issue in battery safety. Over-reaction to the threat of thermal runaway has led to recommendations for “copious amounts of water” [12] for the extinguishing of Li-ion battery systems. Such recommendations inflate the perceived water requirement. The reasoning for this is logical; it is better to err on the side of caution and advise first responders to use as much water as possible to indirectly cool the battery system.

This work has demonstrated that excessive water need not be the design criteria but should instead be considered part of an intelligent set of safety systems including external fire ratings, internal cascading protections, and fixed suppression systems to slow the propagation of heat in a combined manner such as in Figure 3. If a systems approach to safety is taken, the water requirements may be far less severe. If and when first responders need to react to a system fire, it may be the case that these systems be overridden or overcome, and a “copious amounts of water” approach may be desired. **Therefore water requirements for the codes and water requirements for first responders are separate issues.**

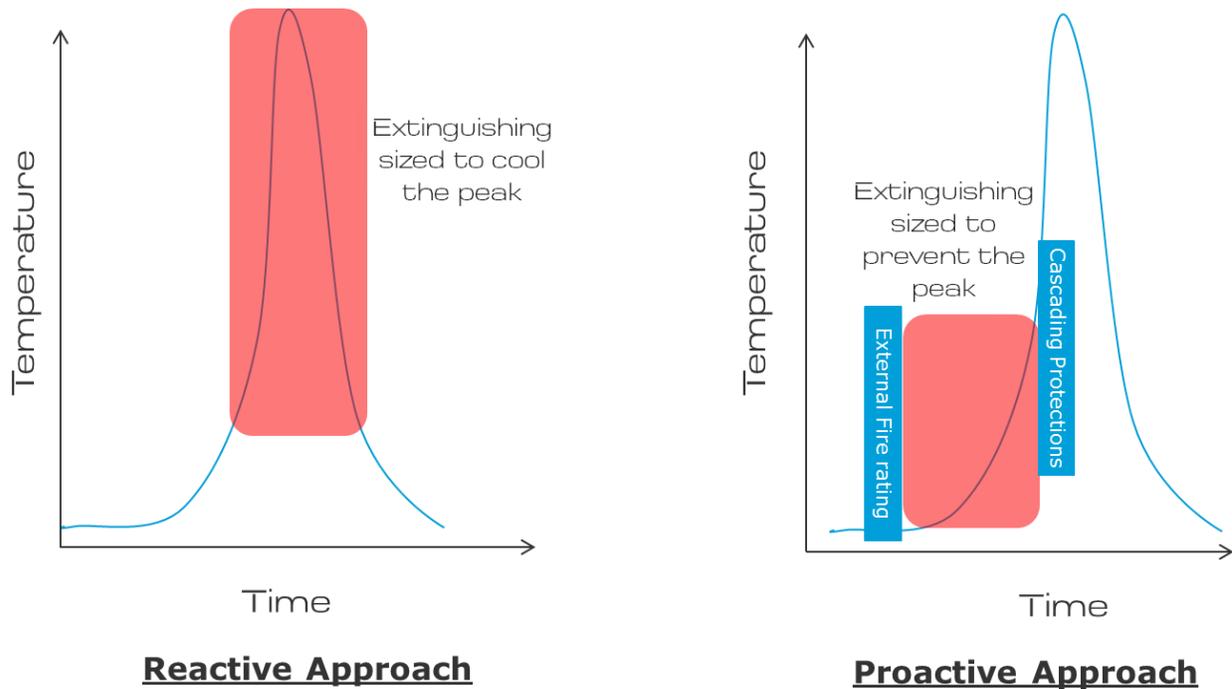


Figure 3 **A proactive, system level approach to extinguishing need not prescribe excessive levels of water if the system also contains a high external fire rating as well as internal barriers to prevent cascading.**

5.3 Challenges with Proposed Codes

The findings from this program indicate that scalable metrics are appropriate for sizing ventilation and water requirements for building sites. A summary of proposed codes is shown in Table 5. For example, in proposed changes to the International Fire Code IFC 608, 20 kWh is cited as a threshold for battery sizes or 600 kWh in a room. The code also proposes 3 feet of clearance between battery arrays. Such prescription threatens the value proposition of energy storage as energy and power density metrics have been increasing rapidly over the last 5-8 years. Limitations placed on kWh or kW will directly limit the energy service function of the device and will therefore limit the market. Providing scalable safety metrics, however, will allow the market to be flexible within safety limits.

6.0 NEW FINDINGS AND ANSWERS TO FREQUENTLY ASKED QUESTIONS IN BATTERY SAFETY

The findings of this program directly address some common misperceptions in battery safety. It is therefore helpful to address some of them directly in this section. These questions are an aggregation of questions posed during the testing program by FDNY, battery vendors, and other stakeholders. Reading through this section may serve as an adequate introduction to the topic and will also guide the reader through the report and its logic.

Question: Are the commonly cited battery fires in the media due to spontaneous ignition events?

Finding: No. The Literature Review (an addendum to this report) covers several incidents in detail. In the context of fire risk and firefighting for batteries, it is helpful to summarize the abuse tests that are performed in United Nations (UN) 38.3, the required testing scope in order to ship and transport Li-ion batteries. The eight separate tests in UN 38.3 are a checklist of nearly all physically conceivable abuses that could cause a Li-ion battery to catch fire. These abuse events are:

1. Low ambient pressure
2. Overheating
3. Vibration
4. Shock
5. External short circuit
6. Impact
7. Overcharge
8. Forced discharge

All of the safety incidents commonly reported in the general media can be traced to one of these abuse mechanisms. In some cases, contaminants in the battery (as a result of manufacturing defects) weaken the ability of the battery to withstand instances of these eight abuse factors. In general it is good practice to avoid any scenario that may introduce the threat of any action on the above list. Three items in particular (overheating, external short circuit, and impact) are the abuse mechanisms that have increased probability of occurring to a battery during and after a fire. The fire is the most obvious heat source, but subsequent heating may occur internally once batteries reach critical temperatures (typically > 120°C). Short circuiting may occur by contact with tools or equipment or by water. Items #7 and #8 are electrical stimuli that are typically monitored and controlled by active safety barriers in the battery management system (BMS).

Question: How is the battery industry handling safety today?

Finding: For most energy storage projects that are not paid for on the “balance sheet”, the typical independent engineering (IE) verifications that are required in the wind and solar industries apply to energy storage projects as well. During the technology review, performance and safety analyses are performed. This may include a review of accredited testing, certifications, and other hazard-consequence analyses. DNV GL routinely supports this with risk analysis to look at the overlap between energy storage system (ESS) safety functions and the site (see “Why Bowtie Models?” on page 74); particularly for energy storage projects that are a portfolio of behind-the-meter devices deployed across a geography in a mix of commercial and industrial applications. In some cases for larger installations a heat and plume study is performed to determine clearances. Such practices are common to energy and petrochemical sectors prior to the commissioning of any new project. IE practices are described in “Present Day Industry-Accepted Safety Practices for Energy Storage Projects” on page 31.

Question: Are battery fires more toxic than plastics fires?

Finding: In general, no, with conditional exceptions. The average emissions rate² of a battery during a fire condition is lower per kilogram of material than a plastics fire, as shown in Figure 5. However, the peak emissions rate (during thermal runaway of a Li-ion

² Emissions concentration in ppm averaged over total minutes of burn time

battery, for example) is higher per kilogram of material than a plastics fire, as shown in Figure 4. This illustrates that a smoldering Li-ion battery on a per kilogram basis can be treated with the same precautions as something like a sofa, mattress, or office fire in terms of toxicity, but during the most intense moments of the fire (during the 2-3 minutes that cells are igniting exothermically) precautions for toxicity and ventilation should be taken. It should be noted that if Li-ion battery modules are equipped with cascading protections, the cell failure rate may be randomized and staggered. The randomized failure rate limits the toxicity and heat release rate of the fire.

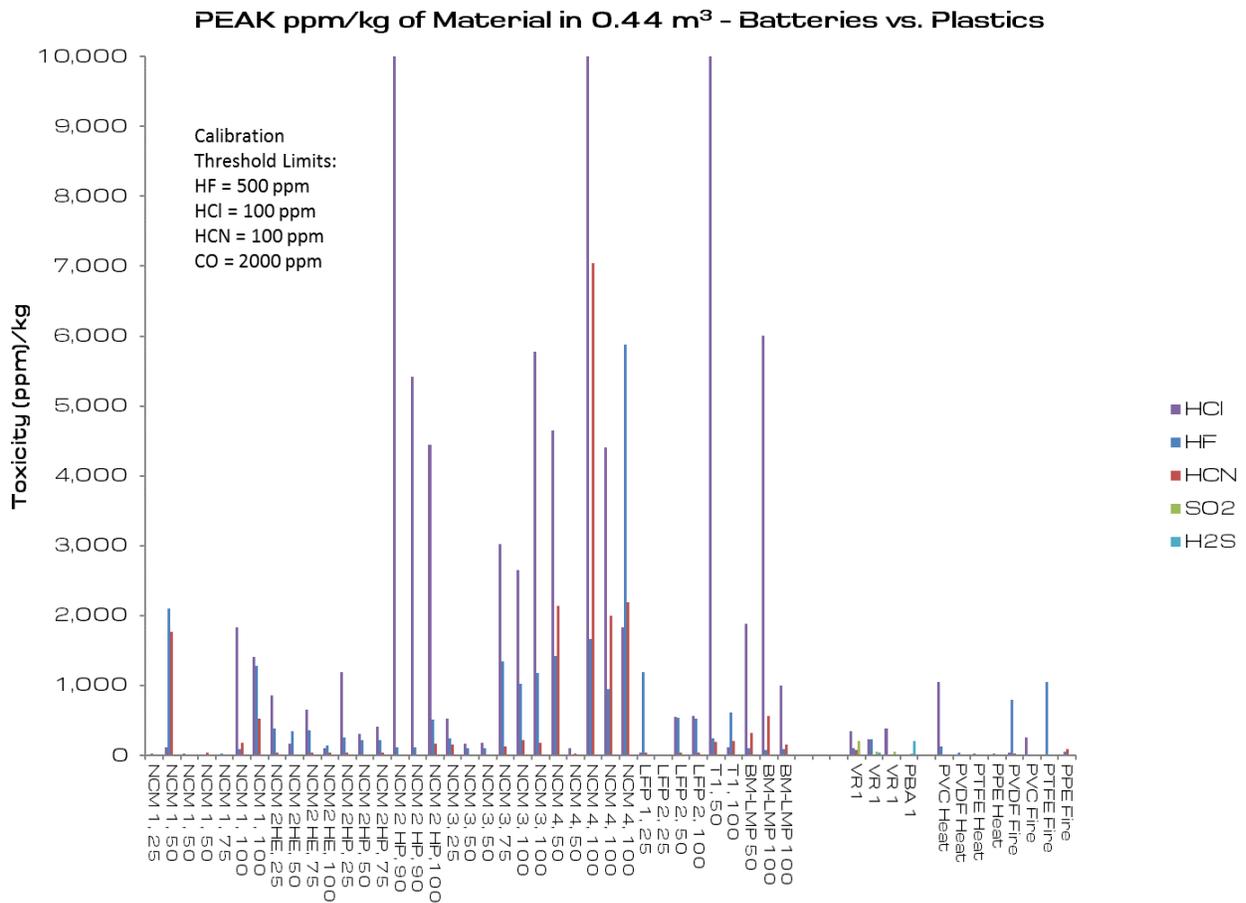


Figure 4 **Peak ppm per kg (in a 0.44 m³ volume) for all batteries tested as compared to plastics.**

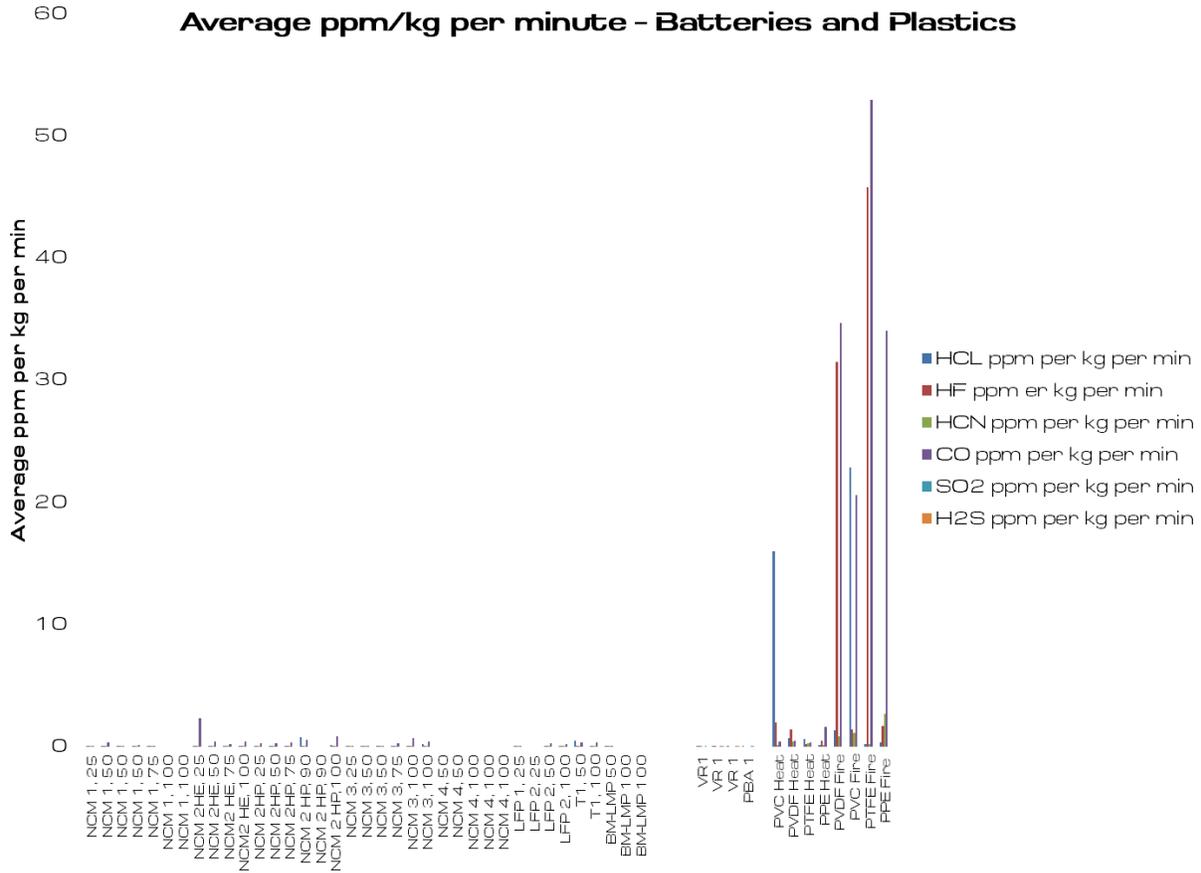


Figure 5 **Average emissions per kg per minute of test mass for plastics vs. batteries.**

Question: Is standard firefighter turnout gear adequate protection from a battery fire?

Finding: DNV GL and the provider of turnout gear (Honeywell Morning Pride) did not note any degradation in PPE as a result of exposure to fire test conditions when the gear was fit on a mannequin and exposed to the fire directly. Therefore first responders equipped with standard issue turnout gear may have protection against the toxic gas species observed under these tested conditions. Limited electrical protection was also observed without modifications to PPE, based on the conditions tested. Rescue Methods used common MSA Altair four- and five-gas sensors during full scale testing. Rescue Methods worked with Honeywell to test turnout gear, and one recommendation from Honeywell was that the general materials integrity of the jacket should withstand most species measured in this testing, cautioning that sustained exposure to Chlorine can have a degrading impact on Kevlar. It should be noted that HCl was observed in the battery fire testing and is also a common byproduct from combustion of most plastics in similar or greater volumes per kilogram of burning material.

Question: Are any batteries excluded from the ventilation requirement?

Finding: Because the volume of the room plays a key role in dictating the ventilation rate, batteries in larger rooms will have lower air changes per hour (ACH) requirements and the size of the room will have a buffering effect on the peak emission rate. The vanadium redox and lead acid batteries tested both emitted HCl upon heating, starting as low level emission around 100-150°C (see Figure 6 for vanadium redox and Figure 8 for lead acid). The findings in this program demonstrate that HCl plays a dominating role in ventilation rates for battery systems in enclosed spaces, and because it is common for all battery types tested, ventilation recommendations (in section "Locations and Ventilation" on page 48) are universal for all battery types. **However, it should be noted that in the smallest unit of failure scenarios, the recommended ventilation rate of 0.25 ACH is well below the typical rating of 3-4 for most general spaces which means that vanadium redox and Pb acid batteries, as well as single cell failure modes for Li-ion, are already within the implied code requirements [27].** Laboratories and server rooms can have ACH ratings > 10. Therefore the DNV GL recommendation for air change rates > 0.25 ACH is already exceeded by the building code in most instances.

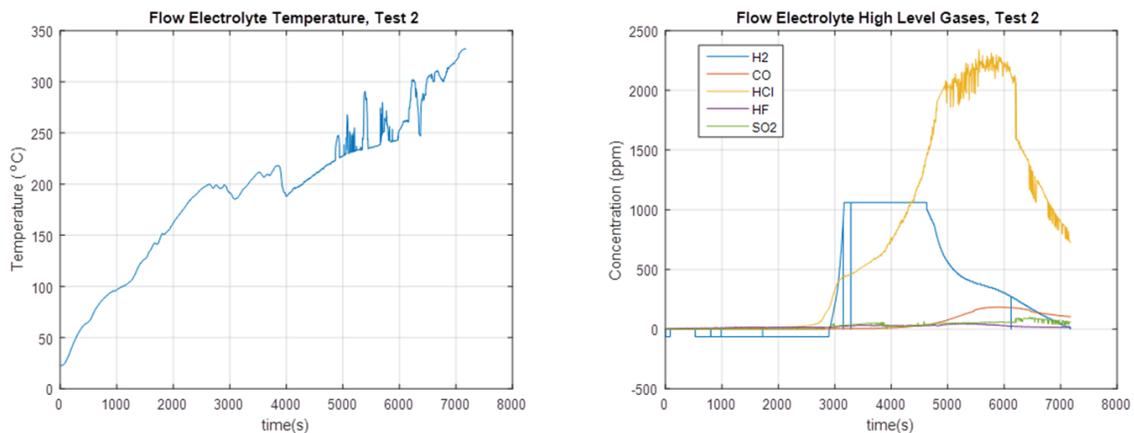


Figure 6 Emission of HCl was observed from the vanadium redox flow electrolyte.

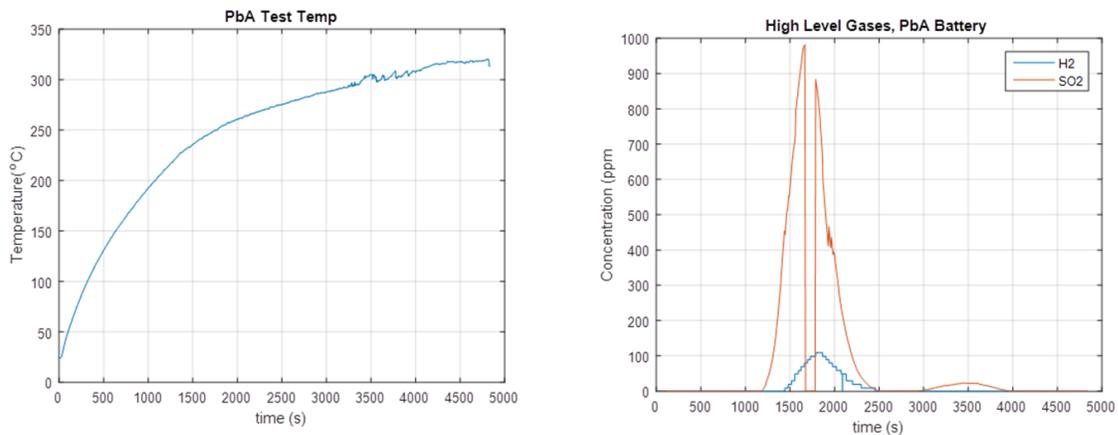


Figure 7 Heating of Pb acid electrolytes yielded SO₂.

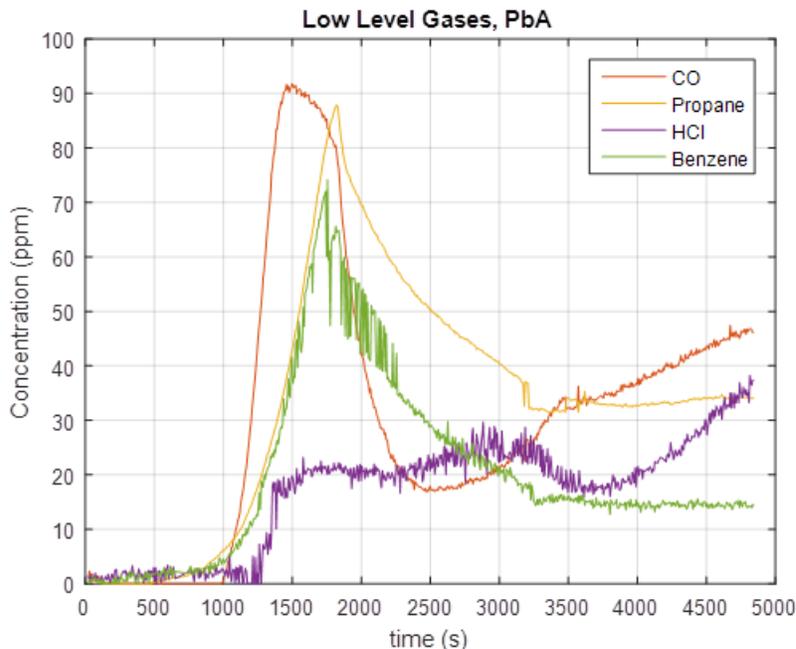


Figure 8 Heating of Pb acid electrolytes also yielded HCl.

Question: What kind of testing is required to certify the safety of battery systems?

Finding: The most commonly referenced system level safety testing the US is Underwriters' Laboratories (UL) 1973. For marine and automotive applications, International Electrotechnical Commission (IEC) 62619 covers many of the same requirements and has a more stringent pass/fail criteria to demonstrate limited cascading between cells. The US market appears to be moving toward UL 9540 which includes aspects of UL 1973 and UL 1642 (for cell safety) in addition to an up-front failure mode effects analysis (FMEA) on the system. As mentioned, such a risk analysis should also include the site under unique circumstances. It is also conventional to have a third party inspect the field installation and provide a sign-off for the local authority having jurisdiction (AHJ). Globally, UN 38.3 is the most widely recognized safety testing for Li-ion battery cells and is a requirement for transport. The results of accredited safety testing are an indicator of the strength of the barriers in a risk model.

Question: Do battery systems have an external display of error or health?

Finding: Yes, in a limited way. The present codes in NYC for uninterruptible power supplies (UPS) require a system health display panel. A primary concern for first responders is lack of knowledge about what is happening inside the battery system upon being called to the scene, which impacts their ability to deem a site under control and then hand off control of the site to the property owner. Some engagement between the systems integration, project development, and first responder community is needed to discuss viable solutions for such a panel, or whether the intent of the panel is met through other means (such as an emergency hotline or remote data access by phone or other means).

Question: Do battery fires re-ignite?

Finding: The term "re-ignition" is a misnomer due to the factors described in the incident history of Li-ion battery fires. Upon extinguishing, great care must be taken to assure that **all electrical, thermal, and mechanical abuse factors** are neutralized. If any remain, it

poses a hazard for *continuing* (not reigniting) the fire. Therefore, it is technically inaccurate to classify this as re-ignition if the primary cause of the hazard is never removed. After a fire, a battery module or system may contain intact cells that still have DC voltage, meaning there is a persisting electrical hazard (Figure 11). Water shorting out cells, for example, is a genuine risk (such as was witnessed in the Chevrolet Volt crash test or the flooded Fisker cars [15,17]). In addition, if the heat deep within the module has not been removed, that heat poses a continued thermal hazard. DNV GL and Rescue Methods witnessed this effect during testing as shown in Figure 9, the cause of which was lack of thermal barriers between cells. DNV GL replicated this effect in more controlled laboratory tests in Figure 10 and observed that temperatures between battery cells can be 300°C higher than the exterior during extinguishing unless there is a means to remove internal heat or prevent its transfer between cells. First responders should be cognizant that all electrical, thermal, and mechanical hazards have been mitigated before deeming a battery fire fully extinguished.

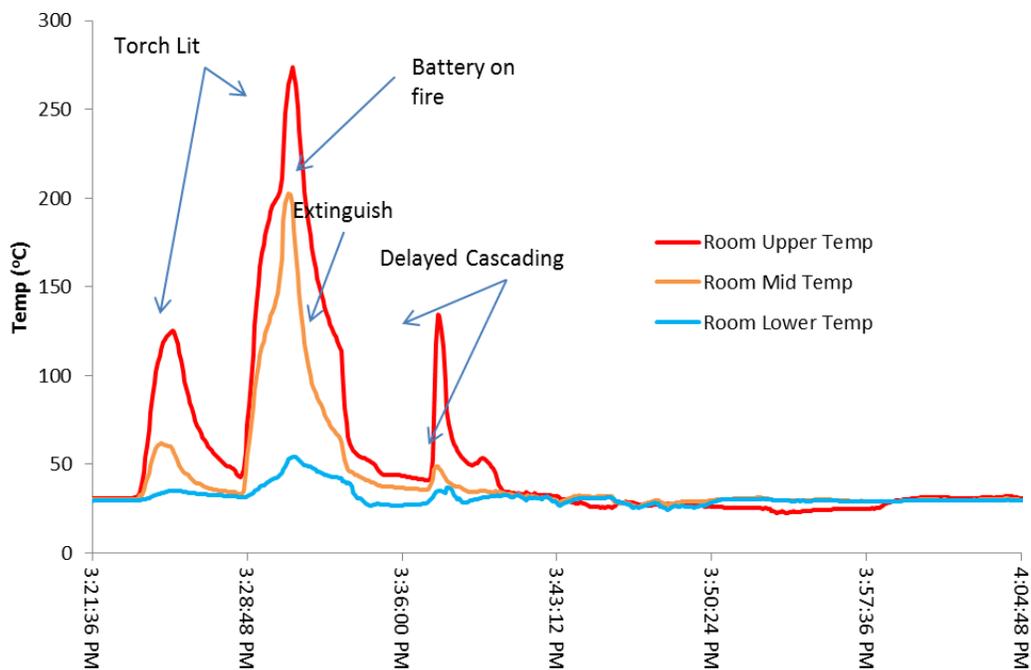


Figure 9 **Observation of delayed cascading during extinguishing in a module without cascading protections.**

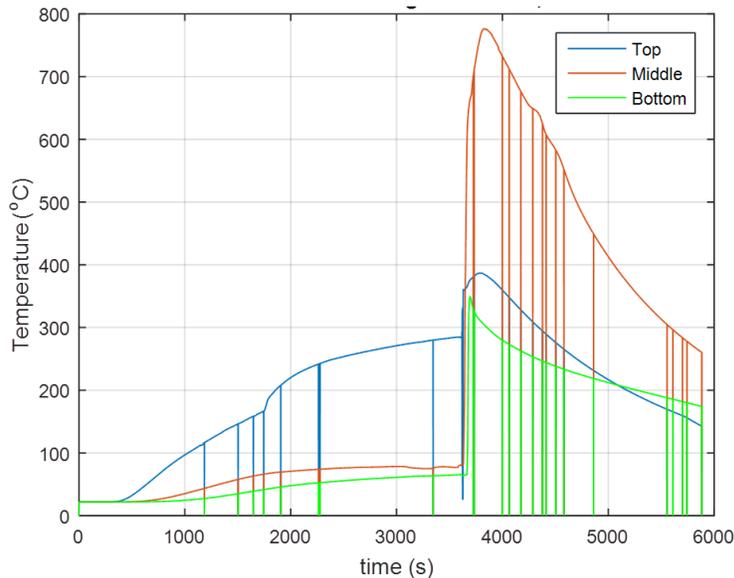


Figure 10 **Internal temperatures between two sandwiched pouch cells remained 300°C higher than external faces after aerosol extinguishing.**

Question: What is the time frame for delayed ignition?

Finding: As mentioned previously, this is entirely dependent on whether the residual hazard is electrical, thermal, or mechanical. If these measures are successfully taken then no delayed ignition should occur. In the case of thermal abuses, DNV GL witnessed the residual heat cause a delayed cascading event within 10 minutes (Figure 9). In the case of the Chevrolet Volt that shorted across the battery pack terminals after the National Highway and Traffic Safety Administration (NHTSA) crash test, the shorting event occurred 3 weeks later and was a separate hazard event.[15] Again, the delay was due to the time it took for the coolant to leak and eventually short the battery; it is not the battery that caused this event but the electrical short hazard introduced by the coolant. Therefore if all electrical, thermal, and mechanical hazards are monitored, controlled, or mitigated, first responders should be able to assess the risk of delayed cascading during the first encounter and the minutes or hours after extinguishing. The signature of any abuse due to shorting, crush or penetration, or residual heating is climbing temperature on the battery, which can be monitored by the system thermocouples (if they are still intact and the data is provided remotely) or by handheld thermal sensors or infrared (IR) monitors.

Question: How long does it take for a Li-ion battery to go into thermal runaway if it is being heated?

Finding: This is entirely dependent on the rate of heat absorption into the cell. DNV GL observed in this work and other projects that a Li-ion cell can smolder for more than an hour if the heat transfer rate is slow. By the time temperatures near 120°C (248°F) were reached, all Li-ion batteries tested (including LiFePO₄ and LTO chemistries) offgassed and/or ruptured. If the threshold near 120°C is never crossed, the battery may smolder and gas but never ignite unless an external spark ignites the flammable gases emitted from it. It was common for LiFePO₄, LTO, and the BM-LMP cells to offgas without flame, but their offgas composition contains the same flammable and toxic constituents as batteries with higher temperature failures.

Question: Are there risks of electric shock?

Finding: During extinguishing, Rescue Methods did not observe transfer of electricity from the battery system to the first responder through the water stream. Some sparks were observed to be thrown during the active burning of some modules. Arcing was also observed when the batteries were disturbed, such as when they shorted to metal tools or the metal support structure upon which they sat. The turnout gear worn by the firefighters provided adequate protection such that no evidence of shock was observed in the conditions of this test program. The shock hazard, as shown in Figure 11, is presented by stranded energy in the form of DC voltage in the remaining intact cells.

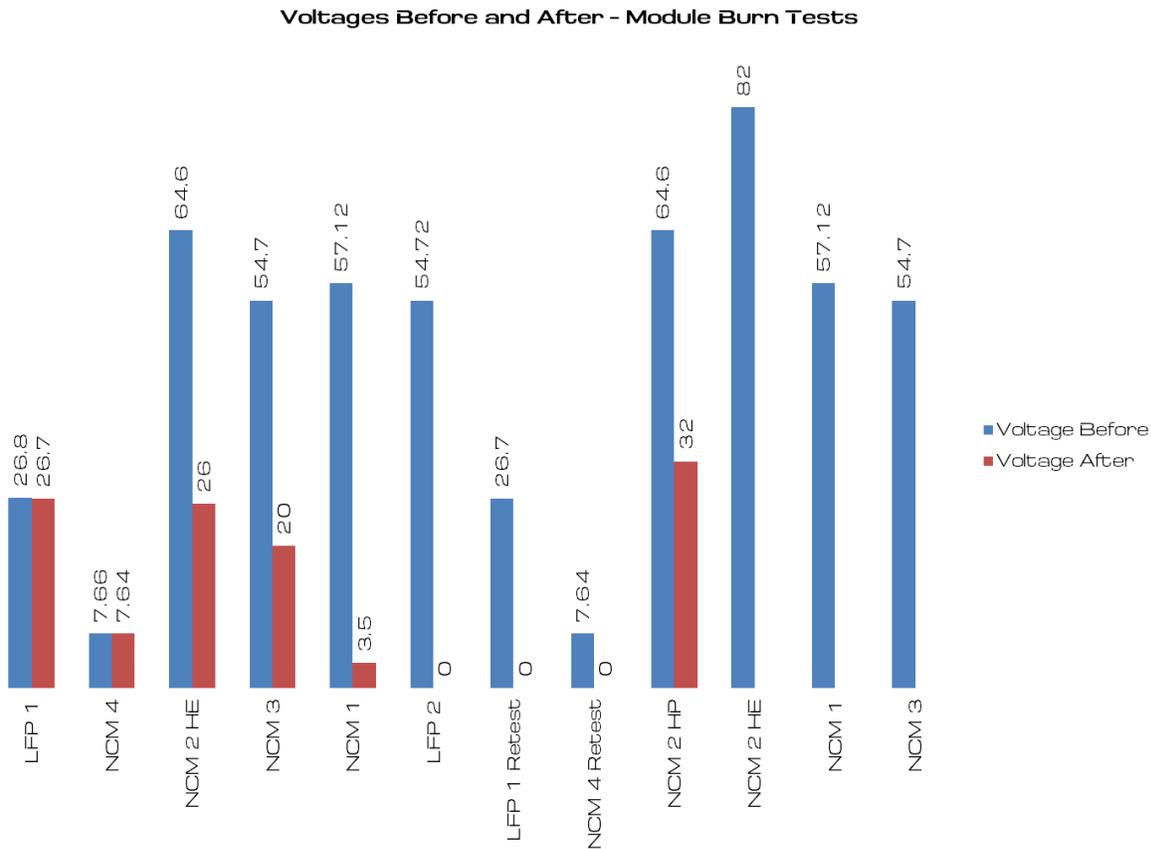


Figure 11 **Some battery modules still had residual voltage after fire testing.**

Question: Is water a sufficient extinguisher?

Finding: DNV GL’s testing indicates that all extinguishers have benefits and drawbacks, including water. Every extinguisher that DNV GL tested put out the flame on battery cells, including the aerosol. During module testing, all extinguishers tested knocked out the flame but in some cases the flame rekindled once the stream was removed because the battery was still hot enough to ignite the remaining fuel. The ideal battery fire extinguisher would be both highly thermally conductive and highly electrically insulating. Water is the former but not the latter. Deionized water is both until it dissolves contaminants from the fire, including ash and soot. In DNV GL’s testing, it was found that other extinguisher types could have equal or poorer heat removal capability to water, but all were electrically conducting due to their reliance on water as a dispersion medium. (Figure 29) Gases or aerosols—due

to lack of thermal mass, poorer thermal conductivity, and restricted access to the deep seated heat source—were not observed to cool as quickly as water can. Water has been historically recommended because of its ability to cool. It was found in this program that water cools best, with the potential unwanted side effect of shorting other cells.

Question: Do battery fires require “copious amounts of water” to be extinguished?

Finding: If appropriate precautions are not taken to limit propagation between cells in the module design, then the water requirement could be described as “copious” as NHTSA coined in 2012. [12] The total content of water is entirely dependent on the water contact efficiency with the battery cells (see the regression coefficients in Figure 36 and the GPM example calculation in Figure 31). This language is anecdotal, however, and requires some quantification. As mentioned previously, lack of barriers between cells results in a deep seated and inaccessible fire (Figure 10). In practice, this would result in the use of more water to cool and contain a battery fire. The use of “copious amounts of water” potentially introduces the unwanted effect of shorting out other cells, thereby perpetuating the fire. The water amount need not be so excessive if heat can be removed from the between cells, and cells have limited ability to transfer heat to nearest neighbors. DNV GL found through testing that this water amount could be increasingly reduced as strategies to direct cooling were learned (Figure 12).

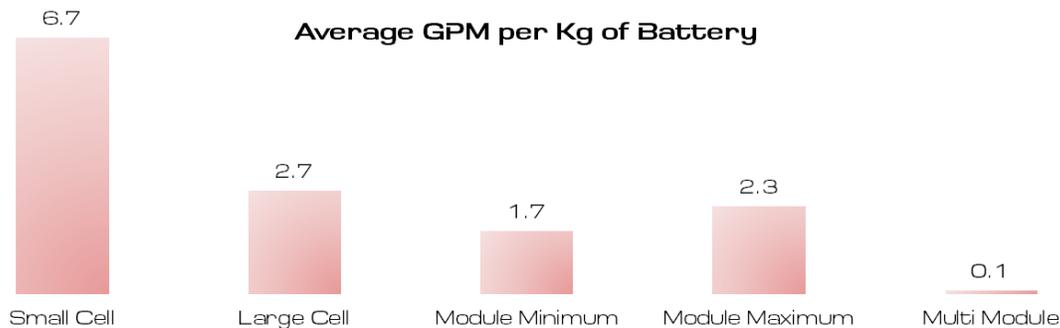


Figure 12 **Progression toward lower water requirements as testing progressed.**

Question: What about fire suppressants other than water?

Finding: DNV GL found that all suppressants put out the fire including an aerosol. The most effective agent for cooling the fire is water. (Figure 29)

Question: Is FM-200 sufficient as an extinguisher?

Finding: FM-200 was not included in the test scope of this program. DNV GL did, however, obtain permission from an aerosol manufacturer to test their product, which succeeded in putting out the cell fire. The testing demonstrated that the cooling rate for the aerosol is less than the liquids (a direct consequence of less thermal mass in a gas versus a liquid, and a reduced effect from latent heat of vaporization). If gases have less thermal mass to take heat from the batteries, then it is the assumption that all gas-based agents are likely to cool less effectively than water. For this reason DNV GL recommends a staged extinguishing approach as demonstrated in “Extinguishing” on page 45.

Question: Do the other extinguishing agents produce slippery conditions?

Finding: DNV GL and Rescue Methods did not observe slippery conditions with the use of the other agents during full scale testing.

Question: Is a 2 ½" hose line with 250 GPM sufficient to put out a battery fire?

Finding: This is dependent on the battery size. DNV GL translated the findings to both GPM/kg and GPM/kWh of battery mass (Table 9). In general, however, if the water can be targeted at the deep seated, highest temperature areas of the fire, it will be most effective and the water requirement will be reduced. It is demonstrated as an example in Table 7 that 250 GPM is more than sufficient for typical battery systems on the market, provided that cascading protections and external fire rating requirements are also met.

Question: How much water is required?

Finding: DNV GL found in Table 17 and Table 9 that a minimum of 0.07-0.1 GPM/kg of battery mass can accomplish both extinguishing and cooling for a battery fire. Accommodation for increasing energy density can be accomplished by dividing this number by the energy density (in Wh/kg) and multiplying by 1000 Wh/kWh.

Question: Is the water extinguisher requirement for batteries significantly larger than what is already prescribed in the built environment?

Finding: This need not be the case if battery firefighting is considered at a system level. Residual heat within a battery module was observed in this program, demonstrating that **battery modules equipped with cascading protections will have a reducing effect on water flow rate requirements because less water will be needed to cool them.** This has direct economic impacts on the overall system installation cost. In Figure 3 it is demonstrated how the combined effect of external fire rating and internal cascading protections works to limit the heat transfer rate, thereby reducing the overall water requirement. Overall, DNV GL found that it is conceivable that water flow requirements would not exceed what is already seen in the built environment when appropriate room volumes are considered (compare Table 10 with Table 8).

Question: Will the ventilation rates for battery systems be excessive?

Finding: They need not be excessive if the appropriate room volume is considered. (Compare Table 10 with Table 8.)

Question: What are the differences in safety considerations for outdoor vs. indoor systems?

Finding: Please cross reference to "considerations for System Types and Locations". Outdoor systems may have standalone safety equipment such as fixed suppression systems and self-contained heating, ventilation, and air conditioning (HVAC). The risk to the site should be considered in all cases, which is intended to be addressed in the FMEA required by UL 9540. A risk analysis should guide stakeholders toward a probable risk consideration during project commissioning. This probability-driven analysis helps avoid over- or under-prescribing safety systems. Outdoor systems may have different or lower ventilation requirements, but their size and proximity to inhabited structures may dictate heat or plume considerations in the event of fire (see Figure 25 and considerations in "Present Day Industry-Accepted Safety Practices for Energy Storage Project" on page 31). Indoor systems may be dependent on the building infrastructure for ventilation and fire suppression. If that is the case, the risk analysis should identify if these systems are adequately sized, using the guidance identified in Table 9.

Question: Are residues left behind after a battery burns?

Finding: There is potential for residues. DNV GL found traces of vanadium after boiling the vanadium redox electrolyte. In the EDS (energy dispersive spectroscopy) scan from the scanning electron microscope, coincident detection of both V and O could indicate vanadium oxide dust (Figure 13). The vanadium peak is low; however, there is no other component of the test that would contribute it other than the vanadium redox electrolyte. Oxygen can also be sourced from various oxides that form on metals. In addition, some Pb residue was swabbed from the burn container where Pb acid batteries were tested, but it was in low amounts and limited to immediate proximity of the burn specimen. Traces of metals were observed in the interior of the battery abuse chamber after Li-ion testing. In addition, the pH of runoff water from the module burn tests was measured to be anywhere from pH 6 to pH 11. However, many of the same contaminants found from plastics fires were common to those found from battery fires. In any case, the precautions recommended for PPE and self-contained breathing apparatus (SCBA) during overhaul apply to solids residues and dusts as well. Bare skin contact with residues should be avoided, as is good practice in the aftermath of most fires.

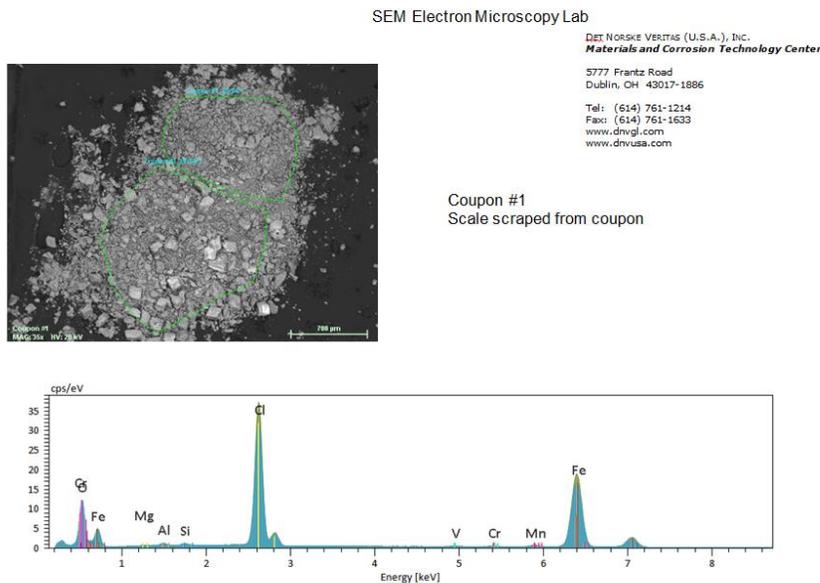


Figure 13 **Residue analysis from a coupon hung in the headspace of the vanadium redox boiling test.**

Question: Are certain form factors of cells safer than others?

Finding: DNV GL saw that unconstrained pouch cells, if given the opportunity, will inflate and then burst catastrophically under extreme heating conditions (Figure 14). However, pouch cells are compressed when engineered into modules, so a free-floating pouch cell is not a realistic representation of a field system. DNV GL did notice, however, that controlled venting of cells is necessary to reduce their volatility. The ability to vent and relieve pressure is critical to whether the cell's failure is benign or sudden. **This illuminates the fact that trapped gases are the cause of explosive failure.** It should be noted that DNV GL did not directly witness any exploding battery cells during testing. However, flashovers of the contained gases within the test chamber were a frequent occurrence for all Li-ion batteries tested.

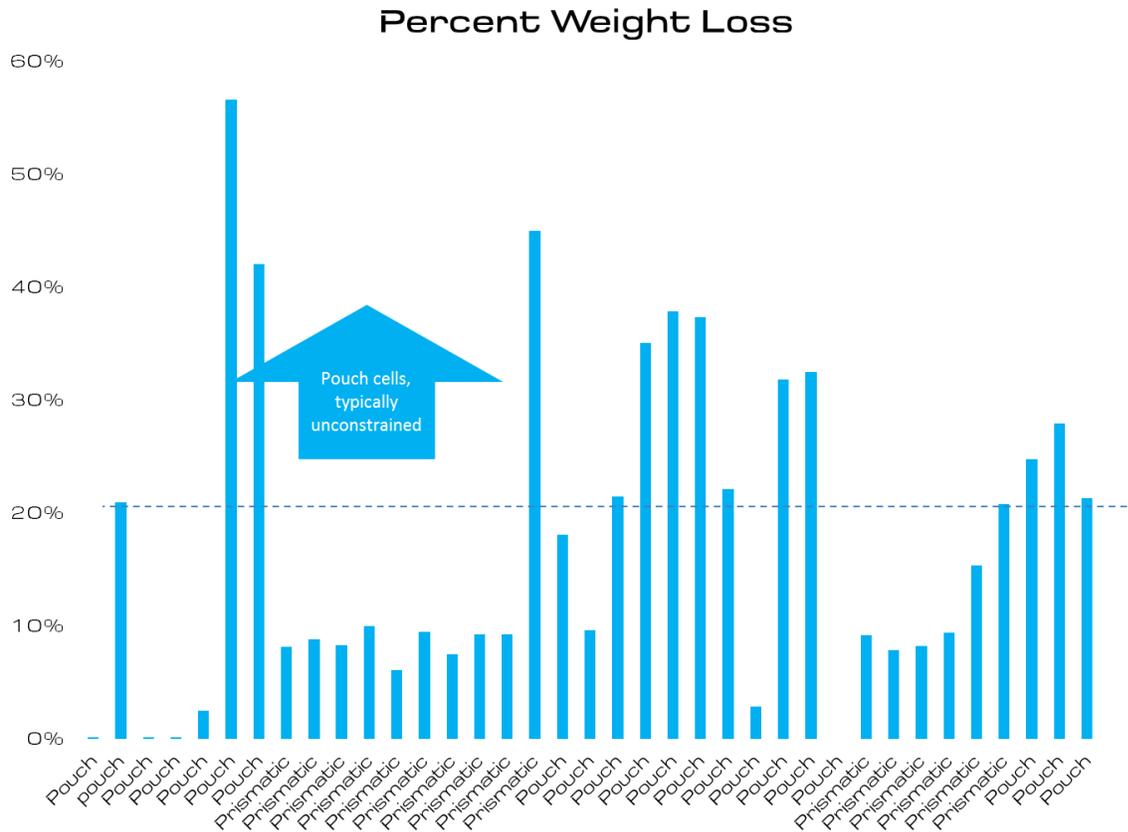


Figure 14 **Percent of mass loss as a function of cell form factor.**

Question: Will Li-ion batteries explode?

Finding: In this program DNV GL tested dozens of Li-ion batteries and could not conclusively say that any of them “exploded.” DNV GL has conducted hundreds of abuse tests on cells in other programs and has not conclusively observed an event where a battery exploded or was the source of a rapid energy event. What is a highly repeatable condition, however, is the degree to which the test chamber fills with flammable gases before those gases ignite. The flashover event could be very rapid. The explosion hazard is not the battery itself, but the gases it may generate. Therefore the requirements for stress-relief by venting of the cells (described above) and the ventilation of the space are emphasized throughout this report.

Question: How long would it take for flammable gases to explode?

Finding: This is entirely dependent on the emissions rate and the ventilation of the surrounding area. It is shown in Figure 5 that the emissions rate varies for all batteries but the diagram indicates the upper and lower boundaries of emissions limits. The emissions rates corresponded to 0-57% mass loss over a period of 13-83 minutes. CO is the primary signature of flammable gases. Sensors detecting CO may be cross-sensitive to hydrogen. Many flammable gas sensors are non-equally cross sensitive across a family of hydrocarbons and provide a general “LEL” audible warning. The emissions rates observed from batteries are included in Table 1.

Table 1 **Statistics on cell failure rates for the entire test program including all Li-ion variants.**

Single Cell Emissions Statistics					
		<i>Average</i>	<i>Std Dev</i>	<i>Min</i>	<i>Max</i>
	Mass Loss	18%	14%	0%	57%
	Duration (min)	41.7	17.1	13.0	83.0
<i>Average ppm per kg per min in 1 m³</i>	HCl	0.057	0.150	0.000	0.719
	HF	0.009	0.010	0.000	0.032
	HCN	0.003	0.005	0.000	0.027
	CO	0.279	0.440	0.000	2.341

Question: What is the energy of the explosions from battery offgas?

Finding: DNV GL did not observe batteries exploding directly, but did observe the energy of flammable gas flashovers. The energy of these events is proportional to the concentration of gases in the enclosed volume. The power of these events (or the heat release rate) is significantly variable depending on the volumes of gases, the duration of their release, the resulting mixture, and the rates of their ignition, DNV GL observed considerable scatter in the HRR (Figure 15). The HRR was observed to be anywhere from 2-8 kW with 100-800 g of released materials. This brackets the value from 2.5-80 kW/kg. By comparison, burned specimens of common furniture items have demonstrated a mass weighted HRR of 32-260 kW/kg. [51] It was found during testing that long periods of smoldering for the batteries resulted in reduction in mass prior to the peak event, which likely produced much of the scatter observed in the measurements.

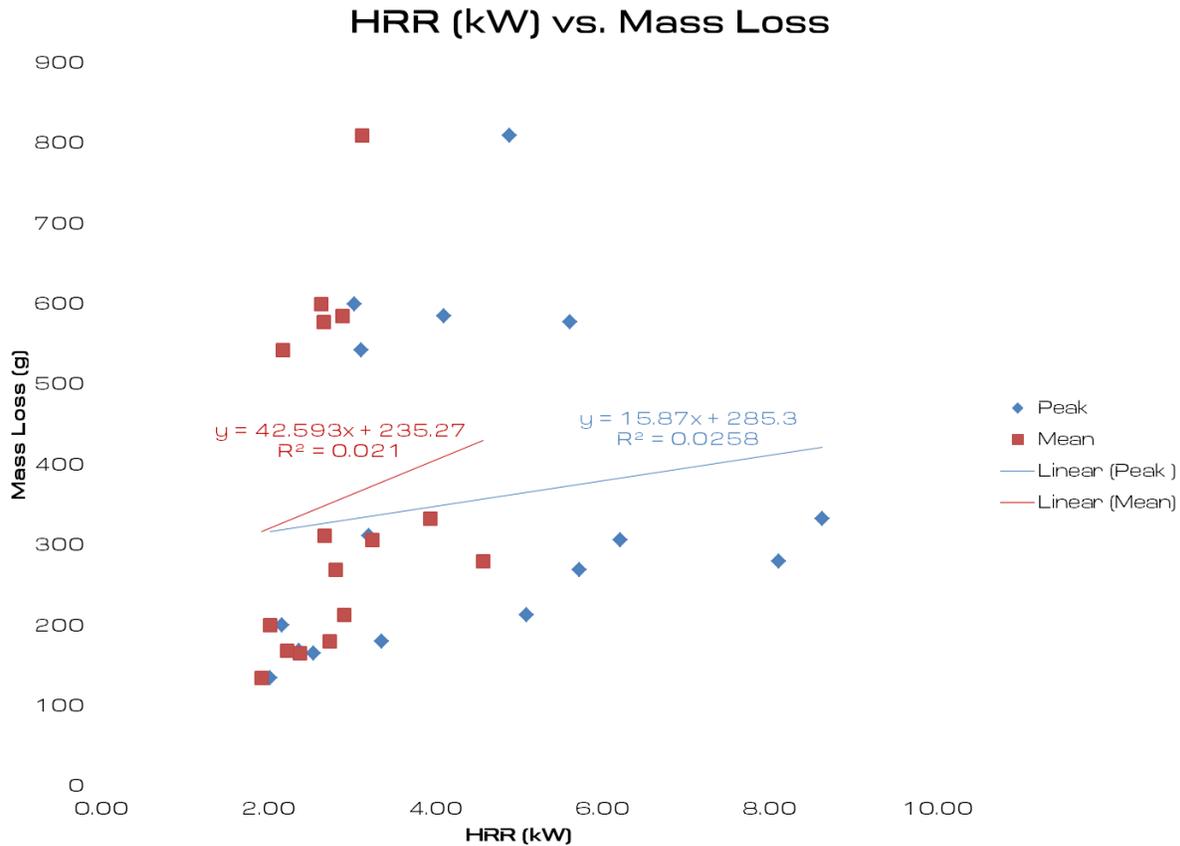


Figure 15 Relationship of heat release rate (kW) per gram of mass lost.

Question: Is the ventilation rate governed by the LEL or Immediately Dangerous to Life and Health (IDLH) limits ?

Finding: IDLH. The concentrations of HCl reach a threatening level much faster than the concentrations of flammable gases. Therefore by sizing the ventilation requirement to the IDLH of HCl, the flammability concern is also mitigated. See Figure 16 and related figures starting on page 23.

Question: What are the ventilation requirements for batteries?

Finding: DNV GL quantified and produced suggested ventilation rates in Table 9. The suggested ventilation rates range from 0.02-0.03 CFM/kg or 0.2-0.32 CFM/kWh. This translates to roughly 0.25 ACH in many cell failure scenarios, climbing to as high at 10-14 ACH in the worst case (see Figure 16 on page 23 and related figures). It should be noted that laboratory spaces, pharmacies, or some manufacturing environments can also have an ACH of 10 or higher (compare Table 15 and Table 8). Therefore, the ventilation rates in most buildings will meet or exceed the ventilation required for the battery system in single cell or low mass failure modes.

Table 2 **Average release rate for battery materials over a 30 minute time period.**

Materials	30 min Release Rate (kg/s)
HCl	2.36E-07
HF	1.74E-07
HCN	1.74E-07
CO	2.00E-07

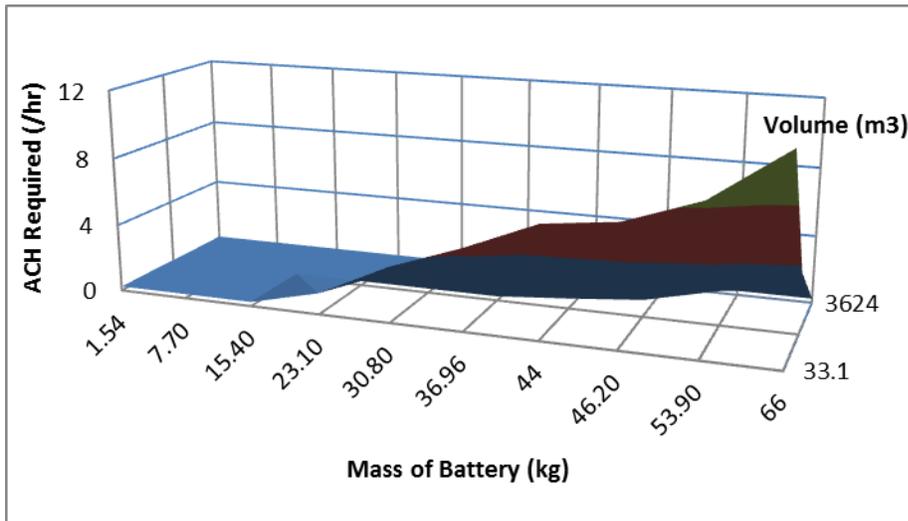


Figure 16 **Estimated ventilation rates (air changes per hour) as a function of room volume and mass of battery undergoing failure for HCl.**

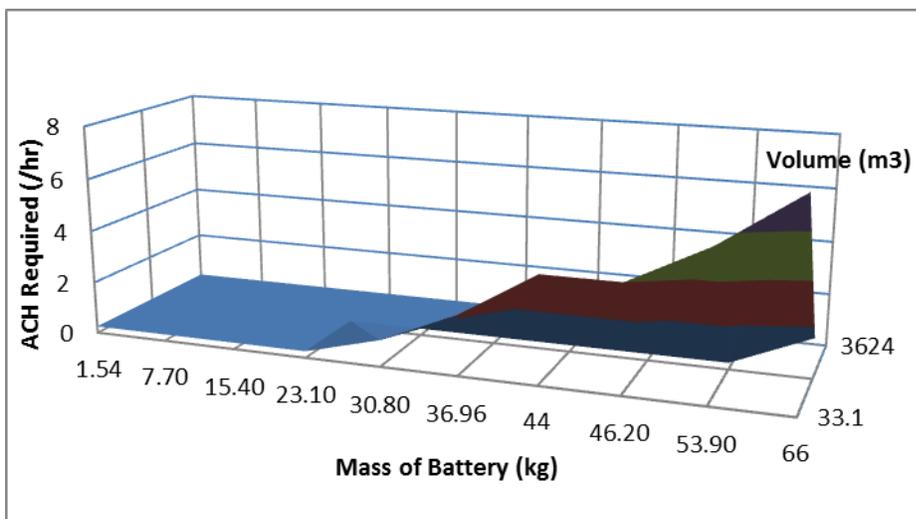


Figure 17 **Estimated air changeover rate (air changes per hour) as a function of room volume and battery mas undergoing failure for HCN.**

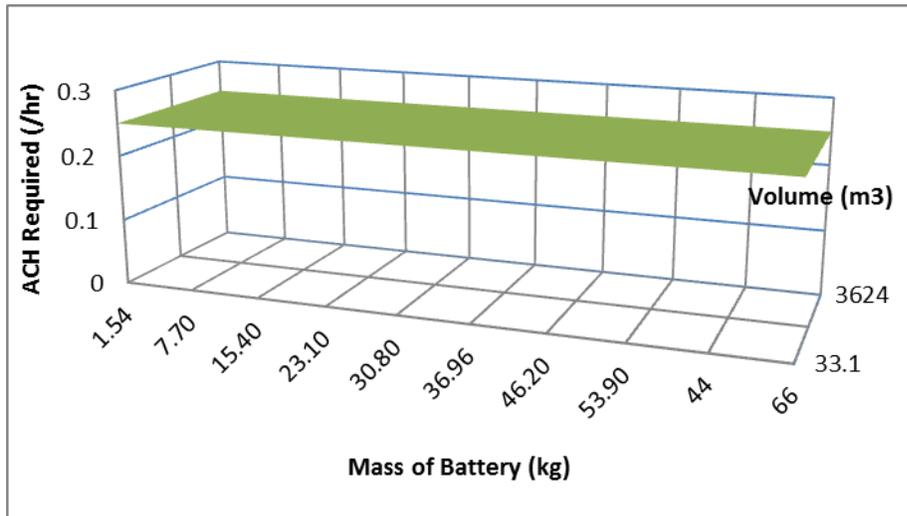


Figure 18 **Estimated air change over rate (air changes per hour) as a function of room volume and battery mass undergoing failure for CO. Because the IDLH of CO is much higher, there is little dependency on battery masses at these scales.**

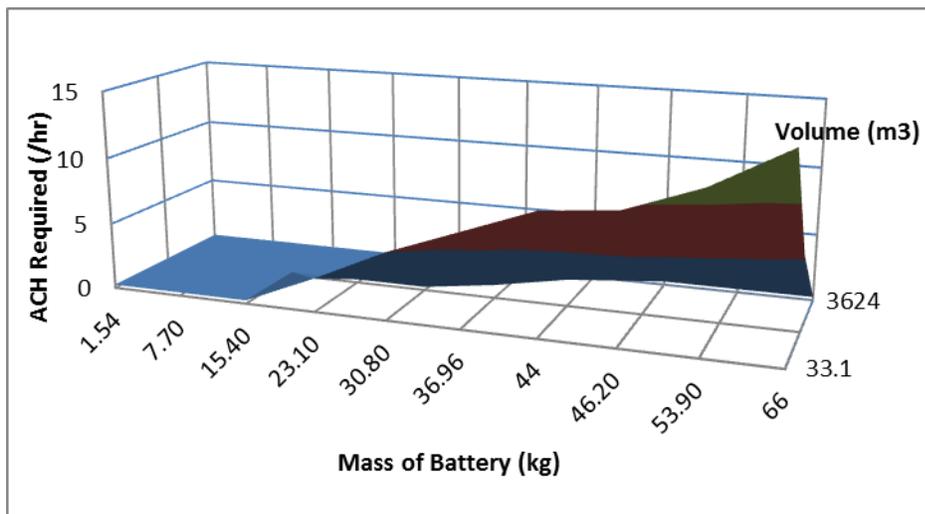


Figure 19 **Estimated air change rate (ACH) as a function of room volume and battery mass during failure for HF.**

Question: Is HF emitted from batteries?

Finding: Yes. HF was observed in all of the Li-chemistries. Vanadium redox also demonstrated HF emissions in 2 out of 3 tests, even after a complete overhaul of the test equipment to remove the possibility of contaminants affecting the result (see Figure 20 as well as Figure 5). However, it is HCl, not HF, that governs the ventilation and toxicity consideration. It was found that on a per kilogram basis, the average emission rate of HF in a plastics fire can be higher than the average emission rate of a battery fire (compare Figure 4 to Figure 5). From this study it was found that the ventilation requirements for

anything less than 15 simultaneously burning battery cells are the same for HCl and HF (see Figure 16 and related figures starting on page 23).

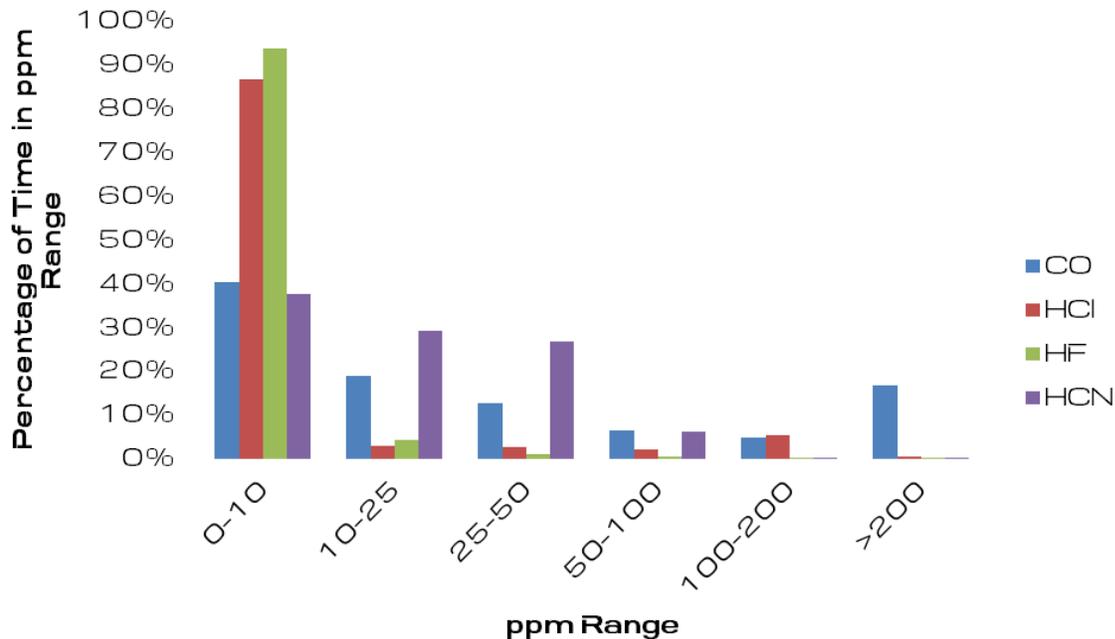


Figure 20 **Representative emissions histogram from a Li-ion battery.**

Question: Is the combined LEL of the flammable gases lower than any of the gases alone?

Finding: Yes. This phenomenon is described by Le Chatelier's Mixing Rule which states that the combined LEL of a mixture of gases is the sum of the weighted ratios of volume to LEL for each individual gas species. Because the emissions rates are constantly varying and therefore never in a prolonged chemical equilibrium such that this simplified textbook solution may apply, DNV GL was able to observe that ignitions occurred as low as 400°C at CO concentrations as low as 3,000 ppm. (Figure 21) Frequently observed gases of C₂H₄, CO, and CH₄, if coexisting in a mixture, have the lowest autoignition temperature of 490°C and 100,000 ppm, respectively (see below):

- C₂H₄ = 2.7% (27,000), 490°C
- CH₄ = 5% (50,000), 537°C
- CO = 10% (100,000), 609°C

As expected the combined LEL is indeed lower than the individual components but as mentioned above, **the ventilation requirements should be set by the IDLH, which should exceed and override LEL considerations. Therefore LEL is less of an immediate concern than IDLH.**

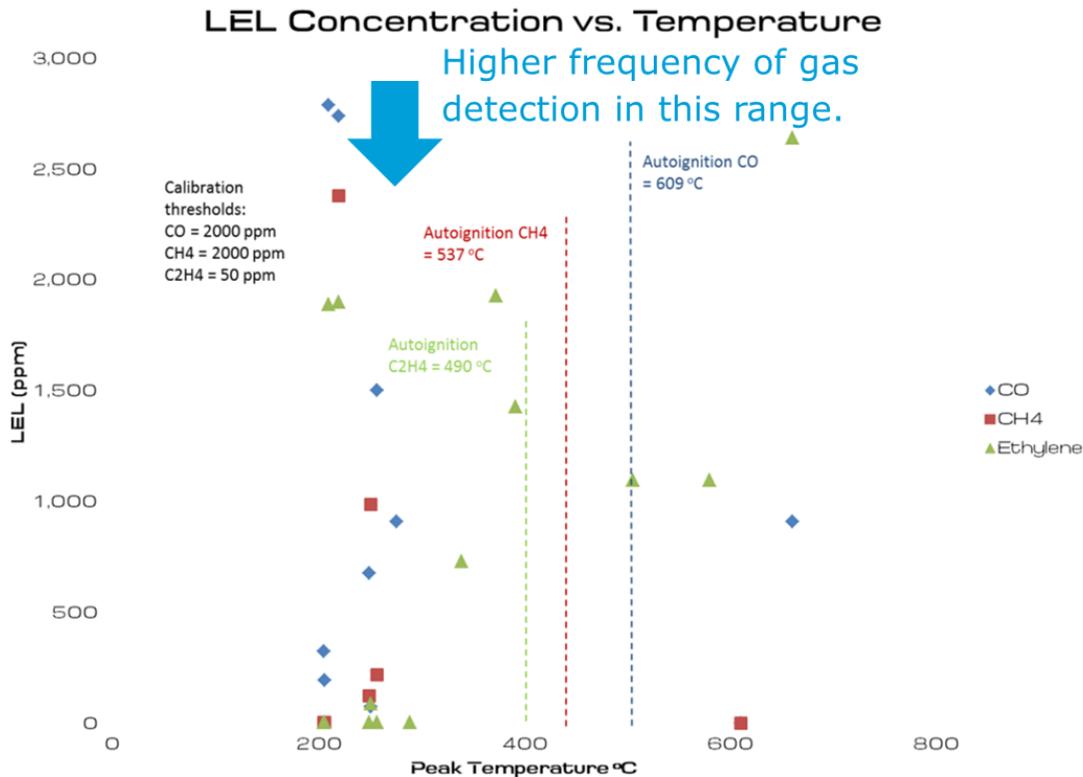


Figure 21 **The combined LEL and autoignition temperature of mixed gases emitted from Li-ion batteries may be as low as 3,000 ppm and less than 400°C, as flammable gases were ignited and burned off above this temperature.**

Question: What is the explosion risk?

Finding: The battery is not the source of an explosion risk, but the flammable gases generated from it are. These gases need to be vented to reduce the risk. Because the ventilation rates are dictated by the lower IDLH thresholds than the LEL thresholds, ventilation sized to the IDLH should exceed the ventilation requirement for explosion hazards.

Question: Are Li-ion batteries more volatile with higher states of charge?

Finding: Yes. There is a very direct increasing relationship between mass lost and the SOC before failure as shown in Figure 22. However, the BMS limits the SOC of the battery intentionally for both longevity and safety reasons. As shown in the figure, the decline in mass loss is significant as the SOC of the battery is decreased from 100% to 90% or 80%. As many battery systems limit the upper electrochemical SOC range to 80-90%, a significant safety precaution has already been made. It should be noted that the GPM/kg and CFM/kg metrics found in this program are inherently conservative because they include the peak emission rates observed at 100 % SOC and they also capture the short lived peak emission events. In reality, a system fire spends most of its time smoldering, and if the BMS is properly functioning, no cells should be at 100% SOC.

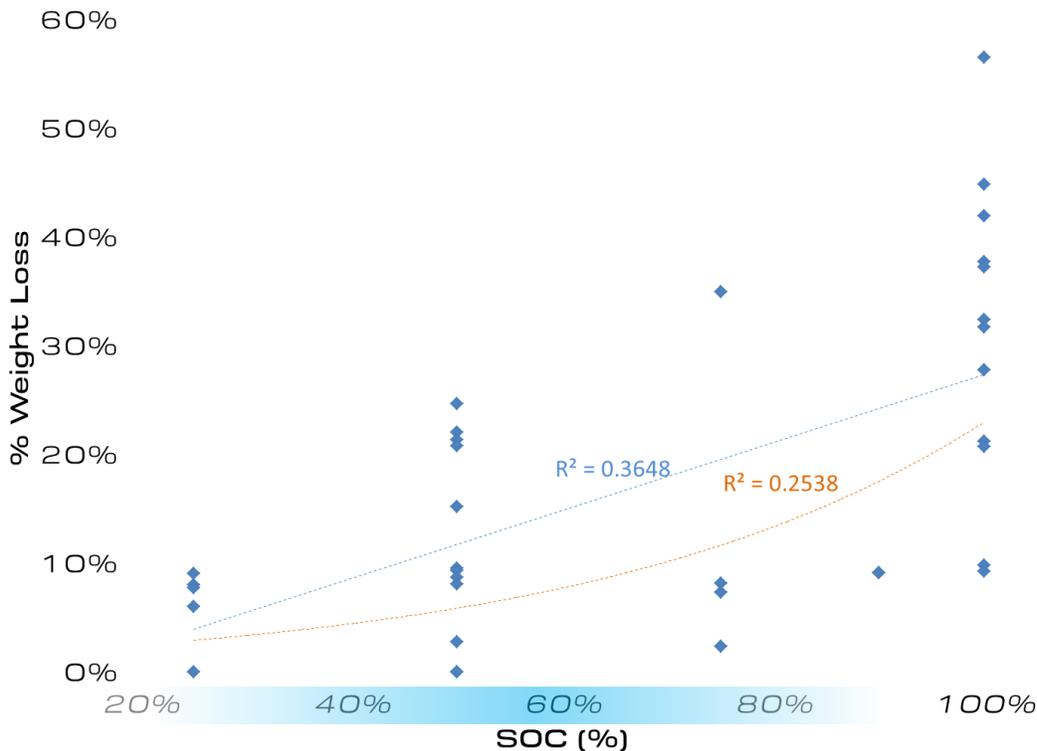


Figure 22 **For Li-ion batteries, the mass loss is directly proportional to the state of charge prior to failure.**

Question: Are some battery chemistries safer than others?

Finding: No battery tested in this program is excluded from toxicity concerns in a fire. In general, it is good advice to treat a battery like any fuel should be treated, and make note that risk is context specific and weighted. In Figure 23 it is evident that iron phosphate, BM-LMP, and titanate batteries have lower heat release rates and less flammability, as does vanadium redox and lead acid which did not exhibit flammability. However, it was shown in Figure 5 that all batteries have varying degrees of emissions of HCl, HF, CO, HCN, and potential SO₂ and H₂S. Because many of them have plastic casing, the plastic itself is a toxicity and flammability hazard. Therefore, there is no single battery chemistry in this testing program that should be excluded from toxicity considerations in an enclosed space or near a populated building. Furthermore, the source of toxicity may be as much plastic componentry as it may be attributed to electrolytes. **Because the toxicity risk is similar to plastics, it is DNV GL's recommendation that toxicity be treated equally across chemistries.** In the case of batteries with non-flammable electrolytes, adequate precautions should be demonstrated that polymer cases or other flammable materials are sufficiently protected against external fire in order to warrant any reduction in the water requirement, if any. It should also be noted that the water requirements for Li-ion batteries need not be excessive if the fire safety measures are viewed as a system rather than standalone requirements. Lastly, it should also be noted that the low level ACH requirements for vanadium redox and Pb acid are well below the typical 2-4 ACH ventilation requirement in most occupied spaces, so the existing infrastructure may be adequate in many instances.

Consolidated Edison
 Considerations for ESS Fire Safety

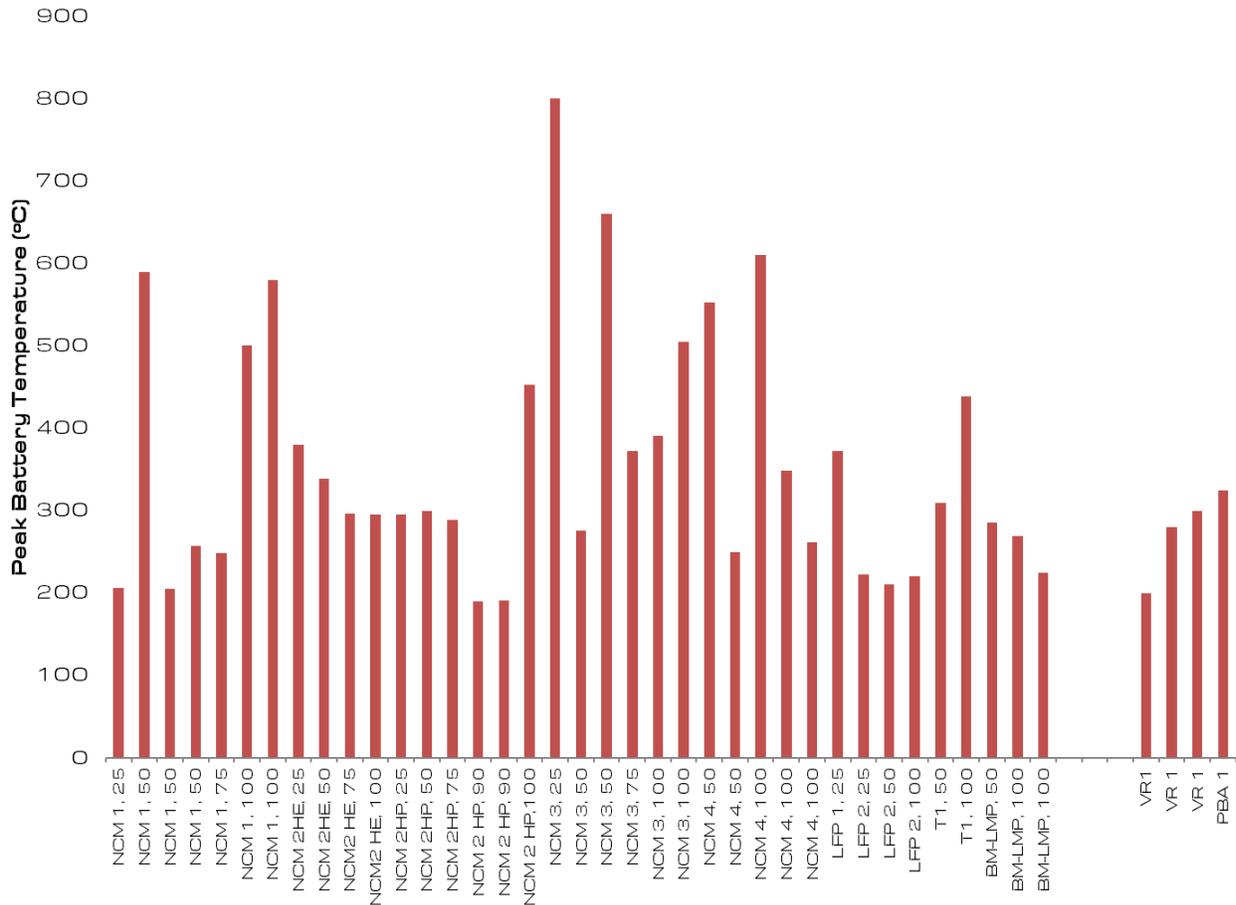


Figure 23 **It is generally true that LiFePO₄, LTO, and BM-LMP batteries demonstrate lower than average temperatures during failure. The temperatures indicated for Pb acid and vanadium redox batteries is the peak heating temperature, as these electrolytes did not demonstrate flammable or exothermic properties as they were tested.**

Question: What is the solubility of liberated gases, and are some of them consumed by fire?

Finding: The solubility of the gases observed is shown in Table 3. Those consumed by fire have an indicated flammability limit and autoignition temperature.

Table 3 **Inventory of Toxic and Flammable Hazards found in this Study**

	Chemistry	Relevant Batteries	Detected State	Concentration (ppm unless otherwise noted)				NFPA Codes (F=flammability, H=health, R=reactivity, S=special)				Ref.
				LEL (Lower Explosion Limit)	IDLH (Immediately Dangerous to Life and Health)	Solubility in Water (mg/L)	Auto Ig. Temp (°C)	F	H	R	S	
Methane	CH ₄	Li-ion	Gas	50,000	5,000	22.7	537	4	1	0		NJ DOH
Carbon Monoxide	CO	All	Gas	12,500	1,500	27.6	609	4	2	0		CDC.gov
Benzene		All except PbA	Gas	12,000	3,000			3	2	0		CDC.gov
Ethane		Vanadium Redox	Gas	30,000				4	1	0		CDC.gov
Ethylene	C ₂ H ₄	Li-ion	Gas	27,000	-	2.9	490	4	2	2		Matheson MSDS
Hydrogen	H ₂ S	Pb Acid, Li-ion	Gas	40,000	-			4	0	0		CDC.gov
Hydrogen Sulfide	H ₂ S	VR, PbA	Gas	4,000	300	4,000.0	260	4	4	0		CDC.gov
Hydrogen Fluoride	HF	All except PbA	Gas	-	30	miscible	-	0	4	0		CDC.gov
Hydrogen Chloride	HCl	All	Gas	-	100	720.0	-	0	3	1		CDC.gov
SO ₂	SO ₂	VR, PbA	Gas	-	100	94,000.0	-	0	3	0		CDC.gov
Hydrogen Cyanide	HCN	All except PbA	Gas	-	50	miscible	-	4	4	2		CDC.gov
Nickel	Ni	Li-ion	Residue / Powder					1	3	0		
Manganese	Mn	Li-ion	Residue / Powder					3	3	3		
Cobalt	Co	Li-ion	Residue / Powder	-	-	Insoluble		0	1	0		
Lithium	Li	Li-ion	Residue / Powder					2	3	2	W	
V2O5 Dust	V2O5	VR	Residue (V)	-	35 mg/m ³	0.8	-	0	3	0		CDC.gov
Pb Vapor, salts, dust	Pb	PbA	Residue	-	700 mg/m ³	10 ⁻⁵ to 4400	-	0	2	0		CDC.gov

Question: Can batteries be “neutralized” by immersing them in water after an incident?

Finding: Partially. Immersion in water provides adequate cooling to prevent violent thermal runaway, but it may not neutralize voltage. DNV GL found the following results should be considered prior to doing so:

- Batteries may have residual voltage on damaged and exposed terminals. (Figure 11) Handling of the battery may produce a shock hazard.
- Batteries persistently gassed even under water. The primary measured component of that gas was CO, though the handheld CO sensors are cross sensitive to H₂.

- For most tests the water runoff was slightly acidic measuring pH 6-7. In one case, however, the water became alkaline climbing to pH 10-11 after a few hours of submersion. This case was observed for a battery that was highly consumed in the fire.
- Batteries did not climb in temperature after submersion, indicating that even if cells short circuited, their temperature was never permitted to climb to thermal runaway conditions.
- Some battery cells still had voltage on them after 24 hours of submersion. While some cells may have shorted, not all shorted. The water did not have any additives such as salt to make it more conductive.

Question: Was hydrogen generated as a result of electrolysis during submersion?

Finding: Possibly, high levels of CO (10-100ppm) were detected on the four and five gas meters right above the submersion pools. These electrochemical sensors are cross sensitive to H₂. High levels of CO were also detected on the FTIR during and after testing though, suggesting that CO generation is real and any cross sensitivity from H₂ is low as CO is the dominant gas. This was further supported by data from cell testing not involving submersion.

Question: How much hydrogen was emitted?

Finding: During cell testing DNV GL witnessed > 1000 ppm (sensor max value) on a few occasions. Hydrogen was not observed directly during submersion, though CO was measured. CO sensors can be cross sensitive to hydrogen. The lower flammability limit for ethylene and related species is 3.6%, which is lower than hydrogen at 4%. Therefore the greater flammability risk is presented by ethylene carbonate decomposition due to its greater volumes, higher emissions rates, and similar volatility. This is supported by gas bag sampling, which showed far higher levels of hydrocarbon gases than H₂, which was still well below the LEL.

Question: Are the liberated gases lighter or heavier than air?

Finding: The molecular weight of air is generalized at 29 g/mol. By comparison the molecular weights of the main gases observed from battery fires are shown below (in g/mol). It can be seen that HCl is heavier than air. Another observation from testing is that the gases are typically hot, which means they are rising as part of the plume.

- CO: 28.01
- HF: 20.01
- HCl: 36.4
- HCN: 27.02

Question: Should exhaust fans be intrinsically safe or grounded?

Finding: DNV GL used an exhaust fan during module testing (Figure 24). After several consecutive fire tests the heat and smoke eventually overstressed the fan. However, it was not observed that the fan ignited the gases. Consideration of intrinsically safe fans may be necessary in sensitive locations.



Figure 24 **Smoke plume rising through door gaps and out of top vents in the burn container.**

Question: Should exhaust fans be variable speed?

Finding: Based on the nonlinear behavior of emitted gases (Figure 16 and related figures) a variable speed fan should be a consideration. This may be a more cost effective solution than a highly rated fan running continuously which may exceed the minimum ventilation requirement of ~ 0.25 ACH. A variable speed fan can accommodate the low level ventilation rate for the majority of the time, with the capability to ramp up in the event of failure.

Question: How were gases measured in this testing?

Finding: DNV GL used a Gaset DX4000 FTIR gas analyzer during cell testing supported by MSA Ultima sensors for IR transparent gases and LEL. The FTIR was used again for module testing. In addition, for module testing, Rescue Methods used MSA Altair handheld four- and five-gas sensors. These tools were used for both LEL and toxicity monitoring. LEL was measured via a photo ionization detector (PID) (10.6eV bulb) on the handheld sensors.

7.0 PRESENT DAY INDUSTRY-ACCEPTED SAFETY PRACTICES FOR ENERGY STORAGE PROJECTS

It is important to place this report in the context of what is actually occurring in energy storage project development today. Presently there are over 400 stationary storage systems comprising 1,200 MW operating around the world, with 600 MW of electrochemical energy storage in the United States [5].

The types of battery energy storage systems being deployed are both utility solutions at the multi-MW scale in consolidated sites, typically with energy storage batteries housed in

shipping-container like systems with integrated BMS, ventilation and cooling, and fixed fire suppression. Smaller, behind the meter energy storage systems are designed to be deployed near the customer and controlled as an aggregate fleet. These smaller systems have a BMS and may have active cooling, but rarely have integrated fire suppression. Shipping container systems are typically located outdoors and are MW scale, whereas behind the meter systems are typically sited at a commercial site (or potentially residential) and may be indoors, and will have ratings in 10's of kW.

Energy storage can be utility owned or it can be owned by an independent power producer (IPP). Much of the US energy storage market is presently being driven by IPPs. The IPP may monetize the energy storage asset through utility contracts or a commercial power purchase agreement. Some IPPs have the balance sheet to pay for energy storage projects themselves, but many seek financing. With financing comes insurance to underwrite risk in both the finance and safety of the project. **Because of these additional parties that are exposed to financial risk, a performance and safety review are a critical piece for financing an energy storage project, which is performed by an independent engineer (IE).**

Independent Engineering is a field of service where independent third-party engineers review the technical specifications of energy projects and provide an assessment of financial or technical project risk. The practice of hiring an IE is common in the wind and solar industries and is now industry practice for energy storage projects. Many insurers and lenders require an IE report – and must feel comfortable with the findings of the report – in order to finance or underwrite an energy storage project. The first step in most IE reports on storage is a review of the technology which will include performance and safety aspects. The IE functions are typically performed during or prior to permitting and before project commissioning, as shown in Figure 25.

In the context of safety the IE is tasked with independently evaluating the adequacy of safety systems appropriate to the project. With the business case and project site(s) identified, the AHJ is likely to become aware of the project when the project developer is seeking permit(s). The AHJ will typically respond with requirements, which may be few or many, at which point the project developer takes actions to fulfill them in order to secure the sites as quickly as possible. Project finance may be secured or will be sought in parallel to this process. Because the project developer is encouraged to obtain the IE report by the financial stakeholders, it is most cost effective for the project developer to use the IE report to simultaneously satisfy requirements for the AHJ and the financial parties. The objectivity of the report should increase comfort in the transaction(s) between parties. Therefore at the request of the project developer, the IE report is written in the context of generalized project specifications so that it may enable as many transactions as possible. Therefore it is never the case that more than one IE report is generated for identical projects because it is a cost that can be practically avoided. It is also common practice for large aggregated projects of similar system types to have inspections performed on a subset of sites.

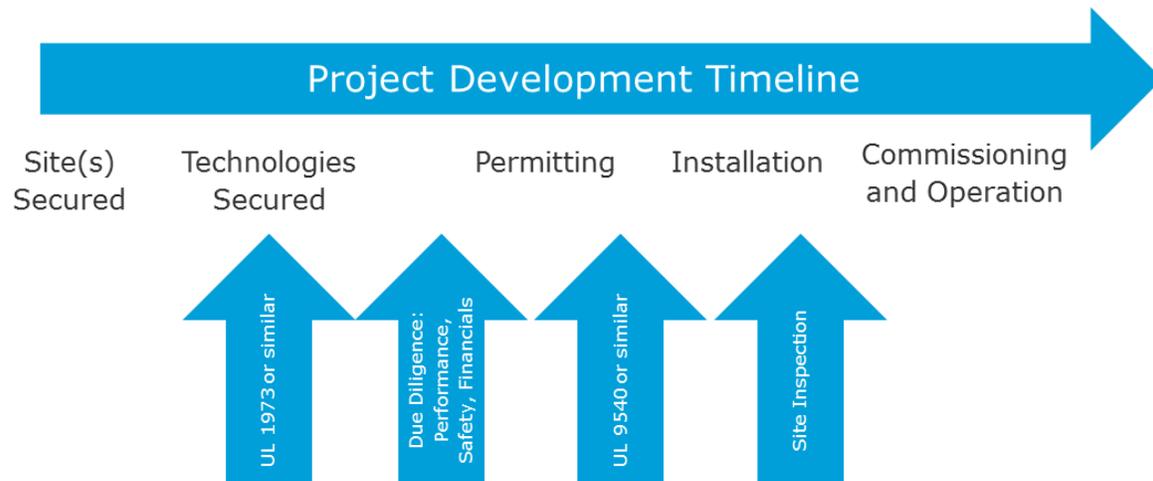


Figure 25 **Project development timeline and the implementation of FMEA or other safety review for the site.**

For an outdoor container system, the IE may provide the following services related to safety:

- Assessment of the adequacy of the safety systems
- Assessment of the safe perimeter around the site
- Emergency response plans
- Review or recommendations of materials to be provided to the local AHJ for permitting or code review
- Adequacy of firefighting equipment
- Impact of a fire scenario on the site or surrounding area, which may include a plume study if residential or populated areas are nearby
- Risk model for the site

For an indoor system, the following IE services related to safety may be requested:

- Review of safety testing
- Assessment of the adequacy of safety systems
- Recommendations on the requirements for indoor room locations
- Adequacy of cooling and venting
- Review of fire ratings
- Inspection of installation
- Risk analysis related to the system and its site(s)

In the case of behind the meter systems, this review is usually done at the **project portfolio level** unless specific site considerations require local review.

8.0 GUIDANCE FOR FIRST RESPONDERS

Many of the questions in the FAQ were intended for first responders, who wish to know what should be done upon encountering a fire that involves a battery.

The first and foremost finding from this report is that the **equipment available to present day first responders can be considered adequate for battery fire fighting** with additional considerations.

8.1 Considerations for Permitting and Siting

If a building or site information summary is available, it should state whether there is a battery on site and its chemistry. The primary concern upon approaching the scene should be HCl toxicity and rising temperatures, and the potential for the fire to expand if it has not already.

- **FMEA, siting, and standard operating procedure (SOP) development:** UL 9540 requires an FMEA for ESS permitting and siting. In addition, DNV GL recommends an FMEA be performed on any system or project portfolio, particularly for behind-the-meter applications.
 - A risk analysis involves review of all potential failure modes for their likelihood of failure and the resulting consequence to determine the total risk. As this process serves as a deep dive into the design and operation of the unit, this process would provide valuable insight for code officials and first responders to better understand the risks and potential faults they may be dealing with during emergency situations.
 - Requesting participation in this process would serve as the best opportunity to become involved in the development process and would allow AHJs and the fire service to best understand the system in the least intrusive way to the project developer (since an FMEA may be required regardless of AHJ participation).
 - In addition to FMEA involvement, DNV GL recommends all AHJs and fire departments perform a walk through for all large ESS in their jurisdictions and develop SOPs according to their level of comfort with the electrical risks. Though small home systems may not exceed 48 VDC and be easily disconnected from the AC source, larger utility scale systems may exceed 1,000 VDC and 10,000 VAC. Again, even prompt disconnect of AC voltage does not eliminate voltage on the DC side.
 - DNV GL recommends all fire departments with large ESSs or ESS portfolios in their jurisdictions work with project developers or system manufacturers to provide emergency contacts and readily available subject matter experts (SME) who can quickly advise fire departments on system status and risks associated with the current fire environment.
 - Finally, DNV GL recommends fire departments and first responders work with system and project developers to understand the level of risk and their appropriate response. A single cell failure in a large containerized system need not require the entire system be destroyed with water. However, a

system with an unknown internal hazard may pose risks to the surrounding environment or to fire fighters and may be better handled via a defensive posture than entry and attack.

8.2 Considerations for Operations at the Scene

Upon arriving at a fire scene, the following considerations should be made:

- Has on-site extinguishing already been triggered?
- Is the system gassing?
- Is the temperature of the system rising?
- Are flames visible?
- Is there a site representative or SME available?

Answers to the above questions will indicate whether the system fire has already peaked or if it is expanding. Support from an SME, an information display panel, or other form of emergency contact will greatly aid in assessing the risk.

If the system is gassing but onboard suppression (if any) has already triggered, and temperatures are remaining stable, it is likely that a single cell or module fire has occurred and been isolated, and may have been managed by the onboard system. Additional suppression may not be required in this case. Eventually, the system will need to be ventilated to remove the internal atmosphere, but only if temperatures have remained stable for approximately 60 minutes.

The list below summarizes key points from this study that are directly relevant to firefighters and other first responders. This section may stand on its own as an independent part of this report and may be distributed to fire departments and first responders nationwide independent of this document. It is not intended to serve as an SOP on its own, but should inform the response and development of SOPs for situations involving ESS. There has been much said about ESS fires in the past which has led to several myths about these fires. DNV GL wishes to dispel the falsehoods while promoting real world, data driven facts when dealing with these systems. Ultimately, findings suggest that while these systems are unique in the combination of threats posed, none of the threats on their own are unfamiliar to firefighters, and they remain manageable so long as certain points are known and followed.

- **Toxicity:** In general, battery fires resemble plastic fires in terms of emission of toxic gases including CO, HCl, HF, HCN, Benzene, and Toluene
 - The average toxicity of the fire is equivalent to many plastics on a per mass basis. Li-ion fires will have short peaks of toxicity as individual cells randomly fail.
 - However, battery fires, even once extinguished, continue to emit CO as long as the batteries remain hot.
 - DNV GL and Rescue Methods (RM) recommend continued monitoring of CO from ESS fires, especially in enclosed spaces, and the continued use of personal protective equipment (PPE), including self-contained breathing apparatus (SCBA), until CO levels are shown to be at normal levels. These practices may include monitoring for HCl, if applicable or possible.

- **Ventilation:** Though integrated ventilation will be recommended for indoor systems, it may not always exist or prove adequate to remove heavy smoke, especially in cases where the surrounding environment is fully involved or the battery is rapidly overtaken.
 - DNV GL and RM recommend sufficient firefighting ventilation, ideally negative pressure, to remove fire gases from enclosed areas.
 - The batteries themselves emit flammable gas and fully involved or improperly ventilated systems may pose a lower explosive limit (LEL) or flash hazard.
 - DNV GL and RM recommend monitoring of LEL levels in the fire ground and surrounding environment to determine if intrinsically safe ventilation is required.
 - Partially burned systems may continue to emit flammable gas even after the fire is extinguished as long as the cells remain hot. Proper cooling of the system is key to remove prolonged fire risks.
- **Temperature:** Climbing temperature is an indicator of increasing risk.
 - If flames are visible and temperature is rising, the system may have more than one battery cell or module engulfed.
 - If temperatures are rising rapidly (>1 °F per minute) and temperatures on the battery are approaching anywhere near 100 °C (212 °F), cooling will be required with water.
 - Monitoring with handheld infrared (IR) thermometers, if available, should provide an assessment of risk.
- **Delayed Cascading Ignition:** On site responders should assess that all thermal, electrical, or mechanical stimuli that may act on the system have been mitigated.
 - In the short term, when cells appear to “reignite” after seconds or minutes, it is almost always a result of incomplete removal of heat from the system, or an electrical short due to liquids or water. Prevention of cascading between cells may be addressed by proper cascading protections in the system, which may retard extinguishing and external cooling but also mitigates the free movement of heat internally in the batteries which can ignite previously undamaged cells. DNV GL refers to this phenomena as delayed ignition.
 - In some cases, the only way to halt this process is to let the system burn itself out (but this may not be practical) or continue to drown the battery until this process stops as the battery finally cools. This decision should be made based on the circumstances of the fire ground.
- **Shock Hazards:** Cells that have not been burned may remain intact in systems and modules.
 - Shock during water suppression (via conduction into the water spray) was not observed in this program.
 - Beware of arcing if batteries are disturbed. Turnout gear was observed to provide shock protection under the conditions tested in this program, but do not touch arcing equipment.
 - Stranded energy in partially burned batteries will likely remain an issue in any system that is extinguished unless it has consumed itself entirely. DNV GL

found that even in systems that appeared thoroughly damaged, live cells and stranded energy can remain. These cells may pose a shock/arcing risk and can reignite if physically damaged, reheated, or allowed to short.

- **Extinguishing:** DNV GL tested several water based extinguishing agents and found none to be as effective for cooling as water. These included PyroCool, F500, and FireIce.
 - The most challenging aspect of the battery fire is its deep-seated nature. Access to the heat source is necessary to provide adequate cooling.
 - Cooling the battery once flames are knocked down is the most important aspect of containing battery fires. The tested agents proved slightly less effective than water at cooling the cells. On a module level, there was no evidence to suggest these agents perform better than water.
 - Because many encapsulating agents, including foam (AFFF) are intended to blanket the fire, and a battery fire needs to have heat removed as quickly as possible, DNV GL generally recommends against using foam for ESS fires. Foam has been tested in other projects and used in real world ESS fires. In testing in other projects, it failed to perform better than other agents.
 - The aerosol may prove effective at knocking down flames from ESS. Gas based agents may suppress the flammability of contained atmospheres with high explosive gas content; however, in the case of severe ESS fires where these agents would be tasked to suppress flammability, cells may be producing heat above the autoignition temperature of their flammable gases. This may result in fire if oxygen were reintroduced to the system. DNV GL recommends gas-based systems be backed up by water-based suppression when cooling becomes a necessity, in combination with cascading protections in the modules and systems.
 - Though water proved most effective for cooling, water and any water-based agent introduces shorting risks when applied on a full system. This may exacerbate the situation in addition to presenting a collateral damage risk.
 - Several entities, including DNV GL, have advised that class D fire extinguishers and agents be investigated for use during the incipient stage of the fire. Based on the findings from this program, DNV GL views the deployment of classical class D agents as impractical due to the short lived peak of a cell fire and its deep seated nature, which prevents direct access.
 - RM's experience during suppression testing suggests forced access to the interior of battery systems may be difficult or inadvisable for first responders. In this case, water should be used to provide indirect cooling on the outside of the system to prevent spreading.
 - Water use inside the system, if applicable, should be done with care to avoid shorting neighboring and surviving cells, i.e., the failing module should be isolated and targeted. Fully involved systems may be compromised enough to allow better water penetration. Fully involved systems posing a risk to surrounding life and property, or neighboring systems, should be suppressed immediately and heavily to avoid spreading.

- If the fire appears to be stable and not expanding, periodically stop water flow and monitor temperatures. Note that the temperature may “spring back” after water extinguishing stops, but it should plateau and stabilize if the fire fuel has been consumed.
- Observe for water shorting other cells. They may begin to heat, meaning the deep seated heat remains.
- Repeat extinguishing process as needed, while ventilating the area as much as possible.
- If the battery system has closed doors, do not open them unless absolutely necessary or it has been determined that opening the doors will not introduce new hazards. Forced entry is discouraged unless a prior access plan has been described.
- Suppression of large, fully involved systems may take more time than fires of similar size with different fuels. It is recommend fire service personnel continue to suppress with water for as long as required and then ensure the system is fully cooled throughout once suppression appears complete.

8.3 Guidance for Isolation and Overhaul

After burning, the removal and isolation of the batteries demonstrated real-world hazards that may be encountered in the overhaul stages of fighting a battery fire. Residual live DC voltages in intact battery cells, and damaged but still live bus bars within modules after a fire represent an electrical shock hazard (see Figure 11). During testing, it was found that firefighters were not shocked while wearing standard turnout gear when arcs and sparks resulted from disturbance of the debris. **For this reason it is recommended that whenever possible, first responders need not open or otherwise disperse burned battery modules and wait for an experienced liaison to arrive on site and take ownership of the site after extinguishing has been achieved.**

As shown in Figure 26, submerging battery modules in water provided adequate cooling to slow and prevent delayed cascading thermal runaway in the remaining battery cells; however, the batteries persistently off-gassed even under water. The primary gases detected in the bubbles generated were CO and possibly hydrogen. The figure demonstrates the bubbles observed even after submersion for over 30 minutes.

Even after submerging, some batteries generated a severely alkaline solution climbing to pH 10-11. Other solutions gradually became slightly acidic (pH 6). There was not a clear explanation for the pH behavior of the solutions, other than one of the most severely burned batteries created the most basic solution. **Therefore, if water submersion is used by first responders for isolating spent modules, preparation to deal with alkaline or basic water for disposal should be a consideration.**

Lastly, it was found that after extinguishing the persistent emission of CO was sometimes in quantities large enough to trigger threshold alarms on the gear worn by fire fighters. The persistent emission is perhaps a more insidious risk than the emissions during the fire, as the apparent climax of the fire has passed, and first responders may be inclined to remove their masks. **After extinguishing, continued ventilation and monitoring of the area with gas monitors is highly recommended.**



Figure 26 **Submerging batteries in water resulted in cooler temperatures, but slow shorting and persistent CO generation (bubbles).**

As the climax of the fire has concluded, but continued ventilation and monitoring is underway, first responders are left with the final challenge of determining when they can relinquish control of the area. There are several risks that first responders wish to avoid and they are prioritized by the list demonstrated on page 57. **It is highly recommended that battery systems installed within buildings have an established emergency contact list and a SME who can arrive on the scene to take over containment, cleanup, and eventual disposal of damaged battery equipment. This recommendation requires involvement from the project development and systems integration community.** This is a necessary risk transfer procedure to mitigate the first responder concern that they are responsible for damaged battery systems for hours or days after they have been involved in a fire or catastrophic safety event.

The following summarizes recommendations for overhaul procedures:

- **Overhaul and Stranded Energy:** As mentioned, stranded energy in the surviving cells remains a risk to first responder during overhaul and post fire operations.
 - Live or damaged but surviving cells may contain voltage that will cause arcing when shorted by debris or metal tools. This arcing may also serve as an ignition source to localized gases if hot batteries are still venting.
 - Firefighters should thoroughly avoid penetrating, cutting, or otherwise damaging batteries in the ESS, especially during overhaul, as live cells that are physically damaged or penetrated are subject to rapid venting.
 - Firefighters should avoid blindly reaching into cabinets to remove damaged batteries as DC energy may still remain active even if AC and site power is cut. It was observed that typical turnout gear provided adequate protection

against shocks in this testing; however, high voltage DC may penetrate PPE in cases where it is damaged or otherwise compromised, such as a torn glove or a exposure to sharp metals. These kinds of hazards were not studied in this testing program.

- DNV GL and RM recommend fire fighters continue to wear PPE and SCBA even during overhaul as CO levels may remain elevated even after flames are extinguished as batteries remain hot and continue to offgas. DNV GL recommends CO levels, especially in enclosed or unventilated spaces be monitored and SCBA worn until levels are shown to be safe.
- Complete submersion of damaged batteries in water provides cooling for damaged batteries; however, batteries continued to offgas CO. Because handheld sensors are cross sensitive to CO, H₂ may have also been emitted while submerged. In addition, this did not always entirely neutralize the voltage on surviving cells. However, cells seem to remain stable once pulled from water and dried. Caution should be exercised when removing damaged batteries from enclosure/containment per the risks discussed above. Whenever possible, a relevant subject matter expert from the site, project owner, or manufacturer should provide guidance or control of removal.

9.0 FINDINGS RELATED TO CODES AND TRAINING

The following summarizes key recommendations from the report study. The findings are sorted in their relevance to sections of precedent codes.

9.1 Fire Rating

DNV GL testing has shown that naked cells³ and modules exposed to direct fire are susceptible to failure within 10 minutes. However, systems deployed in the field, when exposed to external flame, are likely to sustain much longer durations because of the shielding and air gap provided by the enclosure since the cells and modules are not likely to be installed “naked” in an installed system. **Because many code precedents such as those shown in Table 4 and Table 5 require 1-hour fire ratings, and more conservative precedents require 2-hour fire ratings dependent on height above the ground floor, DNV GL recommends a minimum 1-hour fire rating with a 2-hour rating in areas with critical population density, and that the fire rating be considered as part of a system level approach to avoid cascading fires.** Exceptions to this general rule may include 1-hour requirement for outdoor locations, similar to combined heat and power (CHP) and backup generator requirements. The finite element analysis (FEA) model in Figure 28 demonstrates an Abaqus FEA model of a fire impinging on a generic battery system.

³ Cells not integrated into modules or systems

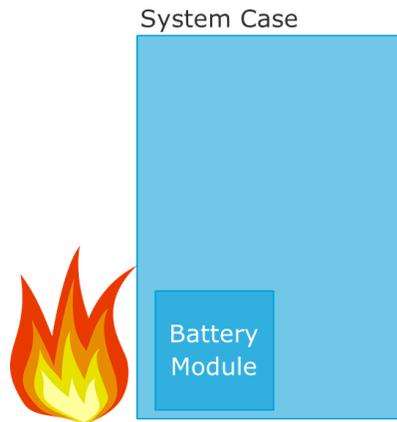


Figure 27 **Simplified diagram of fire impinging on the external wall of a battery energy storage system.**

The model demonstrates the heating effect on a battery module after 60 minutes of a 1000°F fire (811K or 537°C) impinging on a steel wall of 1/16" thickness, with a 1" air gap between the wall and the nearest inner battery module. For simplicity, the battery is assumed to be constructed of entirely aluminum or polypropylene in order to bracket the low and high temperature scenarios, because many battery modules are a composite of these or similar materials. After 60 minutes of exposure the model predicts the battery temperature to be 84°C for the aluminum and 231°C for the polypropylene⁴. Because a critical temperature for Li-ion batteries is ~120°C, a conservative 2-hour rating on the system metal enclosure would slow heat absorption for the worst case polypropylene estimation.

The boundary conditions are a fixed wall temperature of 811K (537°C or 1000°F). Model components are a steel wall with temperature-dependent conductivity, an air gap (1 in) with temperature-dependent conductivity, and a composite battery case made of aluminium with fixed conductivity and polypropylene with fixed conductivity. The heat transfer modes are natural convection and conduction.

⁴ This may seem counterintuitive; the aluminum conducts heat away faster and therefore maintains a lower temperature than polypropylene.

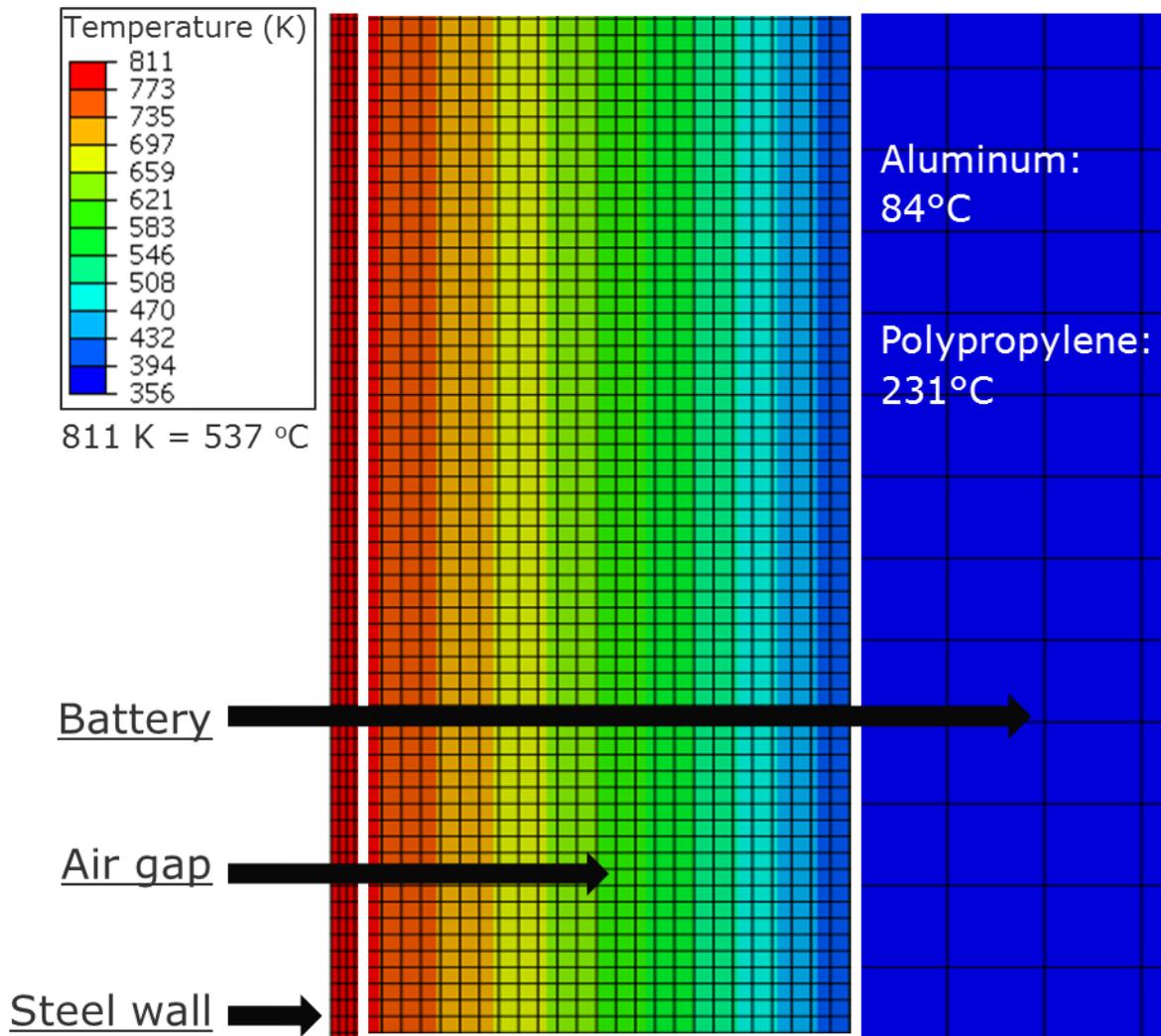


Figure 28 **Direct fire exposure model to a steel wall with a 1/16" thickness and 1" air gap between the wall and battery modules.**

Table 4 **Non-battery related codes for energy systems in buildings.**

Non-Battery Codes				
<u>Code Item</u>	<u>CHP</u>	<u>Backup Diesel Generator</u>	<u>Confined Spaces</u>	<u>OSHA Flammable Liquids 1926.152</u>
Ventilation	Rated to maintain gas concentrations below 25% LEL of the fuel gas, or at an exhaust or makeup rate equal to 80 times the maximum leakage rate		Effective engineering controls required rather than dependence on respirators	Should be constructed to keep vapor at or below 10% of the LFL. Shall have pressure release capability to relieve pressure during a fire.
Fire suppression	Fully sprinklered	Automatic fire sprinkler system		Sprinkler, water spray, or CO2 or other system approved by nationally recognized test laboratory (NRTL).
Monitoring: Detection, alarm, display	Gas detection and alarm in supervised location		Monitor and display that potential hazardous atmosphere can be mitigated by forced ventilation	
Capacity limitation dependent on space	1 MW in dedicated room, 0.5 MW in boiler room	Fuel stored limited to 10 gallons		25 gallons outside storage cabinet, 60 or 120 gallons in cabinet depending on flammability category
Clearance		5 ft from other structures		3 ft wide aisle access
Thermal runaway protection	NA	NA	NA	NA
Fire rating	If indoors or in a dedicated room, 2-hour fire rating on external walls	Up to 2 hours		Compatible with NFPA 251-1969, 1-2 hour rating
Location	Outdoor, penthouse, boiler room, dedicated room	Outdoor, penthouse, boiler room, dedicated room		Electrical rated for Class I, Division I Hazardous Locations
Seismic rating	Appropriate for zone	Appropriate for zone	Appropriate for zone	
Accountable parties				
FMEA/HMA				
Inspections				
Signage				Flammable, keep away from open flames

Table 5 Battery specific codes for battery systems in buildings, existing and proposed.

Battery Related Codes				
<u>Code Item</u>	<u>IBC</u>	<u>IFC 608</u>	<u>NFPA 1 Chapter 52</u>	<u>FDNY Certificate of Fitness (COF) B-29 (Uninterruptible Power Supply)</u>
Ventilation	307.1.1 Rooms shall have ventilation, batteries shall have venting caps	None for Li-ion		Required for Valve Regulated Lead Acid (VRLA) only, designed to limit H2 buildup to 1% of the entire room volume; Continuous ventilation = 1 CFM per ft ² of room
Fire suppression	403.3 and 903.2 Not required in external structures with fire detection	Proposed Chapter 5 of NFPA 13.		Sprinklers not required but recommended. Portable Class ABC on hand.
Monitoring: Detection, alarm, display	907.2.23 Smoke detection system			Hydrogen monitoring or handheld detector for COF holder, system health status
Capacity limitation dependent on space		> 50 gallons electrolyte or 1000 lbs. Li-ion. Proposed 20 kWh limit for single units, 600 kWh limit for total in a room.	100 gallons of electrolyte (sprinklered) or 50 gal electrolyte (unsprinklered) or 1000 lb. Li-ion	50 gallons of electrolyte for Pb acid, VRLA, NiCd, or 1000 lbs. for Li-ion
Clearance		Proposed 3 ft between arrays no larger than 50 kWh. 5 ft from lot lines for outdoor.		
Thermal runaway protection			Required	Required for both VRLA and Li-ion
Fire rating	Table 509 1 and 2 hour ratings			
Location		Proposed no more than 75 ft above or 30 ft below fire access, exceptions on non-combustible rooftops		
Seismic rating	Appropriate for zone	Required for zone	Appropriate for zone	Appropriate for zone
Accountable parties				Equipment shall be under "general supervision" of certificate holder, in case of emergency there shall be a hazardous materials liaison, contact info available to fire command center
FMEA/HMA		HMA required		
Inspections				Performed by COF holder. Record keeping on site.
Signage				Warning against electrolyte or voltage. Battery information on Building Information Card.

9.2 Extinguishing

DNV GL tested a number of extinguishers during cell and module testing. During testing, DNV GL found that all extinguishers tested⁵ could put out the fire if applied immediately upon detection of a thermal spike (indicating the immediate onset of thermal runaway). While extinguishing was accomplished with all extinguishers, water demonstrated the best ability to cool and maintain cool temperatures on the battery.

9.2.1 Class D and Deep Seated Fires

During testing, DNV GL witnessed firsthand how residual heat between batteries can lead to delayed cascading and prolonged extinguishing for battery modules. This highlights the importance of cascading protections between cells and inter-cell cooling in battery modules. Cascading protections can be tested by the UL 1973 internal fire test, the IEC 62619 internal propagation test, SAE J2929 propagation test, or similar standards. DNV GL recommends more stringent criteria such that a single cell failure cannot propagate to neighboring cells, with the intent of maintaining manageable heat release rates that can be otherwise managed by the water extinguisher flow rate and/or the system's external fire rating enclosure. This recommendation illuminates that the extinguishing solution and the module design are interlinked; a module with adequate cascading protection is more likely to be appropriately designed with a gas-based suppression system.

Because the consumption of a single cell is rapid, the metal fire fuels (Class D) are rapidly consumed and the fire evolves to Class A, B, or C quickly. **Because of the rapid evolution of a cell fire, DNV GL does not see an advantage to using a Class D extinguisher on a single cell or system fire.** This has direct implications for first responders who are accustomed to using water as their primary extinguishing agent. In the event of a single cell fire, cascading protections should limit propagation to other cells. First responders may still respond to a call reporting smoke, but in the best case scenario the fire has consumed itself and burned out. If a fixed suppression agent is installed within an enclosed environment containing the single failed battery cell, it may suppress flammability in the enclosed space. The use of water may be unnecessary at this point unless the fire has progressed. A key issue to be addressed in later sections is how the first responder is able to determine if this single cell fire has been mitigated or if further action (and water extinguishing) is needed, and hence some system health information, an emergency response phone line, or some other means to gain information on system health is a need that requires industry engagement to overcome. The first responder is not comfortable deeming the site extinguished and is technically responsible for the scene until this information allows them to make the decision to leave the control of the scene with a responsible party.

9.2.2 Cooling and Collateral Damage

Cooling is a secondary component of extinguishing that has not been previously discussed in the literature. In 2011, the NHTSA recommended "copious amounts of water" in an official release concerning the extinguishment of battery fires in hybrid and electric vehicles. [12] The intent and purpose of this recommendation was to introduce cooling to the fire.

DNV GL found that water extinguishes, cools, and maintains lower temperatures on a battery fire than other tested agents. As shown in Figure 29, water consistently maintained a 50-100°C sustained cooling advantage over equivalent volumes of other water borne

⁵ For the complete list of extinguishers tested, see the Appendix, page 82.

agents in the seconds and minutes following extinguishing. The behavior demonstrated in the figure is consistent for all battery types, with the heat decay duration, "reheat" period, and peak temperatures varying as a function of cell mass.

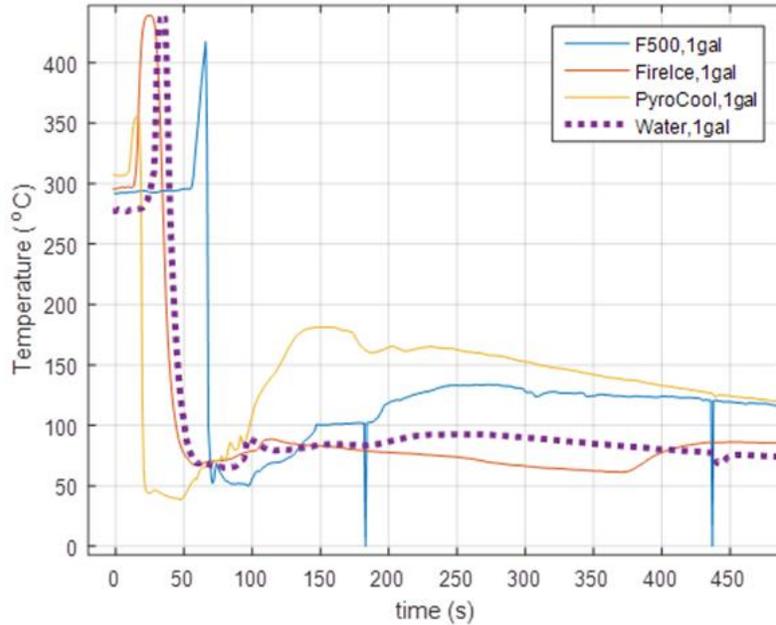


Figure 29 **Performance of water compared to other agents as water additives, top temperature of battery cell.**

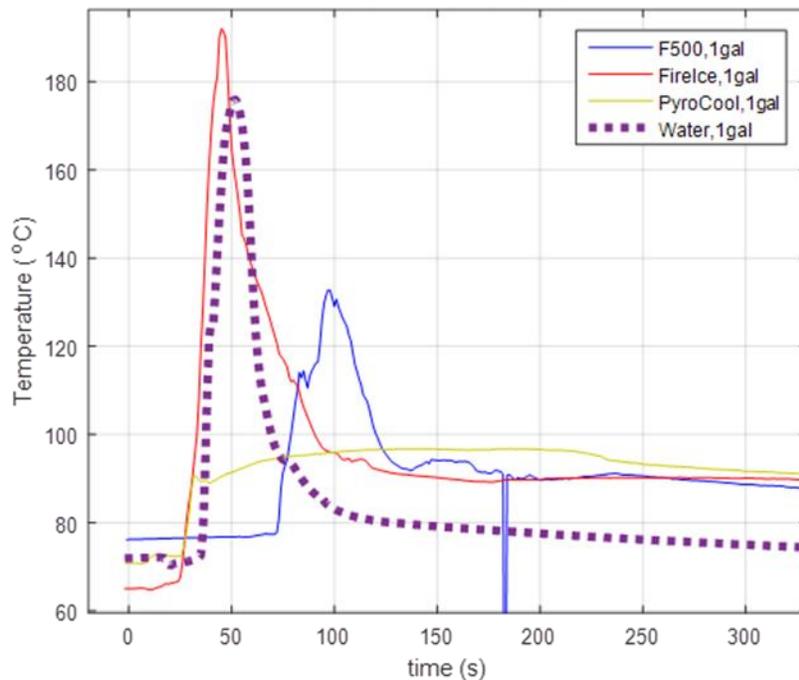


Figure 30 **Cooling performance of water compared to other extinguisher types, bottom temperature of cell.**

The initial cooling rate is nearly equivalent for all extinguisher types, but the thermal mass of the battery causes the extinguishing agent to evaporate as temperatures climb back to 250-275°C. Extinguishers were triggered the moment the battery fire climbed above 350°C. In each case 1 gallon of water was applied. In all instances the total extinguishing time spanned less than 60 seconds, or about 1 GPM.

The duration of this “reheating” is approximately 200s for non-water agents, whereas water is shown to reheat for about 100 seconds. Therefore, DNV GL saw no particular cooling advantage of water borne agents such as F-500, FireIce, or Pyrocool over water alone. (Figure 29) Some of these agents are encapsulators, which are designed to blanket a fire and insulate surrounding areas from heat; in an exothermic battery fire, trapping heat is undesirable. The figure demonstrates that cooling with water persistently achieves lower sustained temperatures after extinguishing, with as much as a 50-100°C advantage within 1-2 minutes of extinguishing (See appendix on page 76). This data demonstrates that water and all water borne agents reduce cell temperatures from > 400°C to near 50°C within 10-30 seconds. Water can maintain cell temperatures after extinguishing below 100°C even as the initial mass of water evaporates.

An additional vendor provided an aerosol agent to be tested. The aerosol was observed to extinguish the cell fire. The aerosol provides some initial cooling but does not reduce cell temperature until the exothermic reactions of the battery begin to decay. It was shown that the cooling ability of the aerosol was significantly less than water.

Because cooling is an inevitable need, a fixed suppression gas agent may reduce or mitigate flammability in an environment until ventilation and/or cooling strategies are implemented.

While the use of water demonstrates excellent cooling capability, it also potentially shorts out undamaged cells or neighboring modules. The use of water is a fully committed extinguishing tactic that is highly likely to result in a total loss of the asset. Because it was noted that the aerosol test demonstrated extinguishment of the fire upon execution, aerosols can potentially serve as an initial attack for the fire followed by water as a backstop.

Therefore, DNV GL recommends the following:

- **Stage 1: If a system can limit cell cascading, a gas based suppression system may be considered for the first stage of fire fighting to extinguish a single cell fire and prevent flashover in a contained environment.**
- **Stage 2: If temperatures continue to rise or if an increasing level of smoke and gas is detected, forced ventilation and water extinguishing should be considered to cool the system and prevent further propagation of fire.**

Stage 1 provides an opportunity for avoiding collateral damage and total asset loss. Stage 2 provides a backstop for a situation when more than one battery cell is on fire. Both stages may also include some form of alarm or notification external to the battery system that notifies first responders of elevated risk.

9.3 Locations and Ventilation

DNV GL quantified that the gases emitted from a battery fire have somewhat differing toxicity and flammability risks across chemistries. However, mitigation of toxic or flammable gases is addressed with ventilation in all cases.

9.3.1 Outdoor Locations

Toxicity of the fire should be modeled to account for the impact on neighboring areas. The fire may be modeled in scenarios of increasing severity, such as a single cell fire of short duration, a module fire of short and long duration, and a total system fire.

The probability of fire, size of the system, plume contents, proximity of nearby buildings, wind direction, and duration of the fire will have an impact on the location of fencing and safety perimeters. It is the discretion of the project owner to consider these hazards.

DNV GL deploys a tool called PHAST for plume models [58] and uses the output to inform the risk analysis. This model directly impacts a FMEA, Bowtie, HAZID, or other hazard analysis as required by UL 9540 or standards with the same intent. It is implied by ANSI and IEEE 1547 updates that UL 9540 will be a requirement for energy storage projects, which includes FMEA for the system and related ancillary equipment. [25] As shown in Figure 25, it is common practice for a safety review to occur during permitting and prior to installation. This review may include the FMEA as required by UL 9540, or it can be part of an independent engineering review on behalf of the lender, project developer, or insurer.

9.3.2 Indoor Locations (Penthouse or Dedicated Room)

Emissions from batteries are simultaneously flammable and toxic during failure. The emissions characteristics of a Li-ion battery are shown in Figure 20. In all of the tests conducted in this program, this behavior was consistent among all Li-ion batteries. The figure indicates that 40-90% of the time, a single battery cell emissions rate corresponds to less than 10 ppm in a 0.44 m³ volume. The peak event can exceed 200 ppm in this volume for a single cell, and it is short lived (2-3 minutes).

Similarly, it was found that vanadium oxide electrolytes emit HCl and HF, with HCl occurring in greatest quantities (see Figure 6 on page 12). Lead acid battery electrolytes emit SO₂ and HCl when heated (see page 12, Figure 7, and Figure 8). The mass and volume equivalent concentrations of emissions from all battery types are included in Figure 4 (peaks) and Figure 5 (average ppm per kg per minute).

A common toxic emission from all battery types was HCl. This is also common with plastics fires. Because the IDLH rating for HCl is low and the quantity of HCl emission is typically largest among the four toxic constituents monitored, the ACH rating is therefore governed by HCl. As shown in Figure 5 all battery types average lower than 2 ppm per kilogram per minute in the categories of CO, HF, HCN, and HCl emissions.

IDLH and Emergency Response Planning Guidelines (ERPG) values for HCl, HF, HCN, and CO are shown in Table 6. The term immediately dangerous to life or health (IDLH) is defined by the US National Institute for Occupational Safety and Health (NIOSH) as exposure to airborne contaminants that is "likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment."

- ERPG-1 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing more than mild, transient adverse health effects or without perceiving a clearly defined objectionable odor.

- ERPG-2 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action.
- ERPG-3 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects.

Table 6 **Immediately Dangerous to Life and Health (IDLH) for the emphasized toxic gases identified in the testing work.**

	IDLH (ppm)	ERPG-1	ERPG-2	ERPG-3
HCl	50	3	20	150
HF	30	2	20	50
HCN	50	n/a	10	25
CO	1200	200	350	500
SO ₂	100	0.3	3	25

This dynamic and varying emissions rate was time-averaged and then charted as a function of air change over rate (air changes per hour, or ACH), of the battery mass undergoing failure, and the room volume. Because this time averaged calculation includes the nonlinear effect of higher emissions during the peak, this ACH calculation is overly conservative for 40-90% of the duration of the battery failure event. As mentioned previously and as shown below, HCl (Figure 16) governs the dominating air change over requirement because of the low IDLH value. The chart in Table 15 on page 67 converts ACH to CFM based on room size and approximate room footprint. In all cases the ACH rate is calculated to maintain gas concentrations below IDLH.

An air change rate of 0.25 ACH is sufficient for limited cell failure scenarios to mitigate HCl in the room sizes considered (see Figure 16). The peak emissions rate for up to 1.5 Li-ion modules (typical masses assumed) would require up to 11.5 ACH. This is within normal laboratory building ACH requirements, by comparison (Table 8 on page 51), and ASHRAE notes that 1 – 4.4 ACH is common in residential and commercial environments. [26] **This clarifies DNV GL’s recommendation that ventilation requirements are within established limits of the built environment as long as the system demonstrates it can limit propagation of cell failures with cascading protections**

- CO (Figure 18 and Table 13 on page 66) can be mitigated in all scenarios with only 0.25 ACH.
- HF (Figure 19 and Table 14 on page 66) can be mitigated with 0.25 ACH in the most probable failure scenarios and may require up to 14.5 ACH in the smallest room considered.
- HCN emissions rates can be mitigated for the most probable failure scenarios (a single or multiple cells) with only a 0.25 ACH. In the worst case scenario of 1.5 failing modules, the ACH is 7.5.

Note that **HCl and HF govern the ventilation requirements, which implies that the ventilation requirement is determined by toxicity, not flammability**. This is because toxic gas IDLH limits are between 30-50 ppm, while flammability limits for many gases are in the 1,000-10,000+ ppm range. The assumptions used in this calculation are shown below. The emissions rates assumed for the ACH calculations are the average of the emissions measured during cell testing. A 30-minute release rate is conservative, and accounts for an average of emissions rate that is higher than the low level emissions leading up to peak failure, and lower than the peak emissions.

9.3.3 GPM and CFM Requirement

It is shown in Figure 15 that the heat release rate has a weak positive correlation to mass lost because the linear fit has a positive slope but the R^2 is low due to scatter in the data. As discussed on page 4, the scatter is due to the nonlinear behavior of battery fires. As shown in Figure 20 the battery spends between 40-90% of the time in a smoldering state, meaning that the exothermic contribution to the fire is low during this period and much of the battery mass is lost during this time, which means there is less to contribute to the peak HRR event. It was also shown in Figure 12 that it was possible to reduce the water requirement as testing progressed on modules and systems. This data was directly measured from the masses of the cells and modules and the water used.

The theoretical minimum water requirement *for the battery mass* (not the system mass) is calculated in Table 7. It should be noted that the water calculation is determined in units of GPM/kg; dividing this number by the energy density (commonly given in Wh/kg) will convert the result to GPM/Wh, and multiplying by 1000 Wh/kWh will convert the result to GPM/kWh. A cross check for these conversions will be needed as energy density of batteries will inevitably increase over time.

For context and benchmarking, typical ventilation and water sprinkler requirements are shown in Table 8 on page 51. The range of possible values for the GPM/kg of battery are shown in Figure 31 on page 54. Table 15 on page 67 shows conversion factors between ACH, CFM, and CFM/ft².

The aggregate of such data is shown on page 67, which demonstrates the means to estimate water flow and ventilation flow requirements based on system size. In some cases it can be seen that the ventilation rates and GPM requirements are within the norm of building codes. This is translated in Table 10 on page 53. However, the factors that affect this most are the mass of batteries, their energy density, and the volume of the room where they are installed. The air volume in larger rooms will dilute emissions, resulting in lower requirements for air change.

DNV GL and Rescue Methods found that the water requirement per kg of battery material decreased as the quantity of modules became larger (Figure 31). It is acknowledged that initial testing began with an arbitrary water volume at the cell level, and it was found that this quantity was more than sufficient—and is therefore excessive—for a practical application. **DNV GL recommends that further study be considered to find the minimum water requirement for extinguishing and measure the physical parameters impacting water contact efficiency**

Because outdoor systems are likely containerized they are also likely to include on-board gas-based fixed suppression systems. As recommended by DNV GL in the extinguishing section (see page 45), a gas based suppression system may serve as a first line of extinguishing. Adequate sizing of nearby fire hydrants should be considered in the context of the maximum possible heat load during a system fire.

Table 7 Example calculation to determine the minimum water requirement per kg of burning cell.

Theoretical Minimum Water Requirement to Cool a Battery	
Battery burn time (min)	42.25
water density (kg/gal)	3.7
m battery (kg)	2.87
c water (kJ/kgC)	4.1
c battery (kJ/kgC) ⁶	1.4
ΔT battery (deg C)	525
ΔT water (deg C)	75
Q battery (kJ)	2,107.0
m water (kg)	6.9
vol water (gal)	1.9
GPM	0.044
Theoretical Minimum GPM/kg	0.015

Table 8 Benchmarks for airflow and water flow for typical structures.

Benchmarks	CFM/ft ²	GPM/ft ²	Sources
Libraries	0.12	0.05-0.3	<i>ASHRAE Addendum n to ANSI/ASHRAE Standard 62-2001 "Ventilation for Acceptable Indoor Air Quality" and NFPA 13 Area Density Curves</i>
Warehouses	0.06	0.05-0.3	
Pharmacy	0.18	0.05-0.3	
Laboratories	0.18	0.05-0.3	

Based on the known test data, DNV GL is able to recommend the following across the aggregate of battery chemistries. The values in Table 9 are derived from Table 16. These are converted to example CFM/ft² and GPM/ft² values in Table 10 on page 53.

⁶ Estimated by phenolic, given that the battery is a composite of multiple polymers, liquids, and some metals.

Table 9 Values derived from probabilistic analysis of water flow rates (GPM) and air flow rates (CFM) per system energy (kWh) or mass (kg).

Scalable Metrics for Systems based on Electrochemical Battery Mass and Energy Content

	25th Percentile	Mean	75th Percentile
Water Flow Rate GPM/kg	0.07	0.10	0.20
Water Flow Rate GPM/kWh	0.70	0.99	2.09
Air Flow Rate CFM/kg	0.01	0.02	0.03
Air Flow Rate CFM/kWh	0.11	0.18	0.31

A sensitivity analysis is demonstrated with calculated regression coefficients. The uncertainty in the calculation is captured by triangular probability distributions created in Table 16. In regression analysis, the coefficients calculated for each input variable measure the sensitivity of the output to that particular input distribution. The sensitivity of the calculation of the ventilation rate is shown in Figure 35.

The energy density, cell mass, and emissions rate from the cell are the greatest influencing factors in 90% of the calculated outcomes. **DNV GL recommends that when calculating the air flow and water extinguishing rate, one must account for battery energy density (only the battery cells, not the entire system) as well as the duration of the event.** The sensitivity of the calculation of the water flow rate is shown in Figure 36. The two main factors influencing the calculation are the range of flow rates found during testing and the range of possible energy densities of the battery system.

These uncertainties demonstrate the following:

- Energy density and the emissions duration should dictate the ventilation requirement
- Energy density and the duration of the event affect the extinguishing requirement

In Table 10 some example ventilation and water extinguisher ratings are calculated based on hypothetical systems. The values in Table 10 are calculated from Table 7 and demonstrate the mean of probability distributions generated from Table 16. The distributions of the water requirement is skewed to the left, as shown in Figure 31. The table demonstrates how these findings translate to codes development via examples. The table demonstrates that the ventilation and water requirements are within the scope of present requirements for the built environment when the system is placed within adequate room volumes (compare with Table 8). Considerations of whether the spaces are occupied or whether they are outdoors apply.

In practice, these results will depend on the actual system weight and room size on a per project basis. When considering a containerized system, the following additional considerations may occur:

- A containerized system may not be considered a livable or occupied space and therefore may have different code considerations.
- The water requirement in Table 10 is equivalent to about 4-5 garden hoses and is less than half the GPM rating of a typical 2.5" line (250 GPM). If the system is already equipped with a gas-based fixed suppression system, a parallel water

connection on the exterior would accomplish the goal for first responders to create a cost effective internal sprinkler system as a backup to the fixed suppression system.

The calculated airflow requirement can be oversized with a variable speed fan that meets the minimum air change requirement and may peak upon detection of smoke or particulates.

The leftward skewness of the distributions for both the GPM requirement and the ACH requirement is demonstrated in Figure 31 and Figure 32.

Table 10 Example implications based on extrapolated findings from testing. It can be seen that the calculated water requirement is within the bounds of what was described for libraries, pharmacies, warehouses, and laboratories; similarly the air flow requirements can be at or below unless the room volume is too small.

Example Code Requirements

<u>System Size (kWh)</u>	<u>System Chemistry</u>	<u>Estimated Mass (kg)</u>	<u>Estimated Room Size (ft²)</u>	<u>Ventilation Requirement (CFM)</u>	<u>Theoretical Minimum GPM Requirement</u>	<u>Median GPM Requirement</u>	<u>GPM Requirement at 0.1 GPM/kg</u>	<u>CFM/ft²</u>	<u>Min GPM/ft²</u>	<u>Median GPM/ft²</u>
20	Li-ion	133.3	100	2.3	2.0	2.2	13.3	0.02	0.02	0.02
100	Li-ion	666.7	146	11.7	9.8	11.2	66.7	0.08	0.07	0.08
100	Pb Acid	3,333.3	200	58.4	UPS Requirement			0.29		
1000	Li-ion	6,666.7	300	116.8	98.1	111.8	666.7	0.39	0.33	0.37
1000	Vanadium Redox	20,000.0	1500	350.4	Standard Commercial			0.23		

Note: Fire flows in excess of 3,000 GPM per buildings are considered impractical for many state fire codes. Consideration of battery flammability, cascading protections, and building water supply should be considered. For containerized systems, a parallel system may be fed externally by fire hose.

Consolidated Edison
 Considerations for ESS Fire Safety

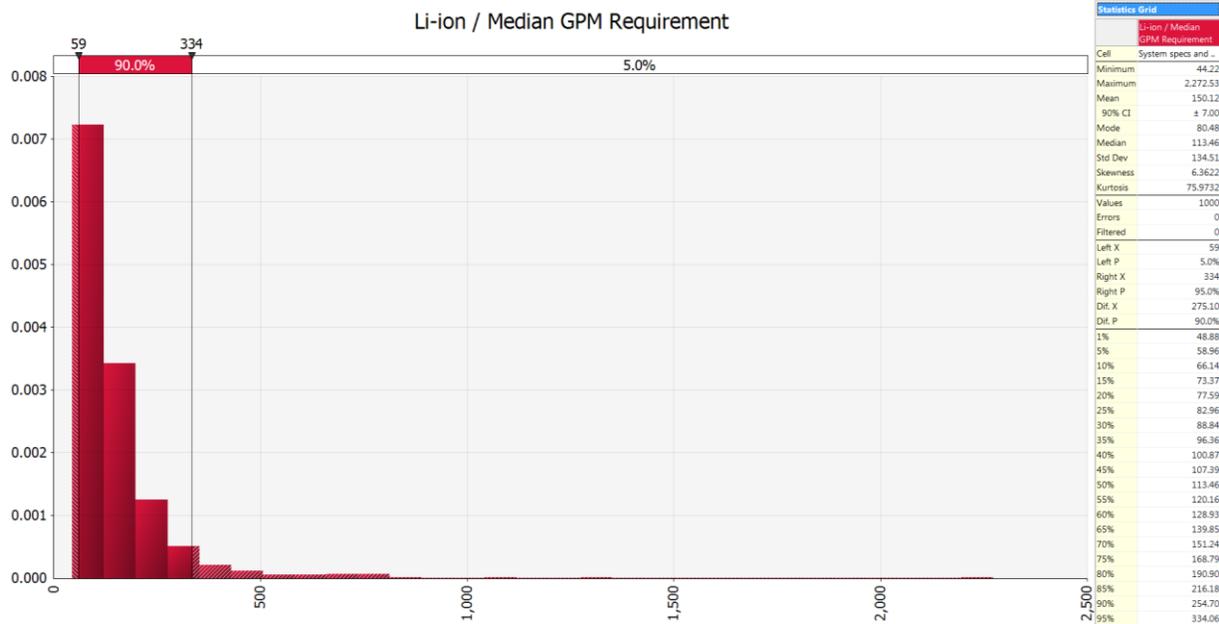


Figure 31 **Distribution of gallons per minute for a 1 MWh battery, calculated from cell testing and extrapolating with the latent heat value, which demonstrates that the 0.1 GPM/kg estimation is highly conservative.**

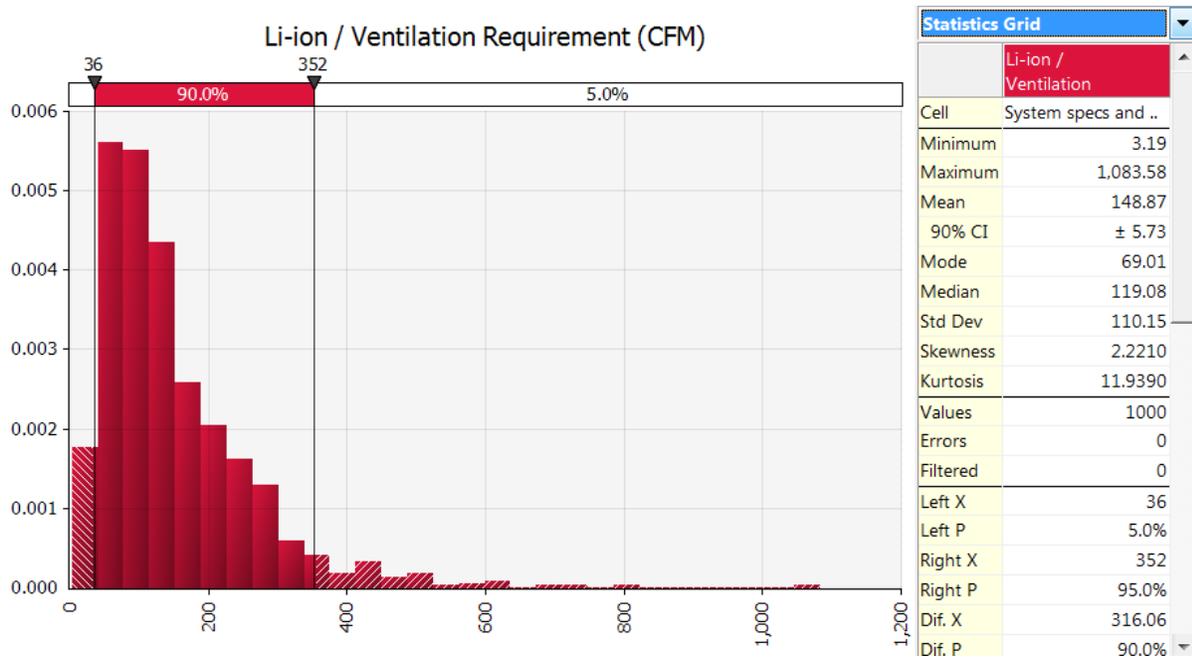


Figure 32 **Example of the air flow requirement for a 1 MWh Li-ion system, demonstrating that the distribution of values is strongly skewed leftward.**

9.4 Inspection and Monitoring

DNV GL's testing revealed that, besides lingering offgases such as CO, lingering (unseen) internal temperatures and residual voltages on unburned cells presented a hazard to first responders.

Similar to the code for uninterruptible power supplies, which recommends hydrogen monitoring and a system health status display (see Table 5), **DNV GL recommends at a minimum that an error status panel, emergency response contact, or other form of error notification be available to first responders, and that the energy storage supply chain engage with first responders to propose a viable solution.** Current codes for UPSs include a display panel for inspection and error notification purposes.

If a system has been in a fire which has been contained by internal fire suppression, such a display panel is enough to alert first responders that the system has sustained damage. They may be able to call in a specialist to handle the hazard and relieve FDNY of their responsibility for the site.

There are technical parameters that have direct impact on the volatility of the system, though it is debatable whether they should be the responsibility of the first responder. Recall that the ultimate objective of the first responder is to protect life, preserve property, and ultimately secure the scene. The intent of system health notifications or an emergency response network is to alleviate the concern of the first responder that he/she will somehow be obligated to own an unknown hazard. The project development community would serve its own interest to support first responders in creating a means to facilitate a hand-off from the first responder to a project owner with good certainty that the hazard is under control.

9.5 Clearances

As referenced in Table 4 and Table 5, the majority of codes identify a 3-5ft clearance on energy devices within enclosed spaces. [4]

In addition, from an economic and technical standpoint, limitation of footprint of energy storage systems directly undermines one of the key value propositions of energy storage, i.e., high density stored electrical energy in a small space where it is most needed. Therefore there is a need to weigh overly prescriptive recommendations against the actual hazard. Recall that in DNV GL's model (also supported by testing) a system could withstand 60 minutes of direct fire at 1000°F with only a metal barrier and an air gap (see Figure 28 on page 42).

The current rule structures (NFPA 855, IBC, and IFC updates may allow for local AHJ exceptions for the spacing and quantity of energy storage systems provided they pass a risk analysis).

With these considerations, DNV GL recommends that all system installations undergo a risk analysis, with particular attention paid to:

- **Cascading protections between cells and modules**
- **Clearances to structures above the energy storage systems**
- **Fire rating of the enclosure**
- **Most probable expected failure mode**

This recommendation is consistent with the IEEE 1547 and ANSI recognition of UL 9540 because of its FMEA process. Because cascading protections have been overlooked in safety incidents (see Literature Review) it is highly important that this consideration be emphasized in the up-front risk analysis. Clearances to nearby structures are presently being recommended on a kWh basis, which may inadvertently limit the effectiveness of energy storage by artificially increasing its footprint and therefore its effective functional power and energy density. The risk analysis should provide a foundation for stakeholder agreement on when the risks are deemed acceptable to exceed these requirements. Similarly, the fire rating of the enclosure, if exceeding specification, may create opportunities to reduce spacing or clearances. And the most probable failure mode is the most important part of the risk analysis; it helps differentiate risks that seem significant but are actually low probability, versus risks that are probable and measurable, and then design with cost effectiveness and practicality.

9.6 Room Capacity Limitations

The holding capacity of an enclosed space is dependent on a number of factors:

- As shown Figure 20 the total quantity of emissions from burning batteries is dependent on the mass available and the nonlinearity of its emissions rate.
- As shown in Figure 20, the battery fire is largely a smoldering event until a 2-3 minute peak.
- It was also mentioned in "Extinguishing" on page 45 that cascading protections between cells have a direct impact on the propagation of the event to the entire system.
- It was also found in this work that peak room temperatures in a fire are directly correlated to the mass of the battery (see Figure 38 on page 76).

Present guidance is suggesting limitations on battery systems as a function of kWh capacity. It should be noted that energy density (kWh/kg) in battery cells is continually increasing as new generations are released. Prescribing a code based on mass (kg), would present the challenge of increasingly higher amounts of energy being deployed under the same mass constraint. The precedent is a limitation of 1000 lbs. (453 kg) of Li-ion batteries in a space without suppression, which at today's typical Li-ion energy density of ~150 Wh/kg, corresponds to about 67.9 kWh. Proposed IFC language will reduce this to 20 kWh for single units with a total limit of 600 kWh in an enclosed space.

As previously stated, DNV GL recommends that a risk analysis be performed on any basis where battery systems larger than 20 kWh and assembled in aggregate shall be installed in an enclosed space, with the intent of answering these questions:

- **Is the system functionally limited by the code rating?**
- **Does the system have design features that prevent cascading failure between cells and modules? (See fire test, UL 1973 test, or IEC 62619 test data.)**
- **Is the baseline and peak ventilation capacity adequate for the potential off gas? (Example, Figure 16)**
- **Is the sprinkler system adequately designed for the potential heat load and battery chemistry? (Example, Figure 29)**

- **Does the protective casing provide adequate insulation and fire blocking? (Example, Figure 28)**

The output of this analysis should determine if the rules are too prescriptive for the case being considered, or alternatively, if the rules have not adequately captured a safety risk.

9.7 Project Development Considerations for Interaction with First Responders and AHJs

DNV GL surveyed several handbooks for fire departments in large cities across the country and found a universal theme in fire fighter training concerning extinguishing. Fire fighters are trained to achieve the following objectives when arriving at the scene:

- **Objective 1:** Remove endangered person(s) and treat the injured.
- **Objective 2:** Stabilize the incident and provide for life safety.
- **Objective 3:** Provide for the safety, accountability, and welfare of personnel (this priority is ongoing throughout the incident).
- **Objective 4:** Protect the environment.
- **Objective 5:** Property conservation.

Note that Objective 5 is often the primary concern of the property owner. It is on the priority list of the first responder, *but safety of life at the scene takes precedence*. The following recommendations for emergency response specific to batteries refer to these objectives. These are based on the UPS battery system precedent that already exists in New York City.

- Battery systems should be described in the Building Information Card (BIC) (see example, Figure 33). This greatly aids in first responders meeting **Objective 2**.
- A building should have an assigned liaison who works with FDNY to update emergency response plans. This liaison may be the same as the certificate of fitness (COF) holder for the battery system, or may be a different individual. This Liaison should be listed in the BIC. **This aids first responders in meeting Objectives 2 and 3, and also protects the property owner's interest relating to Objective 5.**
- Battery systems should have a COF similar to what is required for UPS systems. Again, this aids in **Objectives 2, 3 and 5.**
- The recommendations for monitoring and system health display are consistent for codes for uninterruptible power supplies. The method of system health display and monitoring should be proposed by the system integrator or project owner.

11. BUILDING FIRE SAFETY INFO:	
(Including Emergency Contact numbers)	
Fire Safety Director/EAP Director:	<u>GERALD DUNLEAVY</u>
Work:	(212) 243-5060
Emergency:	(917) 416-6322
E-mail:	gdunleavy@111eighth.com
Building Engineer:	<u>RICHARD LAVINO</u>
Work:	(212) 243-5060
Emergency:	(917) 567-0952
Managing Agent:	<u>TACONIC MANAGEMENT COMPANY, LLC</u>
	<u>CHRIS MACARTHUR</u>
Work:	(212) 243-5060
Emergency:	(914) 462-8503
E-mail:	cmacarthur@111eighth.com

LAST UPDATED 12/3/2012

Figure 33 **The FDNY Building Information Card (actual example) contains emergency contact information for fire safety and building engineers.**

9.8 Considerations for Battery Chemistries that are not Li-ion

Much of the data in this report pertains to Li-ion because the majority of battery cells tested are variants of that chemistry. However, the data contained in this report should concisely demonstrate the following:

- Vanadium redox and Pb acid electrolytes are not flammable.
- Vanadium redox and Pb acid electrolytes do represent a toxicity hazard when heated.
- Polymer cases for any battery are flammable and will contribute to a fire as fuel and a source of toxic emissions.

While not tested explicitly in this study, it is also worth mentioning that under rare circumstances lead acid batteries are also capable of so-called thermal runaway, i.e., an exothermic failure. Because the members of the battery industry have taken great care to differentiate themselves in the area of safety, with nearly all chemistries that are *not* Li-ion using marketing language such as “safe”, “nonflammable”, “thermally stable”, “environmentally benign” or “incapable of thermal runaway”, there is a need to clarify a universal finding in this program: in the case of external fire, all batteries emit toxic gases. It should also be noted that the average emissions rates of equivalent masses of plastics exceed those of batteries. Every battery tested either emitted a gas or left a residue that has a varying degree of hazard (Table 3 on page 29); however, this can be expected from most fires. The general findings of this work conclude that water and ventilation requirements are within the technical limitations of legacy building codes, i.e., there are precedents for managing these hazards.

All of the batteries tested carry with them a risk in their deployment; however, all of the risks identified are manageable within the realm of today’s engineering controls for safety. In addition, the toxicity and flammability risks identified are not insurmountable or highly unique when compared to the challenges of burning hydrocarbons or plastics, and the resulting requirements in codes, if implemented, are within the boundaries of the typical built environment.

DNV GL’s recommendations are the following:

- **If a battery is demonstrated to have a non-flammable electrolyte, there may be considerations for a reduced water extinguisher requirement, or at a**

minimum a water requirement equivalent to that required for the space without battery systems installed.

- **The ventilation requirements should be the same for all battery chemistries tested in this program because they all have varying degrees of HCl or similar toxic emission upon heating.**

Lastly, the emissions rates of equivalent amounts of plastics during a fire, including common every day materials that are found in office environments, commercial and industrial settings, and even residential homes, can exceed the quantity of emissions from a battery fire and will emit HCl as well.

10.0 SUMMARY OF MAIN FINDINGS AND RECOMMENDATIONS

The below directly summarizes key findings and recommendations from this study. These are placed in list form up front in the document for access and readability. The reader is strongly encouraged to use the cross references in the report to learn the reasoning behind the recommendations, or read the FAQ section for clarifications.

- The toxic emissions from fires in this study are not necessarily excessive in content or quantity, and can be managed by today's engineering controls.
- The code requirements for battery systems have the potential to fall within the boundaries of legacy codes, provided that technical and practical engineering considerations are made concerning room volume and battery size.
- DNV GL recommends a minimum 1-hour fire enclosure rating with a 2-hour rating in areas with critical population density.
- For the intent of delaying the escalation of the fire, all systems with individual cells as part of their assembly should either demonstrate that a single cell failure cannot propagate to neighboring cells in a module design or demonstrate that a module design contains adequate external fire protection to contain the heat and flames to that module, which may exceed the acceptance criteria for UL 1973 or the IEC 62619 internal propagation test.
- Because of the rapid evolution of a cell fire, DNV GL does not see an advantage to using a Class D extinguisher on a single cell fire, given the difficulties of access and timing. While technically appropriate, the deep seated nature and window for access present technical challenges; the need for cooling should be prioritized.
- Fixed suppression gas agents may reduce or mitigate flammability in an environment until ventilation and/or cooling strategies are implemented, though their actual cooling capability should be scrutinized in comparison to water.
- DNV GL recommends the following for extinguishing:
 - Stage 1: If a system can limit cell cascading, a gas based suppression system may be considered for the first stage of fire fighting to extinguish a single cell fire and prevent flashover in a contained environment.
 - Stage 2: If temperatures continue to rise or if an increasing level of smoke and gas is detected, water extinguishing accompanied by forced ventilation should be considered to cool the system and prevent further propagation of fire.

- For nearly all chemistries, the ventilation of HCl, CO, and HF govern the ACH requirements, i.e., toxicity considerations dominate the ventilation need rather than flammability.
- The gases emitted are also found in plastics fires in greater time-averaged quantities. This should be considered in the context of prescriptive codes because these hazards are likely to already exist in the built environment.
- DNV GL recommends that the lowest level ventilation rate - if prescribed - be continuous under normal systems operation. The study concludes this may be as low as 0.25 ACH, which is lower than what is required for most occupied spaces.
- Regardless of chemistry, DNV GL recommends sizing for ventilation and extinguisher systems as the following (these may be translated to GPM/ft² and CFM/ft² or ACH starting on page 50).
- DNV GL recommends that minimizing the water requirement be an area of further study as it has likely been overstated in these recommendations for conservativeness.
- DNV GL recommends at a minimum that an error status from an operating energy storage system be readily apparent to first responders for the following parameters, and recommends **that a dialog be opened with system integrators to determine the most effective and economic way to address this need:**
 - Internal atmosphere (normal or gas detected)
 - Temperature (above normal or normal)
 - Current (normal or threshold exceeded)
 - Voltage (normal or threshold exceeded)
- During and after fire extinguishing, it is recommended that if first responders choose to use water submersion to cool and isolate battery modules, that preparation to deal with alkaline or acidic water be considered.
- After extinguishing, continued ventilation and monitoring of the area is highly recommended to protect first responders from continued toxic and flammable gas emissions. The first responder team can monitor the area with handheld sensors to determine the appropriate time to stop ventilation.
- It is highly recommended that an emergency contact list and/or subject matter expert be available for all battery systems installed in buildings in order to introduce the opportunity for first responders to relinquish control of the scene to the system developer or a designate after the site has been secured and extinguishing has been completed. This is likely to require involvement from the project development and systems integration community.
- If a battery is demonstrated to have a non-flammable electrolyte, there may be considerations for a reduced water extinguisher requirement, or at a minimum, a water requirement equivalent to that required for the space without battery systems installed.
- The ventilation requirements—if prescribed—should be the same for all battery chemistries tested in this program because they all emit similar HCl levels.
- In order to meet or exceed UL 9540 requirements, DNV GL recommends that a risk analysis be performed on any basis where a battery system or portfolio of systems

shall be installed in an enclosed space near occupants. The analysis should look at the general safety picture of the project(s) —in aggregate if possible—with a focus on these risks:

- Does the system have design features that prevent cascading failure between cells and modules? (See fire test, UL 1973 test, or IEC 62619 test data.)
- Are ventilation systems at the intended site(s) adequately rated to handle the most probable failure mode? (Example: Table 7)
- Are sprinkler systems at the intended site(s) adequately designed for the potential heat load and battery chemistry? (Example: Figure 29 and Table 7)
- Does the protective casing provide adequate insulation and fire blocking? (Example: Figure 28)

10.1 Conclusions

- Many historic battery incidents are due to external damage factors which have created confusion and overreaction to the topic of battery safety.
- Existing building codes and engineering controls can be adequate in many cases to handle battery safety issues.
- The toxic emissions from fires in this study can be managed by today's engineering controls and are not anomalous or excessive when compared to a plastics fire. Plastics fires can generate similar gases in larger quantities over the average emissions duration on an equivalent mass basis.
- The water requirements from this study can be lessened for building fire extinguisher systems when combined system-level safety approaches are implemented.
- Legacy codes could provide insightful interim requirements for battery systems used in energy management, provided that technical and practical engineering considerations are made.
- Gas-based agents that can reduce flammability in an enclosed environment can put out single battery fires, but should not be considered an adequate cooling measure.
- Water demonstrated the highest cooling efficacy of all extinguishing agents tested. The use of water should only be considered if there is an acceptable risk of shorting additional cells or collateral damage to the remainder of the system.
- Water volumes for cooling can be minimized based on the expected duration of a failure event. Systems with adequate internal cascading protections will minimize the water volumes required for extinguishing.
- Staged extinguishing with fixed aerosol or gas suppression agents first, followed by water in the event of a cooling need, is recommended. It may be possible to use parallel water inputs on fixed suppression systems for containerized battery systems.
- Forced ventilation is recommended for first responders, even after the fire has been extinguished.
- The historical legacy of safety concerns has validity, though understanding of the root causes and failure modes is necessary in order to understand the true threats and failure modes.

Appropriate mitigation of risk shall include a pre-commissioning design review per accepted industry practices that are presently being used in California and other states. Overall DNV GL's findings are that these hazards are manageable for building code officials and first responders. No significant technology barrier exists that prevents code officials or first responders from doing their duty when encountering battery energy storage systems.

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12.0 APPENDIX 1: REFERENCED DATA

12.1 Assumptions for Air Changes per Hour (ACH) Calculations

Statistics for mass loss, duration of failure, and HCl, HCN, HF, and CO emissions are shown in Table 1. This data is taken directly from all of the cell tests. It can be seen from the data that the mass loss ranges from 0-57%, the duration of the event lasts from 13-83 minutes, and the emissions rate (in ppm per kg per min) in the 0.44 m³ chamber ranges from zero to 0.719 for HCl, 0.032 for HF, 0.027 for HCN, and 2.341 for CO. This data demonstrates that CO is emitted in greatest quantity and HCl is emitted in the second greatest quantity, but because HCl has a lower IDLH this threshold is met first in most scenarios.

The following tables demonstrate the calculated ACH as a function of burning battery mass and room size. The tables below are the same data that is visually presented in Figure 16 and related figures. It is clear from the visual representation of the data that these relationships are nonlinear. The estimations limit the failure to 1.5 modules, with the presumption that the system should demonstrate adequate separations, cascading protections, and suppression systems to limit failure to a single cell or at least a single module. The probability of failure for multiple modules should be very low for systems with these active and passive barriers to catastrophic failure. Catastrophic failure scenarios can be examined by risk analysis to determine which barriers are in place to prevent it and the relative strength of those barriers. The risk analysis places practical boundaries on the probability of high consequence events, and should either 1) tame the deployment of extreme safety measures with a low probability of utilization or 2) identify likely failure scenarios that have been overlooked in the context of the site and system.

Table 11 **Air change rates based on HCl emissions as a function of room size and quantity of failing cells.**

		20 ft container	40 ft container	80 ft X 80 ft room
	HCl	33.1	67.6	3624
1 cell	1.54	0.25	0.25	0.25
5 cells	7.70	0.25	0.25	0.25
10 cells	15.40	0.25	0.25	0.25
15 cells	23.10	1.25	0.25	0.25
20 cells	30.80	3.25	0.25	0.25
24 cells	36.96	4.75	0.25	0.25
1 module	44	6.5	0.6	0.25
30 cells	46.20	7	1	0.25
35 cells	53.90	8.5	2	0.25
1.5 modules	66	11.5	3.5	0.25

Table 12 Air change rates based on HCN emissions as a function of room size and quantity of failing cells.

	20 ft container	40 ft container	80 ft X 80 ft room
HCN	33.1	67.6	3624
1 cell	1.54	0.25	0.25
5 cells	7.70	0.25	0.25
10 cells	15.40	0.25	0.25
15 cells	23.10	0.25	0.25
20 cells	30.80	1	0.25
24 cells	36.96	2.25	0.25
1 module	44	4	0.25
30 cells	46.20	4	0.25
35 cells	53.90	5.5	0.25
1.5 modules	66	7.5	0.25

Table 13 Air change rates based on CO emissions as a function of room size and quantity of failing cells.

	20 ft container	40 ft container	80 ft X 80 ft room
CO	33.1	67.6	3624
1 cell	1.54	0.25	0.25
5 cells	7.70	0.25	0.25
10 cells	15.40	0.25	0.25
15 cells	23.10	0.25	0.25
20 cells	30.80	0.25	0.25
24 cells	36.96	0.25	0.25
1 module	46.20	0.25	0.25
30 cells	53.90	0.25	0.25
35 cells	44	0.25	0.25
1.5 modules	66	0.25	0.25

Table 14 Air change rates based on HF emissions as a function of room size and quantity of failing cells.

	20 ft container	40 ft container	80 ft X 80 ft room
HF	33.1	67.6	3624
1 cell	1.54	0.25	0.25
5 cells	7.70	0.25	0.25
10 cells	15.40	0.25	0.25
15 cells	23.10	2.5	0.25
20 cells	30.80	5	0.25
24 cells	36.96	7	0.25
1 module	44	9	0.25
30 cells	46.20	9.5	0.25
35 cells	53.90	11.5	0.25
1.5 modules	66	14.5	0.25

Table 15 shows conversion factors from air changes per hour to CFM and CFM/ft² for the modeled energy storage rooms and enclosures.

Table 15 Conversions from ACH to CFM based on the example room volumes for energy storage systems.

	m ³	ft ³	ft ²	ACH (row) to CFM (column)					CFM/ft ² @ ACH				
				<u>0.25</u>	<u>1</u>	<u>5</u>	<u>10</u>	<u>30</u>	<u>0.25</u>	<u>1</u>	<u>5</u>	<u>10</u>	<u>30</u>
Shipping Container, 20 ft	33	1,168	146	5	19	97	195	584	0.03	0.13	0.67	1.33	4.00
Shipping Container, 40 ft	68	2,407	301	195	781	3,906	7,811	23,434	0.65	2.60	12.98	25.96	77.88
Room, 80x80 ft	3,624	128,290	16,036	417,549	1,670,195	8,350,973	16,701,946	50,105,838	26.04	104.15	520.76	1041.52	3124.55

Notes: Occupied laboratories = 4-12 ACH, emergency ventilation ~ 30 ACH.

In Table 16, useful metrics derived directly from testing are provided. As mentioned previously these values are input into a probabilistic model⁷ to generate the sensitivity analysis demonstrated in Figure 35 and related figures. The min, average, and max values are used to generate triangular probability distributions. The GPM/kg measurement is a direct measure of the water used to extinguish fires across the entire spectrum of cell to module testing. The cell masses, mass loss, emissions range, HRR, and duration are the ranges of values observed from cell testing. The energy density is calculated directly from the cells. The estimated peak cell temperature is directly sourced from the cell data. The fraction of cells simultaneously burning is a factor used to estimate the impact of total emissions rate and account for the observed fact during module testing that cell failures were rarely simultaneous and occurred as discrete events. It should be noted in the table that the water contact efficiency averages 1-2%. This highly conservative number greatly drives the water requirement estimation. Any method by which a battery manufacturer or system integrator can demonstrate that the water contact efficiency is higher will reduce the water requirement overall.

⁷ Palisade @Risk

Table 16 **Aggregation of data regarding battery fires, extinguishing, emissions rates, and extinguishing. Distributions in the column labeled "Dist" are triangular; the mean is shown.**

Probabilistic Inputs					
Parameter	min	avg	max	Dist	Notes
Cell Mass kg	0.5	1.6	6.5	2.867	From cell test data
Peak Cell Temperature (°C)	350	525	700	525	From cell test data
Duration (min)	2	47	83	43.882	From cell test data
Water Contact Efficiency	0.001	0.01	0.04	0.017	Estimated
Energy Density (Wh/kg)	30	120	150	100	Pb Acid to Li-ion
Probabilistic Outputs					
Delta T to Cool Battery to 25 C	325	500	675	500	Calculated from Above
Energy to cool battery (kJ)	227.50	1120.00	6142.50	2006.67	mcdT
Required Water Mass including heat of vaporization (kg)	0.09	0.44	2.39	0.78	Q battery = Q water, m_water = Q battery / (energy to heat water to 100 C + dHv)
Required Water Volume (gal)	0.02	0.12	0.65	0.21	divide by 3.7 kg/gal
GPM	0.012	0.003	0.008	0.005	divide gal by duration
GPM/kg	0.024	0.002	0.001	0.002	divide GPM by battery mass
GPM/kg with water contact efficiency	23.916	0.158	0.030	0.099	Divide by water contact efficiency
Additional Probabilistic Parameters					
Testing GPM/kg	0.105	0.881447	1.65789474	0.881	From cell, module, and system test data
Emissions range kg/min per cell	0.0002	0.0077	0.0152	0.0077	From cell test data
HRR kW/kg (of mass lost)	17	31	45	31	From cell test data
Fraction of cells simultaneously burning	0.12	0.16	0.2	0.16	From module testing, 1-3 out of 8-15

12.2 Water Mass Requirement Calculation

There are two ways to calculate the water mass requirement. One method is to calculate the rate of energy released, which assumes that the extinguishing event is perfectly timed with the peak energy release of the cell. The other method is to size the water requirement to the battery mass, acknowledging that the cell failure event is not a single peak event, but is instead characterized by long periods of smoldering (40-90% of the total event duration) and a 2-3 minute peak event (accounting for 1-15% of the event duration).

The latter method was observed to be effective during testing as the water use in DNV GL and Rescue Methods' testing became progressively smaller (on a GPM/kg basis) as the timing of the extinguishing event became decoupled with the peak HRR. In other words,

extinguishing the module or large pack was an exercise of removing distributed heat and preventing perpetuating failure modes.

12.2.1 Sizing the Water Requirement to Peak HRR

Sizing the water requirement to the peak HRR involves the calculation of the amount of energy required to raise the temperature of 1 kg of battery⁸ by 500 degrees Celsius. Using the average HRR in Table 16, 1 kg of battery emits 31 KJ/second. This would be the heat release rate \dot{Q} and the formula used to calculate the mass flow rate of water is $\dot{Q} = \dot{m}c_p\Delta T$. This results in a flow rate of **1.7 GPM per kg of battery. This is an oversized water requirement, as shown below.**

12.2.2 Alternative Strategy for Sizing the Water Requirement: Preventing the Peak HRR Altogether

There are minutes of opportunity to simply cool the cell and avoid the peak event altogether. Recall from Figure 20 that a Li-ion battery smolders for minutes before eventually failing. Also recall from Figure 28 that the metal enclosure around a battery system can provide a window as long as 60 minutes to respond to a fire. Thermal runaway risk builds, but can be arrested by cooling and preventing the battery from reaching temperatures near 120°C. A strategy in the marine sector is exactly this: cool the battery and prevent thermal runaway temperatures from ever being reached, resulting in very benign cell failure even during aggressive overcharge. [33]

Therefore the extinguishing strategy should be arrest the climbing temperatures before they reach the transition temperature at 120°C. This more practical approach takes into account that automatic fixed suppression systems typically lack the intelligence to sense and trigger according to specific gas species or gas emission rates; i.e., they are discharged upon detection of smoke via a sensor that is generally sensitive to multiple particulate and hydrocarbon species. As a result, fixed suppression will trigger very early in the cell failure process. *This would be the case for all battery types tested*, as smoldering and gaseous emissions from the plastics used for containment began as early as 60°C. Just the fumes from the plastics may be enough to trigger a smoke alarm.

If the module has adequate cascading protections and a 1-hour fire rating, there is an opportunity to contain the cell failure and avoid the issue of oversizing the water requirement to the peak and instead size the water requirement to the battery mass.

As a result the water calculation is simplified by sizing the water flow to the battery mass rather than the HRR at thermal runaway. This strategy is only valid if the cascading protections are demonstrated to contain single cell failures and prevent cascading from cell to cell and module to module, and the fire rating of the system provides adequate time to address an external fire.

Following this method, the energy to be removed from the system is:

$$Q = mc\Delta T$$

⁸ Simulated as phenolic due to its specific heat which is near the average of the battery composition by material

And thus the thermal equilibrium requirement is:

$$Q_{water} = Q_{cell}$$

For a 1 kg battery cell with an estimated composite specific heat similar to phenolic (1.4 kJ/kg°C), and a temperature change of 525°C – 25°C = 500°C, the energy of heat transferred is 700 kJ. This calculation neglects the additional removal of heat by water from the heat of vaporization, which is addressed below.

The specific heat of water is 4.1 kJ/kg°C. The objective is to use the minimum amount of water before water flashes into steam. If we target a volume of room temperature water necessary to prevent the water from flashing off into steam, we assume $\Delta T = 70^\circ\text{C}$ (70+25 = 95°C, or just under the boiling point). This translates to

$$m_{water} = 700 \text{ kJ} / (4.1 \text{ kJ/kg}^\circ\text{C} * 70^\circ\text{C}) = 2.43 \text{ kg}$$

This states that 2.43 kg of water is required to cool a 1 kg battery from 500°C to 25°C, and the water will have risen in temperature to 95°C. This calculation should be very conservative, as it neglects the vaporization of water into steam and assumes the entire mass of the battery is contributing to the heat.

The density of water is 3.7 kg/gal, and therefore the theoretical conservative minimum volume of water required is **0.65 gal**. However recall that this reaction occurs over 1-3 minutes during the peak, and up to 40 minutes over a slow duration, and therefore the **gallons per minute required is 0.02-0.6 GPM/kg with the latter being conservatively sized to still address the peak**. The major factors driving the GPM/kg requirement are the battery mass and the duration of the event.

The water requirements need not be excessive if the battery system employs simple, industry proven safety measures such as an external fire rating and cascading protections between cells and modules. Most of the batteries tested had masses from 0.5-1.5 kg, with one battery being particularly large at 6 kg, which skews the average to 2.8 kg and therefore makes this calculation more conservative. The values in the table are probabilistic and the resulting distribution of water flows is shown in Figure 31. The skewness of the distribution demonstrates that **the theoretical minimum water requirement mean is actually 0.019 GPM/kg**, or very near the minimum.

12.2.3 Additional Consideration: Heat of Vaporization

When the heat of vaporization of water is included, the water volume requirement is further reduced. The latent heat of vaporization is the energy required to accomplish the phase change from liquid to gas. This property is given in kJ/kg and there is no change of temperature to make the transition at 100° C at atmospheric pressure. This factor is important because the latent heat of vaporization is larger than the energy required to heat water from 25 to 100° C.

The required energy to heat water from 25° C and then vaporize to steam at 100°C is:

$$E = mC\Delta T + m\Delta H_v$$

The specific heat of water C is 4.187 kJ/kgC and the latent heat of vaporization ΔH_v is 2257kJ/kg. Using these numbers, the energy required to heat and boil one kilogram of water from 25° C is:

$$E = 1kg * 4.187 * (100 - 25) + 1 * 2257$$

$$314kJ + 2,257kJ = 2,571kJ$$

It can be seen from the calculation that the latent heat of vaporization is 7x greater than the energy required to heat from 25-100° C. This is important for cooling considerations because the heat energy of the fire is transferred from the fire to the heating and boiling of water; water withdraws energy from the fire, reducing its destructive power and energy. Every kilogram of room temperature water that that is heated and flashed into steam draws 2,571 kJ from the fire.

Energy is most efficiently drawn from the fire when water contact is as complete as possible. The method of delivery for the water will affect this contact efficiency such as mist, spray, and jet. Access to the deepest seated batteries will govern the water contact efficiency as well. When more water is in contact with the hot surfaces of the battery, the rate of the water-to-steam conversion process increases, which saps energy from the fire and reduces overall temperature as a result.

Expanding on the prior section, if the following assumptions are reconsidered with the inclusion of latent heat of vaporization, the calculation follows:

$$mc\Delta T + m\Delta H_v = Q_{cell}$$

Where $Q_{cell} = 700$ kJ. Therefore for 1 kg of battery cell:

$$m_{H_2O} = Q_{cell} / (c\Delta T + \Delta H_v) = 700 \text{ kJ} / (4.1 \text{ kJ/kg } ^\circ\text{C} * 75 ^\circ\text{C} + 2257 \text{ kJ/kg})$$
$$= 700 \text{ kJ} / (307.5 \text{ kJ/kg} + 2257 \text{ kJ/kg}) = \mathbf{0.27 \text{ kg}}$$

Using the conversion factor 3.7 kg/gal, the resulting water volume is 0.07 gal. Again assuming 1-3 minutes of battery burn duration, and up to 40 minutes for a slow duration failure, the water requirement is 0.07 gal over 1-40 minutes or **0.001-0.07 GPM per kilogram of battery. Note that this requirement is nearly 10x less than the thermal mass balance calculation in the previous section.** The latent heat of vaporization is therefore a significant contributor to the cooling of the battery fire.

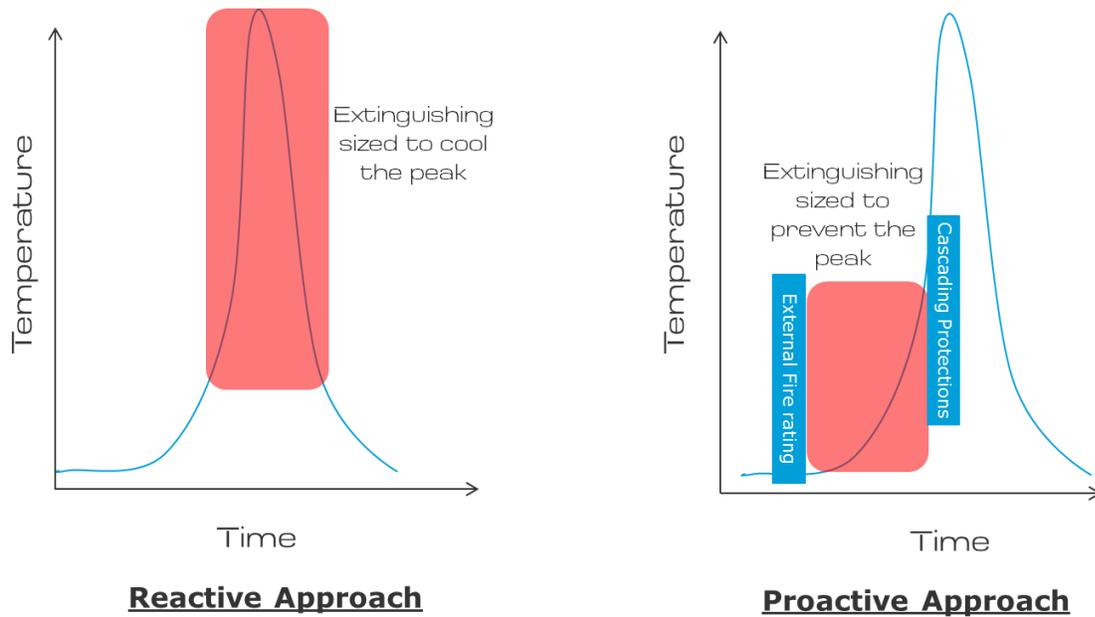


Figure 34 **A reactive cooling approach requires an oversized water flow requirement; whereas a system-level proactive approach enables a reduced water requirement.**

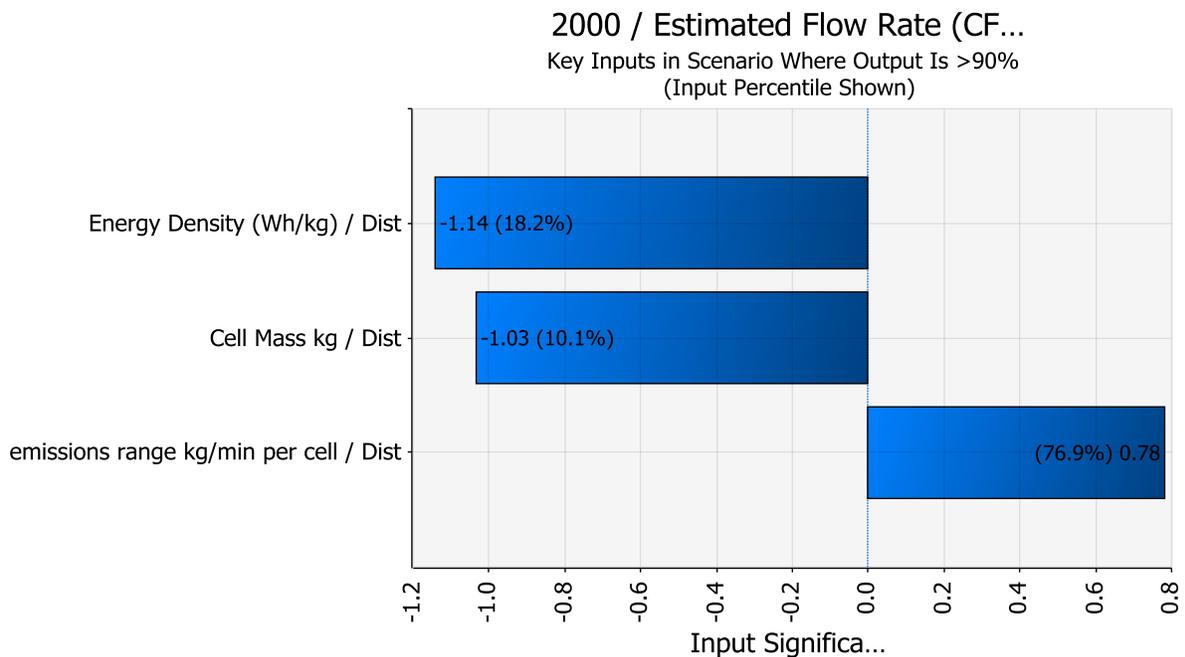


Figure 35 **Regression coefficients of the ventilation requirement.**

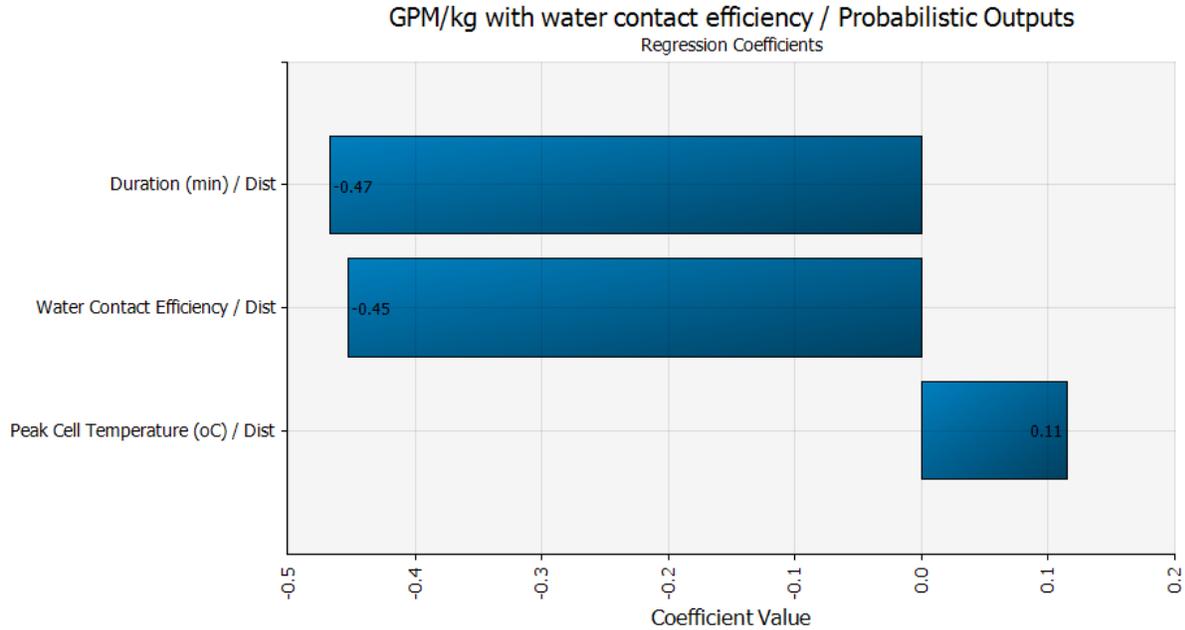


Figure 36 **Regression coefficients for the water flow rate in GPM/kg demonstrate that the duration of the event and the water contact efficiency are the strongest drivers in reducing the water requirement.**

12.2.4 Summary of Water Extinguishing Calculations

It can be seen in Table 17 that sizing the water requirement to the peak HRR leads to a 4-170x oversizing of the water extinguishing system, when proactive and integrated safety approaches are more efficient and reduce the water requirement.

The water contact efficiency of the extinguishing method is highly relevant to the overall cooling effectiveness. The calculations demonstrate physically possible water flow rates, however the testing is the most telling. As testing progressed, DNV GL was able to reduce the water requirement from 1.7 GPM/kg at the module level to 0.1 GPM/kg. Conservative factors accounting for water contact efficiency have resulted in DNV GL's recommendations in Table 9.

Table 17 Summary of methodologies and results of the water requirement calculation.

<u>Method</u>	<u>Water Requirement (GPM/kg)</u>	<u>Cross Reference</u>
Module Testing	0.1 – 1.7	Figure 12 on page 17
Calculated by Peak HRR	1.7	Page 69
Calculated Minimum Static Thermal Mass Balance	0.015	Page 51, Table 7
Calculated Time-Dependent Thermal Mass Balance	0.02 - 0.6	Page 69
Calculated by Thermal Mass Balance and the Latent Heat of Vaporization of Water	0.001 – 0.07	Page 70

Based on the testing results and the calculations, 0.07 GPM/kg (including latent heat of vaporization) and 0.1 GPM/kg (observed in testing a multi-module configuration) brackets a significant range in heating and cell failure rate scenarios. A value of 0.1 GPM/kg appears to be a highly conservative extinguishing rate as it does not account for the added benefit of latent heat of vaporization and it provides a substantial compensation for water contact efficiency.

12.3 Why Bowtie Models?

Cell level safety and system level safety are two different things. Assessing the risk of external abuse factors can be accomplished with a risk analysis at the site. This technique permits the visualization of all possible threats that may cause a top event, such as battery failure, to occur. Putting barriers in place to prevent such events may increase safety of the system overall. The diagram illustrates a generic battery failure model, illustrating that a number of threats (left side of the diagram) can be prevented from leading to the top event – which is loss of battery control – with barriers in place such as active monitoring and proactive controls.

An example shown is mechanical damage by the red arrows progressing from the left of the diagram to the right. In this example, there may be monitoring methods in place that did not react quickly enough to identify and prevent consequences of mechanical damage, and other barriers (such as physical barriers) may have failed. If these barriers are breached and the top event occurs, then a possible consequence is thermal runaway. There may also be reactive controls such as fire alarms, automatic module disconnects, or emergency cooling systems to draw heat from the battery before the thermal runaway threshold is reached. Either side of the Bowtie model may be expanded into multiple threat or consequence layers, depending on the detail of the model.

The Bowtie model is the highest level analysis that can be done and may be performed in tandem with or in lieu of a failure mode effects and criticality analysis (FMECA). The FMECA process involves a listing of all possible failure modes and a relative ranking of the probability of their occurrence. The Bowtie model adds a visual representation of the incident paths, the consequence of their occurrence, the barriers that are in place to prevent

the occurrence, and the escalation factors that can either defeat barriers or increase the probability of the event occurring. Escalation factors are typically included on the left hand side of a Bowtie model and demonstrate how outside factors increase the likelihood of a barrier failure. Barrier defeating mechanisms can occur on either side of the top event in the figure, but are more commonly included in the right hand side. The list of possible failure modes in the FMECA analysis is a rank order list of all possible incident pathways diagrammed in the Bowtie model. Thus the Bowtie model is descriptive and qualitative in nature, while the FMECA analysis is more quantitative. The Bowtie output can easily be converted to a FMEA output and vice versa. Together, the Bowtie and the FMECA listing can be used to address risks and outline recommendations for improvement in safety systems.

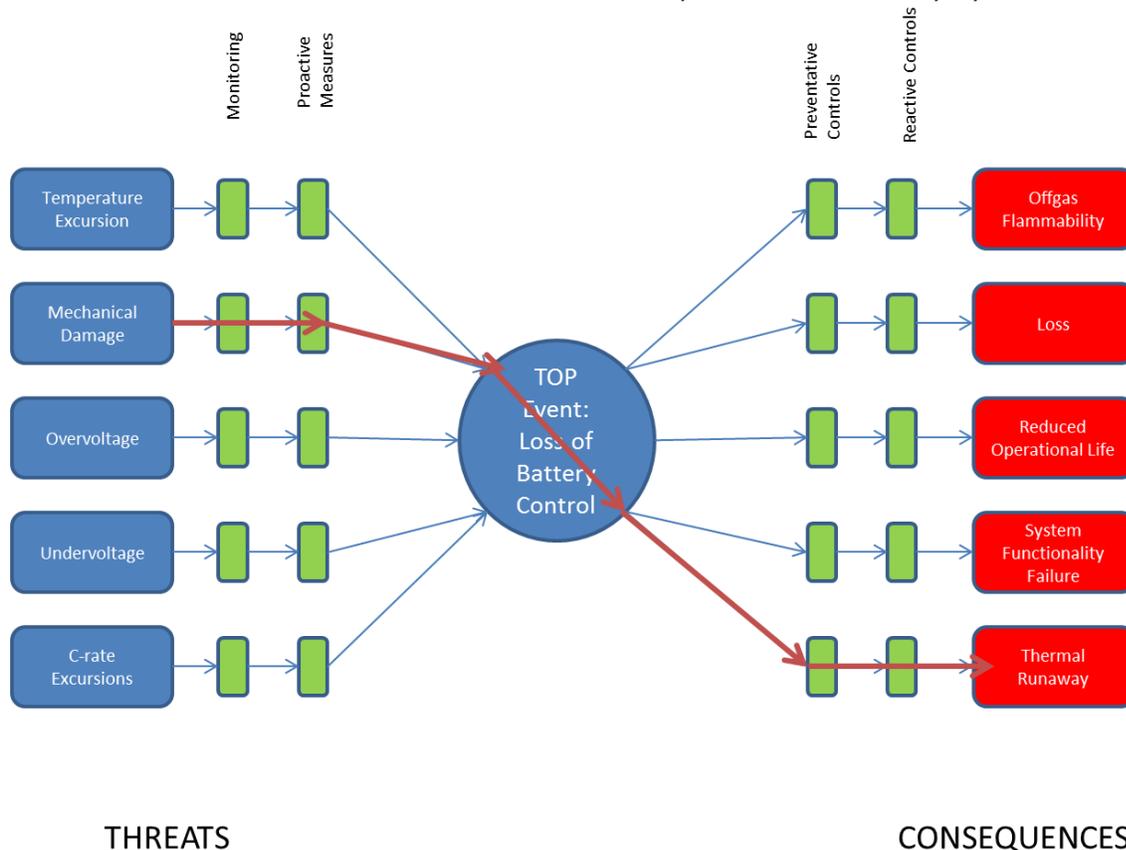


Figure 37 **BowTie analysis permits the visualization of threats to a top event, such as loss of battery control, and ties these threats to consequences.**

12.4 Heat Load from Li-ion Battery Failures

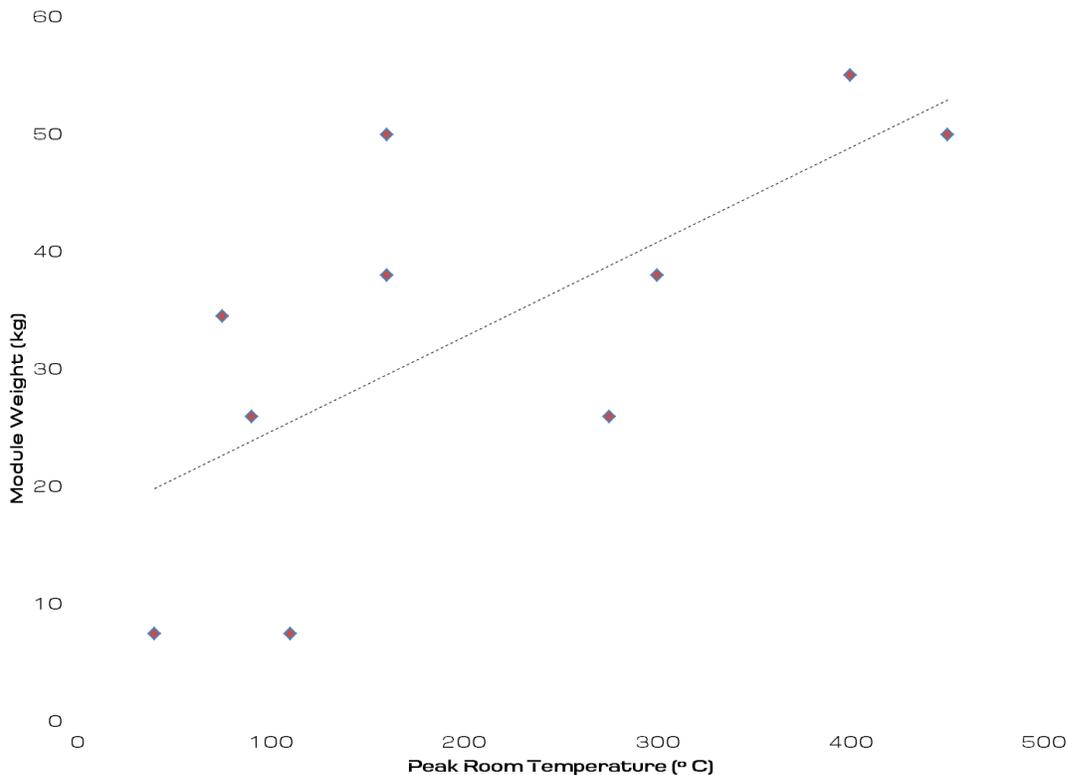


Figure 38 **Battery weight and the peak room temperature are positively correlated.**

13.0 APPENDIX 3: TESTING PLAN AND APPROACH

The total project scope for the Consolidated Edison-New York State Energy Research and Development Authority (NYSERDA) BESS program is shown below. It includes four project tasks with a final report, which also includes the development of guidelines and training materials.

Literature Review

A literature review concisely summarizing the findings from previous safety testing conducted on the specific battery chemistry families tested in this scope of work. Additionally, a review of sodium sulfur and nickel sodium chloride batteries, not being tested in this scope of work, was completed.

Chemistries Participating in the Program

1. NCM (4 vendors)
2. LiFePO₄ (2 vendors)
3. LTO
4. Lead Acid
5. Vanadium Redox
6. An additional Li-ion chemistry described as BM-LMP

Small Scale Testing Parameters Measured

1. Heat release rate
2. Species and rate of release of gasses liberated during a burn and as a result of application of suppression agents
3. Species and volume of liquids or solids released during a burn and as a result of application of suppression agents
4. Perform limited suppression agent testing of a small number of suppressants: Water, F-500, FireIce®, and PyroCool®. Testing of suppression release rates for water, or if water is deemed ineffective or unsafe the next best candidate suppressant identified, will also be performed.
5. Observe for presence of electrical arcing or mini-explosions and post burn re-ignition

Computer Modeling

Computer modeling was used to extrapolate small scale burn test results to larger scale fire scenarios involving battery racks. A model at the system scale (rack level) was constructed for each of the chemistries tested. Model predictions were validated through comparison with burn testing of small units.

Final Report

The final report (this document) includes the following for each family of chemistries: findings from the literature review, results from the small scale cell level tests, results of the system size modeling, an assessment of risk at the system scale, effectiveness of extinguishers and techniques, and any other code relevant findings that emerge. First responder training materials and guidelines are also a deliverable from this report. The testing program is designed to address two hazards: 1) toxic or flammable off gases as well as solids and liquids released during the burn and during fire suppression, and 2) heat load and release rate. The testing program is designed to determine what toxic and flammable gases are present as a function of chemistry and when they are released during the fire. The heat release data provides scalable data as a function of chemistry to determine passive fire protection requirements (as part of container or room design), as well as the quantity and duration of release for fire extinguishers.

13.1 Design of Experiments

Extinguisher tests were performed on cells that demonstrated the best burn properties for testing. All module tests were also subject to extinguishing. Vanadium redox and lead acid electrolyte tests were performed in an autoclave (without direct fire) to examine the volatility of the electrolyte in high heat conditions. There were seven donated battery chemistries to the program as well as two volunteer participants.

13.2 Combustion Gas and Particulate Matter Analysis

Of chief concern to the fire services and first responders are CO, O₂, H₂S and LEL/combustible values. There are additional risks of fluoridated compounds (F₂ and HF), SO₂, VOCs and H₂. DNV GL monitored these during the tests using an FTIR gas analyzer from Gaset (Figure 39) as well as gas chromatography bags for post-test analysis. Additionally, coupon sampling was performed to measure ash, soot and particulate matter emitted and deposited during the fire, in addition to analysis of the battery debris. These coupons and debris measurements will inform hazmat risks during overhaul and after fire ground operations.

13.3 Heat Release Rate

ASTM⁹ tests were modified and combined to measure the heat release rate of the batteries. Heat release rates as a function of time and fire stage were calculated using a thermopile built around the battery as well as thermocouples around the chamber including at inlet and outlet. DNV GL was able to quantify *heat release rate* (kJ/s or kW or BTU/min) and *fire load per mass of battery* (BTU/lb. or kWh/kg). As standardized sizes and footprints do not yet exist, these parameters provide better insight into the fire hazard than the typical ASTM approach per unit area (per ft² or per m²).

The power and energy of the fire per unit mass of battery provided data to estimate the required extinguisher flow rates or mass. The heat removal potential of the extinguisher was estimated by calculation prior to the extinguisher test by matching the battery mass to the required extinguisher mass ($mc\Delta T$) with an added safety margin.

13.4 Procedure

The setup for all tests is depicted in the figure below. Additionally, all batteries underwent multiple tests and state of charge (SOC) was varied to account for differences in energy levels¹⁰. Battery voltages were measured during and after each test to determine their potential for re-ignition, if any.

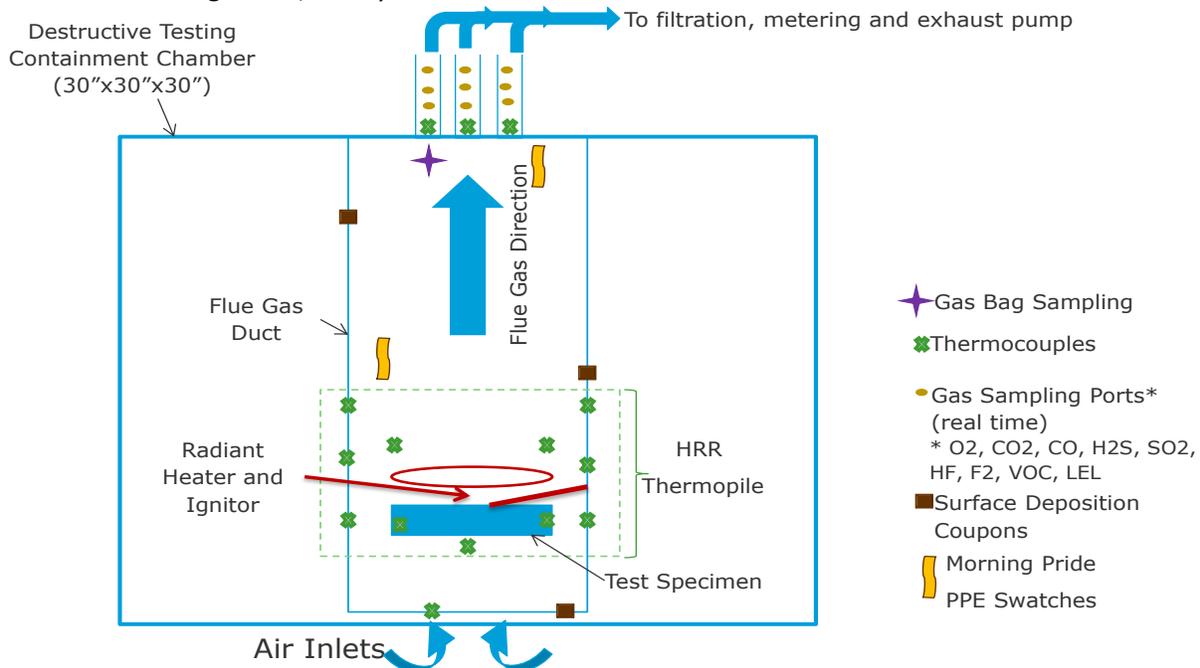


Figure 39 Large abuse test chamber design for battery fire and extinguishing testing.

⁹ ASTM 906: Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using a Thermopile Method, ASTM 1354: Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter, and ASTM E1623: Standard Test Method for Determination of Fire and Thermal Parameters of Materials, Products, and Systems Using an Intermediate Scale Calorimeter (ICAL)

¹⁰ Current plan is for testing at 50% and 100% SOC

13.4.1 Testing Procedure: Lithium Battery Gas Sampling, No Extinguishing¹¹

Heating was accomplished with a radiative electrical heating element and hot point ignitor to heat the lithium batteries to the point of sublimation or off gassing and ignite any flammable gases produced or released. Testing was recorded with regular image and thermal video.

- Step 1: Put battery in chamber, verify function of all sensors. Begin filming.
- Step 2: Compile gas sensor baselines, capture ambient **gas bag** for baseline
- Step 3: Initiate radiative heating element. Monitor temperature battery.
- Step 4: **Gas bag** sample. Monitor temperature and gas sensors. Heat rise may last 10 minutes to one or more hours. Monitor for flammables such as hydrogen and VOCs.
- Step 5: Record increasing heat with thermocouple measurements. **Gas bag sample** as appropriate
- Step 6: Monitor for peaking heat. **Gas bag sample** as appropriate. Monitor gas sensor and thermocouples. This may occur in durations < 5 minutes.
- Step 7: Monitor decaying heat. **Gas bag sample** as appropriate. Monitor and record gas sensor and thermocouple data.
- Step 8: Monitor decaying heat until temperatures reach safe levels. May take hours or overnight.
- Step 9: Once battery remains are deemed safe, collect surface swabs, coupons, PPE swabs, and secure battery in flame resistant enclosure for posttest observation.
- Step 10: Battery remains will be secured and monitored (video and temperature) for 24 hours. If re-ignition does not occur, batteries will be observed and intentionally re-ignited the following day to observe remaining fire load.¹²

13.4.2 Testing Procedure: Lithium Battery Gas Sampling With Extinguishing¹³

With basic off gas testing complete, a range of extinguishing agents as well as water were tested for effectiveness and reaction. Heat release rates were used to estimate required extinguisher flow rates and volumes. Battery remains were stored in flame resistant enclosures for 24 hours and monitored with video and thermocouples for re-ignition. Testing was video recorded with regular image and thermal video.

- Step 1: Put battery in chamber, verify function of all sensors. Begin filming.
- Step 2: Compile gas sensor baselines, capture ambient **gas bag** for baseline
- Step 3: Initiate radiative heating element. Monitor temperature battery.
- Step 4: **Gas bag** sample. Monitor temperature and gas sensors. Heat rise may last 10 minutes to one or more hours. Monitor for flammables such as hydrogen and VOCs.
- Step 5: Record increasing heat with thermocouple measurements. **Gas bag sample** as appropriate

¹¹ Items in bold are actions to be determined as a function of testing progress – requires attentive monitoring by technician.

¹² No such events were observed.

¹³ Items in bold are actions to be determined as a function of testing progress – requires attentive monitoring by technician.

- Step 6: *Execute extinguisher based on recommended extinguisher use¹⁴. Monitor and record temperature and gas sensors. **Gas bag sample** immediately after.*
- Step 7: Monitor decaying heat. **Gas bag sample** as appropriate. Monitor and record gas sensor and thermocouple data.
- Step 8: Monitor decaying heat until temperatures reach safe levels. May take hours or overnight.
- Step 9: Once battery remains are deemed safe, collect surface swabs, coupons, PPE swabs, and secure battery in flame proof enclosure.
- Step 10: Battery remains will be secured and monitored (video and temperature) for 24 hours. If re-ignition does not occur, batteries will be observed and intentionally re-ignited the following day to observe remaining fire load. Battery will be allowed to burn out on its own to ensure complete destruction and remove change of re-ignition.

13.4.3 Testing Procedure: Flow and Lead Acid Battery Electrolyte (liquid)

A sealed autoclave with heater was used to contain the test. A sample of either liquid (vanadium redox) or acid soaked glass mat (Pb AGM) was placed in a smaller container within the autoclave. The autoclave was heated and off gases measured.

- Step 1: Put electrolyte (liquid or wet glass mat) in autoclave, verify function of all sensors. Electrolyte for each test will be taken from batteries charged to different SOC's to maintain SOC variance in testing.
- Step 2: Compile gas sensor baselines, capture ambient **gas bag** for baseline before heating
- Step 3: Initiate radiative heating element. Monitor liquid and ambient temperature.
- Step 4: **Collect gas bag sample**. Monitor temperature and gas sensors. If electrolyte is not expected to heat exothermically, monitor that heat rise is consistent with controller setting. Monitor for flammables such as hydrogen, VOCs, and sulfuric gases (SO₂ and H₂S).
- Step 5: Record increasing heat with thermocouple measurements. **Gas bag sample** as appropriate
- Step 6: Continue heating to predetermined temperature¹⁵. **Collect gas bag sample** as appropriate. Monitor gas sensor and thermocouples. This may occur in durations < 5 minutes.
- **Option Step 7A:** *Attempt spark ignition. If fluid vapor is known to be inert, this step shall be skipped.*
- **Option Step 7B:** *Execute extinguisher. Monitor and record temperature and gas sensors. **Gas bag sample** immediately after.*
- Step 8: Monitor decaying heat. Gas bag sample as appropriate. Monitor and record gas sensor and thermocouple data.

¹⁴ Different extinguishers, including automated extinguishers, have different guidelines for use and deployment. Execution of extinguisher will be based on FDNY recommendations and use cases.

¹⁵ Peak temperature for flow batteries may vary. Temperature may be based on common class A/B/C/D fire temperatures to determine fluid behavior during boiling or combustion. Max testing temperature may specified by NYSERDA or Con Ed.

- Step 9: Monitor decaying heat until temperatures reach safe levels. May take hours or overnight.

13.4.4 Testing Procedure: Lead Acid Battery Lead (solid)¹⁶

As multiple risks exist with burning lead and lead oxides, a different approach was taken to test the lead acid batteries. This test involved burning a small amount of lead in a simple, class "A" fire¹⁷ to determine the amount of lead vaporized and deposited on the surrounding surfaces. This testing took place in a tightly contained enclosure to minimize lead contamination. As class "A" fires are not uncommon to the fire service, the focus was to quantify the risk posed by lead and lead oxides.

- Step 1: Place small, known quantity of lead plate and lead oxide in class A material. Material will be taken from batteries charged to different SOC's to maintain SOC variance in testing.
- Step 2: Place coupons and ensure swab areas are clean, ensure container sealed except for air inlets
- Step 3: Ignite class "A" materials
- Step 4: **Collect gas bag sample**, monitor temperature. Allow fire to burn out on its own.
- Step 5: Let container sit, allowing lead vapor to settle
- Step 6: Open container with appropriate PPE, collect sample coupons, all solid waste, and surface swabs.
- Step 7: Reseal container for disposal or re-use.

¹⁶ No HRR will be performed on the lead acid or flow components as the energy storage portions of these technologies are non flammable, only the balance of system will add to the fire load.

¹⁷ Likely PTFE or PET plastic or basic construction materials (wood).

Table 18 **Battery burn tests without extinguishing, combustible batteries only**¹⁸

Stage of Fire	Gases Analyzed	Information Gained From Gas Analysis	Information from Coupons and PPE samples	Information from Heat Release Rate	Testing Standards used
Before fire	(Background)	Background gases, baseline measurement. Coupon and turnout gear prior to damage.	Turnout gear "as is" condition. Bare coupons before contamination		
Incipient/ Ignition	Sensors: CO, CO ₂ , O ₂ , H ₂ S, HF, F ₂ , SO ₂ , VOCs, H ₂ , LEL Gas Chromatography Bags, post test analysis: VOCs, fluoride compounds, CO, CO ₂ , heavy metals ¹⁹	Toxic or flammable gases during fire incipient stage.		Early stage heat release rate, potential combustibility of radiantly heated batteries	Modified ASTM 906 (thermopile); modified ASTM 1354 (O ₂ consumption calorimetry) ; modified ASTM 1623 (intermediate scale calorimetry)
Rising heat	Same	Evolution of gases as fire climaxes		Accelerating heat release rate, O ₂ consumption, CO production ²⁰ , thermopile temperatures	Same
Heat Climax	Same	Gas composition during fire climax		Peak heat loads, O ₂ consumption	Same
Decaying fire	Same	Gas composition as fire evolves and decays		Heat decay rate	Same
Fully decayed fire	Same	Background gases after fire has decayed completely		Determination of potential for re-ignition	Same
Debris	(Background)	Residues and HAZMAT conditions.	Residues and HAZMAT considerations, degradation to PPE	Turnout gear after exposure. Coupons for SEM/EDAX/XRD. Ion chromatography may be performed with swabs from turnout gear.	

¹⁸ See below test procedures for flow battery electrolytes

¹⁹ If contained within battery, based on MSDS

²⁰ Compliments gas analysis

Table 19 **Battery burn or heat²¹ tests with extinguishing**

Stage of Fire	Gases Analyzed	Information Gained From Gas Analysis	Coupons and PPE samples	Heat Release Rate	Testing Standards Used
Before fire	(Background)	Background gases, baseline measurement. Coupon and turnout gear prior to damage.	Turnout gear "as is" condition. Bare coupons before contamination		
Incipient	Sensors: CO, CO ₂ , O ₂ , H ₂ S, HF, F ₂ , SO ₂ , VOCs, H ₂ , LEL Gas Chromatography Bags, post test analysis: VOCs, fluoride compounds, CO, CO ₂	Toxic or flammable gases during fire incipient stage.		Early stage heat release rate, potential combustibility of radiantly heated batteries	Modified ASTM 906 (thermopile); modified ASTM 1354 (O ₂ consumption calorimetry) ; modified ASTM 1623 (intermediate scale calorimetry)
Rising heat	Same	Evolution of gases as fire climaxes		Accelerating heat release rate, O ₂ consumption, CO production ²²	Same
Heat Climax	Same	Gas composition during fire climax		Peak heat loads, O ₂ consumption	Same
Extinguisher Deployment	Same²³	Changes in gas composition as a result of extinguishing	Changes in residues as a result of extinguishing, HAZMAT impact	Heat removal rate²⁴ achieved with extinguisher	Same
Decaying fire	Same	Gas composition as fire evolves and decays. Changes in gas composition as a result of extinguishing		Heat decay rate, ability to sustain cooling with extinguisher	Same
Fully decayed fire	Same	Background gases after fire has decayed completely. Changes in gas composition as a result of extinguishing.		Accelerated cool down rate with extinguisher	
Debris	(Background)	Residual fumes. Changes in gas composition as a result of extinguishing.	Residues and HAZMAT considerations. Changes in residues as a result of	Turnout gear after exposure. Coupons for SEM/EDAX/XRD.	

²¹ Flow battery electrolytes may be heated to achieve the simulation of external heating due to a fire. Some flow battery electrolytes are not expected to be exothermic.

²² Complements gas analysis

²³ To be compared against benchmark "without extinguishing"

²⁴ Evaluation of heat management as a result of extinguishing will inform firefighter extinguisher guidelines

			extinguishing, HAZMAT impact, degradation to PPE	Ion chromatography may be performed with swabs from turnout gear. Change in residues as a result of extinguishing. Liquid samples for IC will determine if extinguisher liquid residues are toxic.	
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13.5 Large Scale Burns

Upon completion and evaluation of the small scale burn tests, and following or in parallel to the modeling of the data from those tests, large scale tests, at the module or pack level or bigger, were conducted to verify modeling results and determine unforeseen risks posed by larger systems. This phase of testing was performed in conjunction with Rescue Methods (RM) and involved the complete ignition of a full system or subsystem of an energy storage unit comprised of cells of the previously tested chemistries. These tests took place in a designated burn trailer used for the development of guidelines and training material for first responders as well as testing the effectiveness of extinguishing agents on a larger scale. Test units were secured overnight for observation of re-ignition and then intentionally re-ignited 24 hours later to determine remaining fire load as well as to ensure complete destruction for safe disposal. Samples of the remaining battery, as well as residual run-off from the extinguisher and coupon samples from within the burn area were collected after each test. Thermal and regular video was taken.



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