



JENSEN HUGHES

Prevention System For Li-Ion Based Battery Energy Storage System

Energy Storage Safety & Reliability Forum 2022

JENS CONZEN | MAY 2022

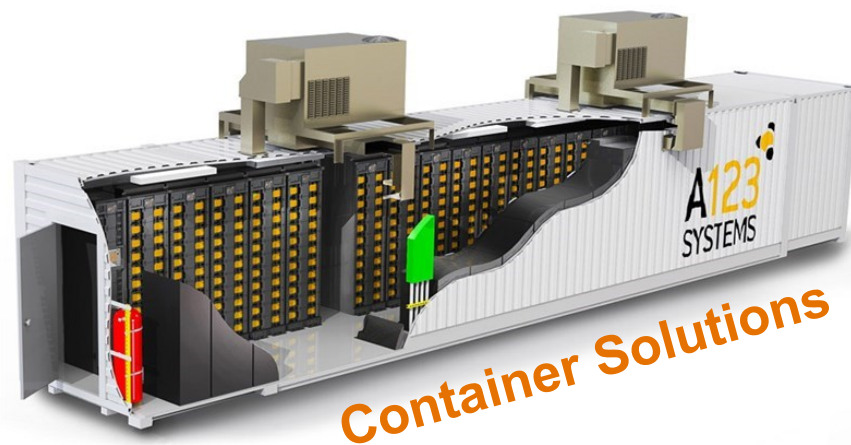
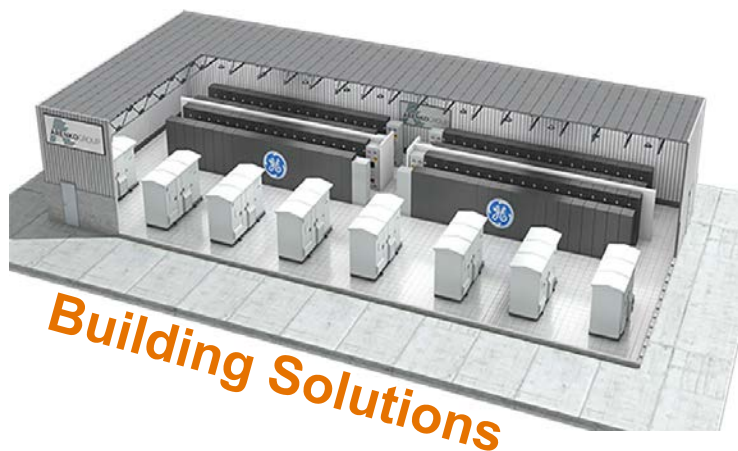
Getting Started

Agenda

- + Introduction
- + Typical BESS applications
- + Hazard evaluation
 - Thermal runaway & UL 9540A
- + Review of incidents
- + Risk
 - Probability and consequence
- + General safety approach
- + Explosion prevention
 - Requirements (e.g., NFPA 69)
 - Software tool (FDS)
 - System operating principle
 - Source term development
 - Sensitivity calculations
 - What to pay attention to
 - Examples for detection delay impacts, clean agent impacts, HVAC impacts, balance between flow momentum and smooth flow regime, hot spots, hot aisle vs. cold aisle and large buildings
 - Model Validation



Typical BESS Installations



Sources: Illustrations from GE, A123, Waldron, PV Magazine, and Simpliphi public domains



Residential



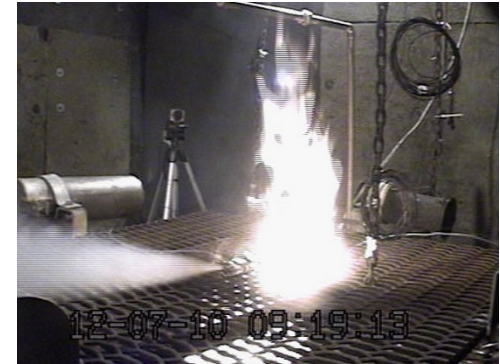
Specialty Applications:

- Roof top
- Black start resiliency for emergency diesel generators
- Repurposed facilities, e.g., factories, turbine halls

Hazard Evaluation

Thermal Runaway

- + Thermal runaway is a process that releases large amounts of energy. Thermal runaway is strongly associated with exothermic chemical reactions. Under a variety of scenarios (i.e., short circuit), batteries can undergo thermal-runaway where the stored chemical energy is converted to thermal energy.
- + Initiating events include:
 - Manufacturing defects in the cells,
 - Overcharging
 - Overheating, and
 - Mechanical abuse.

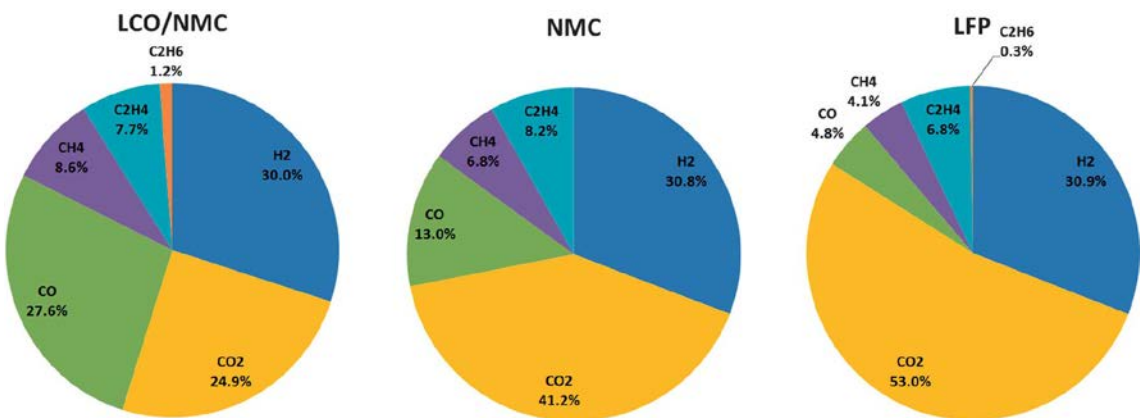


All initiating events have in common that they result in an internal short circuit of the cell, which initiates a heat-generating reaction and may subsequently lead to thermal runaway.

Hazard Evaluation

Thermal Runaway

- + The typical consequence is cell rupture and the release of flammable and toxic gases
- + Explosion control, ventilation, and egress are an important consideration in particular if the BESS is adjacent to exposures



- + “Battery Gas” is usually comprised of Carbon Dioxide, Carbon Monoxide, Hydrogen, Hydrocarbons



Table 1 – Lithium ion cell vent gas statistical properties of 21 varieties at 100% SOC (Archibald [11])

Parameter	Symbol	Mean	Min	Max	Units
Gas Volume Released per Cell Energy	r'	0.40	0.12	0.63	l/Wh
Lower Flammability Limit	LFL	10%	5%	13%	
Upper Flammability Limit	UFL	47%	27%	60%	
Stoichiometric Gas Concentration	X_{st}	21%	11%	30%	
Maximum Pressure	P_{max}	7.85	6.44	8.95	bara
Burning Velocity	S_u	0.48	0.22	0.75	m/s

Table 1 from Electric Power Research Institute (EPRI), 2021, Battery Energy Storage Systems Explosion Hazards, referencing E. J. Archibald, Fire & explosion hazards due to thermal runaway propagation in lithium-ion battery systems, PhD Thesis, 2021.

Hazard Evaluation

UL 9540A

- + Several codes and standards, such as NFPA 855, IFC, and UL 9540, state that the fire characteristics of a BESS that undergoes thermal runaway should be evaluated
- + UL 9540A test data provides safety relevant information for safety system design such as:
 - Battery gas composition
 - Flammability limits
 - Quantity of gas generated over time
 - Heat release
 - Information on thermal runaway propagation timing and behavior
- + This data can be used for explosion prevention system design
- + Good input data is key for any model



Review of Selected BESS Explosion Incidents

Possible Consequences

- + Jet flames
- + Blast waves
- + Flying debris and projectiles



Bodnegg, Germany, 2022
Residential BESS installed in basement.
A technical defect in the batteries caused an explosion where the resulting pressure wave inside the house pushed out windows, doors, and lifted the roof structure.

<https://www.bild.de/regional/leipzig/leipzig-news/stromspeicher-aus-leipzig-haus-nach-explosion-nicht-mehr-bewohnbar-79419550.bild.html>



Liverpool, UK, 2020
BESS in container.
Battery thermal runaway with explosion.

https://storgewiki.epri.com/index.php/Failure_Event_-_UK,_Liverpool_-_15_Sep_2020

Surprise, AZ, USA, 2019
BESS in prefab building.
Battery thermal runaway with explosion.

<https://spectrum.ieee.org/dispute-erupts-over-what-sparked-an-explosive-li-ion-energy-storage-accident>



Risk Reduction via Explosion Prevention

- + An explosion prevention system via mechanical exhaust ventilation reduces the probability of occurrence for an explosion as well as its consequences. However, the explosion risk is not fully eliminated:

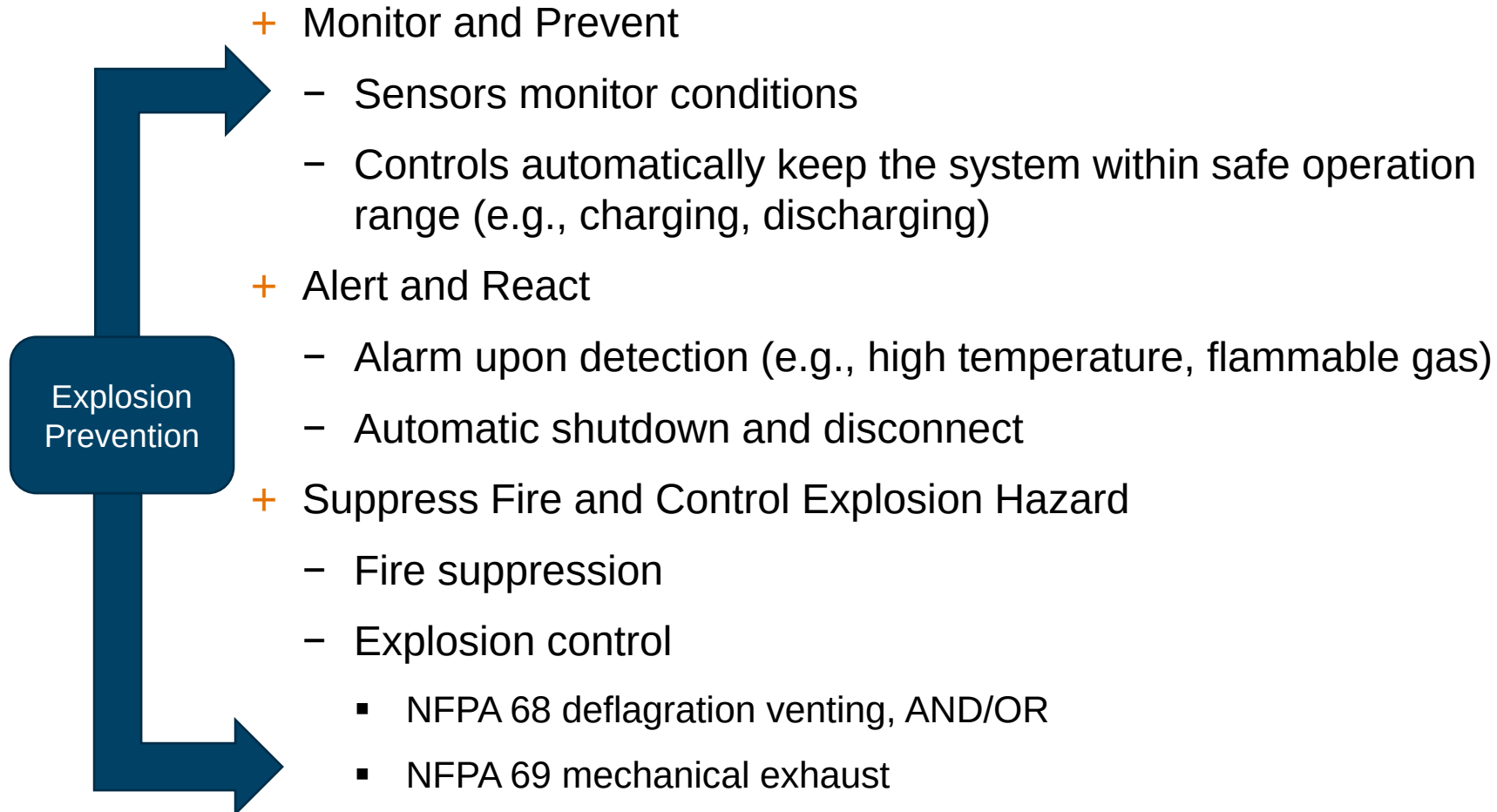
Risk = Probability X Consequence

- Less likely to have an explosible atmosphere
- Atmosphere may be explosible for a shorter time frame (depend on detection speed)

- Controlled and automatic removal of flammable gases protects first responders
- Properly timed activation dilutes flammable concentration (less intense or no explosion)
- Toxic gases are also released in a controlled way allowing for dispersion models to find consideration in emergency response planning

General BESS Safety Approach

General Requirements from Industry Standards



Explosion Prevention

Standard on Explosion Prevention

- + **Deflagration prevention by combustible concentration reduction (Chapter 8)**
- + **Performance-based design option (Chapter 5)**
- + For the electrical installation (Chapter 15), explosion prevention system controls installed after November 5, 2021, shall be implemented as a Safety Instrumented Systems!
 - Certified, installed, and maintained to safety integrity level 2 (SIL-2) or better

Fire Dynamics Simulator

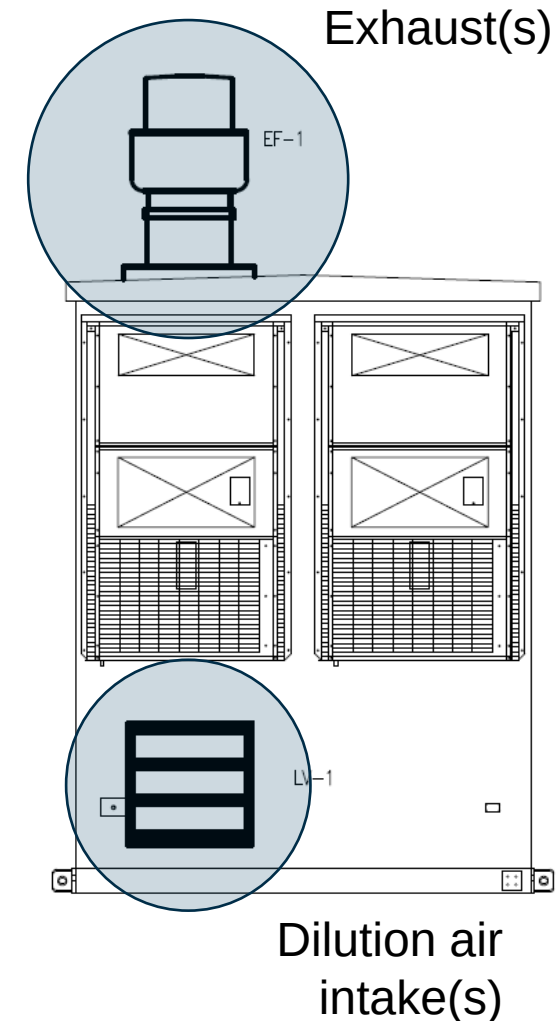
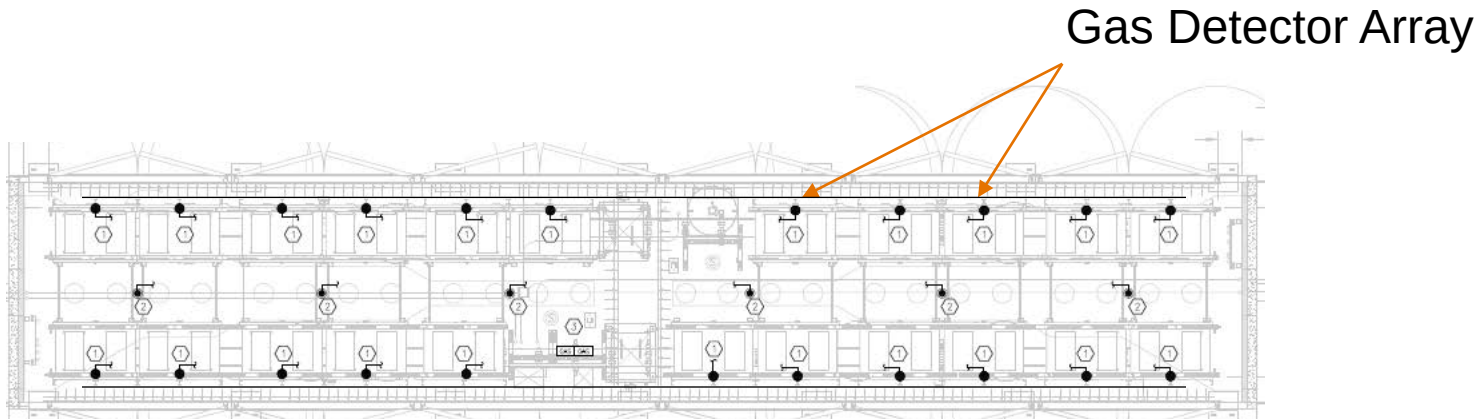
- + Computational fluid dynamic (CFD) code developed by the National Institute of Standards and Technology (NIST) for the analysis of fire and dispersion of smoke and gas
- + Provides gas concentration within the enclosure volume as function of time
- + Results can be animated and visualized in contour plots as well as graphs
- + Used for performance-based design option



Explosion Prevention

System Operating Principle

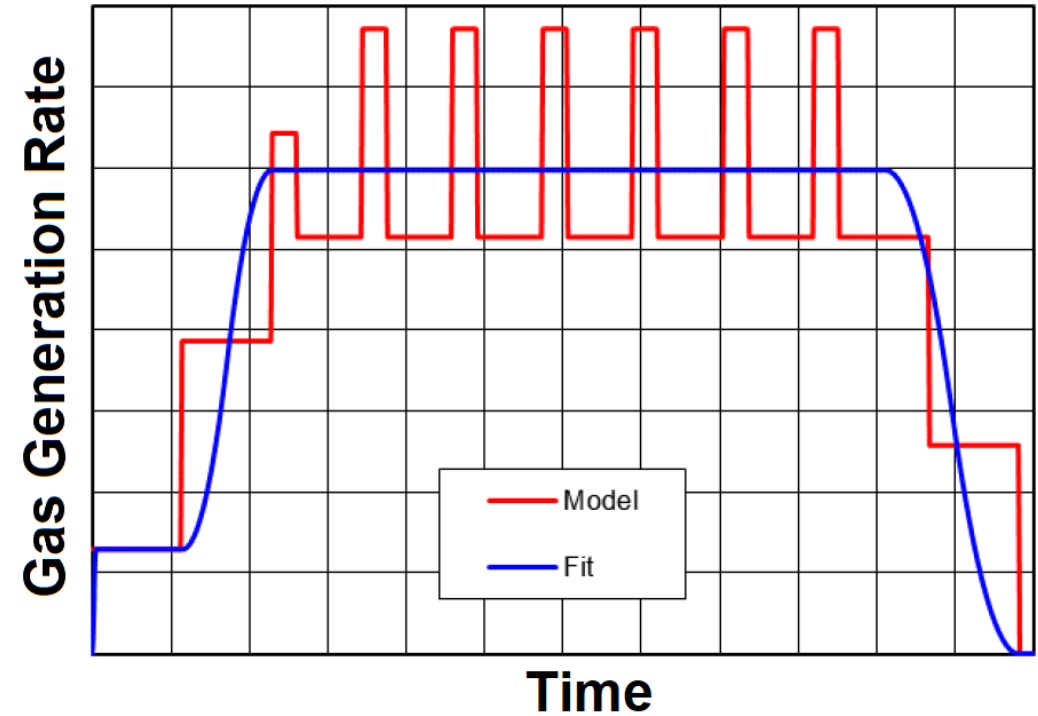
- + Gas alarm (or other viable parameters) activates explosion prevention system
- + Ventilation strategy: Diluting and exhausting the flammable battery gases so that the global concentration is maintained below 25% (by volume) of the lower flammability limit (LFL)



Explosion Prevention

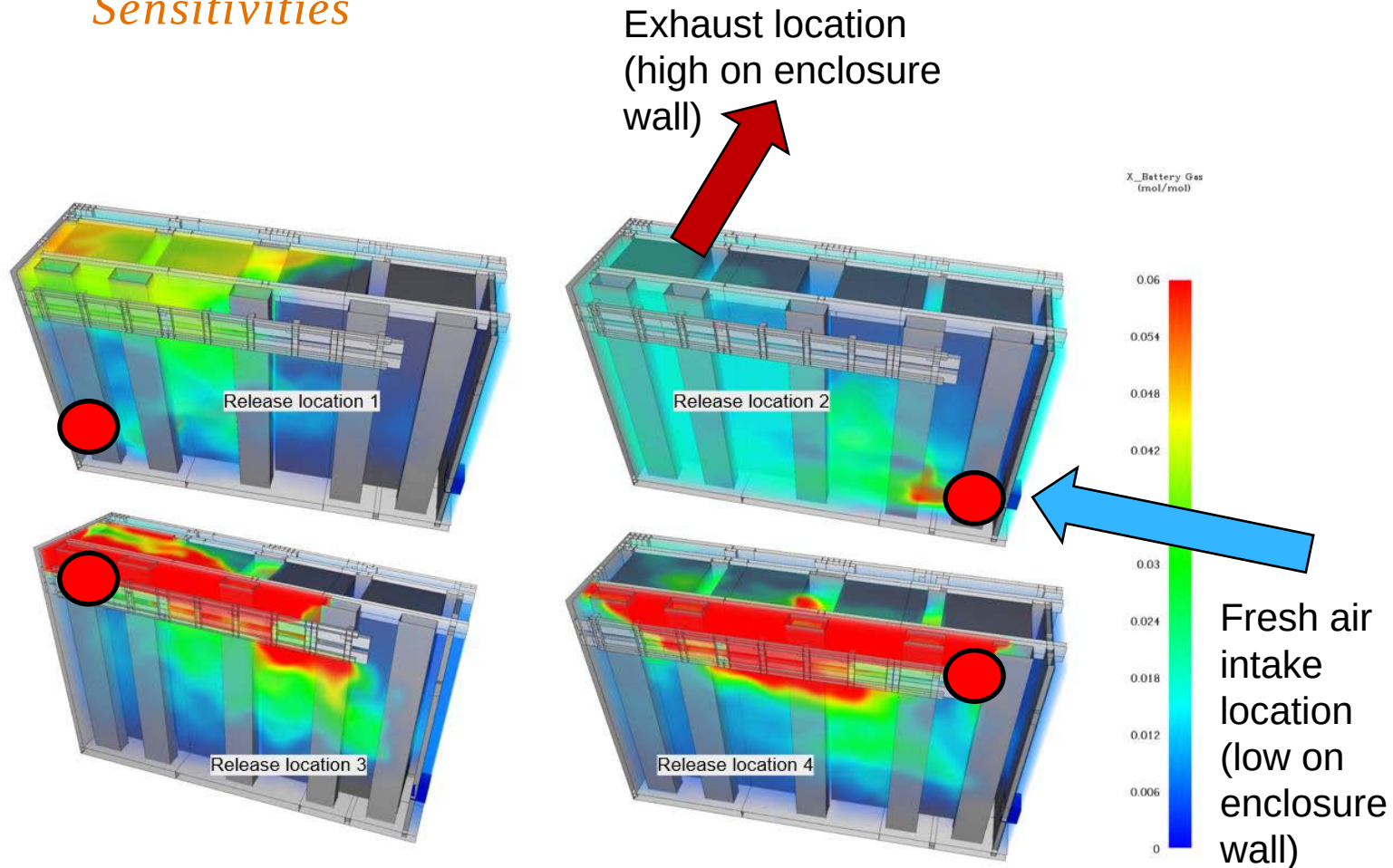
Source Term Development

- + To support the design of an explosion prevention system by means of reduction in combustible concentration, the release of combustible species (battery gas) over time into the room or enclosure must be known
- + Review UL 9540A test data to determine composition, temperatures, release volume, and thermal runaway behavior (e.g., cascading time and vent duration per cell)
 - Might need to supplement with literature data, if test report is incomplete
 - Use curve fit as CFD model input



Explosion Prevention

Sensitivities

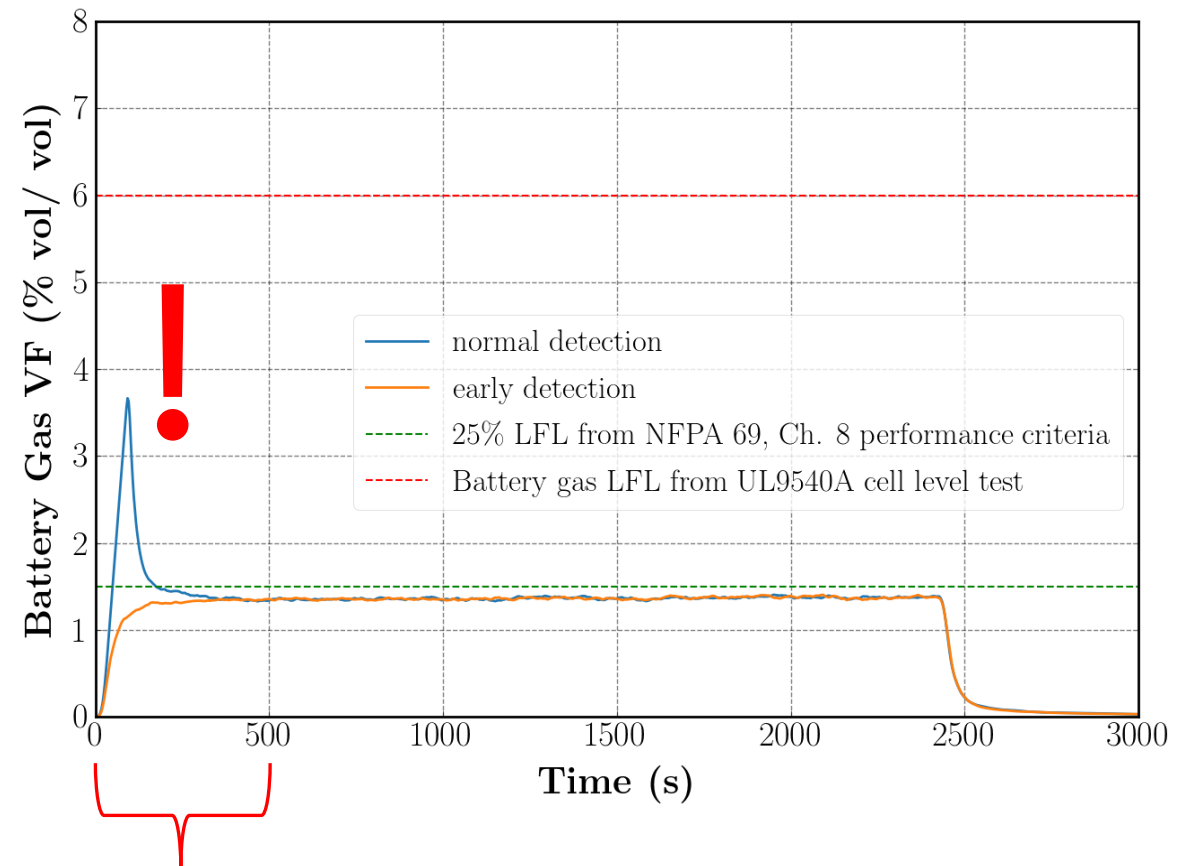


- + The performance-based design option via CFD can be leveraged to check the explosion prevention system performance for:
 - Detection effectiveness
 - HVAC mode
 - Failure event location sensitivity
 - Placement of exhaust(s) and intakes(s) sensitivity
- + These transient and local details would not be captured in a hand calculation

Explosion Prevention

Thoughts on Explosion Prevention for BESS Containers

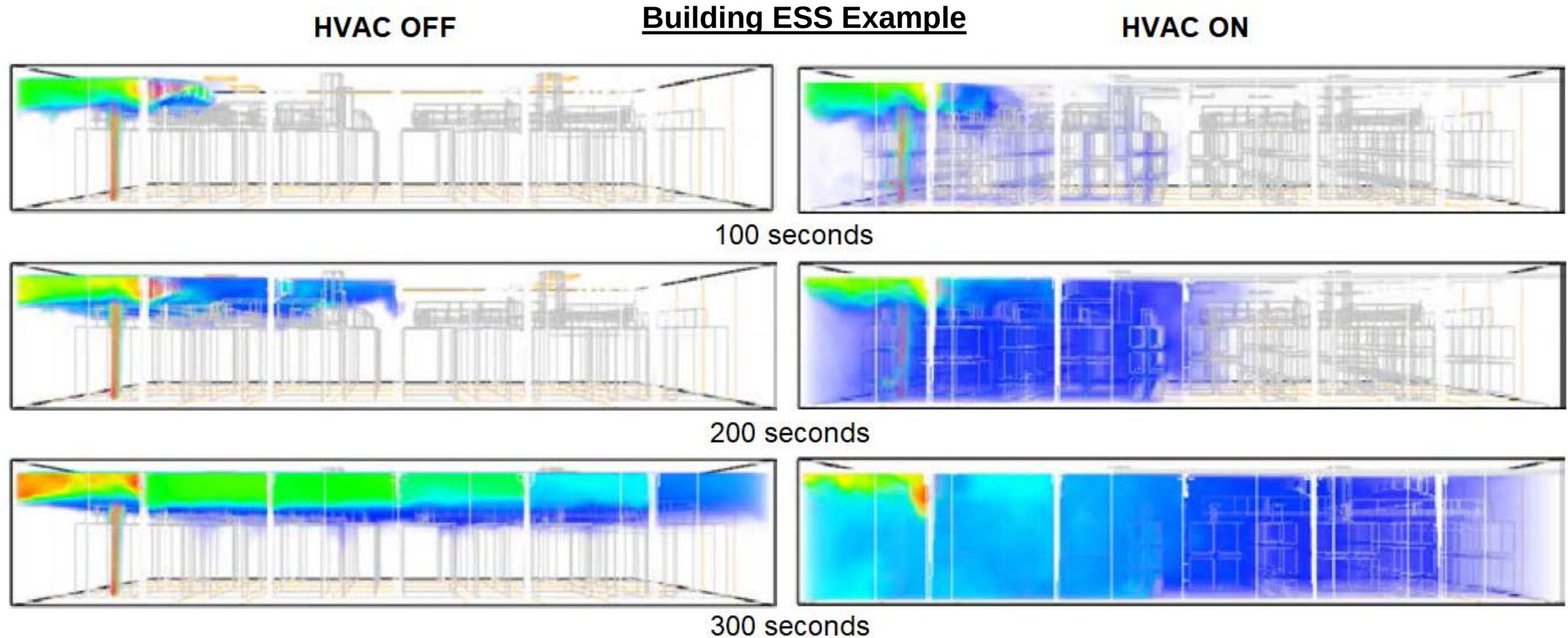
- + Detection timing quickly affects explosion prevention effectiveness
- + What is the worst-case for the exhaust system and what is the worst case for the detection system?
- + Explosion prevention can be challenging for ESS with little free air volume. Options for remedy include:
 - Early detection
 - Utilize a safety integrated system
 - Create free air volume
- + Air-cooled BESS: Hot and cold aisle separation might require control dampers or two explosion prevention systems



Modelling is particularly helpful to get the early timing right or least it provides the situational awareness

Explosion Prevention

HVAC Mode Can Affect Alarm Thresholds and Detection Time

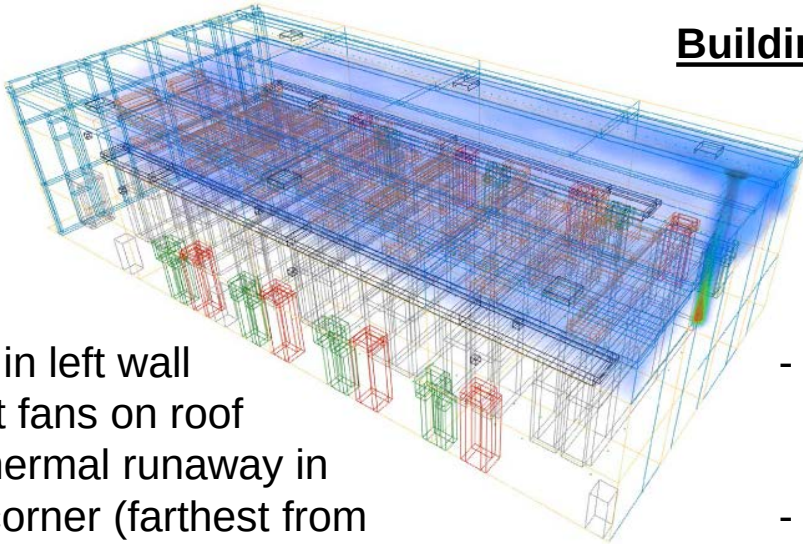


Explosion Prevention

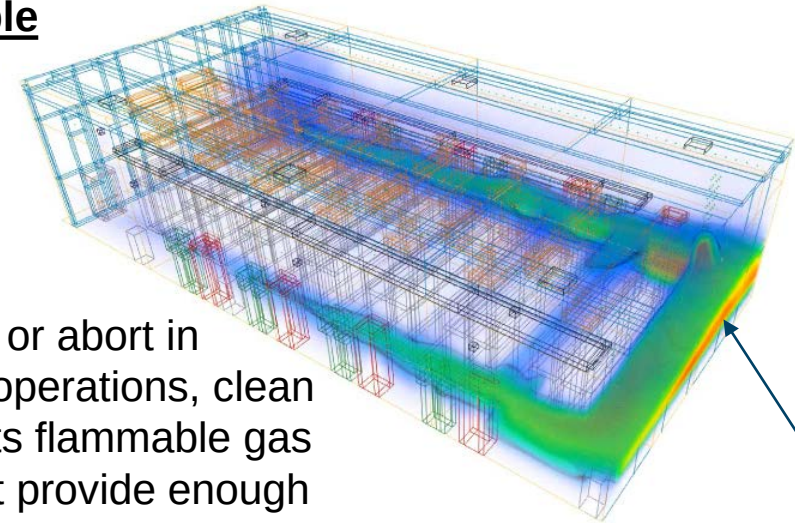
General Thoughts on Explosion Prevention

- + The explosion prevention system must be properly integrated in the sequence of operations
- + There could be conflicting fire protection goals (e.g., clean agent versus exhaust)
- + The explosion prevention system must be “right-sized” for the challenge. It is a balance between air changes and maximum possible flow velocities to provide an effective “sweep” (more is not necessarily better)

Building ESS Example



- 2 intakes in left wall
- 6 exhaust fans on roof
- Battery thermal runaway in far-right corner (farthest from intakes)



- If no override or abort in sequence of operations, clean agent blankets flammable gas
- Exhaust must provide enough momentum to remove clean agent

Above
LFL

Explosion Prevention

Summary

Considerations	Advantages
- Right-size the system - Properly integrate the system in the sequence of operations. Designing and installing (or retrofitting) a stand-alone explosion prevention system is only half of the work! - Reliable and fast thermal runaway detection is key - Perform various sensitivity cases to assure that the system can detect and control the explosion hazard under worst-case conditions - The performance criterion is less than 25% of the LFL on the volume concentration. Due to the possibility of local hotspots, the explosion concern may not be fully eliminated but significantly mitigated. - Validate the model against literature data, flow tests, alternative models, and analytical calculations	- Mitigation of the explosion risk through the reduction of the probability and consequence of an event - Avoidance of a catastrophic event - Controlled release of flammable and toxic gases - Analysis results can be used for emergency response planning Explosion control is a requirement for li-ion based BESS. A mechanical exhaust ventilation system designed and maintained according to NFPA 69 provides compliance and risk mitigation.

Thank you!



JENS CONZEN

DIPL.-ING. | EUR ING | MS | MBA

Director / Market Leader

jconzen@jensenhughes.com

M: +1 773-733-1242



jensenhughes.com