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How to Prevent Thermal Runaway in Li-Ion Batteries

“Deep Dive”

Presented by: William Sudah

Lithium-Ion Applications

- Energy Storage
- Data Centers
- Gigafactories
- EVs
- Battery Recycling Plants

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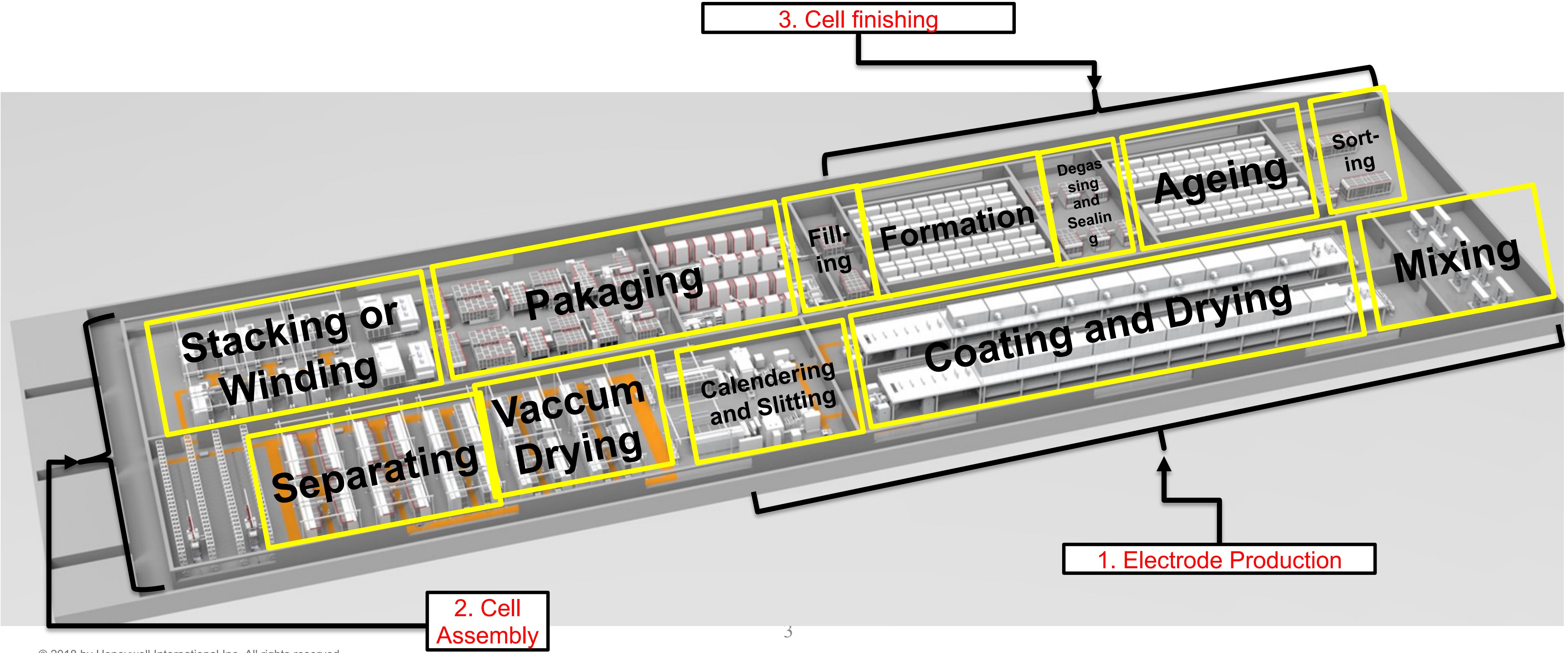
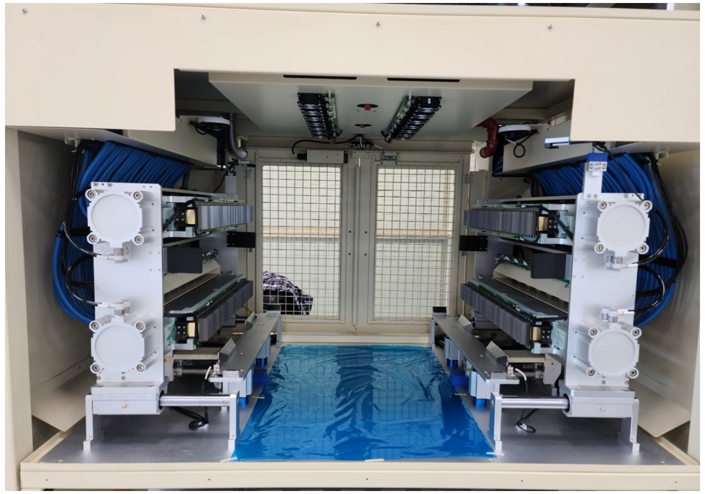
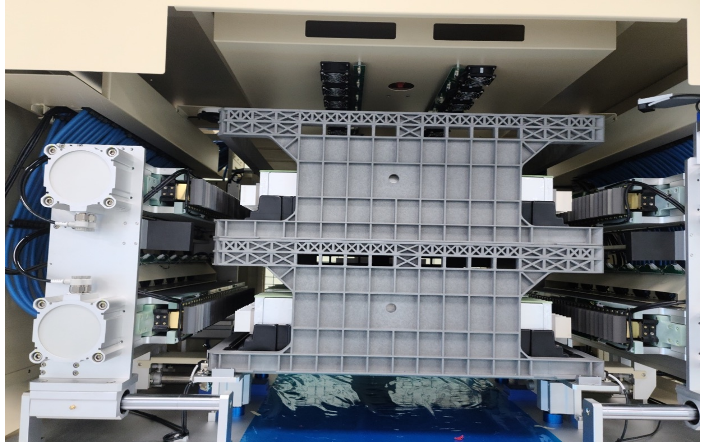
Preview

Battery Cell Production for EV Manufacturers:
The GIGA Factory



Formation

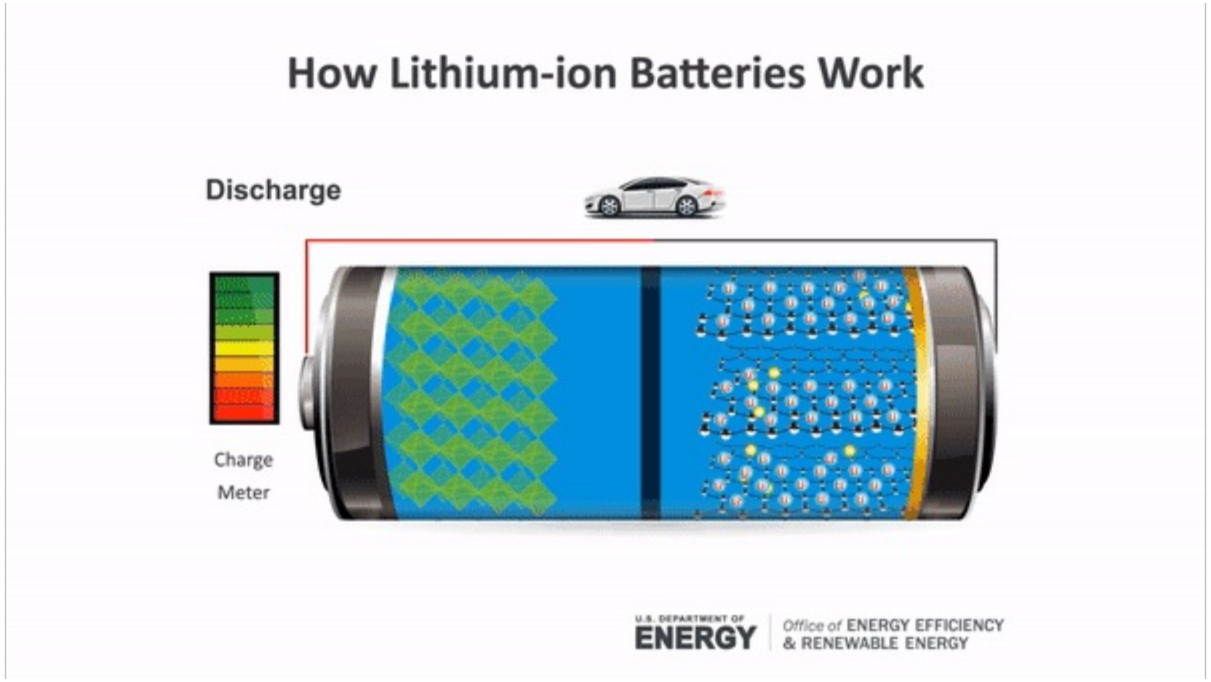




AGENDA

- Understanding the 4-stages of Li-Ion battery failure
- Learn about the gases being released prior to TR and after TR
- Go over testing results, including UL and other 3rd party findings

How it Works



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Li-ion Battery Failure

- Overcharging
- Battery misuse or abuse
- Exposed to high temperatures
- Manufacturing defects
- Short circuits caused by dendrites whiskers

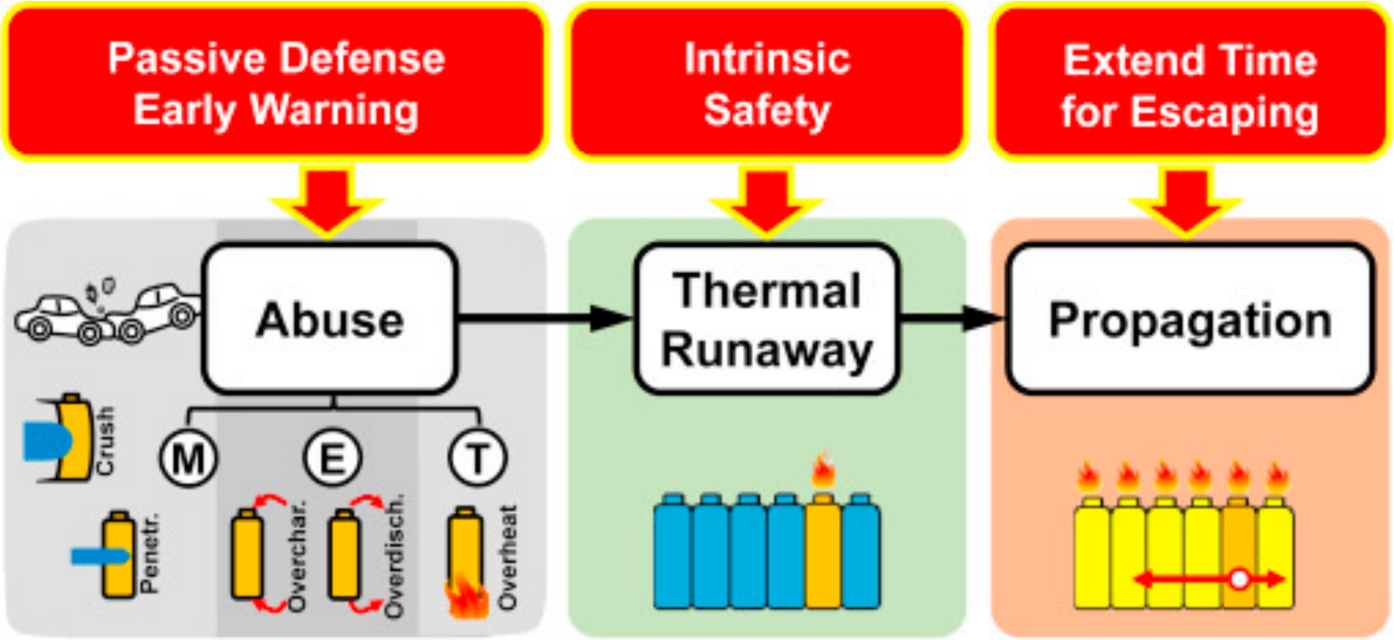
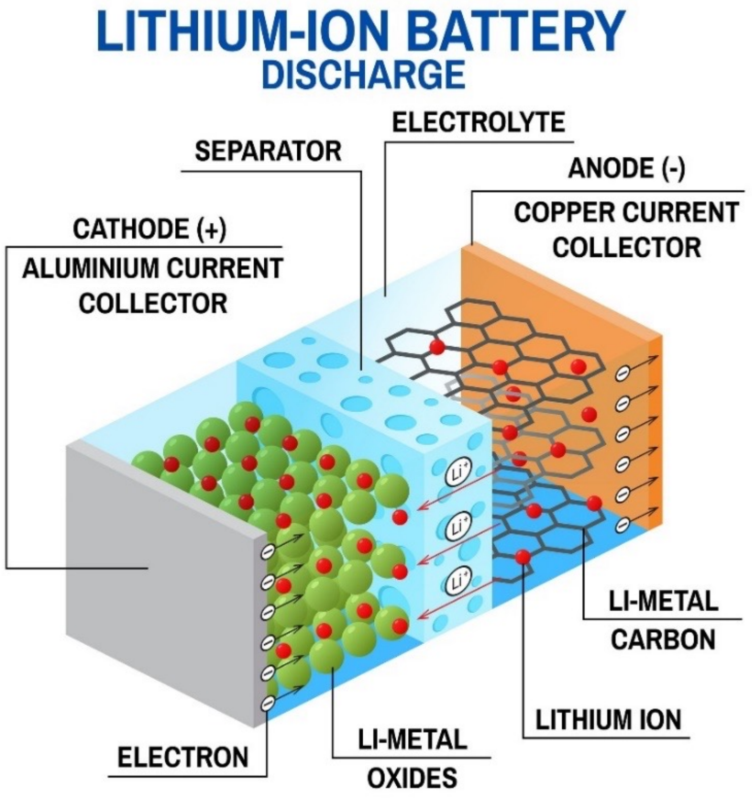


Image Source: https://www.powerelectronictips.com/thermal-propagation-triggering-and-mitigation-in-medium-and-large-format-battery-modules/

Li-ion Battery Failure Thermal Runaway



1. Overcharging creates a chemical reaction btw the electrolyte & the electrode. Changing electrolyte to gas.

2. Overheating heats up the electrolyte/chemicals inside causing a change in state from liquid to gas.

3. Exothermic reaction begins causing the separator to degrade.

4. When the separator is breached, it causes a short circuit

5. Thermal runaway occurs

Thermal Runaway occurs most often in a **battery** when the rate of internal **heat** generation exceeds the rate at which the **heat** can be expelled.

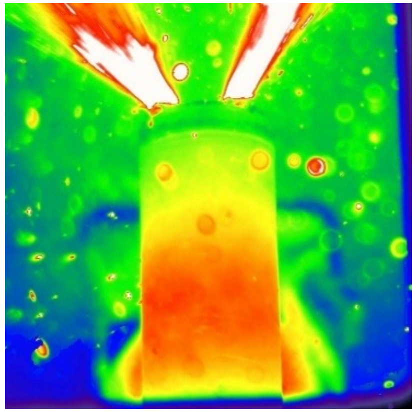


Image Source:
https://www.livescience.com/50643-watch-lithium-battery-explode.html

Image Source:
https://lh3.googleusercontent.com/proxy/SO0cR9bdaK2URnDBCQMMZxMP_4DH33DxiqBhqZcseAQvoKYeFuxFkZbrI1ZlGfz9FeyyfrKNliSYNbmjSsnqxFzPqqxPu5uwzpVVpntl

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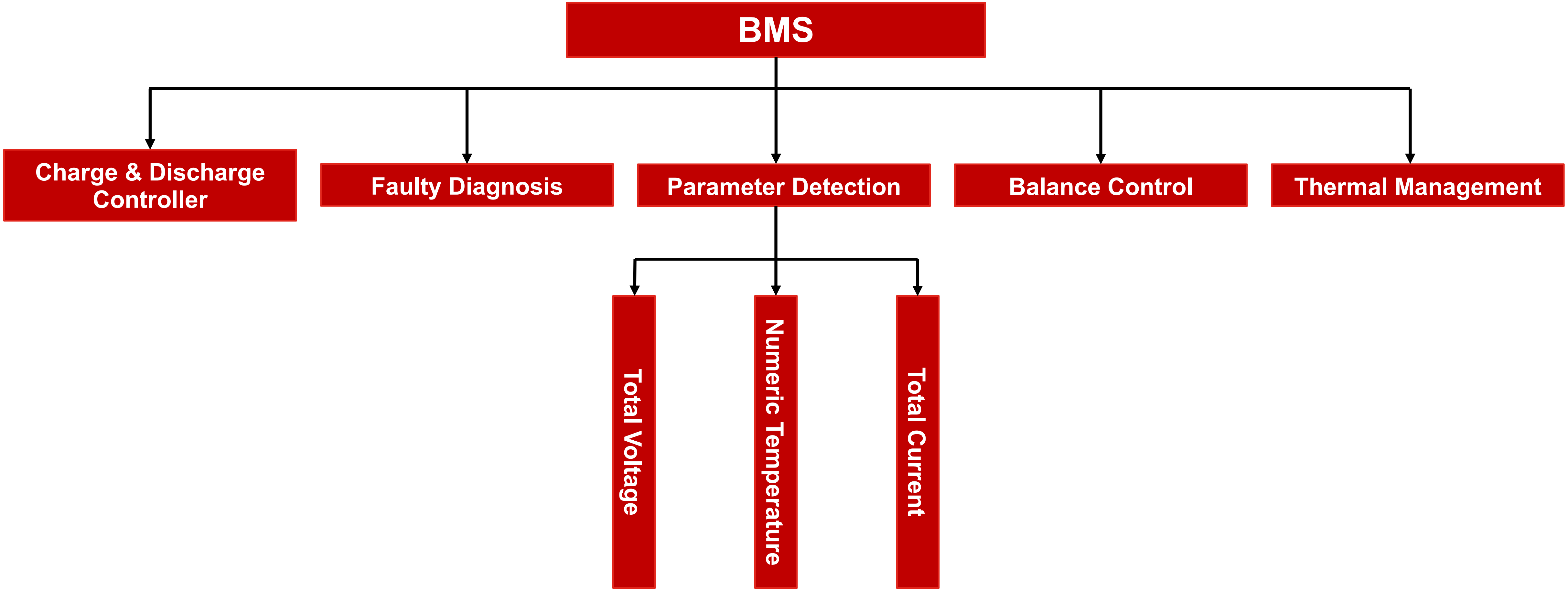
Battery Management System



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Battery Explosions

April 19th 2019

- Explosion at an Arizona Public Service facility in Surprise. The explosion occurred at the APS McMicken Energy Storage facility near Grand Avenue and Deer Valley Road in Surprise on Friday evening. The facility houses utility-sized batteries on the site used in the storage and distribution of solar energy. Eight firefighters were injured.

Starting from August 2017

- Fires at 23 energy storage installations in South Korea:
  "…Battery manufacturers, system integrator companies and power conversion system companies are all at fault," Kim Jung-hoon, an electrical engineering professor at Hongik University who headed the investigative committee."

- Fire at 20MW UK battery storage plant in Liverpool
  There has been a fire at the Carnegie Road 20MW battery energy storage system (BESS) project in Liverpool, England, project owner Orsted has confirmed.

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Battery Failure Stages

Stage 1: Abuse Factor

- Thermal, Electrical or Mechanical abuse

Stage 2: Off-Gas Generation

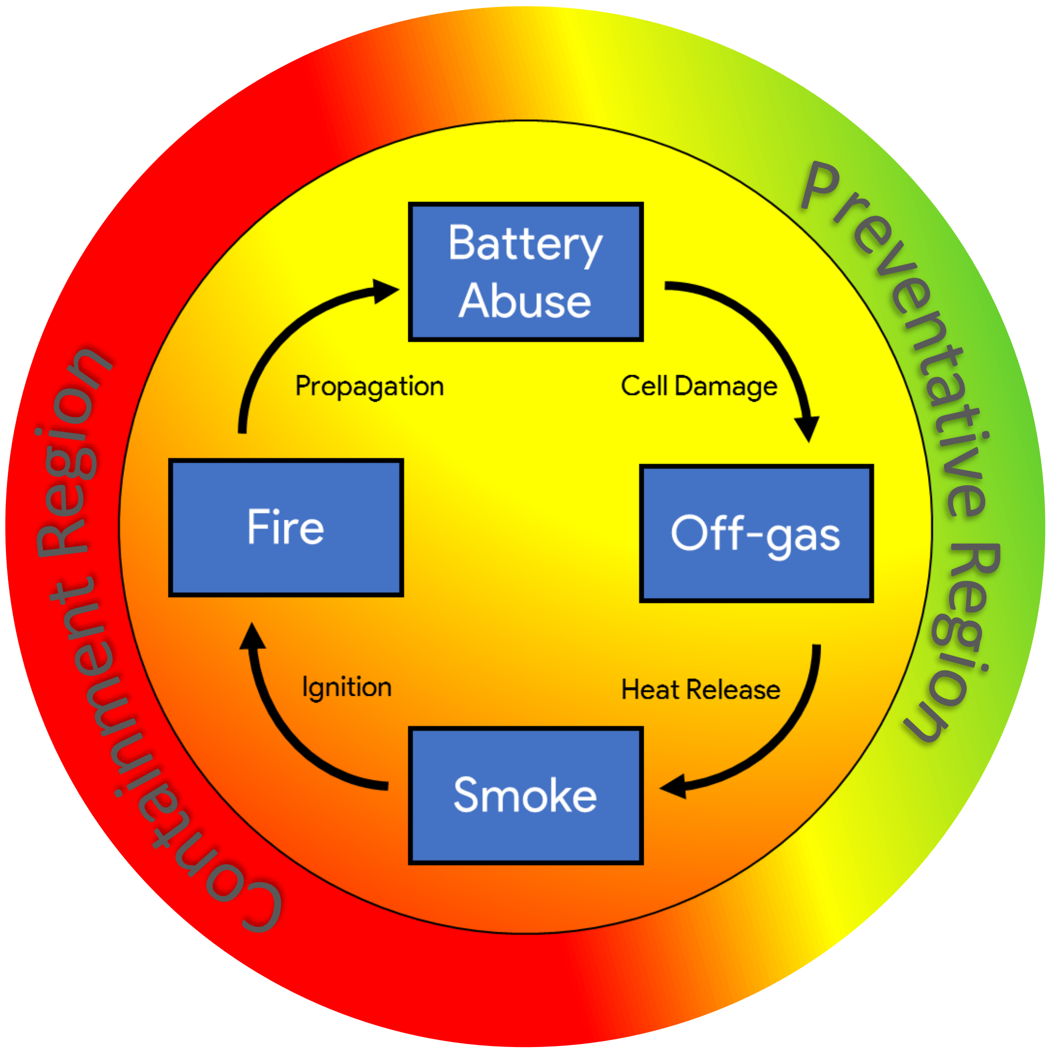
- Golden Time

Stage 3: Smoke Generation

- Catastrophic failure is imminent

Stage 4: Fire Generation

- Propagation occurrence



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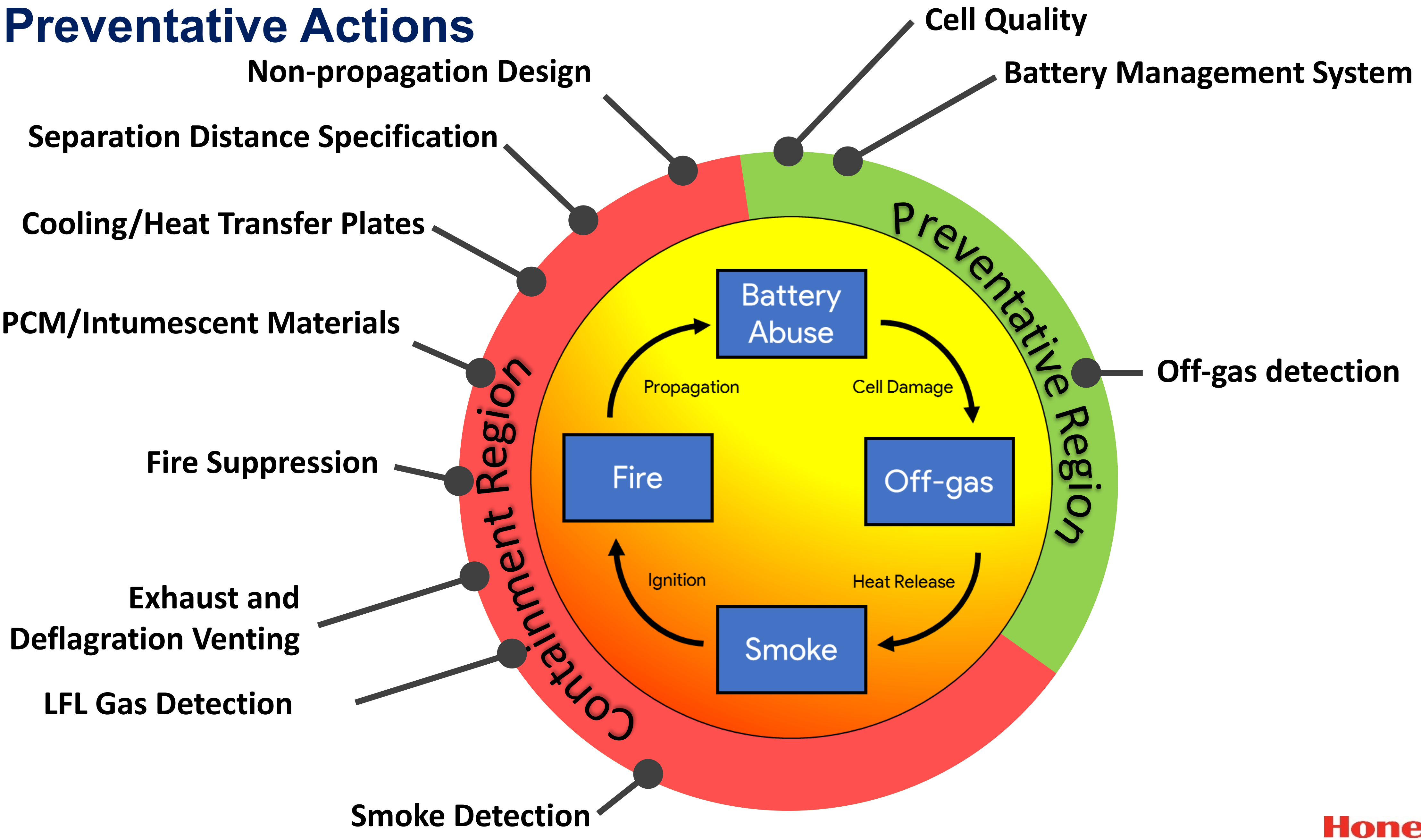
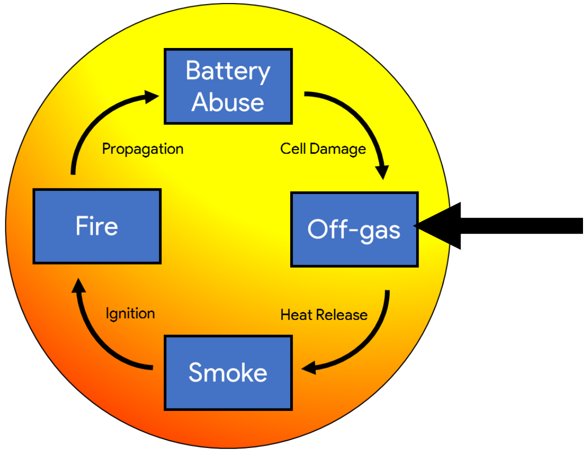
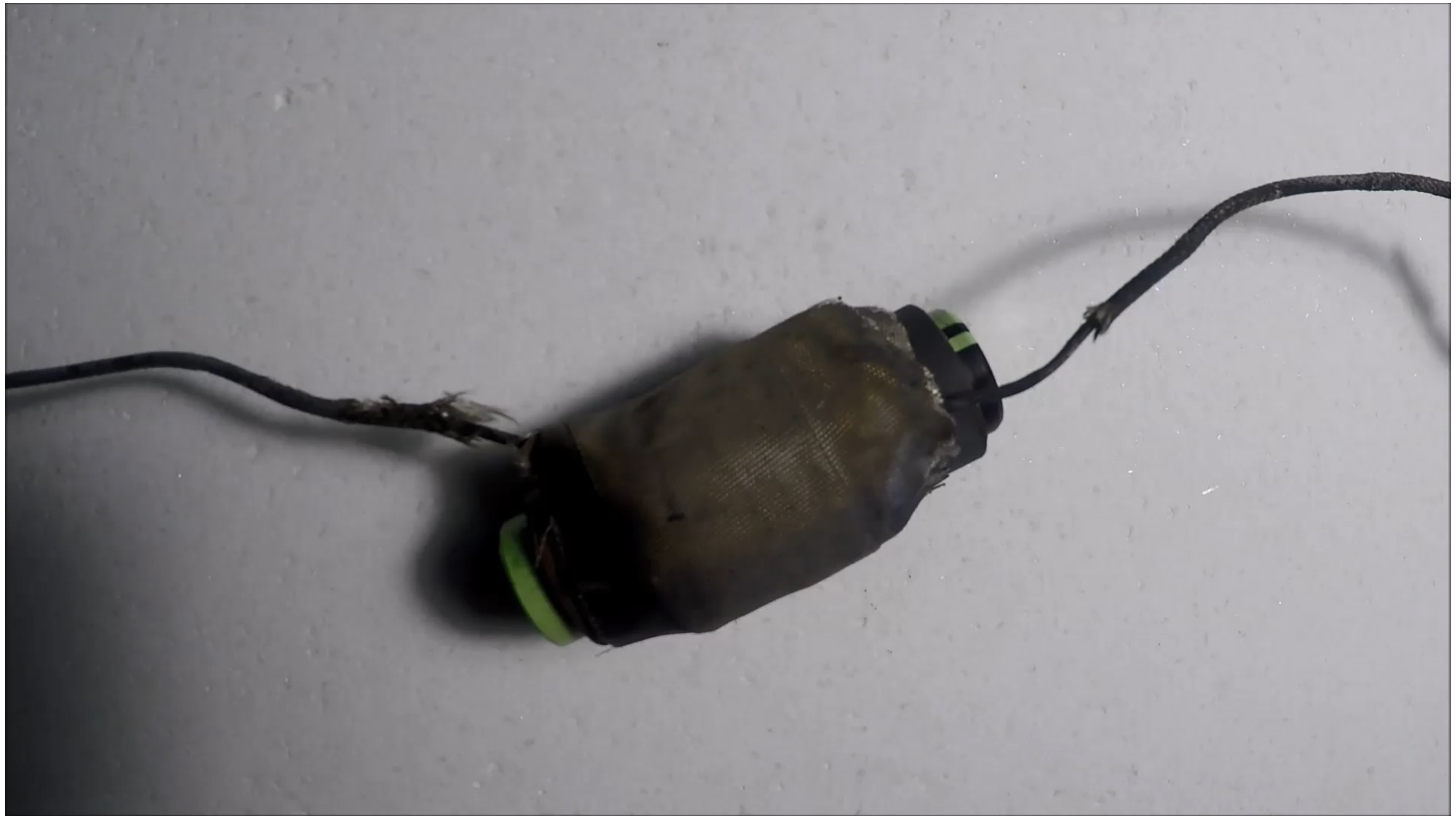
Preventative Actions



Off Gas Video





Not all batteries are made equal

What gases do we monitor?

- Manufacturers are constantly improving lithium-ion. New and enhanced chemical combinations are introduced every six months or so. With such rapid progress, it is difficult to assess how well the revised battery will perform or what specific gases it will emit during a thermal runaway.
- To detect off-gases, we must be capable of detecting a blend of off-gases.

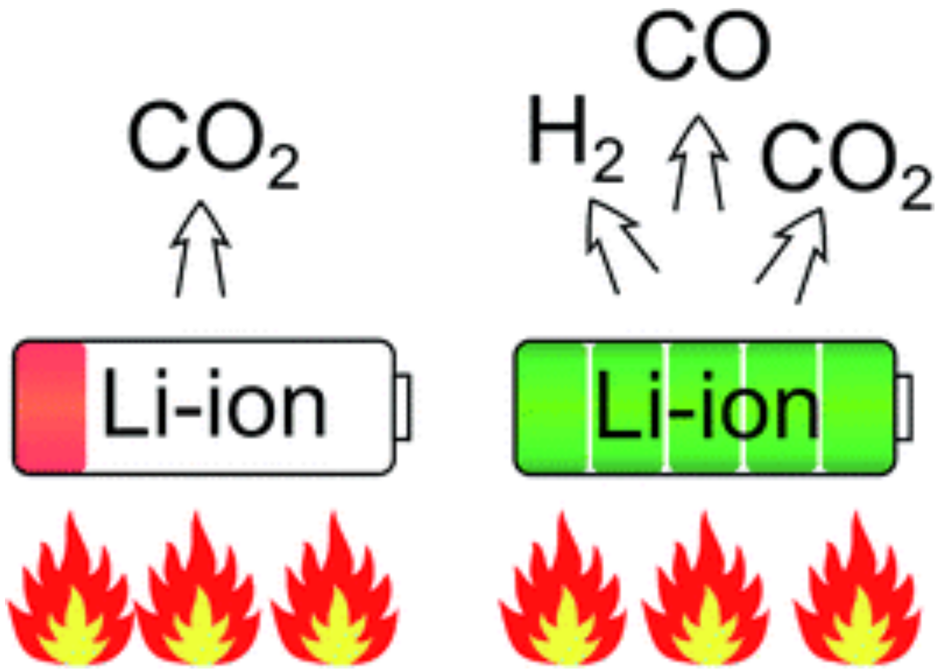


Image Source:
https://pubs.rsc.org/en/content/articlelanding/2015/ra/c5ra05897j#!divAbstract

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Very Early Detection

Conventional Gas Detection will not work

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UL 9540A Latest Test Report (April 12, 2021)

Takeaway from UL Fire Test Report:

- UL very clearly states that traditional detectors are not capable of detecting gas/smoke before TR
- H2, CO, LEL and smoke only alarm only after TR occurs

Fire Test 1: Page 51

- Venting at 23 minutes & 43 sec.
- TR at 26 minutes & 22 sec.
- **Early Warning: 2 minutes & 39 sec.**
- **UL Findings**: Smoke Observed at TR, 30 seconds later gas detectors reacted

Fire Test 2: Page 88

- Venting at 22 minutes & 30 sec.
- TR at 28 minutes & 9 sec.
- **Early Warning: 5 minutes & 39 sec.**
- **UL Findings**:
  - Smoke Observed at TR, within 30 seconds another cell went into TR
  - CO & combustible sensors reacted 30 seconds after second TR
  - (2) Smoke detectors reacted @ 53 & 55 seconds, respectively, after TR

Fire Test 3: Page 139

- Venting at 21 minutes & 37sec.
- TR at 29 minutes & 53sec.
- **Early Warning: 8 minutes & 16 seconds**
- **UL Findings**:
  - All gas detectors alarmed 30 seconds after TR
  - Smoke detectors alarms 60 seconds after TR
  - Propagation occurred after 8 min & 49 seconds

Here is the full document:
https://d1gi3fvbl0xj2a.cloudfront.net/files/2021-07/UL9540AInstallationDemo_Report_Final_4-12-21.pdf

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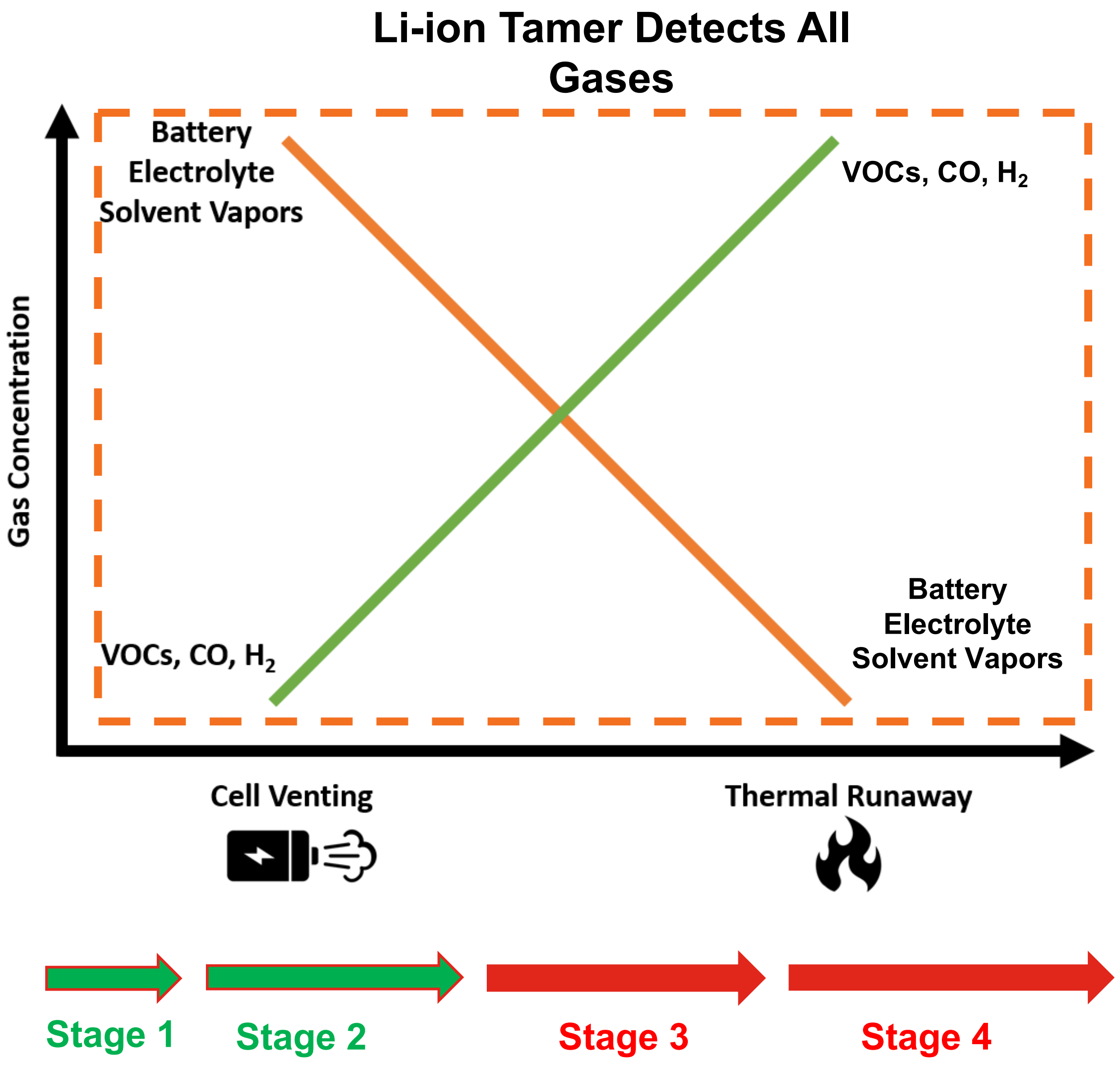
Cell Venting vs Thermal Runaway



3rd Party Testing Data with GC-MS, FTIR

Stage 2

Cell venting gas composition:

45% Battery Electrolyte Solvent Vapors (DEC, DMC)

<0.1% H_2

0% CO

55% Rest (water vapor, CO_2, etc)

Stage 3 & 4

Thermal runaway gas composition:

5% Battery Electrolyte Solvent Vapors (DEC, DMC)

15% H_2

32% CO

15% tVOC (Propane, Butane, Ethane, Methane, etc)

33% Rest (water vapor, CO_2, etc)

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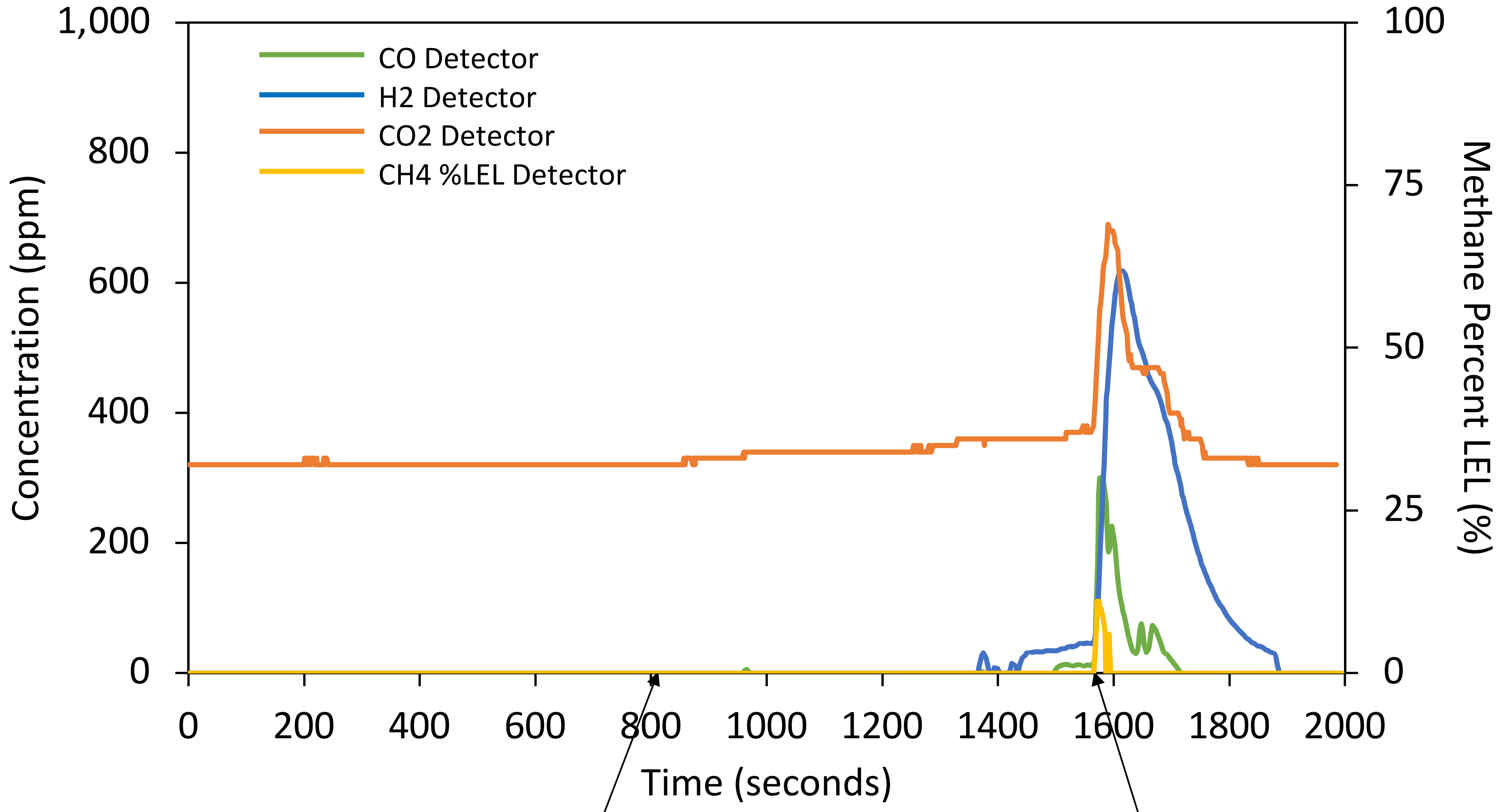
Conventional Gas Detector Response



First venting @ 810 seconds

Second venting @ 1575 seconds

CO Monitor
Peak response: 300 PPM
First venting response: No
Second venting response: Yes

H_2 Monitor
Peak response: 600 PPM
First venting response: No
Second venting response: Yes

CO_2 Monitor
Peak response: 670 PPM (320 PPM ambient)
First venting response: No
Second venting response: Yes

CH_4 Monitor
Peak response: 10% LEL
First venting response: No
Second venting response: Yes

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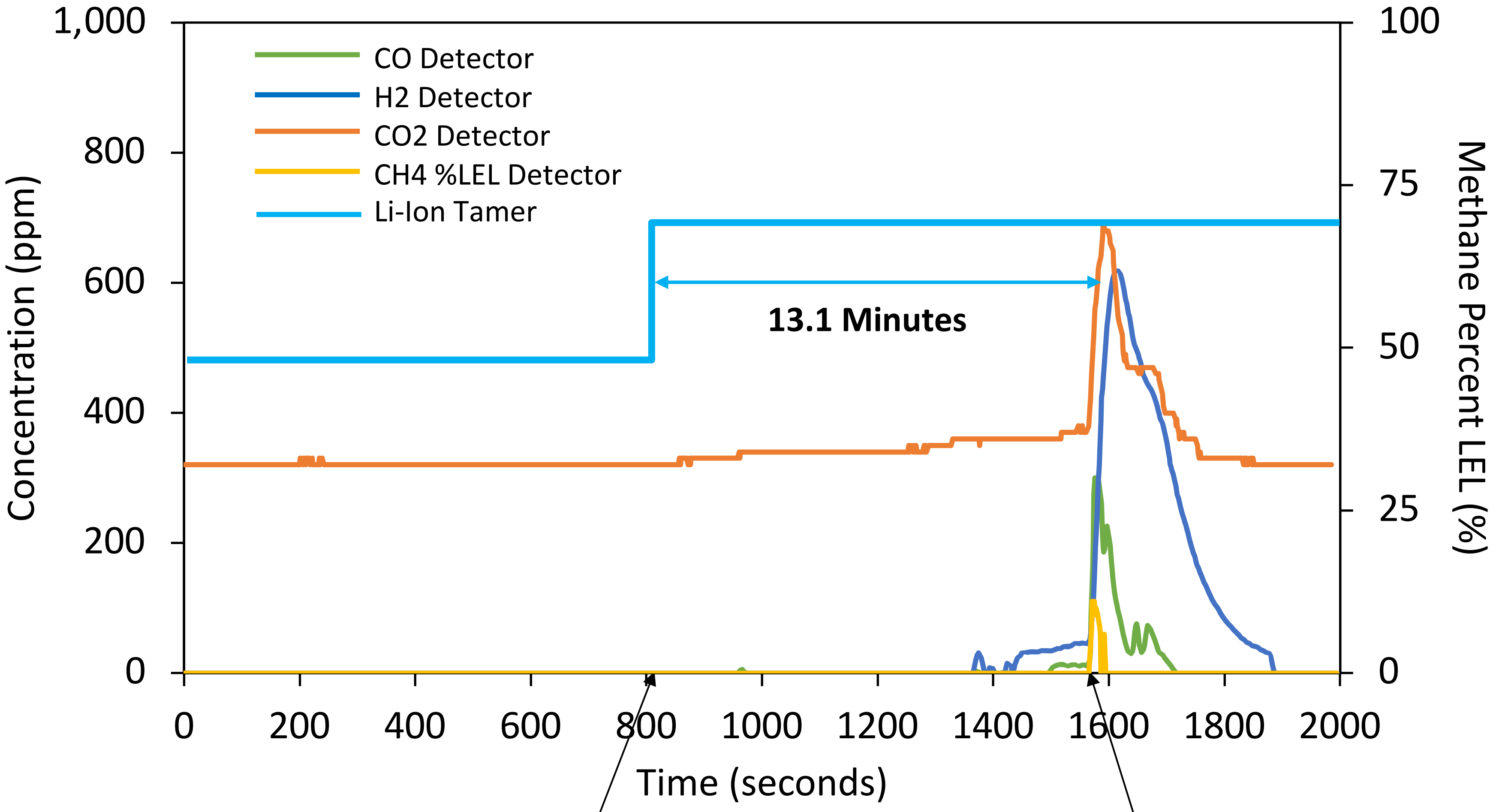
Off-Gas Detector Response



First venting @ 810 seconds

Second venting @ 1575 seconds

Li-ion Tamer response

First venting response: **Yes**
Second venting (TR) response: **Yes**

Li-ion Tamer responds immediately to first venting

Li-ion Tamer provides 13.1 minutes of early warning!

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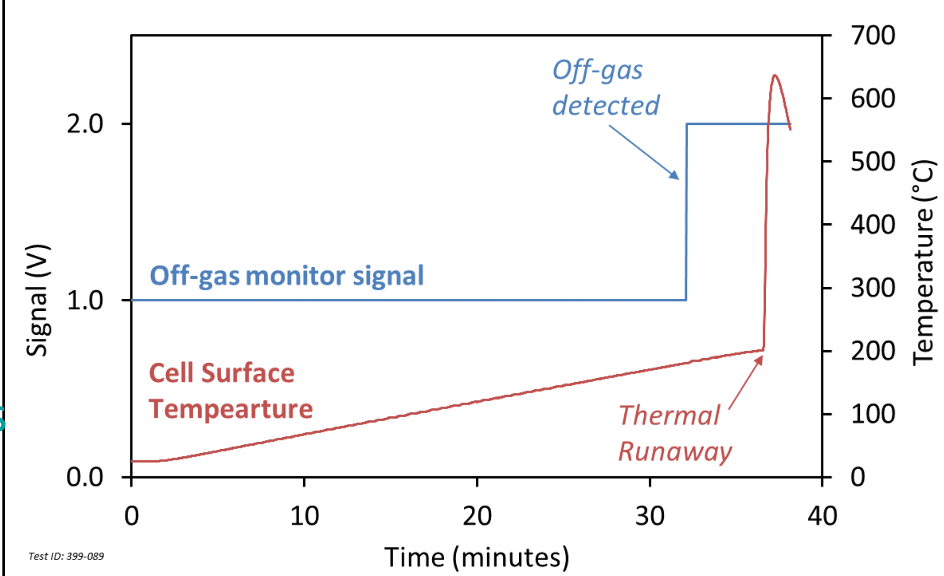
Battery Failure (overheat)

Battery Fault Detection

- Off-gas is precursor to battery failure
- Detection of off-gas can provide early warning
- Advanced safety diagnostic for battery systems



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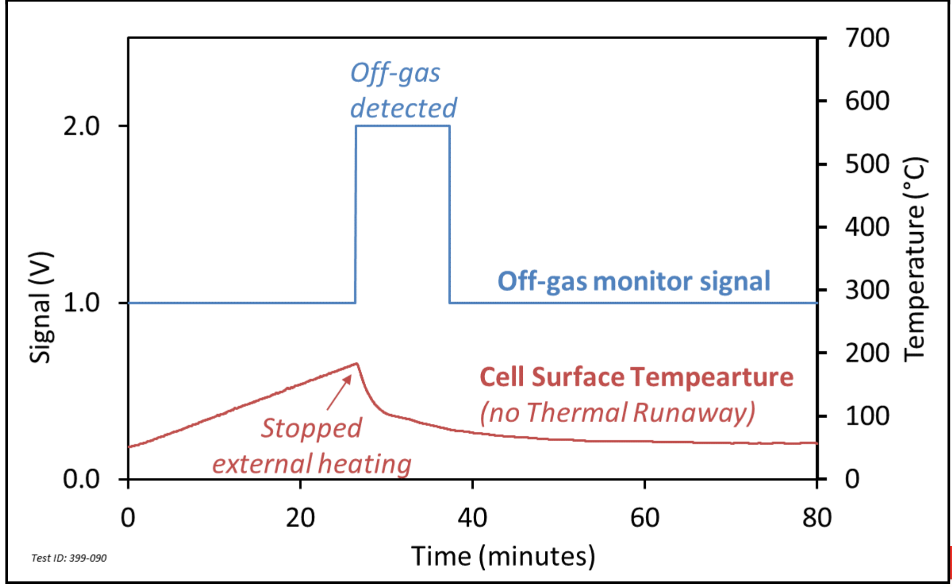
Battery Fault Mitigation

- Off-gas monitoring can enable mitigation
- Isolate from charge/load when off-gas occurs
- Enables thermal runaway prevention



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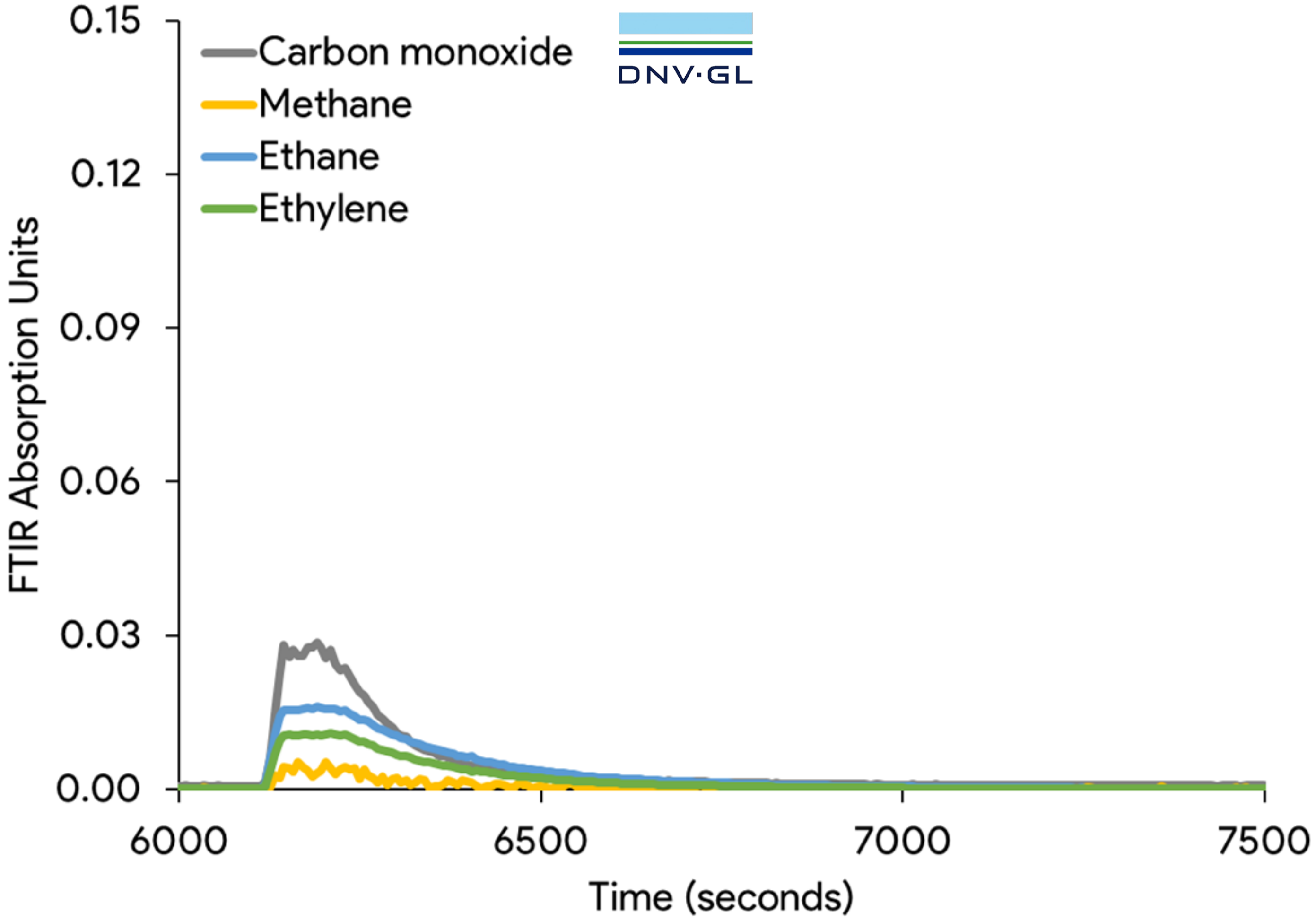
Battery Failure (overcharge & mitigation)

Test #2 conditions

- Third-party data (DNV-GL)
- 100% SOC, constrained
- Overcharged at 50A (0.8C)
- 63 Ah Pouch Cell Type
- Charge is stopped at Li-ion Tamer indication



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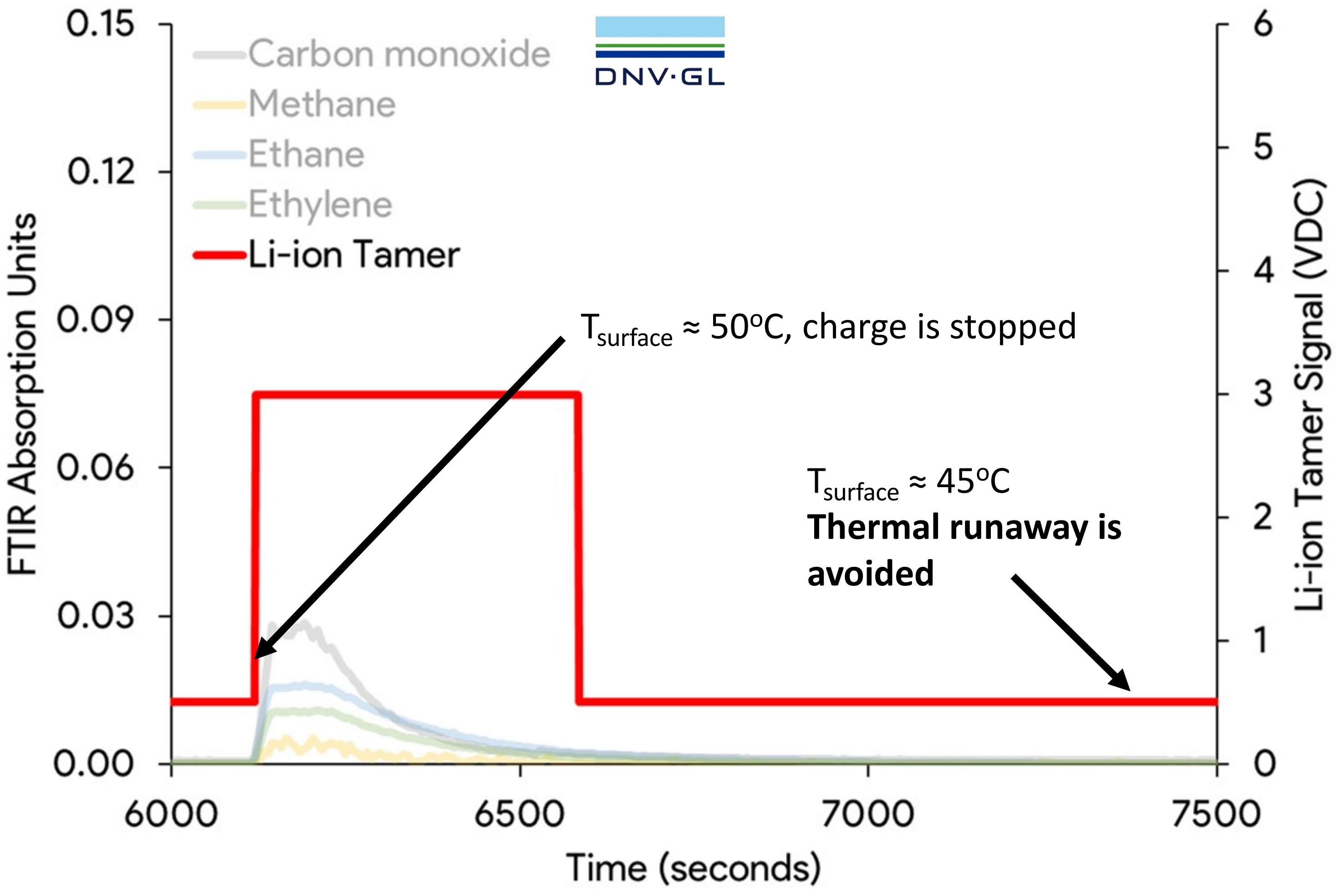
Remarks

- Li-ion Tamer correlates to first FTIR off-gas signatures
- Thermal runaway of cell is avoided by removing charge at Li-ion Tamer indication



Battery Failure (overheating)

Test #1 conditions

- Third-party data (DNV-GL)
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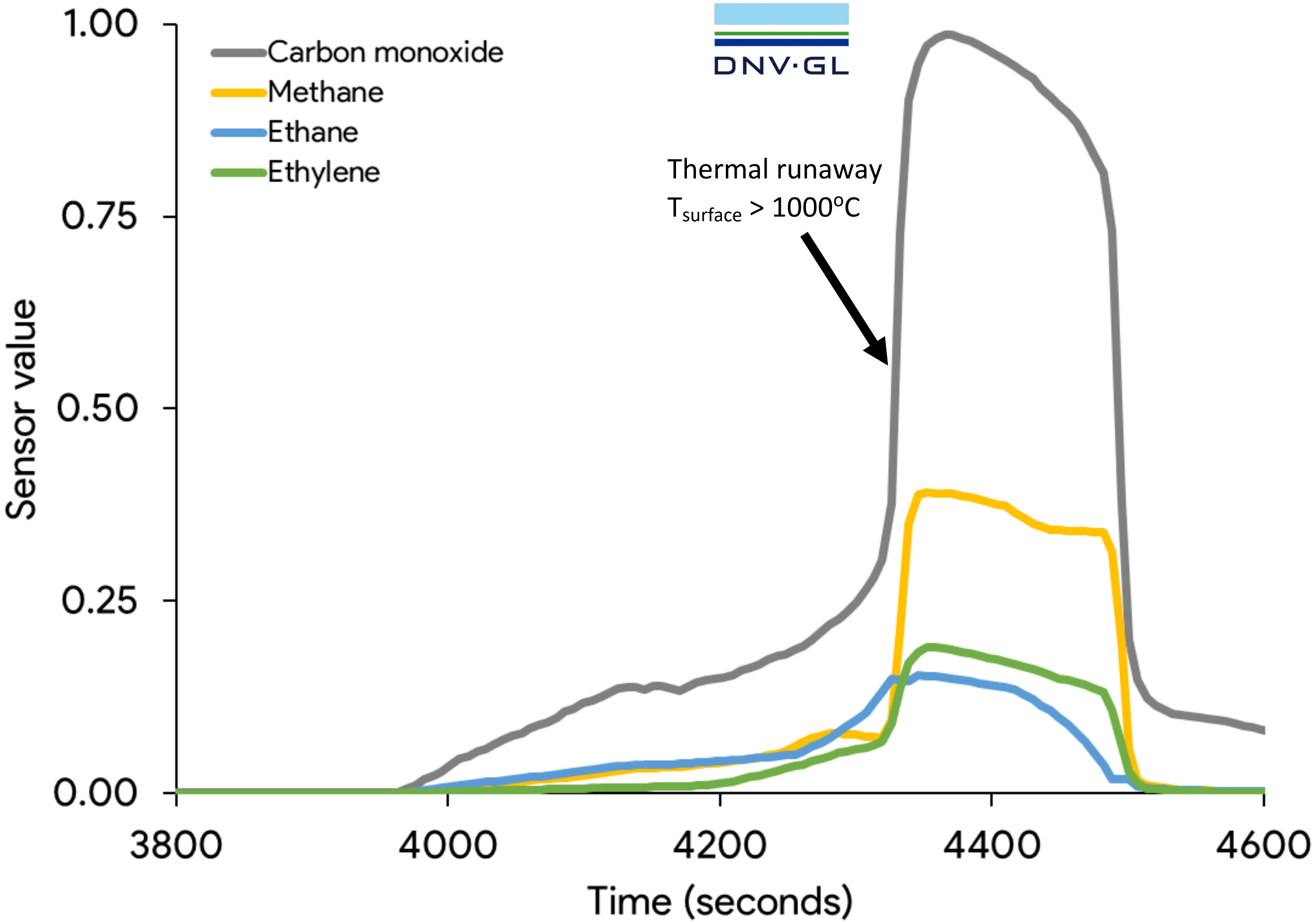
- FTIR data gathered during failure (plus H_2 and LEL monitors)

Remarks

- Low-level off-gassing occurs early, prior to thermal runaway



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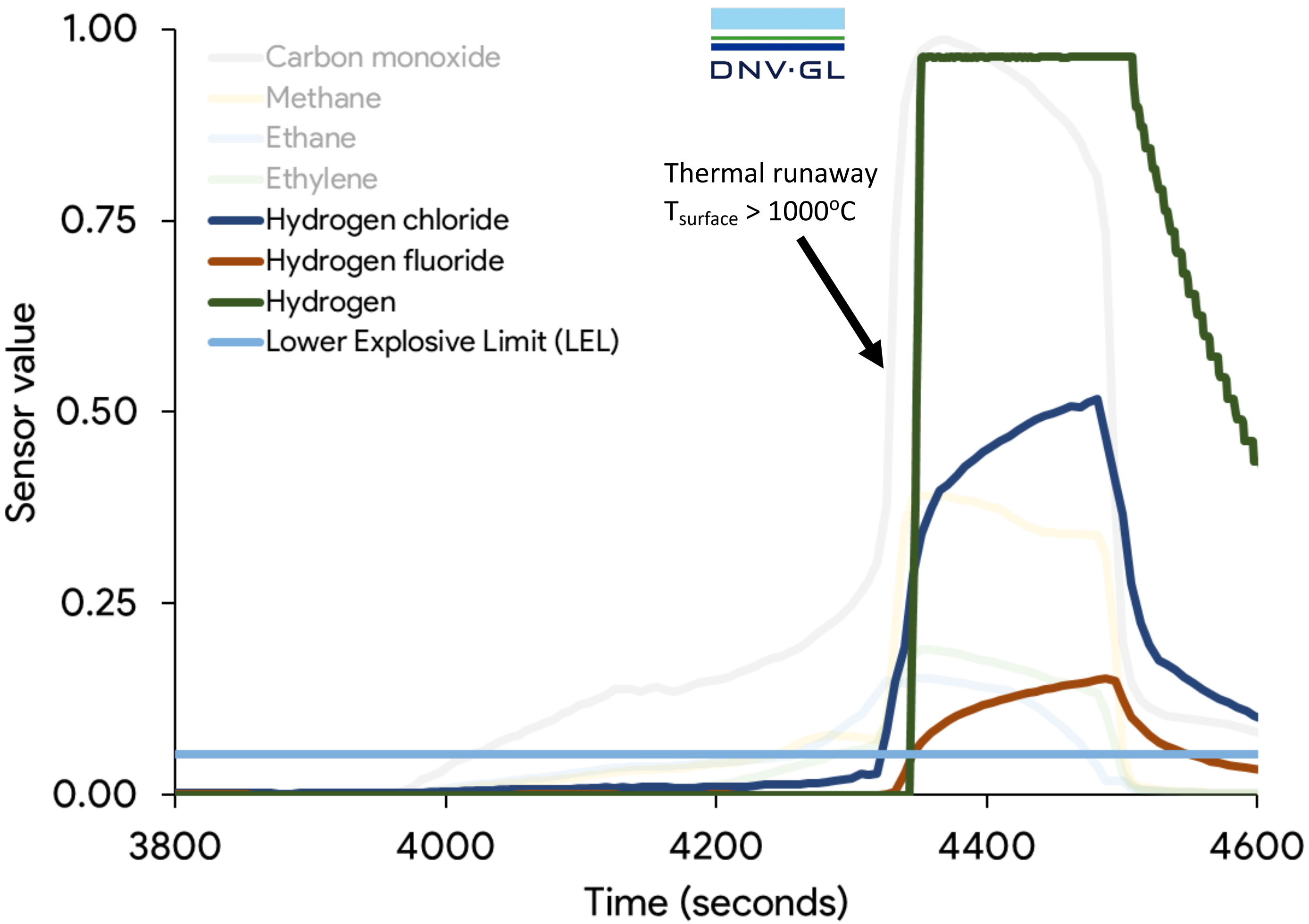
- H_2, HCl, and HF generated during thermal runaway
- LEL monitor does not alarm



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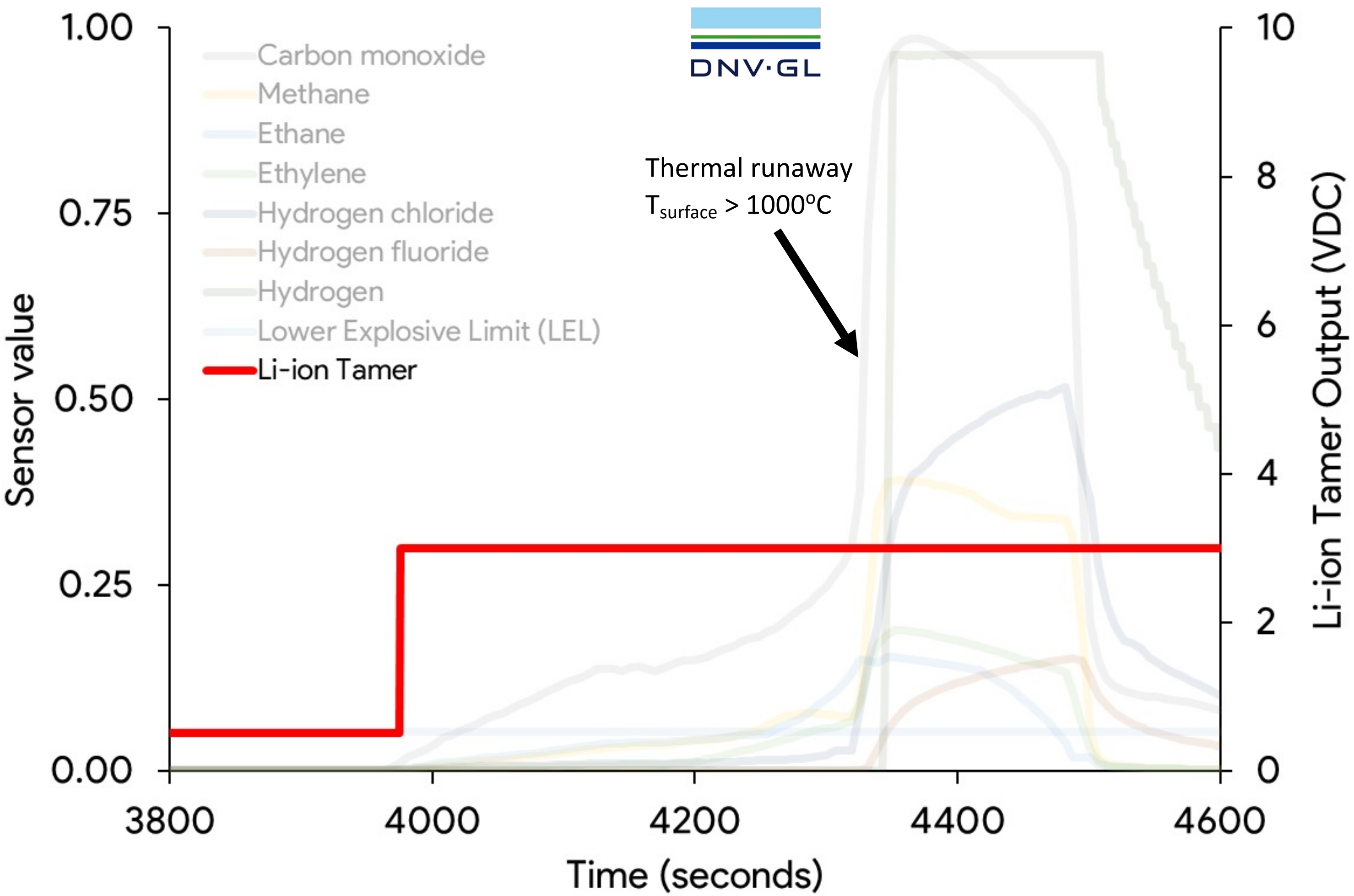

Li-ion Tamer provides 6.4 minutes of early warning prior to thermal runaway

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The DNV GL Report

Norwegian ship classification organization

- Released a report, outlining new rules for improving ship battery safety.
- The report analyses the risk of explosion and fire in battery installations on ships and the efficiency of fire extinguishing systems in case of a fire due to battery. Jan 8, 2020

Summarizing their conclusions:

"…LEL sensors and voltage do not provide a mechanism for early warning. **In comparison, the electrolyte vapor sensor indicates only seconds after off-gassing occurs. In addition, testing was performed where a cell was being overcharged and charging stopped when off-gas was released as indicated by the Li-Ion Tamer sensor. The cell temperatures ceased to increase, and off-gassing started to decline until the cell was considered stable.** Thus, demonstrating it is feasible to 'pull back' a cell after it has begun off-gassing but before thermal runaway occurs. **Meaning early detection, coupled with correct system shutdown measures is an important safety barrier."**

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Stage 1 Stage 2 Stage 3&4

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IFC Codes Chapter 12: Energy systems

TABLE 1207.6 ELECTROCHEMICAL ESS TECHNOLOGY-SPECIFIC REQUIREMENTS

COMPLIANCE REQUIRED[b]		BATTERY TECHNOLOGY				OTHER ESS AND BATTERY TECHNOLOGIES[b]	CAPACITOR ESS[b]
Feature	Section	Lead-acid	Ni-Cd and Ni-MH	Lithium-ion	Flow		
Exhaust ventilation	1207.6.1	Yes	Yes	No	Yes	Yes	Yes
Explosion control	1207.6.3	Yes[a]	Yes[a]	Yes	No	Yes	Yes
Safety caps	1207.6.4	Yes	Yes	No	No	Yes	Yes
Spill control and neutralization	1207.6.2	Yes[c]	Yes[c]	No	Yes	Yes	Yes
Thermal runaway	1207.6.5	Yes[d]	Yes	Yes[e]	No	Yes[e]	Yes

a. Not required for lead-acid and nickel-cadmium batteries at facilities under the exclusive control of communications utilities that comply with NFPA 76 and operate at less than 50 VAC and 60 VDC.

b. Protection shall be provided unless documentation acceptable to the fire code official is provided in accordance with Section 104.8.2 that provides justification why the protection is not necessary based on the technology used.

c. Applicable to vented-type (i.e., flooded) nickel-cadmium and lead-acid batteries.

d. Not required for vented-type (i.e., flooded) lead-acid batteries.

e. The thermal runaway protection is permitted to be part of a battery management system that has been evaluated with the battery as part of the evaluation to UL 1973.

1207.6.5 Thermal Runaway

- Where required by Table 1207.6 or elsewhere in this code, batteries and other ESS shall be provided with a listed device or other approved method to prevent, detect and minimize impact of thermal runaway. (1st venting)

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City of Austin, TX and State of CT - New IFC Code Chapter 12

- Edit Footnote e:

~~The thermal runaway protection is permitted to be part of a battery management system that has been evaluated with the battery as part of the evaluation to UL 1973~~

<u>**1207.6.6.** The thermal runaway detector shall activate upon detection of gas vapors produced by liquid electrolyte in a lithium-ion cell at the start of a battery venting event. Upon detection of gas vapors, the detection system shall shutdown the affected ESS rack and transmit a supervisory fire alarm signal. Detection of a thermal runaway event shall activate the mechanical ventilation when it is provided as method of explosion control.</u>

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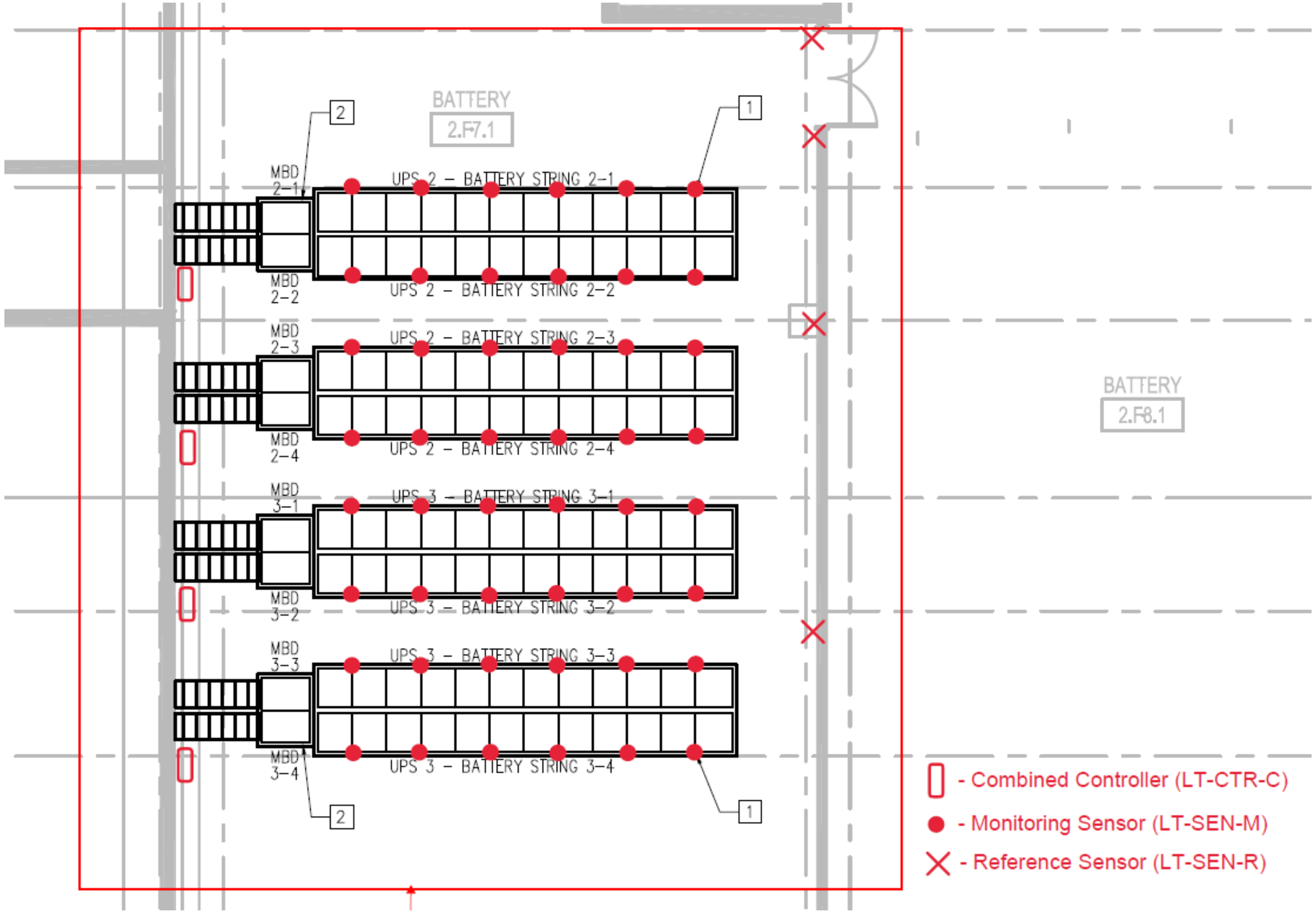
Design Examples

Design Options



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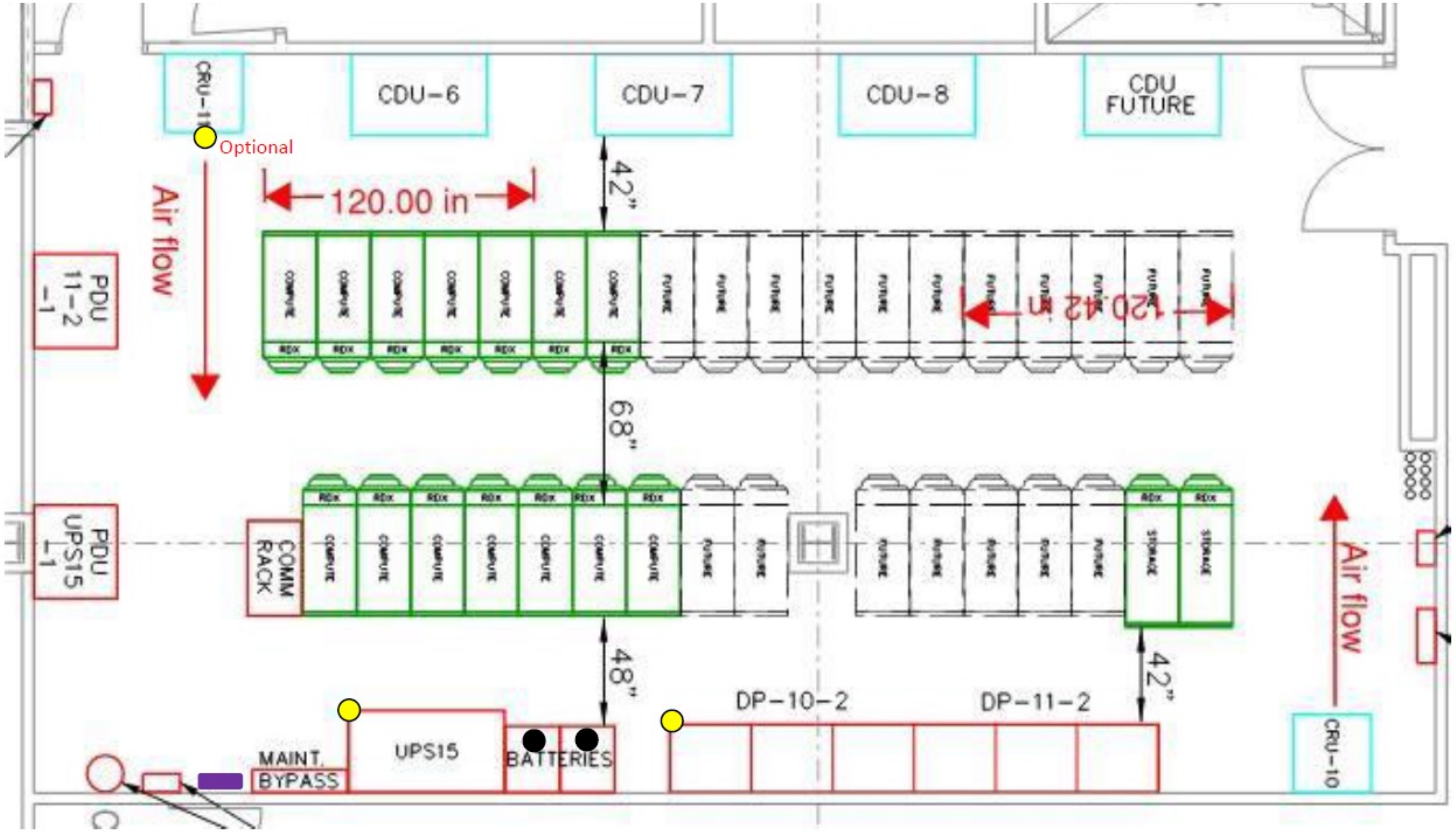
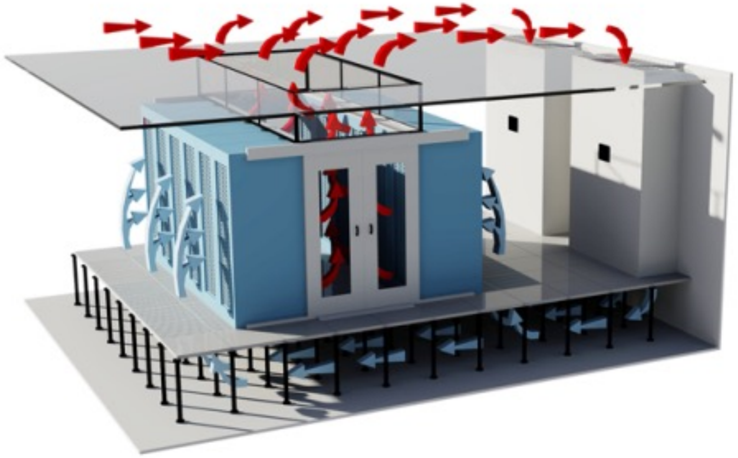
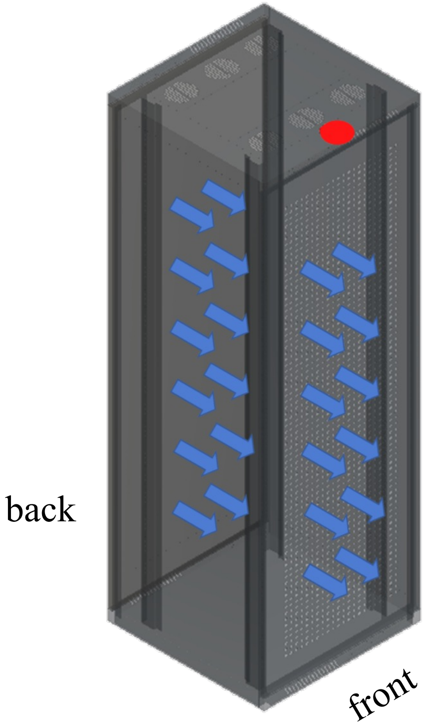
Design Options



Monitoring Sensor Placement

- Monitoring sensors are placed near or on the battery rack to detect off-gas from rack.
- Locate near vent outlets on the exhaust side of the cooling air.
- Airflow is not required for sensor operation.
- Four examples of these air flow patterns are covered below.



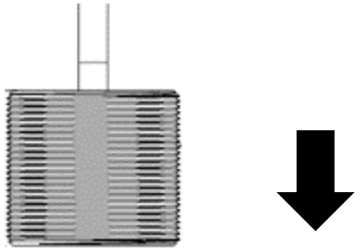


Example #1

Type: air in the back of the rack and out the front

Sensor placement: top front of the rack

Sensor orientation: sensing face pointing down



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Review

What are the three takeaways:

Golden Stage

- The limits of Lithium-ion batteries.
- Understanding four stages of failure: Abuse, Electrolyte vapor, Smoke & Fire
- Off Gas monitoring can prevent thermal runaway and avoid fire & smoke mitigation

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Thank you for Attending!

Technical Support

William Sudah
Tel: 786-299-2173
Email: William.Sudah@Honeywell.com

Greg Kaufman
Tel: 860.936.0583
Email: Greg.Kaufman@Honeywell.com

Industry Affairs

Scott Lang
Tel: (630) 715-7206
Email: Scott.Lang@honeywell.com

Richard Roberts
Tel: 630-338-7025
Email: Richard.Roberts@systemsensor.com

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