A*STAR
Battery Centre
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Fire Safety
Seminar 2025

Fire hazards of battery energy storage

The role of standards and testing in safe deployments

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Battery hazards

Hazards of batteries

Batteries (especially those utilizing flammable organic electrolytes) present a number of hazards

Cell opening / leakage

Release of substances and decomposition products that are:

- An irritant / harmful
- Corrosive and flammable
- Toxic (or highly toxic) and carcinogenic

Thermal runaway

Self-accelerating, exothermal chemical reaction, leading to fast increase in temperature:

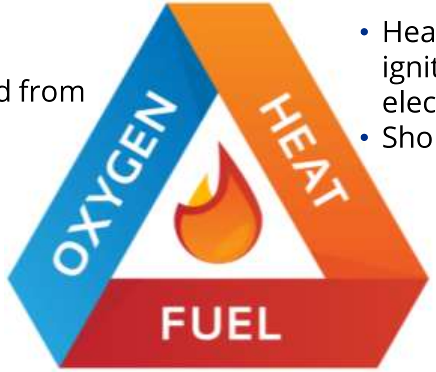
- "Containment" very difficult
- Rapid pressure increase → release of smoke, possible rupture of cell
- Possible Fire / Explosion

Fire

Internal (e.g. misuse, production issue) or external (e.g. neighbouring cells) sources of heat lead to:

- Electrolyte evaporation / decomposition
- Decomposition of SEI & cathode materials
- Internal pressure increase & venting
- Ignition energy available → Fire

- Air
- Released from cathode



- Heat beyond auto-ignition temp. of electrolyte
- Short circuit, sparks

- Electrolyte, separator
- Carbon from anode
- Other cell components

Hazards of batteries – fundamentals of battery fire

Triggers

Charging related

Overcharge
(i.e. BMS failure)
Joule heating
Low temp. charging

Discharging related

High-rate discharge
Deep discharge
(i.e. BMS failure)
Unequal discharge of
cells in series

External sources

External fire
High heat environment
Cell production issue
Mechanical damage / stress
(i.e. puncture, dent, drop, vibration)
Leakage

High heat generation

External short circuit

Water / contamination,
arching discharge,
mechanical short

Internal short circuit

Cu / Al dissolution, Li plating
(dendrites), separator
damage, decomposition
(electrolyte, cathode, anode)

Exothermic reactions,
Thermal runaway
(i.e. positive feedback)

Cell temperature increase

Impact on cell

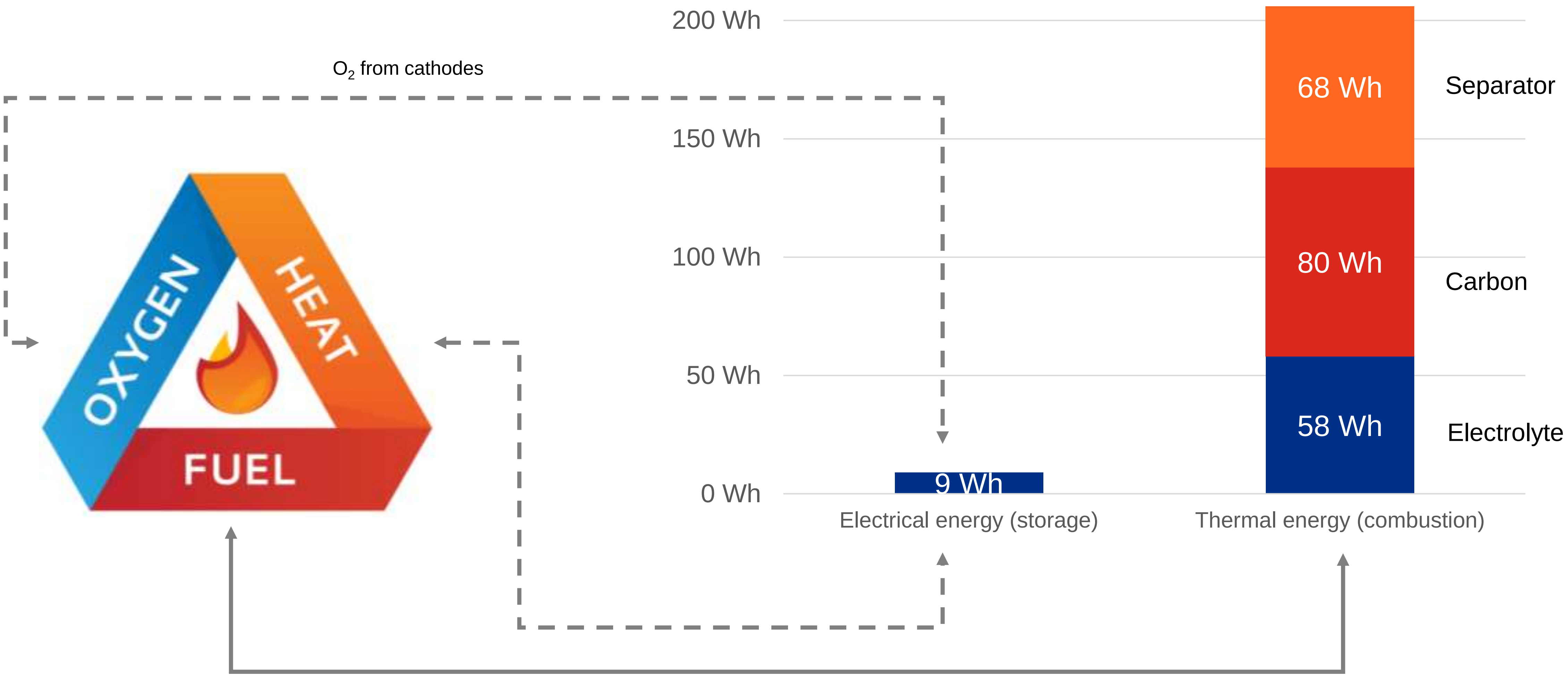
Degradation, capacity loss

Physical changes: Swelling, Venting, Leakage, Rupture

Fire Explosion

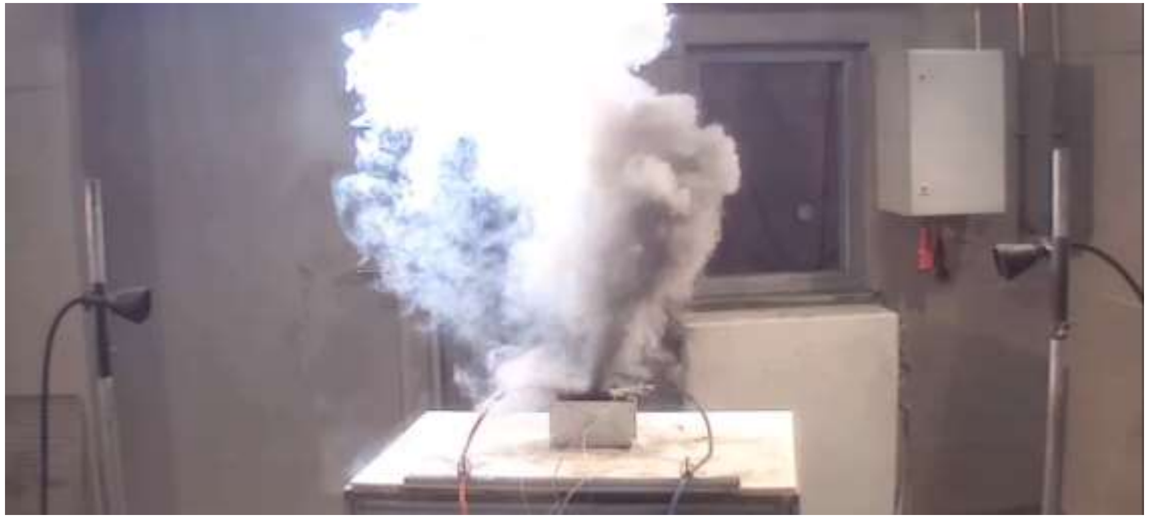
Propagation (cell, module, system)

Hazards of batteries – Energy stored in small-format li-ion cell



Hazards of batteries – gas composition from venting cell

Abuse - Overcharge



→ large gas volume 360 L

- flammable: hydrogen (50.4 L), methane, ethane, ethylene, propane, propylene
- suffocating: nitrogen, carbon dioxide
- toxic: phosphine, hydrogen fluoride (150 ml), carbon monoxide
- carcinogenic: aldehydes, Co/Ni powders

	Unit	Overcharge test in autoclave
V(released gas)	L	360
Fluorine	µg/L	353.3
O_2	vol %	1.3
N_2	vol %	13.7
H_2	vol %	14.2
CO_2	vol %	22.4
CO	vol %	15.2
Phosphine	mg/m^3	0.1
Formaldehyde	$µg/m^3$	<2
Acetaldehyde	$µg/m^3$	1,720
Propionaldehyde	$µg/m^3$	214
Butyraldehyde	$µg/m^3$	112
Methane	vol %	8.7
Ethane	vol %	4.5
Ethylene	ppm (vol)	34,000
Propane	ppm (vol)	4,900
Propylene	ppm (vol)	17,000

Hazards of batteries – Safety incidents

Consumer

1. There have been 586 injuries, 104 fatalities, reported across 12 countries in 2024
2. Average of more than 2 battery incidents per week for air travel
3. In Singapore, average one consumer battery fire every 4-5 days in 2024

Stationary/Industry

1. Generally, one fire incident every 35 GW deployed
2. In Singapore, 3 reported incidents in 2024
3. Singapore data centre fire in Loyang took more than 36 hours of fire-fighting

Electric Vehicles

1. Only 1 reported EV fire in 2024 (<0.01%)
2. However, current stock of EV is still low (~4%); at full electrification, ~1 EV fire a week
3. Confined parking spaces

Sources: UL, Energy Storage News, SCDF annual statistics

Hazards of batteries – field incidents

Gothenburg, Sweden, April 2023


- Fire of a battery container (part of a larger BESS installation) during commissioning
- Batteries were not in operation at the time of the incident
- Smoke release caused fire fighters to deploy cutting extinguishers to cool battery
- 5 min later, an explosion occurred, resulting in doors blasting open and visible flames inside the container
- Investigations revealed most likely cause water leakage during pressure test of battery liquid cooling system resulting in short-circuit
- Process failures and filling errors by the third-party system integrator pointed at as cause for leakage

McMicken in Surprise, Arizona, April 2023


- Sudden voltage drop in a cell during charging & thermal runaway moments later propagated through system
- Installed Novec 1230 agent deployed; 3h later, explosion occurred when fire fighters opened the container door, resulting in severe injuries to fire fighters
- Several cell samples from BESS showed evidence of lithium plating (indicating prolonged wrong usage); internal short determined to be root cause of incident
- No anti-propagation measures, insufficient fire suppression and no gas sensors that could have warned responders

Sources: Official investigation reports (Räddningstjänsten Storgöteborg, DNV-GL)

Hazards of batteries – fire fighting solutions

Gasses (CO_2, N_2, aerosols)

- Feasible in enclosed spaces
- Relatively light, stored compressed
- Good to protect equipment / further shorting in BESS
- Limited cooling effect
  → propagation cannot be effectively stopped
- Risk of re-ignition
  → empty gas cylinders after first discharge

Water

- Lithium-ion bat. fire not a metal fire (≠ lithium metal bat.)
- Well-established deployment mechanisms, available in abundance
- Large amount of water needed, run-off contaminated, can cause further shorts / damage
- High cooling effect prevents propagation and re-ignition
- Water misting & mixing in additives can improve response further
- Overall best method for extinguishing

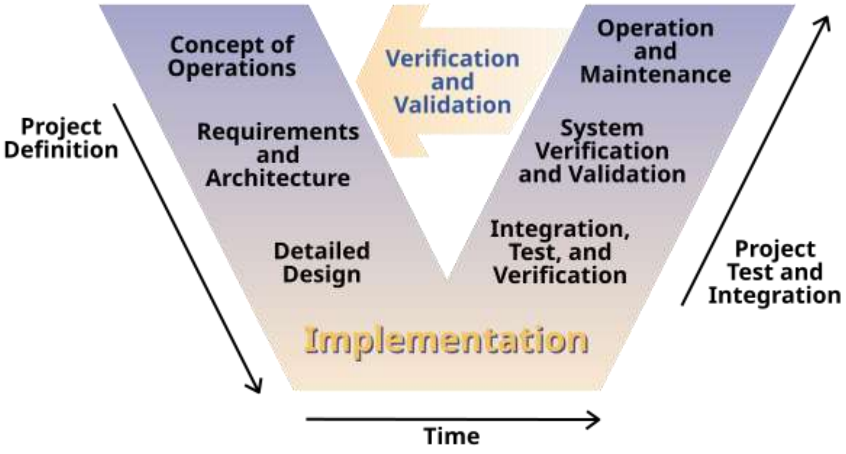
Powder

- Insulating, prevents further shorts
- Low cost
- No cooling effect
  → propagation cannot be effectively stopped
  → risk of re-ignition
- Various tests show poor initial extinguishing effect against lithium-ion fires

Sources (Images): Johnson Controls, Winan, iCO

Battery safety testing

Battery safety testing – ensuring safe deployments of BESS



Core principle in safe technology is risk assessment, implementation of measures & validation

Risk = Probability x Severity → lower only due to fundamental technology change

↓

Implementation of measures to lower probability
→ need to be verified to be effective

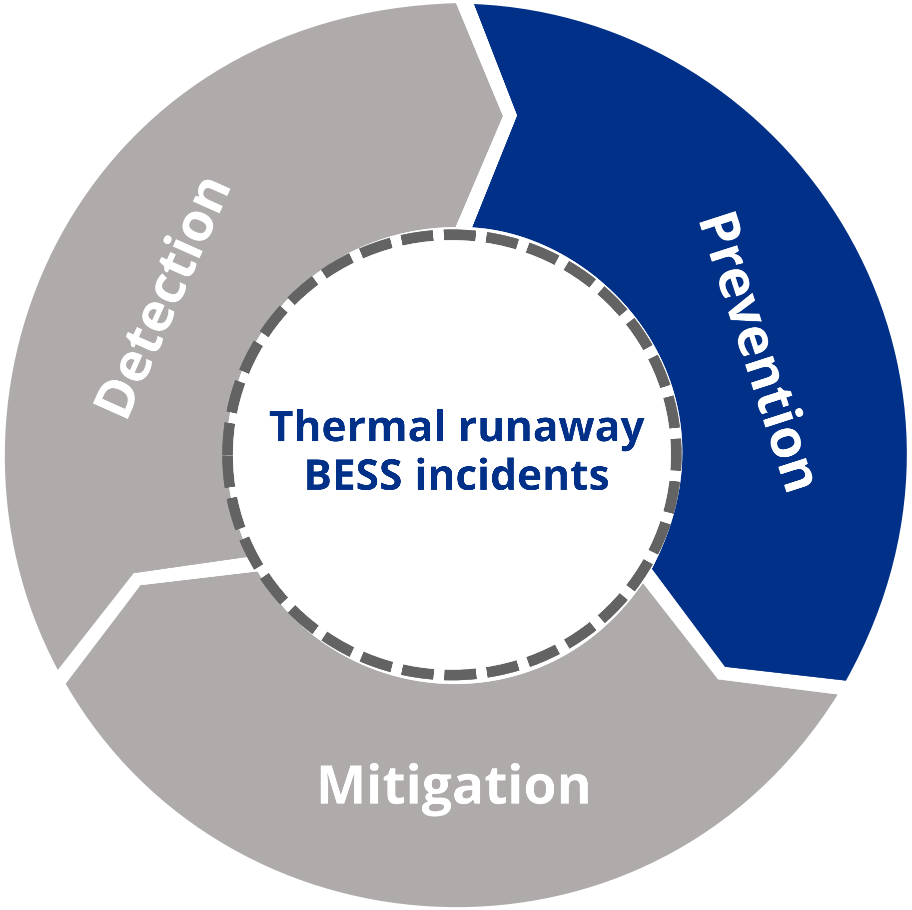
Testing essential to:

- Identify systematic failures that occurred in design phase before such failures become costly (recalls & legal cases)
- Uncover system response to unexpected & worst-case scenarios in application
- Understand & characterize system behaviour (thermal runaway & fire simulations challenging) to develop emergency procedures & fire fighting response

“You've got to be very careful if you don't know where you are going, because you might not get there.”
- Yogi Berra

Source (Image): US Federal Highway Administration

Battery safety testing – ensuring safe deployments of BESS



Prevention by Design, QC, BMS & EMS

Quality control

- Usage of certified components & hazard analysis in planning phase
- Factory- / facility inspections & assessments
- Trained personnel (also at installer)

BMS & EMS

- Monitoring of voltages, temperatures and currents
- Control of cooling strategy & detection of cooling issues (e.g. coolant leakage)
- Energy management, e.g. predictive load reduction
- Access control & Cybersecurity

Constructive measures / design

- Thermal- and mechanical design

→ Testing essential to verify design & effectiveness of measures

Battery safety testing – landscape of safety standards

ISO 12405-4: Test specifications for li-ion traction battery packs
IEC 62660: Secondary li-ion cells used for propulsion of electric vehicles
UN ECE R100: Safety requirements on electric powertrain
UL 2580: Batteries for use in EV

ISO 18243: Safety requirements & tests for electric mopeds / motorcycles
EN 50604-1: Secondary li-ion batteries for light electric vehicles (LEV)
UN ECE R136: Safety requirements on electric powertrain for motorcycles
UL 22271, 2272, 2849: Batteries for use in LEV, PMD, Ebikes

IEC 62841-1: Electric hand-held tools
IEC 62133-2: Secondary li-ion cells & batteries for portable applications
UL 2054: Household and commercial batteries
IEC 60335-1: Safety of electric household appliances

IEC 62619: Secondary li-ion cells & batteries for industrial applications
IEC 62485, 62933-5: Safety of (grid-integrated) battery installations
UL 1973, 9540 & 9540A / 9540B: Stationary (battery) energy storage systems
CSA TS-800: Large-scale fire test procedure for stationary ESS

UN 38.3: Transportation testing
IEC 62281: Transportation testing

Sources (Icons): Freepik, berkahicon and monkik

Battery safety testing – Common tests from standards

Electrical tests

- Abnormal charge, continuous charge, overcharge
- Forced discharge (polarity reversal) / deep discharge
- External short circuit
- Insulation resistance & HV test
- Internal short circuit (*)

Thermal tests

- Thermal cycling (e.g. -40 °C to +70 °C)
- Thermal stress (up to +130 °C)
- Molded case stress test
- Projectile- & external fire test

Mechanical tests

- Crush
- Vibration
- Shock
- (Blunt) Nail penetration – ceramic & steel nail
- Impact & drop (free fall)

Others

- High altitude (low pressure)
- Propagation testing
- Heat release rate & heat flux, vent gas composition
- Saltwater submersion
- (Functional) safety testing of BMS
  - Over / under voltage & current, overtemperature
  - Insulation resistance, Dielectric strength

(*) Requires cell preparation during cell manufacturing

Battery safety testing – Singapore context

Cell / battery level

- Adoption of IEC 62619 and UL 1973 for secondary cells, cell blocks and batteries with national foreword
- Adoption of IEC 62932 2-2, UL 1973 for flow batteries
- Code of Practice for Transport and Storage of New and Spent Batteries in planning, likely to include harmonized transportation test requirements

System level

Technical Reference (TR) 77 - Electrical Energy Storage (EES) System

- Part 1: Modified adoption of IEC TS 62933-3-1 (Planning and performance assessment of ESS)
- Part 2: Modified adoption of IEC TS 62933-5-1 (Safety considerations for grid-integrated EES system)
- Maximum 600 kWh, cluster of battery rack max. 250 kWh, spacing 1m from other clusters
- Additions for flood protection, thermal runway handling, dust / moisture / corrosion protection

UL 9540, UL 9540A for ESS at system level (inclusive propagation testing)

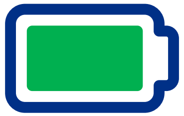
Battery safety testing – Singapore context

ESS requirements in the Singapore Fire Code (Section 10.3)

- In general max. 600kWh per fire compartment, 2h rated compartment, doors, automatic sprinkler (or mist) is required, same level as fire engine accessway, mechanically ventilated to be ≥6 air changes per hour
- Special requirements for temporary ESS on construction sites, Battery swap stations and Basement ESS installations
  - Basement ESS classified as small underground ESS (up to 250 kWh per compartment & 500 kWh in aggregate) and large underground ESS (up to 600 kWh per compartment)
  - Requirements on separation distances, compartment size, fire protection system, monitoring & alarm system, smoke purging & pressure relief, fire fighting access, etc.
  - For large underground ESS & small underground ESS not fulfilling spacing / requirements subject to UL 9540A testing and NFPA 855 Hazard Mitigation Analysis

Battery safety testing – UL 9540A

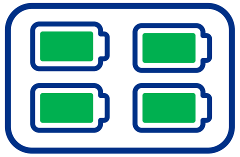
- UL 9540A is test method (only test report, no certification) for evaluating the thermal runaway propagation & fire / explosion hazard in BESS for residential & industrial usage (no mobility applications covered)
- Testing conducted in four levels (cell, module, unit, installation) – when defined performance criteria are met for a level, testing can stop at respective level; during test, collection of vent gasses, heat flux, HRR



Cell level

Test purpose:
- Determine if cell exhibit thermal runaway & TR characteristics
- Gas composition and flammability

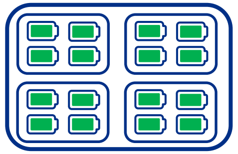
Pass criteria:
- TR cannot be induced *and*
- Cell vent gas is nonflammable



Module level

Test purpose:
- Propensity for TR propagation
- Heat & gas release rates
- Fire / explosion hazards

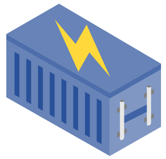
Pass criteria:
- Cell vent gas is nonflammable
- No spread of fire outside module
- Module exterior temperature not exceeding cell venting temperature



Unit level

Test purpose:
- Heat & gas release rates (severity / duration)
- Evaluation of fire spread & explosion hazards

Pass criteria:
- Target BESS unit temperature less than cell vent temp.
- Temp. increase of walls < 97°C
- No fire outside initiating BESS & no explosion
- Heat flux (egress) ≤ 1.3 kW/m^2



Installation level

Test purpose:
- Effectiveness fire protection
- Heat & gas release rates & explosion hazards

Pass criteria:
- Target BESS unit temperature less than cell vent temp.
- Temp. increase of walls < 97°C
- No fire outside test room, no explosion hazards exhibited
- Heat flux (egress) ≤ 1.3 kW/m^2

THANK YOU

ASTARSG

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