



Energy Storage Safety & Risk Mitigation

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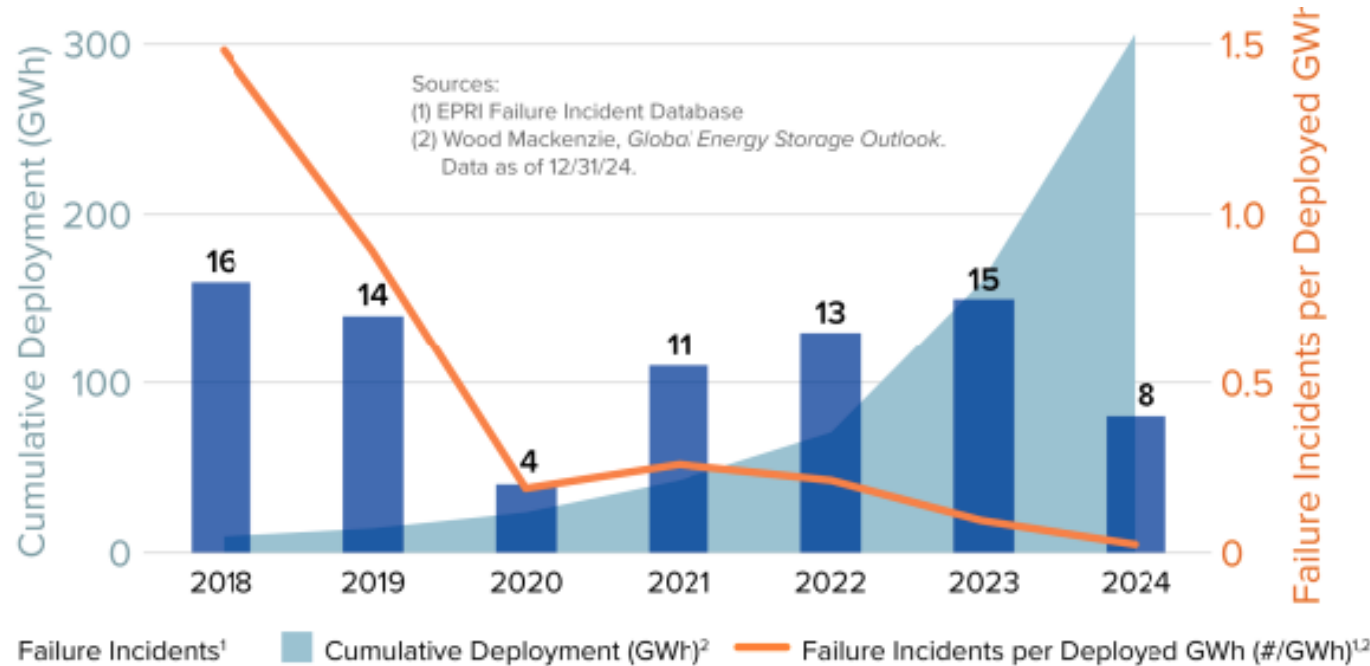


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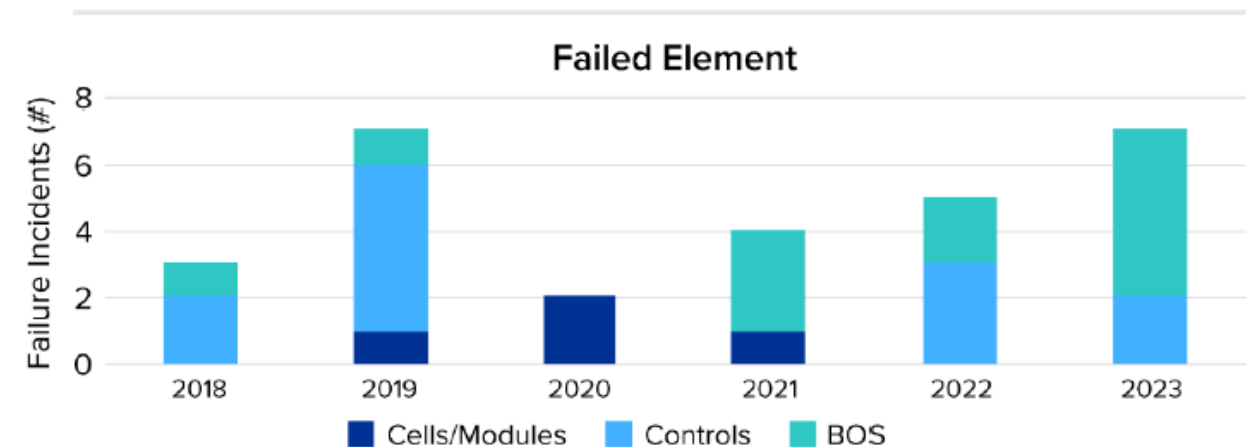
W O R K S H O P

Safety related incident trends and associated mitigation steps



- Codes and Standards development enhance safety
- UL 9540 establishes system level safety requirements
- UL 9540A provides test method in support of UL 9540 to evaluate fire propagation behavior at cell, module and system level
- NFPA 855 establishes requirements for siting, spacing, ventilation and coordination with fire authorities for effective emergency response.

- Better BMS design enables monitoring of voltage, temperature and current at the cell & module level and early fault detection
- Gas detection, improved venting and cell/module level thermal isolation further enhance safety
- The EMS controls battery operation within the parameter range allowed by the BMS. The battery parameters accessed by EMS at the power control system interface



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Source: EPRI Control and balance of system failure dominate



Fire at largest Storage Site – Moss Landing January 16, 2025



LG Energy Solution TR1300 NMC battery racks inside MOSS300, pictured in 2020. Image: LG Energy Solution



Aerial view of the site taken in 2020: the long building in the foreground is a former turbine hall which housed MOSS300. Image: LG Energy Solution

- Moss Landing Energy Storage Facility in Monterey County, California, US
- Project owner Vistra Energy
- Insufficient release of HF gas or particulate matter to cause risk to public
- Active flames lasted 2 days, smoldering still seen 6 days later
- Existing buildings that houses gas turbines repurposed for 300 MW. 1200 MWh
1st Phase (2nd Phase 100 MW, 400 MWh, 3rd 350 MW, 1400 MWh)
- Phase 1 BESS within the gas turbine repurposed building burned down (used NMC batteries from LG Energy Solution)
 - The repurposed building did not appear to have fire barriers between racks
- Faulty sprinkler systems led to spraying of water onto modules on two separate occasions earlier – resulting in revamp of the sprinkler system
- The 250 MW Gateway project in Otay Mesa , CA experienced a fire in September 2024. This was also situated in a building; but this had fire barriers, hence only a fraction of the building was damaged.
- Both these projects built before CA fire codes updated
- The 183 MW/730 MWh Eikhorn Battery at Moss Landing, owned by PG&E had one Tesla Megapack catch fire on September 2022, which lasted 5 days

Risk Mitigation Strategies

- Movement towards LFP for BESS – greater onset temperature and lower energy associated with thermal runaway, lower maximum temperature
- Attack problem at the root
 - prevent cell to cell propagation
 - prevent module to module propagation
- NFPA 855 - limits the energy per rack & unit, requires minimum distance between racks and containers, and mandates large scale fire testing (CSA/ANSI C800:25, UL 9540A) if these limits exceeded
- Thermal propagation mitigation using heat absorbing material, explosion risk reduction using NFPA69-compliant ventilation, retrofit options for legacy systems to improve safety (see Moss Landing Phase 1)



Li-ion battery BESS accidents in 2024

| Location | Event date | Description |
|---------------------|----------------|--|
| Neermeer, Germany | April 27, 2024 | One of several lithium-ion containers was observed to be smoking. The fire department consulted with the operator and opened the container, resulting in an explosion. Two firefighters were injured. The fire was extinguished in ten hours. |
| San Diego, CA, U.S. | May 15, 2024 | The energy storage facility was involved in a fire, and water was pumped into the building's fire suppression system to extinguish it. A 600-foot safety barrier was maintained for over twenty two hours due to air monitors showing high levels of hydrogen. The fire was declared extinguished the next day but reignited several times until the fire department left the scene nearly seventeen days later. |
| Santa Ana, CA, U.S. | July 17, 2024 | A Battery Energy Storage System BESS fire occurred in an industrial area, leading to a one-hour evacuation in the area due to smoke. |
| Escondido, CA, U.S. | Sept. 5, 2024 | One of twenty four containers caught fire. Businesses adjacent to the substation or within approximately 0.25 mi were evacuated. |
| Singapore | Sept.10, 2024 | An explosion and fire occurred in a lithium-ion BESS at a data center. Four water jets and the sprinkler system were used to contain the fire, and an unmanned firefighting robot was used to cool the batteries. The fire was declared to be under control after two days. |

[1] BESS Failure Incident Database - EPRI Storage Wiki

- Accidents involving Semi-truck hauling batteries
- Batteries being stored in shipping containers, warehouses (for recycling)
- Lithium-ion battery recycling plant
- Incidents at test & engineering site
- Battery containers not connected to grid caught fire. **Firefighters opened the container which resulted in explosion injuring two firefighters. Similar incidents have occurred in the past**



Standards Framework for Li-ion battery storage

- UL 1642 – single cells
- UL 1973 – modules and packs
- UL 9540 – for battery energy storage system (BESS)
- UL 9540A, CSA/ANSI C800:25 – Fire test, supports UL 9540
- NFPA 855

NFPA 855 Standard for the Installation of Energy Storage Systems

- NFPA 855, “provides guidelines and requirements for the safe design, installation, operation, and maintenance of energy storage systems”
 - Li-ion, lead acid, flow, fuel cells, other
 - focuses on “fire protection and prevention”
- Describes proper siting, including clearance and separation from buildings, minimum distance from other systems/equipment, clear signage, ventilation requirements
- Fire resistance barriers to contain fire, guidelines for fire suppression system installation
 - Interacts with NFPA 69 “to provide engineering design and risk mitigation” for explosion/deflagration
 - Provided recommendation for large scale fire testing (LSFT)
 - ✓ **2026 edition makes this mandatory**
- Ensure BESS equipped with BMS that monitors key parameters to prevent abuse and identify problems early
- Electrical wiring & safety – “requirements for cable management, grounding, and circuit protection”
- O&M guidelines
- Emergency response plan
- End of life considerations / decommissioning
- NFPA compliance requirements vary by location; developers & operators should consult with local authorities



Large Scale Fire Testing CSA TS-800:24, UL 9540 A

- NFPA 855 2026 makes large scale fire testing (LSFT) mandatory
- Several companies have announced test results, and several expected to do these tests
- UL 9540A developed cell (and module level) fire tests
- LSFT tests developed under Technical Specification CAS TS-800:24) as companion to UL 9540A cell tests
- LSFT done to ensure if protection devices fail (fire suppression technologies such as immersion cooling, aerosol-based, off-gas detection) and fire occurs, the fire is contained to a single unit (a container or a cabinet with several racks)
 - Moss Landing Phase 1 fire not repeated, more like Thurrock BESS in UK where fire limited to one unit
 - Latter complies with NFPA 855: fire hydrants + adequate spacing between units, emergency plan in place

| Company | Product | Date |
|----------------|---|-------------------------------|
| BYD | MC Cube | June 2025 |
| Canadian Solar | SolBank 3.0 BESS | June 2025 |
| Clou ESS | Aqua C2.5 | May 2025 |
| Envision | Envision Smart Energy Storage | July 2025 |
| Fluence | Gridstack Pro 5000 | June 2025 |
| Hithium | Block 5MWh BESS | June 2025 |
| Huawei | LUNA2000-4472 Series | February 2025 |
| Prevalon | HD5 | April 2025 |
| Rept Battero | Grid-scale BESS product | July 2025 |
| Sungrow | PowerTitan 1.0, PowerTitan 2.0 | June 2024, April 2025 |
| Trina Storage | Elementa 2, Elementa 2 Pro | September 2024, December 2025 |
| Wärtsilä | GridSolv High Energy, Quantum 2 and Quantum 3 | 2023/2024 |

- Sungrow 2024 test broadcast live (DNV)
- Sungrow 2025 test 25-h burn with no unit to unit spread
- Hithium 15-h “full combustion” at 100% SOC (CSA)
- Fluence 5 days fire test (CSA)

Large Scale Fire Test Procedure CSA TS-800:24, CSA C800-2025

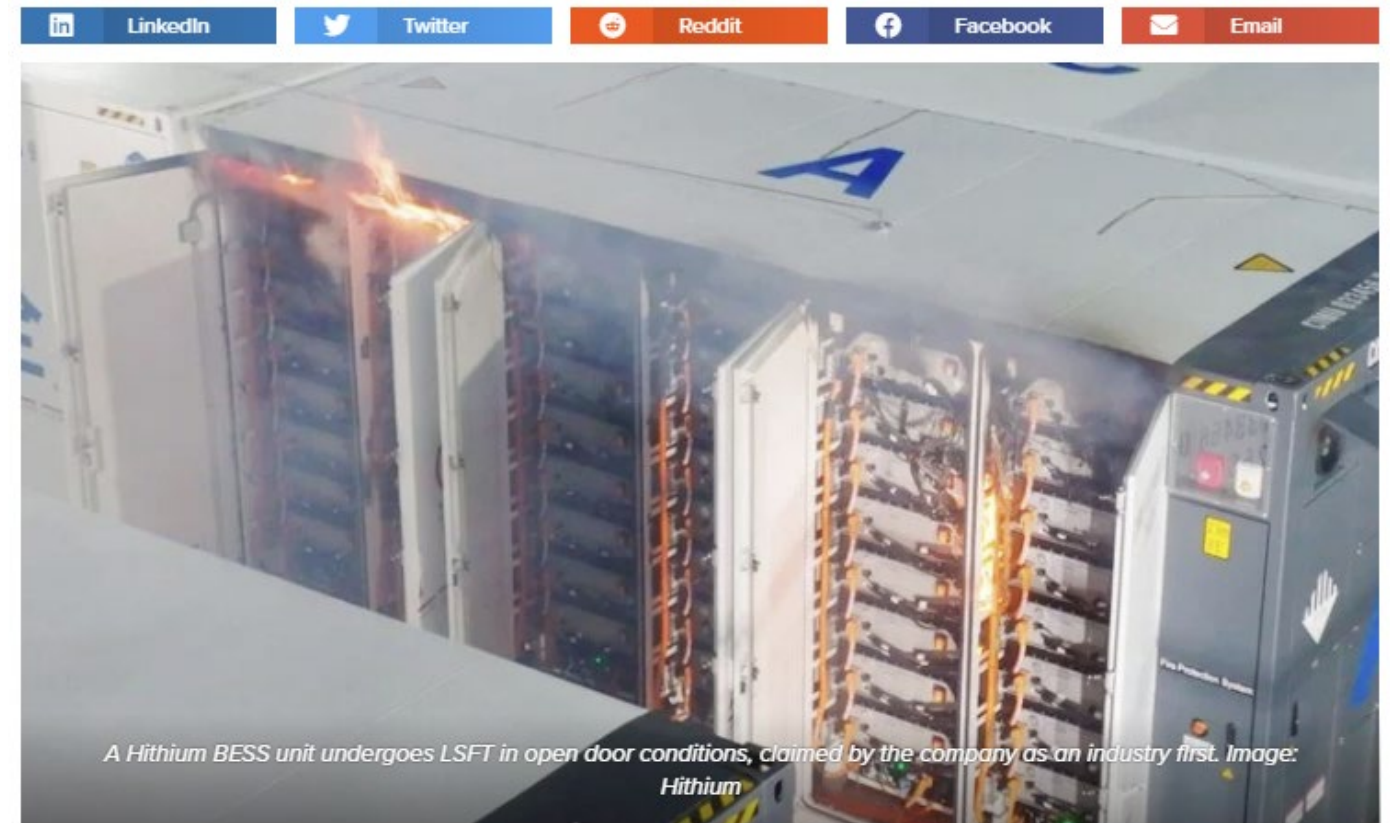
- TS-800 test procedure to verify fire events from a BESS unit does not propagate to adjacent units
- Aligns with International Fire code (and CA fire code)
- UL 9540A testing of cells & modules does not include ignition of released flammable gases
- TS-800 “forces fire condition in one unit to determine if fire propagation occurs to adjacent units
- This has now been converted to a national standard CSA C800-2025 recognized in the US and Canada



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Large Scale Fire Test UL 9540A New (6th) Edition Test method for evaluating thermal runaway fire propagation in BESS

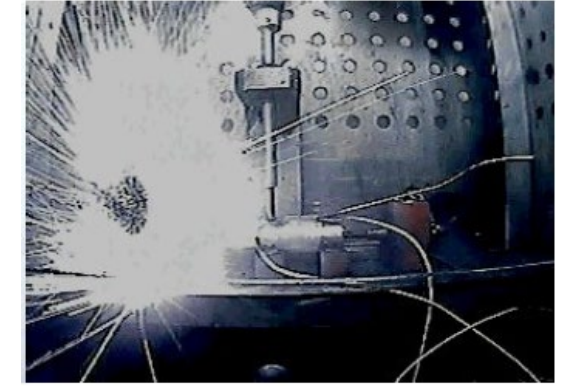
- Adds requirements for LSFT, in addition to cell & module tests – adds system level safety
- A single BESS unit is set on fire, with fire suppression and detection systems disengaged, with other units nearby
- Hailed by CSA Group “new precedent in the energy storage system (ESS) testing and certification ecosystem.”
- Per CSA Group, the CSA/ANSI C800:25 is complimentary to UL9540A
 - Provides data on heat release rate, gas composition
- It appears there is sufficient commonality between the two standards



Hithium BESS undergoes LSFT in open door conditions

<https://www.csagroup.org/testing-certification/product-areas/power-generation-energy-storage/battery-energy-storage/large-scale-fire-testing-lsft-procedure-csa-ts-80024/?srsltid=AfmBOoqEWvGY9AOom8KNx3XUZDINwlj-2fiXCtA3nhFyB0LsMHstnUIQ>

<https://www.energy-storage.news/the-energy-storage-industrys-new-standard-for-safety-and-reliability-csa-c800-2025/>



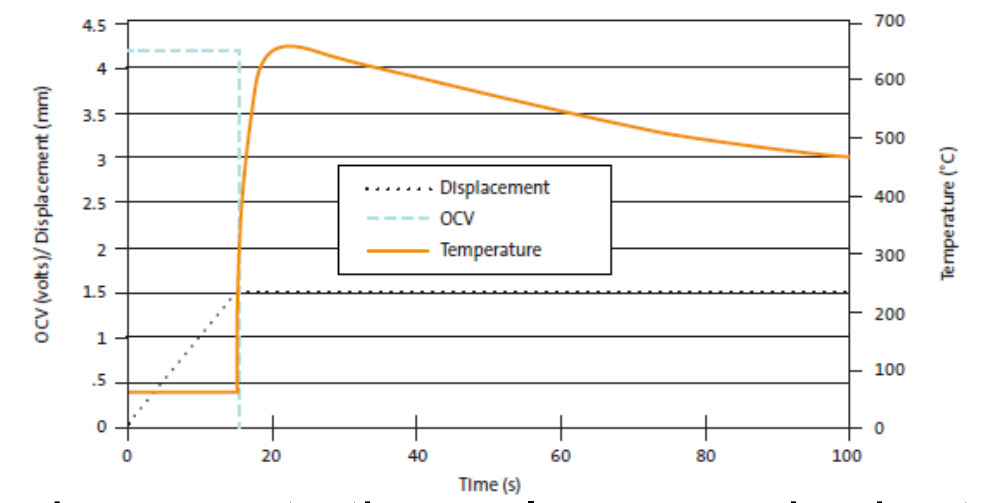
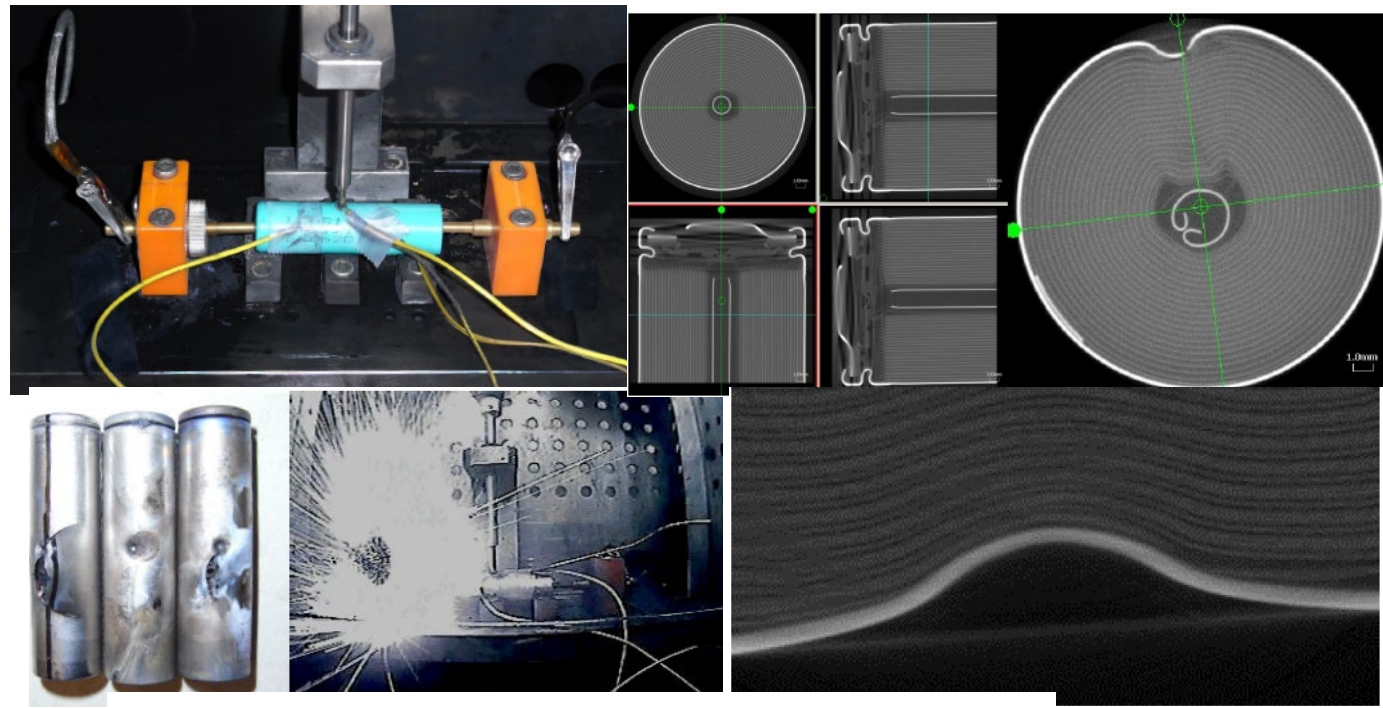
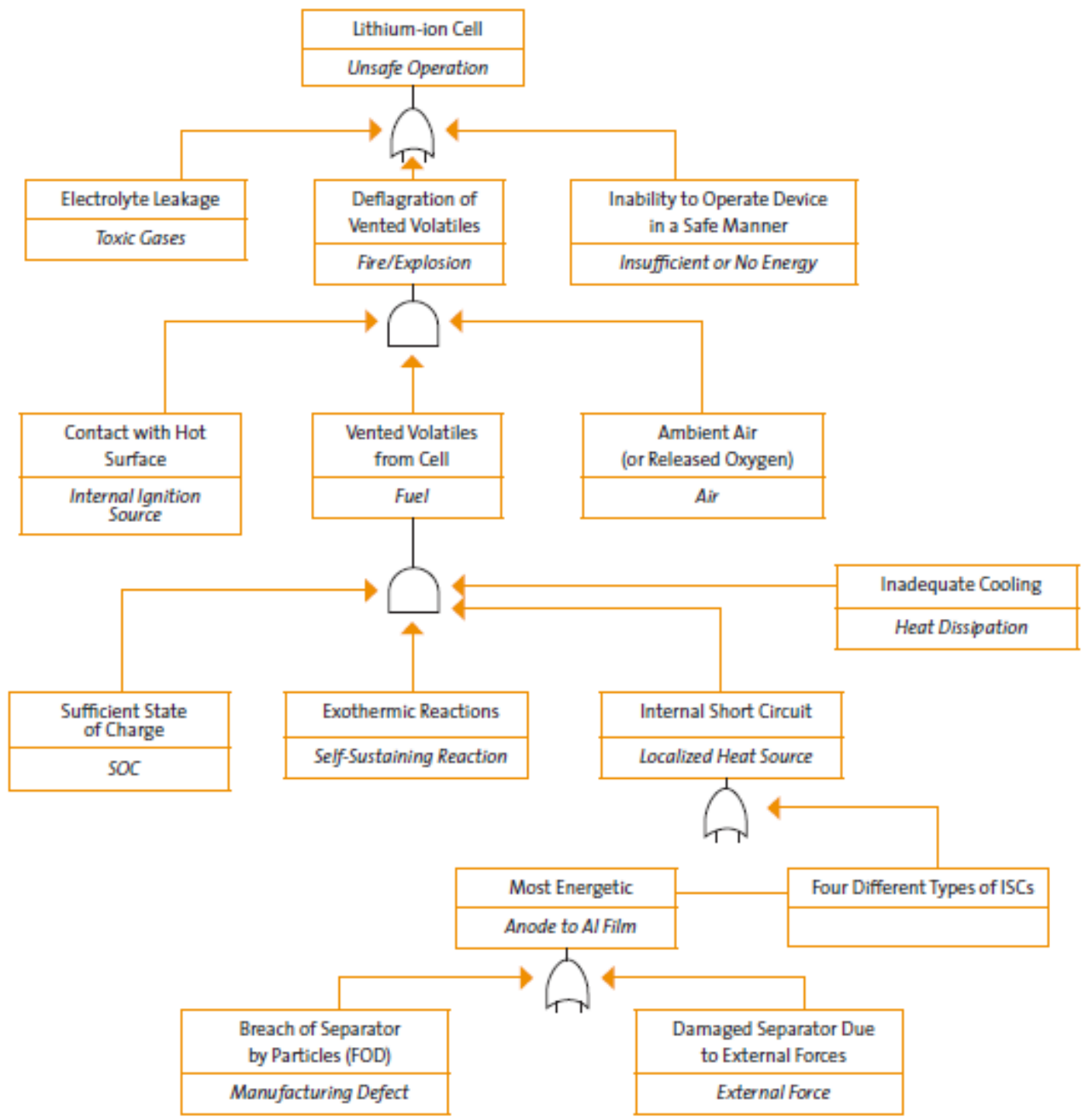
- UL 1642 – various safety tests
 - similar tests described in UL 1973 for modules and packs, UL 2054 for household and commercial batteries – separate tables for cells and packs, UL 2580 for batteries used in EVs, UL 2271 for Light EVs
- Short circuit, overcharge, overdischarge, vibration, shock, crush, impact, heating, fire
- Short circuit – connect battery terminals to low resistance load. Continue discharge till fire or explosion occurs, or cell voltage $< 0.2V$ and case temperature within 10 deg C of ambient.
- Nail penetration, indentation (latter is more severe)
- Abnormal charge current – overcharge at current below level where protective device opens for 7 hours.
- Heating test. The battery is heated at a rate of 5 deg C/min in an oven from 20 deg C to 130 deg C, and left at the high temperature for 10 minutes.
- Fire exposure – the sample placed on a screen (Al wire) and heated from below by a burner with bright blue flame till sample explodes or has ignited and burns out

UL 1973 for modules and packs

- UL 1973 – various safety tests
 - similar tests described in UL 2054 for household and commercial battery pack, UL 2580 is for batteries used in EVs, UL 2271 for Light EVs
- Crush, drop, short circuit, overcharge, overdischarge
- Short circuit – connect battery terminals to low resistance load. Continue discharge till fire or explosion obtained, or cell $V < 0.2V$ and case temperature within 10 deg C of ambient.
- Abnormal charge current – overcharge for at least 7 hours.
- Heating test. The battery is heated at a rate of 5 deg C/min in an oven from 20 deg C to 130 deg C, and left at the high temperature for 10 minutes.
- Fire exposure – the sample placed on a screen (Al wire) and heated from below by a burner with bright blue flame till sample explodes or has ignited and burns out

UL Standards for Li-ion battery storage – fault tree & indentation test

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- Predecessor to thermal runaway is short circuit
- Indentation short circuit test is worst case, hence developed by UL
- Layers below indent deformed, separator mechanical failure leads to short circuit
- Worst case is direct contact of +ve and -ve current collectors



Mapping of Li-ion cells and batteries standards

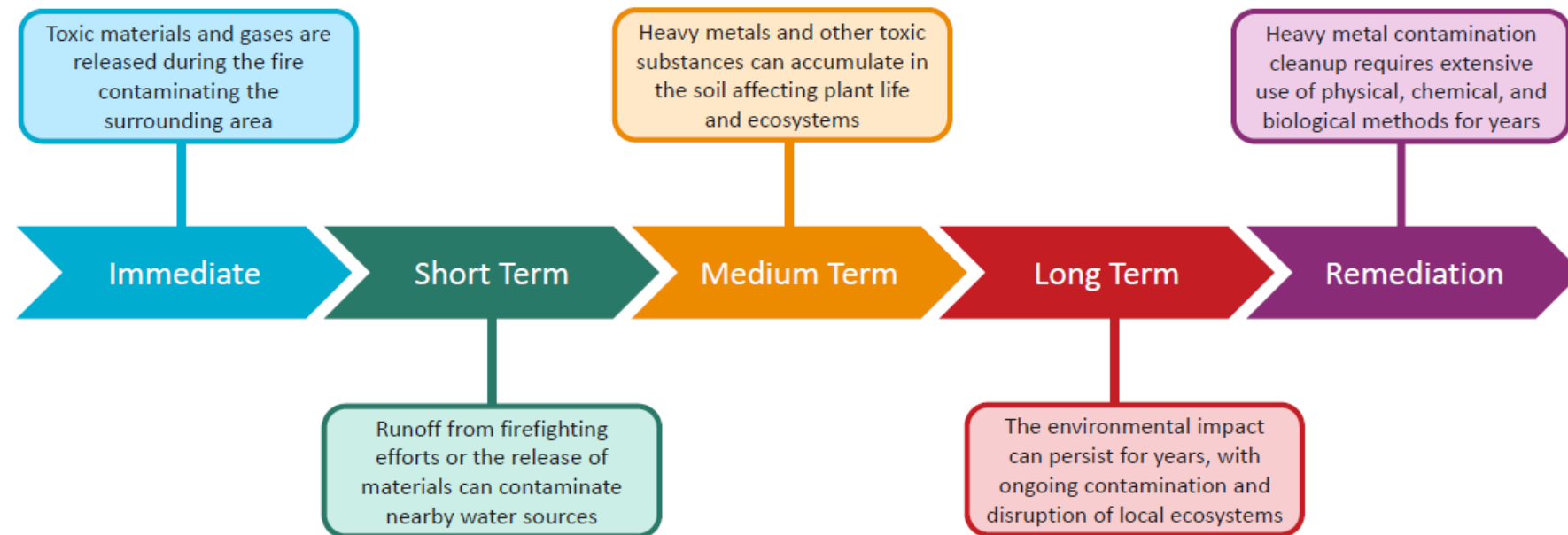
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| TEST | CERTIFICATION | | | | | SELF DECLARATION | | | | | | | | | |
|--|---------------|---------|-----------------|---------|---------|------------------|------------|-------------------|-----------|-------------------|------------|------------|------------|------------|--|
| | UL 1642 | UL 2054 | UL SUBJECT 2271 | UL 2580 | UL 1973 | IEC 62133 | IEC 62281* | NEMA c18.2 M, Pt2 | SAE J2929 | UN Pr.III, S 38.3 | IEEE 1625* | IEEE 1725* | JIS C8714* | SBA 51101* | |
| External short circuit | x | x | x | x | x | x | x | x | x | x | x | x | x | x | |
| Abnormal charge and overcharge | x | x | x | x | x | x | x | x | x | x | x | x | x | x | |
| Forced discharge & overcharge | x | x | x | x | x | x | x | x | x | x | | | | x | |
| Crush | x | | x | x | x | x | x | x | x | x | | | x | | |
| Impact | x | | | | | | x | x | | x | | | | x | |
| Shock | x | | x | x | x | x | x | x | x | x | | | | | |
| Vibration | x | | x | x | x | x | x | x | x | x | | | | | |
| Heating | x | | | | | x | | x | | | x | x | x | | |
| Temperature cycling | x | | x | x | x | x | x | x | x | x | | | | | |
| Low pressure | x | | | | | x | x | x | | x | | | | | |
| Projectile and external fire | x | | | x | x | | | | | | x | x | | | |
| Drop | | x | x | x | x | x | | x | x | | x | x | x | x | |
| Continuous low-rate charging | | | | | | x | | | | | | | | | |
| Molded casing heating test | | x | x | x | x | x | | x | | | | | | | |
| Insulation resistance | | | x | x | | x | | | x | x | | | | | |
| Internal short circuit or internal fire test | in progress | | | x | x | x | | | | | | | x | x | |

- UL 1642 – single cells Li-ion
- UL 1973 (ANSI) – Li-ion modules and packs for stationary use (PV/wind firming/smoothing, UPS). Also covers light electric rail and stationary rail applications
- UL 2054 primary and secondary cells (Ni-Cd, Ni-MH), lead acid, alkaline, carbon-zinc portable applications
- UL 2054 modules/packs portable applications all chemistries listed above + li-ion, lithium primary.
 - requires Li-ion cells to comply with UL 1642
- UL 2580 (ANSI) for EV battery assemblies (packs)
 - Not chemistry-specific
 - Includes batteries, electrochemical capacitors, battery/capacitor hybrid
 - Includes safety requirements for cells and electrochemical capacitors
- UL 2271 (ANSI) for Light EVs
- All of these are periodically updated

Li-ion BESS Incidents' impact

Summary



IEC 62933-5-2 Safety Requirements for grid integrated Electrical Energy Storage Systems (electrochemical based)

- Protect DC system against current overloads and short circuits
 - Each parallel connected string shall have a fuse or DC breaker that protects the strings against excessive currents
 - Both negative and positive ends of the string must have this protective device
 - A module with multiple cells in parallel (xPyS) shall have fuse protecting each cell from high current if one cell develops an internal short
- The stopped state (shut down sequence performed) is when the DC battery is disconnected from the power conversion system (PCS) and the PCS is disconnected from the grid
- The isolated state enables working on the DC battery (for maintenance or repair). To get to the isolated state, the system is brought to the stopped state, then brought to a grid disconnected state and locked in that state, and then isolated
 - Individual battery strings disconnected from DC bus-bar
 - Individual strings isolated with respect to earth, so that accidentally touching the other terminal will not cause current flow. These strings now float electrically with respect to earth and rest of the system
 - For flow batteries, electrolyte flow to the stack is also isolated by using lockable plastic ball valves



IEC 62933-5-2 Safety Requirements for grid integrated Electrical Energy Storage Systems (electrochemical based)

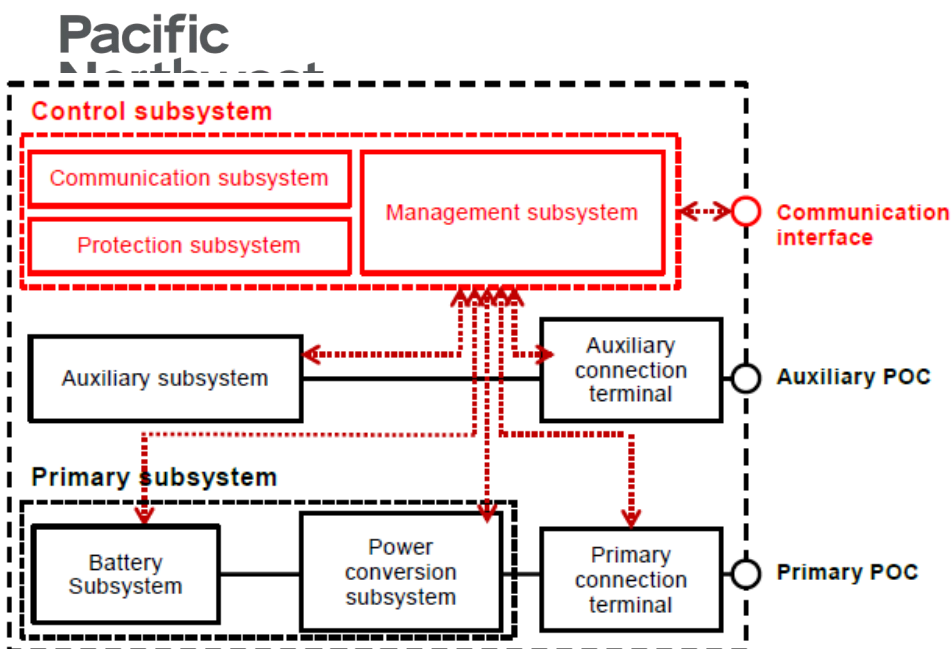
- BESS typically operated remotely
- Parts replaced as part of scheduled maintenance or unplanned events
- Monitoring of system condition, having a maintenance plan in place, component and subsystem repair/replacement, derating based on degradation are key issues related to system safety
- Original parts may not be available for replacement; replacement parts shall be confirmed to be safe and compatible
- Safety manual shall:
 - Describe how to detect & communicate BESS problems such as fire, explosion, toxic or flammable gas release
 - Clearly state safe operation limits to avoid overcharge, overdischarge, crossing safe temperature range, excessive current
 - Describe how to use safety & protection subsystems
 - Clearly identify hazardous parts of BESS

IEC 62933-5-2 Safety Requirements for grid integrated Electrical Energy Storage Systems (electrochemical based)

- IEC 62933-5-1 refers to general ESS, -2 refers to electrochemical based ESS
- All the requirements in 5-1 apply
- Battery Chemistry Categories
 - Group A - Non-aqueous electrolyte (Li-based)
 - Group B - Aqueous electrolyte (Lead acid, Ni-based)
 - Group C - High Temperature (NaS, NaNiCl) - needs heating circuit
 - Group D – Flow - needs heat exchanger, fluid management system
 - Group R - Others
- Safety considerations of BESS include:
 - Product design, chemistry specifics & suitability for application
 - BESS compatibility with any interacting systems
 - ✓ Generation that is backed up by BESS
 - Location
 - Monitoring of system parameters
 - Component compatibility
 - Ability to detect onset of incidents early
 - Proper installation and compatibility of replacement parts and re-commissioning if needed



IEC 62933-5-2 System Schematic and Hazards Specific to each Group



| "subsystems" | "components" |
|-------------------------------|--|
| Management subsystem | System controller and/or energy management system |
| Communication subsystem | Operation panel (human interface), system communication and/or monitoring, meter communication, |
| Protection subsystem | Relays (earth, overcurrent, over voltage, under voltage, over frequency, under frequency, etc.), fuses |
| Auxiliary subsystem | Fire and/or smoke detection system, Fire suppression system, fire extinguisher, HVAC (Heating, ventilation and air conditioning), cabinet, anchors |
| Auxiliary connection terminal | Connection terminal, electric wire (type, thermal rating, chemical rating, size and flexibility) |
| Battery subsystem | Battery (incl. battery management system), communication devices, protective devices, mechanical fixing, cables Note: There are many cases where BESS include multiple numbers or types of battery subsystems |
| Power conversion subsystem | Transformer, AC/DC converter, PCS controller, AC switches, DC switches |
| Primary connection terminal | Connection terminal, electric wire (type, thermal rating, chemical rating, size and flexibility) |
| Others | Room and/or building, foundation, water supply, fire extinguisher (sprinklers), Fire suppression system, fire and/or smoke alarm system, HVAC system of the building, and evacuation, |

- Main hazards common to all BESS
 - Insufficient insulation
 - Inadequate "earthing"
 - Power conversion system malfunction
 - Subsystem malfunction caused by electric noise and electromagnetic induced vibration
 - Workspace related hazards – confined, restrictive
 - Water and dust ingress – unsuitable IP grade
- Hazards specific to Group A (non-aqueous electrolyte)
 - Thermal propagation
 - Retention (worse) or Release of flammable liquid and gas & sparking of gas
 - Increase of pressure
 - Toxic release from materials during fire
- Hazards specific to Group B (aqueous)
 - H2 gas propagation & sparking of gas
 - Retention (worse) or Release of flammable liquid and gas & sparking of gas
 - Increase of pressure
 - Toxic chemical (electrolyte propagation)
- Hazards specific to Group C – high T
 - Dissolution of conductive parts by molten sodium
 - Thermal propagation due to failure in subsystems
 - Propagating hot melt from subsystems causing burns to people and cascade failure to other key system components
- Hazards specific to Group D – flow
 - Toxic chemical {liquid (electrolyte), gas (bromine)} propagation
 - Retention (worse) or Release of flammable liquid and gas & sparking of gas



IEC 62933-5-2 Hazards – Fire, Chemical, Electrical, Energy, Physical, High Pressure

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- Fire: need appropriate concentration of fuel and oxidant, and a heat source
- Chemical – corrosive electrolytes, toxic liquids, oxidizers, flammable/toxic gases, water reactive and toxic metals
 - OSHA and NIOSH have guidelines on exposure to hazardous materials for normal operation
 - NFPA 704 for emergency incident – corrosive spills, toxic liquid vapor exposure (level 1 irritation, 2 temporary incapacitation, 3 permanent injury, 4 lethal), toxic gases (4 levels, similar increase in severity level 1 to 4)
- Electrical hazards: $> 50V$ per NFPA 70E, arcing electrical energy $> 5J/cm^2$ (2nd degree burn).
 - Acceptable levels for normal repair vs emergency response differ
- Energy hazards: allowed levels depend on if this is for repair by trained workers or for emergency responders to damaged ESS situation with stranded energy
- Physical hazards: contact with parts with high kinetic energy (unguarded fan blades), high temperature, or containing fluids at high pressure
- High pressure hazards: under normal operation, may not be present. Under abnormal conditions, overheating may lead to pressure build-up



IEC 62933-5-2 Hazards – Vanadium Redox Flow

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- Fire hazards – not applicable
- Chemical Hazards: Corrosive electrolyte – need to have procedure in place to replenish electrolyte as part of maintenance
- Electrical hazards during routine maintenance at high voltage and energy levels
- Stranded or stored energy – as long as tanks have secondary containment and posolyte and negolyte do not mix, this is not an issue
- Physical hazards: unguarded fan blades, pump impellers



IEC 62933-5-2 Hazards – Zinc Bromine Flow

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- Fire hazards – not applicable under normal operation. For abnormal conditions, flammable gas evolved can result in fire if near ignition source
- Chemical Hazards: Corrosive and toxic electrolyte (level 3 NFPA 704)
- Electrical hazards during routine maintenance at high voltage and energy levels
- Stranded or stored energy – as long as tanks have secondary containment and posolyte and negolyte do not mix, this is not an issue
- Physical hazards: unguarded fan blades, pump impellers



IEC 62933-5-2 Hazards – Vented or flooded Lead acid

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- Fire hazards – under normal operation, possibility of H₂ gas accumulating (near ceiling) without adequate ventilation. Not an issue if installation complies with codes. Under abnormal conditions, potential for short-circuit
- Chemical Hazards: Corrosive electrolyte needs proper PPE, with spill control and “neutralization per code”. First responders need to be aware of potential acid spills
- Electrical hazards during routine maintenance and abnormal conditions at high voltage and energy levels
- Stranded or stored energy – batteries strings need to be isolated for maintenance
- Physical hazards: : unguarded fan blades



IEC 62933-5-2 Hazards – Valve Regulated Lead acid

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- Fire hazards – under normal operation, no combustible gas release if operated as intended. Under abnormal conditions, potential for H₂ release, short-circuit and thermal runaway
- Chemical Hazards: Not an issue under normal operation. Potential for some leakage if battery case cracks or leaks
- Electrical hazards during routine maintenance and abnormal conditions at high voltage and energy levels
- Stranded or stored energy – batteries strings need to be isolated for maintenance
- Physical hazards: : unguarded fan blades



IEC 62933-5-2 Hazards – Li-ion

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- Fire hazards – latent defects, poor design for control (BMS), operation beyond safe range, thermal runaway and associated propagation
- Chemical Hazards: Not an issue under normal operation. Potential for off-gassing of flammable and hazardous vapors under abnormal operation
- Electrical hazards during routine maintenance and abnormal conditions at high voltage and energy levels.
- Stranded or stored energy – batteries strings need to be isolated for maintenance. Could present hazard during disposal.
- Physical hazards: : unguarded fan blades



IEC 62933-5-2 Hazards – high temperature sodium beta batteries – NaS/ Sodium nickel chloride

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- Fire hazards – latent defects, poor design for control (BMS), operation beyond safe range, thermal runaway and associated propagation
- Chemical Hazards: Not an issue under normal operation. Exposure to water-reactive molten sodium if hermetic seals broken under abnormal operation
- Electrical hazards during routine maintenance and abnormal conditions at high voltage and energy levels.
- Stranded or stored energy – batteries strings need to be isolated for maintenance. Could present hazard during disposal.
- Physical hazards: if accessible parts are overheating under abnormal conditions



Thank you