Lithium-ion Batteries

Scope and Application

This Operational Guide applies to all operational personnel to ensure safer management of battery related incidents.

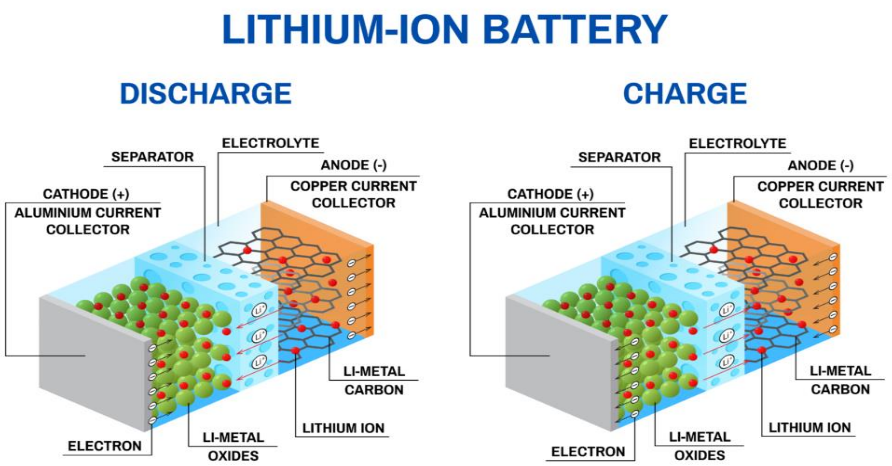
This guide provides basic knowledge of the chemistry of batteries, identification of batteries, and safety considerations.

This guide applies to Lithium Cobalt Oxide ($LiCoO_2$ or LCO), Lithium Titanate ($Li_4Ti_5O_{12}$ or LTO), Lithium Iron Phosphate ($LiFePO_4$ or LFP), Lithium Nickel Manganese Oxide ($LiMn_2O_4$ or LMO), Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO or NMC).

Definitions for commonly used terms relating to ARET can be found at ARET – Glossary of Terms.

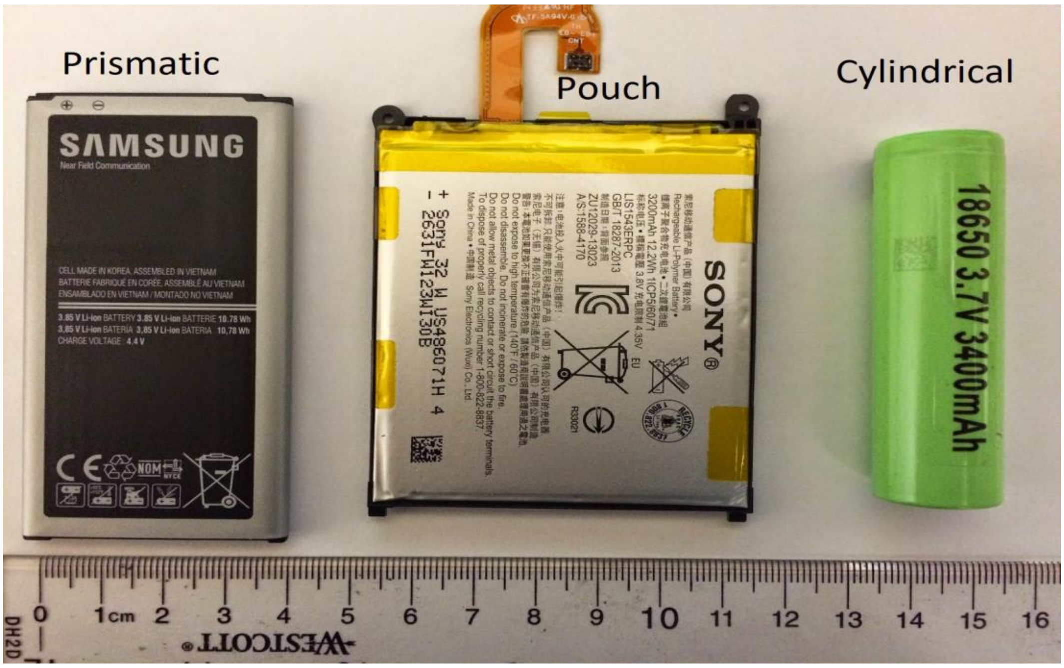
1. Battery Cell

- A battery is made up of an anode, cathode, separator, electrolyte, and two current collectors (positive and negative). The anode and cathode store the lithium ions.
- The electrolyte carries positively charged lithium ions from the anode to the cathode and vice versa through the separator.
- The movement of the lithium ions creates free electrons in the anode which creates voltage at the positive current collector.
- During discharge the electrical current flows from the positive current collector through a device being powered (e.g. mobile phone, laptop) to the negative current collector. During a charging phase, the reverse is true.
- The separator insulates the anode from the cathode, preventing a short circuit.



2. Identifications

- Most portable and rechargeable devices are powered by a derivative of Li-ion batteries. It can be assumed that most mobile phones, laptops, Light Electric Vehicles (LEV) such as e-scooters and e-bikes are powered by Li-ion.
- Battery cells may have different construction methods, the 3 main types are:
- **Pouch**: Usually used in small portable electric devices, has a lightweight casing, can swell under heavy use, and is easily punctured.
- **Cylindrical**: Typical for larger battery packs, cylindrical cells are low cost, and the metal outer casing provides considerable physical protection. Cylindrical cells are used in e-bike batteries, Electric Vehicles (EV), and off-grid batteries.
- **Prismatic**: Predominantly used in EVs, mobile phones, medical fields, communication-based stations.



3. Identification of Electric Vehicles (EV)

- Number plate blue triangle. Regulated in most states' registrations.
- External badging may be "Electric", "Hybrid", "EV", "Zero emission". Located typically on the rear and/or sides on vehicles. Not a requirement and may not exist.
- "100% Electric" or similar phrases may exist on Buses or other public transport.
- Battery Packs on roofs.

- Manufacturer QR codes, some builds have these with a link to that vehicle's emergency response guide, likely to be on the windscreen or one of driver side door pillars.
- No exhaust pipes, no front grille (may have a mimic grille).

4. Identification of Light Electric Vehicles (LEV)

Scooters, Skateboards, Bicycles, Surfboards, Hoverboards, One-wheel balance boards, mopeds, may have some or all of the following features:

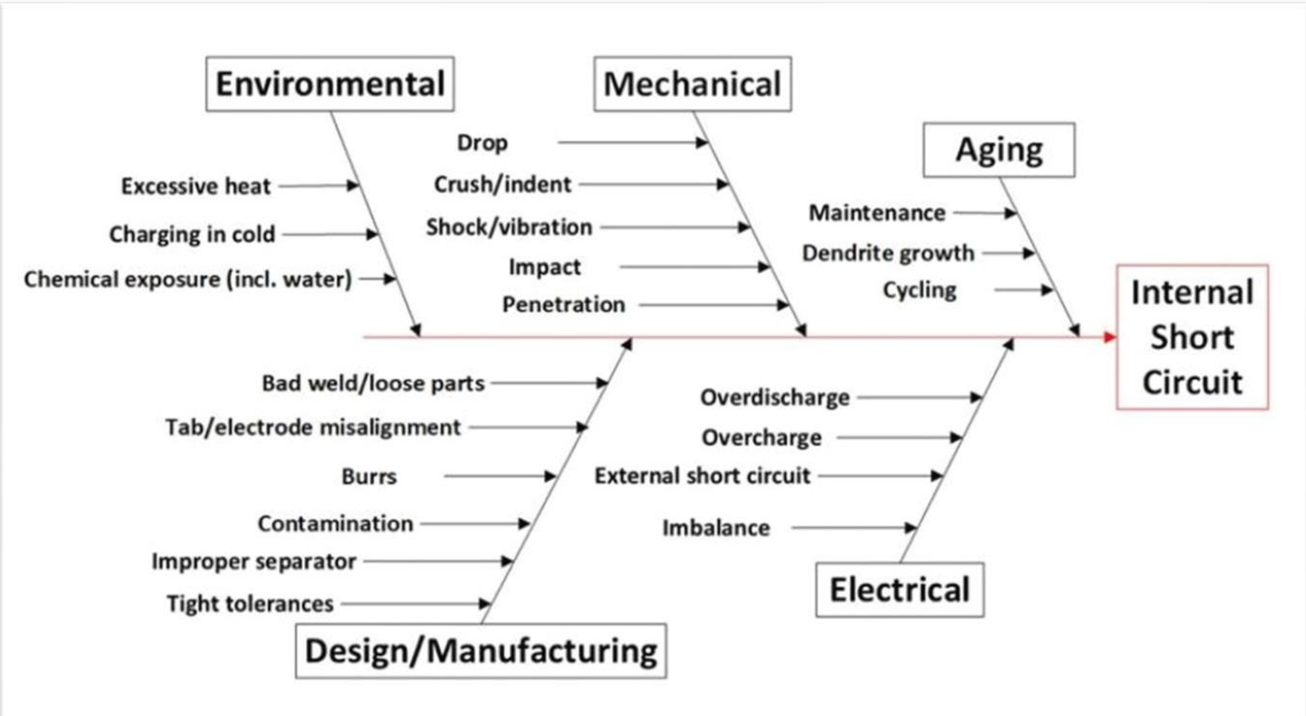
- Presence of throttle and brake, LEDs, upgraded suspension, no exhaust.
- Thicker deck/frame/base with irregular shape, brake lights.
- Visible battery pack, charging port, display unit.
- DIY conversion kits are also sold and may have the appearance of non-electric light vehicles with a control unit and battery pack attached.




5. Safety Considerations

Causes of cell failure:

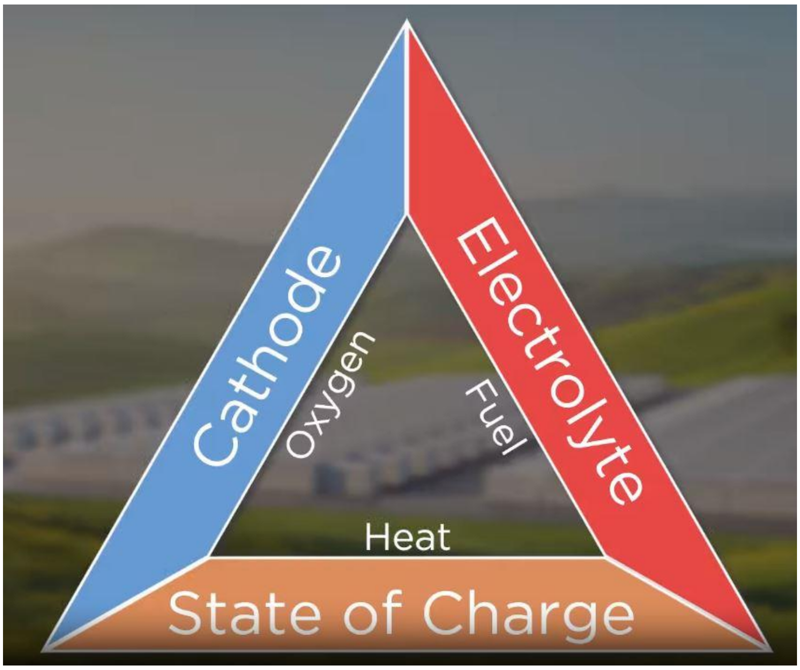
- Physical (mechanical) abuse
  - Puncture, dent, crush, or impact.
- Thermal abuse
  - Prolonged heat source above 50°C. Can also include cold temperatures or cycling between extreme temperatures.
- Overcharge
  - Failure of the battery management system (BMS), causing too many lithium-ions to be removed from the cathode, leading to decomposition of the cathode materials, releasing oxygen and thermal energy.
- Rapid discharge
  - Failure of the BMS where the differing voltages across cells causing energy to be released too quickly.
- Internal cell failure
  - Poor cell/pack design, resulting in electrochemical or mechanical failure.
- Impurities in the cell
  - Metal deposits can form on the battery's anode creating dendrite growth structures that look like horizontal stalactites.



Note: In all types of cell failure, the separator will have sustained some form of damage enabling the rapid movement of ions between the anode and the cathode. The internal short circuit and heating of the electrolyte results in the chemical breakdown of the electrolyte, a build-up of internal pressure in the cell and possible ignition of the escaping gases.

Thermal Runaway

- A chain of chemical reactions within the cell where the rapid discharge of electrically charged ions moving from cathode to the anode occurs.
- This rapid discharge results in uncontrolled chain of exothermic chemical reactions leading to rapid temperature rises in the electrolyte and decomposition/volatilisation of the electrolyte leading to generation of flammable and toxic vapours.
- As the temperature rises, the pressure within the cell increases and activates the pressure relief ports, this allows the release of vapour to the atmosphere.
- The exterior temperature of the cell casing can reach temperatures of above 1000°C. The vapour may be ignited from contact with the hot cell cases or from burning packaging ignited by hot cells.
- Thermal runaway can be propagated to adjacent cells by the heat from exothermic thermal runaway reaction, and furthermore by fire.
- Lithium-Ion Thermal runaway fire is not dependant on oxygen supply, as the cathode breaks down it releases enough oxygen to supply the fire.



Note: Fire is not the propagation mechanism for thermal runaway, but if present it provides for more rapid propagation.

Indications of Thermal Runaway

- High velocity smoke (greyish in colour) or white coloured vapour emitting from the battery, battery casing or underside of vehicle/appliance.

- A loud hissing noise (like a gas leak), popping or crackling sounds.
- Jet-like flames releasing under pressure from openings in the battery pack.
- Intense or uneven areas of heat may be evident on the battery surface. Use of a TIC to monitor temperature is recommended.
- Projectiles or explosions, this is from build-up of pressure within the cell or pack.

Electrolyte Leak

- Electrolyte leak can appear as a fluid leaking from the pack, it may also appear as pressurised vapour. It can be detected at low concentrations with the use of appropriate detection equipment. It will be detected as a Volatile Organic Compound (VOC), correction factors are available for some of the electrolyte solvents.
- It is very difficult to mechanically damage cells in such a way as to cause leakage of electrolyte. Even if a single cell were damaged in a manner that could cause electrolyte leakage, it is extremely difficult to cause a leak from more than a few cells due to any incident. The more likely scenario is that if several cells appear to be leaking electrolyte, it may be that thermal runaway has begun and should be treated as such.
- Leaking electrolyte is more likely to be caused by battery cell walls being corroded or degraded by non-mechanical causes such as submersion.
- Any released electrolyte liquid is likely to evaporate, leaving a white salt residue. Evaporated electrolyte is a flammable vapour and will contain alkyl-carbonate compounds.
- Leaked electrolyte is colourless and characterized by a distinct acrid, fruity, solvent like smell. If an odour is obvious, evacuate or clear the surrounding area and ventilate the area as it is flammable and corrosive/ irritating to the eyes and skin. If a liquid is observed that is suspected electrolyte, ventilate the area and avoid contact.

- Electrolyte venting from Battery pack may be vapour and signals the initial stages of thermal runaway.
- Vent gases may include volatile organic compounds (VOCs) such as alkyl-carbonates, methane, ethylene, and ethane; hydrogen gas; carbon dioxide; carbon monoxide; soot; and particulates containing oxides of nickel, aluminium, lithium, copper, and cobalt. Additionally, Phosphorus Pentafluoride, Phosphorous Fluoride, and Hydrogen Fluoride vapours may form.
- Fluorinated polymers are used in LiB manufacture and may produce Per- and polyfluoroalkyl substances (PFAS) including Perfluorooctanoic acid (PFOA) and Perfluorohexanoic acid (PFHxA) during incomplete combustion, vent gases and electrolyte must be considered as contaminated with PFAS.

- PFAS are contained in the battery structure, compromising the structural integrity of the battery pack will result in increased levels of PFAS being released.

Toxic gases

- A multitude of flammable gases and vapours are released when lithium-ion batteries are involved in fire.
- On top of other products of combustion from materials within the fire, Lithium-ion battery fires also emit in dangerous quantities Hydrogen Fluoride (HF), Hydrogen Cyanide (HCN), Hydrogen Chloride (HCl), Carbon Monoxide (CO).
- The vapour cloud emitting from a battery in thermal runaway has the risk of a vapour cloud explosion (VCE) resulting in extreme fire behaviour.
- VCE is the explosion resulting from the ignition of a cloud of flammable vapor, gas, or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure.
- Ignition of gases can occur rapidly and result in jet-like flames, particularly from the floor pan or sides of battery packs.
- A build-up of vapour clouds in an enclosed space is possible, which can result in an explosive hazard and lower visibility, making identification of batteries difficult.
- According to research studies: if the battery is involved in fire, HF concentrations can be approximately double in EV fires than Internal Combustion Engine (ICE) fires. Structural PPC and BA is sufficient PPE for protection for up to 2 hours in working conditions.

High Voltage (HV)

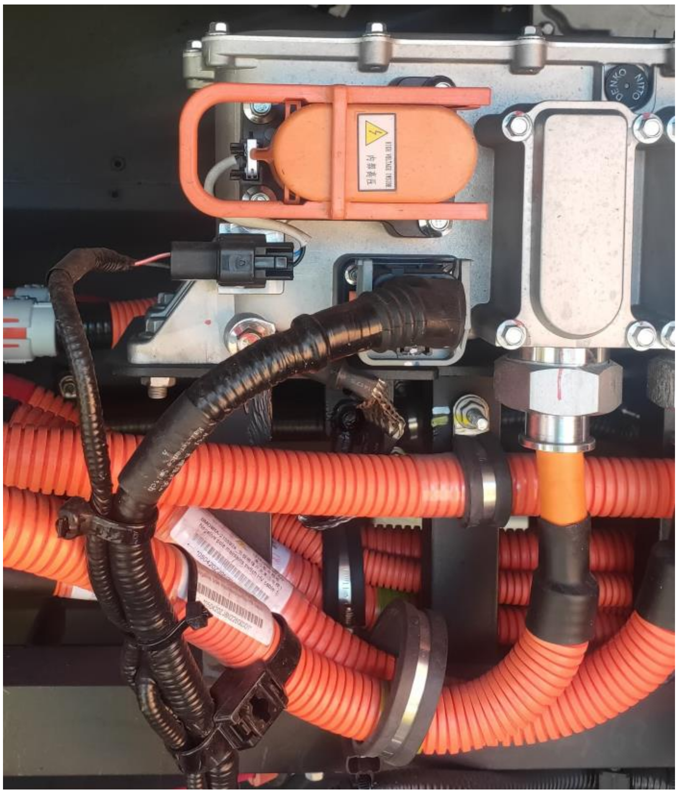
- HV cables are orange in colour.
- HV stored electricity is direct current (DC) and may be as high as 1000 V in EVs.
- Stranded energy is HV energy trapped in cells due to the circuit being damaged.
- After shutting down of the HV system EV's equipped with an inverter/converter have capacitors that will take a minimum of 10 minutes to drain down.
- An un-impinged cell cannot ever reach a state of total discharge.
- EVs generate power through a process called "regenerative braking". Regenerative braking is an energy recovery mechanism that slows down a moving vehicle or object by converting its kinetic energy into a form that can be either used immediately or stored until needed. In this mechanism, the electric traction motor uses the vehicle's momentum to recover energy that would otherwise be lost to the brake discs as heat.

HV disconnections

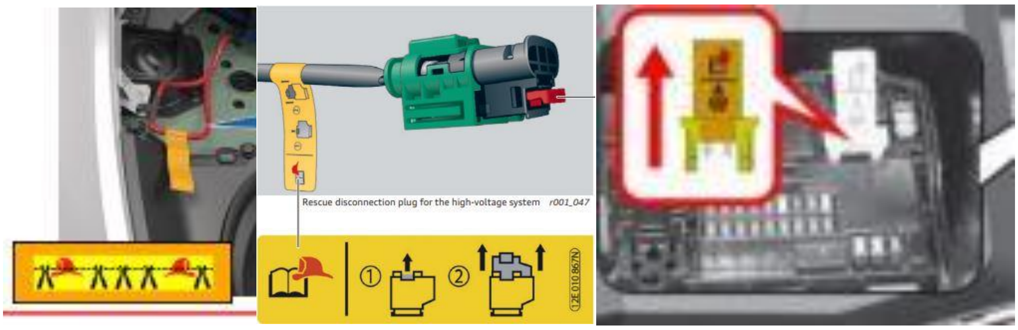
- Stored energy is DC and undetectable with AC monitoring.
- Varied positions and styles in every manufacturer. May be a fuse pull, manual plug, firefighter loop or interlock connector. Some fuses may disengage but not be fully removable.

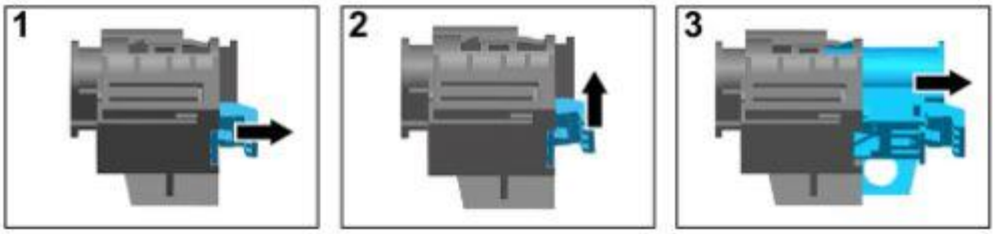
- Service plugs are for maintenance workers and are not part of the disconnection process for emergency response. They can be located in several places, however are typically in the internal floor pan in passenger cars and have direct connection to the battery pack.

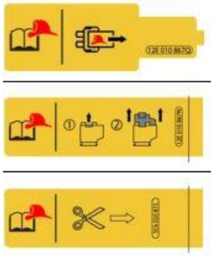
- EVs involved in collision that have deployed airbags have in built safety systems that should have automatically disconnected the HV system.
- Risk of electrocution is present and should be monitored by OIC, especially around exposed wiring.
- Bus HV disconnections may be similar, however, not all but manufacturers install them, relying on a shutdown button in the driver area.



- Low voltage control points are typically labelled by a red “Firefighter helmet” and will depower the HV and are to be utilized as they will open the contactors to the HV battery pack.







- Battery Energy Storage Systems (BESS) can be isolated at either the physical switch in the vicinity of the battery or from the switchboard.
- Utility scale BESS will be able to be remotely isolated by facility managers, BESS owners or the Australian Energy Market Operator (AEMO). Contact information will be in the Emergency Information Containers located at vehicle entry points.
- Community or neighbourhood BESS can be remotely isolated by the grid operator e.g. AusNet.

Towing/Moving

- Regenerative braking on EVs can generate power on wheel turn even after vehicle is disconnected.
- Caution should be used when loading on tow trucks, must be fully loaded on a flatbed, and not towed behind. Wheel spin can generate significant energy and heat and may result in fire.
- Immobilization is key and should be done as soon as practicable to prevent unexpected movement of vehicles.
- Some vehicles can be set to “Transport Mode” on the vehicle’s touch screen. This is to be utilised if moving off the road or onto a tow truck if the driver isn’t present or neutral can’t be engaged.

Firefighting

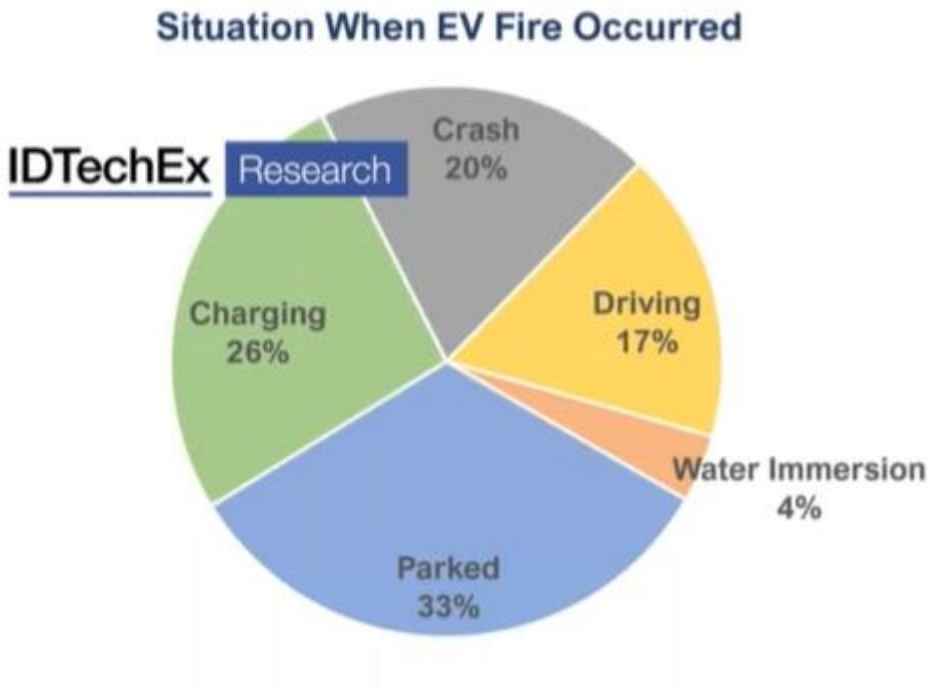
- Water is the recommended medium for firefighting in AUS/NZ.

- Thermal runaway in a cell cannot be stopped, only prevention of propagation to further cells can be achieved.
- Batteries involved in thermal runaway may burn themselves out much faster than extinguishment with water can be achieved.
- Applying water directly to the affected enclosure will not stop the thermal runaway event, as the fire will be located behind several layers of steel material, and direct application of water has shown to only delay the eventual combustion of the entire unit.
- OICs may consider managing what the greatest hazard may be i.e. smoke, VCE, fire, traffic.
- Firefighting crews must be aware that if fire is no longer occurring in a battery cell that is in thermal runaway, the risk of explosion from VCE is increased.
- Burn studies in EV Batteries have shown fire intensity can diminish significantly after 30-35 minutes but continue to off-gas for an extra 30+ minutes on self-extinguishment.
- Some extinguishers claim to be specifically designed for Lithium-ion may have been used on premises, these can form a barrier in between cells to hinder propagation however they don't stop thermal runaway so caution is advised as the packs or cells may have become pressurized and explosion hazard still exists and may be enhanced.
- All battery packs have vents or create vents in the event of thermal runaway, this may give Operational Personnel an opening to use to cool battery cells, considering: a battery pack on fire with jet like flames or venting is under significant pressure at atmospheric conditions and water will not be able to penetrate through that opening.
- Running water through burnt out battery packs to flush the battery packs to cool after combustion is not advised as it may significantly increase concentration levels of PFAS in runoff water.
- Flushing of Battery Packs is not advised without a carefully and thoroughly planned out water runoff management plan with relevant water authorities and EPA.
- Special consideration should be used for house fires, particularly garage fires, as Battery Energy Storage Systems (BESS) or EV may be present in the premises and there is no requirement for placarding to make crews aware.
- Premises with solar photovoltaic (PV) panels are more likely to have BESS onsite.
- Premises may have placards or signage stating PV for Solar Panels or ES for BESS. These are typically located on the switchboard of the premises and should be considered on size up.

Signage indicating presence of a PV Array System

Signage indicating presence of a BESS

- The risk for VCE is increased in this case, crews should approach and apply techniques that apply to an under ventilated fire.
- If the BESS is involved in fire, VCE is no longer the concern, but fire spread will occur more rapidly.



EV Fire Blankets

- Private industry have the ability to purchase these blankets and are being sold with minimal instruction and no training.
- Gases underneath the blanket can pressurised and released through an opening. Increasing the risk of VCE.
- Once the blanket is deployed, fire suppression is achieved, however the process of thermal runaway cannot be stopped, toxic/explosive gases are still being released.
- The vehicle fire may appear to have been successfully suppressed, however, upon removal of blanket: ignition of the gas build up may occur and the battery fire resume.
- Blankets may have been used multiple times, each time losing integrity.
- After 40 minutes of the test beginning, the fire is still venting dangerous gases.
- If not deployed to a high standard with proper training, while wearing PPC and BA, the risk for injury is high whether it be explosion, fire, or exposure to toxic gas.
- This will be appealing to businesses that store and/or transport EV's to protect their assets as it's seen as a low-cost exposure protection.
- This is being marketed to anyone that stores or transports EV's such as ferries, car yards, car wreckers etc.

Lithium-ion Extinguishers

- There are varying types of extinguishers on the private market that claim to be specifically designed for Lithium-ion fires or Thermal Runaway.
- They are made with chemicals that are designed to both cool and encapsulate the cells, claiming to stop propagation.
- Evidence shows that once Thermal Runaway has started in a Li-ion cell, it cannot be stopped.
- FRV have not investigated the efficacy of these extinguishers.
- CSIRO have published an Advisory Note as well as an Advisory Note from FPA Australia, both stating how these extinguishers don't meet standards and aren't to be used.
- While providing adequate extinguishing capabilities on controlled small fires, depending on several variables, it may be just shifting the hazard risk from fire to a pressurised flammable vapour.
- Caution is advised if these extinguishers have been used on premise, identification of the extinguishing agent varies greatly, the writing on the extinguishers may be "Lith-ex" "Li-ion" or similar or by the substance being a golden-brown colour liquid or similar to a low concentration foam application.

- Gaseous fire suppression systems may also have activated in confined spaces containing BESS and should be treated as an under ventilated fire as the gas provides no cooling ability and thermal runaway may be active within the compartment.
- EV Buses may contain fire suppression systems in built into the Battery Pack, at present they are using a dry powder system, that may become a "Lithium Ion" extinguishing media in the future.

State of charge (SOC)

- Research has shown that fire intensity is directly associated with SOC of a battery or cell.
- A vehicle with a 50-100% SOC will behave more violently in a fire than one at 30%.
- Batteries with less than 50% SOC may not result in fire when in thermal runaway. This increases the risk of VCE.
- It has been identified that batteries connected to or recently removed from charging present a higher risk of experiencing a fire event.

Secondary ignition

- Can occur up to 4 weeks after an initial thermal event.
- Is a new failure of a cell that has been damaged due to initial abuse.
- Can occur from degradation of a cell over time and doesn't need a specific trigger to happen after the initial event.

Salvage and Overhaul

- With any handling of batteries post incident; chemical gloves should be worn due to the risk of injury from caustic/corrosive substances.
- Avoid handling the cells if possible. Consider use of non-conductive small gear.
- Cells may ignite when disturbed post ignition as the vibration may be enough force to cause a short circuit in a damaged cell.
- If cells are submerged, they may still burn underwater and off gas. Which may produce Hydrogen (H), Hydrogen Fluoride (HF) or if in salt water: Chlorine gas (Cl2).

Charging stations

- Roadside chargers are DC, can be operating at 25-350kW, grid fed.
- No static power supply held within the unit, except to power small LED.
- Has in-built protections against electrical surge, overheating, and tilting.
- Isolations aren't regulated so they may have manual isolations on the post, a separate cabinet or on a switchboard.
- Handles are connected magnetically to the vehicle and controlled by the vehicle.
- Handles above 60° may indicate fault and should be approached with caution.
- If handles cannot be removed without damaging vehicle, the manufactures roadside assist call number may be able to remotely disconnect.
- At home chargers can be bought from non-compliant retailers.
- Up to 22kW AC power supply in residential units.
- Isolating power to the premises should be considered to isolate at home chargers.
- At time of document EV charging stations do not incorporate BESS systems.

Supporting Documents

- AFAC Incidents Involving Electric Vehicles Guideline v1.0.
- Full-scale fire testing of battery electric vehicles - Fire Testing & Research Centre, Fire & Disaster Management Division, Korea Conformity Laboratories.
- FPRF Lithium-ion Batteries hazard and use assessment.
- FIA Guidance on Li-ion Battery fires.

- The Science of Fire and Explosion Hazards from Lithium-ion Batteries – UL Research Institutes.
- Investigation of extinguishing water and combustion gases from vehicle fires Jonna Hynynen, Ola Willstrand, Per Blomqvist, Maria Quant - RISE Report 2023:22.
- Gaseous HF in case of fire in confined spaces - risker for skin absorption during interventions – Swedish Civil Contingencies Agency (MSB).
- CSIRO - Advisory Note AN-004 Extinguishment of Li-Ion Battery Fires.
- FPA - TAN 09 Portable Fire Extinguishers: Lithium-ion Batteries.

Document Information

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