THEME

Risk assessment and handling of fire in lithium-ion batteries

Guidelines for fire and rescue services

Version 1 – November 2021

dsb Norwegian Directorate for Civil Protection

Published by: Norwegian Directorate for Civil Protection (DSB) 2021

ISBN: 978-82-7768-529-8 (PDF)

Cover image: Kurt Tofte Rusås

Graphic design: ETN Grafisk, Skien

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SUMMARY

This guide is tailored to the fire and rescue services in Norway. It deals with the risk and measures for extinguishing fires in lithium-ion batteries (LIB).

The guide deals with fires involving thermal runaway in one or several battery cells. It operates with four risk levels; from simple and small fires in batteries, to complex and high-risk operations in large battery systems. There is a differentiation between risk levels in relation to the size of the battery, but also whether a thermal incident occurs outdoors or in a confined space. This risk interpretation can be critical for fire service crews. Responses must be based on knowledge, not simply luck and random risk management.

The initial description relates to risk levels. Here you will find practical advice and measures that can form a basis for the individual fire service, such that they can draw up their own response procedures or action plans. Thereafter, there follows a little more thorough specification of LIB. Health, safety and the environment (HSE) has been included, in addition to information on extinguishing agents and environmental challenges.

For those that wish to read more about LIB, there are seven appendices that provide further information on various subjects such as battery technology at cell level, detection, marking and specific incidents.

Finally, also included are literary references and links to various sources with access to supplementary information.

This is the first edition, published in Autumn 2021. Amendments and the most recent version will be published as required on dsb.no and nbsk.no.

WORKING GROUP

The guide has been drawn up by a working group comprised of persons from larger Norwegian fire services, the Norwegian Fire Academy and the Norwegian Directorate for Civil Protection.

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Professional review
The guide has been subjected to professional review by the Norwegian Defence Research Establishment, c/o Sissel Forseth, Gylling Teknikk AS c/o Erik Karlberg and Jørgen Løvli, and NELFO c/o Marie Koldrup. Thank you all for your professional input.

Direktoratet for samfunnssikkerhet og beredskap

Norges brannskole

CHAPTER

01

Introduction

During the last few years, there has been a major increase in the use of lithium-ion batteries (LIB) as energy carriers in the transport sector and in energy storage in dwellings, commercial buildings, construction sites etc.

LIB technology is good and the likelihood of fires in LIB is low; however, we have already seen several examples of LIB fires. The fire service has acquired some experience in these types of fires, and in orders to safely get control of these incidents there must be a significant increase in knowledge throughout the whole fire service.

In Norway, there has been major expansion in the use of battery powered transport and energy-generating sources connected to battery systems. These chiefly use LIB for energy storage.

We can find LIB practically everywhere. There are millions of the smallest batteries in watches, PCs, electric bicycles etc. Larger battery modules are found in electric and hybrid cars, electric ferries and hybrid ferries. As of July 2021, there are approximately 450 000 fully electric cars and approximately 300 electrified ferries in Norway.

Battery systems in buildings are now becoming very common, frequently in combination with solar cell systems. At present, most of these use lead-acid batteries; however, LIB are becoming more common.

LIB technology is dominant because batteries have high energy density and cost less than before. However, in contrast to the older types of batteries such as lead acid, alkaline and solid-state batteries, LIB present a greater challenge to the fire services. New types of solid-state batteries are also being introduced.

The professional conference in Bergen in 2020, held after the fire and explosion on board MS Ytterøyningen, brought together several professional environments and authorities. This accelerated the work of focus on safety in connection with battery fires. Expertise in the area of fires in LIB is developing all over the world. Norway is part of this development, in fact in many aspects Norway is at the forefront.

If something goes wrong, fire and rescue services in Norway depend on being able to handle the incident. The guide points out, however, that the fire services have limited capacity for extinguishing battery fires, larger fires cannot be extinguished, or should not always be extinguished.

LIB fires are still unusual, and there are very few who can draw support from experience. Battery technology is undergoing rapid development and larger and larger battery systems will be introduced in the coming years.

Objective of the guide
The guide is intended to provide the fire and rescue services in Norway with a professional basis in order to draw up internal procedures or guidelines for interventions. The guide describes four different risk levels. Response plans must be adapted to the specific organisation in relation to capacity, expertise, equipment etc., preferably through separate ROS-analyses, preparedness analysis, preparedness plans and response plans in the individual fire services.

The guide is not exhaustive. A complete overview of the challenges involved with LIB is not possible at this present time. Best practice is described; however, all those who are responsible for handling the relevant incident must make independent assessments.
The objective is that the guide can inspire, impart knowledge and instigate preliminary activity.

We recommend that you read the entire guide, in any case as far as the appendices, before using the response plans. These must be tailored, and quality assessed within the individual fire service, based on relevant risk. An overview of abbreviations and terms used can be found on page 37.

Target groups
Leaders, fire and rescue personnel and preventive personnel in Norwegian fire and rescue services. Operators at 110 emergency call centres.

1.1 TRAINING

The guide assumes that the reader has fundamental expertise and training from within the fire service.

The guide has the objective of providing fire and rescue personnel with knowledge of the hazards and challenges, so that these can be managed in a safe and effective manner. The guide will provide supplementary knowledge about the risk of explosion, flammable and toxic gases, and the hazards that exist in relation to electricity.

Handling of fire in lithium-ion batteries is a relatively new challenge facing the fire services and incidents can involve a major degree of uncertainty. Potentially, it can be dangerous to handle these incidents without the appropriate knowledge. It is therefore important that all fire and rescue services received training in handling battery fires.

The guide is intended to assist in education and training at the Norwegian Fire Academy.

1.2

RISK LEVELS

Responses to fires in lithium-ion batteries are divided into four risk levels:

- Level 1: Low risk
  E.g. PCs, mobile telephones, electric bicycles, electric scooters and similar.
- Level 2: Low to medium risk
  E.g. Electric cars, hybrid cars, buses or similar - outdoors.
- Level 3: Medium to high risk
  E.g. Electric cars, buses or similar - indoors. Energy storage (BESS) in homes or industry and similar.
- Level 4: High risk
  E.g. Large system battery fire in fully electric or hybrid vessels, larger buildings or industry.

For each of the risk levels, initiatives are described using a staged model. It is assumed that the 7-stage model is familiar.

The guide assumes that a battery is involved in the fire and that thermal runaway (TR) has started in one or several battery cells. This means that in incidents where the LIB itself is not on fire, or is not at risk of becoming part of the risk picture, is perceived as a “normal” fire. This type of incident is managed in the normal manner and is not part of these guidelines.

RISK LEVEL 1

Examples of fires in: PCs, electric bicycles, electric scooters, hoverboards or similar.

Fires in this type of device must be able to be managed by all fire services, several can also be handled by civilians provided they are not exposed to hazardous fire smoke.

RISK LEVEL 2

Examples of fires in: Electric cars, hybrid cars, buses or similar - outdoors. The fire services will handle the incident.

RISK LEVEL 3

Examples of fires in: Battery energy storage systems (BESS), electric cars, buses or similar in garages. Energy storage in homes or industry, battery fires in tunnels without ventilation or corresponding incidents.

This type of fire requires that fire service crews responding to the incident have fundamental expertise in handling battery fires. There can be a risk to life and health when handling such incidents.

RISK LEVEL 4

Examples of fires in: Battery fires in fully electric or hybrid vessels, larger buildings - for example hospitals and larger energy storage systems.

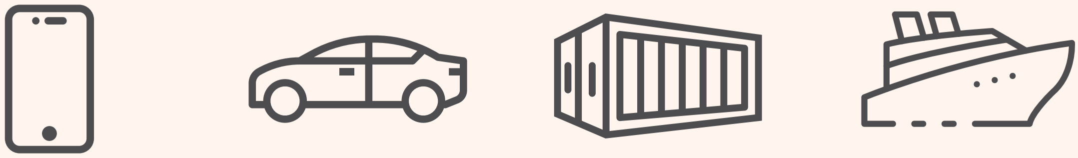
These are challenging fires and extinguishing them will require expertise from specially trained fire crews. These must have undergone training and have conducted exercises in the handling of battery fires. It is recommended that pre-defined resources are notified. These can be RITS-Chem fire services or CBRNE groups.

Safe distances and safety zones must be established. The normal standard will be 300 metres due to the risk of explosion.

All responses, apart from life-saving actions, are on the premise that the fire services have control of risk elements in relation to HSE, particularly the risk of explosion, electrical hazards and adequate availability of resources in order to carry out the response over time.

Fire in lithium-ion batteries

Risk levels



LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4
Fires in smaller LIB	**Fires in larger LIB**	**Fires in larger LIB, in confined spaces**	**Fires in larger LIB on board a vessel or in a larger building**
• Mobile telephones • Electric bicycles • PCs • Electric scooters	• Electric cars • Electric buses • Electric commercial vehicles • Electric plant machinery and battery banks for charging the above.	• Electric car in garage • Energy storage, container (ESS) • Battery storage in homes and industry	• Fully electric or hybrid vessels • Buildings with large battery systems, e.g. hospitals or industry
Low risk	**Low to medium risk**	**Medium to high risk**	**High-risk**
Extinguishing can be carried out by civilians, provided that these are not exposed to hazardous gases from the fire. The fire services should control the incident.	Extinguishing must be carried out by the fire services. Can require large amounts of water (over 10 000 litres) and intervention over time.	Extinguishing will require appropriate expertise in the form of training in battery fires.	Extinguishing will require expertise from specially trained fire crews in the form of RITS-group or CBRNE unit that has undergone, training in, and has practiced, handling of battery fires. A specialist group must be set up. Resources must be called in.

Risk level 1
Fire in smaller lithium-ion batteries

STAGE 1
Acquire an overview of the incident and make a risk assessment.

Risk assessment:
- High risk of spreading of fire.
- Inhalation of hazardous fire smoke.
- High temperature in the fire.
- Small explosions in battery cells can occur.

Incident development:
- Batteries can spontaneously ventilate large amounts of gas without warning.
- Batteries can spontaneously ignite without warning.
- Can burn for a long time, more than normal materials.

STAGE 2
Evaluate possible initiatives.

Access to resources:
- The caller will be able to make initial efforts, provided that he/she is not exposed to fire smoke. Use available extinguishers, garden hose, hand fire extinguishers, fire blanket or similar.
- The fire services will be able to carry out a secure and good response with one firefighting unit/fire engine.

STAGE 3
Tactical.

Aim of response:
- Prevent the spread of fire.
- Prevent exposure to hazardous gas.

Level of protection:
- Normal clothing, provided that the person is in a smoke-free environment.
- Normal fire protective clothing.

Tactical plan:
- Water is an ideally suitable extinguishing agent for extingushing smaller battery fires.
- LIB that are on fire can be difficult to extinguish; use a large amount of water or place the battery in a water-filled container.
- Other extinguishing agents such as foam, dry chemical and fire blankets can be used; however these will have a lesser cooling effect
- The battery can be moved to a safe area where any self-ignition will not lead to a risk of the fire spreading.
- Smaller batteries can be rendered harmless by placing them in a container of salt water. This both cools and discharges the battery slowly.

Risk level 2
Fire in larger lithium-ion batteries

STAGE 1
Acquire an overview of the incident and make a risk assessment.

Risk assessment:
- High risk of spreading of fire.
- Inhalation of hazardous fire smoke.
- High temperature in the fire.
- Small explosions in battery cells can occur.
- Electrical hazard.

Incident development:
- Batteries can spontaneously ventilate large amounts of gas without warning.
- Batteries can spontaneously ignite without warning.

STAGE 2
Evaluate possible initiatives.

Access to resources:
- Extinguishing/cooling of fire in larger LIB requires access to larger amounts of water. Assess access to water, bring water tank if necessary.
- It is not recommended that civilians extinguish this type of fire.

STAGE 3
Tactical.

Aim of intervention:
- Prevent the spread of fire.
- Prevent exposure to hazardous fire smoke.

Level of protection:
- Ordinary fire protective clothing with full respiratory protection apparatus.

Tactical plan:
- Chock the vehicle to avoid self-driving.
- Switch off the external electrical source if the vehicle is being charged. See for example Crash Recovery/ Euro Rescue for information on the relevant vehicle.
- Activate the stop switch on the charger if this is found. If the external electricity source is not switched off, the fire must be handled as a fire in a live installation. Use the correct protective equipment (1000-volt gloves).
- Use large amounts of water to extinguish/cool the battery fire. For electric car fires, water jets aimed underneath the vehicle, or at openings that lead to the battery are most effective.
- Fire blankets can be used to dampen smoke production, to prevent the spread of fire and to extinguish interior fires. Should be used in combination with cooling on the underside.
- Tow any nearby vehicles away to prevent the spread of fire.
- Never snip, cut or slice into the battery to gain access for extinguishant water.
- Use a fan to control the smoke.
- Vehicles that have been exposed to fire/collision can self-ignite.
- Heat generated in batteries is difficult to measure, as batteries are well sealed and protected by covers.
- Transport the vehicle to an appropriate place – a minimum of 10 metres distance from other flammable materials.
- Avoid tunnels, consider following the breakdown truck.
- Inform the breakdown truck of the risk of new internal short-circuits in the battery and re-ignition.

Risk level 3
Fire in lithium-ion batteries, confined spaces

STAGE 1
Acquire an overview of the incident and make a risk assessment.

Risk assessment:
- Risk of gas explosion
- High risk of spreading of fire.
- Risk of inhalation of toxic fire smoke.
- Risk of corrosion injury.
- Risk of short-circuit in battery, high short-circuit current and arcing.
- Risk of current flow.
- Is the gas over LEL? If you see flames, there is a minor risk of explosion.

Incident site factors:
- *Fire*: In the event of a battery fire in a confined space, fire gases, without complete combustion, can accumulate and form an explosive atmosphere. Even small batteries ventilate a great deal of gas and can represent a risk.
- Evaluate the degree of encapsulation against the flammability range.
- *Environment/building*: Evaluate the risk of the fire spreading.
- Persons: Evacuate.

STAGE 2
Evaluate possible initiatives.

Immediate initiatives:
- Evacuation – no person without protection close to the battery fire.
- Visible fire must be cooled and extinguished with water.

Possible initiatives:
- Begin cooling, if it is safe <LEL
- Begin ventilation, if it is safe <LEL

Access to resources:
- Competent fire crews with training in battery fires.
- A large battery fire will require large amounts of water – assess the location in regard to water supplies.
- Acquire resource persons.

STAGE 3
Tactical.

Aim of intervention:
- Prevent explosion.
- Avoid injury to persons.
- Prevent the spread of fire.
- Prevent exposure to hazardous fire smoke.

Level of protection:
- Ordinary fire protective clothing with full respiratory protection apparatus.
- Evaluate the use of a splash/chemical protection suit when entering battery rooms.

Entering battery rooms:
- Entry into battery rooms must **<u>not</u>** take place before acquiring a full overview of the concentration of gases in the room.
- Always use full protective equipment.
- Batteries subjected to heat can spontaneously ignite.
- Batteries subjected to heat can spontaneously ventilate large amounts of hazardous gases.
- Do not touch batteries as these are live.
- Gases can collect in lower areas of the construction – also outside of the battery room.

Tactical plan:
- Defensive approach until you have obtained a complete overview of explosive gases in the room.
- Carry out gas detection with suitable detection equipment.
- Explosions seldom occur during fires. If you see flames, you have control of the situation. Explosive gases combust.
- In garage and house fires, consider using a cutting extinguisher/fog nail to reduce the risk of explosion.
- Do not use a cutting extinguisher/fog nail directly on/in batteries as this can cause an internal short-circuit.
- Ensure that fire gases are not ventilated to an area in which persons are located.

Damping after a battery fire
- Extinguishant water can have a high pH value (alkaline with pH 8–14).
- Cool batteries with large amounts of water.
- Battery rooms can be monitored by monitoring the gas concentration in the room. Use calibrated measuring instruments.
- Begin continuous ventilation of battery rooms.
- Equipment and clothing that has been exposed to smoke must be decontaminated.

Risk level 4

Fires in larger LIB on board a vessel or in a larger building

STAGE 1
Acquire an overview of the incident and make a risk assessment.

Risk assessment:
- Major risk of gas explosion.
- Risk of inhalation of toxic fire smoke.
- Risk of corrosion injury.
- Risk of short-circuit in battery, high short-circuit current.
- Risk of current flow.

Incident site factors:
- *Vessel/building:* Type of vessel/type of building.
- *Fire:* TR indicated or fire in battery room?
- *Position:* Is the vessel at the quayside or out at sea?
- *Persons:* Establish the number of passengers and crew. Passengers in need of assistance can present additional challenges.
- *Weather:* Evaluate weather conditions.

STAGE 2
Evaluate possible responses.

Immediate initiatives:
- Inform the crew/staff of potential hazards.
- Consider deploying the vessel's/building's own suppressant systems.
- Begin evacuation.
- Consider isolating the battery room.

Possible initiatives:
- Begin cooling, if it is safe <LEL
- Begin ventilation, if it is safe <LEL
- Acquire information from the vessel's/building's monitoring system.

Access to resources:
- Response will require competence from specially trained fire crews, in the form of Maritime Incident Response Group or CBRNE unit that has undergone training in, and has trained, in the handling of battery fires.
- Establish communications with HRS.
- Establish communication with vessel/captain.
- Acquire resource persons.
- Contact the manufacturer of the battery installation.

STAGE 3
Tactical.

Aim of intervention:
- Prevent explosion.
- Avoid injury to persons.
- Prevent the spread of fire.
- Prevent exposure to hazardous fire smoke.

Level of protection:
- Ordinary fire protective clothing with full respiratory protection apparatus.
- Evaluate the use of a splash/ chemical protection suit when entering battery rooms.

Tactical plan:
- Acquire information from the vessel's/ building's monitoring system, Battery Management System (BMS). Monitor the cell temperature and cell voltage. In some cases this can be read externally. Contact the battery manufacturer.
- The alarm system can be interconnected to gas sensors and video monitoring.
- Acquire a plan drawing and assess the risk of spreading.
- Ensure that fire gases are not ventilated to an area in which persons are located.
- Consider deploying the vessel's extinguishing system (if not already deployed).
- Avoid introducing oxygen if the battery room is closed.
- If possible, carry out detection with suitable detection equipment.
- Explosions seldom occur during fires. If you see flames, you have control of the situation. Explosive gases combust.
- Displacement of fire gases with inert gas (from UEL to LEL).
- Avoid using saltwater.
- Short-circuits in battery installations can occur even if fresh water is used.
- Water binds particles such as ash, soot, salts and metal particles, making it conductive – use large amounts of water.

Entering battery rooms:
- Entry into battery rooms must not take place before acquiring a full overview of the concentration of gases in the room.
- Always use full protective equipment.
- Batteries subjected to heat can spontaneously ignite.
- Batteries subjected to heat can spontaneously ventilate large amounts of hazardous gases.
- Do not touch batteries, as these can be live.
- Gases can collect in lower areas of the construction – also outside of the battery room.

Damping of battery rooms:
- Extinguishant water can have a high pH value (alkaline with pH 8–14).
- Cool batteries with large amounts of water.
- Battery rooms can be monitored by monitoring the gas concentration in the room. Use calibrated
- measuring instruments.
- Begin continuous ventilation of battery rooms.
- Equipment and clothing that has been exposed to smoke must be decontaminated.

STAGE 4
Organise the incident site and appoint Incident Leader.

Organisation of incident site:
- For vessels at sea, consider access to the vessel. Can the vessel be brought to the quayside, or do firefighting personnel have to be transported to the vessel?
- Consider location of vessel. Important factors; opportunity for evacuation of personnel, access for firefighting personnel – can the buildings around the quayside be exposed to smoke/explosion?
- Is a port of refuge available?
- Is there a need to introduce measures against critical contamination?

Leadership support:
- Contact resource persons; other fire services, local expertise, Defence Force, marine resources, battery system supplier.

CHAPTER

02

Battery construction

There is differentiation between battery cells, battery modules, battery racks, battery packs and battery systems. In everyday language these are often mixed up together.

The basic unit is called a battery cell. A battery cell is comprised of an anode and a cathode, divided by a separator, in a liquid, flammable electrolyte. A battery cell normally has a voltage level of between 3.0 and 4.2 V.

A battery module is comprised of a number of connected battery cells and may contain a cooling system, temperature monitoring and safety systems. Some battery modules have their own BMS.

A battery rack is comprised of several connected battery modules. In the battery rack you will find a number of safety systems that may contain fuses, sensors, detectors, communication systems and BMS. Some battery racks also have their own exhaust system, designed to extract gases from the battery module into the open air.

Several battery racks connected together via a bus bar form a battery pack. When a battery pack is connected to an overarching control system, then we have a battery system.

Battery casing

Protective covers and casings are used to protect batteries from external damage and interference. Casings around batteries present a challenge, as these will prevent extinguishants and cooling from reaching the cells. Due to casings around batteries, it is difficult to cool them to below a critical temperature.

Bruk av IR-kamera vil ha mindre verdi ved en batteribrann da innkapslingen gjør det svært vanskelig å måle temperaturutviklingen i og rundt battericellene. Men IR-kamera kan benyttes for å måle temperaturendringer. Økende temperatur tyder på pågående kjemisk prosess i batteriene som danner varme, over tid kan dette skape TR. Synkende temperatur kan indikere at situasjonen stabiliseres.

Batterier i kjøretøy blir plassert ulikt, f.eks. under bunnplaten, mellom kupe og bagasjerom eller integrert i gulvet under seter. Lastebiler kan ha batteripakkene på siden av rammen eller i midten av rammen.

Noen bilfabrikanter har laget åpninger for slukking, såkalte "Firemans Access." Dette er åpninger som er beregnet for innsats ved at man har mulighet for å tilføre vann eller annet slokkemiddel direkte rundt batteriene. For å vite hvilke bilmodeller dette gjelder kan man benytte apper som Crash Recovery System eller Euro Rescue.

Det er ikke standardiserte påkoblinger for tilførsel av slokkemidler, hverken i biler, båter eller store energilagre (BESS).

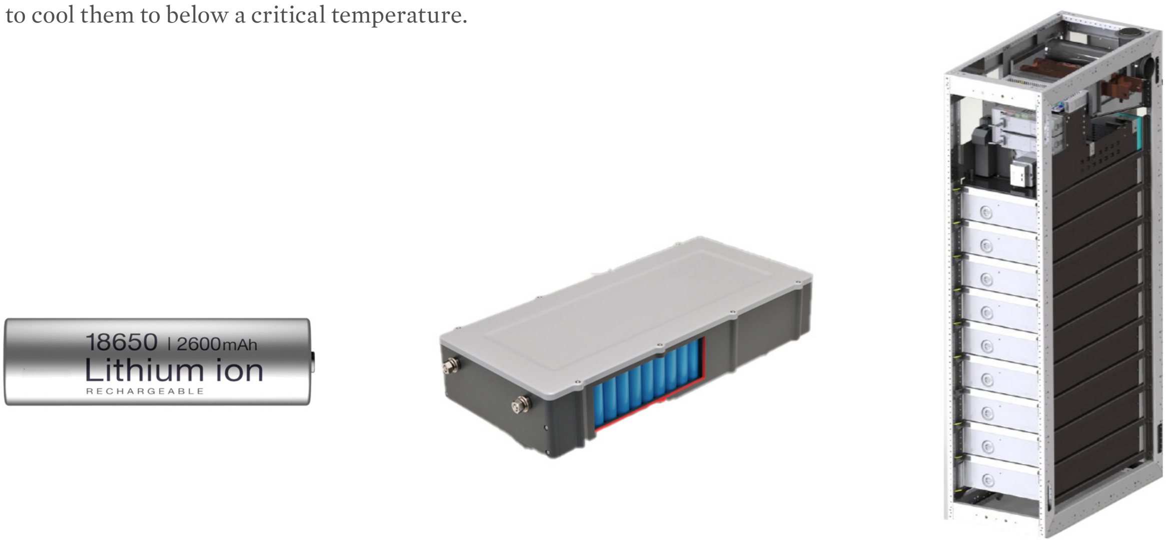


FIGURE 1. Battery cell, battery module and battery rack. Source: Siemens.

Battery system. Source: https://www.europower-energi.no.

2.1

SAFETY SYSTEM BMS

A Battery Management System (BMS) is the most important safety system in a lithium-ion battery. Its purpose is to monitor that the battery does not operate beyond safe operational parameters. Larger batteries often have more advanced BMS that monitor several parameters. The simplest of these control voltage and current only.

The BMS can monitor the following:

- Temperature of batteries and coolant (°C).
- Cell voltage and total voltage (V).
- Charge level of batteries (SOC%)
- Amperage draw (A).
- Coolant flow rate (l/min).
- Calculate available power based on voltage, amperage draw and battery temperature.
- Ensures that all cells in a battery module are charged evenly.
- Calculates battery health and calculate available charging capacity in relation to when the batteries were new.

The BMS protects against and prevents:

- Overvoltage, excessive charge voltage
- Overvoltage, excessive charge amperage
- Undervoltage
- Overcharging – charging continues after full charge.
- Deep discharge
- Excessive temperature.
- Insufficient temperature.
- In some cases, ground/earth faults

Larger systems can be monitored from outside the battery room. This means that the BMS displays information, for example, on the bridge of a ship, in control rooms and in some cases the BMS can also be read externally via the Internet. This will be able to provide critical information to response crews about the stability, charge status, temperature etc. of the battery pack.

MS Ytterøyningen, the battery fire destroyed the steel casing. Image: National Criminal Investigation Service.

2.2
THERMAL RUNAWAY

Thermal runaway (TR), is an exothermic chemical reaction which is a self-energising heat reaction. This process creates immense amounts of heat and several hazardous gases. A larger TR is not possible to extinguish using conventional extinguishing equipment, as this involves an internal exothermic (heat-generating) chemical reaction between substances in the battery.

Propagation
Propagation is a term used to describe a chain reaction that can occur when a battery cell goes into thermal runaway. When a battery cell goes into thermal runaway, the surrounding temperature becomes so high that adjacent battery cells are heated beyond their stable temperature - these will then also go into thermal runaway.

To extinguish a lithium-ion battery fire, it is this type of propagation that we wish to arrest. This is done by cooling the battery cells as much as possible so that these do not get heated beyond their stable temperature.

Battery systems can have their own cooling systems. These can be air cooling (fans) or liquid cooling. The liquids used are water, glycol or similar. These are pumped around the modules to dissipate excessive heat.

Experiment in which battery cells are subject to mechanical influence, leading to puncture and jet flames.

2.3

CAUSES OF FIRE AND THERMAL RUNAWAY

There are several causes of fires in a battery cell. Common to all of these is that they affect the battery cell – they either create their own heat or the heat up the battery cell with an external heat source.

Below is a list of causes that can lead to heating of a battery cell:

Internal short circuit
An internal short-circuit means that contact is made inside the battery cell between the anode and the cathode. The resistance of the internal short-circuit will determine heat generation. High resistance will lead to a controlled discharge of the battery cell, whilst low resistance will mean that the battery cell is discharged rapidly, which will lead to significant heat generation.

There are varying causes of internal short-circuits.

Particles
During the manufacturing process, metal particles can enter the battery cell. When the battery is subjected to vibration and impact, these metal particles can dislodge and come between the anode and cathode, perforate the separator and cause an internal short-circuit.

Collision
Deformation (impact, strikes, crushing etc.) of the battery cell can lead to contact between the anode and cathode, which will cause an internal short-circuit.

Dendrites
Dendrites are crystals of lithium metal that build up on the outside of the anode during charging. A needle-like structure is formed inside the battery cell. If these become too large, they can penetrate the separator and cause an internal short-circuit.

Dendrite formations can occur after overcharging or when the battery is charged in low temperatures.

Overloading

If the battery is subjected to high loads, the power from the battery is drained rapidly.

This can result in heating, as the battery has an internal resistance. If the drain is not regulated, this can lead to damaging heating of the battery cell, that can cause a TR. It is therefore important to have a good battery monitoring system (BMS) which will ensure that the load is regulated according to the temperature of the battery.

Overcharging

LIB tolerate high charging voltages well; however, this also causes heating of the battery. If this heating is not monitored, this can lead to excessive heating of the battery, which in turn can result in a TR. Overcharging can, over time, also lead to the formation of dendrites in battery cells.

Deep discharge

"Deep discharge" means to drain the battery completely of any stored energy. When LIB are discharged, the chemical components inside the battery can break down. Over time, this can lead to alteration of the structure inside the battery, which can cause an internal short-circuit. A BMS is important in preventing deep discharges.

External short circuit

An external short-circuit means that the positive and negative terminals are connected together with a connection that has low resistance. This will lead to a rapid discharge of the battery. Heat is released both in the battery and in the connection between the terminals.

External heat influence

This is an external heat source that heats up the battery cell, for example a fire that has started outside of the battery pack. The greatest danger from external heat is that it can heat up several battery cells at the same time, meaning that an entire battery pack can go into TR simultaneously. Frequently, safety mechanisms built into battery installations are not designed to handle TR in several cells simultaneously.

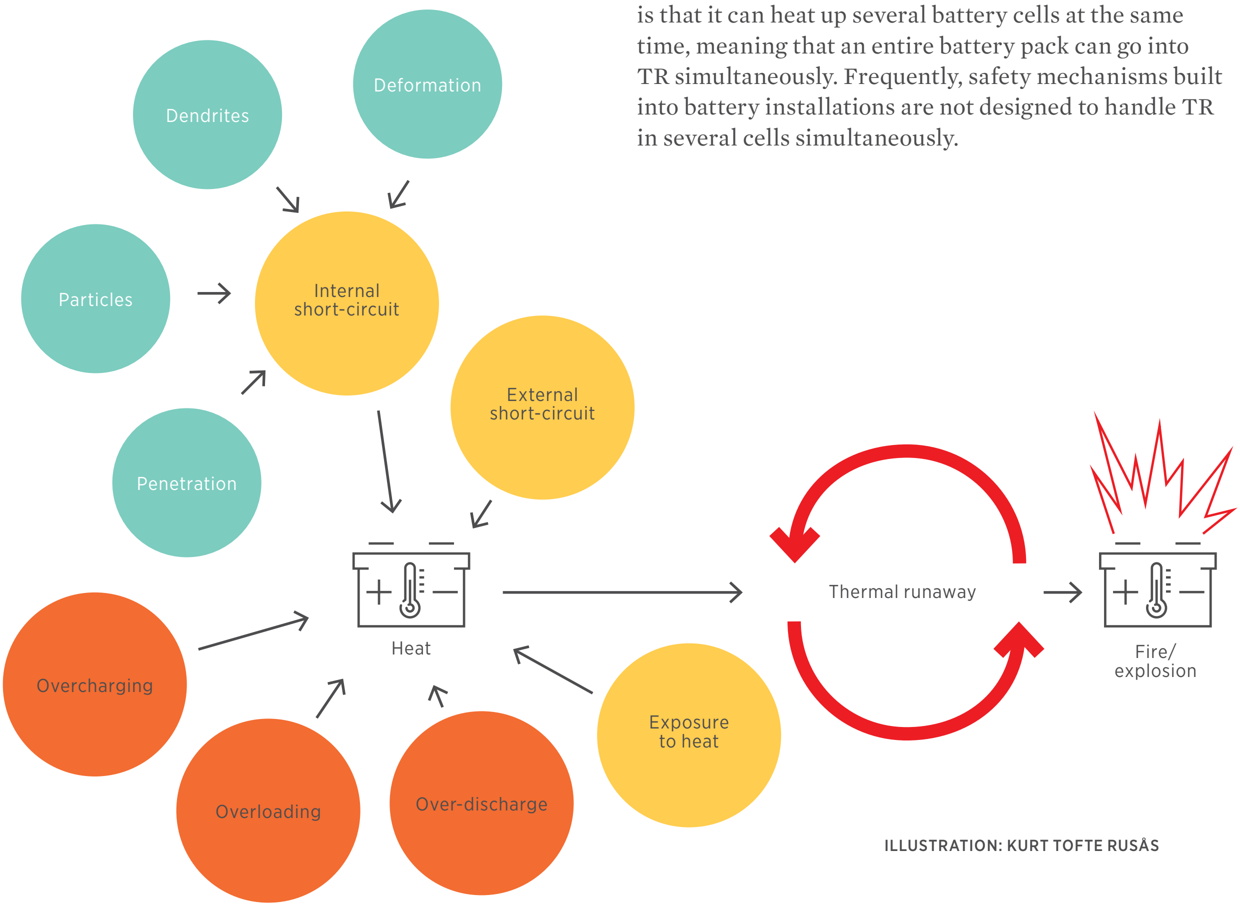


ILLUSTRATION: KURT TOFTE RUSÅS

FIGURE 2. There are many causes of thermal runaway.

Gas production
The extent of heat generated during a TR depends on several factors; however, these are chiefly associated with the charge level of the battery. The more fully charged the battery, the more energy is available and therefore more heat can be generated. The extent of heat generated is of major relevance for whether gases are released without igniting or become heated beyond ignition temperature.

A fully charged battery that goes into TR generates a considerable amount of heat and gas that can ignite when ventilated from the battery cell. Short-circuits will contribute to ignition. If, however, the battery is discharged, or has a low charge level, there will be insufficient energy in the battery cell to heat up the gas produced and gas can be ventilated from the battery cell without igniting.

Gas that is ventilated but not ignited from a TR, can accumulate in confined spaces. Under certain conditions (relative proportions of gas and air) this can create an explosive atmosphere.

2.4

COURSE OF FIRE IN A LITHIUM-ION BATTERY

The stated temperature limits below vary somewhat, as batteries are constructed differently. Tests that have been carried out can have varying set-ups and objectives. The course of events described below are however the same.

1. When the temperature in the cell reaches approximately 80°C (176°F), the anode will begin to decompose. This reaction generates heat, also known as an exothermic reaction. (The battery cell now exceeds its stable temperature).
2. At approximately 100°C to 120°C (100–248°F), the electrolyte itself breaks down. Gases are formed inside the battery cell.
3. When the temperature approaches 120–130°C (248–266°F) the separator dividing the anode and cathode electrodes melts. When these make contact, an internal short-circuit will occur which also generates heat, as the electrochemically stored energy in the cell is released.
4. At around 130–150°C (266–302°F), the cathode will begin to decompose. When the cathode reacts with the electrolyte, several gases can be formed, among them oxygen. The reviewed literature does not fully concur as to whether the generated quantity of oxygen is sufficient to maintain full combustion internally in the battery. The breakdown of the cathode is an extremely exothermic reaction that generates a great deal of heat, that will also continue to drive the cell towards ignition.
5. When the temperatures rise to 150–180°C (302–356°F), and if the cell is not able to quickly dissipate the heat generated, the temperature will increase further. At this point the cell is in TR. Oxygen production makes the fire fully or partially self-maintaining and the temperature will continue to rise such that adjacent cells will also be heated and go into is TR. This type of spreading is known as propagation.
6. The sound of small explosions and crackling is a signal that individual cells are opening and that a TR is occurring. This can continue, or die out by itself – although this depends, among other things, on the construction of the modules or batteries. There are many different types of battery, so this audible indication is not an exact indication upon which firefighting assessments should be based.

The speed of this type of thermic incident, the amount of gas released, and how much energy is contained in the fire will depend on the charge status of the battery, the battery chemistry and its construction. If the battery is fully charged, the cell temperature can reach as much as 900°C (1652°F) and jet flames well over 1 000°C (1832°F) can occur.

When the lithium-ion battery cell is heated to beyond approximately 80°C (176°F), a self-energising exothermic chemical process begins in the battery cell. This is the start of thermal runaway. During this process, gases are formed that are both flammable and toxic. The amount of gas produced will vary; however, it will largely lie between 1 to 2 litres per amp-hour (Ah) battery capacity.

CHAPTER

03

Hazards

3.1
HAZARDS

During all firefighting responses, health, safety and the environment must be given priority.

- Greatest hazards to persons.
- Explosive and/or toxic gases.
- Jet flames, explosion and/or particle ejection.
- Short-circuits in larger batteries with subsequent extreme arcing.
- Current flow.

Particular to LIB fires:

- Develop oxygen from the cathode that contributes to combustion.
- Significant heat generation.
- Significant gas production.
- Electrical energy present.
- Can self-ignite, also after the fire has been extinguished.

In fires in battery packs where life-saving intervention is not involved, it is important to have the shortest possible exposure to smoke gases. Consider alternative initiatives to internal measures if possible – ensure effective ventilation and extinguish at a safe distance.

A risk assessment must always be carried out before initiating a response.

A combination of extremely flammable, explosive, toxic and corrosive gases are formed in all LIB fires.

The degree of danger will depend on how these gases can accumulate. With good ventilation, or if the fire is outdoors, the level of risk will be reduced to a small area around the incident itself.

Composition of gases is influenced by the battery chemistry within the battery, availability of oxygen and the energy level in the battery. The energy level of the battery (SOC) influences the speed and temperature of gas production. The gas and smoke are vaporised electrolyte and decomposed products from the components in the battery.

Flammable gases
A number of highly flammable gases are formed in an LIB fire, including hydrogen, ethylene, carbon monoxide (CO), methane and propane. The composition of flammable gases will vary for each individual battery fire; thus, the properties of the gas composition will change. Despite the fact that the gas composition will indeed vary, we can however make some general comments concerning the properties of the gas mixture.

The gas mixture is comprised of both lighter and heavier gases (in relation to air). This means that the gas mixture will be able to spread throughout the entire fire space. There is a large variation in regard to the flammability range of the various gases. Some gases have a large flammability range, others less so. It should be assumed that the gas mixture overall has a large flammability range and that it is not necessary to have a large volume percentage mixture of gas in the space before the gas mixture reaches the flammability range and becomes flammable/explosive.

In an LIB fire in a closed area where gases can accumulate, you should assess whether the gas mixture is over LEL, and thereby possibly explosive. Assessing this can be difficult.

Toxic gases
The gases produced during an LIB fire can be compared to those from a plastic fire. Large quantities of CO are formed, in addition to several other highly toxic gases, including phosphoric and fluorine compounds, cyanides and chlorides. If gas and smoke from an LIB fire are inhaled, those affected must be followed up by the health services. In the event of serious irritation of the airways, consider possible exposure to hydrogen fluoride.

Irritant and corrosive gases
In addition to the above stated gases, other gases are formed that irritate the airways and can be corrosive on exposure, e.g. hydrogen chloride, sulphur dioxide and hydrogen fluoride.

There is some uncertainty in regard to the gas hydrogen fluoride (HF), which forms hydrofluoric acid on contact with water and water vapour. The Swedish Civil Contingencies Agency (MSB) and the Norwegian Institute of Public Health (FHI) have good articles on the subject, see link at the end of this guide.

It is important to highlight that HF is not a new phenomenon that has recently appeared in connection with LIB fires. HF is produced in all fires in which products containing fluoride burn, i.e., HF gas is formed in all car fires and in most plastic fires. It will also be possible to measure certain levels of HF in virtually all house fires. In other words, HF is a gas that the fire services have had to deal with for quite some time.

Exposure to HF and hydrofluoric acid may be in the form of inhalation or absorption through the skin. Breathing/inhaling fire smoke and gas, including HF gas, can lead to damage deep inside the lungs and will reduce the ability of the lungs to take up oxygen. When handling LIB fires, firefighting personnel must at all times use full safety clothing with respirators. For firefighting personnel, skin absorption will therefore be the only way to be exposed to HF.

When the gas mixture from an LIB fire is below LEL, there will not be sufficient concentration of HF to represent any significant risk to personnel.

When managing LIB fires, it is primarily flammable/explosive gases that need to be controlled. If personnel have control that the gas mixture is below LEL, then the HF gases are also under control.

Normal firefighting clothing will in most cases offer good protection against HF. In the event of extended exposure in spaces with poor ventilation, a splash suit can be used as an extra barrier.

Hydrogen fluoride is lighter than air and is highly reactive. In open areas, the gas will quickly dissipate. In confined spaces, the gas will react with all surfaces, including the humidity within the space, which will lead to the gas concentration diminishing rapidly. HF is infinitely soluble in water, and if a higher concentration of HF is suspected in a space, water can be used, ideally water mist, to reduce the concentration.

Electrical hazards
An electric battery is a component that has energy stored in chemical form, i.e. it is not possible to switch off or to rapidly discharge batteries. Therefore, battery terminals, cables and connectors must always be considered to be live. Additionally, physical damage and fire can lead to live components becoming exposed, such that firefighting personnel can inadvertently come into contact with these. It is therefore important to maintain a safe distance and use 1000-volt gloves when firefighting close to batteries and electrical connectors – a typical scenario is extraction of persons from vehicles when the vehicle is severely damaged.

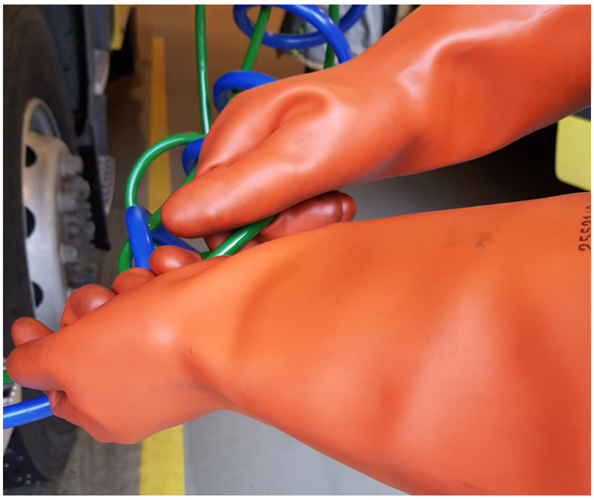
Cables carrying hazardous voltages will in the majority of cases be orange in colour (applies to electric vehicles).

If the body comes into contact and becomes part of the electrical circuit, this is called current flow. Limit values set for contact voltages must not exceed 50 volt AC current or 120 volt DC. Electric cars have DC voltages between 400–800 volts, whilst BESS and larger propulsion batteries can have voltages up to 1000 volts. Coming into contact with live cables with such high voltage can be fatal.

The extent of injury will depend on the intensity of the current, voltage level, conductive path through the body and length of exposure.

If firefighting personnel are exposed to electric shock, they must be followed up by the health services.

Short-circuit
In battery systems with large amounts of stored power, for example BESS or large propulsion batteries, short-circuits represent a major hazard. If the short-circuit occurs in the battery system with a large amount of stored power, arcing may occur that will lead to a severe increase in temperature and pressure. This leads to the danger of extremely high-speed ejection of glowing fragments and metal particles, in addition to generation of intense UV light and loud explosions that can damage both hearing and vision. The danger increases in proportion to the size of the battery system.



1000-volt gloves. Image: Drammen Regional Fire Service IKS.

CHAPTER

04

Handling

4.1
EXTINGUISHING METHODS

To gain control over a battery fire, there are two factors you must control: cooling and ventilation. If you have control over the cell temperature in the batteries, and at the same time have control of gas ventilation from the batteries – you have control of the battery fire. However, this is easier said than done.

To gain control of the battery temperature you must be able to measure the temperature and have a method of introducing cooling. The only way to measure the cell temperature is by reading the battery's safety system, i.e. the BMS. However, you must consider that it may not be possible to get good data from the BMS, as the system may have been damaged by the fire. In smaller battery systems, for example those in electric cars, it is not possible to read the BMS. So how do you measure the temperature when it is not possible to measure the temperature? The answer is to overcompensate with cooling. This means introducing sufficient cooling so that you are completely sure that you have control over the temperature.

Measuring the temperature with an IR camera will provide good information; however, it is important to remember that it is not possible to measure the actual cell temperature with an IR camera – only the external temperature, i.e. the temperature around the batteries, module temperature or casing.

LIB ventilate large amounts of gas in a TR. It is important to have control of these gases. In incidents where the fire is outdoors and the gases are not able to accumulate, you automatically have control of gas emissions. The challenge arises when the battery fire is within a confined space and gases can accumulate. In the latter case you depend on having control of ventilation.

Battery rooms are currently constructed with varying ventilation functions. Some battery rooms have fans that extract the smoke from the room, or dedicated exhaust ducts designed to channel the gas out of the room. Others use suppressant gas systems that hermetically seal the battery room and thereby contribute to the accumulation of gas in the room.

Before ventilating can begin, it is essential to be aware of the gas concentration in the room:

Are the gases <LEL, in the flammability range or UEL? The only way to discover this is to perform gas measurements with a calibrated measuring instrument.

It can be challenging to perform gas measurement in a safe manner. Opening the battery room, with the subsequent introduction of oxygen, can lead to the gas and air mixture reaching the flammability range and becoming explosive.

There are many ignition sources in a battery room. Fire gases that reach the flammability range have a major likelihood of igniting.

The only way to safely bring a fire gas from UEL to LEL is to introduce an inert gas such as nitrogen, CO_2, argon or similar. You will then reduce the oxygen level in the battery room and thus alter the flammability range of the fire gases. When the fire gases reach <LEL the gases can be ventilated out of the room. It is important that during the ventilation process, you monitor the gas concentration and ensure that this is at all times below LEL.

Sometimes the right strategy is to allow the battery to burn out. The result will be complete combustion and fewer toxic gases and substances. Additionally, a burnt-out battery cannot reignite.

4.1.1 EXTINGUISHANTS

Water

The properties of water on fire are familiar. For fires in LIB, water is the best known extinguishant. Therefore, all fire services have this basic extinguishant available! Water is the best cooling agent. A lot of water works even better!

Water can be introduced as water mist or in the liquid phase. It is the cooling effect of the water that is desired. The water must be used such that it beats down flames, cools and prevents propagation to other cells or modules.

Foam

Foam should have low density as it is primarily cooling that will prevent the spread of TR. Water with up to 1% mixture of foam liquid in the extinguishant water will help to break up the surface tension of the water and give increased coolant effect. Higher foam density will not have the same cooling effect, but can isolate unaffected cells from heat radiation from cells in TR. This can prevent further heating and spread of fire in air-cooled batteries. Light foam can be used to prevent small gases and temperature building up in a specific volume, but does not flow into battery modules.

Some stationary suppressant systems that use foam are designed to inject foam into the modules and battery rack.

F 500
F 500 is a relatively new additive, an "encapsulation agent"; there are great expectations, and some scepticism in relation to F 500. With a 3% mixture in water, it is intended to have properties that envelop and bind hydrocarbons to prevent these from being part of combustion. Foam is not generated; however, the additive reduces the surface tension of the water, which makes the water "creep" into, and flow across, larger surfaces. This increases the cooling properties, which reduces water consumption. The manufacturer claims that it is ideally suited for battery fires, both due to its ability to bind hydrocarbons and by imparting the water with additional cooling effect.

Saltwater
Sea/saltwater is electrically conductive and can lead to short-circuits in the battery system, which can lead to fire occurring around connector terminals on the batteries. There is also the possibility of the saltwater reacting in contact with live components in the battery installation. The saltwater will then decompose into hydrogen (H2) and chlorine (Cl2). This is most relevant in larger battery systems in ships that can have suppressant systems in which the primary agent is seawater, or switch over to seawater when the freshwater reserve is empty.

Fire blankets
Fire blankets will isolate the object and the fire is extinguished due to the absence of oxygen. A fire blanket is well suited to damping smoke from a vehicle fire and will be able to extinguish a fire effectively in a compartment or load area. However, fire blankets have no effect on a battery fire and will actually contribute to increasing the temperature around the batteries and thereby lead to more rapid spreading and propagation to adjacent modules. In an electric car fire, a fire blanket must therefore be used in conjunction with active cooling, for example a water wall placed beneath the vehicle. A fire blanket can also be used to protect other vehicles. It is important to be aware that re-ignition can occur when the fire blanket is removed from the vehicle. Fire blankets intended for re-use are now on the market. Cleaning and storage are important to plan with good HSE.

AVD
AVD is a new extinguishant in handheld fire extinguishers for fires in LIB. The product uses Vermikulitt, a clay mineral dissolved in water. When the product is used in a battery fire the product will take energy from the fire in order to "set" thus forming a ceramic mass which cools and isolates the fire. This extinguishant is designed for smaller battery fires.

Dry chemical
ABC powder has no effect on a battery fire, as it is unable to reduce the temperature. Secondary fires can be extinguished with ABC powder.

CO_2
CO_2 is not able to provide sufficient cooling to be an effective extinguishant when handling a battery fire. Secondary fires can be extinguished with CO2 extinguishers.

4.1.2 SUPPRESSANT SYSTEMS

Sprinklers
Sprinklers are a common form of suppressant system onshore and on board vessels. This type of suppression system is ideally suited to fires occurring outside of the battery that may then become a risk to lithium-ion batteries. In the event of a battery fire, a sprinkler system will introduce an imprecise supply of extinguishant water. This will be able to limit a TR to only a minor degree. If there are large gas or smoke concentrations in the battery room, a sprinkler system, in a worst-case scenario, will lead to a greater risk of explosion, as the water displaces the smoke in gas pockets that increases the concentration of explosive gases. A sprinkler system requires large amounts of water. On board a vessel, quantities of fresh water are often limited and so there are solutions that automatically switch over to seawater when the freshwater tanks are empty. In some cases seawater is used directly.

Mobile sprinkler systems have been developed; these are placed beneath the vehicle in the event of fire in electric cars. This involves a piping system with numerous small nozzles that spray water along the entire underside of the vehicle. The effect of this is that cooling is introduced as close as possible to the battery itself.

Water mist
Water mist systems, also called Hi-Fog, are suppressant systems that use high pressure and small nozzles to break down the water into a fine mist. Small water droplets increase the surface area of the water and thereby its ability to absorb energy from a fire. Hi-Fog is therefore an ideal extinguishant for extinguishing flame fires and for binding up smoke gases in the fire space. In contrast to a sprinkler system, Hi-Fog uses significantly less water and the risk of the suppressant system automatically switching to seawater on board a ship is thus reduced. Hi-Fog equipment can be located such that it protects both the battery room and the battery racks. The cooling effect on a battery fire is less.

Foam fire suppression systems
Foam fire suppression systems use a foam concentrate, compressed air and water to generate foam, also known as CAFS (Compressed Air Foaming System). CAFS can be directly injected into the battery rack. The system can be divided into zones so that only the battery rack or cell in which the fire has occurred is filled with foam.

CAFS has a good ability to extinguish flames from a battery fire and it contributes to increased cooling around the battery modules. Zoning ensures that only the affected battery rack is exposed to extinguishant. The disadvantage is that CAFS decomposes rapidly on contact with warm surfaces, so that regular top-up of foam is necessary. CAFS also has a limited ability to bind up and cool gases.

Fire tenders with CAFS face the same challenges as with jet nozzles, i.e. actually getting the extinguishant into the battery.

Extinguishant gases
There are no extinguishant gases that are able to prevent a fire in a battery that has exceeded its critical temperature. All extinguishant gas systems currently available are designed for conventional fires, in which a reduction of the volume percentage of oxygen is the primary extinguishing factor. Some solutions also reduce the temperature, but not to the extent required for a TR. When a system is designed, the amount of gas is calculated based on the volume in the room. The systems have varying design volumes, but the same principle applies. The self-weight and the gravity of the gases, and miscibility in air, are elements to consider up against the gas production from batteries in a confined space. Extinguishant gases will prevent the spread of fire by preventing the combustion of battery gases. The concentration of flammable gases will then increase more quickly and exceed the flammability range (UEL) both in the battery room and in adjacent rooms via gaps/openings.

Cooling extinguishant gas
3M Novec 1230™ is a fire extinguishant gas developed as a replacement for halon and hydrofluorocarbon (HFC) extinguishants. It is part of a group of chemicals called halocarbons, which contain HFC and fluoroketones.

In 2018, 3M™ publicly acknowledged that Novec 1230™ is not designed or suitable for extinguishing electric fires in batteries. Unfortunately, it is still in use, and is still incorporated in new installations. Novec 1230™ is used for extinguishing fires in switchboard rooms and other conventional fires in data and server systems, where early detection, automatic activation and disconnection of electricity optimises the function of the gas. The gas is introduced as an aerosol from nozzles on pipes from a bottle array.

The gas chiefly reduces the temperature in the room; however, it does not have sufficient cooling effect for LIB fires.

IAccording to 3M™ data sheets, only minor amounts of air are displaced and there is a residual O_2 of 19.8 % if it is added according to its design proportions.

Fluorocarbon-based gases, on coming into contact with warm surfaces, can breakdown to HF.

N_2 and CO_2
These are simple and cheap gases that displace oxygen. Nitrogen and carbon dioxide can be used in confined spaces to replace, or dilute any flammable gas mixtures. These can also help to reduce the temperature, if they are introduced as aerosol or liquid. The gas then draws energy from the surroundings during the phase transition.

Inergen
An Inergen (IG541) system extinguishes a fire by reducing the oxygen content to approximately 12.5% - a level where combustion is no longer possible. The extinguishing system does not need to wait for evacuation of persons who may be present in the extinguishing zone. A higher proportion of CO_2 increases the rate of breathing and therefore provides a sufficient safety margin so that extinguishing and evacuation can be carried out at the same time.

As the extinguishant gas is composed of gases that are already naturally present in the atmosphere, it is considered an environmentally-friendly gas.

It is an inert gas, which means that it does not play any role in the combustion process. Inergen contains no liquid and is composed of:

- 52 % Nitrogen
- 40 % Argon
- 8 % CO_2

Inergen has no major cooling effect and is not suitable for fires in LIB. Inergen reduces the risk of explosion; however, it can confuse gas measuring instruments which depend on oxygen to indicate a correct level of EX (LEL and UEL).

Cutting extinguisher
At present (June 2021) tests are being conducted, applying techniques using a cutting extinguisher to force water into casings and mechanical protections surrounding battery modules. The technique has been tested on batteries up to 500 kg. Experiments have been carried outusing additives, but the provisional Nordic conclusion is that pure water is the best solution. Testing in the Czech Republic involved a foam variant, and development is ongoing. The environmental disadvantage of foam is known, was that the same time it is desirable to maximise the effect when this is first selected as a method. Suppliers will draw up procedure for how the fire services can use cutting extinguishers in a correct and safe manner. The discussion is not whether it is effective to get water into the casing, but rather more about the cutting extinguisher as a technique. Damage to unaffected cells, the need for grounding/earthing, and battery stability over time after extinguishing are relevant aspects.

X-Fog
Some cutting extinguisher systems have additives in the water. The effect of the additive X-Fog on battery fires is presently not known. The supplier or the research environment should specify the effect as this is an additive that many fire services already have.

4.2

GAS DETECTION

In regard to gas detection, what are the answers are we looking for? To find these we have to first define the incident. We divide an incident into three phases: The critical phase, the stabilisation phase and the normalisation phase.

In the critical phase it is decisive to map out the areas or rooms with an explosive atmosphere. Detection can be a challenge, as opening rooms can lead to oxygen being introduced into flammable gases. Read more about detection equipment in the appendix.

In the stabilisation phase, gas detectors can be used to check whether chemical reactions are still ongoing in the batteries.

In the normalisation phase, gas detectors are used to safeguard personnel security and to monitor the batteries. See Appendix 2.

4.3

PROTECTIVE CLOTHING

New studies conducted in Sweden have attempted to find out the protection efficiency of regular fire safety clothing against HF. The results from the studies show that normal fire safety clothing offers good protection against HF. On average, the clothing had a 1/120 degree of protection. i.e., the concentration was 120 times lower beneath the fire safety clothing than the reference value in the test chamber.

Responses in the critical phase in level 1 and level 2 incidents will always be able to be carried out in normal fire safety clothing, with respiratory equipment.

Responses in the critical phase in level 3 and level 4 incidents will always be able to be carried out in normal fire safety clothing, provided crews have control over LEL. There will be no major/hazardous concentration of toxic acidic gases (HF) when the concentration of flammable gases is below LEL.

In the stabilisation phase and normalisation phase, for level 3 and level 4 incidents, a splash suit can be used as an extra barrier.

After a response, remember to remove clothing first, and a mask/respirator last. Undress from the head downwards.

Have good routines for sealing and cleaning of contaminated clothing.

Risk to firefighters in extinguishing fires
Questions have been asked as to what degree skin exposure to hydrogen fluoride gas can represent a risk to smoke divers who work in fire smoke. Firefighter clothing is not sealed in the same way as the suits used for protection against chemicals; however, fire safety clothing with full respiratory protective equipment offers good protection, also against fire smoke from lithium-ion battery fires.

Experience from several major battery fires, and laboratory tests carried out on fire safety clothing, where the clothing is exposed to hydrogen fluoride gas, found that there is an extremely small risk of skin exposure to hydrogen fluoride for smoke divers. Nor have any reports been found in literature of skin damage or systemic effects as a result of skin exposure to hydrogen fluoride in gas form.

Skin exposure to aqueous solutions of hydrogen fluoride leads to irritation, pain, corrosion damage and necrosis of the skin and underlying tissue. Injury can occur after a latent period, after contact with weaker solutions of hydrogen fluoride solution. This has been reported after direct skin exposure to HF in solution, but not for exposure to HF gas.

4.4

CBRNE

An incident in which an explosion is thought to be imminent, or has occurred, should be defined as a CBRNE incident. This is not a regular fire. Applies to levels 3 and 4 in this guide. If the incident is defined as a CBRNE incident, zones are established – HOT, WARM and COLD zones – to make it easier to safeguard crew safety. Interventions in connection with larger systems can take a long time, and a defensive approach is required.

The method of operation should be:

- Establish reliable measurement of any gas concentrations, also in low-lying parts of rooms/ vessel hull.
- Do not dispatch more crews than necessary.
- Always wear full safety clothing.
- Work in dense fire smoke for the shortest possible time.
- Quickly in – quickly out. The risk must be ALARA (As Low As Reasonably Achievable).
- Consider allowing the battery to burn out if the risk of spreading can be prevented.
- If an early intervention is possible, spread of fire further into the battery system (propagation) can be prevented with cooling.

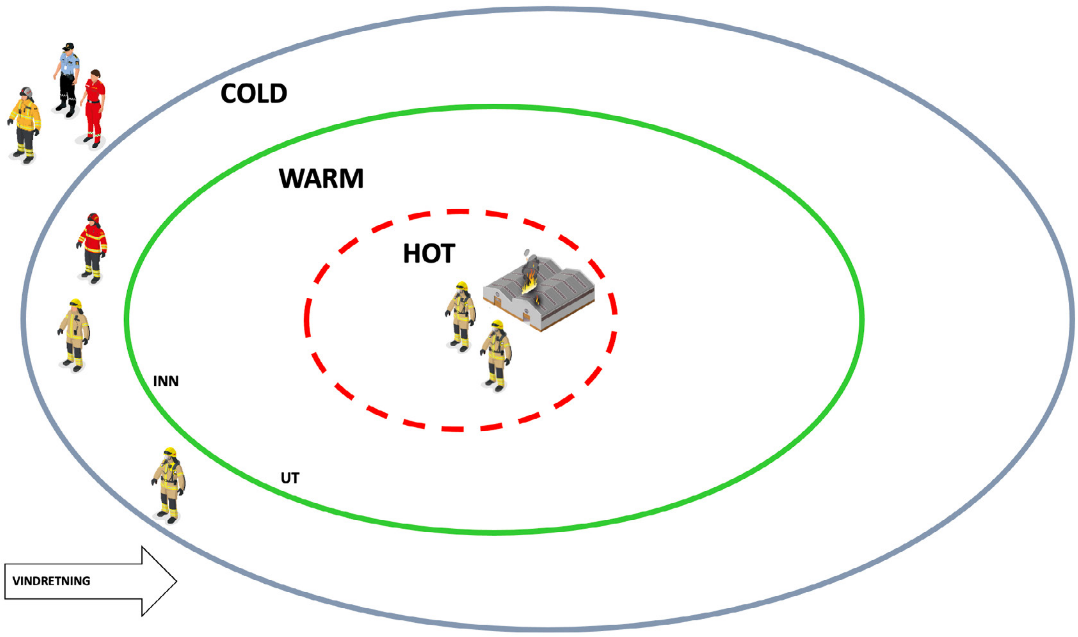


FIGURE 3. Schematic structure of a CBRNE incident site. Source: Jørn Kristiansen, Oslo Fire and Rescue Service.

4.5
SECURE THE LOCATION

After a fire in batteries where not all of the batteries have burnt out, there is a real risk that the batteries that are not burnt out can self-ignite or ventilate gas. This can occur a long time after the primary incident – but exactly how long is hard to specify. Not least this can occur due to a short-circuit in the batteries when these are moved during cleanup.

It is therefore important when entering a fire damaged battery room that full safety clothing, with respirator, is used at all times.

To monitor a fire damaged battery room, two measurement parameters can be used – temperature monitoring and gas concentration monitoring. With temperature monitoring (IR camera) it will only be possible to measure surface temperatures (not cell temperatures) in the battery, assuming that BMS is out of operation. Temperature measurements must only show stable or declining values.

If the temperature increases, this is an indication that there is a continuing process in the battery system generating heat, that over time can lead to self-ignition or gas ventilation.

By measuring the gas concentration in the room, you will form an overview of whether there are ongoing chemical processes in the batteries and whether there is a safe atmosphere in the battery room.

Gas concentration monitoring will be the most important measurement parameter for working safely in a fire damaged battery room.

Measuring instruments that measure oxygen levels, flammable gases and CO can be used. It is important that the measuring instrument is calibrated and that personnel using the measuring instrument are trained in its use. See Appendix 2 Detection.

When the situation at an incident site has been appraised and is stable, it is normal that the fire service hands over the responsibility, for example, to the police (in order to secure forensic evidence), insurance company or owner. In regard to battery fires, particularly in permanent systems (BESS) that cannot be moved, the above are unlikely to have the appropriate expertise to be able to evaluate the incident site.

If it is relevant for the police district to obtain assistance from the National Criminal Investigation Service (KRIPOS) and/or the Norwegian Safety Investigation Authority, further assistance may be requested from the fire service.

The risk of reignition can be present for days and weeks. Battery modules may need to be disassembled and undamaged batteries should be discharged. Evaluating whether a battery is undamaged is perhaps not possible without disassembling the modules. In such case, other professional expertise must assist. Relevant expertise can be the battery supplier, companies that can handle used and damaged batteries or others with specific battery expertise. We recommend that the police, in collaboration with the fire service, ensure that professional expertise assists in the evaluation of risk before the incident site is handed over. Defective and damage batteries must be removed by specialist companies. Transport of damaged batteries must be in accordance with ADR regulations. In such case, each individual fire service must assess what is available in their own district and make local arrangements in regard to division of responsibility.

4.5.1 DURATION

In Norway, there are at present only a few incidents from which we can draw experience. However, the incidents that we have seen are of international scope and interest. Experience from incidents involving larger batteries shows that these take considerable time. There can be many response orders of short duration, without visible or noticeable progress. This frequently leads to a feeling of not being particularly effective. However, with experience, new knowledge and new methods, we will be able to manage these incidents in a better, safer and more effective manner.

In major incidents with a suspicion of battery fires, planning should take into account that it will be a prolonged response. Reducing the expectation that the incident will be resolved quickly will possibly help to instil patience and perseverance early on in the incidents. If we take the boat BRIM as an example, this incident went on for 5–6 days, involving several sectors, in respect of both the boat and the environment. A large amount of the time was spent on measurements and preparations, without major active responses in the stricken ship.

4.5.2 DECONTAMINATION

Personnel that have been exposed to smoke must change all clothing immediately after the response has concluded. A shower should be taken as soon as possible.

Cleaning of personal protective equipment and other equipment used must be carried out in accordance with routines for contaminated equipment.

The odour from LIB fires can be intense. After the fire in Ytterøyningen, the odour in firefighter clothing and chemical suits could not be removed by washing, and the clothing had to be destroyed.

Consider setting up an agreement with, for example, an incident response company for cleaning of clothing and equipment.

4.5.3 HIGH RISK OBJECTS SECTION 13

Based on what we have of known problem issues associated with LIB, large battery systems (BESS) should be something that the fire services are familiar with. It is recommended that the fire services register larger battery storage installations in accordance with the Fire and Explosion Prevention Act Section 13. The prevention department in the fire services must increase their level of expertise in relation to BESS, so that they can offer good follow-up after any inspections. Some installations will be registered via Planning and Building Services; however, it is known that energy storage facilities are set up without them being registered in a planning application.

Many businesses also handle large quantities and volumes of batteries. Car accessory shops, sports shops handling the sale and repair of electric vehicles, contractors, network companies, waste handling companies, scrapyards and similar.

The inspection section should be proactive in finding and registering information regarding capacity, safety measures and individual businesses' internal control routines. Standards can be imposed for certification and control of personnel – however, also in this respect regulations are at present somewhat lacking.

Used batteries are a high-risk sport! The authorities are working on establishing control of the entire value chain, i.e. batteries from cradle to grave. Battery modules will be disassembled for resale by both serious, and some less serious, operators. These must be tested according to national standards for control and documentation, but this is unlikely to be done by all companies. A quick search for used batteries online will convince everyone in the fire services of the possible risk factors from used LIB.

Firefighting personnel must be aware of the risk object in their area. Registration as a Section 13 object can provide the initiative for drawing up an action plan for the object. Documentation of procedures should be drawn up to comply with regulations in the Working Environment Act.

4.6 ENVIRONMENTAL CONSEQUENCES

Contamination to air, water and ground.

Contamination to air takes place during all fires; smoke is spread over a large area, but it is diluted significantly. In high temperatures, combustion will also reduce emissions and possibly reduce environmental consequences. It is therefore not always the best course of action, in terms of the environment, to extinguish a fire.

More concentrated contamination to water and ground occurs primarily due to extinguishant water. If contamination can be reduced or prevented due to accumulation of extinguishant water, this should be done. What we know about the extinguishant water from battery fires is that it has a raised pH level and contains electrolyte and metals from electrodes, wired networks and circuit boards – but it is unlikely to be any more than in other fires involving modern materials.

Smaller batteries should most likely be extinguished to reduce negative environmental consequences. In the case of larger systems, it may be necessary to allow them to burn out, provided the spread of fire can be prevented.

Delivery and disposal of burnt out batteries must only via authorised sites. There are only a few companies in the country with this type of authorisation. The fire service will generally not be responsible for delivery to these. See also the section on transport/ADR.

Waste disposal plant
In the period 2016 to 2021, 288 fires in waste disposal plants were reported in Norway. In the RISE report section on "Fires in waste disposal plants", NOMIKO (Norwegian environmental and waste consultancy) highlights that lithium-ion batteries are one of the ignition sources. Used and scrap batteries can still contain a high amount of energy. If batteries are incorrectly sorted during waste handling, during unloading, crushing and shredding the battery may be subjected to mechanical damage that increases the risk of fire. Storage is now more frequently in doors due to environmental concerns. This presents new challenges in this particular industry. We recommend that the fire services contact local waste facilities. Further details are contained in the RISE report from 2019.

4.7

ABBREVIATIONS AND TERMS

- ADR: Regulations relating to transport of hazardous goods.
- AFP: Alternative Fuelled Vehicle: Vehicles using alternative fuel (other than petrol and diesel), for example hydrogen or electricity.
- BESS: Battery Energy Storage System – large battery storage systems.
- BMS: Battery Management System, Digital management component for battery systems.
- Fuel cell: Technology in which hydrogen is used to produce electricity, hydrogen-driven vehicles have electric motors.
- CBRNE: Chemical – Biological – Radiological – Nuclear – Explosive.
- Exothermic reaction: Chemical reaction generating heat.
- Ex: Explosive atmosphere.
- Hydrofluoric acid: Hydrogen fluoride dissolved in water HF: Hydrogen fluoride in gaseous phase.
- IUA: Inter-municipal committee on serious pollution
- LEL: Lower Explosion Level
- LIB: Lithium-ion battery: Li-ion describes a rechargeable type of battery in which lithium-ions are an important component
- Propagation: TR that spreads from one battery cell to another.
- SOC: State of Charge: Charge status of the battery stated in percentage of fully charged.
- TR: Thermal runaway: Describes a battery that has a self-energising, accelerating rise in temperature.
- UEL: Upper Explosion Level.

4.8

PUBLICATIONS AND COURSES

The guide is not published in a printed version; however, it is permitted to print it out if so required. It is available via the DSB website (www.dsb.no) and the Norwegian Fire Academy www.nbsk.no.

Veilederen publiseres i 1. utgave i 2021. Revisjoner og nye utgaver publiseres på nytt ved behov.

NAKOS
An e-learning course of this guide is published at: www.nakos.no. **(only available in Norwegian)**. The course is free of charge. Log in via ID portal. The course will also provide others in the emergency services with information about the guide's professional area. For firefighting personnel, the course will also provide additional knowledge of possible health consequences.

E-Training course with instructor
An e-learning course and a classroom course have been developed by Bergen fire services in collaboration with a commercial company. It provides basic competence concerning LIB and somewhat deeper introduction to risk, battery chemistry, handling and electricity than is covered in this guide. The course is suitable for 110 emergency call operators and the fire services.

Supplier responsibility
Training provided by suppliers of larger battery installations is the first step in the knowledge ladder for the fire services, that have these installations in their district. Contact owners of buildings/battery systems and request documentation for administration, operation and maintenance.

Appendices

APPENDIX 1: BATTERY TECHNOLOGY AT CELL LEVEL

Primary batteries are not rechargeable. LIB are rechargeable and are also known as secondary batteries. Research and development are ongoing, and the definitive version has not yet been manufactured yet!

The "holy grail" for manufacturers and developers is:

- Higher energy density, i.e. the ability to store more energy with less weight.
- Increased lifetime.
- Reduced charging time - being able to accept "supercharging"
- Higher power.
- Safety.
- The advantage of the cell is high energy storage and low weight. They have minimal memory effect and low self-discharge and therefore can tolerate repeated charging and discharge.

It is known that today's battery chemistry with high energy density is less stable compared to cells that have lower energy density.

Several different types of cells are used. The figure shows examples of the three most common cell designs for LIB.

There are a number of different types of lithium-ion battery cells (LIB). Common to them all is that they are comprised of two electrodes, electrolyte and a separator.

Anode and cathode
A battery is comprised of two electrodes. The electrode that delivers electrons on discharge is called the anode (negative), whilst the electrode that receives electrons during charging is called the cathode (positive). Anodes most frequently use differing compounds of carbon/graphite. Cathodes have various compositions, differing metal alloys are common.

Electrolyte
Electrolyte is a liquid that helps to transport ions between the cathode and the anode.

The lithium ions are found mainly in the cathode. When the battery is in use, lithium ions are transported from the anode to the cathode via the electrolyte - and in the opposite direction when the battery is discharged. The electrolyte in LIB is comprised, in most cases of ethyl and carbonates with a solution of lithium hexafluorophosphate (LiPF6). When this electrolyte vaporises, flammable gases are emitted.

Separator
The separator, or membrane, has the function of preventing the transport of electrons, but at the same time allowing transport of lithium ions between the electrodes.

There are different types of separators, these are normally made from porous polyethylene and/or polypropylene film, with a thickness of around 20 µm (microns).

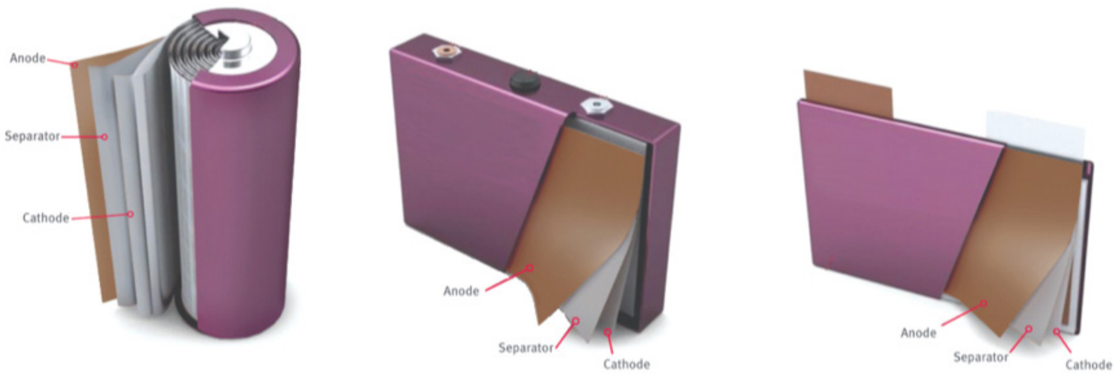


FIGURE 4. From left to right; cylindrical, prismatic, pouch cell. Source: http://imformed.com/.

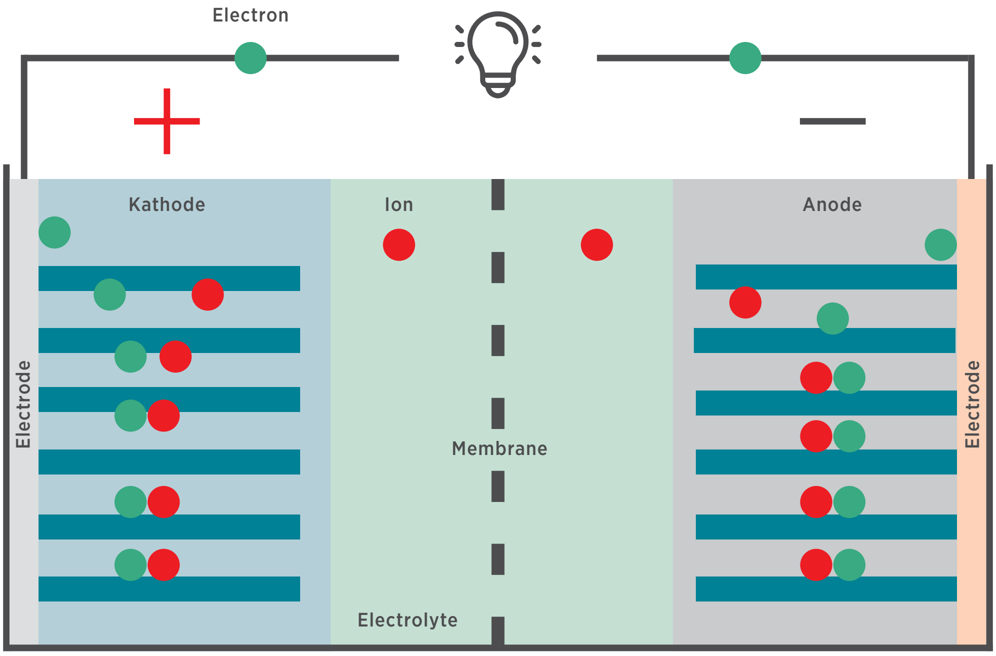


FIGURE 5. Schematic structure of a single battery cell. Source: Kurt Tofte Rusås.

The separator is in the centre of the battery, between the anode and cathode. If there is a breach in the separator, direct electrical contact will occur between the electrodes, which can lead to an internal short-circuit.

Battery chemistry
LIB use differing chemistries. Known chemical types in LIB are:

LCO – Lithium cobalt oxide (mobile telephones, PC, cameras, tablets).

LMO – Lithium Manganese Oxide (medical equipment, electric bicycles and electric tools).

LFP – Lithium iron phosphate (electric cars).

NMC – Lithium nickel manganese cobalt (electric ferries, electric cars, electric tools).

NCA – Lithium nickel cobalt aluminium oxide (electric cars, Tesla).

LTO – Lithium-titanate (astronautics, battery banks, electric cars, UPS).

The chemistry used in the battery determines some of its properties.

Lithium
Lithium as a metal can be present in primary batteries (non-rechargeable). Lithium is a shiny silver soft metal that in the open air is covered with oxide of a gold/grey colour. It is normally stored in paraffin. Lithium in itself is not flammable; however, it reacts with moisture and heat. On contact with water, hydrogen gas is generated, which can ignite. In pulverised form, lithium can self-ignite at temperatures over 20°C (68°F), and burn at temperatures around 1000°C (1832°F).

The metal lithium must not be confused with LIB and is not discussed further in this guide. It is known that so-called dendrites of lithium ions in LIB generate free metallic lithium, but the quantity is insufficient for a metal fire to occur. However, it can contribute to a puncture in the separator, and this is a safety risk.

Lithium–ion
Li-ion are charged particles (ions). Here used as a term for battery cells in which lithium salt is dissolved in an electrolyte.

APPENDIX 2: DETECTION

Use full safety clothing and full respiratory protection before starting detection!

Many fire services have detection equipment for specific gases, primarily to investigate whether there is a risk of explosion, and if applicable, oxygen levels. It is important to be familiar with the equipment and to know what can be read from the measurements. Knowledge of flammability ranges (previously known as explosion ranges) is required in order to assess whether an intervention can be carried out or must be suspended. The terms LDL and UEL must be understood.

Knowledge of how to carry out measurements is important. Measurement should be taken both at a height and at ground level, both outdoors and indoors. Gases can collect in layers. Discharged extinguishants can also promote the formation of layers.

In the event of a fire in LIB, hydrogen gas H2 and HF will be generated, therefore it is perhaps not necessary to carry out detection for these initially. Carry out detection/identification of the stated gases in phase 2 (stabilisation phase) and phase 3 (conclusion/ cleanup) for both the selection of safety clothing, but also control when the area can be declared clear.

Simple indication equipment
Litmus paper – acid indication. Litmus paper provides an indication of acidity primarily in liquids. Both strong acids (pH 1–4) and strong alkalis (pH 11–14) can cause corrosion injury. Avoid contact with liquids, including extinguishant water.

F-paper – fluoride paper. F-paper gives an indication of the presence of fluoride. The paper detects fluoride in liquids or in gas dissolved in water.

For the practical use of F-paper and Litmus paper, see the film from MSB (link below in the document).

Measuring instruments
In can be a challenge to get good measurements in a critical phase. Nor is this possible in open combustion and established secondary fires. However, if we transfer some of the CBRNE mindset from flammable gases, it can be relevant to obtain an overview whether there is a flammable atmosphere in adjacent or confined spaces in connection with a battery incident. Particularly if there are no visible flames, or if an explosion has already occurred.

It is also important to consider whether the measuring instruments available can actually provide an indication in an incident involving batteries. There have been good developments in regard to which relevant gases can be detected; however, the majority of measuring instruments cannot differentiate in the composition of flammable gases. Catalytic combi-EX O2 instruments are frequently calibrated with a specific gas, e.g. methane or toluene. If a more specific measurement is desired, there is a measurement principle known as LEL-MPS which can actually detect a concentration ratio in 10–12 gases. Mobile rigs with several detection zones have also been developed, and these are intended to monitor levels in damaged ships or BESS over several days, without risk to crews when the system has been set up. It is possible this should be available to regional incident response groups. Several larger fire services are now acquiring measuring instruments for HF.

Prioritisation of good detection solutions for flammable gases is recommended, before eventually investing in individual gases. Remember that measuring instruments are set up in relation to a working atmosphere. Limit values are set up for unprotected personnel without full respiratory apparatus.

Limit values: Maximum value for the average concentration of a chemical substance in the breathing zone of an employee in a determined reference period of eight hours. Consider placing the measuring instrument on unprotected personnel such as crew commander/ chemical dive commander who remain within a warm zone.

It is vital to know the threshold values in the measuring instrument used, if these cannot be read off from the display. As examples, alarm A1 and A2 can vary in % of lower level for 100% LDL on instruments, so that if two instruments are used with differing set-ups, one can indicate A2 and the other be within A1, in the same concentration. Some instruments can switch off at excessively low oxygen levels, or high gas concentrations. Sensors can also show incorrect readings due to cross-sensitivity, so this must be known in information and tables provided by the manufacturer.

The section below provides basic information about available sensor technology and the limitations that apply to measuring instruments.

Technical information – measuring instruments
Source: Vestteknikk AS:

Electrochemical sensors *– typically, hydrogen and CO belong to this category. Without going into too much detail regarding measurement principles, we can say that gas reacts with an electrolyte; this generates an electric signal which is converted to a gas concentration value. As permanently installed detectors, these are generally placed in a room or in a ventilation system. Here the measurement principle is based on that the gas concentration must build up over time before the cell detects gas. This is what we call a 'dead band' in the lower detection area, and slower response to gas.*

In most applications this is not a problem in relation to the task to be caried out; however, it becomes a problem in a battery installation, based on information about gas concentration and distribution. The advantage is primarily a low price and availability (many manufacturers).

Catalytic sensors *– these involve a measurement principle for LEL (flammable gas) and is the technology used in the vast majority of measuring instruments used by the fire services. Put simply, gas is fed into a type of combustion chamber, where the gas is burned across a platinum filament. Resistance in the filament changes and this is converted into a gas concentration. The disadvantage is that combustion cannot take place without the presence of sufficient oxygen. These types of cells also have a tendency to drift more and thereby require a number of bump tests (functional tests) and more frequent calibration. There must be a sufficient quantity of gas to start combustion. It should be mentioned that LEL is a collective term. Both catalytic and IR-based sensors measure the total quantity of LEL gases and do not indicate a concentration ratio of the individual gases.*

Infra-red sensors (IR) *– these are based on an optical measurement principle, in which an infra-red light (IR) beam is transmitted through a chamber through which gas flows. Compared to a corresponding "clean" reference chamber, the beam reflected back to a detector will change as a result of the gas quantity, and this difference is converted into a gas concentration. These are typically used for* CO_2 *detection, but can also be used for LEL detection. The disadvantage is that the system is optical and thereby vulnerable to dirt, particulate material and moisture/condensation. IR sensors are also more expensive. Nor can IR detect hydrogen and acetylene, as the molecules are too small. The advantage is increased service lifetime, lower energy consumption (particularly relevant in portable measuring instruments), and that oxygen is not required to detect LEL.*

VOC sensors *– also an optical principle, based on that a beam of UV light is aimed at a gas, which is ionised and gives off light that is converted into a concentration. In the same manner as with LEL, VOC sensors are not gas-specific, which means that it is the total amount of gases that is detected.*

Metal oxide electrode *– based on a metal oxide element that varies electrical resistance and converts this into gas concentration. The technology has at present only been implemented in stationary systems. The advantage is that these are extremely sensitive and possible to manufacture with an extremely small detection surface. This is a technology that has proved to be highly effective as a supplement to BMS monitoring, as measurements are down to ppm levels on gases that are released before the battery cell temperature becomes critical.*

Mobile gas detection rigs *have been specially developed with the mapping of industrial sites in mind. These represent an alternative to personal, portable and stationary alarms. They have a high battery capacity and can relatively simply be moved around within an area or to new areas. They will largely offer the same sensor configuration as a personal alarm in relation to gas types and quantity. The battery capacity varies from manufacturer to manufacturer and whether the instrument is fitted with a pump or not. The battery capacity can typically last between 30–100 days. The hose length for the pump is often limited to 30 metres. Data can be transmitted by various means, either post-measurement or continuously. Some units upload data continuously to the cloud (Internet portal) via the 4G network, whilst others use Wi-Fi and an intermediate data solution and software.*

Gas measuring instrument. Image: Drammen Regional Fire Service IKS.

APPENDIX 3: LABELLING

Marking/signage
There are no marking standards for all usage areas for LIB. It is therefore not possible, based on markings, to be sure that the object you are approaching contains LIB, or not.

Exterior marking of vehicles
It is most common for fully electric cars in Norway to have a registration number that begins with the letter E. However, it has always been possible to have a geographical registration number, and most recently personal registration numbers. It is therefore not given that all electric cars or hybrid cars can be identified by their registration number. Many cars have blue or green markings indicating that it is an AFV (Alternative Fuelled Vehicle). In the event of accidents, vehicles can be so severely damaged that it can be difficult to identify them as an AFV vehicle.

Crash Recovery or CTIF's app Eurorescue can be used to establish whether the vehicle is AFV or a hybrid. CTIF has developed a system for marking drive systems for vehicles that are ISO certified 17840-4. This marking system allows rescue crews to identify the type of drive system, for example fully electric, hybrid or gas type.

This system is completely new and its use is voluntary for a car owner – but it continues to be implemented around the world. The system is part of ISO 17840. The marking system does not differentiate between the various types of battery.

If a vehicle has been identified as AFV, actions are carried out as for risk level 2 or 3 as referred to above.

Interior
In a vehicle, cables carrying high voltage are marked with a strong orange colour – this is as a warning to technicians carrying out repairs or to rescue crews. This applies to fully electric vehicles, hybrid vehicles and vehicles with fuel cells, i.e. hydrogen vehicles. The cables receive electricity from the drive battery, which can have a voltage of up to 1000 VDC. In a rescue (release of passengers) incident, it is important to look for cables that are screened and protected by strong orange-coloured covers/sleeving. These indicate high voltage and a possible hazard to crews if these are damaged or cut.

Their location can be checked with apps such as Crash Recovery System or Euro Rescue.

Disconnection of battery source is also covered in the apps.

Labelling of solar cell systems
Solar cell systems can be connected to battery storage systems. The fire services should be aware of larger battery systems in their areas. Solar cell systems often have their own markings, some also for rescue crews. For more complete information concerning solar cell systems, we recommend www.nelfo.no/batteri.

Crash Recovery System.

Norway is a world leader in the electrification of shipping traffic.

FIGURE 6. European marking system – alternative energy sources in vehicles. Source CTIF.

Marking of ships
There is no international system for marking of battery systems in boats/ships. Some shipping companies advertise that the ship is battery driven as an environmental initiative. Local fire services must be aware of the ships operating in their area which use alternative fuels.

An international project is currently underway via IMO; however, at present the standard is not familiar or applied.

Marking of battery rooms
At present, this has not been standardised in Norway, but many installers follow the request from their own industry organisation (NELFO) and use their marking system. Among others, these markings are useful to rescue personnel:

- Dangerous voltage.
- Open flames prohibited; explosive gases may be present.
- Risk of corrosive gases.
- Requirement for use of personal protective equipment.
- Requirement for marking of switches that isolate the batteries from the electrical installation, so that the batteries do not cause an electrical hazard in other parts of the building during rescue responses.

APPENDIX 4: ELECTRIC CARS

A fire in an electric car is defined as risk level 2 or 3. Battery-powered vehicles are found in several variants.

1. Purely electrical vehicles: These have an electric motor and a battery which is charged from a regular power plug, or via rapid charge from a special rapid charge station.
2. Hybrid cars: These have a combustion engine, a battery and an electric motor. The battery is charged by the combustion engine.
3. Plug-in hybrid cars: Hybrid cars that can also be charged via a plug.
4. Fuel cell cars: Electric cars in which the battery is charged using a fuel cell that in turn uses hydrogen from a pressurised tank (700 bar) and oxygen from the air.

Rechargeable vehicles are charged from the electricity network or solar cell systems. Disconnection of a charging cable can be a challenge, as many have proprietary locking mechanisms or can be disconnected via an app. Removing the charging plug whilst the vehicle is being charged can cause powerful arcing, with potentially deadly voltage.

This is particularly relevant for rapid charging stations with high current. These types of charging stations shall have emergency stop buttons, or power must be disconnected via the fuse box or by the network company. Ensure that charging is interrupted before any interventions involving the vehicle. Some charging plugs can be released from the interior, i.e. inside the car/boot.

In the autumn of 2021, a system has been established for battery exchange for NIO type electric cars. These are fully-automated systems in which the car battery is exchanged for a fully charged battery. A number of batteries are stored in the building, ready for the next customer.

Reignition, transport and storage of damaged vehicles and batteries

It is known that batteries reignite long after they appear to be fully burnt out. This can occur in the hours, days or weeks after a battery fire. It is therefore important for the fire services to make those that secure the incident site and handle the battery pack after the incident aware of this issue. For example, damage vehicles with batteries must be placed such that in the event of reignition they do not present a risk to the surrounding environment, i.e., outdoors at a safe distance from dwellings etc.

APPENDIX 5: INCIDENTS

MAJOR AND MINOR INCIDENTS IN NORWAY AND AROUND THE WORLD

MF Ytterøyningen
MF Ytterøyningen is a Norwegian ferry constructed in 2006. In 2018, the ferry was rebuilt and converted to electric operation and operated on the ferry route Fjelberg-Sydnes-Utbjoa-Skjersholmane. On 10 October 2019 a fire broke out in the battery room on board the hybrid ferry. The ferry was located just off Sydnes quayside when the fire started.

When the fire broke out, the ferry quickly docked at the quayside and notified the emergency services. The Kvinnherad part-time fire services were called out to extinguish the fire. Initially, there was an extreme amount of smoke coming from the stricken ship and some uncertainty about what was actually burning. The crew on board the ferry had made attempts to extinguish the fire themselves, but chose to prioritise evacuation rather than fighting the fire. The suppression system and sprinkler system on the ferry had been activated.

When the fire services arrived, they were informed by the fire service 110 emergency centre of the risk of the development of hydrofluoric acid in fires in LIB. The fire services sent in smoke divers for shorter periods and a plan was established for temperature measurement in several areas on board the ferry. Initially, it was reported that the situation was beginning to come under control; however, smoke emissions increased later in the evening. Smoke divers were sent in to extinguish the fire, but without success. Regular temperature measurements were taken throughout the night.

Early the following morning an explosion occurred on board the ferry. The fire services withdrew, established a safety zone and at the same time requested assistance from Bergen fire services. RITS-Chem crews with a drone were sent to the damaged ship. After the explosion, things were relatively calm. Chemical divers carried out gas measurements to measure possible HF. HF was registered down in the battery room, and major damage was discovered, caused by the explosion. After this, the incident was normalised and resources were eventually recalled. This incident has been of great importance for the understanding of the risk of explosion when lithium-ion batteries are involved in a fire.

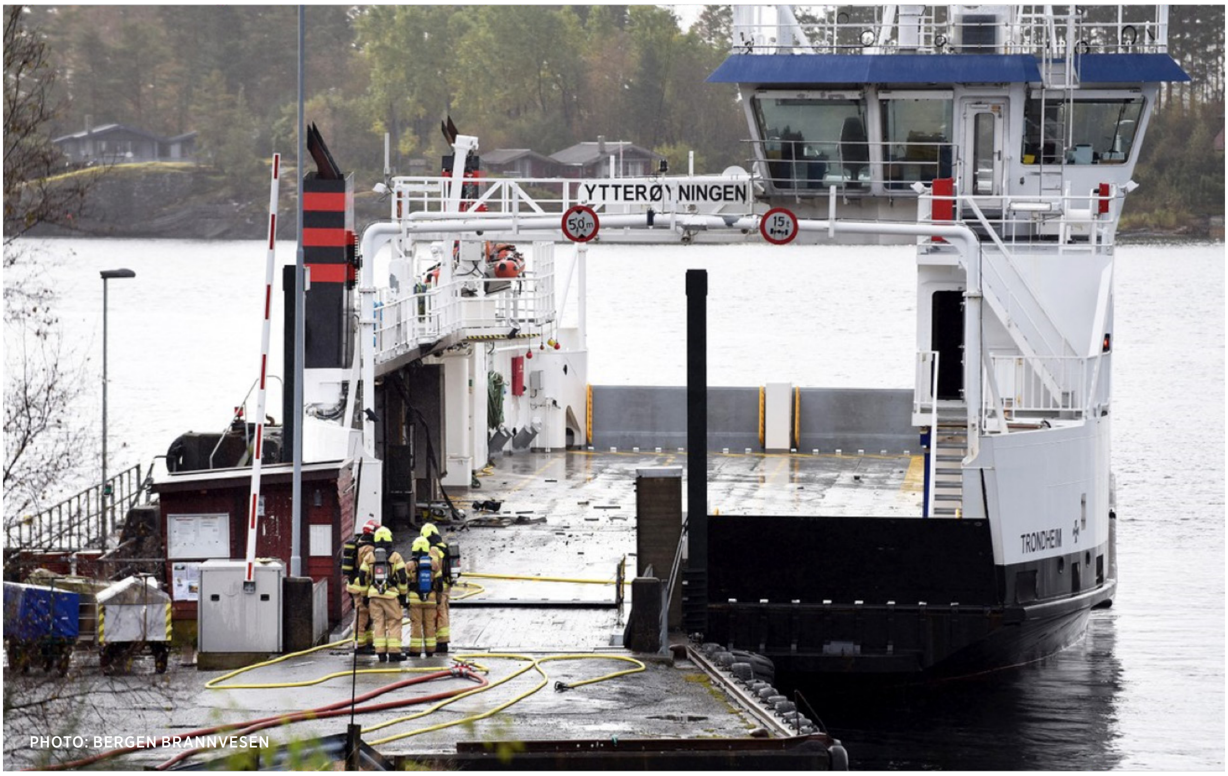
Subsequent to the incident, some disturbing elements came to light. One of the crew of Kvinnherad fire services had shown symptoms of exposure to HF. As a result of this it was decided to send 12 firemen, that could have been exposed, for further checks at a hospital. All of the firemen that were sent to the hospital later proved to be in good health. Corrosion damage on the fire service's equipment was also later discovered.

Kvinnherad fire services had damage to smoke diver equipment, whilst Bergen fire services had to scrap their chemical protection suits used during the incident. The images show some of the damage that was noted on smoke diver equipment after the incident.


PHOTO: NORDLED A/S

Technical room on board MS Ytterøyningen before the explosion.

Technical room on board MS Ytterøyningen before the explosion.



MS Ytterøyningen.

Four firemen on the way to the incident with VIB's self-developed connections to BRIM on day four. Nitrogen and extractor truck are ready, the operation to eliminate the explosion hazard is underway!

BRIM

BRIM (constructed in 2019), a catamaran designed to carry up to 140 passengers, experienced a fire in the battery pack on the starboard side in March 2021. It was towed to shore in Tønsberg. With experience from the explosion on board MS Ytterøyningen in October 2019, the fire services adopted a defensive approach to BRIM, as they chose to take time to approach the fire systematically and to test out new methods. It was assumed that there was an explosive atmosphere in the hull. It was decided that the air/ gas mixture in the boat would be replaced before the rescue crews were allowed onto the boat. Nitrogen (N_2) was introduced and extraction of air/gases was carried out. The action took place over 4 days and is described in more detail in a separate report. The scenario and the long intervention time can be a good example of an approach to fires in LIB in confined spaces. Resources were also allocated by the fire service to assist the police and the Safety Investigation Authority after the incident. This was crucial in order for the incident to be properly investigated.

Carila Sis.

Carila Sis, Sneek, Netherlands
On 4 May 2019, the fire services in Sneek, Netherlands, received reports of a fire on board a boat. A fire had broken out on board a private hybrid yacht, type Greenline 40, with two 11.5 kWh lithium-ion batteries. When the fire services arrived at the site, they observed white smoke coming from the boat.

The fire services created an opening in the cabin and hosed in water, without having an effect on the fire. In order to improve access, they opened the door into the cabin. A short time later an explosion occurred. Two firemen were thrown into the sea by the explosion and received minor injuries. The exact cause of the fire has not been determined, but it is most likely due to a fault in the battery.

The battery before the fire. Source, both images:
https://www.youtube.com/watch?v=ImOXKrI8Ezw

Electric car fire in Oslo
In Oslo in June 2021 a fire occurred in a car, a Hyundai Kona. On arrival, the fire services noted minor smoke emissions; however, this developed extremely quickly into severe smoke emerging at high pressure from the rear wheel well. Eventually the smoke gases ignited and almost the entire rear portion of the vehicle caught fire.

The solution in this incident was application of a fire blanket over the car and a 2.5” hose with a water wall beneath the vehicle for constant cooling of the battery. Thereafter a container was brought in and the vehicle was lifted up and into a water bath. The recovery service then transported the container with the car to a suitable place where it was placed under quarantine for 72 hours.

Photo: Oslo Fire and Rescue Services
1. The fire in the initial phase.
2. Vehicle packed in fire blanket, water cooling from beneath.
3. Vehicle lifted up into a container, which was filled with water.

ARIZONA
In 2019 an explosion occurred in Surprise at the McMicken Energy Storage Facility. The incident has several similarities to MS Ytterøyningen. The cause of the explosion was a fire in a battery rack, and the suppressant gas 3M™ Novec 1230™ was released. It was the same battery type, from the same manufacturer; however, it was not liquid cooled as on-board MS Ytterøyningen. The container had a capacity of 2 MW and it was chiefly one rack that caught fire. The battery manufacturer LG Chem disagrees with DNV-GL as to the cause of the fire. Cell failure and the presence of dendrites is contradicted by LG, which claims that faulty construction and short circuit were the actual causes. However, both agree with UL (Underwriters Laboratories) which has taken part in the investigation – that it was an accumulation of flammable gases in a confined space that led to the explosion, in which four members of the fire service crew were seriously injured. The accident occurred two minutes after they opened the door to the battery storage area, two hours after the first unit arrived, and approximately three hours after the owner had received an error code and a warning of a fault.

Smoke emissions were diminishing and exterior measurements were decreasing. No particularly high temperatures had been measured and there was no indication of hydrogen. There were however indications of hydrogen cyanide and CO. When the crew opened the door they observed light grey-white smoke that had accumulated in the lower part of the battery container. This "heavy" white smoke was something that they also saw early on in the response, on the outside, where a technician who was present stated it was halon, even though this was not the case. It was not correct that it was halon.

The response crew was not contacted by the company who was responsible for the battery storage facility, even though they already had a technician on site. It was a passer-by who saw smoke and reported what they thought could be a grass fire. Much indicates that the company had received warnings of irregularities 40–50 minutes before the fire services arrived on site. None of the crew were aware that it was an energy storage facility and therefore they had no advance knowledge of the applicable procedures. The building had not been re-registered with a new fire code after the building had been taken over by the company that set up the energy storage facility in 2017.

When the energy storage facility in McMicken was constructed, NFPA had started on Procedure 855, and 3M™ had already at that time informed that Novec 1230™ was not designed for or suitable for extinguishing electrical fires in batteries. The first unit on site set up a safety cordon and alerted a HAZMAT team. It was this HAZMAT team that was injured. There is a great deal to learn from this incident. We recommend listening to two podcasts that are available:

- https://www.afterthefirepodcast.com/atf-episodes/atf-episode004-4x2ce
- https://www.afterthefirepodcast.com/atf-episodes/atf-episode006-4x2ce-rbtx6

Summary of incident:
https://www.utilitydive.com/news/aps-says-runaway-thermal-event-caused-2019-battery-explosion-outlines-4-st/582475/

The image shows the damage after the explosion. The entire building is bulging and the steel doors have been blasted off their hinges.

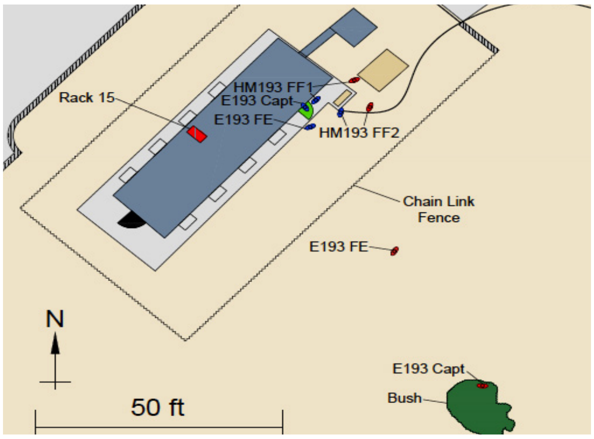


FIGURE 7. The figure shows the location of the firemen standing closest to the incident, before and after the explosion.

VEDLEGG 6: LAWS AND REGULATIONS

Transport of lithium-ion batteries – ADR-regulations
According to the regulations for transport of hazardous goods, the sender has the responsibility for classification and marking of the goods. LIB are encompassed in the regulations for transport of hazardous goods. In relation to road transport, it is thereby the international ADR regulations that apply.

Lithium-ion batteries must pass a number of tests for robustness (section 13.3 in the FN test manual) to be able to be transported as regular goods. However, it is worth noting that these requirements relate to new batteries sent from the manufacturer. In general, one can therefore say that new and unused batteries are safer than used batteries. Used batteries have generally gone through many charge cycles, are subject to ageing and various influences throughout their use, all of which can have an impact on the fire risk.

It is also worth noting that the transport regulations do not apply to batteries that are no longer under transport.

Requirements for hazard marking during road transport
Vehicles or transport units transporting LIB as goods must carry hazard markings, with a blank orange sign (400 x 300 mm) at the front and rear. The goods themselves with LIB must carry a *small* hazard label no. 9A. Goods containing typical consumer products such as mobile telephones and PCs (with a power rating of up to 100 Wh) must be labelled with a separate battery label.

When the batteries have been taken into use and are no longer under transport, the hazard markings for the goods will no longer be present.

Drivers must have valid ADR authorisation
Transport in which the total mass of batteries is less than 333 kg can take place in accordance with exceptions in ADR 1.1.3.6. The requirement for hazard marking of vehicles and ADR authorisation for drivers then no longer applies. The goods themselves, however, must always carry hazard markings with label no. 9A.

Lithium-ion batteries that have been subjected to major stresses (fire, heat, collision etc.) cannot be transported further as goods without special permission from DSB.

Batteries that are damaged or defective have lost their integrity and therefore carry a greater risk of self-ignition than intact batteries. A damaged lithium-ion battery can be unstable and must therefore be inspected. These can be batteries that have been declared defective due to safety reasons; that have leaked or ventilated, that cannot be diagnosed prior to transport; or have been subjected to physical or mechanical damage.

Assessment of the battery must be carried out by technical expertise with the necessary training and knowledge. An assessment, or inspection, can include:

- Critical hazard, such as gas, fire or leakage of electrolyte
- Use or misuse of the cell or battery
- Signs of physical damage, such as deformation, or discolouration of the cell or battery casing
- External and internal protection against short circuiting, such as measures relating to voltage or insulation

ORANGE SIGN (BLANK)	HAZARD LABEL NO. 9A	BATTERY LABEL
		
400x300 mm	100x100 mm	1000x1000 mm

FIGURE 8. ADR marking.

- The condition of the cell or battery's safety devices; or
- Damage to internal safety components, such as the battery's control system, BMS.

There are no exceptions for batteries in this condition, and the goods, in addition to the UN number and hazard label 9A must carry the text "DAMAGED/ DEFECTIVE LITHIUM-ION BATTERIES". Transport documentation must contain the following declaration: *"Transport in accordance with special regulation 376"*.

Installation of batteries in low voltage systems in dwellings and industry
Electrical design and installation are regulated by DSB *regulations pertaining to electrical low-voltage systems*. The regulations refer to NEK 400 Electrical low-voltage installations as a method for safe installation. In sub-standard 551, special general requirements are specified as to how power supply devices, including battery installations, must be installed to protect against electric shock and fire as a result of overloading or short-circuiting. Here, specifications are also stipulated regarding power supply devices used in a safe manner in parallel with the general electricity supply network. Compliance with these requirements will be of importance for secure operations and safety for fire service personnel in the event of an incident in battery systems - particularly in relation to the risk of electric shock.

In addition, NEK 400 has a sub-standard, 806 Battery installations, that includes requirements relating to installations of all types of stationary secondary batteries (rechargeable). The most recent version of the standard (2018) now also contains special requirements regarding secure installations of battery banks containing lithium-ion batteries.

The use of LIB in building installations is fairly new, both nationally and internationally. The regulations are currently under development. DSB and the norm committee with responsibility for NEK 400, therefore adapting the standard to safeguard these circumstances.

A new electrical standard has recently been issued for requirements relating to the installation of lithium-ion batteries. The standard is NEK EN IEC 62485-5: 2021 and will be integrated in the next revision of NEK 400: 2022, in force from 1 July 2022. This will contain specific requirements for installations with LIB, including safety functions and marking.

Planning and Building Act and location of batteries in buildings
The Planning and Building Act is administered by the National Office of Building Technology and Administration (DiBK) and has no specific requirements in relation to the installation of batteries beyond general requirements regarding risk assessment. Reference is made to DSB's electrical safety regulations and applicable guidelines concerning good installation practices. See also guide from NELFO concerning battery installations in dwellings https://www.nelfo.no/batteri. The guide has been developed by DSB, DiBK, NELFO and DRBV.

Requirements concerning installation of battery systems on board ships
DSB's *regulations on maritime electrical installations* contains requirements concerning the design and implementation of electrical installations on board all ships in the Norwegian register (NIS and NOR). No ships are allowed to sail before DSB has issued an inspection certificate. The regulation stipulates requirements for installations in regard to electric shock, fire and secure power supplies for important functions.

In particular this concerns marking of hazardous voltages on the outside of switchboard rooms/battery rooms and labelling of distribution.

In regard to requirements for batteries, this will be stipulated in memorandums drawn up by the Norwegian Maritime Authority in collaboration with DSB, along with special regulations for battery installations in the classification authority regulations that can vary between classification authorities. The consequences are therefore that ships can have differing safety requirements for marking and implementation of battery rooms/systems, as classification authorities can have differing detailed requirements for compliance with IMO (International Maritime Organisation) standards.

It is important to note that Norway is the first country in the world to adopt the use of electric ships. This means that there are limited international regulations to consult - Norway must do the job itself. Therefore requirements for installations with LIB on ships are still under development.

APPENDIX 7: CHARGING

It is important that the charger and battery are matched to each other. The combination of battery and charger must correspond. This is rather loosely followed in relation to consumer electronics, however larger systems are in accordance with manufacturers requirements.

The use of an incorrect charger can lead to excessively high temperatures, which can cause fire. Surplus heat is always generated during charging and discharge. The battery system must be designed to manage the heat produced. Larger battery packs have cooling systems to manage the temperature, these can be air cooling or liquid coolant with varying chemical properties.

Charging in cold conditions can lead to dendrites and short-circuits in batteries. This does not apply to electric cars sold in Norway and in the Nordic countries; these manage this particular issue with their own battery heating systems.

Charging via solar cell system
Solar cell systems generate electricity during daylight hours. For the customer, it is perhaps more relevant to use the electricity during the evening and night - a battery system can be installed to provide the energy.

It is also possible to purchase electricity from the network when this is on a cheaper tariff and charge up battery banks that are used when electricity is otherwise expensive.

Charging via regular electricity supply (230 volt)
All small devices are charged by the 230 V system, including battery systems up to electric car size (100 kW). The circuits into the charging units must be robust enough to ensure that the charging does not cause heating in the electrical system.

Charging via high-voltage system
A typical ferry quayside system for electric ferries is comprised of an integrated charging station on shore. The charging station is frequently equipped with a battery pack onshore that will function in parallel with the electricity network, **provided by the network supplier**.

The battery pack onshore is charged by the local electrical network when the ferry is not being charged (out at sea), and will typically use between 25–55 minutes for charging, depending on the number of ferry crossings. The local electricity network will be able to supply for example 2500 kW, and the battery pack a further 2000 kW, which corresponds to a total of 4500 kW. The journey itself of the ferry takes place in approximately 4 minutes, then with 4500 kW.

The power supply to the charging station is generally high voltage (for example 22 kV). The charging voltage from the charging station to the ferry is typically 11 kV. Contact between the charging equipment and the ferry takes place via induction or via a type of pantograph, not via regular industry contacts.

Transfer takes place via a pantograph - high voltage 11 kV - from a charging tower. The pantograph has a mechanical and electrical connection and has the appearance of a cut-off pyramid. The entire charging tower is considered to be a high-voltage area and the quayside is cordoned off with a fence/gate. The charging tower is in principle closed off when it is not in use. During use, a rolling door rises between the tower and the ferry, whereupon the pantograph emerges - here there will be the risk of contact. The red boxes are magnetic plates that more the vessel and hold it in place.

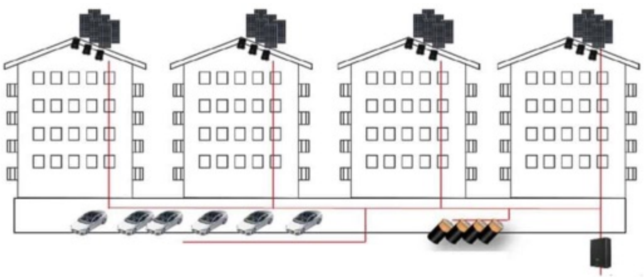


FIGURE 9. Integrated system with solar cells, rectifier (AC to DC), electric cars and dwellings in network.
https://www.greenbuilt.no/2018/05/03/solcelleanlegg-smart-energibruk-og-lagring-av-energi/

Charging of buses via a pantograph.

Remotely-controlled land-based electricity connection at the quayside in Flåm. Image: CAVOTEC.

LITERATURE AND FURTHER READING

(mostly in Norwegian)

Bergen brannvesen
- 2020 – *Håndtering av utilsiktede hendelser som brann, eksplosjon og avgassing knyttet til bruk av Li-ion batterier*

Vestfold interkommunale brannvesen VIB
- 2021 – *Evaluering av hendelse på MS Brim*

MSB Sweden
- 2016 – *Nya risker för räddningspersonal vid bränder/gasning av batteripack hos e-fordon*
- 2018 – *Brandsyddskläders skyddskapacitet materialtester med kemikalier som bildas vid bränder och termisk rusning i Li-ion batterier i e-fordon.*
- 2021 – *Gasformig HF ved brand i trånga utrymmen-risker for hudupptag vid insatser*

DNV-GL
- 2019 – *Technical reference for Li-ion battery explosion risk and fire suppression*
- 2020 – *Sikker bruk av litium-ion batterier i petroleumsnæringen*
- 2020 – *McMicken Battery energy storage system event technical analysis and recommendations*

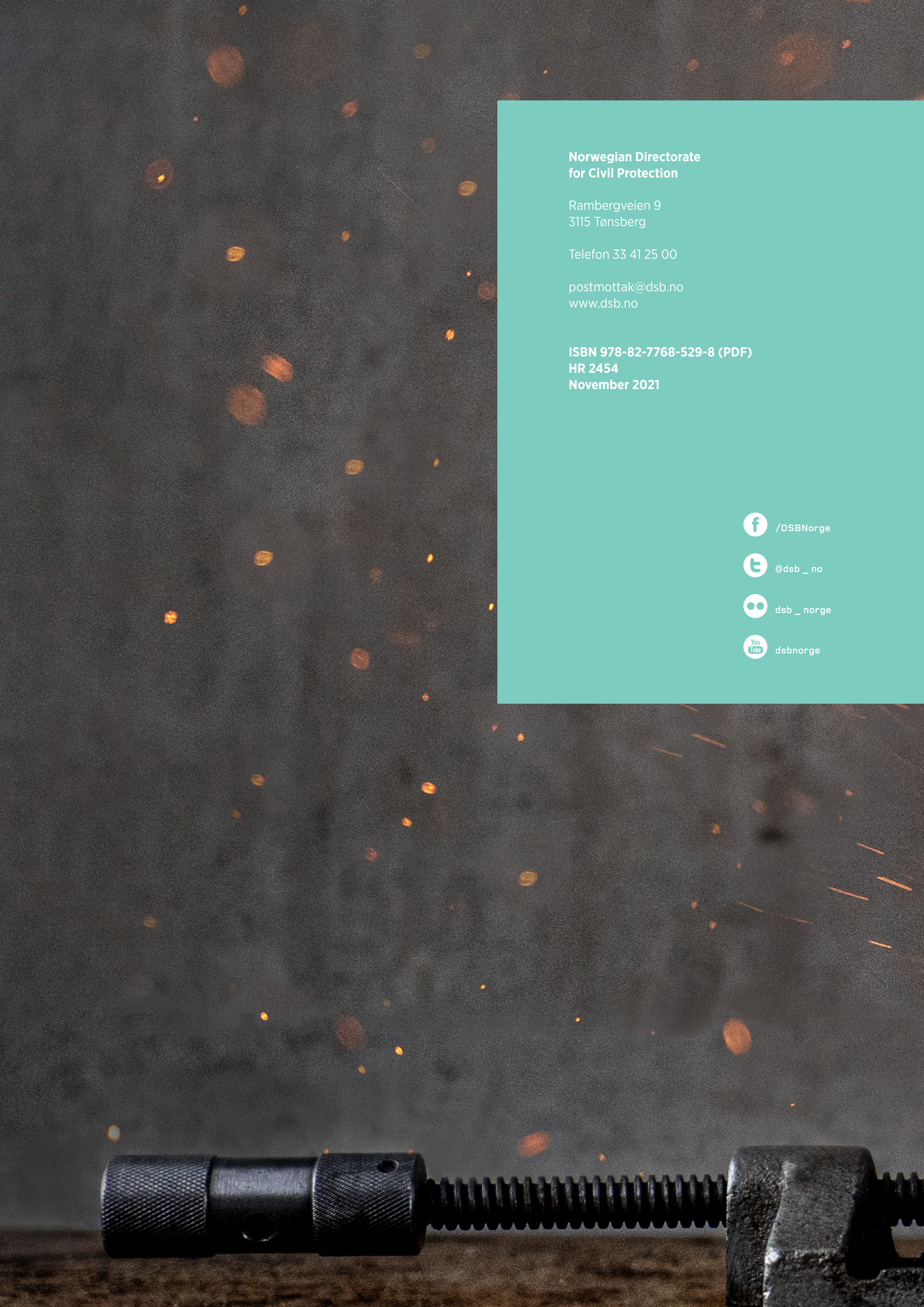
RISE FIRE RESEARCH
(risefr.com has a number of publications in English)
- 2017 – *Fullskala branntest av elbil*
- 2019 – *Lading av elbiler i parkeringsgarasje*
- 2019 – *Brannrisiko ved lagring av ikke-tilkoblede litium-ion- og litiumbatterier*
- 2019 – *Energieffektive bygg og brannsikkerhet*
- 2019 – *Brannrisiko ved lagring av ikke-tilkoblede litium-ion og litiumbatterier*
- 2020 – *Solabrannen, brann i parkeringshus i Stavanger*
- 2021 – *Avgassing fra LIB i hjemmet*

NELFO
- 2021 – *Batterisystemer i boliger, brann- og elsikkerhetsveileder*
- 2021 – *Merking av batterirom.*

DSB
- 2015 – *Brann og redning elektriske*

Beredskapsstyrelsen i Danmark
- 2021 – *Temahæfte om brand i el- og hybridbiler*

Folkehelseinstituttet FHI
- *Batteribrann, Litiumionbatteri-behandlingsanbefaling ved forgiftning*



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ISBN 978-82-7768-529-8 (PDF)
HR 2454
November 2021

/DSBNorge

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