Swedish Civil
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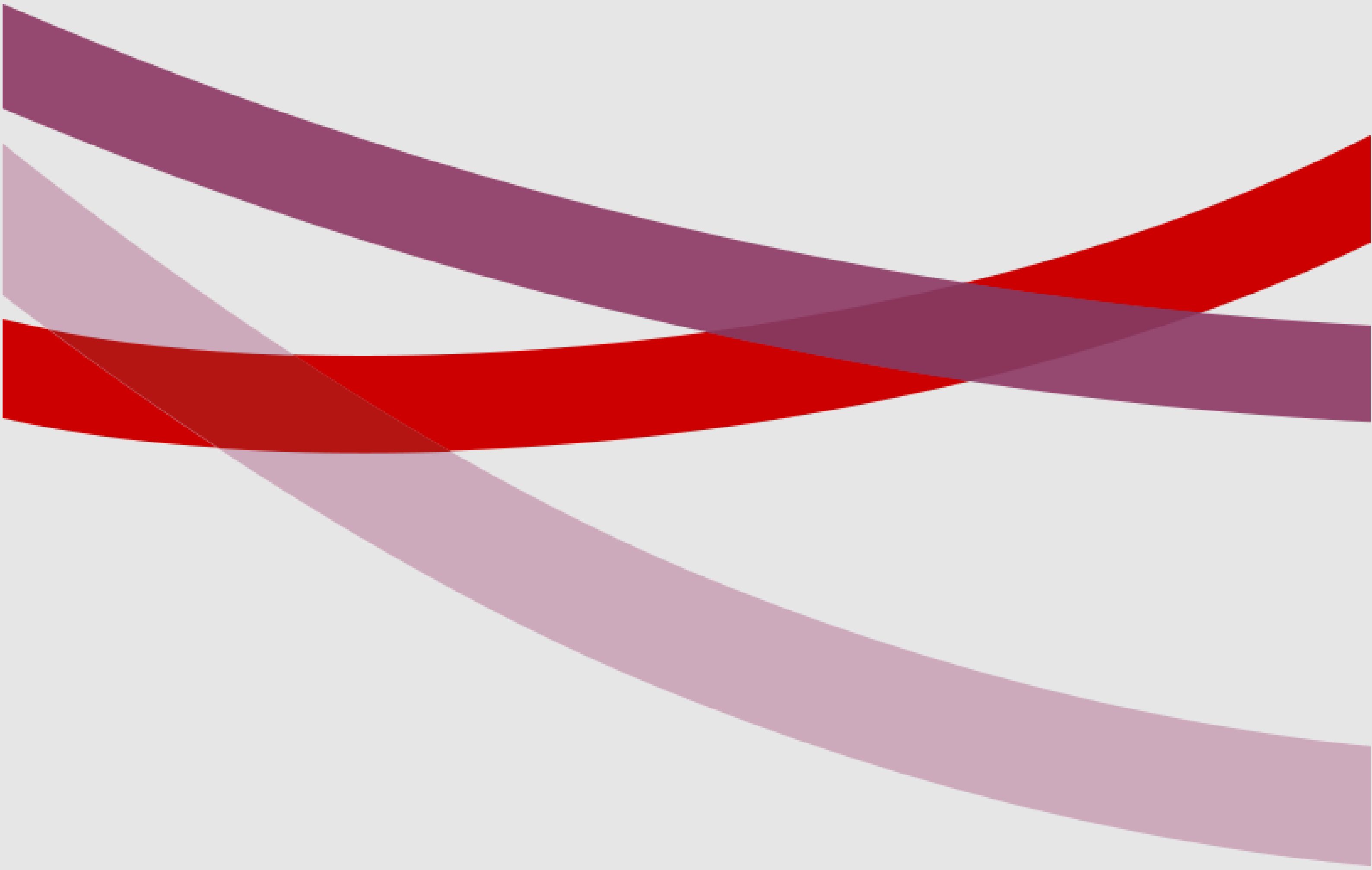
Agency



Demonstration of firefighting methodology for lithium-ion batteries

Application of methodology at various assembly levels (module, sub-pack, EV battery pack and vehicle)

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Section: Fire and rescue

Design: Advant

Order Nr.: MSB2184 – March 2023
ISBN: 978-91-7927-376-7

Preface

The following report is based on a collaborative project between the Swedish Civil Contingencies Agency (MSB) and manufacturers and distributors of emergency vehicles and tools as well as representatives from the automotive industry. The aim of the project has been to present a guide for addressing lithium-ion batteries in a state of thermal propagation and to provide and increase knowledge and understanding of electric vehicles and other battery-powered applications. The results of the project are based on requirements and recommendations from manufacturers and other stakeholders active in the industry and emergency services.

This report describes experiments carried out to develop a proposal for a method of addressing lithium-ion batteries under thermal propagation in vehicle battery packs in the form of a partial watertight container. The strategy of introducing water into a battery pack has been studied. The report is based on current research knowledge, industry knowledge and stakeholders in Swedish emergency services, and is confirmed using tests carried out on a specific type of lithium-ion battery.

The methodology proposed is to be considered a guideline and guidance. Where laws, rules, regulations, manufacturer's or organisation's instructions impose stricter or different requirements, these take precedence.

Procedures, training, technical aids and proper protective equipment can prevent accidents while minimising the consequences of accidents that do occur.

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Description of terms

Table 1. Here we describe the meaning of some terms used in this report.

Term	Description
Battery cell	Basic rechargeable energy storage device consisting of electrodes, electrolyte, containers, terminals and often separators. The battery cell is a source of electrical energy obtained by direct conversion of chemical energy.[1]
Battery module	Several battery cells forming a subsystem of the battery pack.
Battery pack	Energy storage device containing cells or cell groupings, normally connected to cell electronics and an overcurrent protection device with electrical interconnections and interfaces to external systems.[2]
Cylindrical cell	Jelly roll-shaped battery cell with metal casing.
Electric vehicle	Vehicles propelled by one or more electric drives.[3] Throughout this report, whenever electric vehicles are mentioned, the fuel for electric propulsion will be lithium-ion batteries.
Emergency response guide (ERG)	Specific information enabling first-responders to appropriately address an emergency with regard to a particular technology or design principles.[4]
Lithium-ion battery	Rechargeable electrochemical cells or rechargeable battery that has an ionic conductive electrolyte that are designed without metallic lithium in either electrode.[5]
Pouch cell	Battery cell where the cell casing consists of laminated metal-polymer films. A pouch cell has high energy density and good heat dissipation.
Prismatic cell	Battery cell in metal casing. A prismatic cell has a high energy density.
Rescue sheet	ISO 17840 document containing vehicle- and model-specific standardised data sheets with technical information for emergency services personnel. Available via Euro Rescue app, the Crash Recovery System (CRS), or others.
State of charge (SOC)	The available capacity of a rechargeable energy storage system (RESS) or an RESS subsystem expressed as a percentage of the nominal capacity.[6]
Thermal runaway	Uncontrollable state when a cell or battery overheats and reaches very high temperatures for very short periods (seconds) through internal heat generation due to an internal short circuit or misuse.[7]

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1 ISO/TR 8713:2019, 2019.
2 ISO 18300:2016 (en), 2016.
3 ISO 13063:2012, 2012.
4 ISO 17840-1:2022 (en), 2022.
5 ISO 17546:2016 (en), 2016.
6 ISO 6469-1:2019, 2019.
7 ISO 17546:2016 (en), 2016.

Term	Description
Thermal propagation	The process by which thermal runaway in a lithium-ion battery cell propagates from cell to cell in the battery.
Traction battery	Grouping of all electrically-connected battery packs to supply electrical power to the electric drive and to any wired electrical auxiliary system.[8]
Re-ignition	When apparently extinguished material starts burning again.

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[8] ISO 6469-3:2011, 2011.

1 Introduction and background

In Sweden, registrations of electric vehicles increased by 370% between January 2021 and January 2022. During the same period, the share of registered vehicles was split between 25 per cent BEV (pure battery-electric vehicle) and 25 per cent PHEV (plug-in hybrid vehicle). Similar figures for the transport sector can be observed across the EU. Other electric applications, such as electric bicycles and mobile phones containing lithium-ion batteries, have also increased. In parallel, the installation of battery storage in homes and offices is increasing with the aim of utilizing solar and wind power around the clock. The regulations and guidelines for battery-storage installations are, in the best case, national.

Fires in lithium-ion batteries can be difficult to manage and require significant human and material resources. One common misconception is that traction batteries are always implicated in an electric vehicle fire, but this is not the case at all. Here in the introduction, it must be made clear that electric vehicle fires can arise in traction batteries, which is a scenario unique to this type of vehicle, as well as in other vehicle components, just as in vehicles with IC engines.

To actively stop thermal propagation in a lithium-ion battery, the exothermic reactions occurring within the battery cells must be slowed down and stopped. One way to do so is with internal cooling of the cells inside the battery.

Several tools on the market can be used to extinguish fires in lithium-ion batteries and facilitate the disposal of the batteries after fires. The purpose of these tools is to accelerate and improve firefighting. Firefighting methods that operate on the principle of flooding batteries with water to cool individual cells are evaluated in this demonstration.

The background to this report consists of prior tests carried out to stop thermal propagation of lithium-ion batteries.[9] The tests were based on a technique that involved establishing an internal water flow inside a battery pack that was experiencing thermal propagation. The technique is currently used as a risk-mitigation measure on the production line of battery manufacturers.

This section will present tests carried out on the firefighting technique which have been confirmed for a specific type of lithium-ion battery.

1.1 Prior tests and trials

A feasibility study was conducted by Cold Cut Systems in Kungsbacka in 2021, with the Swedish Civil Contingencies Agency (MSB) participating as a reference[10] The aim was to investigate whether it was possible to stop thermal runaway in an

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[9] Trewe, 2021.

[10] Trewe, 2021.

EV lithium-ion battery pack by establishing an internal water flow in the battery pack. Cold Cut Systems used a cutting extinguisher in the feasibility study with good results.

Evidence was judged to exist for further research and testing to develop guidelines for offensive extinguishing of lithium-ion battery fires. The demonstration was an activity within the framework of this work.

1.2 Aim and goals

The overall aim of the demonstration is to provide experimental experience regarding the methodology of flooding lithium-ion batteries with water during fires as well as showing that this can contribute to faster, more efficient firefighting given safe access to the battery.

The aim of the firefighting measures was to stop thermal propagation of the lithium-ion battery.

1.3 Study limitations

The demonstration is limited to specimens composed of lithium-ion cells with no more than 60 per cent nickel content in the cathode material. More nickel-rich and energy-dense electrode systems have higher reactivity and must be investigated separately.

Both prismatic cells and pouch cells are represented among test samples. Cylindrical cells have not been studied in this demonstration.

To facilitate the test, the test samples have been modified by removing the safety systems normally found in lithium-ion batteries. Past experience has shown that it can otherwise be difficult to induce thermal runaway and ignite the battery. The modification may have affected the course of the fire in the experiments, but is not considered to have a significant impact on the effect of extinguishing efforts.

Only water has been used as an extinguishing agent.

The demonstration method is designed to reflect the state of knowledge at the time of the test. New methods and guidelines are being developed as battery technology evolves and new research findings emerge. New methods and guidelines are also being developed as field experience with regard to best practice grows.

The results of this report are to be seen as an example of how the method and tools that are tested can be applied to the type of objects included in the study.

2 Methodology

The method used to develop and conduct the tests is largely based on knowledge acquired from previous tests and studies.[11] The method is based on creating access to the traction battery and then establishing a flow of water.

2.1 Test objects

The tests were carried out on four different set-ups:

- sub-pack
- detached electric car battery
- fully electric vehicle
- battery module.

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[11] Trewe, 2021.

2.1.1 Test 1: sub-pack

Test 1 consisted of a total of three sub-tests performed at the sub-pack level. The configuration of the sub-batteries is shown in Figure 1 and consists of four battery modules as well as an ignition module (hot plate) and six thermocouples mounted in different positions to measure the temperature. The modules consisted of prismatic cells that were fully charged (i.e., 100 % SOC).

Technical specifications

- Battery module: 24 volts, 6.54 kWh
- Sub-pack: 26 kWh.

Figure 2 shows the sub-pack with lid, ready for transport to the test site.

Figure 1. Configuration of modules in the sub-pack. Placement of hot plate and thermocouple for temperature measurement as shown in the figure.

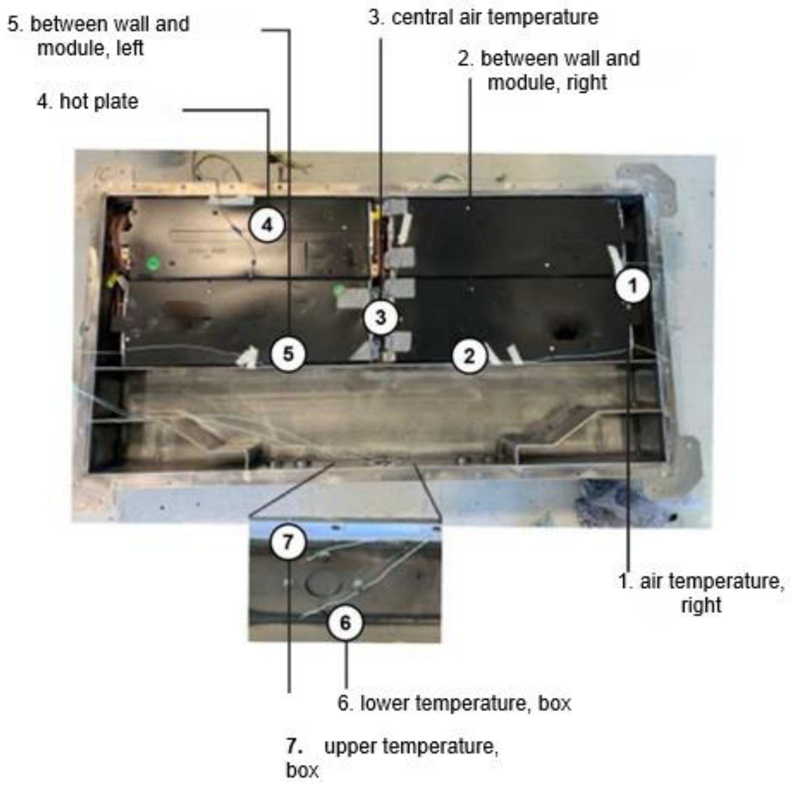


Figure 2. Sub-pack with attached lid, ready for transport to the test site.

2.1.2 Test 2: detached electric car battery

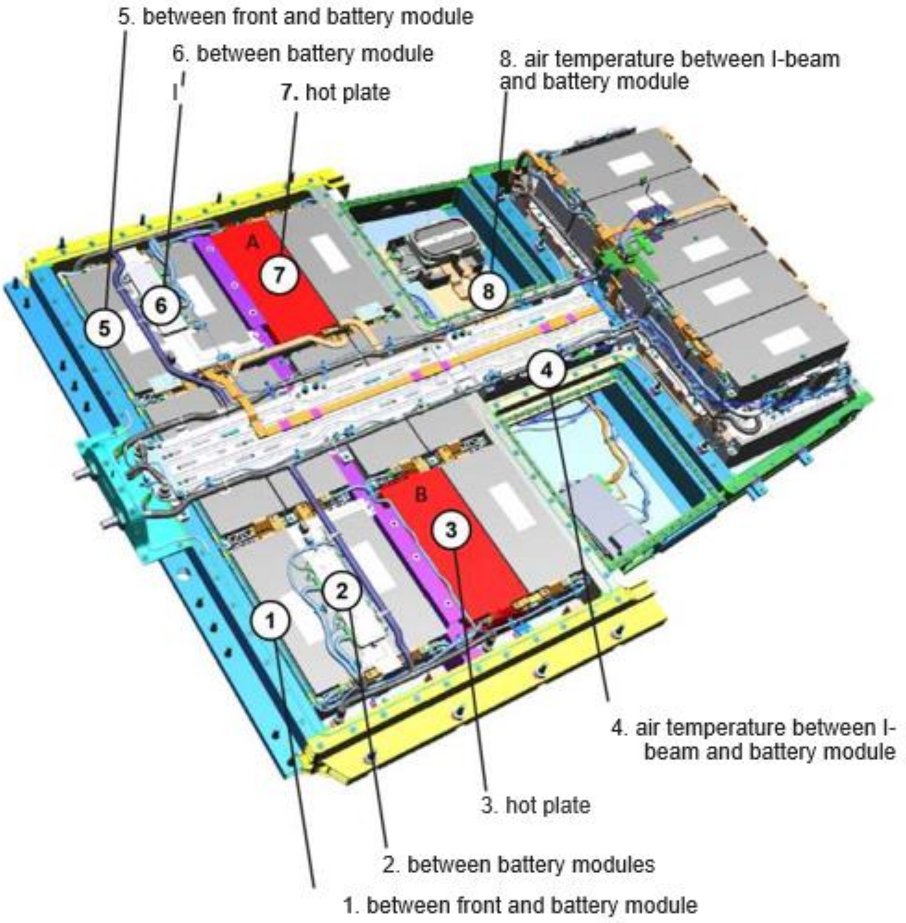
Test 2 was performed on a full-scale traction battery from an electric car consisting of a total of 24 battery modules, two ignition modules (hot plates) and instrumentation for temperature measurement as shown in Figure 3. The modules consisted of prismatic cells that were fully charged (i.e., 100 % SOC).

Technical specifications

- Battery module: 14.8 volts, 2.8 kWh.
- Battery: 67 kWh.

Two ignition modules (hot plates) were installed for two possibilities to initiate thermal runaway.

Figure 3. Configuration of modules in the traction battery. Placement of the hot plate in module A and B and thermocouples for temperature measurement as shown in the figure.



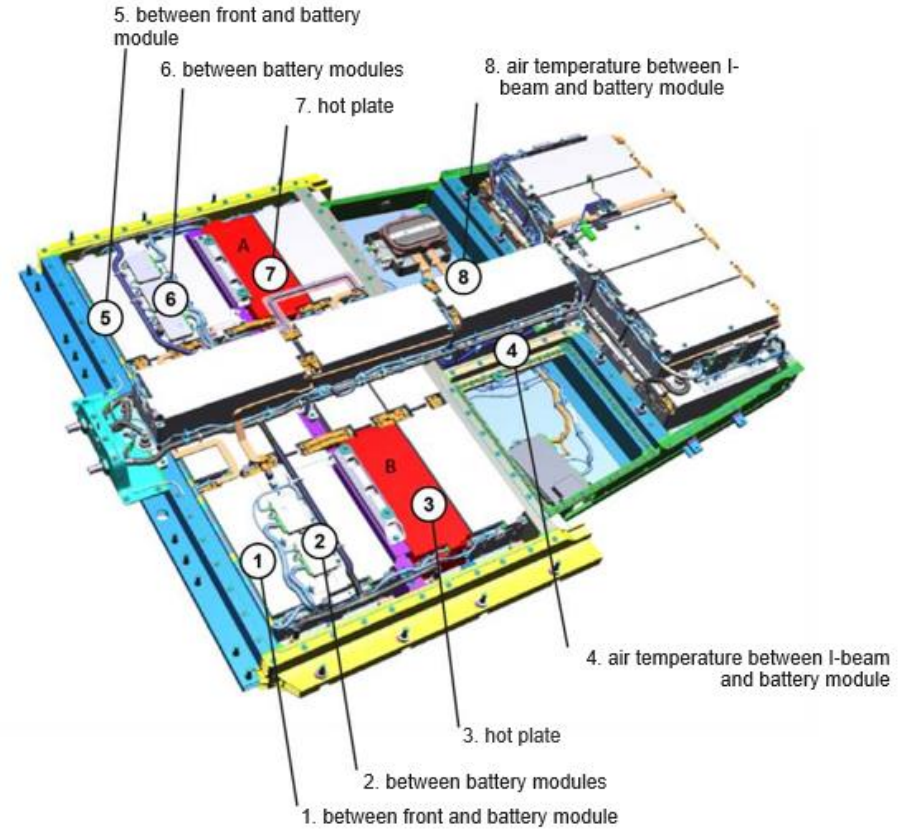
2.1.3 Test 3: Fully electric vehicle

Test 3 was conducted on a fully electric vehicle. The traction battery consisted of a total of 27 battery modules, two ignition modules (hot plates) and instrumentation as shown in Figure 4. The modules consisted of pouch cells that were fully charged (i.e., 100 % SOC).

Technical specifications

- Battery module: 14.8 volts, 2.8 kWh.
- Battery pack: 75 kWh.

Figure 4. Configuration of modules in the traction battery. Placement of the hot plate in module A and B and thermocouples for temperature measurement as shown in the figure.



Two ignition modules (hot plates) were installed for two possibilities to initiate thermal runaway.

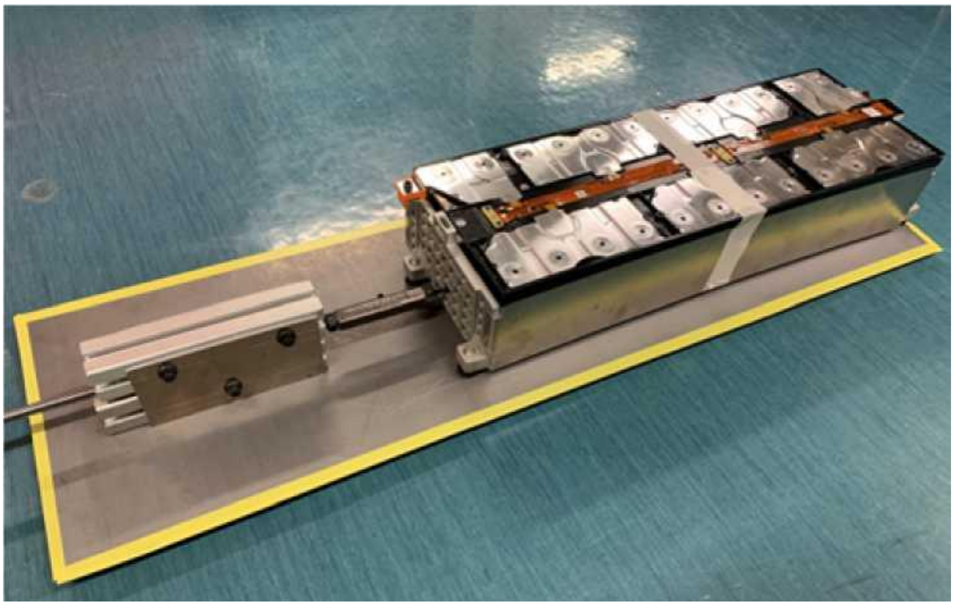
2.1.4 Test 4: module

Test 4 consisted of a total of three sub-tests, with the module charged to different states of charge: 100 %, 70 % and 40 % SOC respectively. The test set-up is shown in Figure 5.

Technical specifications

- Module: 24 volts, 6.54 kWh at 100 % SOC.

Figure 5. Test set-up of module samples.



2.2 Implementation

The tests were carried out over two days in April 2022 at a training field at Södra Älvsborgs räddningstjänstförbund. Tests 1 and 2 were carried out on day one, and tests 3 and 4 on day two. A total of eight trials were conducted across four different tests. Tests 1-3 included extinguishing attempts using various tools. Test 4 was for observation only, and no extinguishing attempts were made. The tests are described in detail below.

The tests were preceded by a risk analysis where all tools were evaluated under specific conditions. The risk analysis also took into account the design of the test samples. The risk analysis showed that there could be difficulties with access to the battery and electrical safety when only the standard equipment currently available on modern fire engines is used. Therefore, it was decided to include two commercially available tools in the demonstration: the cutting extinguisher and the e-extinguishing lance, which are described in detail in section 2.2.5 below.

2.2.1 Test 1: sub-pack

The sub-pack test was designed in order to:

- confirm that the flooding strategy is effective in terminating thermal runaway in lithium-ion batteries, and to
- compare three different tools.

Three sub-tests were conducted, with different tools used in each trial:

- 1A: cutting extinguisher
    - water flow: 58 litres per minute
    - pressure at pump: 300 bar
- 1B: e-extinguishing lance
    - water flow: 25 litres per minute
    - pressure at pump: 3 bar.
- 1C: copper pipe connected to narrow hose, 25 millimetres in diameter (constructed from standard equipment available on fire trucks). A pick axe was used to make holes in the casing.
    - water flow: 75 litres per minute.

Thermal runaway in a cell was initiated by overheating using an ignition module (hot plate) mounted in the battery. Heat generation was tracked with thermocouples. A handheld thermal-imaging camera was used for direct feedback regarding heat generation.

The extinguishing effort was initiated when heat generation indicated that the process had propagated from the module where the initiated cell was located to a battery module located next to it.

Extinguishing ceased immediately when ocular observation indicated that thermal propagation had ended. The observations included the following:

- The thermal-imaging camera showed a stable temperature below 50°C.
- The amount of smoke, flames and sound produced was decreasing.

After the extinguishing effort ceased, continuous monitoring of the temperature with a thermal-imaging camera continued for 15 minutes to ensure that the thermal propagation had stopped.

2.2.2 Test 2: detached electric car battery

Test 2 is designed to evaluate the effect of an additional type of tool, based on equipment available on a modern, standard-equipped fire engine. The tools used were a pick axe to punch a hole in the outer casing of the traction battery and a spray pipe with 7-millimetre nozzle to introduce water into the battery pack.

Technical specifications

- Narrow hose, 42 millimetres in diameter, with a spray pipe with 7-millimetre nozzle
- Water flow: 80 litres per minute
- Pressure at pump: 6 bar.

Thermal runaway in a cell was initiated by overheating using ignition module number 3 mounted in battery module B. Heat generation was recorded with thermocouples. A handheld thermal-imaging camera was used for direct feedback regarding heat generation. At the first sign of thermal propagation, a 15-minute countdown began to mimic the response time of the emergency services. As the propagation seemed to stop, ignition module number 7 in battery module A was also activated. After waiting a further period of time for thermal propagation to spread, extinguishing was commenced with an attack on battery module A with the firehose nozzle after first piercing the battery module with the pick axe.

The test was concluded when the thermal-imaging camera showed a stable temperature below 50 °C. After the extinguishing operation was ended, continuous monitoring of the temperature with the thermal imaging camera continued for 15 minutes to ensure that the propagation had stopped.

2.2.3 Test 3: fully electric vehicle

A full-scale extinguishing trial on an electric vehicle was conducted to demonstrate that the method of flooding the battery pack can be applied at the vehicle level under certain conditions. The test was designed to cover the entire course of the fire, from the initiation of thermal runaway in a cell, propagation and full-blown fire to confirmed extinguishment.

The tools used were abrasive and water-based cutting extinguishers as well as a conventional firehose for protection of the cutting-extinguisher operator. Abrasive is a cutting agent that is added to water to pierce materials and spray water as desired. The cutting extinguisher had a pressure of 300 bar and a water flow of 58 litres per minute.

Thermal runaway was initiated in module A with ignition module number 7. Heat generation was tracked with thermocouples. A handheld thermal-imaging camera was used for direct feedback regarding heat generation.

At the first sign of thermal propagation, a 15-minute countdown was started to mimic the response time of the emergency services. Extinguishing then commenced. To control the fire, water mist from the cutting extinguisher was used to knock down the flames and try to extinguish the passenger compartment fire. Once it was possible to open the rear door, a thermal-imaging camera was used to scan the interior of the vehicle and look for hot spots in the battery pack. This was done by measuring thermal gradients in the passenger compartment floor. Wind and use of a Positive Pressure Ventilation (PPV) fan to direct gases meant that one side of the vehicle was difficult to access due to thick smoke and flames. The attack of the cutting extinguisher was directed above the drive-shaft, and lance extensions were used to facilitate access and avoid contact with the bodywork. During operation of the cutting extinguisher, a conventional firehose was used to protect the cutting-extinguisher operator.

When the flames closest to the operator were knocked down, the person with the protective hose (hose operator) continued to focus on extinguishing the passenger compartment fire. Note that the primary task of the hose operator throughout the operation was to protect the cutting-extinguisher operator from flames.

The test was concluded when the thermal-imaging camera showed a stable temperature below 50 °C. After concluding the extinguishing operation, monitoring of the temperature with the thermal-imaging camera continued for 15 minutes to ensure that the propagation had stopped. To simulate removal of the vehicle, it was lifted several times using a forklift, approx. half a metre, then dropped to the ground to see if it was possible to provoke a reaction that could lead to re-ignition.

2.2.4 Test 4: module

Test 4 involved no extinguishing and could be carried out independently of the outcome of the other tests. Three sub-tests were carried out on modules with different charge statuses (100 %, 70 % and 40 % SOC) to study the effect of state-of-charge on fire behavior.

The end of the battery module was pierced with a 6-millimetre drill bit to initiate thermal runaway in a battery cell. The drill bit was about 3 metres long, permitting a safe distance for the person performing the test. This method was judged easiest for initialisation at this trial level.

As the drill bit pierced the outer casing and entered the battery cell, thermal runaway commenced. At that point, drilling was stopped, the drill bit was withdrawn, and the module was left for observation.

2.2.5 Extinguishing tools

- A cutting extinguisher initially cuts with abrasive and water. Once the material is pierced, only water is sprayed and the whole process is carried out with one movement. The abrasive is loaded into an abrasive container located on the vehicle and is activated, together with the water, by means of wire control. With a lance extension, the operator can spray into a vehicle and attack a propagating battery with the cutting extinguisher.

  The cutting extinguisher is applied with support from the three- or four-point support attached to the outer end of the lance. In this case, the support prevents the nozzle from coming into contact with destroyed battery cells.[12]

- The e-extinguishing lance has previously been tested in Germany and Austria. The e-extinguishing lance is a tool specifically designed to get water into a battery pack. The e-extinguishing lance has a bevelled tip that allows only the part of the tip that sprays water to enter the battery without damaging more battery cells than necessary. The handle of the lance is coated with electrically insulating paint, and the lance itself is fitted with a handle that prevents its operator from being hit by the sledgehammer used to drive the lance into the battery pack. The handle can be extended to allow the user to stand further off, but this feature was not available at the time of this demonstration.[13]

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[12] Cold Cut Systems, 2022.

[13] Murer-Feuerschutz GmbH, 2021.

2.2.6 Risk-mitigation measures

The risk analysis resulted in recommendations for risk-mitigation measures that were communicated to the first responders participating in the demonstration.

Before each test, participants were informed about safety measures.

In all tests, breathing apparatus complying with CSN EN 469 was used. Respirators and protective masks were worn during extinguishing operations in all tests where responders worked close to the burning batteries.

The tests were carried out outdoors with good ventilation. The wind was blowing from the same direction during all operations. To ensure a good working environment, a PPV fan was used. Spectators were allocated seats at a safe distance, with clear barriers.

Thermal measurements and recording of data from thermocouples were carried out during the tests involving an active extinguishing operation (tests 1, 2 and 3). A handheld thermal-imaging camera was used to directly monitor heat generation and continuously follow the course of the fire during the operation. Several thermocouples were installed in the test samples in order to monitor heat generation in the battery both in real time and afterwards.

The test sequence and tools to be used were predetermined in the tests involving active extinguishing. Tests 1 and 2 guided the choice of firefighting tools in the fully electric vehicle test (test 3). As the extension of the extinguishing lance was not sufficient, the cutting extinguisher was judged most suitable for test 3 as it enabled work at a distance from the burning object.

2.3 Assessment criteria

At the end of the test, all battery modules in the test sampled were analysed with voltage measurements. The voltage measurements were carried out three days (tests 1 and 2) and two days (tests 3 and 4) after the test.

It was assumed that a partially damaged battery may retain voltage, while a completely burnt-out battery, where the electrolyte has been burnt, is dead. The voltage of the battery module after the test was thus a measure of how much damage the fire caused in the module and thus how extensive thermal propagation was in each test sample as a result of the initiation.

The degree of thermal propagation achieved, and the effectiveness of the extinguishing effort, was directly assessed during the test by observations in the form of temperature estimation with a thermal-imaging camera, as well as the amount of smoke, flames and sound produced. Temperature stabilisation below 50°C and decreasing smoke, flame and sound were judged as evidence of a successful extinguishing operation.

3 Results

The results of each firefighting operation were continuously evaluated during the tests and after each test to keep the test set-up dynamic. The aim was also to optimise the methodology for firefighting in lithium-ion batteries.

3.1 Test 1: sub-pack

The first tests were conducted at the sub-pack level.

3.1.1 Firefighting with cutting extinguisher

After initiation of thermal runaway and ignition, thermal propagation in the battery commenced. Popping sounds could be heard when the cell valves were opened. Jets of flame and a relatively small amount of smoke seeped out because the sub-pack was glued and screwed shut, and the sheet-metal lid bent with the increasing pressure. A distinct discolouration appeared on the lid where the heat was most noticeable.

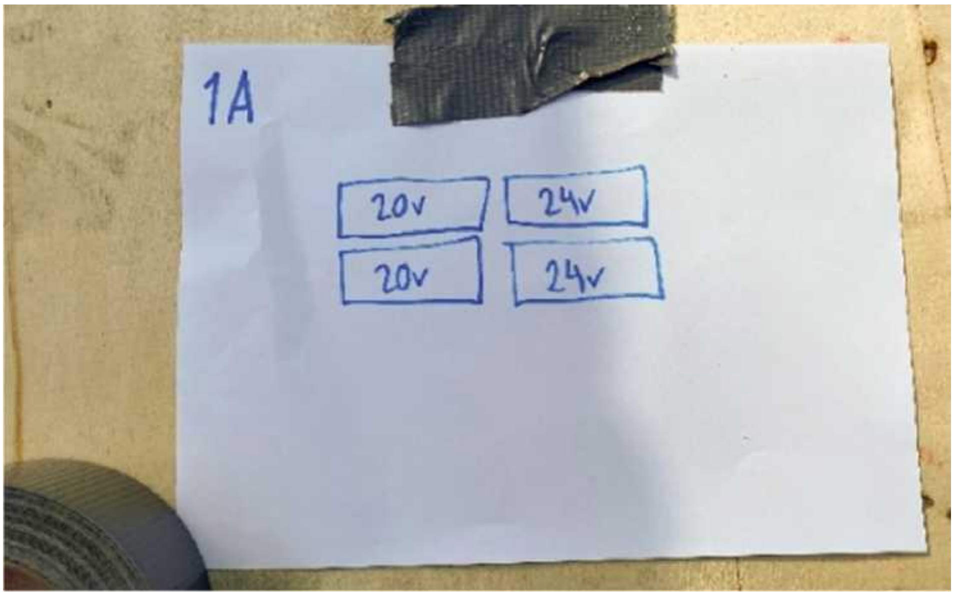
Figure 6. Firefighting with cutting extinguisher - test 1A.

The strategy involved delaying the extinguishing operation until the heat had spread to a second battery module and started thermal propagation inside of the second battery module. It proved difficult to confirm whether thermal propagation had indeed spread further between modules. The cutting extinguisher attacked the end of the first propagated module and was directed in an area that was visibly affected by the heat and which the thermal-imaging camera indicated was hottest (see Figure 6). Once the sub-pack was pierced it was flooded with water to cool the surrounding modules until the extinguishing operation was ended when the temperature was stable below 50 °C. No arcs or jets of flame were produced during the penetration of the casing. No re-ignition was observed.

Voltage measurements of the battery modules showed that two of a total of four modules had full voltage (24 volts) and the other two modules measured 20 volts (see Figures 7 and 8).

Figure 7. Sub-pack after extinguishing with a cutting extinguisher.

Figure 8. Remaining voltage in the battery modules after extinguishing.



3.1.2 Firefighting with e-extinguishing lance

After the initiation of thermal runaway and ignition, heat generation continued, but at a slower rate than in the previous sub-test. To speed up fire development, gas burners were used at the bottom and side of the pack. Propagation could finally be detected with a popping sound. Jets of flame and a relatively small amount of smoke seeped out due to the tight closure of the sub-pack, and the sheet-metal lid bent with the increasing pressure. A distinct discolouration appeared on the lid where the heat was most noticeable.

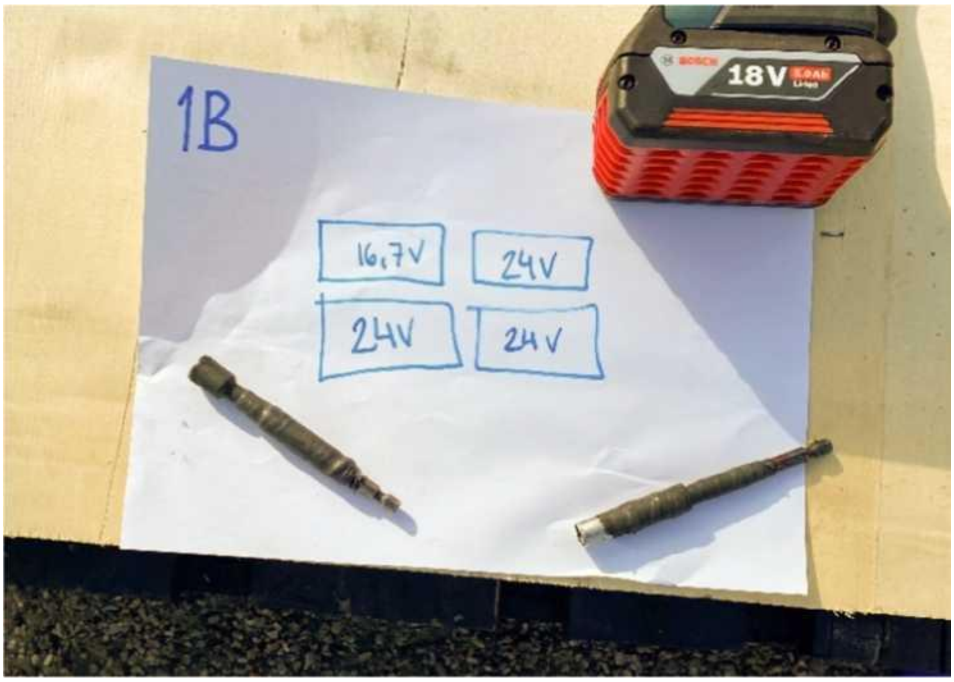
Figure 9. Firefighting with extinguishing lance - test 1B.

As the previous sub-test (test 1A) had shown that it was difficult to determine when the propagation had spread to a second battery module, it was decided to wait to apply the e-extinguishing lance until the heat had clearly spread within the sub-pack. The e-extinguishing lance struck where the heat impact was greatest, which was visible to the naked eye, but the thermal imaging camera was used for confirmation. The e-extinguishing lance was driven into the battery pack using a sledgehammer. The surrounding battery modules were then cooled with introduction of a constant flow until the extinguishing was ended when the temperature was stable below 50 °C (see Figure 9). There were no arcs or jets of flame upon penetration of the battery pack. No re-ignition was noted.

The voltage measurements of the battery modules showed that three of a total of four modules had full voltage (24 volts) and the pierced one measured 16.7 volts (see Figure 10 and Figure 11). This result indicates that propagation from the first to the second module did not occur. This further reinforces the assertion that it is difficult to determine the extent of thermal propagation in the battery during the fire.

Figure 10. Sub-pack after extinguishing with e-extinguishing lance.

Figure 11. Remaining voltage after extinguishing.



3.1.3 Firefighting with narrow hose connected to copper pipe

> **Note!**
>
> This approach is **not recommended**, as it requires detailed knowledge of battery architecture. In this trial, carefully considered measures were taken to reduce risks The test was conducted solely to confirm the principle of flooding burning lithium-ion batteries.

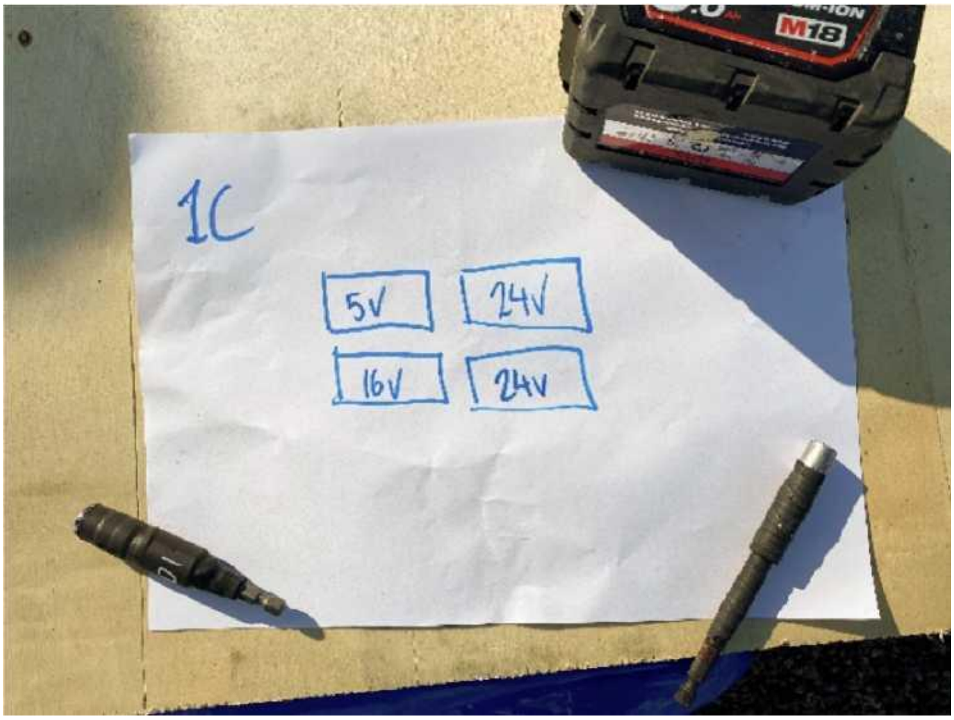
Following the initiation of thermal runaway and ignition, thermal propagation began in the battery, which could be heard and seen by smoke seeping out and the sheet-metal lid bending. A distinct discolouration appeared on the lid where the heat was most noticeable. The extinguishing was commenced when thermal propagation reached battery module 2 and the heat had clearly spread within the sub-pack. Holes were drilled, the copper pipe was inserted, and water flowed to cool the surrounding battery modules (see Figure 12). Extinguishing was ended when the temperature was stable below 50°C. Penetration of the battery pack produced strong jets of flame and small arcs. No re-ignition was observed.

Figure 12. Firefighting with narrow hose and copper pipe - test 1C.

The voltage measurements of the battery modules showed that the module where thermal runaway was initiated had 5 volts, the neighbouring module had 16 volts and the two remaining modules had full voltage, i.e., 24 volts (see Figures 13 and 14).

Figure 13. Sub-pack after extinguishing with narrow hose and copper pipe.

Figure 14. Remaining voltage after extinguishing..



3.2 Test 2: detached electric car battery

Note!

This approach is **not recommended**, as it requires detailed knowledge of battery and vehicle architecture. In this trial, carefully considered measures were taken to reduce risks The test was conducted solely to confirm the principle of flooding burning lithium-ion batteries.

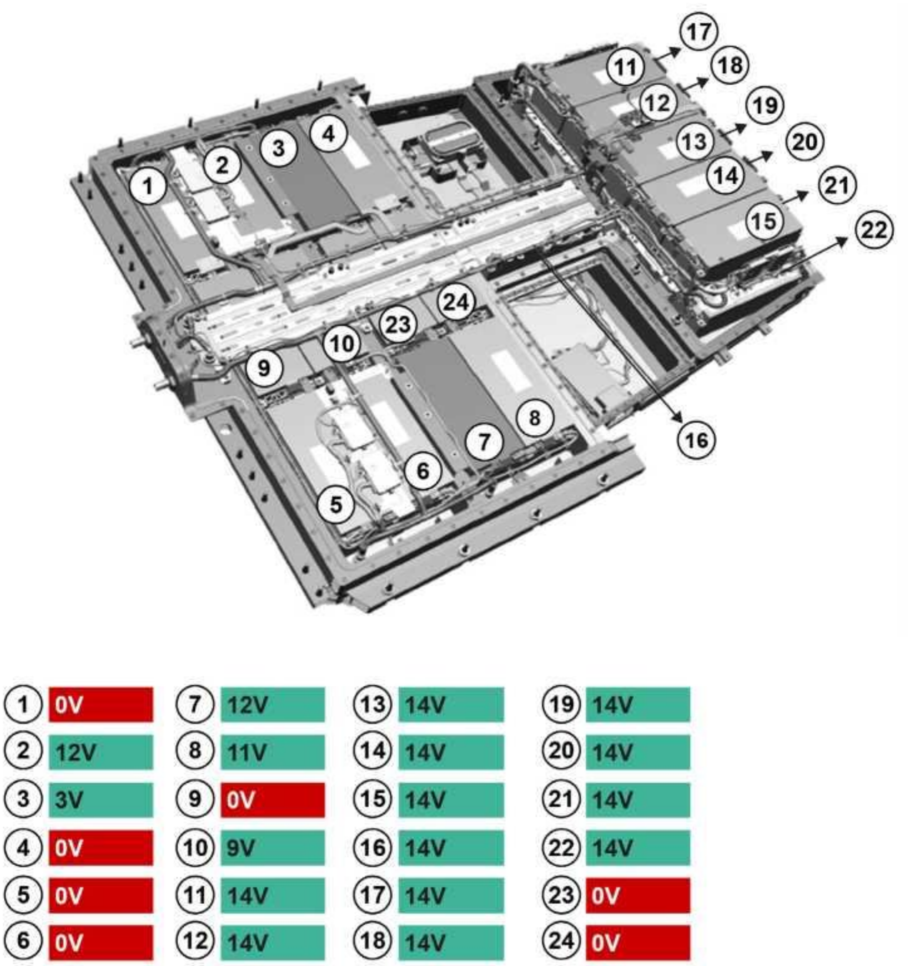
After initiation of thermal runaway, there was a delay before heat generation indicated that thermal propagation had started. After 15 minutes of thermal propagation, the process seemed to slow down. However, the thermal-imaging camera showed high temperatures in the area around the battery module where thermal runaway had been initiated as well as inside the drive-shaft casing. The decision to initiate the second ignition module resulted in slightly greater heat generation with visible smoke but no flames.

Extinguishing commenced. Piercing with an axe revealed jets of flame and small arcs, and battery module A was attacked with spray pipes that established a water flow and cooled the battery pack (see Figure 15). The piercing damaged unaffected battery cells, resulting in localised thermal runaway that was extinguished with application of water. Extinguishing was ended when the temperature was stable below 50 °C. No re-ignition was observed.

Figure 15. Extinguishing with narrow hose and spray pipe - test 2.

The voltage measurements of the battery modules showed that the two modules where thermal runaway was initiated had 3 volts and 12 volts respectively. Of the battery modules, 17 out of 24 had stranded energy. Figure 16 shows the voltage distribution in all modules and Figure 17 shows the battery after extinguishing.

Figure 16. Remaining voltage per module after extinguishing - test 2.



1	0V	7	12V	13	14V	19	14V
2	12V	8	11V	14	14V	20	14V
3	3V	9	0V	15	14V	21	14V
4	0V	10	9V	16	14V	22	14V
5	0V	11	14V	17	14V	23	0V
6	0V	12	14V	18	14V	24	0V

Figure 17. Detached electric car battery after extinguishing with lid removed - test 2.

3.3 Test 3: fully electric vehicle

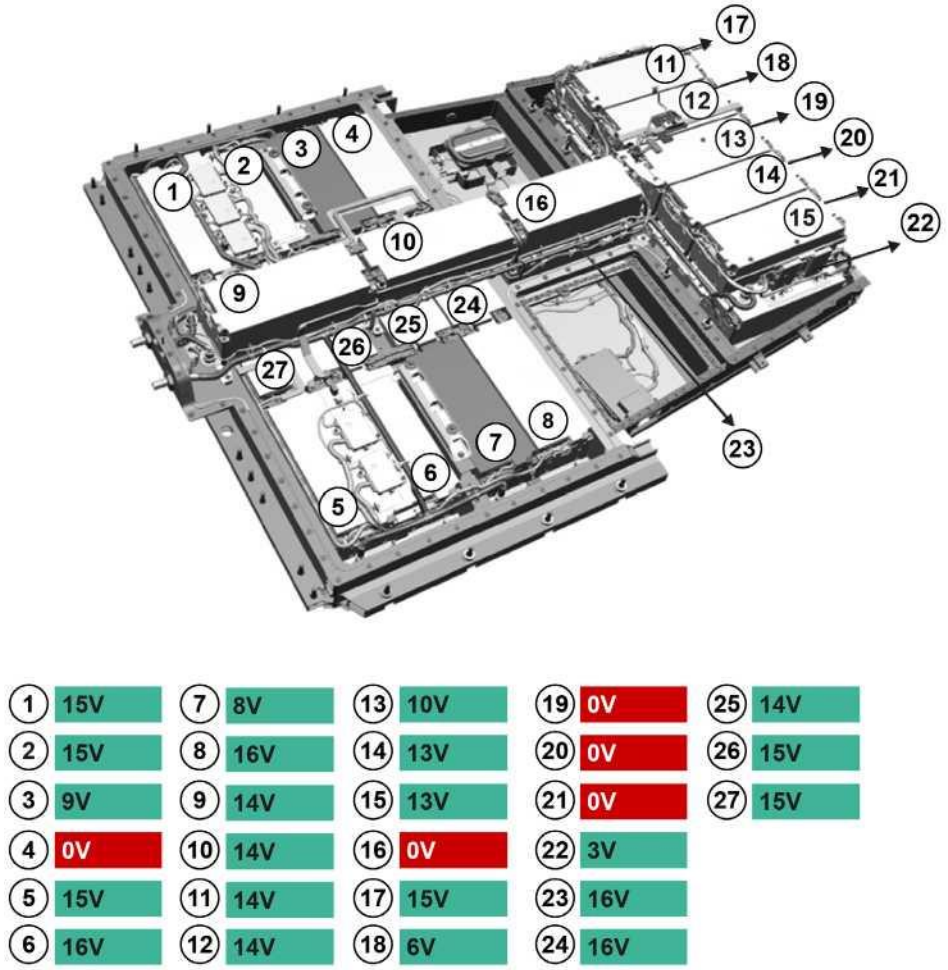
Thermal runaway was initiated in ignition module number 7 (battery module A) and the first signs of thermal propagation came quickly in the form of visible smoke. Within 3 minutes of the first signs of thermal runaway, flames were observed. After fifteen minutes, a fully developed fire was observed in the vehicle and extinguishing was initiated (see Figure 18).

Figure 18. Firefighting with cutting extinguisher on electric vehicles (image from a separate project, but depicts the same type of operation).

The extinguishing operation as a whole, from the first water sprayed on the fire to the last, took 10 minutes. When analysing the course of events, the total consumption of water as an extinguishing medium has been calculated at approx. 750 litres. The cutting extinguisher was actively used for about 5 minutes , 300 litres, while the fire hose nozzle was actively used for about 4 minutes, 450 litres.

The voltage measurements of the battery modules showed that the module attacked by the cutting extinguisher (number 16) had no stranded energy. Of the battery modules, 22 of 27 had stranded energy. Figure 19 shows the voltage distribution in all modules and Figure 20 shows the battery pack after it has been removed from the vehicle two days after extinguishing.

Figure 19. Remaining voltage per module after extinguishing the lithium-ion battery in an electric vehicle - test 3.



①	15V	⑦	8V	⑬	10V	⑲	0V	㉕	14V
②	15V	⑧	16V	⑭	13V	⑳	0V	㉖	15V
③	9V	⑨	14V	⑮	13V	㉑	0V	㉗	15V
④	0V	⑩	14V	⑯	0V	㉒	3V		
⑤	15V	⑪	14V	⑰	15V	㉓	16V		
⑥	16V	⑫	14V	⑱	6V	㉔	16V		

Figure 20. Battery pack removed from electric vehicle after extinguishing - test 3.

3.4 Test 4: module

Test 4 examined the significance of SOC. The fire's course at 100 % SOC was experienced as very reactive, as well as at 70 % SOC. The third battery module, with 40 % SOC, had a somewhat calmer course. Course of fire at 100 % SOC is shown in Figure 21.

Figure 21. Course of fire in battery module (100 % SOC).

4 Discussion and analysis

The results of this demonstration show that a constant water flow through the battery can be effective in firefighting. All tools used in the demonstration managed to control the fire. It is worth noting that both the architecture of the battery and where and when the thermal propagation was initiated in the battery were known and determined by the test conditions. At the same time, the demonstration confirmed the difficulty of determining the degree of thermal propagation, despite ideal conditions and the availability of internal temperature data, external temperature measurement with a thermal-imaging camera and observations such as smoke, flames and sound. Extinguishing efforts in the demonstration started early in the thermal-propagation phase, which may have influenced the outcome. It is not certain that more widespread thermal propagation can be tackled with the same success. If a decision regarding a firefighting offensive is made in the field, only tools intended for the purpose and authorised by the employer can be used.

When we made holes while adding water, no new jets of flame occurred. However, when we made holes without adding water, jets of flame appeared.

Two firefighting trials were carried out with ad hoc tools assembled from equipment that can be found on a standard modern fire engine: a spray pipe and narrow hose, as well as a pick axe, which was used for punching holes. While it worked in the demonstration, this type of approach is **not recommended** because the technique is difficult to implement in a real vehicle fire, where access to the battery is limited, and would require work inside a burning vehicle. Piercing holes is only to be done with tools designed for this purpose and approved by the employer.

The state of charge (SOC) of the battery has an impact on the course of the fire. Tests performed at full versus low SOC had different outcomes. Batteries with 100 % SOC were highly reactive, as were batteries with 70 % SOC. The test sample at 40% SOC was not as reactive, but still felt powerful and had enough energy to permit thermal propagation through the battery. Therefore, without reliable information regarding the vehicle's charge status, it should always be assumed that a battery is fully charged, which corresponds to a worst-case scenario.

During the demonstration, it was assumed reasonable to stop extinguishing when a stable temperature below 50°C was reached. This temperature was determined in consultation with battery experts, and was based on knowledge of the battery chemistry of the battery types in question and their propensity to enter thermal runaway at a temperature of 70-100°C. Battery cells exposed to temperatures higher than the manufacturers' technical specifications must be destroyed as they may have suffered irreversible damage that could affect their safety characteristics. The temperature limit varies between manufacturers and cell types, but can range upwards of 80°C.

Monitoring for any re-ignition was limited to 15 minutes, which may be acceptable in a designed test situation. However, field experience has shown that re-ignition can occur after a considerable period - hours or days after the fire. During the two/three days during which the battery pack was stored after the fire and before dismantling, there was no re-ignition. However, electric vehicles and batteries that have caught fire must be handled with great care. Information regarding re-ignition risks must always be provided upon consigning a fire-damaged electric vehicle or lithium-ion battery to, e.g., a salvage yard, workshop or scrap yard.

Figure 22. Example of smoke and flame propagation from the sub-pack in test 1C. The thermal propagation pattern varies between different vehicles and battery architectures and must be studied on a case-by-case basis before first responders approach the fire scene. The green shape shows the area deemed safe in this case.

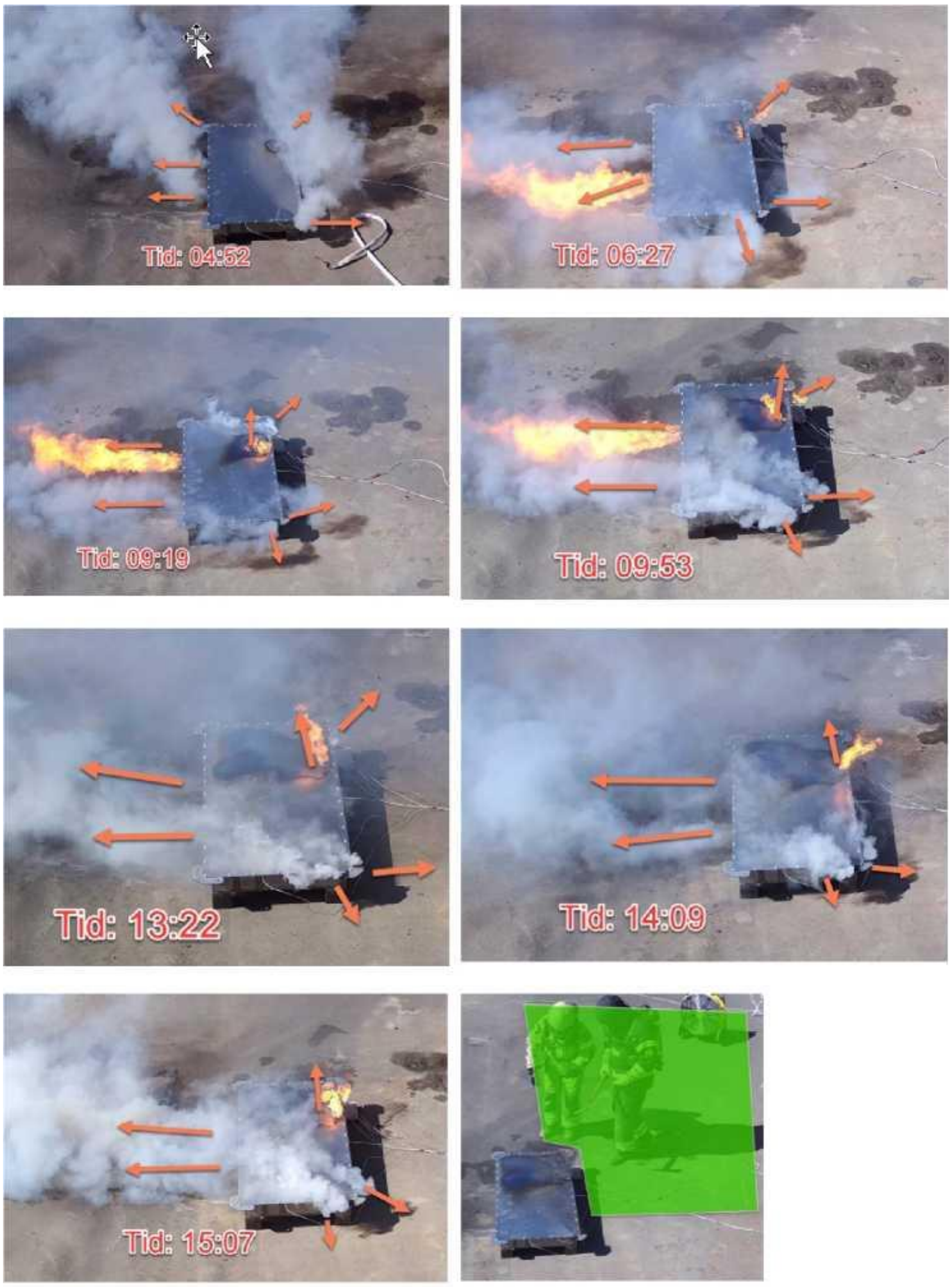


Figure 22 shows an example of smoke and flames propagating from a battery in the current demonstration. The green shape shows the area deemed safe in this case. Since the spread depends on several factors, no general conclusions can be drawn about safe zones, but it is necessary to observe the behaviour of the fire in each individual case. Factors involved in the spread of fire include the following:

- chemistry of the battery in question and its reactivity,

- battery construction, and
- type and location of pressure-relief valves or rupture disks.

Those approaching the vehicle should be positioned in areas where flames and smoke have not previously been observed. However, it is worth noting that the flame spread can be several metres and that jets of flame can arise very suddenly.

Active extinguishing efforts carried out in the demonstration stopped thermal runaway and left stranded energy in the battery. There was a risk of re-ignition, which must be taken into account in the further handling, transport and storage of the fire-damaged object.

The risks associated with handling a burnt-out battery containing a significant amount of stranded energy must always be weighed against the benefits of shortening the response time. Note that even lithium-ion batteries that have been allowed to burn out may contain stranded voltage and must always be treated as such until it is confirmed that the battery is dead.

This demonstration used both a thermal-imaging camera and a thermocouple. It is important to note that the thermal imaging camera is sensitive to reflection, so it can be difficult to get a true picture of the heat distribution inside the battery.

First-responders to fires occurring in electric vehicles or their batteries must take note of the vehicle manufacturer's safety and response information in the vehicle's rescue sheet and emergency response guidebook (ERG) in order to plan a response based on the specific conditions of the fire in question.

5 Conclusions

- The demonstration showed that it is possible to stop thermal runaway in a lithium-ion battery using an extinguishing operation that floods the battery with water.
- Flooding the lithium-ion battery with water can shorten the extinguishing time and reduce human and material resources.
- It is difficult to determine the degree of thermal propagation in a lithium-ion battery during an ongoing fire based on externally observable factors such as thermal-imaging temperature monitoring, smoke and sound.
- Cell chemistry, state of charge, battery architecture and vehicle architecture are several system properties affecting how thermal runaway and propagation develop during a thermal event in an electric vehicle.
- For firefighting planning, it is important to first consult the vehicle's rescue sheet and ERG to assess the conditions for an active firefighting operation.
- The trials carried out show that it is possible to access the battery with the tools tested in the trials. Thermal imaging and rescue sheets can provide information to improve success rates.
- The risk of stranded energy, which can lead to re-ignition, must always be considered when handling an electric vehicle and its traction battery after a thermal event.

6 References

Cold Cut Systems. (2022). *Cold Cut Systems.* Retrieved from Products: https://www.coldcutsystems.com/products.

ISO 13063:2012. (09-2012). *Electrically propelled mopeds and motorcycles — Safety specifications.*

ISO 17546:2016 (en). (03-2016). *Space systems — Lithium ion battery for space vehicles — Design and verification requirements.*

ISO 17840-1:2022 (en). (02-2022). *Road vehicles - Information for first and second responders - Part 1: Rescue sheet for passenger cars and light commercial vehicles.*

ISO 18300:2016 (en). (11-2016). *Electrically propelled vehicles -Test specifications for lithium-ion battery systems combined with lead acid battery or capacitor.*

ISO 6469-1:2019. (04-2019). *Electrically propelled road vehicles - Safety specifications - Part 1: Rechargeable energy storage system (RESS).*

ISO 6469-3:2011. (12-2011). *Electrically propelled road vehicles - Safety specifications - Part 3: Protection of persons against electric shock.*

ISO/TR 8713:2019. (04-2019). *Electrically propelled road vehicles.*

Murer-Feuerschutz GmbH. (09-2021). E-Extinguishing Lance Retrieved from Murer: https://www.murer-feuerschutz.de/pdf/e-loeschlanze/E-Loeschlanze_EN_20211026_WEB.pdf?m=1643720727& accessed 30/06/2022.

Trewe, A. (2021). *Li-Ion Battery Pack Extinguishing Tests.* Kungsbacka, Sweden: Cold Cut Systems.

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Order Nr. MSB2184 – March 2023 ISBN 978-91-7927-376-7