Myndigheten för samhällsskydd och beredskap

Demonstration of quench method for lithium ion batteries

Method application at different levels of aggregation – module, sub-battery, electric car pack and vehicle level

Demonstration of extinguishing method for lithium ion batteries. Method application at different levels of aggregation – module, sub-battery, electric car pack and vehicle level

Unit: Fire and rescue

Production: Advant

Publication number: MSB2184 – March 2023
ISBN: 978-91-7927-376-7

Preface

The following report is based on a project carried out in collaboration between the Swedish Public Safety and Emergency Services Agency (MSB), manufacturers and distributors of emergency vehicles and tools for the emergency services and representatives from the automotive industry. The goal of the project has been to present a guide for actions against propagating lithium-ion batteries and to add and increase knowledge and understanding about electric vehicles and other battery-powered applications. The project's results are based on requirements and recommendations from manufacturers and other actors active in industry and the emergency services.

This report describes conducted trials aimed at producing a proposal for a method for handling propagating lithium-ion batteries in vehicle battery packs in the form of a box that can hold water. The tactic of introducing water into a battery pack has been studied. The report is based on current knowledge in research, industry and actors within the Swedish rescue service, and is confirmed through tests conducted on a special type of lithium ion batteries.

The proposed methodology should be seen as a guideline and guidance. Where laws, rules, regulations, the manufacturer's or own organization's instructions set higher or other requirements, these take precedence.

With the help of routines, training, technical solutions and the right level of protective equipment, accidents can be prevented and the consequences reduced if the accident were to occur.

Content

Description of words and expressions

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

Expression	Description
Battery cell	Basic rechargeable energy storage device consisting of electrodes, electrolyte, reservoir, terminals, and usually separators. The battery cell is a source of electrical energy obtained by direct conversion of chemical energy.1
Battery module	Assembly of several battery cells that form a subsystem of the battery pack.
Battery pack	Energy storage device containing cells or cell assemblies normally connected to cell electronics and an overcurrent shutdown device with electrical interconnections and interfaces to external systems.2
Cylindrical cell	Spiral-shaped battery cell with metal casing.
Electric vehicles	Vehicles with one or more electric drives for propelling the vehicle.3 Throughout this report, the fuel for the electric drive is intended to consist of lithium-ion batteries when electric vehicles are mentioned.
Emergency Response Guide (ERG)	Specific information that enables those responsible to take appropriate action in an emergency with respect to a particular technology or design principles.4
Lithium ion battery	Rechargeable electrochemical cells or rechargeable battery in which both the positive and negative electrodes are intercalation compounds (the intercalated lithium exists in ionic or quasi-atomic form with the lattice of the electrode material) that are constructed without metallic lithium in either electrode.5
Pouch cell	Battery cell where the cell casing consists of laminated metal polymer foils. A pouch cell has high energy density and good heat dissipation.
Prismatic cell	Battery cell in metal casing. A prismatic cell has high energy density.
Rescue Sheet	Documents within ISO 17840 with vehicle and model-specific standardized data sheets with technical information for rescue service personnel. Found, among other things, in the app Euro Rescue or CRS Crash Recovery System.
SOC	State of Charge – available capacity of a rechargeable energy storage system (RESS) or a RESS subsystem expressed as a percentage of the nominal capacity.6
Thermal rush	Uncontrollable condition where 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 due to abuse.7

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.

Expression	Description
Thermal propagation	The process by which a thermal surge in a lithium ion battery cell propagates from cell to cell in a battery.
Traction battery	Collection of all battery packs electrically connected to supply electrical power to the electric drive and to the wired electrical auxiliary system if present.8
Re-ignition	When an apparently extinguished material starts to burn again.

8. ISO 6469-3:2011, 2011.

Introduction and background

1. Introduction and background

In Sweden, electric vehicle registration increased by 370 percent between January 2021 and January 2022. During the period, the proportion of registered vehicles was divided between 25 percent BEV (pure battery-powered electric vehicle) and 25 percent PHEV (hybrid vehicle). Similar figures for the transport sector can be found in the rest of the EU. Other electrical applications, such as electric bicycles and mobile phones that contain lithium-ion batteries, have also increased. At the same time, installations of battery storage in homes and offices are increasing with the aim of being able to use solar power and wind power around the clock. The regulations and guidelines for battery storage installations are national at best.

Fires in lithium-ion batteries can be difficult to manage and require extensive personnel and material resources. A common misunderstanding is that the traction battery is always involved when an electric vehicle catches fire, which is not the case at all. It is necessary to clarify right here in the introduction that fires in electric vehicles can both affect the traction battery, a scenario unique to this type of vehicle, and other components in the vehicle in the same way as combustion vehicles.

In order to actively stop an ongoing propagation in a lithium-ion battery, the exothermic reactions taking place inside the battery cells must be slowed down and stopped. One way to achieve this is to establish an internal cooling of the cells inside the battery.

There are several tools on the market that can be used to extinguish fires in lithium-ion batteries and to facilitate the disposal of the batteries after fire incidents. The purpose of the tools is to speed up the extinguishing effort and provide a more efficient extinguishing. Quenching methods based on the principle of flooding the battery with water, thus directly cooling the individual cells, are evaluated in this demonstration.

The background to the report is previously performed tests where propagating lithium-ion batteries have been stopped.9 The tests were based on a technique that involved establishing an internal water flow inside a propagating battery pack. The technology is used today as a risk-reducing measure at the production line of battery manufacturers.

In this part, completed tests for the extinguishing technology are presented, which are confirmed for a specific type of lithium-ion batteries.

9. Trewe, 2021.

1.1 Previous tests and attempts

A preliminary study was carried out by Cold Cut Systems in Kungsbacka in 2021, where the Swedish Agency for Community Safety and Preparedness (MSB) participated as a reference.10 The purpose was to investigate whether it was possible to interrupt the thermal process in a propagating lithium ion battery by establishing an internal water flow in the battery pack. Cold Cut Systems used a cut extinguisher in the pilot study with good results.

It was judged that there was evidence for further studies and tests to develop guidelines for offensive extinguishing efforts of lithium-ion battery fires. This demonstration is an activity within the scope of this work.

1.2 Purpose and goals

The overall aim of the demonstration is to contribute with experimental experience of the methodology of flooding lithium-ion batteries with water in the event of a fire, and to show that it can contribute to a faster and more efficient extinguishing, provided that it is possible to access the battery in a safe way.

The goal of the extinguishing efforts was to stop the thermal propagation in the lithium-ion battery.

1.3 Limitations of the study

The demonstration is limited to test objects that are composed of lithium ion cells with a maximum of 60 percent 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 in the sample objects. Cylindrical cells have not been studied in this demonstration.

In order to facilitate the execution of the test, the test objects have been modified by removing the safety systems normally found in lithium-ion batteries. Previous experience has shown that it can otherwise be difficult to induce thermal rush and ignite the battery. The modification may have affected the progress of the fire in the tests, but is not judged to have any significant effect on the extinguishing effect.

Only water without any additives has been used as extinguishing agent.

The demonstration method is designed based on the state of knowledge that was current at the time of the test. New methods and guidelines are developed as battery technology develops and there are new research findings. New methods and guidelines are also being developed as field experience of "best practice" increases.

The report's results should be seen as examples of how the method and the tested tools can be applied to the type of object included in the study

10. Trewe, 2021.

Method

2. Method

The method that has been used to develop and carry out the tests is largely based on acquired knowledge from previously performed tests and studies.11 The method involves creating access to the traction battery and then establishing a flow of water.

2.1 Test item

The tests were carried out on four different types of setups:

- sub-battery
- standalone electric car battery
- complete electric vehicle
- battery module.

11. Trewe, 2021.

2.1.1 Test 1: sub-battery

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

Technical specifications:

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

Figure 2 shows the sub-battery with cover, ready for transport to the test site.

Figure 1. Configuration of modules in the sub-battery. Placement of heating plate and thermocouple for temperature measurement according to instructions in the picture.

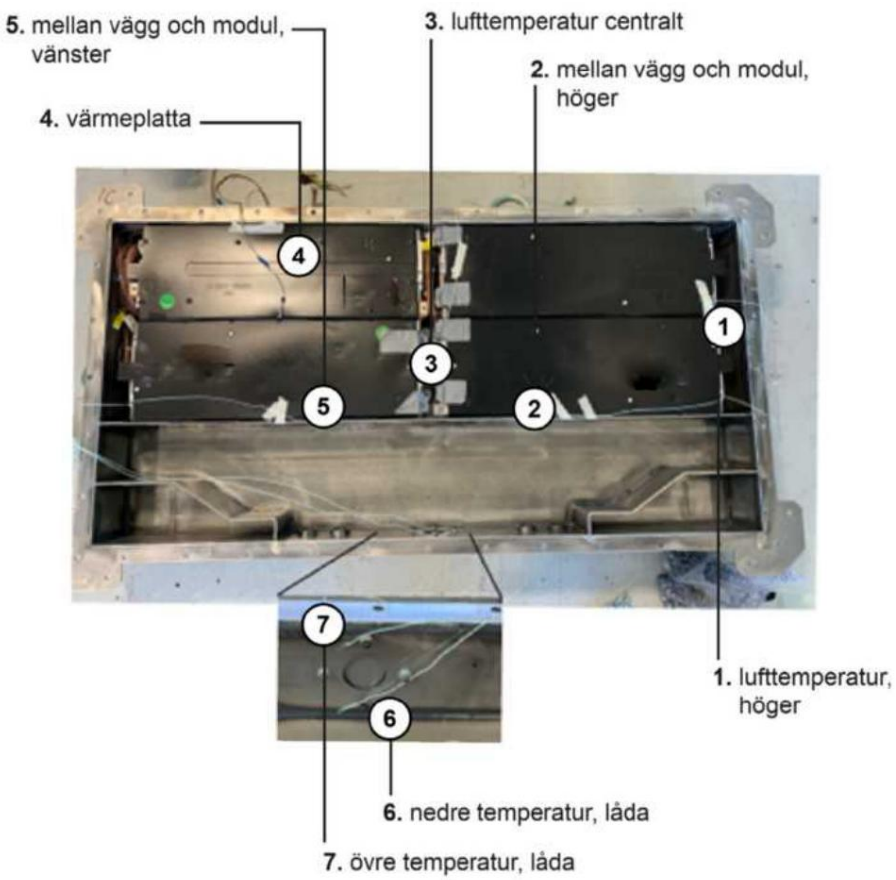


Figure 2. Sub-battery with cover attached, ready for transport to test site.

2.1.2 Test 2: standalone electric car battery

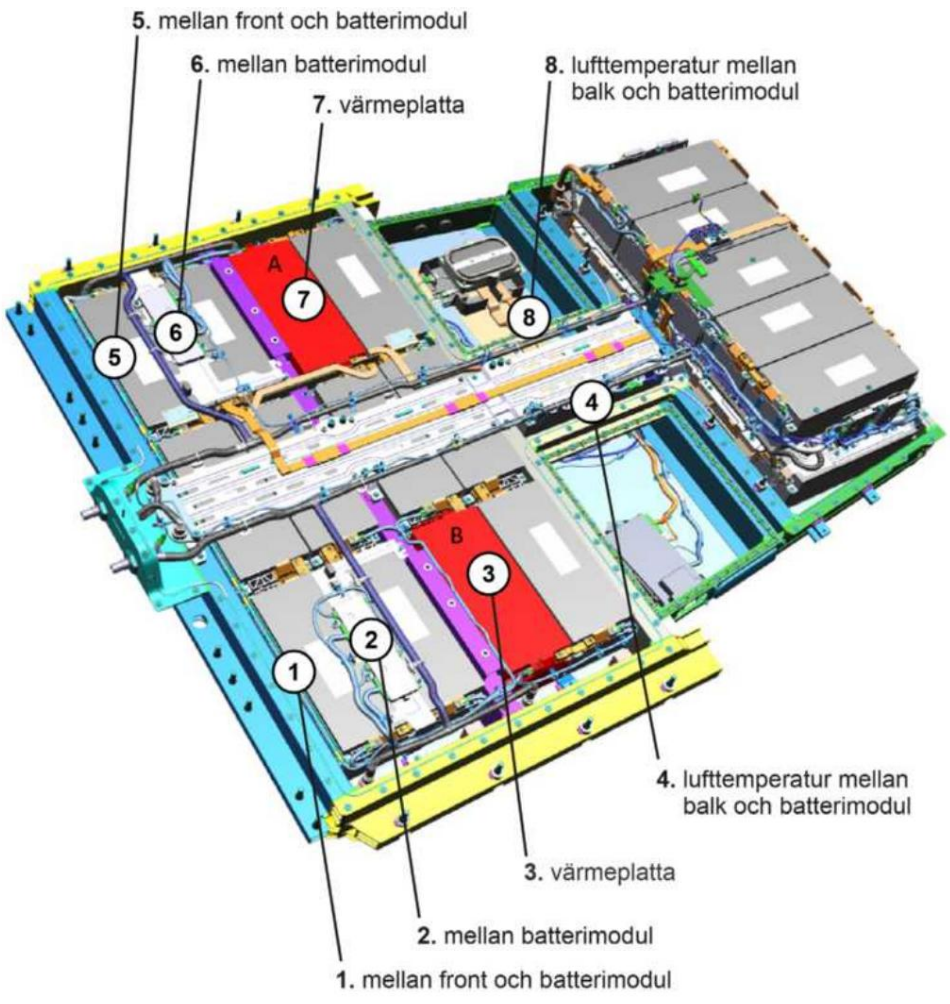
Test 2 was performed on a full-scale traction battery from an electric car consisting of a total of 24 battery modules, two ignition modules (heat plates) and instrumentation for temperature measurement as shown in Figure 3. The modules consisted of prismatic cells that were fully charged (ie 100% SOC).

Technical specifications:

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

Two ignition modules (heat plates) were installed to have two possibilities to initiate thermal rush.

Figure 3. Configuration of modules in the traction battery. Placement of heating plate in module A and B respectively and thermocouple for temperature measurement according to instructions in the picture.



2.1.3 Test 3: complete electric vehicle

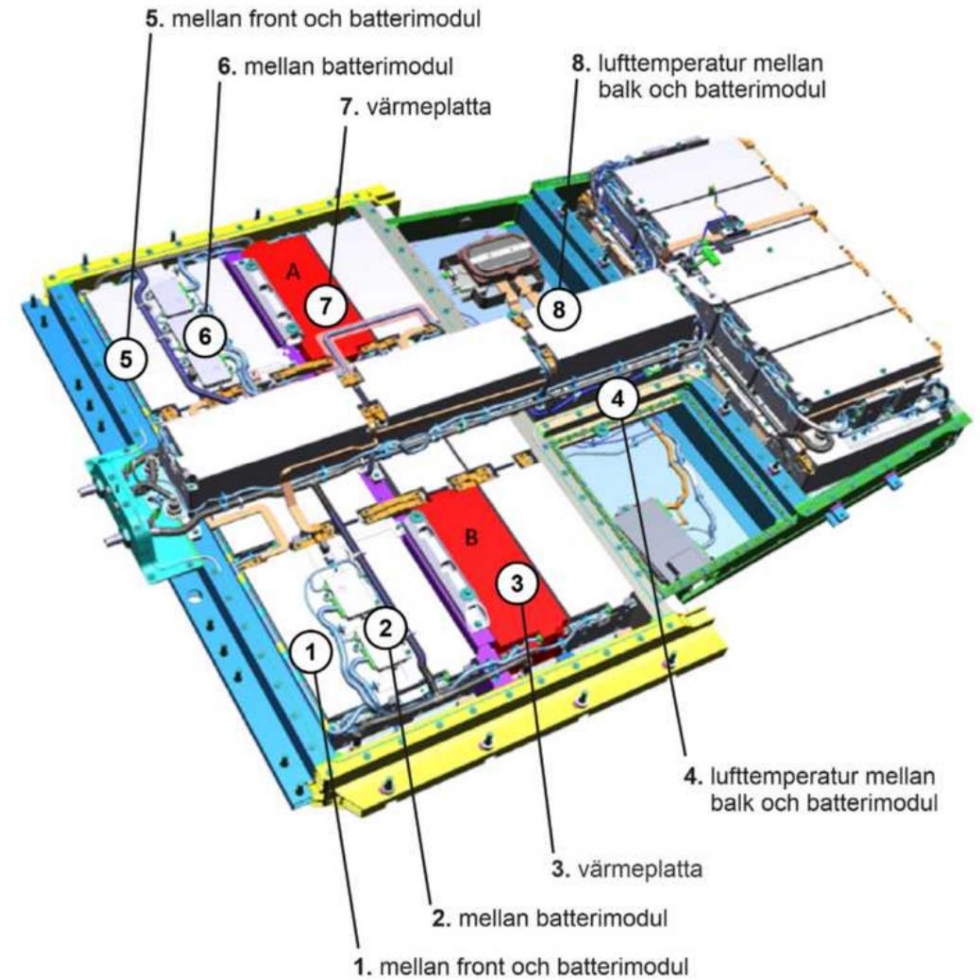
Test 3 was conducted on a complete electric vehicle. The traction battery consisted of a total of 27 battery modules, two ignition modules (heat plates) and instrumentation according to Figure 4. The modules consisted of pouch cells that were fully charged (that is, 100% SOC).

Technical specifications:

• Battery module: 14.8 Volt, 2.8 kWh. •

Battery pack: 75 kWh.

Figure 4. Configuration of modules in the traction battery. Placement of heating plate in module A and B respectively and thermocouple for temperature measurement according to instructions in the picture.



Two ignition modules (heat plates) are installed to have two possibilities to initiate thermal rush.

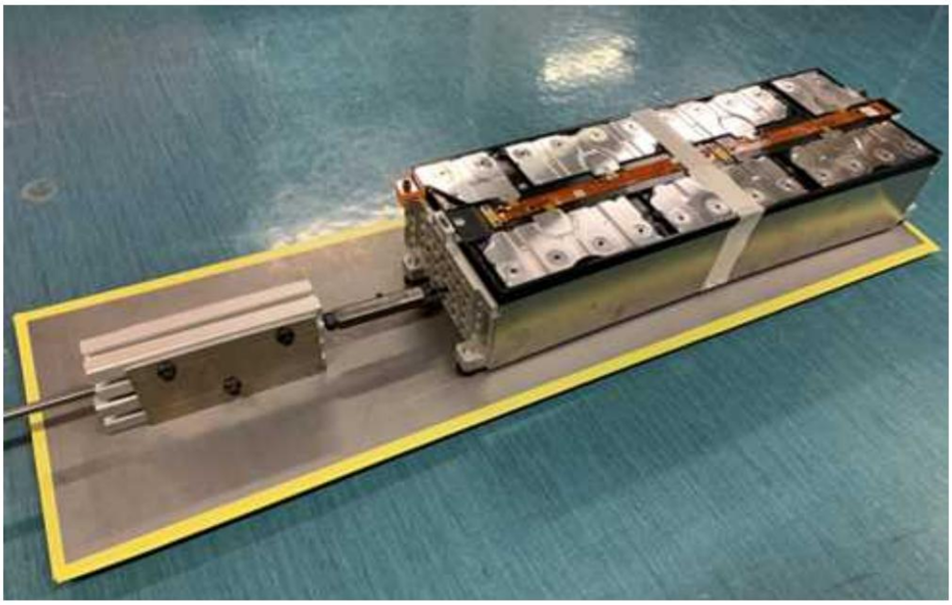
2.1.4 Test 4: module

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

Technical specifications:

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

Figure 5. Test setup of module samples.



2.2 Implementation

The tests were carried out over two days in April 2022 on a practice field at Södra Älvsborg's rescue service association. Tests 1 and 2 were performed on day one and tests 3 and 4 were performed on day two. A total of eight trials were carried out, distributed over four different tests. Tests 1–3 included extinguishing attempts using different tools. Test 4 was for observation purposes only, and no extinguishment trials were conducted. The tests are described in more detail below.

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

2.2.1 Test 1: sub-battery

The sub-battery test was designed to

- confirm that the quenching strategy with water flow is effective in interrupting a thermal propagation process in lithium-ion batteries
- compare three different tools.

Three subtests were conducted, with different tools used in each trial:

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

Thermal surge in a cell was initiated by overheating using an ignition module (heat plate) mounted in the battery. The heat development was recorded with thermocouples. A handheld thermal imaging camera was used for direct feedback of the heat development.

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

The effort was stopped immediately when ocular observations indicated that propagation was complete. The observations included the following:

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

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

2.2.2 Test 2: standalone electric car battery

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

Technical specification:

- Narrow hose, 42 millimeters in diameter, with unit jet pipe with 7 millimeter nozzle.
- Water flow: 80 liters per minute.
- Pressure at pump: 6 bar.

Thermal surge in a cell was initiated by overheating using ignited module number 3 mounted in battery module B. Heat development was recorded with thermocouples. A hand-held thermal camera was used for direct feedback of the heat development. At the first sign of propagation, a countdown was started from 15 minutes to mimic the response time of the emergency services. After the propagation seemed to stop, ignition module number 7 in battery module A was also activated. After waiting for a further time for the propagation to spread, the extinguishing effort was started by using battery module A with a jet tube after making a hole with the pick axe.

The test was terminated when the thermal imager showed a stable temperature below 50 °C. After the extinguishing effort was interrupted, continuous monitoring of the temperature with a thermal imaging camera continued for 15 minutes, to ensure that the propagation had stopped off.

2.2.3 Test 3: complete electric vehicle

A full-scale extinguishing test on an electric vehicle was carried out to demonstrate that the method of water flooding of battery packs can be applied at the vehicle level under certain conditions. The test was designed to cover the entire fire progression, from initiation of thermal rush in a cell, propagation and fully developed fire to established extinguishment.

The tools used were fire extinguishers with abrasive and water, as well as a conventional jet tube as personal protection for the fire extinguisher operator. Abrasive is a cutting agent that is added to the water to cut holes in the material so that the water reaches where you want it. The fire extinguisher had a pressure of 300 bar and a water flow of 58 liters per minute. The cutting extinguisher was chosen because it proved to be the most suitable for the task according to the experiences from tests 1 and 2.

Thermal rush was initiated in module A with ignition module number 7. Heat development was recorded with thermocouples. A hand-held thermal camera was used for direct feedback of the heat development.

At the first sign of propagation, a countdown was started from 15 minutes to mimic the response time of the emergency services. The extinguishing attempt was then started. To control the fire, water mist from the cutting extinguisher was used to knock down the flames and try to extinguish the cabin fire. When it was possible to open the rear door, thermal imaging was used to scan the interior of the vehicle and look for hot spots in the battery pack. It was done by measuring thermal gradients in the cabin floor. Wind and control of gases using a PPV fan (Positive Pressure Ventilation) meant that one side of the vehicle was difficult to access due to thick smoke and flames. The cutting extinguisher was used in the gimbal tunnel and lance extenders were used to facilitate access and avoid contact with the bodywork. During the time that the fire extinguisher was in operation, a conventional jet pipe was used as personal protection for the fire extinguisher operator.

When the progress of the fire calmed down and the flames closest to the fire extinguisher operator were extinguished, the person with the protective beam (the beam operator) continued with the focus on extinguishing the compartment fire. Note that the x beam operator's primary duty throughout the operation was to protect the fire extinguisher operator from flash and flames.

The test was terminated when the thermal imager showed a stable temperature below 50 °C. After the extinguishing effort was interrupted, continuous monitoring of the temperature with a thermal imaging camera continued for 15 minutes, to ensure that the propagation stopped. To simulate a removal of the vehicle, the vehicle was lifted about half a meter a couple of times with the help of a forklift, and 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 effort and could be carried out independently of the outcome of the other tests. Three sub-tests were carried out on modules with different charge status, 100%, 70% and 40% SOC, respectively, to study how the fire progression was affected by the degree of charge.

The end of the battery module was pierced with a 6 millimeter diameter drill, to initiate thermal surge in a battery cell. The drill was approximately 3 meters long, which provided an acceptable safety distance for the person performing the test. This was judged to be the easiest method of initiation at this trial level.

In connection with the drill going through the outer casing and into the battery cell, a thermal rush started. At that point, drilling was terminated, the drill was withdrawn and the module was left for observation.

2.2.5 Extinguishing tools

- A cut quencher initially cuts with abrasive and water. When the material is pierced, only water is added, and the whole process is carried out in one and the same movement. The abrasive is filled in an abrasive vessel located on the vehicle and activated, together with the water, by means of wire control.
  With a lance extender, the operator can reach into a vehicle and apply the cutting extinguisher to a propagating battery.

  The cutting extinguisher is used with support from the three- or four-point support that is attached to the far end of the lance. In this case, the support prevents the nozzle from coming into contact with damaged battery cells. 12

- The extinguishing lance has previously been tested in Germany and Austria. The extinguishing lance is a tool specifically adapted to get water into a battery pack. The extinguishing lance has a chamfer at the tip which means that only the part of the tip that sprays water should enter the battery without damaging more battery cells than necessary. The lance is powder coated on the handle part with electrically insulating paint and it is fitted with a handle which prevents the person holding the lance from being hit by the sledgehammer used to strike the lance in the battery pack. There is an extension to the handle to allow the user to stand with a greater distance, but it was not available at the time of this demonstration.13

12. Cold Cut Systems, 2022.
13. Murer-Feuerschutz GmbH, 2021.

2.2.6 Risk Mitigation Measures

The risk analysis resulted in recommendations for risk reduction measures that were shared with the response personnel who participated in the demonstration.

Before each test, the participants were informed about safety measures.

In all tests, protective clothing for smoke diving was used that met SS-EN 469. Breathing apparatus and protective masks were worn in connection with extinguishing efforts in all tests where the emergency personnel worked near the burning batteries.

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

Heat measurement and recording of data from thermocouples were carried out during the tests that involved an active extinguishing effort (tests 1, 2 and 3). In order to be able to directly follow the heat development and continuously follow the progress of the fire during the operation, a hand-held thermal camera was used. Several thermocouples were mounted in the test objects in order to be able to follow the heat development in the battery both in real time and afterwards.

The test sequence and which tools were to be used were predetermined in the tests that involved active extinguishing efforts. Tests 1 and 2 were indicative for the selection of input tools in the complete car test (test 3). As the extension of the extinguishing lance was not sufficient, the cutting extinguisher was judged to be most suitable for test 3 because it enabled work at a distance from the fire object.

2.3 Assessment criteria

After the test was completed, an analysis of all battery modules in the test objects was carried out with voltage measurement. The voltage measurements were performed three and two days after the test for tests 1 and 2 and tests 3 and 4, respectively.

An assumption was made that a partially damaged battery may have voltage remaining, while a completely burned-out battery, where the electrolyte has been burned, is voltage-free. The voltage of the battery module after the test thus became a measure of how much damage the fire caused in the module and thus how extensive the propagation was in each test object as a result of the initiation.

Propagation achieved and the effect of the extinguishing effort were assessed during ongoing testing directly via observations in the form of temperature estimation with a thermal camera, as well as the amount of smoke, flames and noise produced. Temperature stabilization below 50 °C and decreasing smoke and flame formation as well as sound were assessed as evidence that the extinguishing effort had been successful.

Results

3. Results

The result after each extinguishing effort was continuously evaluated during the tests and after each test, in order to keep the test setup dynamic. The aim was also to optimize the method of handling burning lithium-ion batteries.

3.1 Test 1: sub-battery

The first tests were carried out at the sub-battery level.

3.1.1 Extinguishing insert with cutting extinguisher

After initiation of thermal rush and ignition, a propagation was initiated in the battery. Pop-like sounds could be heard when the cell valves were opened. Jet flames and a relatively small amount of smoke seeped out because the sub-battery was sealed with a glued lid and several screws, resulting in the sheet metal lid buckling due to the pressure build-up. A clear discoloration occurred on the lid where the heat was most noticeable.

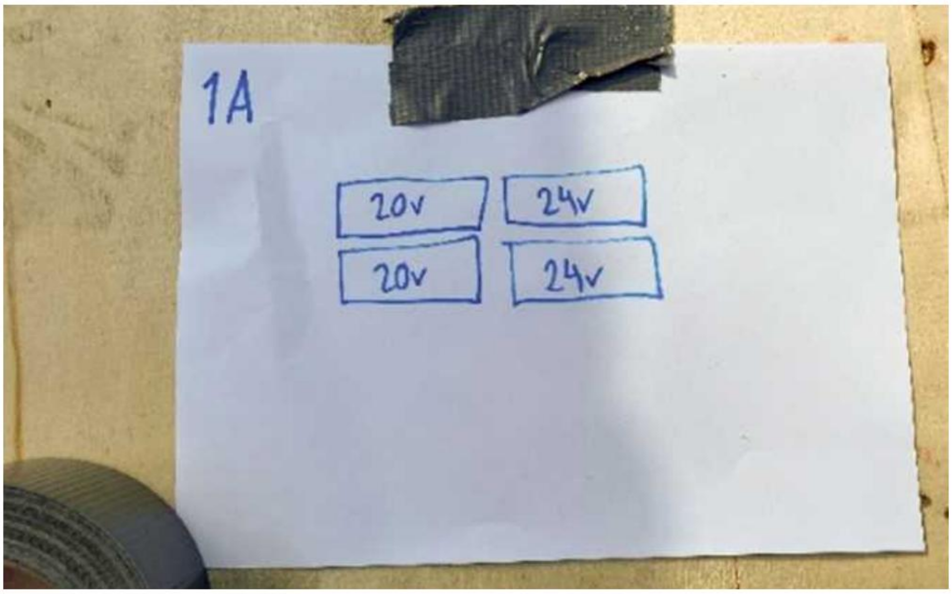
Figure 6. Extinguishing insert with cutting extinguisher - test 1A.

The strategy was to wait to start the extinguishing effort until the heat had spread to a second battery module and started a propagation in it. It proved difficult to confirm whether the propagation had indeed spread further between the modules. The shear extinguisher was used at the end of the first propagated module and placed on an area that was visibly heat affected and hottest according to the thermal camera, see Figure 6. When the module was pierced, water was flowed to cool surrounding modules until the extinguishing operation was stopped when the temperature was stable below 50 °C. In connection with the penetration of the casing, no arcs or jet flames occurred. No re-ignition could be noted.

The voltage measurements of the battery modules showed that two out of a total of four modules had full voltage, 24 volts, and the other two modules measured 20 volts, see Figure 7 and Figure 8.

Figure 7. Sub-battery after extinguishing operation with cutting extinguisher.

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



3.1.2 Extinguishing insert with extinguishing lance

After initiation of thermal rush and ignition, heat development continued, but at a slower rate than during the previous subtest. To speed up the development of the fire, gas burners were used underneath and on the side of the package.
A propagation could finally be ascertained, through a pop-like sound.
Jet flames and a relatively small amount of smoke seeped out due to the tight seal of the sub-battery, resulting in the sheet metal lid buckling due to the pressure increase.
A clear discoloration occurred on the lid where the heat was most noticeable.

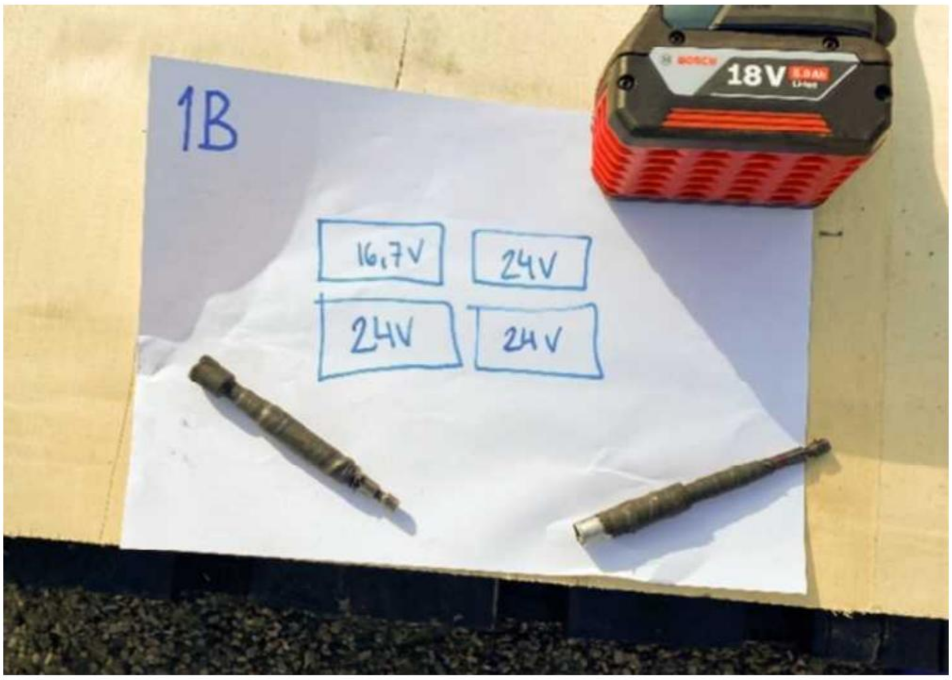
Figure 9. Extinguishing insert with extinguishing lance – test 1B.

Since 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 instead chosen to wait to deploy the extinguishing lance until the heat had clearly spread within the sub-battery. The extinguishing lance was struck where the heat impact was greatest, which was visible to the naked eye, but the thermal camera was used for confirmation. The extinguishing lance was knocked down into the battery pack with the help of a sledgehammer. The surrounding battery modules were then cooled with an established static flow until the extinguishing effort was interrupted when the temperature was stable below 50 °C, see Figure 9. In connection with the penetration of the battery pack, no arcs or jet flames occurred. No re-ignition could be noted.

The voltage measurements of the battery modules showed that three out 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. The result means that propagation from the first to the second module did not occur. It further reinforces the claim that it is difficult to determine the extent of propagation in the battery during ongoing processes.

Figure 10. Sub-battery after extinguishing operation with extinguishing lance.

Figure 11. Residual voltage after extinguishing operation.



3.1.3 Fire extinguisher with narrow hose and connected copper pipe

Note

This method choice **is not recommended** as it requires detailed knowledge of the battery architecture. In this trial, carefully considered measures were taken to reduce risks. The test was performed only for the purpose of confirming the principle of flowing burning lithium-ion batteries.

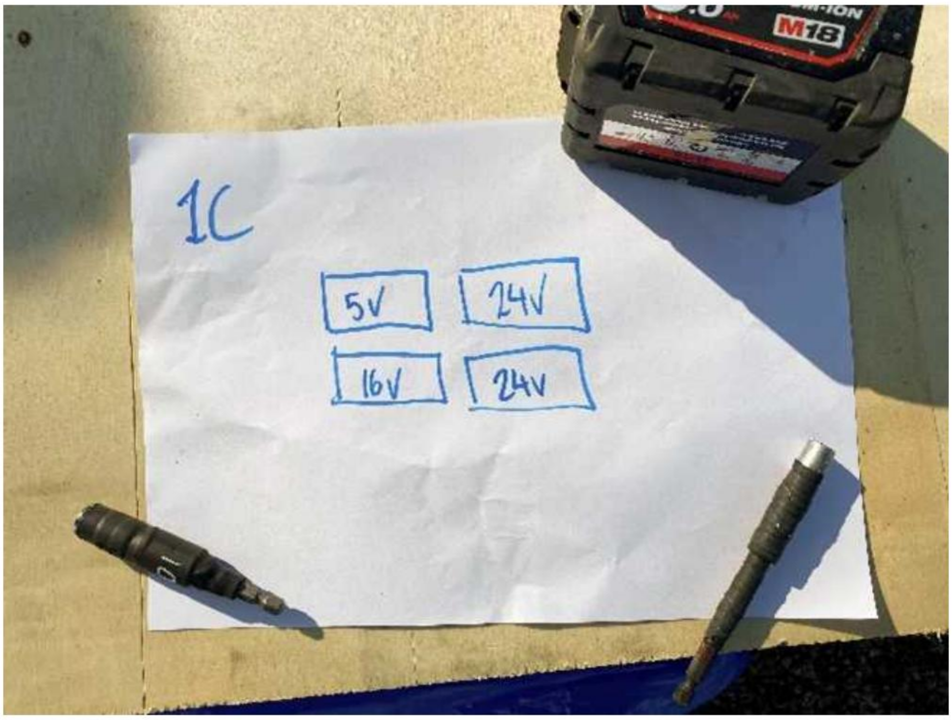
After initiation of thermal rush and ignition, a propagation was initiated in the battery, which could be heard and seen by smoke seeping out and the sheet metal lid bending. A clear discoloration occurred on the lid where the heat was most noticeable. The extinguishing effort was started when the propagation reached battery module 2 and the heat had clearly spread within the sub-battery. Hole drilling was carried out, the copper pipe was used and water flowed to cool the surrounding battery modules, see Figure 12. The extinguishing operation was stopped when the temperature was stable below 50 °C. In connection with penetration of the battery pack, strong jet flames and small arcs occurred. No re-ignition could be noted.

Figure 12. Fire extinguisher with narrow hose and copper pipe – test 1C.

The voltage measurements of the battery modules showed that the module where thermal rush was initiated had 5 volts, the adjacent module had 16 volts and the two remaining modules had full voltage, 24 volts - see Figure 13 and Figure 14.

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

Figure 14. Residual voltage after extinguishing operation.



3.2 Test 2: standalone electric car battery

Note

This method choice **is not recommended** as it requires detailed knowledge of the battery and vehicle architecture. In this trial, carefully considered measures were taken to reduce risks. The test was performed only for the purpose of confirming the principle of flowing burning lithium-ion batteries.

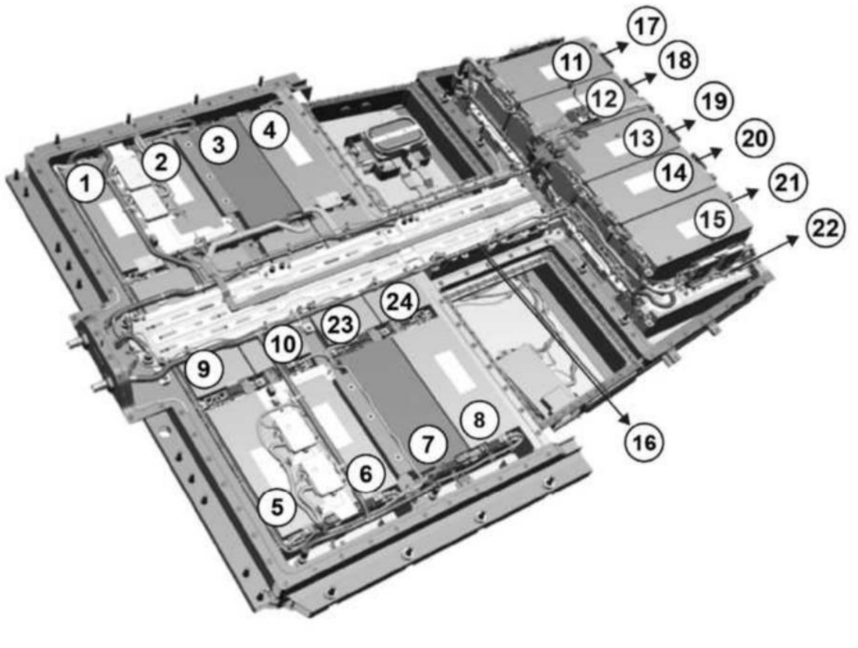
After the initial initiation of thermal rush, there was some delay before heat development indicated that propagation had started. When the propagation was allowed to continue for 15 minutes, the process seemed to stop. However, the thermal camera showed high temperatures in the area around the battery module that had been initiated, as well as inside the gimbal tunnel. The decision to initiate the second ignition module resulted in a slightly greater heat development with visible smoke but no flames.

The extinguishing operation was started. Hole punching with an ax showed jet flames and small arcs, and battery module A was used with jet tubes that established a water flow and cooled the battery pack, see Figure 15. During the hole punching, unaffected battery cells were damaged, which resulted in a local thermal surge that extinguished when water was applied. The extinguishing effort was interrupted when the temperature was stable below 50 °C. No re-ignition could be noted.

Figure 15. Extinguishing insert with narrow hose and unit jet tube – test 2.

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

Figure 16. Residual voltage per module after shutdown – test 2.



Module	Voltage	Module	Voltage	Module	Voltage	Module	Voltage
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. Stand-alone electric car battery after extinguishing operation with cover removed – test 2.

3.3 Test 3: complete electric vehicle

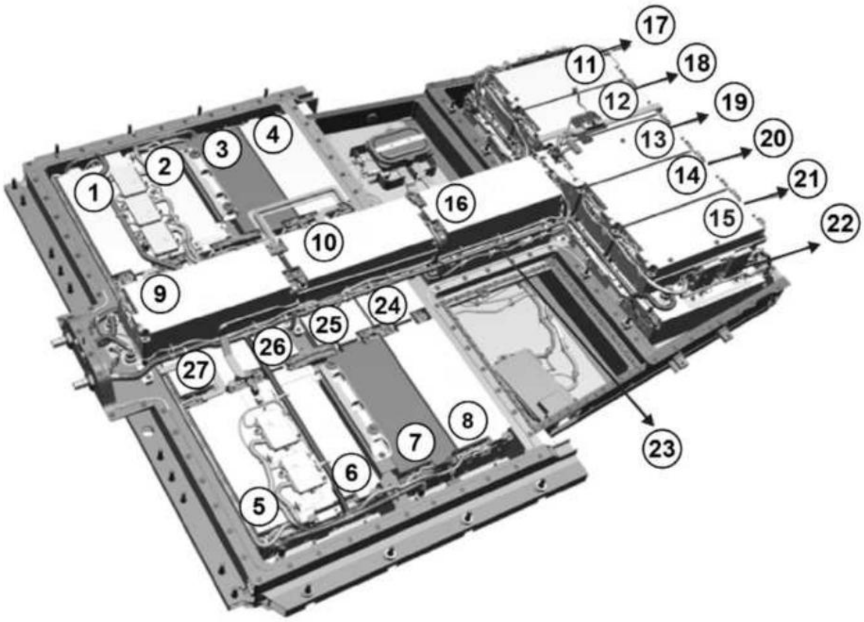
Thermal rush was initiated in ignition module number 7 (battery module A) and the first signs of progaging quickly came in the form of visible smoke. Within 3 minutes of the first signs of propagation, visible flames were observed. When 15 minutes had passed, a fully developed fire was noted in the vehicle and the extinguishing operation was initiated, see Figure 18.

Figure 18. Extinguishing insert with cutting extinguisher on electric vehicles (the image is from another project, but represents the same type of insert).

The total extinguishing effort, from the first water on the fire to the water stop, took 10 minutes. When analyzing the process, the extinguishing water consumption has been calculated at a total of approximately 750 litres. The fire extinguisher was actively used for about 5 minutes and the blast tube was actively used for about 4 minutes.

The voltage measurements of the battery modules showed that the module where the fire extinguisher had been installed (number 16) had no residual voltage.
Of the battery modules, 22 out of 27 had residual voltage. 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 the extinguishing operation.

Figure 19. Residual voltage per module after extinguishing lithium-ion battery in electric vehicles – 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. Removed battery pack from the electric vehicle after extinguishing operation – test 3.

3.4 Test 4: module

In test 4, the importance of SOC was investigated. The fire progress at 100% SOC was experienced as very reactive, likewise at 70% SOC. The third battery module with 40% SOC had a somewhat calmer course. The fire progress at 100% SOC is shown in Figure 21.

Figure 21. Fire progression in battery module, 100% SOC.

Discussion and analysis

4. Discussion and analysis

The results of this demonstration show that a static flow of water through the battery can be effective in firefighting. All tools used in the demonstration managed to control the fire. It may be worth noting that the architecture of the battery as well as where and when the thermal process was initiated in the battery were known and determined by the test conditions. At the same time, it was found that it was difficult to determine the degree of propagation, despite ideal conditions and access to internal temperature data, external temperature recording with a thermal camera and observations of, for example, smoke development, flames and sounds. The efforts in the demonstration were started early in the propagation stage, which may have affected the result. It is not certain that a more widespread propagation ring can be mastered with the same success. If a decision on an offensive effort is made in the field, only tools intended for the purpose and approved by the employer must be used.

When we made holes while adding water, no new jet flames appeared.
However, when we made holes without adding water, jet flames appeared.

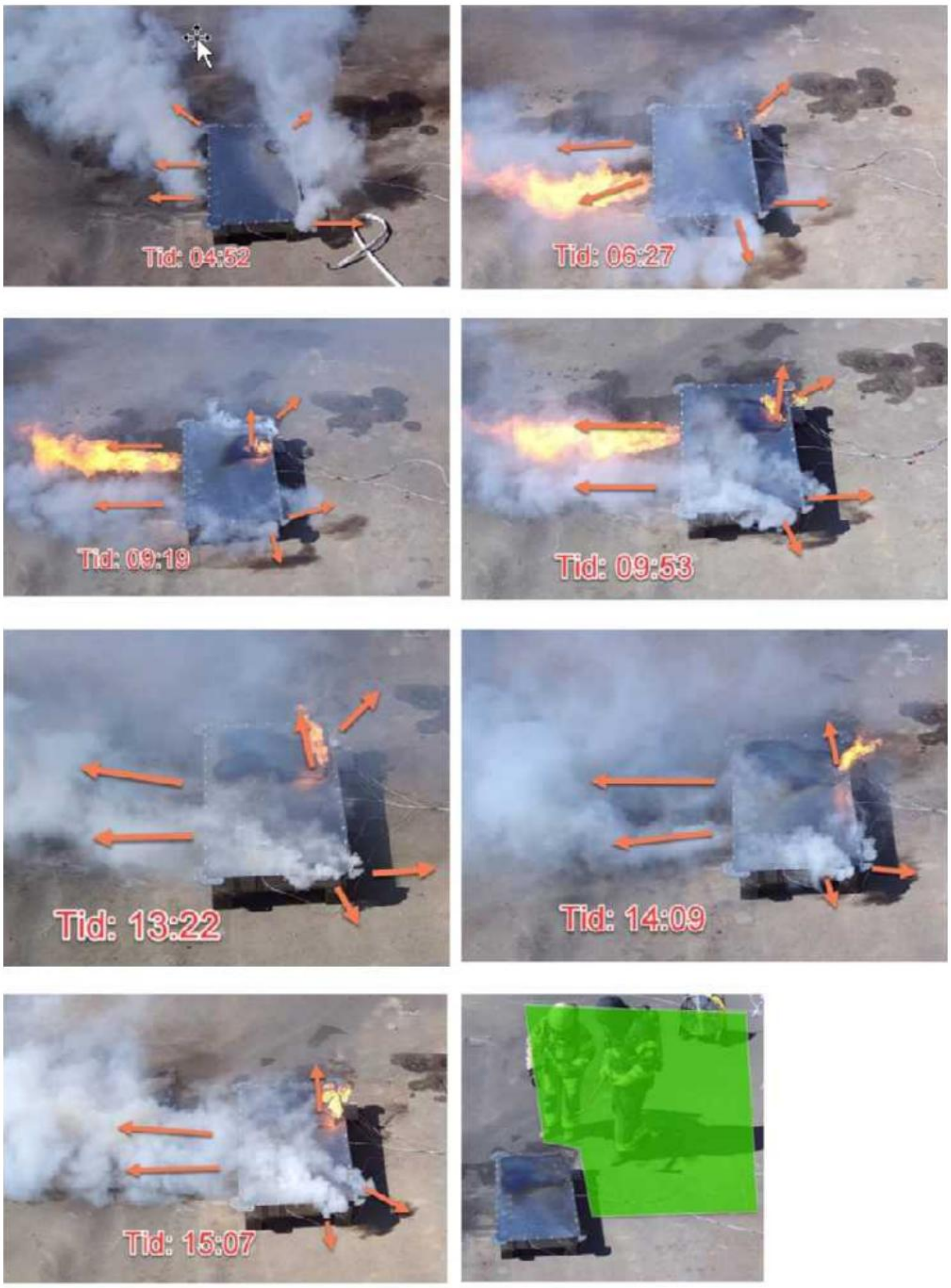
Two extinguishing attempts were carried out with self-constructed tools assembled from equipment assumed to be on a modern standard fire engine: jet pipe and narrow hose and pickaxe, which was used for punching holes. Although it worked in the demonstration, this type of approach is **not recommended** because the technology is difficult to implement in a real vehicle fire where access to the battery is limited and would require working inside a burning vehicle.
Hole punching must only be done with tools intended for this purpose and approved by the employer.

The state of charge of the battery, SOC, is important for the progress of the fire. Tests performed at full SOC or low SOC had different outcomes. Batteries with 100% SOC were very reactive and so were batteries with 70% SOC. The test object that was at 40% SOC was not as reactive as the others, but was still perceived as powerful and had enough energy for propagation through the battery to occur. If there is no reliable data on the vehicle's charge status, one should therefore always assume that the battery is fully charged, which corresponds to a worst-case scenario.

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

Monitoring to detect possible re-ignition was limited to 15 minutes, which may be acceptable under an engineered test situation. However, experience from the field has shown that re-ignition can occur after a considerable time - hours or days from the time of the fire. During the two and three days that the battery pack was stored after the fire and before dismantling, no re-ignition took place either. However, it is still important to handle electric vehicles and batteries that have burned out with great care. Information about the risk of re-ignition must always be given when handing over a fire-damaged electric vehicle or lithium-ion battery to, for example, a salvage company, a workshop or a scrapyard.

Figure 22. Example of spread of smoke and flames from the sub-battery in test 1C. The propagation pattern varies between different vehicles and battery architectures and must be studied on a case-by-case basis before emergency personnel approach the fire object. The green marking shows the area deemed safe in this case.



The photo collage in Figure 22 shows an example of the spread of smoke and flames from a battery in the current demonstration. The green marking shows the area deemed safe in this case. Since the spread depends on several factors, one cannot draw general conclusions about safe zones, but must observe how the fire behaves in each individual fire incident.
Factors that play a role in the spread of fire include:

- current battery chemistry and its reactivity
- the battery construction
- type and location of pressure relief valves or burst plates.

When approaching the vehicle, you should position yourself in areas where you have not previously observed flames, flames and smoke. However, it is worth noting that the flame spread can be several meters and that so-called jet flames can come very suddenly.

The active extinguishing efforts carried out in the demonstration interrupted the ongoing propagation and led to residual voltage, so-called "stranded energy", in the battery. It posed a risk of re-ignition, which must be taken into account during further handling, transport and storage of the fire object.

The risks associated with handling a burnt battery with a significant amount of residual 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 residual voltage and should always be treated with this in mind until it is confirmed that the battery is dead.

During the demonstration, both a thermal camera and a thermocouple were used. It is important to note that the thermal camera is sensitive to reflection, and it can therefore be difficult to get a completely truthful picture of the heat spread on the inside of the battery.

In the event of a fire in an electric vehicle and its battery, it is of the utmost importance that the response personnel take note of the vehicle manufacturer's safety and response information in the vehicle's rescue card (Rescue Sheet) and rescue instructions (Emergency Response Guide, ERG) in order to be able to plan a response based on the specific conditions in the current case.

Conclusions

5. Conclusions

- The demonstration showed that it is possible to interrupt a thermal propagation in a lithium-ion battery through an aggressive extinguishing operation where the battery is flooded with water.
- Extinguishing operations where the lithium ion battery is flooded with water can shorten the operation time and reduce personnel and material resources.
- It is difficult to determine the degree of propagation in a lithium-ion battery during an ongoing fire based on external observable factors such as temperature monitoring with a thermal imaging camera, smoke and sound.
- Cell chemistry, degree of charge, battery architecture and vehicle architecture are examples of system properties that affect how a thermal surge and propagation develops during a thermal event in an electric vehicle.
- When planning an action, it is important to first take a look at the vehicle's Rescue Sheet and ERG to assess the conditions for an active extinguishing operation.
- Conducted trials show that it is possible to access the battery with the tools tested in the trials. Thermal cameras and rescue sheets can provide information that provides better conditions for success in an operation. • The risk of residual electrical and

chemical energy ("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.

References

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 (a). (03-2016). *Space systems – Lithium ion battery for space vehicles – Design and verification requirements.*

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

ISO 18300:2016 (a). (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-Löschlanze.* Retrieved from Murer: https://www.murer-feuerschutz.de/pdf/e-loeschlanze/E-Loeschlanze_EN_20211026_WEB.pdf?m=1643720727& on 06-30-2022.

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

Myndigheten för
samhällsskydd
och beredskap

651 81 Karlstad Phone 0771-240 240 **www.msb.se** Publication
no. MSB2184 - March 2023 ISBN 978-91-7927-376-7