DIVISION SAFETY AND
TRANSPORT
FIRE SAFE TRANSPORT

Lion Fire II - Extinguishment and Mitigation of Fires in Lithium-ion Batteries at Sea

Roeland Bisschop, Petra Andersson, Christian Forsberg and Jonna Hynynen

RISE Report 2021:111

Lion Fire II - Extinguishment and Mitigation of Fires in Lithium-ion Batteries at Sea

Roeland Bisschop, Petra Andersson, Christian Forsberg and Jonna Hynynen

Abstract

Lion Fire II - Extinguishment and Mitigation of Fires in Li-ion Batteries at Sea

Fire safety of ships is a key issue as evacuation and extinguishment is more difficult at sea than it would be on land. There is therefore a long tradition and regulations in place to maintain the fire safety of ships. The current shift to more sustainable transport solutions has now led to the introduction of lithium-ion batteries for ship propulsion. These can offer significant benefits in terms of reducing greenhouse gas and particulate matter emissions. They also introduce new risks, however. When damaged, li-ion batteries may go into thermal runaway, a state that produces significant amounts of heat combined with flammable and toxic gas. This is a challenge, and safety is one of the key questions asked when introducing battery propulsion at sea.

Extinguishment of battery fires is a piece of the puzzle when it comes to enabling safe battery propulsion at sea. Fire suppression systems are used today for such applications, yet no standard test method exists to evaluate their performance. This work proposes an approach that may be used to evaluate such systems and that can be used as input towards the development of a test method. Specifically, a test method aimed at evaluating the performance of fire suppression system under critical battery failures and at lowering the risk for module-to-module propagation.

The test method designed here performed well and sustained the 18 tests that were done. Overall, repeatable test conditions were obtained that allowed for the performance of fire suppression systems to be investigated. All fire extinguishing systems had a positive impact in some position but not all points and it was not possible to draw any conclusion on their ability to mitigate the risk for module-to-module propagation. The tests showed that mitigating this can be possible with careful design of systems and perhaps combinations of different means.

Key words: Li-ion batteries, Electric ships, Fire suppression, Thermal runaway, Thermal propagation, Extinguishing tests

RISE Research Institutes of Sweden AB

RISE Report 2021:111
ISBN: 978-91-89561-02-1
Borås, 2021

Cover image: An image taken during one of the fire suppression tests performed. A flame extends from a li-ion battery towards the ceiling and is met by a fire suppression system.

Contents

Preface

This work was financed by the Swedish Transport Agency under contract 2019/119203 which is gratefully acknowledged.

The project was further supported by the project partners, a group consisting of the following members:

- Henrik Johansson, Johan Hellsing and Knut Linrud, Johnson Controls
- Johan Ringström, Cinus
- Melker Lang, GPMB Nordic
- Henrik Lundgren and Sven Bergqvist, Polarium
- Fredrik Almlöv, Trafikverkets färjerederi.
- Martin Carlsson and Lisa Gustin, Stena

Their contribution to the project was invaluable, donating their time, expertise and materials to the project as well as supporting with personnel to aid with the tests.

The following persons made up the reference group, contributing to the project with their time and experience:

- Joakim Birgander and Anders Höfnell, Lloyd’s Register
- Mattias Hörnquist and Saeed Mohebbi, Transportstyrelsen
- Ola Willstrand and Magnus Arvidson, RISE

Acknowledgements

We would like to extend our gratitude to our colleagues at RISE Safety Research, including Vasudev Ramachandra and the technicians who supported us in preparing for the tests, Emil Norberg, Anders Älvskog, Sven-Gunnar Gustafsson, and Michael Magnusson. In particular, we would like to acknowledge Emil Norberg and Anders Älvskog. They were able to solve any technical issues and allowed us to move forward, even when faced with adverse weather and long working days.

The tests would not have been possible without the support and assistance from the staff at Guttasjön, the training site for the rescue services in Borås. Special gratitude to Johan who made sure everyone was safe during these tests, even if this meant staying with us after working hours. Thanks to Lennart as well, who made sure we had coffee and were fed.

Finally, we would like to extend our gratitude to Christian Andersson, ForSea Ferries and Torbjörn Cederberg, Styrsöbolaget for their hospitality and showing us around on the M/S Aurora and M/S Elvy, respectively.

Sammanfattning

Batteridrift och användande av batterilager för reservkraft är viktiga komponenter för att minska emissionerna från sjöfarten, framför allt när fartygen går inomskärs men i framtiden även för internationell fart. De batterier som ligger närmast till hands att använda för elektrisk framdrift är Li-jonbatterier. De har många fördelar, såsom hög energitäthet, men även nackdelar vad gäller säkerhet, då de endast är stabila inom ett visst temperatur- och spänningsintervall. Utanför detta intervall kan Li-jonbatterier hamna i termisk rusning, ett stadium av mycket snabb självuppvärmning som resulterar i utsläpp av toxiska och brännbara gaser och kan resultera i brand och explosion. Brandsäkerhet till sjöss är viktig då det är svårare att evakuera och släcka till sjöss än på land och en termisk rusning måste hanteras på plats.

Ett sätt att göra detta är med hjälp av släcksystem. Det finns många olika typer av släcksystem och släckmedel på marknaden men begränsat med oberoende utvärderingar av dessa och deras förmåga att begränsa spridning av termisk rusning. Dessutom saknas en testmetod för utvärdering av släcksystem mot Li-jon batteribränder och råd om hur man ska utvärdera sådana test. Detta arbete ger underlag för utveckling av en testmetod och då specifikt för begränsning av spridning från modul till modul.

Inom ramen för projektet genomfördes studiebesök på befintliga installationer samt så togs informationsmaterial in för att designa ett standardrack bestående av tre rack 4 moduler höga med en aktiv modul. Två olika batterikemier användes för den aktiva modulen, prismatiska LFP celler och cylindriska NMC celler. Övriga moduler var dummymoduler som fylldes med sand för att få samma termiska massa som en riktig modul. Alla moduler förseddes med flera termoelementen på utsidan, termoelement placerades även inne i modulen precis ovanför den aktiv modulen.

Termisk rusning initierades med hjälp av en brännare och kriterium för aktivering av släcksystem bestämdes genom att köra fribrinnande test utan släcksystem. Kriterium valdes för att ge en säker propagering av termisk rusning genom modulen men ändå så tidig ti förloppet som möjligt. Kriteriet valdes också för att efterlikna en situation man kan få med normal branddetektion ombord på ett fartyg. Kriteriet sattes på modulen precis ovanför den aktiva modulen.

I projektet studerades även tidigare studier samt det regelverk och standarder som finns på området för att säkerställa att eventuella befintliga råd och anvisningar täcktes in av metoden. Det som framförallt har en bäring på en testmetod är DNVs nuvarande anvisning om att om man använder dummymoduler i ett termisk propageringstest så ska temperaturen i dummymodulerna inte överstiga 85 °C.

I projektet användes 4 olika typer av släcksystem, ett sprinklersystem, ett vattendimsystem, ett punktskyddssystem med media avsett för Li-jon batterier och ett gasfassystem. Både sprinkler och vattendim-systemen kördes både med endast vatten och med vatten med ett additiv, F500. Punktskyddssystemet kördes på samma sätt både med media (AVD) och med vatten endast. Detta gjordes för att kunna särskilja effekter som kom av att man sprutar på släckmedlet på ett annorlunda gentemot effekter av ämnet som sådant. Sprinkler och vattendimsystemen var inte optimerade för applikationen utan man körde med normal design. Punktskyddet var första gången

det användes mot en uppställning som denna och man använde ett system som normalt används för mobila boendesprinkler vid testen. Gasfassystemet med Inergen var designat med en högre koncentration mot vad man normal använder eftersom det sedan tidigare är känt att gasfassystem har svårt att ha någon effekt på termisk rusning.

Testen kördes utomhus i containers. Vid testen var dörrarna öppna till containern vilket innebar att designkoncentrationen för vattendimsystemet inte upprätthölls. Testen med gasfassystem kördes i stängd container.

Testen visade att den rackuppställning som valts var tillräckligt robust för att köra flera test på. Testen med NMC moduler var väldigt repeterbara så länge som man hade precis samma konfiguration av celler inne i modulen. Testen med LFP moduler var inte lika repeterbara dock. Skulle man köra testen med endast en typ av modul skulle man kunna förfina aktiveringskriteriet något också.

Risken för propagering till närliggande moduler utvärderades baserat på uppmätta temperaturer. Alla system hade en positiv påverkan på risken för spridning vid någon modul. Risk för propagering förelåg dock i samtliga fall förutom för gasfassystemet mot LFP modulen. Det var svårt att dra några säkra slutsatser om hur stor påverkan additiven hade då skillnaderna mellan med och utan additiv även kunde bero på variationer mellan hur propageringen utvecklade sig. Även om försöken var väldigt repeterbara finns det alltid en variation och utan att köra mer än ett test går det inte att riktigt uttala sig om eventuella skillnader i dessa försöken där systemen inte var optimerade för uppställningen. Utvärderingen skulle också kunna förbättras genom att använda fler termoelement placerade inuti modulerna.

Testen och försöken bekräftar att hindra termisk rusning från att sprida sig mellan moduler är en utmanande uppgift men kan gå med noggrann design av systemen, kanske genom en kombination av olika system.

Vid dessa försök användes även en ganska så tät konfiguration av moduler eftersom det är detta man ofta ser i installationer idag. Resultaten kan bli väldigt annorlunda med en mindre tät konfiguration. En mindre tät konfiguration kan till exempel vara större avstånd mellan racken men också större avstånd mellan moduler i racken. Andra parametrar att studera och variera för att utveckla en testmetod är själva modulerna, ska det vara en särskild IP-klass på dem, vilken typ av celler ska man använda, går det att ta fram en standardmodul som används i testen på samma sätt som man till exempel har ett standardgods för test av sprinkler. Kriterier för aktivering av släcksystemen behöver förfinas och utvärderas. Slutligen bör det utredas vilka utvärderingspunkter man ska använda för att bedöma systemets förmåga att förhindra termisk propagering.

Summary

Fire safety of ships is a key issue as evacuation and extinguishment is more difficult than it would be on land. There is therefore a long tradition and regulations in place to maintain the fire safety of ships.

Today there is a strive to reduce the greenhouse gas emissions from ships by e.g., introducing battery propulsion. The most common battery type for this is Li-ion batteries. Li-ion batteries has however a drawback in their thermal instability, which may cause the battery into a thermal runaway, a state that produce significant amount of heat and the release of flammable and toxic gases and pose thus a significant fire risk. In fact, fire safety for battery systems has been identified as a key question when introducing battery propulsion at sea.

To maintain the fire safety of a ship it is important to be able to mitigate the spread of thermal runaway. The use of different types of extinguishing systems can be a mean to achieve this. There is however no test method available to demonstrate a suppression/extinguishment systems ability to prevent the spread of thermal runaway. Also, advice is lacking on how to evaluate systems for mitigating fires and spread of thermal runaway in batteries.

This work provided input towards the development of a method for fire extinguishing tests on battery systems. Specifically, extinguishing systems whose aim it to prevent module-to-module, and beyond, propagation. In addition, the tests performed added to the publicly available full-scale tests results, information that is limited yet essential to design safe battery systems.

Study visits were performed to ships operating in Sweden and having li-ion battery systems on-board in order to design a mock-up for the tests. Unfortunately, the ongoing global Corona pandemic meant that not all visits could be carried out as planned. Instead, information and documentation of the different installations, granted to the project, were reviewed. This background information was the foundation upon which the experimental setup was built. It also showed the different safety solutions that are considered today, apart from fire suppression, that enable safe operation.

Guidelines and requirements from ship classification societies for battery systems have been, and are still, under rapid developments. More and more countries are also becoming increasingly aware that li-ion batteries places new demands for fire safety at sea. Much work remains in this area, as knowledge on these fires is still being developed. A few test methods have been developed to issues such as thermal propagation. Details are however often lacking in terms of how the test should be executed or interpreted. This information needs to be developed further, with significant steps having been made by UL, FM Global and DNV-GL.

One of the contributions of this work, which builds upon the work of the aforementioned, was the development of a standardised battery rack. This rack, comprising of open 19” racks that combines live and dummy modules, may be used to evaluate the performance of fire suppression systems. The dummy modules were filled with sand to reach a similar thermal mass as the live module. Temperature sensors were used to evaluate the risk for module-to-module and rack-to-rack propagation.

Different thermal runaway initiation methods were investigated, and it was decided to utilise a localised burner.

Two test series were conducted. The first series focused on verifying the mock-up and chosen experimental parameters. The thermal runaway initiation method was investigated as well as suitable criteria for fire suppression system activation. These tests were conducted without any extinguishing systems, i.e., free burning reference tests. Tests were conducted using two different module types, one with NMC cylindrical 185650 cells and one with prismatic LFP cells.

The NMC tests showed great repeatability and allowed for the onset of thermal runaway propagation to be easily identified. This proved more challenging for the LFP test. A criterion was developed based on surface temperatures of the dummy module directly above the live module. Specifically, the surface temperature underneath and on either side of this dummy module. These surfaces were required to measure above 70°C for 10 seconds and, at least for one of the sides, above 100 °C for 10 seconds, respectively.

The second series involved fire extinguishing systems. These tests were conducted at an outdoor facility, while the developed test setup was installed in standard 20-ft. shipping containers. The considered extinguishing systems were selected to represent both those systems already used today in e.g. machinery spaces on-board and systems that are under development. This included water-based systems test, which were evaluated with only water and water plus an additive. The same principle, i.e. pure water and water plus additive, was followed for a local application system. Finally, a gaseous based system, utilising higher than normal design concentration, was used.

A total of fifteen tests were performed during the second test series. The developed rack was robust enough to manage this large number of tests without failing. The importance of using the same live battery modules became very clear from these tests. Especially if they are to be used as a reference to later compare other tests with. In two of the tests the modules were slightly different which affected the fire development and resulted in the activation criterion no longer being valid. In all other cases however, this criterion was effective in both the LFP and NMC tests. To improve the developed methodology however, the criterion should be developed for the specific live module that fire suppression systems are to be tested on.

A tremendous amount of data was gathered from these tests, in particular temperature measurements on the dummy modules. It was challenging to carefully evaluate such a volume of data. Temperatures varied with the locations that were considered. This was found to relate to differences in the trajectory of flames. Although most of the sensors were located external to the dummy modules, the internal sensors provided useful when interpreting results. A greater number of internal temperature sensors would be recommended in future tests.

All fire extinguishing systems achieved a positive impact on the temperature development at some point. For the local application system, it was difficult to assess performance due to the different module that was used. In some cases, the additives had a positive impact on module-to-module propagation risks. These differences were however small and almost in the same order of magnitude as the variation observed from reference tests. It should be noted that none of the tested systems, except for the gaseous system, was designed for handling fires in li-ion battery systems. Rather, conventional systems and water densities were used. To arrive at such solutions, objective testing under repeatable conditions is a must, so that manufacturers may arrive at the effective solutions.

The gaseous system had the greatest impact. Its activation significantly lowered the immediate risk for module-to-module propagation. This specific system was not representative of a conventional system, however. It was over-dimensioned compared to what is normally used for volumes of the same size as what was considered in the tests. Regardless, this result is very interesting as its shows that gaseous system can be an effective approach. Arguably even more so when followed-up by other means of cooling.

1 Introduction

Fire safety of ships is a key issue as evacuation and extinguishment is more difficult than it would be on land. There is therefore a long tradition and regulations in place to maintain the fire safety of ships.

Today there is a strive to reduce the greenhouse gas emissions from ships by e.g., introducing battery propulsion. This shift is enabled by significant developments in lithium-ion (Li-ion) batteries. These offer significant benefits compared to other technologies, which includes their ability to store and release power quickly, high energy density, no memory effect, long life, and low self-discharge rate. This comes however with a drawback in terms of safety due to their thermal stability and flammable electrolyte. When damaged, li-ion batteries may go into thermal runaway, a state that produces significant amounts of heat combined with flammable and toxic gas. This is a challenge, and safety is one of the key questions when introducing battery propulsion at sea [1].

To maintain fire safety on a battery electric ship it is important to mitigate the spread of thermal runaway. The use of different types of extinguishing systems can be a means to achieve this. There are however no test methods available to evaluate the performance of such systems on fires in battery systems. Guidelines and advice on how such systems should be evaluated for mitigation of thermal runaway are very limited. As a result, systems suppliers lack the means to develop and demonstrate effective solutions.

There are many different types of extinguishing systems and agents on the market. Some of them claim to be efficient towards li-ion battery fires, despite very limited independent tests that demonstrate their performance. Instead, ship owners and designers must rely on extinguishing system suppliers for test data. In addition, li-ion batteries are in many cases still new to ship owners and designers. This creates a major challenge for them in reviewing the information provided and to evaluate the performance of the extinguishing system against li-ion battery fires. There is therefore a need for an impartial test method, and data, which examines different systems and their performance when protecting battery systems.

Ships using battery propulsion are approved by classification societies. Many of them have requirements related to thermal propagation. The Norwegian Maritime Authority demands that thermal runaway propagation shall be demonstrated through testing. Thus far, such tests have been ad-hoc and through cooperation between ship owners, suppression system suppliers and battery system suppliers. There is however a need for a standardized test method so that suppression system suppliers can test their product without having to do so for each specific application. A general approach useful in evaluating and demonstrating the performance of different systems is needed to arrive at effective solutions. Such an approach would also make it easier for ship owners and designers to select appropriate mitigation systems.

A preliminary study on what such a method could look like was conducted by Andersson et.al. [2]. Here, different types of extinguishing systems were put up against li-ion battery fires. The tests were conducted with different extinguishing agents and its application towards a module mock-up. It was shown that the agent must penetrate the cells within the module to limit cell-to-cell propagation and that cooling was important.

DNV-GL conducted a study in 2019 [3] on module-to-module propagation. They used 5 different types of extinguishing systems in their study: sprinklers with water without additives, a high-pressure water mist system (Hi-Fog), a gaseous agent (Novec 1230), direct injection of water into the module, and direct injection of a CAFS foam into the module (FIFI4Marine). They used modules of NMC pouch cells and LFP cylindrical cells.

This work seeks to build upon the DNV-GL's study and arrive at a generic method for evaluating the performance of fire suppression systems when faced with battery fires. Here, the considered problem is restricted to preventing fire spread from a failed module. The method should be independent of safety solutions that may be present within a module to 1) not be battery specific and 2) allow for fire suppression system performance to be the key focus.

The contribution to developing a test method is arrived at by means of a literature review and experiments. The literature review investigates what battery electric ships look like today and which safety related requirements they need to comply with. In addition, previous studies on fire suppression of battery fires are reviewed. The lessons learned from these works, combined with an understanding of the battery electric ships, are the foundation upon which the experimental set-up is developed. This set-up is reviewed through two independent test series, where both free-burning and fire suppression tests are considered.

2 Battery electric ships

Electrification and hybridisation of drivelines has been a major trend for land-based vehicles. This is largely thanks to significant technological developments in the field of li-ion battery technologies and the need to meet increasingly ambitious environmental goals. Now, the maritime industries are also looking to reduce their impact on the environment and reap the benefits of this maturing battery technology.

2.1 From electric vehicles to electric ships

Battery electric vehicles were first introduced in in the 19th century. They were quickly replaced by internal combustion engine vehicles however, due to mass production and technological advances. Finally, as highways started connecting cities, long-distance roads promoted cars capable of greater ranges than electric vehicles, leading to their disappearance [4]. A century later, the first commercially available fully electric battery electric car, the Nissan Leaf, was released in 2010 [5]. Since then, the li-ion battery industry has continued to develop significantly. It is projected now that the global manufacturing capacity for these batteries will grow from 34 GWh in 2020 to 600 GWh in 2030 [6]. With a greater supply of batteries, their price will drop and thus become more attractive to electric ships as these ships require a huge number of battery cells to operate.

The maritime industry is largely dependent on fossil fuels to power its vessels. Despite being relatively climate friendly when compared to road transport, i.e., road transport shared 72 % of greenhouse gas emissions compared to 13 % from maritime [7], total emissions from the maritime industry are still significant. In April 2018, the International Maritime Organization decided to drastically reduce emissions. By 2050, the 173 member states of the UN organization want to at least halve CO_2 emissions from ships compared to 2008. One solution in reaching this goal is to use electric propulsion with batteries.

In the coming years the number of electrified ships is expected to increase as shown in Figure 1. For electrification to be feasible there is the issue infrastructure and of cost. Not only the cost for the batteries, but also for the charging infrastructure and a supporting generator set if larger distances are to be covered. While with the current battery technology, electrification of trans-oceanic ships and cargo vessels seem bleak, there have been advances in the electrification of ferries. Many existing ferries have also been retro fit with a BESS to supply for a part of the needed energy, see Figure 2.

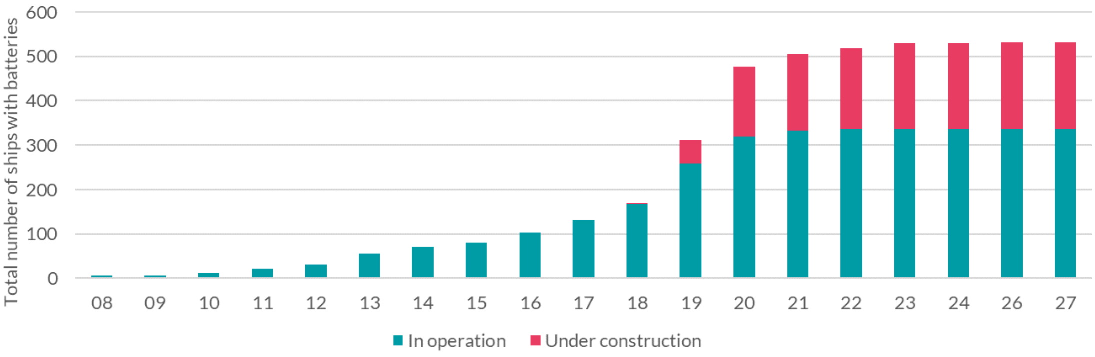


Figure 1 Total number of ships with batteries [8]

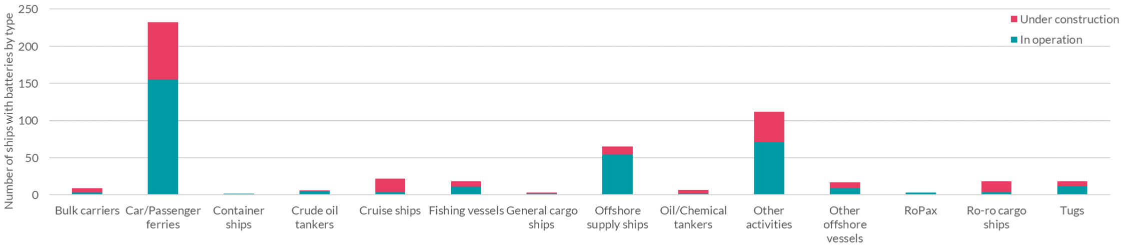


Figure 2 Number of ships with batteries by type [8]

Few pure electric ships exist today, as shown in Figure 3. In most cases, the first step to electrification is hybridisation of existing drivelines. The benefit of this approach is the reduction in battery cost and lower charging requirements. Furthermore, the approach may be to modify existing vessels. Examples of such hybrid ships in Sweden are Aurora (Helsingborg-Helsingør), Elvy (within Gothenburg), Tellus (Uddevalla-Lysekil) and Jutlandica (Fredrikshamn-Gothenburg). Other ships with batteries in Sweden that were identified are listed in Table 1.

With the addition of batteries, ships like Aurora, Elvy and Tellus may be battery powered for an entire crossing between ports. Upon arrival, the batteries may be charged and if necessary, the generator set kicks in to produce more electricity. For larger ships travelling long distances, such as the Jutlandica, battery power may be used while manoeuvring in port. For example, while on its way out to open sea from its dock in the city of Gothenburg in Sweden, it may operate fully electric. As such, noise and gas emissions within the city can be kept to a minimum.

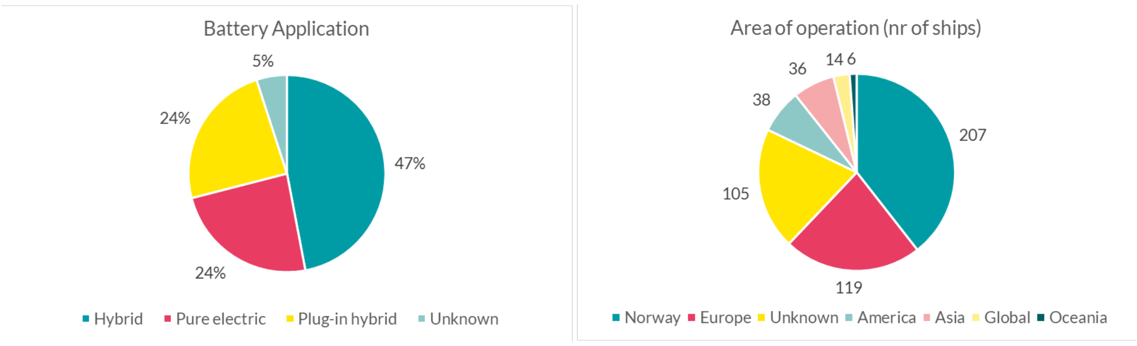


Figure 3 left) Application of batteries in ships; right) Operational areas for ships with batteries [8]. Not all makers share their data hence the application/area of operation is unknown in some cases.

Table 1. Ships with battery propulsion in Sweden

Ship name	Operator	Route	Type	Drive	Battery size [kWh]
Elvy	Västtrafik	Stenpiren - Lindholmen (Gothenburg)	Pax	Battery-hybrid	1008
Tellus	Trafikverket Färjerederiet	Finnsbo - Skår (Västra Götaland County)	Ropax	Battery-hybrid	948
BB green	Green city ferries	Prototype, Stockholm	Pax	Pure electric	200
Movitz	Echandia / Green city ferries	Riddarholmen - Solna strand, Stockholm	Pax	Pure electric	120
Linje 80	Rederiaktiebolaget Ballerina	Linje 80 (Sjövägen, Nybroplan - Frihamnen), Stockholm	Pax	Battery-hybrid	500
Vilja	Port of Luleå	Port of Luleå	Tug	Battery-hybrid	600
Aurora af Helsingborg	ForSea	Helsingör - Helsingborg	Ropax	Battery-hybrid	4160
Jutlandica	Stena Line	Gothenburg - Fredrikshamn	Ropax	Battery-hybrid	1000

2.2 Battery installations on ships

Depending on if the vessel is a new build or an existing ship that needs a BESS seem to affect the installation largely. New builds like the Basto Electric, a Norwegian electric ferry with a passenger capacity of 600 and a car capacity of 200 cars or 24 trucks, running around a 10-kilometre line, have integrated battery systems stored in the hull. On the other hand, retrofit BESS systems must be installed using other techniques.

The technology and structure of the BESS is introduced, and some retrofitted ships are reviewed in this section. In the latter case, physical study visits were performed to the M/S Aurora af Helsingborg and M/S Elvy. Visits were also planned for the other ships presented here but this was not possible due to the onset of Covid-19 in Sweden. Available literature and documentation provided by the ship operators were reviewed instead in those cases.

2.2.1 Battery systems

As battery propulsion for ships is new there is not yet much advice and standards for design of such systems. The lack of specific regulations regarding details like maximum energy stored in each compartment, standards for the battery management system, ventilation requirements, etc are a challenge for ship designers. The fact that a lot of factors to be considered also change with the kind of batteries used, their physical forms and their chemistries pose as a challenge when designing a battery system for ship propulsion. Some battery manufacturers today offer marine grade batteries for use on such ferries. While these batteries themselves conform to different standards such as relevant IP ratings, vibration tests, et cetera, there are many gaps in the standards regarding their installation onboard.

The average energy density of li-ion cells today is about 250 Wh/kg. This is a key factor in deciding the trade-off between range and weight of the vessel. The range is implied by the amount of energy stored on board in the batteries and the physical parameters of the vessel like its weight, drag coefficients, et cetera. Currently, the previously mentioned Basto Electric is the largest fully electric ship in operation with 4.3 MWh of stored energy. A concept design for a ferry travelling between Gothenburg and Frederikshavn with 3000 lane meters[1] and 1000 passengers, required approximately 60 MWh of energy to be stored. This corresponds to about 800 tonnes in just battery weight [9]. Battery systems of this size correspond to very high initial costs and requires the development of custom power transfer solutions to charge them when docked. Robotic plug-in charging solutions are mainly used for large BESS while pantographs and inductive charging techniques, in addition to plug-in solutions, are used for powers up to approximately 1 MW.

A complete BESS can be described by defining the following components.

- **Cells**: Cells are the smallest energy storage units that make up the battery. Generally, all Li-ion cells are defined by their physical type, nominal voltage, their capacity, their C rating, and their chemistry. Physically, cells are of three types: canned, prismatic and pouch. For high capacities and better fill factors in spaces, pouch or prismatic cells are used. The nominal voltages of cells are usually 3.2 or 3.7 VDC. Their capacity defines how much current they can provide over time and their C rating defines how quickly they can be charged or discharged.
- **Modules**: Modules are the first step towards increasing the voltage and the capacities to the required levels and are a series-parallel combination of cells. Modules can be flexible in terms of size, weight and capacity.
- **Strings**: Modules that are connected in series with each other are strings and these determine the overall BESS voltage level. The number of strings also generally define the battery management system requirements as it is often so that each BMS units monitors a certain number of strings.
- **Racks**: Racks are a more physical description of the arrangement of the strings and can consist of multiple strings in parallel. This maintains the voltage level but increases the current delivering capacity. In this report a rack refers to a physical object where several modules are mounted on top of each other.
- **Packs**: Packs can consist of multiple connected racks.
- **Array:** Arrays can consist of multiple connected packs.

The structure of a battery installation is rather similar across applications, e.g. stationary, vehicles, maritime etc. Individual cells make up modules; modules are connected to make strings and the strings are interconnected to make up the overall battery. Figure 4 gives an example of a rack configuration that may be found in ships and stationary applications. Here the modules are typically arranged vertically as space

---

[1] A lane meter is a unit of deck area in cargo vessels. It is defined as a strip of deck one meter long. A lane is conventionally 2 m wide so a lane meter is equivalent to 2 m^2.

is usually not a limiting factor. A flat layout is used in vehicles, with the battery pack underneath the vehicle between the front and rear wheel axles [10].

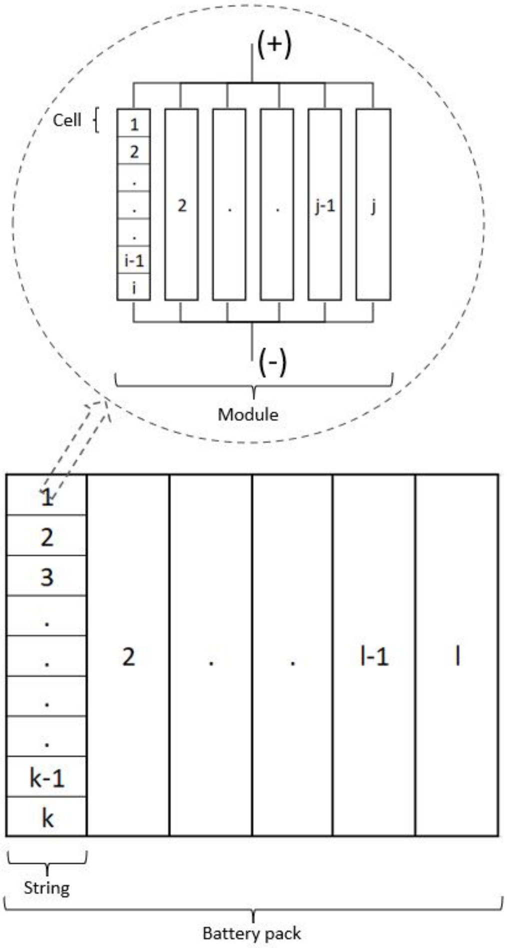


Figure 4 Schematic of a battery pack excluding the BMS system

Apart from these, an active BMS system, adequate ventilation and other fire protection is necessary as required. These measures are aimed at preventing thermal runaway and mitigating the consequences should thermal runaway occur. On the prevention side, there is the battery management system. The BMS makes sure all cells in the system are comfortably within safety and operational limit. For example, the BMS watches over the temperature of all battery cells. In case of elevated temperature, an alarm is triggered. If temperatures continue to increase more severe measures are taken. If needed the BMS mechanically disconnects power to the pack where this cell temperature is recorded.

2.2.2 M/S Aurora af Helsingborg

The M/S Aurora af Helsingborg, often referred to as M/S Aurora, is a passenger-car ferry. This ship was built in 1991-1992 in Norway and has been in operation between Helsingør, Denmark and Helsingborg, Sweden since April 1992. Some facts about the vessel are given in Table 2. In 2014, the project to add battery operation to the ship was initiated. There were two main considerations for this work, an economic aspect related to high oil prices as well as minimising the environmental impact. The project was finalised in 2018 and the ship is approved by the Swedish Transport Agency [11]. Its sister vessel is the M/S Tycho Brahe [12]. That ship has the same design and function as the M/S Aurora but was approved by the Danish Maritime Authority [13].

According to the operator, full electric operation results in 97 % CO_2 reduction for the Aurora af Helsingborg and Tycho Brahe. This potentially reduces total emissions from their fleet, consisting of 5 ships, by 65 %. So far, since the ships were electrified, the total CO_2 reduction is 38 000 tonnes. Operation in full electric mode also eliminates the production of NO_x, SO_x and particulate matter. From a working environment point and travel comfort perspective, battery operation was also positive as there was less noise and vibration on-board.

Table 2 Overview of the M/S Aurora af Helsingborg

Length over all	111.2 m	 M/S Aurora af Helsingborg
Width	28 m	
Average speed	~15 km/h	
Passengers	1200	
Vehicles	240	
Gross tonnage	10 918 tonnes	
Generators	4 independent, ~2.5 kW each	
Battery energy	4 160 kWh	

The battery energy storage systems (BESS) are located on top of the vessel. The battery system is distributed over four shipping containers (32 foot), see Figure 5. This adds a about 285 metric tonnes, including all steel reinforcements from deck 4 to deck 7 as well as all additional equipment. The battery modules themselves weigh about 57.6 metric tonnes. There were also significant weight savings however as less liquid fuel needed to be stored on the ship. In the end, the change in weight due to the new BESS was insignificant.

Each trip takes about 20 min, where about 5.5 min and 9 min is typically spent in port in Helsingør, Denmark and Helsingborg, Sweden, respectively. The slightly longer docking time in Sweden is to accommodate for loading of food and drinks. A single trip consumes about 1 135 kWh, meaning that about 3 single trips can be performed without having to charge. When operating in hybrid mode, the ships use about 250 L of diesel. It may be charged on either shore. This process was automated by using charging robots. The laser-controlled robot arms automatically connect the ship to the charging infrastructure, in about 45 s once the car ramp goes down. The battery pack is then charged by 833 kWh from the shore in the first five minutes. Nine minutes after charging start, about 1500 kWh has been supplied to the batteries. The ship can also operate in hybrid mode and charge about 976 kWh in 30 minutes, but this is not normal procedure.

Figure 5 The BESS are located on top of the vessel, inside 32-foot shipping containers.

The modules used in the BESS, see Figure 6, have about 6.5 kWh of energy at about 100 V DC. There are 160 of these modules inside each container, with each rack having 8 modules that are connected in series to reach 800 V. Within each module, there are two types of NMC pouch cells. Specifically, 40 and 63 so-called “high power” and “ultra-high energy” cells, respectively. Their effective SOC range is between 39 % – 66 % to keep the lifetime length of the batteries high.

The containers themselves are air ventilated while the batteries are water cooled. There is one 78 kW chiller on each side of the vessel. When the batteries are charged or discharged, they generate heat and heat up the water that flows through them. This heat is recovered by a heat recovery system. The water used is de-ionised to mitigate the risk of a potential leakage causing damage. If there is leakage, detected by monitoring the pressure in the cooling system, the batteries are disconnected.

The water-cooling system not only functions to optimise the conditions for the battery cell, but it is also a method to reduce thermal runaway and thermal propagation risks. Each cell is part of a protective assembly. This consist of the NMC pouch cell, compression foam, a thermal barrier and finally cooling plates (water flows through to cool). This can lower the risk for thermal runaway, as cooling slows down self-heating chain reactions. According to the manufacturer, the design can prevent thermal runaway from occurring. In addition, the BMS can disable a string of cells if needed based on the recorded cell voltages and temperatures.

1 3.737 20.6	2 3.737 20.5	3 3.737 20.5	4 3.737 20.4	5 3.737 20.5	6 3.737 20.4
7 3.737 20.5	8 3.737 20.5	9 3.737 20.4	10 3.737 20.4	11 3.737 20.6	12 3.737 20.5
13 3.737 20.4	14 3.737 20.4	15 3.737 20.4	16 3.737 20.5	17 3.737 20.4	18 3.737 20.4
19 3.737 20.4	20 3.737 20.4	21 3.737 20.4	22 3.737 20.5	23 3.737 20.4	24 3.737 20.7

Figure 6 left) Overview of some modules in the container, note that each rack consists of 8 modules connected in series vertically; right) Battery cell temperatures and voltages.

Should thermal runaway occur, the heat produced is thus managed by the cooling system. Flammable gases released by the cell are still released however and they can potentially ignite. In this battery system, the goal is to prevent these gases from igniting by enclosing the cell and active gas extraction. The gas is ventilated from a pressure relief valve in the module so that it flows through an integrated duct in the rack to a location outside the ship. If needed, ventilation to the container can be shut-off by an emergency stop.

Each container has an aerosol system to deal with electrical fires, for example in cables. The system may be released manually or automatically at 300 °C. There are also drenchers located outside the containers to prevent an external fire from increasing the temperature inside the container. As a last resort, if the total loss of a container cannot be prevented, there is a fire hose connection to sprinklers inside the container. This allows the complete container to be filled with water from the sea if needed. This option is only possible after the emergency stop button is pressed, some of these are shown in Figure 7. Several emergency stops are considered to for example disconnect a container or rack (with 8 modules). There are also detection systems located inside the battery containers. In case of gas leaking inside the container, for example flammable gas from the batteries, there is a flammable gas detector. Furthermore, in case the fans to the gas extraction systems fail, an alarm will sound.

Figure 7 Sprinkler inside the battery container (left); emergency stop on a battery rack (middle); emergency stop outside battery container (right).

2.2.3 M/S Elvy

The M/S Elvy, seen in Table 3, is a ferry that operates in Gothenburg, Sweden to transport people across the Göta älv [14] from the south shore at Stenpiren to the north shore at Lindholmen and back. It is in operation about 13 hours each day and shares the route with its sister vessels Älveli and Älvfrida. The route is about 1 100 m long. Elvy became operational in 2019 and was the first hybrid ferry operated by the public transport operator Västtrafik.

Table 3 Overview of the M/S Elvy

<table>
<tr><td>Length over all</td><td>33 m</td><td rowspan="8">
M/S Elvy [15]</td></tr>
<tr><td>Width</td><td>8.5 m</td></tr>
<tr><td>Average speed</td><td>~15 km/h</td></tr>
<tr><td>Passengers</td><td>300</td></tr>
<tr><td>Vehicles</td><td>80 bicycles</td></tr>
<tr><td>Gross tonnage</td><td>306 tonnes</td></tr>
<tr><td>Generators</td><td>1 total, 257 kW</td></tr>
<tr><td>Battery energy</td><td>1 008 kWh</td></tr>
</table>

Elvy is 33 m long and 8.5 m wide. She can accommodate 300 passengers and 80 bicycles. The battery capacity is about 1 000 kWh, which is assumed to allow for fully electric operation about 4-6 hours each day, depending on weather conditions. The batteries are charged overnight when its docked. Its generators also charge, in intervals, to provide some charge if needed. They automatically start should a battery group be discharged to about 20 % SOC. In emergencies, the batteries may be discharged beyond 20 % SOC so that the ship may safely return to port.

By hybridising the ship, emissions were cut by one third. The fuel consumption was also reduced, 45 % compared to its sisters' vessels, to an average consumption of about 110 kW. Each crossing requires roughly 20 kWh. An additional benefit of choosing hybridisation over going fully electric, is that there are redundant power sources that can step in if needed. In Elvy's case, there are three such systems located in different watertight compartments. That is the diesel generator, battery pack 1, and battery pack 2, located in the engine room, aft propulsion room and fore propulsion room, respectively. Should there be a failure in one of the systems, then the vessel can still be controlled and safely brought to shore.

Each of the battery packs on the Elvy has 48 battery modules of 10.5 kWh. One of these packs is shown in Figure 8. Each battery pack consists of four strings, where 12 modules are connected. These modules have a voltage of 52 V and a capacity of 200 Ah, while weighing 81 kg. There is a BMS for each string, as well as for each module. Inside each module, there are 14 pouch cells.

Figure 8 One of Elvy's battery packs (left); BMS, referred to as Battery control unit here, for one of the strings (right)

The modules are equipped with a burst disc in the rear. Should there be a thermal runaway event, this disc will be released from the battery. Hot gasses are then automatically released into the ducting of the exhaust system connected to the battery pack. Neighbouring modules in the rack are thermally isolated from each other to lower the risk for thermal propagation.

In case of a fire or thermal runaway, there is an emergency stop for the battery space. This can disconnect the batteries from the main switch board or converter should the power cables short circuit in some way. Inside the battery room there are fire detectors, sprinklers, and an aerosol system, see Figure 9. The aerosol nozzle is in the middle of the walkway that separates the two battery racks. On the opposite ends of the racks there are sprinkler nozzles. Finally, there are several fire detectors located throughout the battery room.

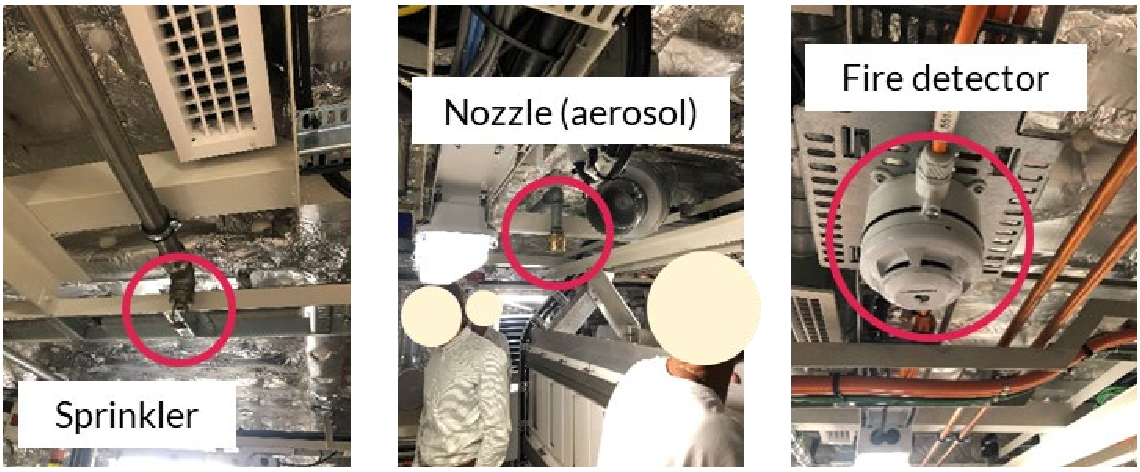


Figure 9 Safety systems located inside the battery room.

2.2.4 M/S Stena Jutlandica

The M/S Stena Jutlandica, see Table 4, is a 182 m combined passenger and freight ferry with capacity for 1 500 passengers and 550 cars. It currently sails between Frederikshavn, Denmark and Gothenburg, Sweden. The ship was retrofitted with a BESS as part of an environmental and energy efficiency improvement program. The primary purpose of the battery generator is to supply electrical power to the bow thrusters, two of the larger electrical consumers on the ship, reducing the usage of the existing diesel generators. The batteries are also used for load management throughout the crossings. In addition, the system may also be used to prevent total blackouts, this could sustain the vessel for about 30 minutes [16].

Table 4 Overview of the M/S Stena Jutlandica

Length over all	182 m	 The M/S Stena Jutlandica [17]
Width	28.4 m	
Speed	39.8 km/h	
Passengers	1 500	
Vehicles	550	
Gross tonnage	29 691 tonnes	
Generators	4 independent, ~6 500 kW each	
Battery energy	1 000 kWh	

The battery system on the Jutlandica consists of two arrays of batteries, which are located inside a shipping container on the vessel's stern shown in Figure 10. For safety reasons the container is erected above deck and separated from other objects on board. This allows the crew to isolate the battery system in case of thermal runaway and reduces the risk for exposure to flammable and toxic gases. As an additional safety measure, the external walls are insulated and the arrays within the container are separated by an internal wall.

Figure 10 The BESS is located near the vessel's stern (Image: Stena Line)

Each array can store 500 kWh of electrical energy and consist of 6 battery packs each that are connected in parallel, delivering a maximum voltage of 750 VDC. Each battery pack comprises of 15 series-connected rack mounted battery modules. Operations of each battery pack are supervised and controlled through communication with each battery module.

As usual, there are safety systems accompanying the BESS. Some safety measures prevent damage to the battery and mitigation of thermal runaway events. Damage prevention is mostly controlled by the battery management system (BMS), located in each battery module, and the accompanying electrical fuses and sensing units. In case of abnormal conditions in the battery system, a fault or warning signal is released. These are sent to the ships alarm, control, and monitoring system so that appropriate actions can be taken. In addition, the fire alarm system associated with the battery system is integrated in existing ship systems.

Mitigation of any thermal runaway events are to be controlled by an aerosol-based fire suppression system. If additional cooling is needed, fire monitors located on the weather deck of the vessel may be employed.

The container is surrounded by A60 rated boundaries internally and externally to reduce the likelihood of heat sources radiating to the battery room. Temperatures of the batteries are managed by circulating air through the cells. There is also an internal ventilation system that extracts any flammable gases that may be released during thermal runaway. These gases are vented to a designated area that is well separated from ventilation intake and electrical equipment.

2.2.5 M/S Tellus

M/S Tellus is a hybrid diesel-electric ferry that operates between Uddevalla and Lysekil in Sweden. An overview of the electric energy capacity of the ship is given in Table 5. The ferry departs every 15 min, for example, it departs at 07:00 from Finnsbo, 07:15 from Skår, 07:30 from Finnsbo then 07:45 from Skår etc. It takes about 9-10 min to cross, meaning that the ferry is stands still/docked for 5-6 min in each harbour.

A single trip consumes about 85 kWh when the ferry operates in fully electric mode. As there is no charging infrastructure yet on land however, the ferry only operates in hybrid mode. In hybrid mode the diesel generator produces 400 kW, the remaining power comes from the batteries. Once the ship reaches its stop, the diesel generator is kept active to support loading/unloading activities (ca. 125 kW) as well as charging the batteries (400 kW – 125 kW = 275 kW).

Table 5 Overview of the M/S Tellus

<table>
<tr><td>Length over all</td><td>99.7 m</td><td rowspan="7">
The M/S Tellus looks like the M/S Neptunus shown here [18]</td></tr>
<tr><td>Width</td><td>18.2 m</td></tr>
<tr><td>Speed</td><td>~20 km/h</td></tr>
<tr><td>Passengers</td><td>297</td></tr>
<tr><td>Vehicles</td><td>80</td></tr>
<tr><td>Generators</td><td>4 independent, ~460 kW each</td></tr>
<tr><td>Battery energy</td><td>949 kWh</td></tr>
</table>

Tellus has a total battery energy of 949 kWh, divided over two battery compartments. One compartment. shown in Figure 11 , is in the bow and one in the stern. Each compartment consists of 6 battery packs. Within each battery pack, there are 14 battery modules and a BMS. Each battery module contains 24 Li-ion battery cells, NMC pouch cells, which are connected in a so-called 2p12s configuration (2 cells in parallel and 12 cells in series).

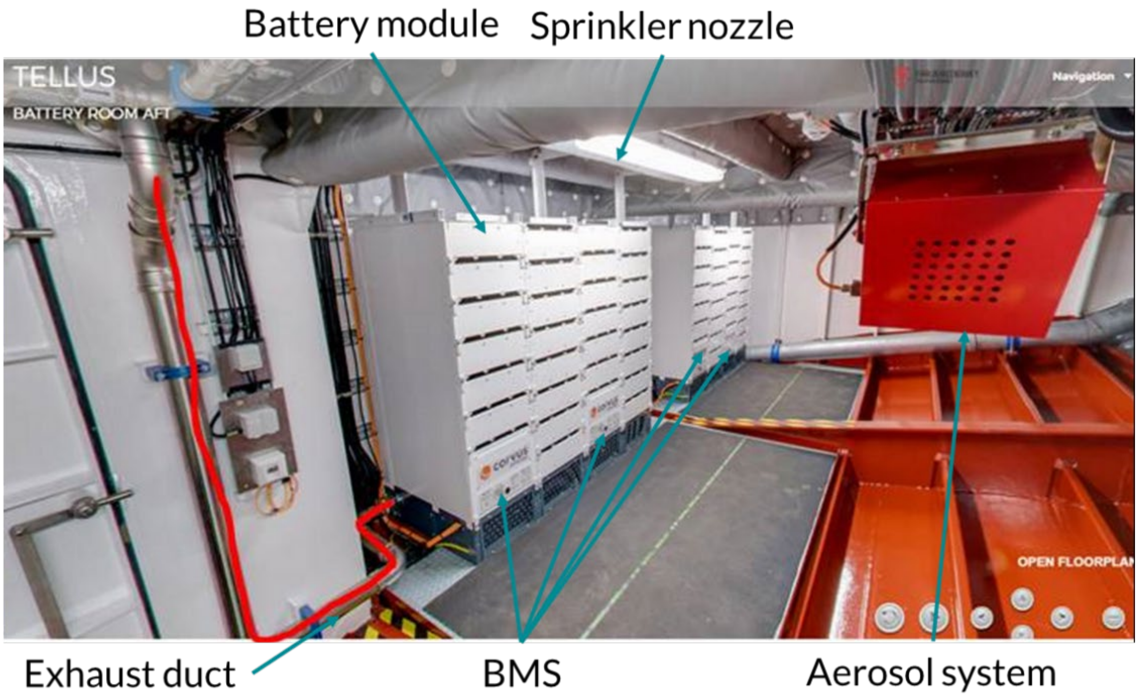


Figure 11 One of the battery rooms on-board the M/S Tellus.

Usually, the full voltage range use is restricted by manufacturers to increase lifetime and extend the performance of the battery cells. This is referred to as the effective SOC range, for these cells the range is roughly 40 to 80 % SOC.

The considered battery system includes several safety and mitigation systems on different levels, i.e. pack, module, cell. These measures are aimed at preventing thermal runaway and mitigating the consequences should thermal runaway occur. On the prevention side, there is the battery management system. The BMS makes sure all cells in the system are comfortably within safety and operational limit. For example, the BMS watches over the temperature of all battery cells. In case of elevated temperature, beyond 60 °C, an alarm is triggered. If temperatures continue to increase more severe measures are taken. At 65 °C the battery management system disconnects power to the pack where this cell temperature is recorded. A mechanical disconnect occurs at 70 °C.

The battery system is from the same manufacturer as that considered for the M/S Stena Jutlandica. If a venting or thermal runaway event would occur the battery system needs to limit the damage as much as possible. One aspect of this is to control the flow of released battery gas and particles as they may ignite and/or damage the entire system. For the battery system on Tellus there is a burst disc on each battery module. Potential emissions should thus be released there, transported to an evacuation pipe, and finally released through a chimney.

As a final safety measure, there are fire detection and suppression systems in the battery compartments. The fire suppression system on Tellus consists of a water sprinkler system (one nozzle for every two packs) and an aerosol system (3 in each battery room). The sprinkler system must be activated manually by the crew, whereas the aerosol system releases automatically once temperatures of 300 °C are recorded.

3 Regulations, rules, and guidelines for battery installations on ships

All ships are required to comply with safety regulations and standards. What regulations to apply depend on the ship type and trade area. There are three main categories of ships: ships with international certificates (hereafter called SOLAS ships), ships with national certificates and pleasure vessels. SOLAS ships consist of cargo ships above 500 gross tons and passenger ships on international voyages. Ships with national certificates can be of all sizes on national water and include also smaller vessels (< 500 gross tons) on international voyages.

3.1 International regulations

The international regulations consist of conventions, resolutions, codes, and circulars issued by the International Maritime Organization (IMO) and ratified through national regulations. In general, the conventions only contain the main requirements while technical details are found in different codes, e.g. the Fire Safety Systems code and the Fire Test Procedures code.

Regulations regarding electric installations are primarily found in the SOLAS convention. However, since the number of ships with large battery installations used for propulsion is relatively small, specific regulations or guidelines for battery storage and installations for electric propulsion have not yet been developed by IMO. The available requirements for electric installations in different parts of the regulations shall or could still be applied to battery installations.

SOLAS Chapter II-1, Part D “Electrical Installations” has the following general requirement (SOLAS II-1/40.2):

> *The Administration shall take appropriate steps to ensure uniformity in the implementation and application of the provisions of this part in respect of electrical installations. **
>
> * Refer to the recommendations published by the IEC (International Electrotechnical Commission) and publication IEC 60092 – Electrical installations in ships.

Footnotes in SOLAS are not mandatory and it is up to each national administration to decide on its application.

Furthermore, SOLAS II-1/45 “Precautions against shock, fire and other hazards of electrical origin” provides several requirements regarding normal precautions against shock, fire, and other hazards of electrical origin. There are also some paragraphs related to batteries (SOLAS II-1/45.9), e.g. 9.1:

> *“Accumulator batteries shall be suitably housed, and compartments used primarily for their accommodation shall be properly constructed and efficiently ventilated.”*

SOLAS Chapter II-2 contains the regulations about fire safety. Most of the regulations in chapter II-2 have general requirements in their purpose statements that could be applicable to battery installations without having detailed requirements, however, at present the safety of batteries is not included in international regulations but left for the classification societies to handle.

In Europe, EMSA's (European Maritime Safety Agency's) role is to offer technical expertise and operational assistance in maritime safety, security, and pollution. Typically, they conduct technical inspections (of e.g. classification societies), ensure consistent investigations of marine accidents, initiate, and fund research, and provide best practices and guidelines. When it comes to the safety of ships using battery systems, EMSA is working together with interested stakeholders on a roadmap, initially by gathering existing information and by conducting a gap analysis. Many stakeholders in Europe are interested in harmonized international regulations regarding battery safety, and the development of guidelines by EMSA will be a step in that direction.

3.2 Classification rules

All SOLAS ships are either required or could be expected to be designed, constructed, and operated according to the rules of a classification society. There are some major classification societies that dominate but there are also many smaller ones. Summaries of the rules from the larger ones are summarised here.

3.2.1 Lloyd's Register of Shipping

Lloyd's Register (LR) has, since July 2020, included requirements on lithium battery system installations in their "Rules and Regulations for the Classification of Ships" (Part 6, Chapter 2, Section 12: Batteries) [19]. Before the updated regulations, LR only required the use of a generic risk analysis procedure, with a guidance note of what to consider in the risk analysis; "Battery installations – Key hazards to consider and Lloyd's Register's approach to approval".

Part 6 Chapter 2 Section 12 states that the goal is to ensure "Safe energy and dependable supply of power to consumers" with the functional requirements that reasonably foreseeable hazards external to the battery shall be identified and managed and that reasonably foreseeable hazards internal within the battery shall be identified and managed.

Battery systems smaller than a total of 20kWh shall be housed in a gastight steel enclosure with ventilation to a safe space. For installations larger than 20kWh several subsections apply: Pt6, Ch2, 12.1-12.5 and Pt6, Ch2, 21.1 regarding testing. For systems with a nominal voltage above 1500 V DC the LR ShipRight Procedure Assessment of Risk Based Designs shall be followed.

A Failure Mode and Effect Analysis is to be carried out for systems larger than 20kWh considering reasonably foreseeable internal and external faults including e.g. fire, explosion, short circuit, venting of flammable gases, ingress of water, etc. The casing shall be equipped with a pressure relief valve or panel. In addition, a minimum list of alarms that the BMS shall give is provided.

Part 6 Chapter 2 section 12.4.7 and 12.4.8 states that suitable fixed detectors in accordance with manufacturer's recommendations and which can provide early identification of a fire or thermal runaway conditions shall be installed in the battery space. Early identification shall include high cell temperature or detection of electrolyte solvent vapours and a combination of smoke and heat detectors.

The fire detection system shall initiate an alarm to the relevant control stations and on the navigating bridge and initiate the automatic isolation of electric systems within the battery space and activate the fixed fire-fighting system. Ventilation necessary for extraction of gases, active cooling systems, and thermal/safety monitoring and alarm are to be continued prior to, during and after an overheating or fire event. Failure of the monitoring system shall be alarmed to the ship's safety system and result in the battery system automatically reverting to a defined safe state.

For the fire-fighting systems paragraph 12.4.9 says that "An appropriate water-based fixed fire-fighting system in accordance with SOLAS II-2, Part C, Regulation 10 – Firefighting 10.4.1.1.3 and the manufacturer's recommendation is to be provided for the lithium battery space. The fixed fire-fighting system is to be suitable for heat removal, boundary cooling and/or extinguishing for the duration that the heat and/or gas release are present. Fixed fire-fighting systems using a medium other than water which provide equivalent heat removal, boundary cooling and/or extinguishing for the duration that the heat and/or gas release is present can be taken into consideration provided that appropriate fire tests have been conducted. In particular, the fire-extinguishing media are to be chosen as appropriate for the specific type and characteristics of fire foreseen."

Paragraph 12.4.10 states where the fixed fire-fighting control system shall be located and activated. In addition to the fixed fire-fighting system, the battery space is to be provided with at least two portable and suitable fire-extinguishers located outside the space at or near the entrance(s). In addition, hydrants shall be available such that at least two jets of water not emanating from the same hydrant, each from a single length of hose, can reach any part of the battery space.

The battery system shall comply with "Type Approval System Test Specification Number 5 – Type testing for lithium battery systems" published in 2019 and the battery management system shall comply with Test Specification Number 1 published in 2020.

Type Approval System Test Specification Number 5 [20] requires a thermal runaway propagation test conducted on module/system level according to IEC 62619 with the following note:

"*Note 2. The propagation test procedure is to be modified so that it is performed with the battery space and battery cells heated to the maximum operating temperature of the battery system prior to initiation of thermal runaway. The maximum operating temperature is to be defined by the battery manufacturer and not less than 45°C. If active cooling is provided for controlling a thermal runaway event and cell temperature, the maximum operating temperature is to be defined by the battery manufacturer. The module is to be monitored for 24 hours following the thermal runaway event. One of the following two test acceptance criterions is to be followed:*

Acceptance criterion for single cell thermal runaway:

No thermal runaway propagation between cells within a module. No other cells within the module or neighbouring module shall see an internal temperature greater to or equal to 90 °C. The test is to be repeated successfully in the 3 worst areas within the module. If any test is failed, the propagation test is considered unsatisfied.

Acceptance criterion for single module thermal runaway:

At least half of all the cells within the module are to have gone into thermal runaway. No thermal runaway propagation between cell modules is achieved. No neighbouring module shall see an internal temperature greater to or equal to 90 °C. The test is to be repeated successfully 3 times. If any test is failed, the propagation test is considered unsatisfied.”

Test specification number 5 requires a gas analysis to be conducted.

Type approval System test specification Number 1: “Performance and environmental Test Specification for the following Environmentally tested products used in marine applications” contains several environmental durability tests such as salt mist, vibration, humidity, dry heat, low temperature etc related to the following equipment:

- Electrical Equipment
- Control and monitoring Equipment
- Instrumentation and Internal Communication Equipment
- Programmable Electronic Systems

3.2.2 DNV

The DNV class notations regarding battery and hybrid ships are found in DNV Rules for classification, Ships, Part 6, Chapter 2 [21] and DNV GL Class programme, Type approval, Lithium batteries [22].

DNV have two additional class notations regarding batteries which are described in “Part 6 Chapter 2 Section 1 Battery Power” in their rules for classification of ships. The notations are denominated “Battery Power” (propulsion) and “Battery Safety” (over 20 kWh except Lead-acid and NiCd batteries).

The additional class notation Battery Power is mandatory for vessels where the battery power is used as propulsion power during normal operations, or when the battery is used as a redundant source of power for main and/or additional class notations. The first requirement is that when the main source of power is based on batteries only, the main source of power shall consist of at least two independent battery systems located in two separate battery spaces.

Further there are requirements for monitoring and managing of the batteries with an Energy Management System. The state of charge (SOC) and state of health (SOH) of the batteries shall also be monitored. Finally, it is required that operating instructions (including charging procedures) shall be kept on board.

The additional class notation Battery Safety is mandatory for vessels where the battery installation is used as an additional source of power and has a capacity exceeding 50 kWh. Battery installations exceeding 50 kWh with lead-acid and NiCd batteries are excluded from this notation and these installations shall instead fulfil the requirements in Part 4, Chapter 8” Electrical installations”. The Battery Safety notation includes requirements on design of ventilation, fire safety, safety philosophy, system design, testing, and operation and maintenance. The overall design principle is that any single failure in the EES system shall not render any main functions unavailable for more than the maximum restoration time.

Battery spaces shall be placed aft of the collision bulkhead and have structural integrity equivalent to the vessels structure.

The fire integrity is specified dependent on size of stored energy (above or below 100 kWh), whether it is a SOLAS or HSC code ship and number of passengers for SOLAS ships.

The battery space shall be equipped with an independent ventilation system activated upon off-gassing from the cells, the system shall be designed to manage the gases from thermal runaway propagation depending on the system is designed for no propagation between cells or no propagation between modules.

The space shall be equipped with off-gas detection and monitoring. The sensors shall be placed to provide as early detection as possible. Detection shall disconnect the ESS, fire alarm to the bridge and start the ventilation in the EES space.

Combined smoke and heat detectors shall be installed in the space. The detection system shall be certified for use in explosive atmosphere.

A fixed extinguishing system shall protect the space. This can be

- a water-based system according to IMO MSC/Circ.1165 as amended by MSC.1/Circ.1269 and MSC.1/Circ.1386 designed for fresh water for 30 min
- a gaseous agent according to FSS Code Ch.5, IMO MSC/Circ.848 as amended by IMO MSC/Circ.1267 and DNV GL Statutory Interpretations, FSS Code Ch.5 designed for flammable gases and with a second independent charge if the stored energy is above 100kWh.
- a CO_2 system as specified in FSS Code Ch.5 and DNV GL Statutory Interpretations, FSS Code Ch.5 designed for flammable gases and with a second independent charge if the stored energy is above 100kWh.

A guidance note is given that a water based extinguishing system is recommended due to its inherent heat absorbing capabilities. Fire hydrants shall not be in the battery space.

Section 4 Battery system contains requirements on design of the whole system and on testing. The design requirements include safety aspects as disconnection, pressure relief, cooling liquid, BMS, alarms etc. etc.

Tests required are according to IEC 62619. The propagation test shall be repeated 3 times and successful all times. They shall be conducted at the maximum operating temperature ± 5 °C. The tests are then followed by an observation period of 24 hours. All cells within the module must be electrically connected, except if an overcharge method is used to initiate the thermal runaway, then the overcharged cell can be electrically disconnected. The initiating cell may burn and release gas while all other cells may not. The remaining cells shall not show external signs of thermal runaway and shall still produce a measurable voltage within normal operating range.

Neighbouring cells equipped with current interrupt device (CID) may have no measurable voltage if the cells' CID is activated due to high temperature. For such cells, it is acceptable that the voltage is not measurable.

For module-to-module propagation the acceptance criteria are defined as follows. Only cells within the module where thermal runaway is initiated may burn or release gas. Cells in neighbouring modules shall show no external signs of thermal runaway and must still produce a measurable voltage within normal operating range. For systems designed for no propagation between modules it can use dummy modules. In this case the passing criteria is that temperatures shall not exceed 85°C anywhere in the neighbouring modules.

3.2.3 Bureau Veritas

Bureau Veritas (BV) includes provisions for Li-ion batteries in “Rules for the classification of Steel Ships – PART C- Machinery, Electricity, Automation and Fire Protection” July 2021 [23]. Part C, Chapter 2 Section 7 states that the additional notation BATTERY SYSTEM in part F, CH 11, sec 21 apply to Li-ion batteries above 20 kWh.

Part F, CH 11, sec 21 [24] contains requirements for ventilation in the battery space, protection against electrostatic, falling objects and water ingress. It also contains requirements on battery cooling and IP class. A risk analysis shall be conducted for Li-ion batteries. The space shall be fitted with a combined heat and smoke detection system. The space shall be considered as auxiliary machinery space category 11 if the ship carries more than 36 passengers and category 7 other machinery space on other ships with some additional requirements on integrity.

The space shall be fitted with a fixed fire extinguishing system appropriate for the battery technology. For testing it is stated that it should be according to IEC 62619, but no additional requirements are given.

Part F, CH 11, sec 21 also says that the requirements in Part F, CH 11, sec 21 are in addition to Pt C, Ch2, Sec 7 (storage batteries and chargers), Pt C, Ch 2, Sec 15 (fire safety systems) and Pt c, Ch4, Sec 12 (dangerous goods).

3.3 National regulations

Several Flag states have published regulations or guidelines regarding battery storage for electric propulsion.

3.3.1 Sweden

The Swedish Transport Agency (STA) published their guidelines for battery and hybrid electrically propelled ships in 2018: “Transportstyrelsens riktlinjer för batteri- och hybriddrivna fartyg” (TSG 2018-735). This contains a list of standards and circulars including IEC 62619. A risk analysis should be undertaken. For fire safety the ship owner is recommended to study the EMSA report on Electrical Energy Storage for ships, The DNV report [3] and DNVs and BVs Classification Rules.

3.3.2 Norway

In Norway, there are several ships with battery installations and Norway has issued a Circular about battery installations (RSV 12-2016). This is applicable for Li-ion or similar battery technologies and for all ships except non-commercial ships below 24 m in length. The circular deals primarily with tests regarding battery installations. It is also required that the installation shall be approved by a classification society.

The circular states that the company should describe their philosophy regarding design and location of battery spaces, explosion relief, as well as ventilation and fire-extinguishment based on the battery technology used. Air extracted from ventilation of battery modules and battery spaces should be carried to areas where it can do no harm and only equipment associated with the battery should be placed in the battery room.

In order to identify the damage potential of a possible thermal runaway event in a specific battery system, the circular requires that testing should be carried out on both cellular, modular and system level. The results from the tests are then used to determine the design of battery spaces with associated systems for fire extinguishment, explosion relief, ventilation, etc.

The required tests include a propagation test that evaluates the possibility for a thermal runaway to spread between modules. The requirement to pass the test is that it should not spread. A gas analysis is also required and should be performed on a cell that is heated until it vents in an inert atmosphere. Finally, an explosion analysis shall be conducted based on the gas analysis from one cell extrapolated to an entire module. If the module is designed so that no spread of thermal runaway occurs between cells, then the explosion analysis can be conducted on one cell.

For battery systems below 20 kWh, no tests are required but only a risk analysis.

The Norwegian regulations has been in place for quite some time now and some countries like Germany refers to these rules.

3.3.3 Denmark

The document MSC 97/INF.8 include the Danish Maritime Authority (DMA) guidelines on battery installations. The document states that the space shall be fitted with a suitable fixed automatic extinguishment system according to the battery manufacturers recommendation. Based on risk analysis a fire test might be conducted.

It can be noted that the two ForSea electric ferries Aurora and Tycho Brahe operating between Helsingborg-Helsingør are in much identical, where Tycho Brahe is approved by DMA and Aurora is approved by STA.

3.3.4 UK

Requirements for battery installations were published by the MCA (Maritime and Coastguard Agency, UK) in 2016: “Electrical Installations - Guidance for Safe Design, Installation and Operation of Li-ion Batteries” (MGN 550).

They state that early detection is important and that it should initiate appropriate alarms and perhaps extinguishing system. An assessment shall be conducted to identify appropriate firefighting equipment and procedures. The firefighting mediums shall be able to penetrate battery casings and the possibility of standing water is not allowed. Standards referred to include EN 62281, IEC 62619, IEC 62620, and UN 38.3

3.4 Standards

There are different standards available that deal with batteries and testing of batteries. Below is a list of the standards that are referred to in the rules and regulations presented in this report:

- IEC 60092 "Electrical installations in ships". Extensive document on more than 1200 pages on the electrical installation in general.
- IEC 60079 "Explosive atmospheres". Extensive document on more than 5300 pages. Includes requirements/information on general equipment, gas detectors, intrinsically safe equipment, a variety of different methods of equipment protection, the classification of areas, material characteristics, and some industry specific standards.
- IEC 60529 "Degrees of protection provided by enclosures (IP Code)"
- IEC 60533 "Electrical and electronic installations in ships - Electromagnetic compatibility (EMC) - Ships with a metallic hull". It assumes that the ship is constructed such that metallic hull and structure parts will significantly attenuate electromagnetic disturbance.
- IEC 62281 "Safety of primary and secondary lithium cells and batteries during transport"
- UN DOT 38.3 "Recommendations on the transport of dangerous goods, manual of tests and criteria."
- MSC.1/Circ.1212 "Guidelines on alternative design and arrangements for SOLAS Chapters II-1 and III", 20/12/2006, provides the design team with a structured approach for the development of AD&A (Alternative Design and Arrangements) studies related to construction and life-saving systems.
- MSC.1/Circ.1455" Guidelines for the approval of alternatives and equivalents as provided for in various IMO instruments", 18/07/2013.
- IEC 62619 (BS EN 62619) "Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for secondary lithium cells and batteries, for use in industrial applications", Gives advice on general safety considerations (e.g. wiring, venting, measurements, contacts, assembling/design and operating range). Includes cell and battery tests (e.g. short circuit, impact, drop, thermal, overcharge/discharge and propagation test).
- IEC 62620 (BS EN 62620) "Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for use in industrial applications", Measurements during normal use and information on marking of cells.

UN 38.3 contains requirements for batteries during transport. These requirements are on batteries that are in storage and not in use and should be considered as a minimum safety level. It is however important to note that these tests do not say anything about the safety of the battery in use.

EN/IEC 62281 concern safety during transport and includes the same tests as UN 38.3.

EN/IEC 62620 contains information on marking of cells and measuring different parameters during normal use such as rating and internal resistance

IEC 62619, which was published in 2017, is referenced for safety testing in most rules and guidelines. An international standard sets the requirements that everybody can agree on is OK and therefore many standards tend to be a bit lenient. It should also be noted that this results in many cases in rather vague standards, which is true for this standard. For example, in the thermal runaway propagation test there are no specific requirements on state-of-charge (SOC), one can choose to test either on cell level or pack level, and the general requirement is that there should be no fire. Testing should be conducted at normal ambient temperature and observation is only 1 hour. No fire and no explosion are recurring in several different standards, while heat generation and ventilation of flammable gases are allowed if they do not ignite in the test. Another potential drawback in most test standards is that abuse testing, in general, is conducted without having the battery under load.

A test standard used for energy storage systems (ESS) is UL9540A, which have a more detailed testing specification and requires both small-scale and large-scale testing. NFPA 855 “Standard for the Installation of Stationary Energy Storage Systems”, published 2020, have prescriptive requirements for common situations, e.g. small energy systems within buildings, but refer to UL9540A for situations that deviate from the standard.

Another new standard regarding safety of battery storage systems was published 2020; IEC 62933-5-2 “Electrical energy storage (EES) systems Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical based systems.” This might also be a relevant standard for ships.

4 Previous studies

Literature regarding large-scale fire testing of li-ion battery energy storage systems (Li-BESS) is scarce, whereas small-scale testing of cells is more frequent. Small-scale testing on cell level can give information about the gas characteristics, volume gas produced, effect of SOC etc. A review of recent literature regarding cell tests, the effect of chemistries, SOC and the hazardous gases formed can be found in work by Baird et al. [25]. Willstrand et al.[26] also reviewed cells, modules, packs, and vehicles.

Large-scale fire tests introduce a range of additional aspects that are hard to cover in small-scale testing. Non-linearity in test results is discovered when comparing results from cell level test with large-scale tests. This non-linearity can be ascribed to the additional effects resulting from for example packaging, enclosure, ventilation, cooling etc. [3].

For evaluation of different suppression techniques and their effect on fires in energy storage systems (ESS) installations, large-scale testing is essential. Work on large-scale fire tests including extinguishment on ESS installations have been reviewed and this includes the work by DNV [3], FM Global [27] and UL [28], an overview of these tests is given in Table 6. The performance of commercial fire suppression systems was evaluated in all studies. In the DNV study the off-gas content was analysed to evaluate the explosion risks. Additionally, various fire suppression and extinguishing media were evaluated with respect to li-ion batteries. Test were performed on Li-ion batteries of NMC and LFP type with liquid electrolyte. The FM Global study comprised of a series of small- to large-scale fire tests using LFP and NMC type batteries The aim of the study was to support sprinkler protection guidance. Finally, UL presented results of three installation level tests according to UL9540A [29], with and without active fire suppression in [28]. The type of cells in the UL report were NCA type cells. The test set-up and results from these previous studies are summarised here.

Table 6 Overview of previous tests performed

	DNV [3]	FM Global [27]	UL [28]
Cells (SOC)	NMC pouch (100%) LFP cylindrical (100%)	LFP prismatic (95%) NMC/LMO prismatic (95%)	NCA 18650 (100%)
Energy capacity per module (kWh)	1.3	LFP 5.2 NMC 7.8	3.2
Extinguishing systems	Sprinkler High pressure water mist Gaseous (Novec 1230) Direct injection in module	Sprinkler (12 mm/min)	Sprinkler (20 mm/min - 0.5 gpm/ft^2) Gaseous (Novec 1230)
Additives	FIFI4Marine CAFS		Novec 1230

4.1 Initiating thermal runaway

To study the effect of suppression techniques, the ignition method should be selected upon the criteria that it is reproducible, and that it develops a self-propagating fire.

Thermal runaway can be initiated by different means, in the report by DNV thermal runaway was initiated using resistive AC heaters in direct contact with the tested cells [3]. This meant that multiple cells were heated simultaneously. It was possible to do so in their case since they constructed the modules themselves. Commercially available battery modules would most likely need to be modified before a resistive heater can be installed.

In the report by FM Global [27], the thermal runaway was initiated using flat-bar heating elements that was mounted below the bottom module. The 900 W heaters were ramped at 5°C min^{-1} to a maximum temperature of 350 °C. The disadvantage of using heating elements to initiate thermal runaway is the risk that off-gases are not ignited. This can be circumvented by adding a pilot flame to the test setup as seen for the LFP cells in the study by FM Global.

In the report by UL [28]thermal runaway was initiated using a flexible film heater. The temperature was increased at a rate of 6 °C min^{-1} and continued until thermal runaway was observed. Thermal runaway was confirmed when the temperature increase of the cell surface exceeded 10 °C/s.

4.2 Test setup

Upon large scale testing the test parameters must be carefully chosen. The aim of the tests considered in this work, is to evaluate module to module propagation and therefore it is important to simulate a worst-case scenario with thermal runaway propagation through the cells in the initiating module.

The severity of the thermal runaway increase with increasing SOC. Additionally, a high SOC leads to higher amounts of H_2 and CO during thermal runaway, compared to discharged cells that mainly produce CO_2 [30]. For a worst-case fire scenario, the SOC should be high. According to the DNV report [3], 100 % SOC should be chosen to provide the most consistent combustion results.

The full-scale testing described in the DNV report [3], was performed in a standard 20-foot container, representing common ESS installations. The container was partitioned in the middle so that the test volume was 19.25 m^3. Tests were performed with and without ventilation, as well as with a sealed or open container. In case ventilation was considered, the number of air changes per hour was either 6 or 30 depending on the test. An open steel rack was used to mimic an operational BESS rack. The rack contained 3 × 6 modules (size 500 × 300 × 200 mm), i.e. 1 live module of about 1.3 kWh and 17 dummy modules. Testing was made using different degree of enclosure of the cell pack, i.e. IP2X and IP4X, where the latter is more enclosed, as well as tests where the lid was removed. The battery cells used were either 63 Ah NMC pouch cells or 1.5 Ah LFP cylindrical cells.

To monitor the temperature during tests, thermocouples were placed inside and on the outside of the failed module and on the closest neighbouring modules. A total of 33 thermocouples were used on nine modules and additional seven thermocouples were used to monitor the thermal gradient in the test area. They also included a smoke detector and a battery gas specific sensor in the tests.

The design and weight of the dummy modules was found to be important when evaluating the risk for module-module propagation. In case of the tests by FM Global [27], the dummy modules were found to heat up much faster than the actual modules, likely due to the higher thermal mass of the live modules. DNV mentions that the dummy modules should be fit with enough thermal mass to represent missing battery cells.

The full-scale testing presented in the FM Global report consisted of a full ESS racks [27]. The tests were performed as free burn fire test (indoors, laboratory). The rack used was of open front type and contained 2 × 8 modules, the SOC of each module was at least 95%. On each side of the rack, a mock rack was installed. The mock racks were used to assess the thermal exposure to equipment adjacent to the fire. 38 thermocouples were used, they were distributed on top of the module as well as on the rack. Heath flux gauges were used to assess the thermal exposure to objects adjacent to the fire.

The choice of cell type may also dictate the fire scenario. As seen for all tests in the investigated reports, NMC type cells show a more aggressive temperature profile, have higher maximum temperatures and are easier to ignite. External combustion (visible flames) produces less gas but more heat, which also needs to be considered upon the design of test set-up. However, even when the same cells were considered there was variation in whether the gas was ignited and when it was ignited. It is mentioned by FM Global that ensuring that the gases are ignited may increase the repeatability of the tests [27].

The tests by UL were performed inside a standard 20-ft container [28], like DNV-GL. Deflagration vents and pressure relief vents were used. They also considered different types of wall constructions within the container, which reflect the interior finish configurations observed in other ESS that were tested in the past. Two racks were located across from each other at about a 35” (0.9 m) distance. One of the racks housed the initiating unit having 28.9 kWh. This unit comprised of live battery modules that were built using many 18650 cells. Target units housed 1/3rd of the cells as the initiating unit and were positioned adjacent to the side and front of the initiating unit. Finally, dummy units were included adjacent to the target units to create realistic obstructions in the ESS installation.

The design of racks and especially the distance between modules was considered a key aspect to hinder thermal runaway propagation between units [3, 27, 28]. In the UL study a distance of 35 inch (88.9 cm) was found to hinder propagation between two adjacent modules [28]. For a worst-case scenario, it can be argued that the racks should be as open as possible as this will allow flames and heat to spread more easily to nearby racks and modules. This configuration can be obtained using a shared cabinet system, where modules are placed next to each other without solid barriers, so-called open rack.

The degree of ingress protection, IP class, also plays a role in the burning behaviour of modules. Open modules have a higher prevalence of combustion as shown in the work by DNV [3]. In this case, IP4X resulted in no external combustion whilst an open lid resulted in 80% of external combustion (open flames and combustion of battery gas).

Limiting the oxygen in the test area will reduce heat and combustion/thermal runaway will be slower (no visible flames). However, limiting the oxygen will increase the off-gassing and therefore also increase the risk of gas explosion. For BESS a lowering of the oxygen content can be achieved by different means e.g., using fire suppression techniques based on gas, enclosure of modules and by the design of racks.

In several of the tests performed the temperature reached above 170°C before the gas was detected by the sensors [3]. Placement of gas sensors should preferable be placed inside the module to enable fast detection. Additionally, the gases formed during the start of a thermal runaway event will be colder than off-gas released at later stages. Cooler gas become heavier than air and might collect at lower levels. Therefore, sensors should potentially be placed closer to the floor to detect off-gas earlier than ceiling sensors [3].

4.3 Suppression systems and cells used

In the work by DNV [3], worst-case fire scenarios were considered for evaluating fire suppression systems. NMC pouch cells and cylindrical LFP cells with a SOC of 100% were used as they are both common in BESS installations. Five suppression techniques were evaluated: water sprinklers, Hi-Fog (water mist system), Novec (gas-based suppression), FIFI4Marine Compressed air foam system (CAFS, foam) and direct water injection. Fire suppression was activated with a 30 s delay after ignition (visible flames), except for FIFI4Marine CAFS and water injection where the system allowed to burn for one min before the suppression was started.

In the FM Global report, [27] a commercial sprinkler system was evaluated. Specifically, a system with a discharge density of 12 mm min^{-1}, 3 × 3 m spacing with the sprinkler link, and located 0.3 m below ceiling hight. For the LFP module tests the sprinkler was activated ~ 3600 seconds after test start. For the NMC modules the first sprinkler was activated at ~ 5700 seconds. The results from the sprinkler test for the LFP racks showed that the overall fire intensity decreased, the sprinkler system could cool the modules within the rack and hindered fire spread to an adjacent rack. For the NMC tests, the cooling may have resulted in a prolonged fire scenario but did not prevent the fire to spread. Due to the tight spacing of the modules the water was not able to penetrate the racks, which reduced cooling efficiency.

UL considered sprinklers and a clean agent system [28]. The latter used Novec 1230 and resulted in a delivered concentration of 8.3 % in 7.5 s. A single discharge nozzle was installed in the centre of the container. It was found that the total flooding system approach considered did not sufficiently cool to prevent propagation of thermal runaway or to prevent thermal exposure to combustible construction materials. The water suppression system considered four nozzles located directly above the ESS enclosures. This system was able to prevent unit-unit propagation and managed to cool the combustible construction materials in the container. However, the effect it had on preventing module-module propagation was limited.

5 Experimental set-up

The experimental setup and procedure for this tests series is based on inspiration from installations on real ships and tests series conducted by others. Available installations show typical form factors of the installation, how modules should be arranged, and the overall dimension to be considered. Review of previous large-scale fire tests gave information on the parameters that needed to be controlled to limit the variations among the tests. This was used to finally arrive at the experimental set-up and procedure used in the test series.

Two test series were conducted. The first series was conducted indoors and was performed to develop the experimental setup and placement of sensors to be used in the second series of test. In the second series of tests which was performed outdoors, fire suppression systems were evaluated.

5.1 Standard battery rack

The goal of the tests is to contribute to the development of a test method for evaluating fire suppression systems for battery installations at sea. However, the installations at sea are not that different from land-based BESS. The batteries are placed inside some type of structure, often a shipping container. The battery cells are arranged in series or parallel to form modules and these modules are placed in vertical racks. In Europe, the standard rack size is 19”. Different types of racks exist for BESS installations. As shown in Figure 12, they may be completely closed, partially open, or completely open. The level of openness refers to how exposed the contents of the rack are, i.e. sides or doors are missing. An open rack only consists of a frame. An open frame was selected for these tests as it would not restrict where flames could impinge, and thus have a minimal effect on heat transfer between modules and racks, also an open rack allows the extinguishing media to reach the modules. The back of the frame was closed with either a 10 mm non-combustible board (indoor tests) or a 3 mm steel plate (outdoor tests), to simulate that the rack was standing against a wall. The openness of the rack may be a variable to consider in a future test method as it dictates how well the suppression medium infiltrates/penetrates the modules and reaches the fire.

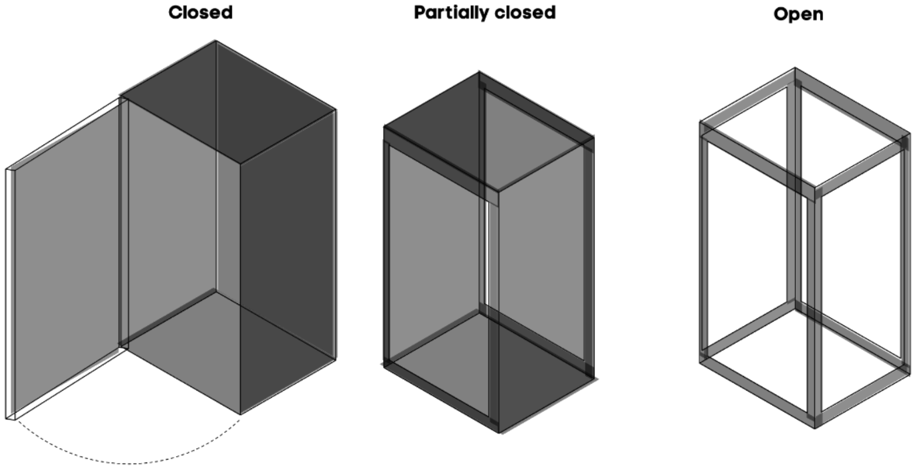


Figure 12 Rack configurations

Next the vertical distance between the modules in the rack had to be chosen. The distance between modules is another important parameter as it will affect heat transfer between modules and affect the access of the fire suppression medium. No or a very small vertical distance would make it difficult for any fire suppression agent to penetrate between modules. As the interest was to also evaluate and compare the effectiveness of different types of fire suppression systems, it was decided to choose a relatively large distance of 2U[2] (88.9 mm). This would make it easier to evaluate the effect that a fire suppression system may have since it increases the chances of the agent reaching external surfaces of the modules.

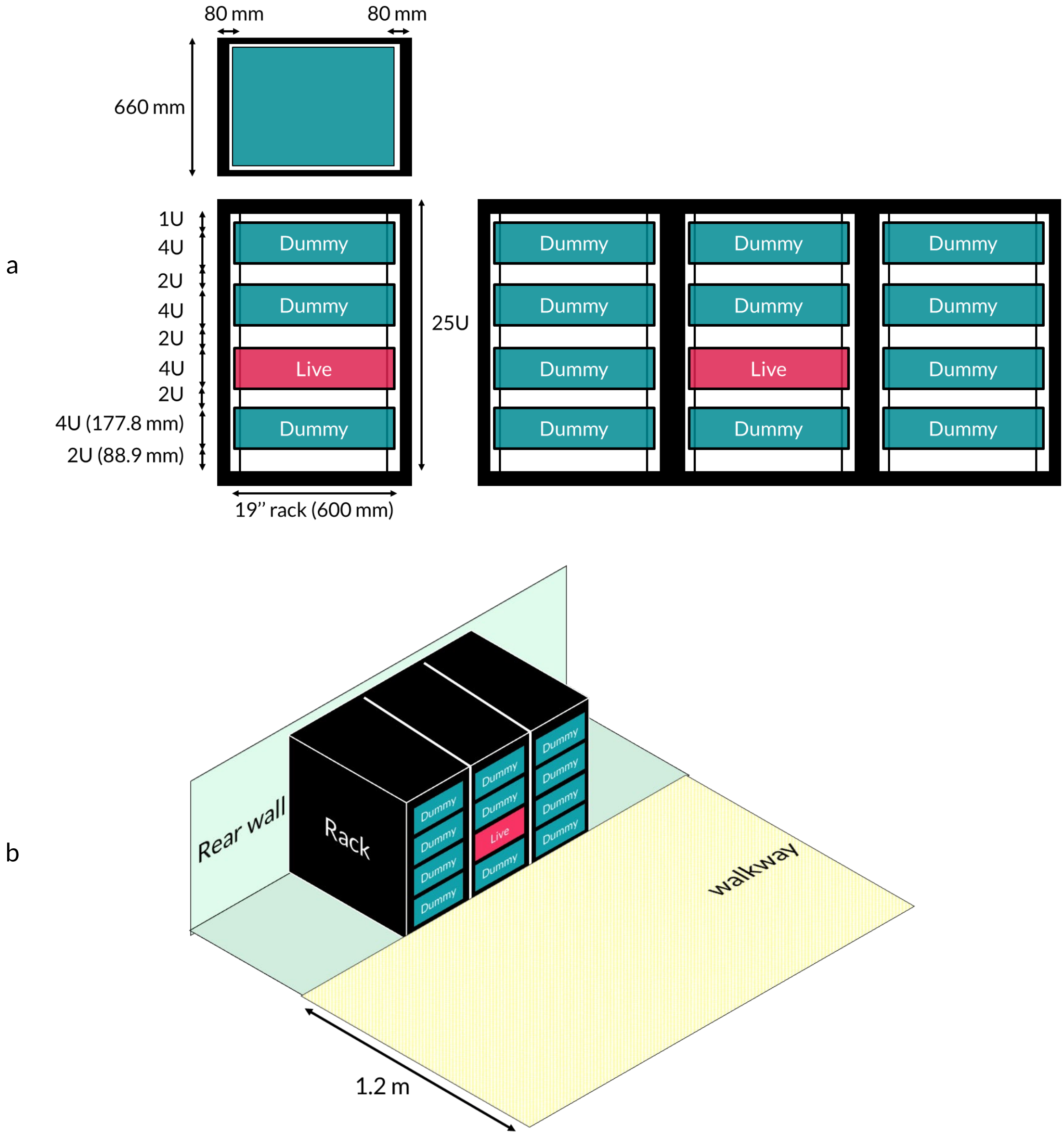


Figure 13 a) Battery rack and its dimensions as well as with racks mounted on either side; b) walkway in front

---

[2] U refers to rack units, a standardized method of tracking mountable height in a rack.

The horizontal distance was the result of the standardised sizing of the 19” rack. This rack is 600 mm wide and accommodates modules having a width of 440 mm. This means that there is 80 mm of free space on either side of each module, and thus the distance between each module being 160 mm.

The number of live battery modules available was limited. Hence, dummy modules were incorporated in the rack in addition to one live module. This would allow the risk for module-to-module propagation to be evaluated based on the temperatures recorded on dummy modules. The use of dummy modules is allowed according to e.g. the DNV classification rules. The live battery module was used to represent the heat source of a real battery fire. The burning behaviour of a battery module is unique and difficult to model and mimic due to its cascading nature, where burst of gas and flames are ejected at intervals.

The rack setup chosen consisted of four battery modules (1 live and 3 dummy) in an open rack as shown in Figure 13. The distance between each module was 2U (88.9 mm). Usually, racks are mounted next to each other in ESS and ships, hence one additional rack with 4 dummy battery modules was placed on either side. To make it possible to manoeuvre the complete setup, the racks were fixed to pallets. In addition, it is common that there is a walkway in between battery racks facing each other. This was seen in the Elvy for example. This distance was assumed to be 1.2 m.

The dummy modules comprised of so-called rack drawers, i.e. empty boxes with built-in drawers. The dimensions of the dummy modules were close to that of the live battery module, namely 440 mm x 352 mm x 173 mm and weighed 10 kg. To simulate that the drawer would be filled with battery cells as shown in Figure 14, the drawers were filled with sand (grain size 1.2 – 2 mm) to a weight of 35 kg corresponding to the weight of the NMC module.

Figure 14 Dummy modules filled with sand

5.2 Battery modules

A set of commercially available battery modules were donated to this project to be used as the live module in which thermal runaway would be initiated. The specifications for these modules are given by Table 7. The main differences between these two modules relates to the types of battery cells considered and how they are connected. Module A has around 500 cylindrical NMC cells (2.55 Ah per cell) in total to reach a nominal energy of 4 800 Wh. This is obtained with fewer cells, but with significantly higher capacity (50 Ah per cell), in Module B.

An important detail when it comes to the battery cell configuration relates to the number of cells connected in parallel. Note that this amounts to 39 cells in Battery module A and 2 cells in Battery module B. When one cell in a string of parallel connected cells has a voltage drop or fails, it can cause an external short circuit condition for the remaining cells in the array. This could accelerate the propagation of thermal runaway in a failure scenario.

The modules were fully operational, and cells connected between each other as they would be in a real application in the tests.

Table 7 Battery modules that were used in this study

Description	Battery module A	Battery module B
Type	NMC	LFP
Nominal capacity	100 Ah (2.55 per cell)	100 Ah (50 Ah per cell)
Nominal voltage	48 V	48 V
Energy	4 800 Wh	4 800 Wh
Dimensions	440 x 358 x 174 mm	440 x 420 x 173 mm
Weight	36.5 kg	45 kg
Cell format	Cylindrical, 18650	Prismatic
Cell configuration	13s39p (507 cells)/ 14s39p (546 cells) [3]	15s2p (30 cells)

5.3 Temperature measurements

Temperatures were measured at several locations to evaluate potential thermal propagation and impact from extinguishing systems. The temperatures were measured using 0.5 mm type-K thermocouples, which were welded to the external surfaces of the dummy modules as shown in Figure 15. It was not possible to weld on the external surface of the live battery module, therefore these thermocouples were taped to the surface. Thermocouples were also placed inside of the live battery module to assess cell to cell propagation ad inside the dummy module above the live module. Details concerning the placement of thermocouples is found in 6.1.3 and 6.2.2.

---

[3] For the module used in Test 10 and 14 during Test series 2.

Figure 15 Thermocouples welded to the external surface of the dummy modules

To investigate the risk for thermal propagation between two opposing battery racks, plate thermometers were used placed across the simulated walkway, at the same height as the centre of the live battery module as well as at the height of the dummy module above, shown in Figure 16. Note that both the indoor and outdoor setups are shown.

Figure 16 Location of plate-thermometers, indoors (left); outdoors – shipping container (right)

5.4 Indoor measurements

For the tests conducted indoors, the standardised rack was placed underneath an exhaust hood that collects smoke and gas emissions as shown in Figure 17. The heat release rate (HRR) can be calculated from the mass flow and concentrations of O_2 and CO_2 measured in the duct. These types of measurements are of particular interest for the assessment on how large the fire is and may be correlated to temperature recordings.

Figure 17 Standardised rack underneath the exhaust hood. The arrows indicate the movement of gas extraction

5.5 Container for outdoor tests

When tests were performed "outdoors" (2nd test series), the standardised rack was placed inside a 20 ft. shipping container as shown in Figure 18. The sides of the rack were at an equal distance from the short ends of the container. The rear of the standard rack was placed 0.6 m away from the wall, so that staff could access this part of the setup. In addition, this also resulted in the opposite container wall being about 1.2 m from the front of the setup.

One of the container doors was kept open during most of the tests. The large opening was considered to reduce the risk for a gas explosion but even more so to simulate a larger room. There was no forced ventilation in the containers.

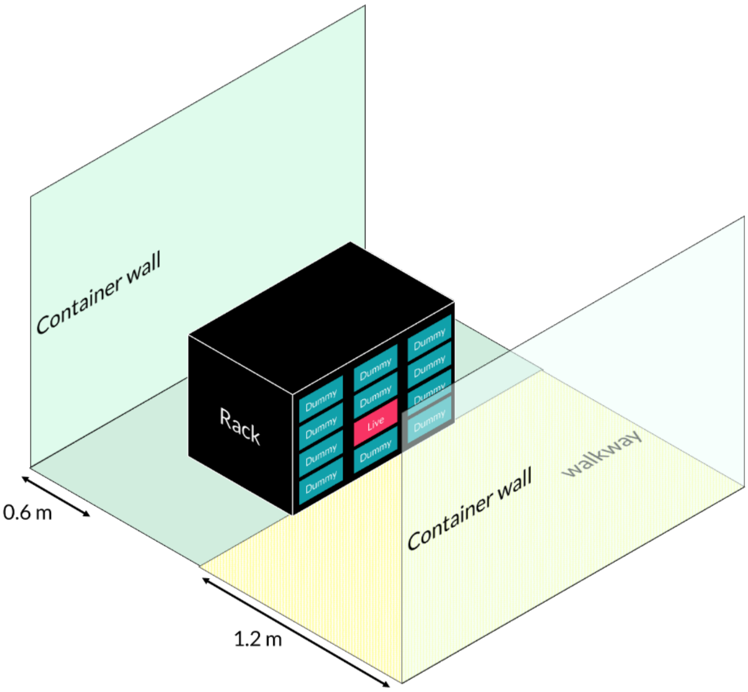


Figure 18 The standard rack setup inside a container

The container did not have an exhaust hood hence gas analysis could not be performed in the same way as for the indoor tests. Gas sensors were considered for some tests, where detected CO and combustible gas would give an audible alarm if concentrations reached certain thresholds. Details concerning the sensors are presented in Table 8.

Table 8 Gas detectors used in the second test series

Alarm	Carbon Monoxide (CO) detector, model no. E2630-CO.	Combustible gas (Methane, Butane, Propane, Acetylene, Hydrogen) detector, model no. E2630-LEL*
Alarm signal 1	25 ppm (0.0025 %)	10 % LEL**
Alarm signal 2	125 ppm (0.0125 %)	25 % LEL**

* Detector calibrated for hydrogen.
** XX % LEL refers to how near the concentration is to reach the lower explosion limit (ignitable gas mixture). For example, 25 % LEL means that the concentration of flammable gas has reached to 25 % of the limit where it can be ignited.

5.6 Repeatable thermal runaway initiation

The way a thermal runaway is initiated can have a large impact on how it develops and propagates. In these tests, the aim was not to evaluate thermal propagation within a battery module but to assess module-module and module-rack propagation and whether fire suppression systems can reduce this risk of propagation between modules. In order to evaluate the impact of a fire suppression system on module-to-module propagation, it is of importance that the cell-to-cell propagation is established in a repeatable fashion so that the start conditions are the same for all evaluated systems.

Li-ion batteries release gas when they vent or go into thermal runaway, but the gas is not always ignited upon release [3, 27]. This varies depending on the initiating method as well as the SOC and chemistry of the considered battery cell. For example, LFP battery cells often release gas clouds that do not self-ignite. However, as the purpose here is to evaluate the module-to-module propagation an external ignition source was used to ensure that any released flammable gas was ignited. As such, two spark plug igniters were placed near the live battery module for all tests performed.

Many methods exist to initiate thermal runaway, for example nail penetration, overcharging, external heating etc. Usually, these methods are considered at the battery cell level during thermal propagation tests. Here the task is often to determine if a single cell failure may propagate throughout the module or pack. There are many factors that affect thermal runaway initiation and propagation as shown in Table 9. These need to be controlled somehow if the goal is to ensure a repeatable module-module propagation and still mimic a plausible scenario.

Table 9 Factors that influence thermal runaway

Factors	Explanation
Pre-heating	Certain methods may heat up not only the battery cell but also its surroundings within and outside of the module.
Energy input	Certain methods may add energy to the battery cell and potentially enhance the severity of the thermal runaway event.
Charge level	Overcharging or over discharging will alter charge levels inside the battery module, which affects their failure behaviour.
Boundary conditions	Some methods require that modifications are made to the battery, i.e. to get access with a nail penetration rig or have space for electric heaters.
Product	Battery cells can be constructed to contain an internal short circuit device. This requires a special step in the manufacturing process.
Application	Some methods are more suited for cell level initiation than module, pack, or system level initiation.
Reliability	Some methods may work on specific battery cells or under certain circumstances but not all. Furthermore, cell-cell propagation should be guaranteed for the purpose of these tests.

The above factors were used to evaluate several initiation methods and used to decide on which one was the best option. The options were as follows 1) external burner, 2) internal heating element, 3) nail penetration and 4) overcharging. Their pros and cons are summarized in Table 10.

Table 10 Pros and cons of different thermal runaway initiation methods

Burner	Internal heating element	Nail penetration	Overcharge
• Representative of “field failures” where cells coupled in parallel discharge through a faulty cell and heat up • External - No modification of the test object needed • Internal – modification of test object needed • Controlled heating • Ensures initiation of thermal runaway and propagation as burner can remain active • High repeatability if consistent placement and aim	• Controlled heating • Well-established method that ensures thermal runaway initiation • Thermal runaway propagation not guaranteed, multiple heaters might be needed. • Modification of the test object needed to insert heating elements between cells.	• Difficult to control • Low repeatability, thermal runaway initiation not guaranteed • Thermal propagation not guaranteed from single cell failure • Modification the test object needed to have an opening for the nail	• Affects the charge level of battery cells • Modification of the test object needed, cells need to be modified as they have built-in protection and overcharging on module level not possible due to existing safety systems • Thermal propagation not guaranteed

Finally, a cause-and-effect diagram was constructed based on the methods presented, this is shown in Table 11. It was judged that an external burner would be most appropriate for these tests.

Table 11 Cause and effect diagram for thermal runaway initiation methods

Cause	Effect						
	Pre-heating	Energy input	Charge level	Boundary conditions	Product	Application	Reliability
External burner	**--**	**-**	**0**	**0**	**0**	**++**	**++**
Internal burner	0	-	0	-	-	+	++
Internal heating element	-	-	0	-	-	+	++
Nail penetration	0	0	0	-	-	-	--
Overcharge	0	--	--	0	-	+	+

To achieve consistent results from all the performed tests, the burner flame should impinge on the same location and the same nozzle should be used. As such, a construction review of the available battery modules was performed. An area where the cells were in the vicinity of the module and where there was no insulation material was identified as the most vulnerable location. The location shown in Figure 19, was considered when placing the gas burner in all the tests. The burner nozzle had a Sievert Pro 86 nozzle. This nozzle has a diameter of 22 mm and. The flame is brush shaped, see Figure 19, and has a heating effect of 3.1 kW at a working pressure of 2 bar.

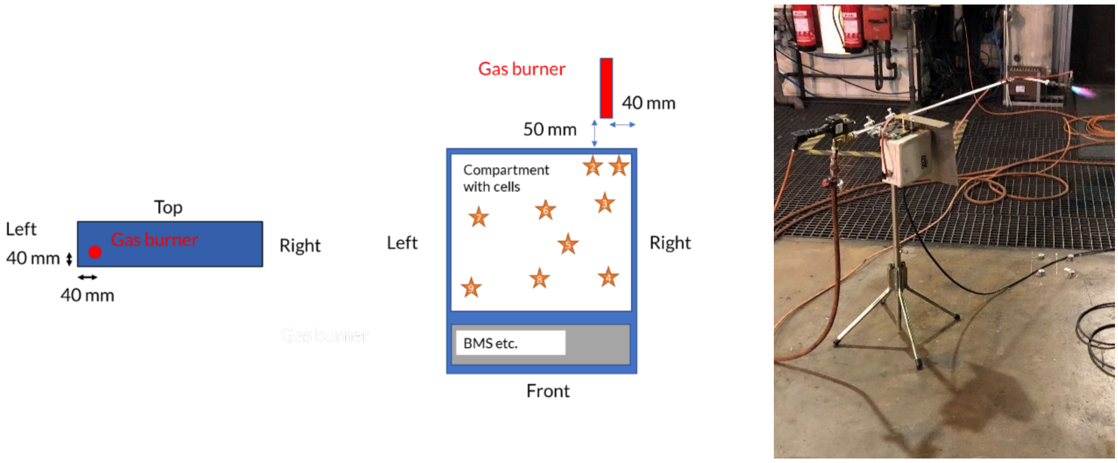


Figure 19 The placement of the gas burner was consistent in all the tests performed

5.7 Fire suppression systems

A test series was designed using different types of extinguishing systems to evaluate the test method and to give some indication of their potential to mitigate thermal propagation. The suppression systems used were:

- A conventional low-pressure water mist total flooding system
- The same water mist system with an additive in the water
- A closed head sprinkler system
- The same sprinkler system with an additive in the water
- Local application of an extinguishing media purposed for Li-ion batteries
- The local application system for the special purpose media utilising only water
- A gas phase extinguishing system

The systems used in this study was designed by the suppliers participating in the study. An overview of the different systems is given by Table 12. The systems were selected to represent systems that are already in use in maritime applications or media developed for use with Li-ion batteries. The selection was also made to complement the systems used in the DNV-GL study [3].

Table 12 Fire suppression systems

No.	Application	Nozzle type	Nr. of nozzles	Flow rate	Total amount	Agent 1	Agent 2
1	Room	Mist	1	12 L/min	120 L	Water + 3 % F500	Water
2	Room	Sprinkler	1	80 L/min	800 L	Water + 3 % F500	Water
3	Local	Mist	1	10 L/min	30 L	Water + AVD	Water
4	Total flood	Gas	2	23 000 L/min	23 000 L	INERGEN® 52 % N_2, 40 % Ar, 8 % CO_2	

The conventional sprinkler system was supplied by Johnson Controls and designed according to normal design principles resulting in a water flow of 800 l/min in a single nozzle giving a spray pattern with 1.2 m radius resulting in a water density of 175 l/min/m at floor level. The additive used was F-500 [31] which was added at a 3% concentration in the water.

The low-pressure water mist system was supplied by Johnson Controls using an AM 4 nozzle at 12 bar. The flow of water was 12 l/min. The additive used was 3% F-500.

For the local application system AVD [32] was used. This was applied using a Q-fog system [33] that is normally used for residential applications but with another nozzle.

The gaseous based system used was INERGEN® [34]. As it is well known that gaseous based agents have little effect on preventing propagation of thermal runaway this system was designed with a higher design concentration than what is normally used for conventional fires.

Some limitations concerning the design and dimension of the fire suppression systems were needed so that they could be 1) compared to one another and 2) so that they were representative of systems typically used. This meant that they were not necessarily designed for optimal performance under the tested conditions. Instead, the test method being developed here, may provide insight into what design may be needed to achieve the best results.

The fixed parameters and variables that the systems were subjected to was decided through discussion with project partners and are summarized in Table 13. This meant that the fire suppression system suppliers were free to select values listed under “variables”, but they all had to comply with the “fixed parameters”.

Table 13 Fixed parameters and variables considered for the fire suppression systems

Fixed parameters	Variables
Placement of nozzles	Flow rate
Activation time	Nozzle type
	Volume of extinguishing media
	Direction

In terms of nozzle placement, it was decided that the nozzle would be installed in the middle of the walkway as indicated in Figure 20. This is also something that was observed in the ship installations discussed in Section 2.2. A single nozzle could be placed at a height of 2.1 m from the floor. For direction it was agreed that solutions like a “back-to-back” placement of nozzles was allowed. The sprinkler and water mist suppliers chose to use nozzles directed downwards while the local application was directed towards the racks.

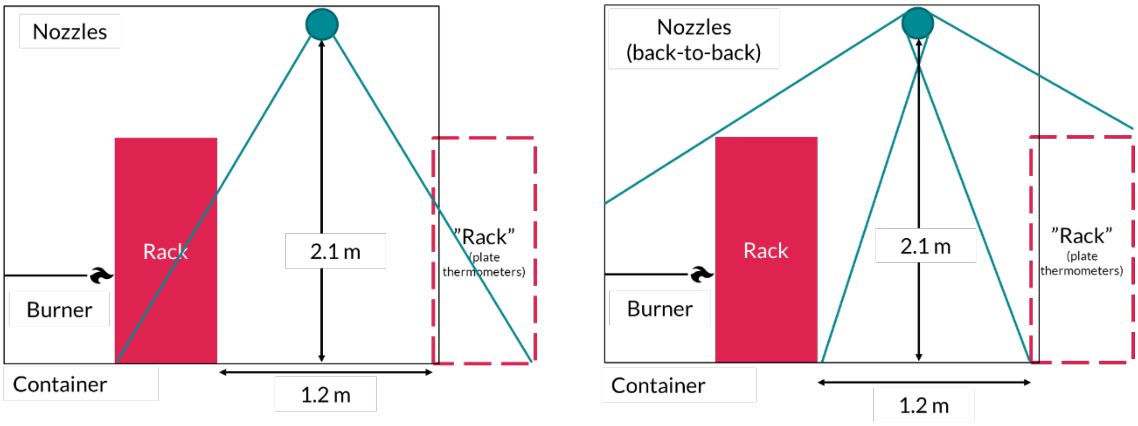


Figure 20 Nozzle placement that was allowed for the tests performed. Note that the spray angles in the sketch are just to give an indication, they are not exact.

The number of nozzles was selected by the system suppliers with the condition that it should reflect a design that one could expect for the given application. This resulted in all suppliers, except for the gas-based system, selecting one nozzle. The gas-based system employed two nozzles. For the water-based test-set-up one could argue that the nozzle placement using one nozzle would correspond to having one nozzle for each rack, however as the temperatures were evaluated also on the neighbouring racks this corresponds more to one nozzle every second rack. It is not possible to determine based on these tests whether placing the nozzle nearby the initiating module represents a worst-case scenario or a more favourable scenario. Note that “rack” in this context refers to one 19” rack housing four battery modules.

It is unreasonable to expect that any of the tested systems can extinguish the fire in the initiating module. It has namely been shown in other tests that suppressing battery fires externally is not effective in limiting thermal propagation within an enclosed battery pack [35]. Instead, the challenge for the considered systems was to keep temperatures of surrounding modules and racks low, and thus lower the risk for module-module and rack-rack propagation.

6 Test results and discussion

Two test series were performed with the setup described in Chapter 5. The first test series were conducted in calendar week 4 of 2021 at RISE, Borås and the second series was done in calendar week 32 and 33 of 2021 at an outdoor training facility operated by the rescue services in Borås.

The 1st series considered reference tests without an extinguishing system with the aim to investigate the repeatability of the fire characteristics of the test setup and to determine a suitable activation time for the second series of tests. The first test series was performed indoors, which allowed gas and HRR measurements to be made. Some modifications could be made after the initial tests and if needed, the test setup and concept could be revaluated.

The second series of tests was conducted outdoors inside shipping containers. Both reference tests (without extinguishing media) and the tests with fire suppression systems were conducted.

6.1 First test series

The first test series was performed in the large fire testing hall at RISE in Borås, Sweden. The tests were performed during calendar week 4, 2021. Results from these tests are presented in this section. Note that these are valid under the testing conditions described here.

6.1.1 Test programme

Three tests were conducted as summarized in Table 14. In all cases, no suppression system was used. The purpose of these free-burn tests was to evaluate the developed concept, the test setup and to determine a repeatable activation time for the upcoming fire suppression system tests. In addition, it provided data that could later be used to compare with tests including fire suppression systems.

Table 14 Overview of the first test series

Test	Test location	Battery	Suppression
1	Indoors	NMC	None
2	Indoors	LFP	None
3	Indoors	NMC	None

6.1.2 Test setup

The test setup that was considered is identical to that which was presented in Chapter 5. An overview of this setup is given by Figure 21. The live battery module was placed in the middle rack. Two spark igniters were placed in front of the module to ignite flammable battery gas. Across the "walkway" there were two Plate Thermometers.

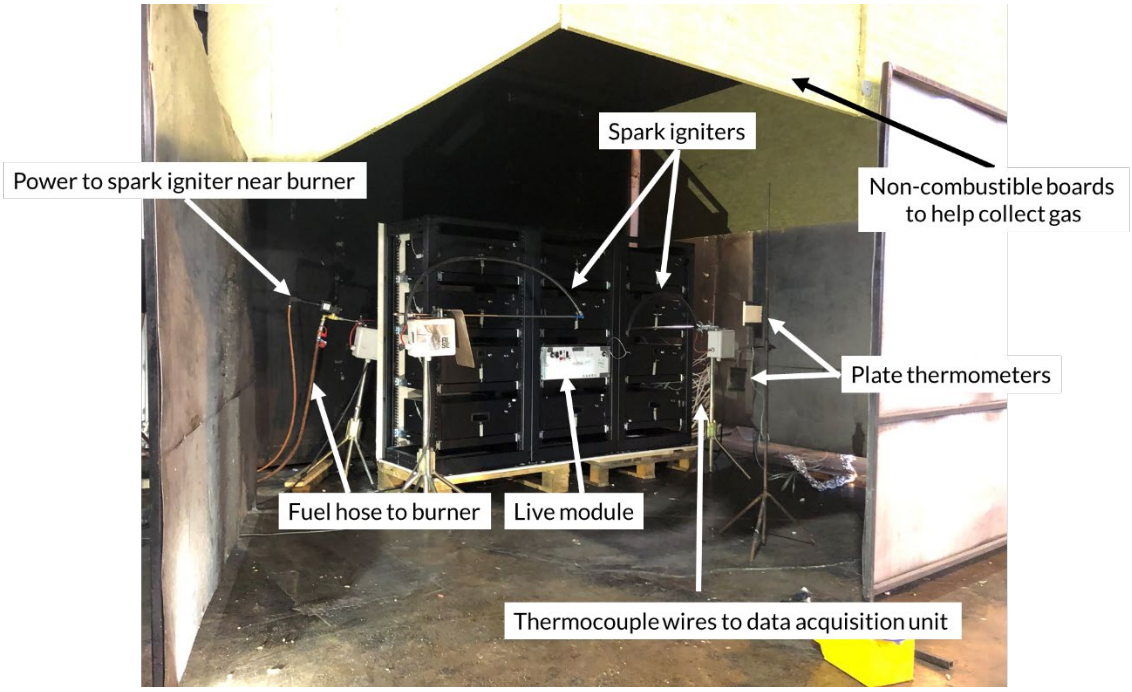


Figure 21 Overview of the test setup

The test setup was closed-off on the rear side of the rack by a 10 mm thick non-combustible board. A hole was cut in this board so that the gas burner could access the live module. The flame was aimed at the location shown in Figure 22.

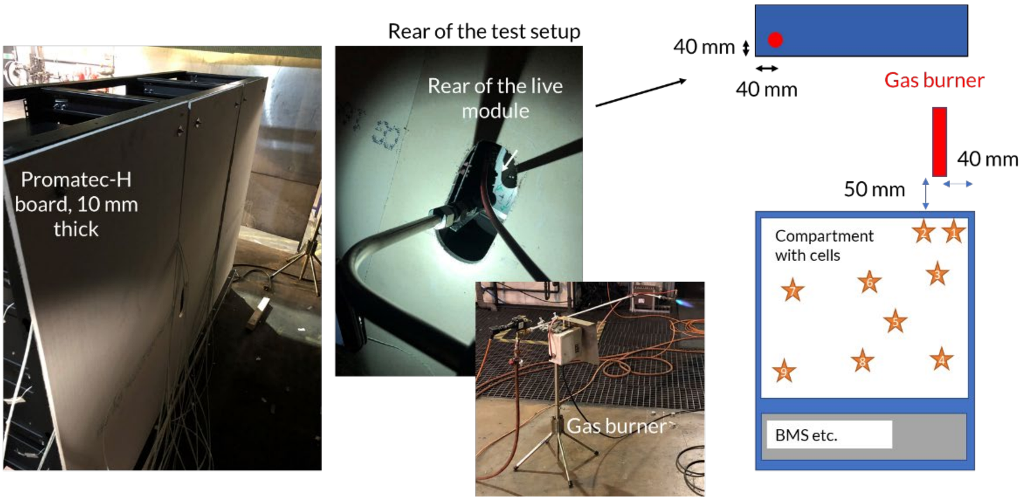


Figure 22 Burner location relative to the test setup and battery module. Note that the 10 mm board was only considered in the 1st test series.

Pressure build-up in the battery cells may cause them to rupture and eject smoke/flames horizontally. If that happens, gas and heat may end up beyond the reach of the collection hood which introduces greater uncertainties in the heat release measurements. To mitigate this risk, the collection hood was extended downwards, towards the battery rack, using non-combustible boards.

6.1.3 Measurements

An overview of the number of temperature sensors and their placement is shown in Figure 23. Dummy modules having both internal and external temperature sensors are marked in light grey. The live module is marked in red.

Figure 23 Overview of the number of thermocouples used

Each module had 6 external thermocouples. The two modules next to the live module and the one above the live module each had one internal thermocouple. The location of internal and external temperature sensors for the dummy modules are shown in Figure 24. The same logic and positions were used for the live battery module except for the temperature sensors inside the modules.

Dummy modules	
TC exterior	★
TC interior	★
Numbering	
1	Front
2	Under
3	Back
4	Left
5	Above
6	Right
7	Inside

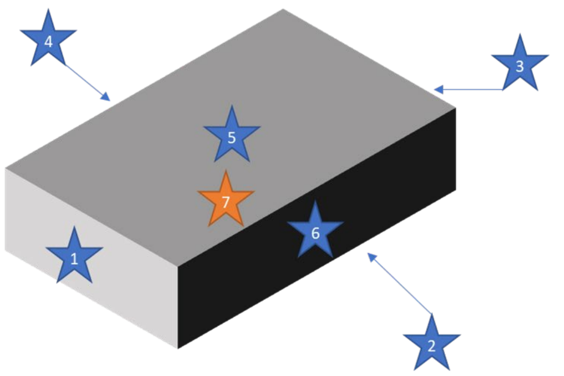


Figure 24 Placement and numbering principle for temperature sensors

Multiple temperature sensors were placed inside the live module to keep track of when thermal runaway occurred and how it spread throughout the module. The approximate position of the temperature sensors inside the module is presented in Figure 25. Where possible the thermocouple wires were attached using tape to the exterior of the cells otherwise, they were pushed in between. The junctions were placed near the pressure relief vent of the prismatic cells (in case of the LFP module). The NMC module had cylindrical cells so the junctions could be tucked into the empty space surrounding the cells. In the first test series a total of 84 temperature sensors were used and the data was sampled with 1 Hz.

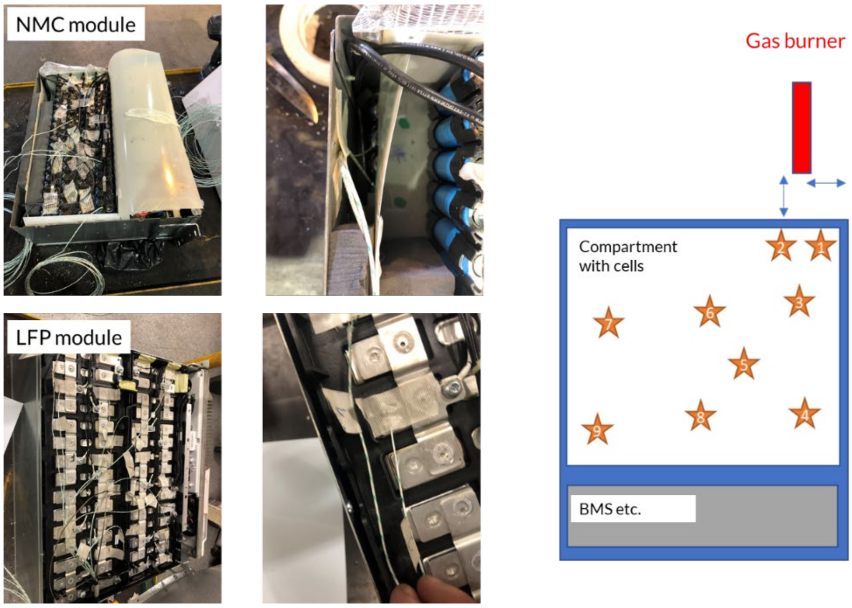


Figure 25 Instrumentation of the live battery modules from within. Note that each star indicates the approximate location of a thermocouple.

6.1.4 Method

The timing for the tests began once the measurement programme was started. Then, after 1 min the video camera's started recording. Finally, the gas burner was activated at the 5 min mark by opening the gas supply. The gas was ignited automatically by the spark plug located at the burner's nozzle. The burner was engaged until it was clear that thermal runaway was initiated and that the fire would continue to propagate to the other cells when switched off. The timing for this event was based on a judgement call of the test leader.

6.1.5 Results

The time needed to initiate thermal runaway in the live battery module varied between the three tests. For the test with NMC cells, Test 1 and Test 3, the time was approximately 14 and 9 minutes, respectively. For the LFP test, test 2, thermal runaway started at around 52 minutes. This can be seen in Figure 26 where the HRR is plotted for the three tests. The variation in time was related to the battery module as well as the burner placement. In the LFP test, it was found that the burner was not receiving enough oxygen, resulting in a weaker flame. As the LFP module was deeper, there was less of an air gap between the steel plate covering the rear of the setup and the back of the module. To solve this issue, a larger section of the rear plate was removed during the test, so more oxygen was available. When the burner was restarted, it functioned as intended.

The burning behaviour after thermal runaway was triggered was very similar for the NMC modules. As shown in Figure 26, the fire growth rate (slope of the heat release rate curve) as well as the peak heat release rate match closely. This suggests that the thermal propagation rate in the modules can be repeated. However, when it comes to the LFP module, no conclusions could be drawn about the repeatability of the test as only one test was performed. Compared to the NMC module however, it is apparent that it takes much more time before thermal runaway is initiated for the LFP module. In addition, this event propagated much slower between the LFP cells. The peak heat release rate that was eventually reached was about 50-100 kW less. The total heat release was roughly the same regardless of whether the NMC or LFP module was considered.

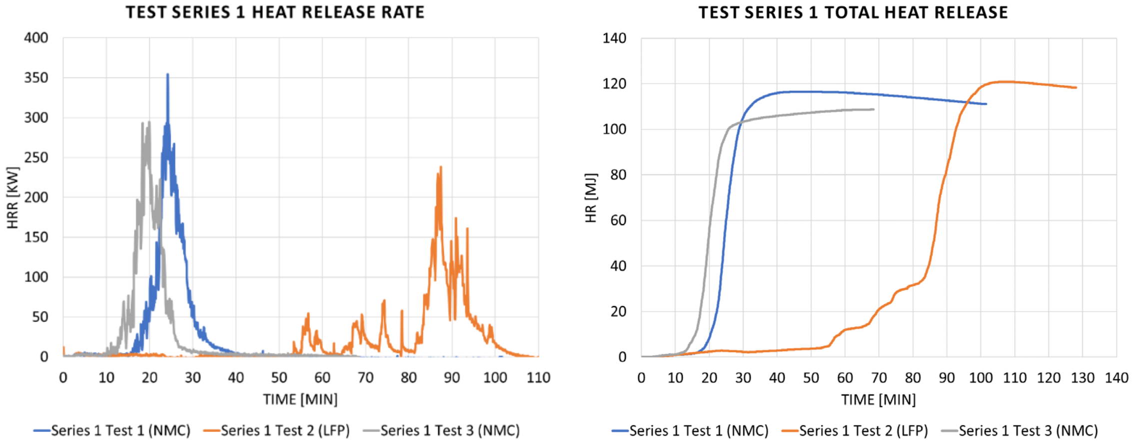
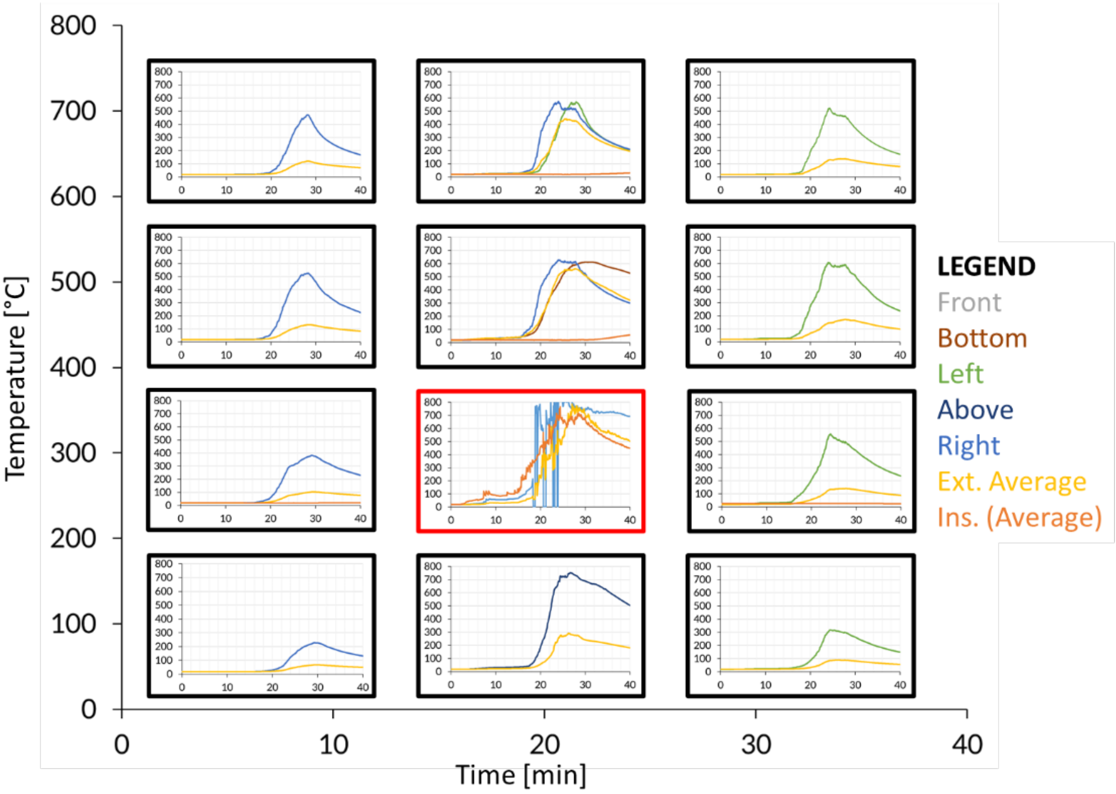


Figure 26 Heat release rate and total heat release from test series 1

The temperature distribution in Test 1 and Test 3 (NMC) is given by Figure 27. Both the average external surface temperatures and the maximum temperatures are shown as well as the average temperature inside the live module.

Test 1 NMC



Test 3 NMC

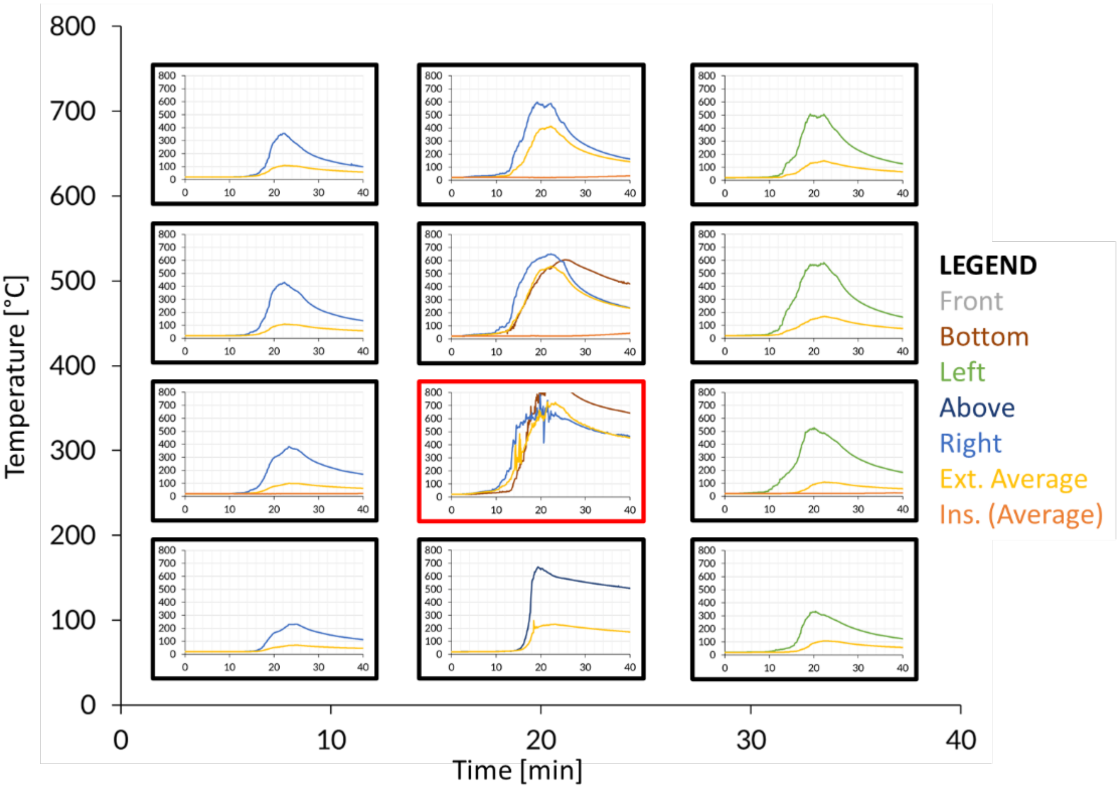


Figure 27 Temperature distribution for Test 1 and 3 (NMC). Each graph corresponds to a module in the standard rack, with the live module outlined in red.

The temperature distribution in the LFP test, Test 2, is given in Figure 28. Temperatures above the live module are comparable to what was observed for the NMC modules. This is not the case for the dummy modules on the left and right of the live module however. The temperatures are much lower there, reaching up to 300 °C as compared to 600 °C for the NMC modules. Although the overall module to module propagation risk is lower for these LFP modules, temperatures are still high enough to potentially trigger thermal runaway in the majority of the dummy modules.

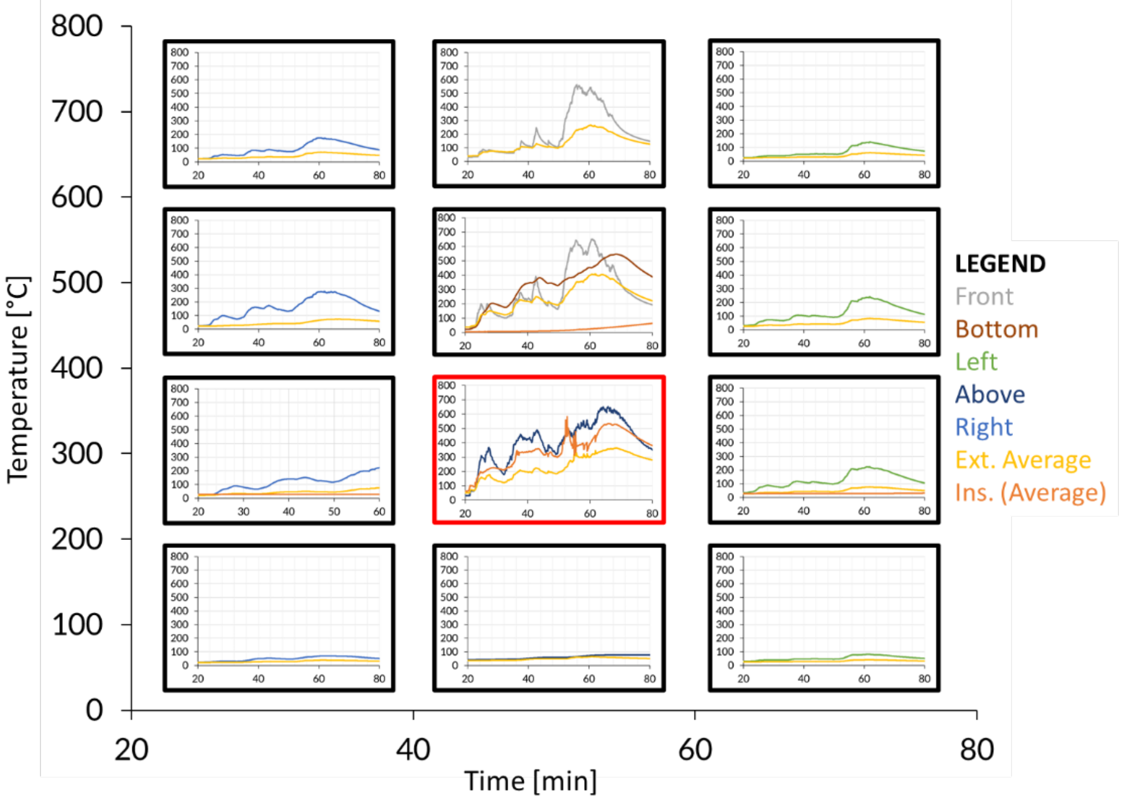


Figure 28 Temperature distribution for Test 2 (LFP). Each graph corresponds to a module in the standard rack, with the live module outlined in red.

Figure 29 shows the temperature readings from the Plate Thermometers placed opposite the live module at a distance of 1 m and 1.2 m, i.e. a distance where potentially an opposite rack would be placed. The temperatures are compared to the heat release rate from the live battery module. It is shown here that if the fire inside the reference module can develop freely, there is a significant risk for propagation to the opposite row of racks. Even more so if module-to-module propagation occurs.

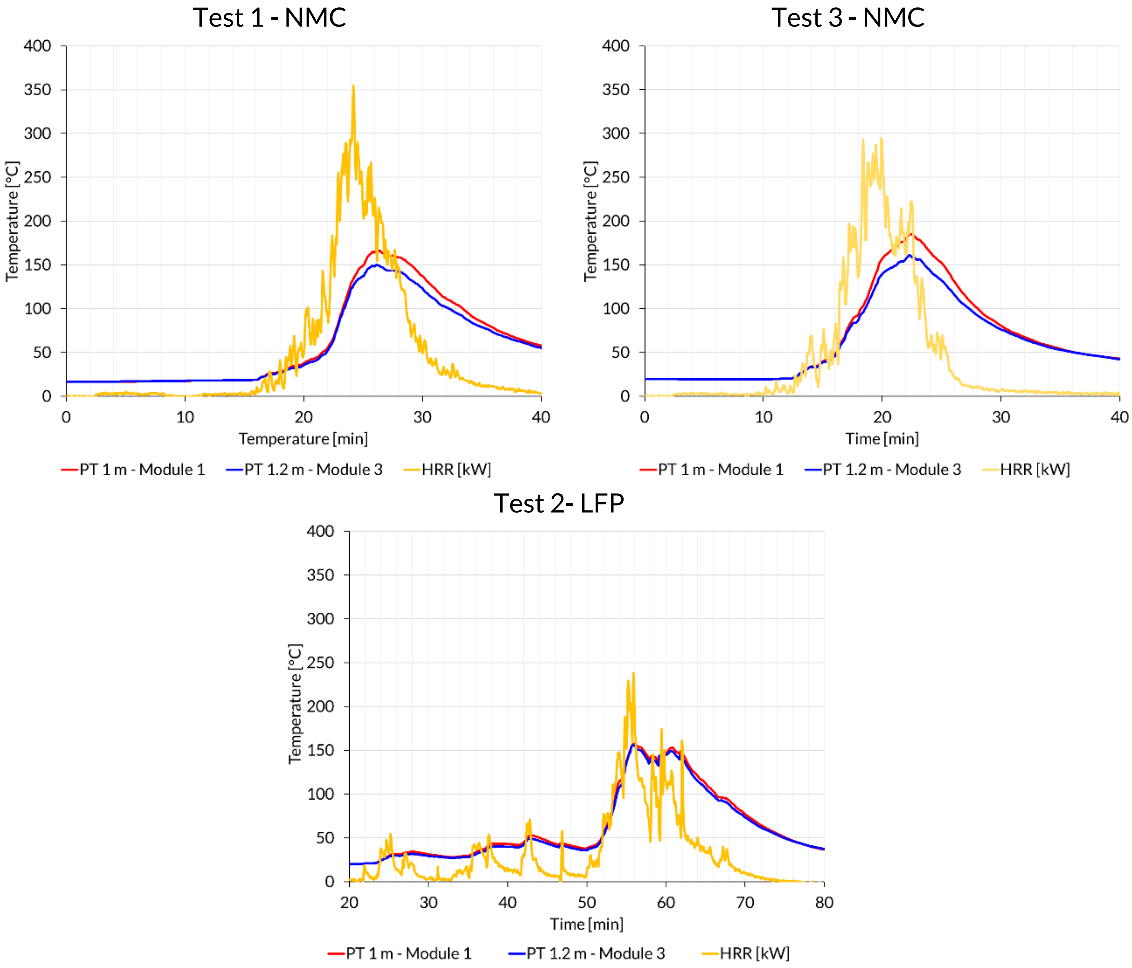


Figure 29 Temperatures recorded on the opposite row of racks position

6.1.6 Determining the activation criteria

To evaluate a fire suppression system's performance in mitigating a module-to-module propagation it is important to find an activation time that:

- ensures a repeatable propagation should the system not be activated.
- reflects a reasonable activation time, i.e. that could be determined based on normal fire detection onboard a ship (typically spot-type heat and smoke detectors).
- is based on measurements conducted in the experimental set-up

The first thermal runaway event and its propagation through the module is shown in Figure 30. After the failure of the first cell, some time passes before there is propagation to other cells. At these early stages, the way the first cell fails and how quickly it propagates appears to vary significantly. Activating a fire suppression system this early may appear positive for the performance of that system. However, it is not possible to draw any conclusions on this performance as the fire size may reduce or increase naturally regardless of if the fire suppression is activated or not. This is also seen from the heat release curves in Figure 26. The initial stages are a bit “jumpy” whereas a steady growth is obtained once thermal runaway propagates to adjacent cells. A suitable activation time for evaluating these systems would be when there is clear thermal runaway propagation between the cells within the live modules. Note that this might not be desirable in case of a real installation, where early detection and activation would be most effective, but this was not the scope here. To evaluate the performance of the fire suppression systems it is necessary that there is thermal propagation beyond the unpredictable initial stages of a battery fire.

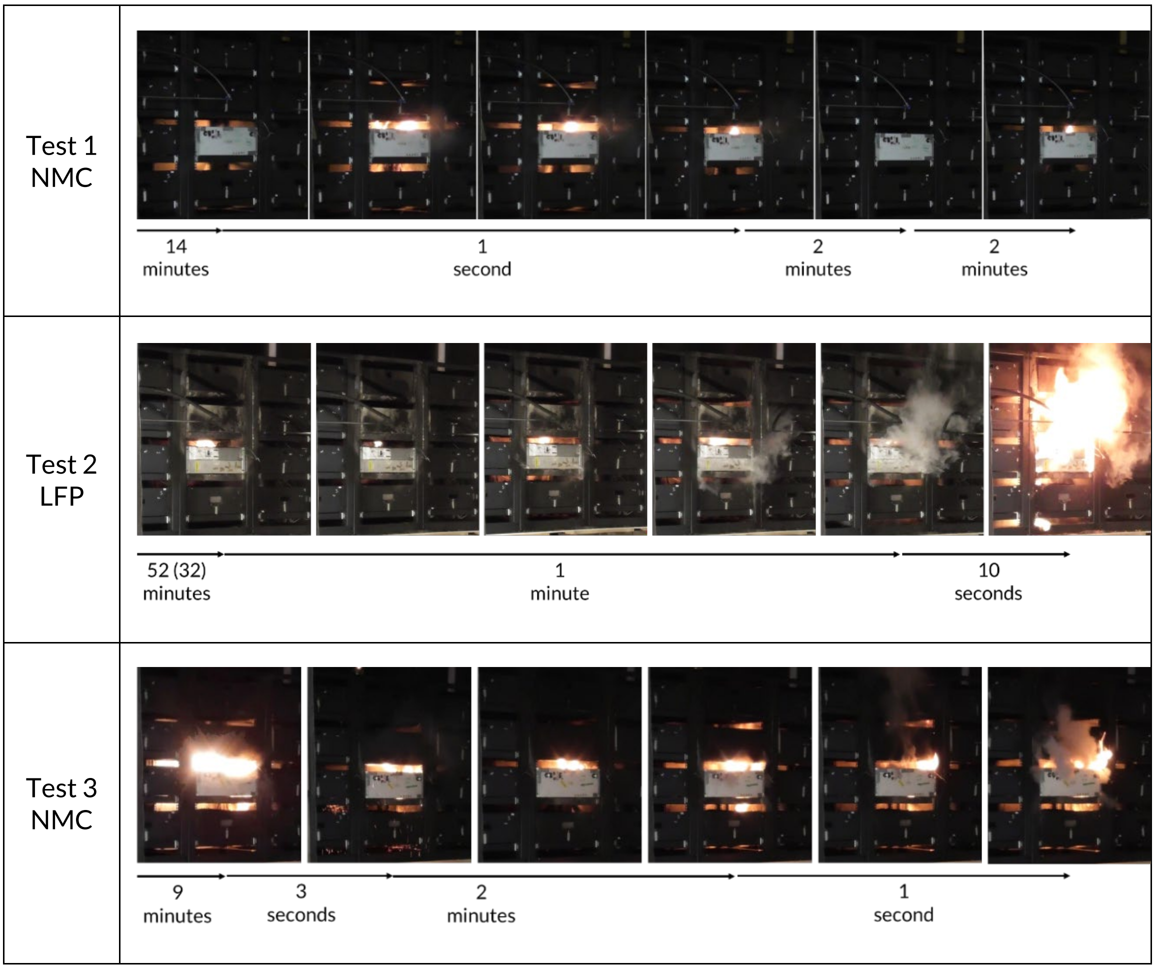


Figure 30 Thermal runaway progression after the first cell fails. The time starts when the burner is activated. In case of test 2, the time with respect to when the burner restarted is given in brackets.

To find the exact point which can be used as a trigger point for starting a fire suppression system for test series 2, temperature measurements from the module placed directly above the live module were used. Ideally the heat release rate would be used, but since tests would be performed outdoors as well where the heat release rate cannot be measured, temperature was used. The temperature criteria shall correspond to a state where the fire would continue to propagate on its own. Based on the results from the first test series a combination of the surface temperature on the bottom of the module and the surface temperatures on the right and left side was selected to cover both the NMC and LFP cases. Both left and right sides need to be considered due to variation in flame impingement. The criteria developed was to reach at least 70 °C on the bottom and at least 100 °C on either side of the module. To avoid having the conditions met due to single spikes in the data the temperature thresholds need to be reached for a time window of at least 10 seconds and 3 data samples. For the three tests these conditions were met after 18 minutes and 28 seconds, 56 minutes and 20 seconds and 13 minutes and 32 seconds, respectively.

The repeatability of the chosen setup and method was also assessed by comparing the surface temperatures of the dummy modules closest to the initiating module. In Figure 31 the temperature measured on different sides of the module above the initiating module is plotted with the time synchronised using the criteria described above. Following this point, a very good match can be seen for the two NMC tests. This means that a similar thermal propagation rate is achieved once the selected criteria is reached, as is needed to objectively compare the effectiveness of fire suppression systems.

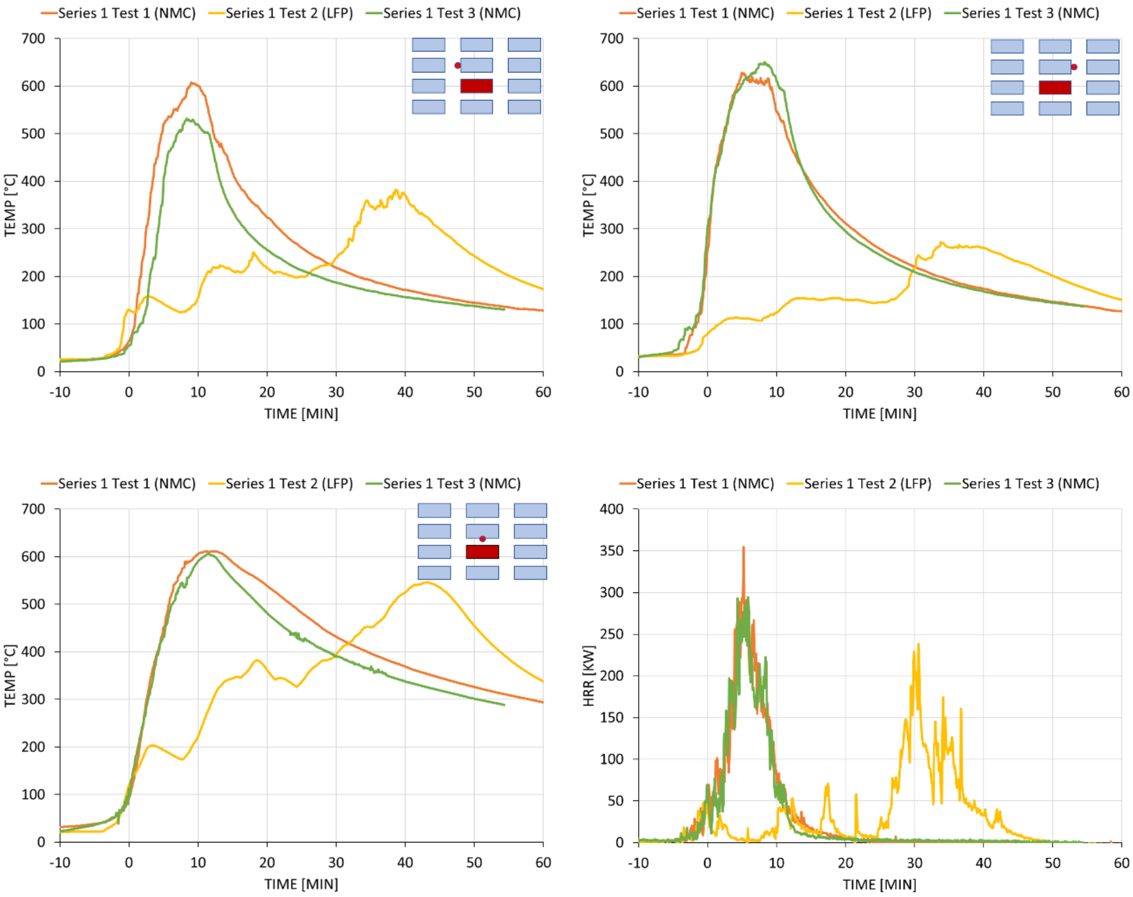


Figure 31 HRR and surface temperature on the module placed above the live module. The time starts when the fire suppression system would activate (30 s after criteria are met).

6.2 Second test series

The second tests series was conducted to evaluate the performance of some fire suppression systems and to further evaluate the test method. Over the course of two weeks 15 tests were performed.

6.2.1 Test programme

The test programme for the second test series was executed from the 9th until the 20th of August at a training facility operated by the rescue services in Borås, Sweden. An overview of these tests is given in Table 15.

Table 15 Overview of the second test series

Test	Battery	Fire suppression system	Agent	Container open/closed
1	NMC	None	None	Open
2	LFP	None	None	Open
3	LFP	None	None	Open
4	NMC	Mist	Water	Open
5	LFP	Mist	Water + 3 % F500	Open
6	NMC	Sprinkler	Water	Open
7	NMC	Mist	Water + 3 % F500	Open
8	NMC	Sprinkler	Water + 3 % F500	Open
9	LFP	Mist	Water	Open
10	NMC	Local	Water	Open
11	NMC	Gaseous	INERGEN® 52 % N_2, 40 % Ar, 8 % CO_2	Closed
12*	LFP*	Local	Water + AVD	Open
13	LFP	Gaseous	INERGEN® 52 % N_2, 40 % Ar, 8 % CO_2	Closed
14	NMC	Local	Water + AVD	Open
15	LFP	None	None	Closed
*Test stopped due to problem with initiating thermal runaway				

The second test series was somewhat adjusted based on lessons learned from the first test series. One such lesson related to the temperatures of the dummy modules. The thermal mass of the sand resulted in that the dummy modules remained warm for several hours after each test. This meant that the timing of the tests could be very dependent on the outcome of previous tests. Ideally the dummy modules would cool down to ambient levels before moving forward with the next test. To circumvent this issue, it was decided to construct an identical rack setup. Then, one test could be done using rack nr. 1 in the morning and then another test with rack nr. 2 in the afternoon, and then a test in rack nr 1 the morning the next day. In doing so, ample time was provided for the dummy modules to return to ambient temperature levels.

The measurement system started first. Then, after 1 minute the cameras started recording the tests. Finally, at time 2 minutes, the burner was engaged and remained active until the trigger criteria were met. See Chapter 6.1.5 for more information about the trigger criteria.

When the trigger criteria were met, the gas supply for the burner was turned off and 30 seconds thereafter the fire suppression system was started (if a system was used). The test was finally terminated when there was no more activity in the live module, i.e., no visible fire or gas released, and as temperatures were steadily decreasing below critical levels.

6.2.2 Test setup

Two test containers were used as shown in Figure 32. They were located inside a concrete embankment. Any fire water runoff or fire suppression agent used would thus remain inside the embarkment, be collected, and then handled appropriately. Measurement equipment as well as video recording equipment were placed inside a separate container. From here, the tests were observed. Container 1 and 2 housed the test setup and auxiliary equipment. Conditions inside the containers were identical unless stated otherwise. During the tests the doors to the container were kept open except for the gaseous agent system tests. There were also some openings in the container so that cables etc. could enter.

Figure 32 Overview of the test site with an indication of the used 20-ft shipping containers.

The test setup inside the container is shown in Figure 33. A walkway of 1.2 m was used in front of the standard rack. Plate-Thermometers were used to simulate an opposing rack and capture its temperature. As in previous tests, spark plugs were placed close to the live module so that potential flammable battery gas was ignited. The burner was aimed towards the same position as in the earlier tests rear of the live module through a hole in the container.

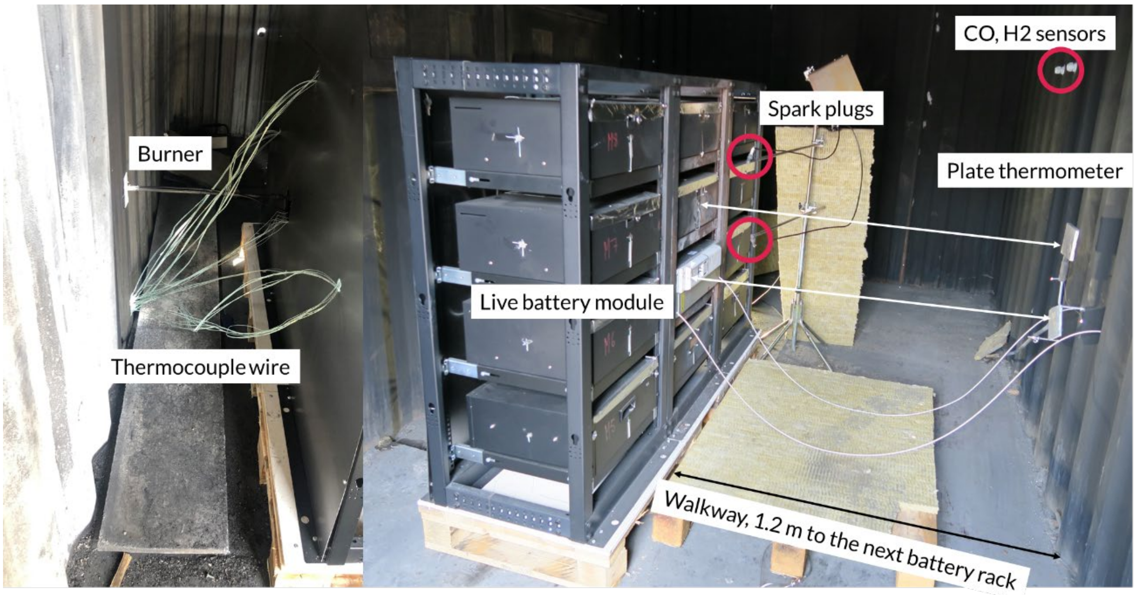


Figure 33 Inside the test containers

The water-based fire suppression systems used one nozzle placed at the centreline of the walkway, i.e. 0.6 m from the standard rack, at a height of 2.1 m as seen in Figure 34. The nozzle was positioned centrally with respect to the longitudinal axis of the live battery module. The spray pattern when these systems activated is shown in Figure 35. In case of the gaseous agent system, two nozzles were placed on either side of the standard rack, at a distance of 0.6 m from its centreline.

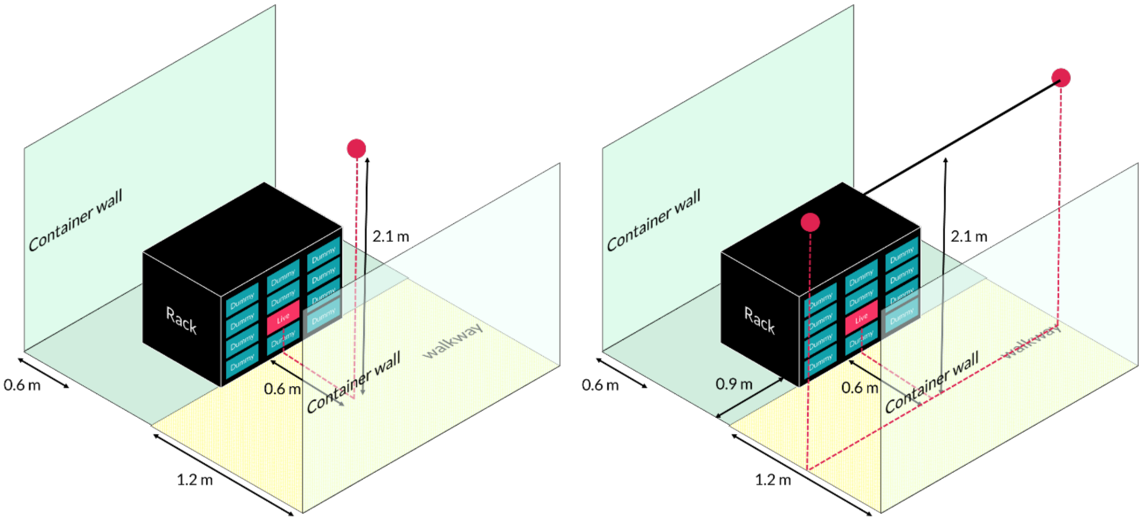


Figure 34 Fire suppression system installation considered; Test 1, 2 and 3 (left) and Test 4 (right)


System 1

System 2

System 3

Figure 35 Fire suppression system, nozzle direction and spray pattern

On the floor, directly in front of the battery rack, as seen in Figure 33, there was a load pallet with a non-combustible board. This was a safety measure to allow for safe removal of the battery module after the test, due to the risk of stranded energy in the module. Stranded energy meant that gases/material could be released/ejected or reignition occur when the module was moved or shifted. To avoid close contact with the tested module, a procedure was developed that allowed for remote removal of the tested module. Two steel wires were fastened to the live module, the ends of the wires were drawn through the container wall to the outside of the container. By pulling the wires from the outside, the live module was detached from the battery rack, landing on the pallet. Another steel wire was attached to the pallet, so that the pallet could be pulled towards the opening of the container, see Figure 36. Once it was close to the opening, the battery and pallet could be lifted and moved to a safe location using a wheel loader.

Figure 36 Example of the battery being removed from the container after testing. First the module was pulled onto a pallet, moved to the opening, and then lifted with a machine.

In case of the tests where gas-based fire suppression systems were used, the container was sealed as much as possible in order for the gaseous system to work, see Figure 37.

In addition, the doors to the container were either closed or covered with a plastic sheet. Normal pressure relief vent designed for gas extinguishing systems were used, the vent was designed to fully open at 95 Pa and close at 70 Pa.

To mitigate the consequences should a gas explosion occur a weak point having a larger surface area was deemed necessary. This was achieved using a plastic sheet to seal the remaining opening of the container. Before testing, it was validated that the plastic sheet would not rupture when the gas-based fire suppression system was activated.

Figure 37 Pressure relief system (left) and plastic sheet used to close-off the container (right)

There is a risk for gas explosion after the test when the container is opened when fresh air enters and mix with the flammable gas inside. This may result in a flammable mixture. The mixture could then be ignited by either the test object or other components in the container. As such, a solution was developed to cut through the plastic sheet that closed off the container. This solution is shown and demonstrated in Figure 38.

Figure 38 Safely opening the closed container at the end of testing

6.2.3 Measurements

Temperatures were measured on the dummy modules and live modules in a similar fashion to what was done in the first test series. However, as the first test series showed that some measurement points were of less interest, the number of thermocouples were reduced in the second test series. Specifically, the temperature sensors furthest away from the live module but also those on the rear of the dummy modules were removed. Instead, additional sensors were installed on module 3, specifically, on the left, right and bottom of the module as this was where the criteria for turning off the burner/activating the fire suppression system was evaluated. An overview of the thermocouples used here is given in Figure 39. Also note that there were four thermocouples inside module 3. Two sensors were placed near the bottom plate as well as two placed 15 mm from this plate as seen in Figure 40.

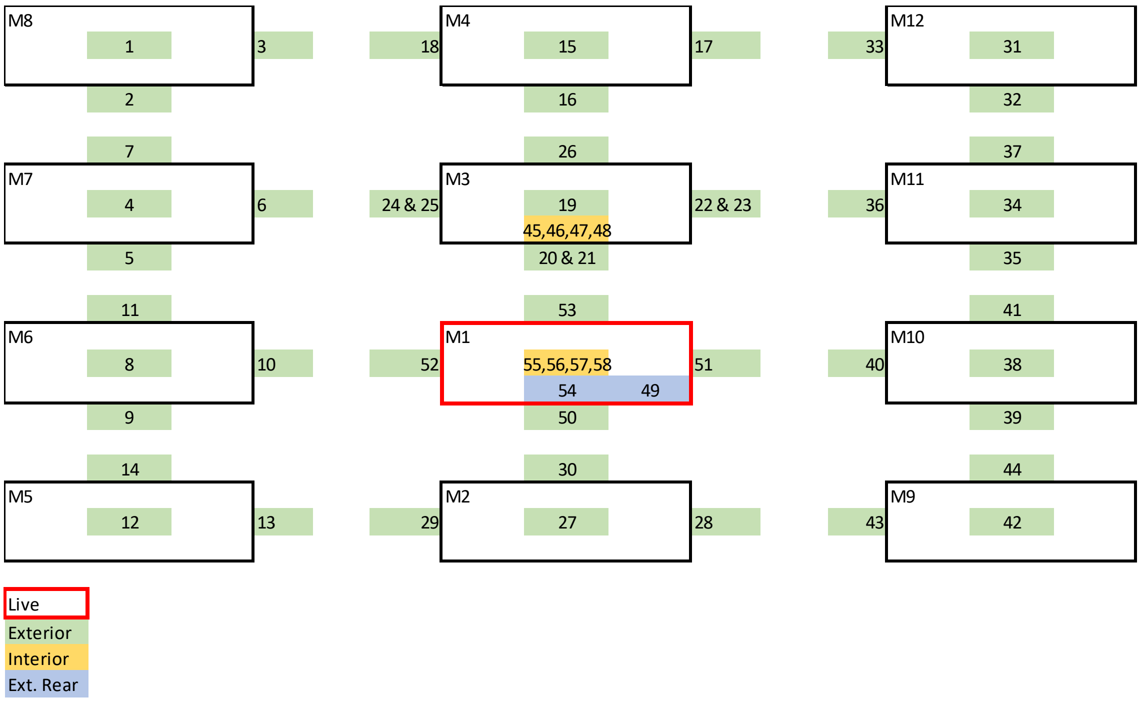


Figure 39 Thermocouples in the second test series

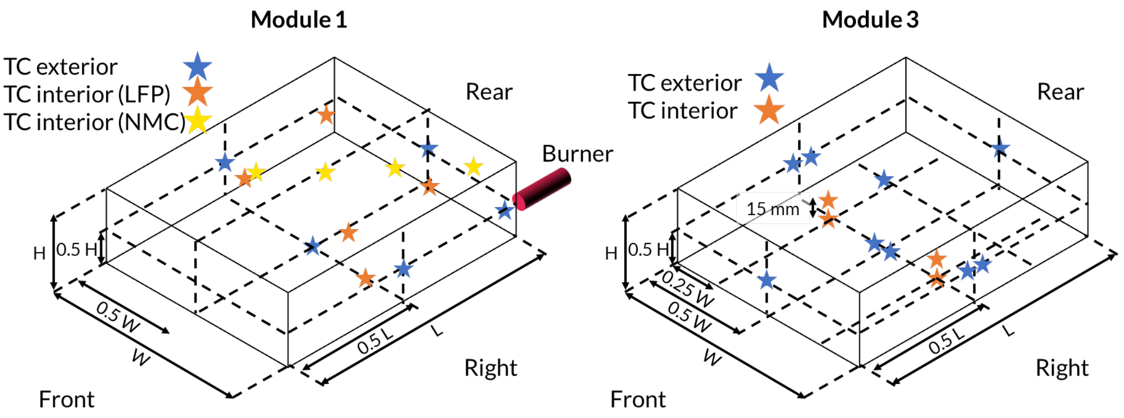


Figure 40 Instrumentation of the live module (module 1) and dummy module above (module 3)

Gas collection, as in the first test series, was not available for the tests performed outdoors. In one of the containers, gas alarms were installed so that gas concentrations in the container could be estimated. These alarms detected CO and combustible gases. When certain thresholds were reached, they sound an audible alarm, and the outgoing voltage is disconnected by an electronic relay. The sensing elements of the detectors, seen in Figure 41, were located at a height of 1.5 m from the container floor.

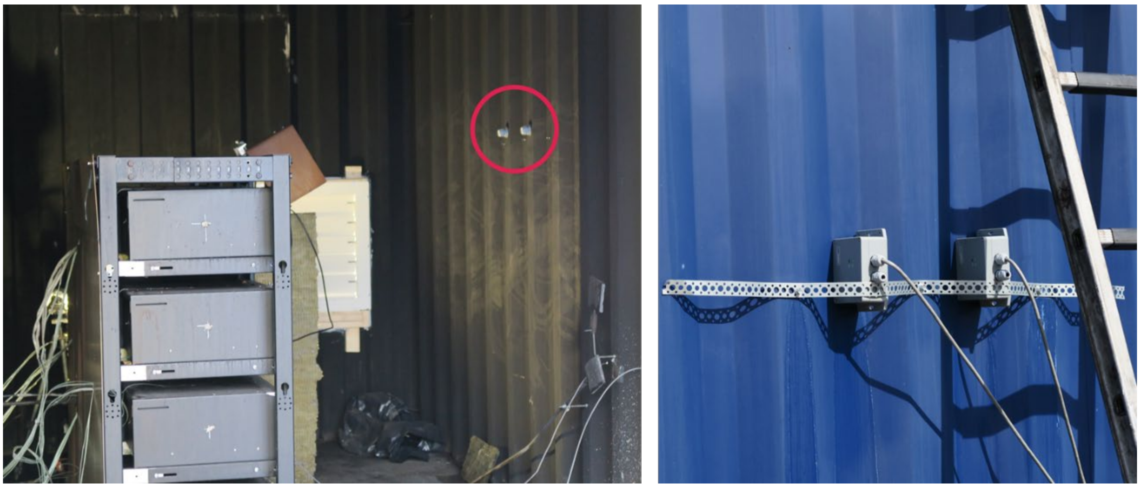


Figure 41 Sensing elements for the gas alarms (encircled) were inside the container while the alarms were on the outside

6.2.4 Results - Reference tests

With 15 tests performed having about 60 measurement points a large amount of data is produced. All the data can be found in Appendix A: Test data, and some data is presented and discussed here.

The first task considered in the second test series was to investigate whether the indoor tests could be repeated outdoors. Most importantly in this case is the module used as a criterion for when the fire suppression systems should be activated in later tests, but also the other modules as the temperatures on these should serve as a basis for performance evaluation.

An overview of the fire development when the first cell goes into thermal runaway and shortly after is given by Figure 42. The initial fire in the NMC module was found to follow a similar pattern as what was observed for the indoor tests. It did however take significantly more time before thermal runaway started. This is most likely due to the gas supply to the burner. The same burner nozzle was used but the gas was supplied from a bottle where the flow was controlled by a needle valve as opposed to the tests conducted indoors where propane was supplied from a large gas tank. The flow rate from the bottle was increased after Test 1 as it became apparent that the setting used did not result in similar heating.

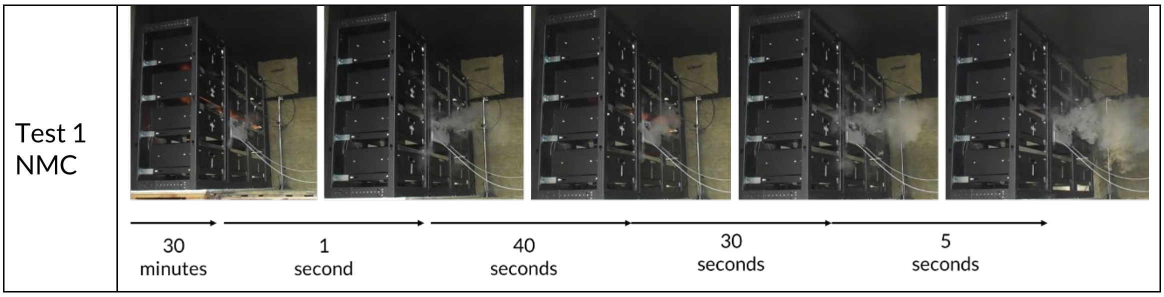


Figure 42 Thermal propagation after the first cell fails in the reference test with an NMC module.

An overview of the temperatures recorded during the reference test with an NMC module are given in Figure 43. Here both the average and maximum temperatures for the modules are shown. The maximum temperatures were observed at the external surfaces closest to the initiating module. Critical levels were reached at all the modules. This was also the case for the first test series.

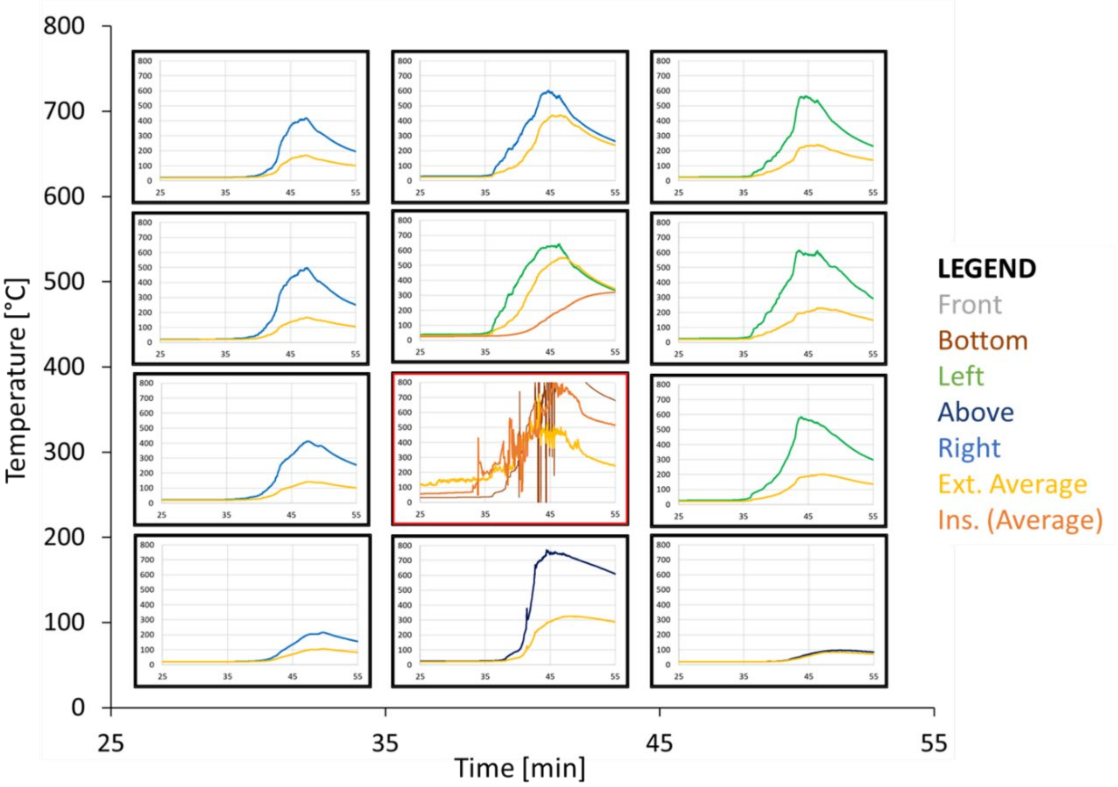


Figure 43. Temperature readings from Test 1, a refence test on an NMC module. The graphs show the average and maximum temperatures on each module.

Two reference tests were performed on the LFP modules. As seen in Figure 44, it took about 80 minutes before thermal runaway started in the first test. Initially, there was a problem with the oxygen supply to the burner which affected the flame. After resolving this issue, temperatures still did not increase as fast as what was observed in the first test series, and the burner settings were therefore also adjusted. After this, it took about 32 minutes before thermal runaway was observed. Due to difficulties with the gas burner in initiating thermal runaway, it was decided that the test had to be repeated, in order to have a useful benchmark for the fire suppression tests.

Test 3 was identical to Test 2 with some adjustments made to the equipment. Modifications were made to the rear of the standard rack to increase the oxygen supply to the burner. In addition, repairs were made to the nozzle to ensure that gas could not leak around the nozzle. Finally, Test 3 gave comparable results to the first test series. Here it took about 30 minutes and in test series 1 roughly 32 minutes (after restarting the burner).

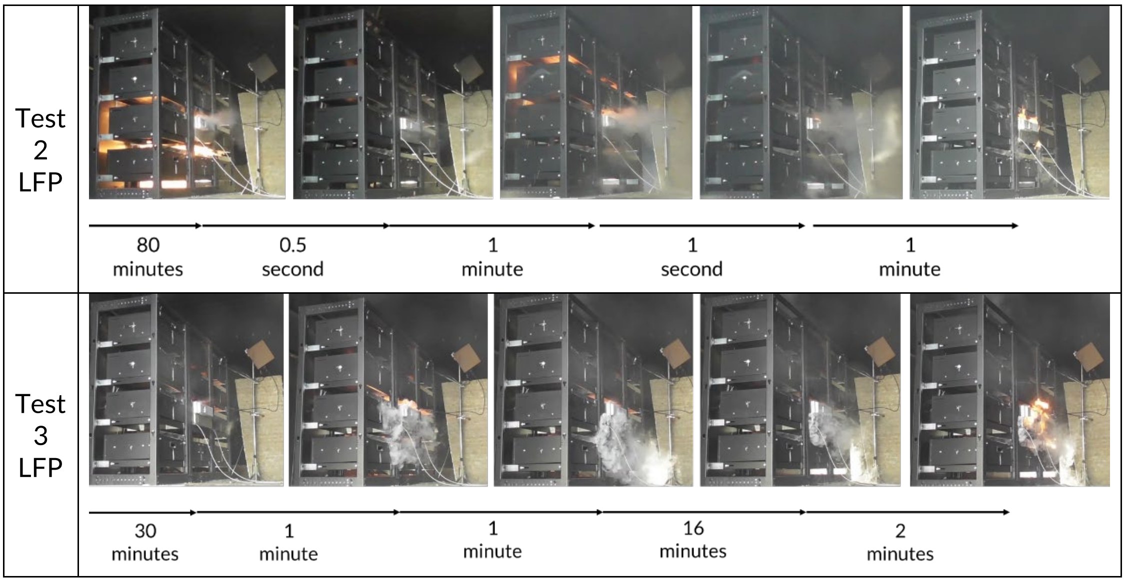


Figure 44 Thermal propagation after the first cell fails in the reference test with an LFP module.

Temperatures observed in the standard rack for the LFP reference tests can be seen in Figure 45. It can be seen here that temperatures are much lower in the different racks than what was seen in the NMC tests. The highest temperatures here were usually observed at surfaces facing the live module. Exceptions to this are the modules above the live module.

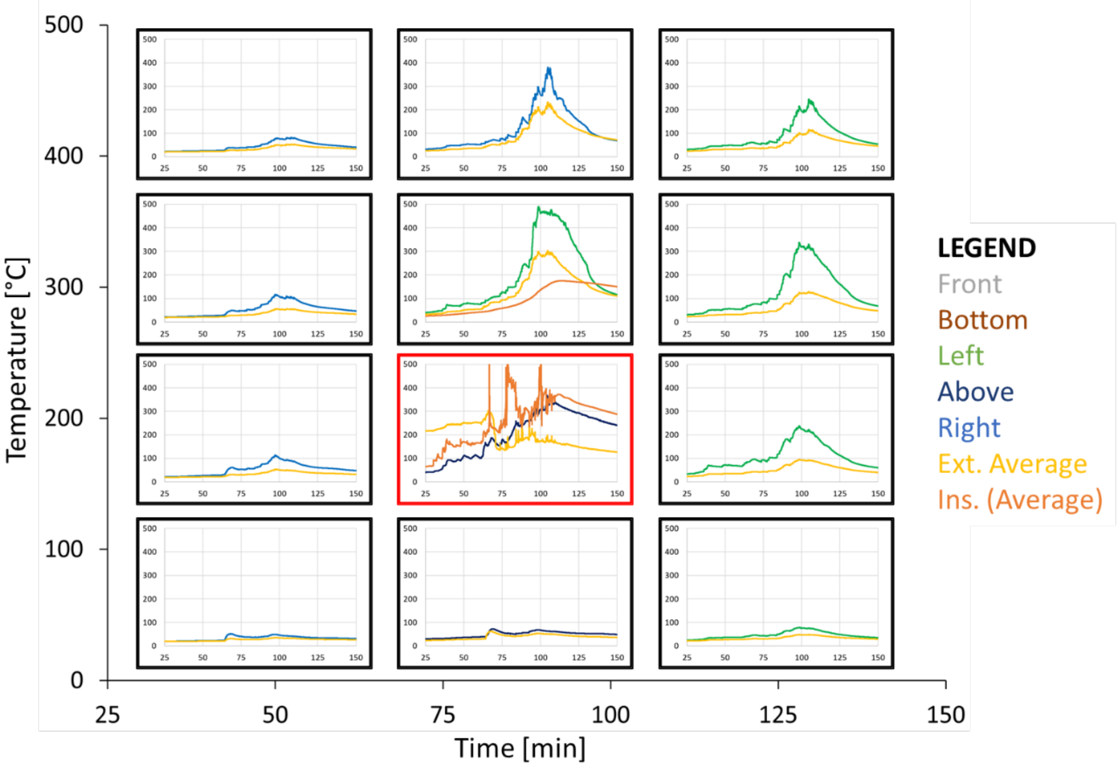


Figure 45 Temperature readings from Test 3, a refence test on an LFP module. The graphs show the average and maximum temperatures on each module.

Synchronizing the obtained temperature measurements with respect to when the activation criteria are met allows for them to be compared with test series 1. This comparison is done in Figure 46 for the NMC case. Note that the criterion is evaluated at the external surfaces of the dummy module directly above the live module. Here, it may be seen that the temperature development after the criteria is met matches very well with the first test series. The bottom temperature appears unaffected the by indoor or outdoor setup. A larger difference may be expected for the other locations, left and right on the dummy module, as these are more sensitive to flames. The direction of flames is influenced by ventilation conditions, which were different between the two test setups. In test series 1, gases were extracted upwards and did not accumulate, while in test series 2 there was no ventilation system. Any smoke or gas exiting from the test container did so through the openings (open door, small holes for cables, etc.) depending on the wind conditions at the test site.

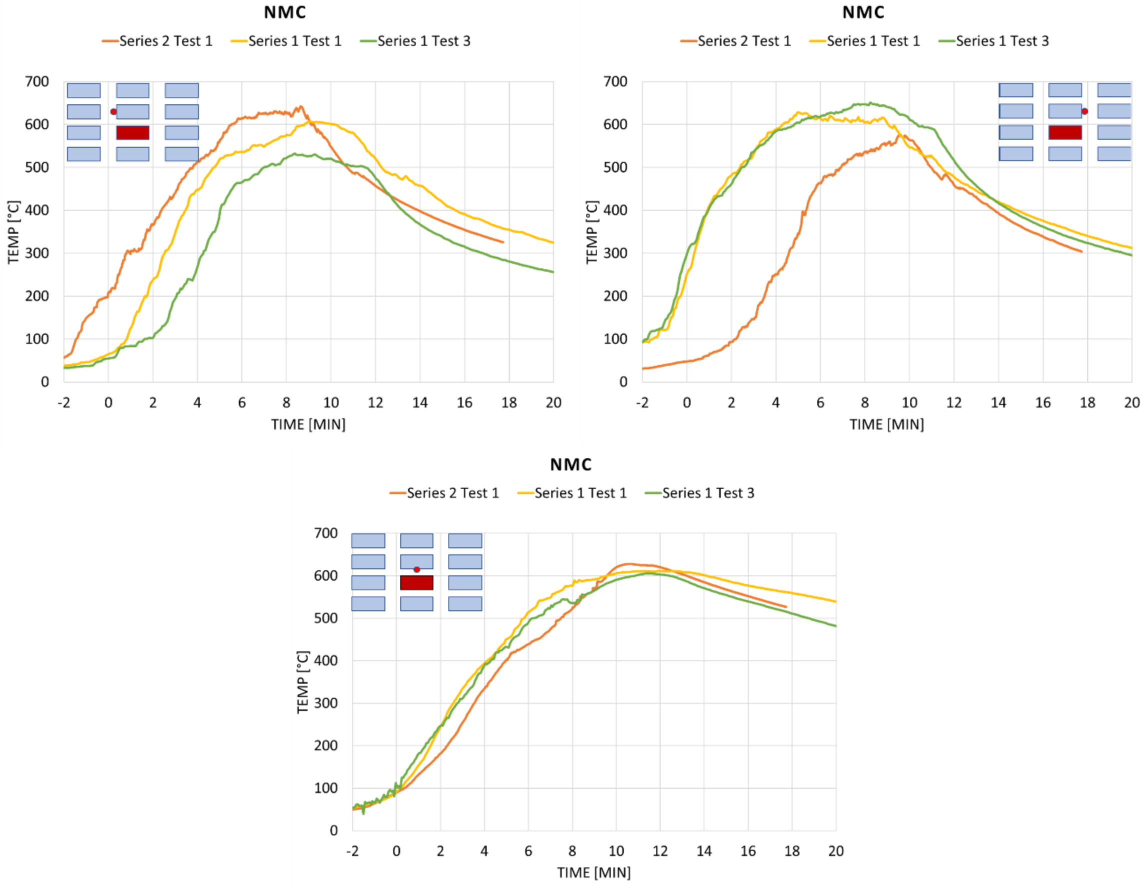


Figure 46 Surface temperatures from reference tests with NMC batteries. The measurement location, relative to the live module is indicated by the red dot

When LFP modules were tested, see Figure 47, there was significantly more variation among the test results. The overall trend, i.e. temperatures continuing to increase after the criteria are met, is captured for all tests. However, the rate at which these temperatures grow, varies a lot. Note that some variation may be since Test 15 was performed inside a closed container. The results match best when looking at the bottom of module 3, which is affected the least by the direction of flames. It appears that in Test 2 most of the flames were impinging on the left of module 3, whereas in Test 3 the flames impinged on the right of module 3. This further motivates why the selected criteria for activation, which considers temperatures measured on both sides of module 3, was appropriate.

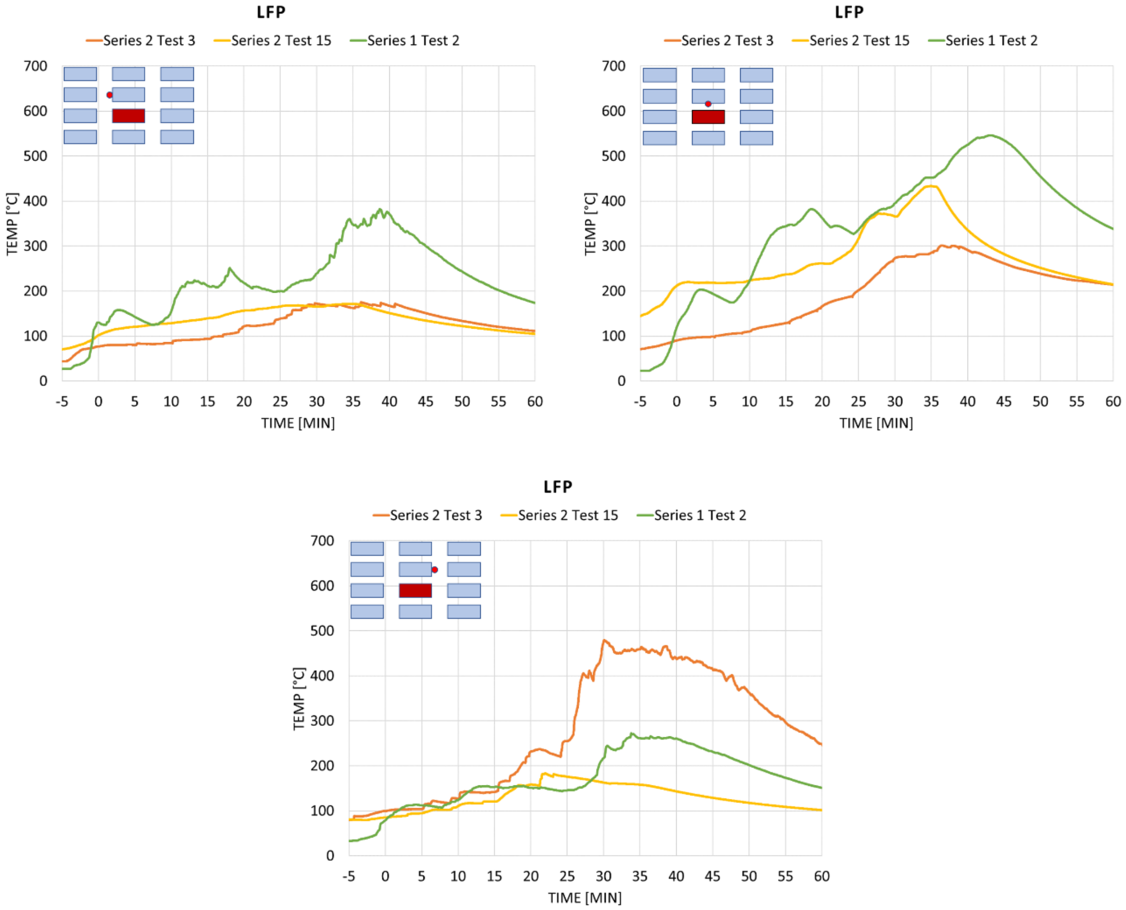


Figure 47 Surface temperatures from reference tests with LFP batteries. The measurement location, relative to the live module is indicated by the red dot

Temperatures measured on external surfaces surrounding the live module during reference tests with NMC batteries are shown in Figure 48. There was a good match at the modules that are adjacent to the live module (left and right). In general, temperatures were higher to the right. This is most likely the result of this external surface being closest to the initiating area (50 mm from the right edge of the live module). As thermal runaway propagates through the module, temperatures continue to increase on the left side while temperatures on the right are on their way down around the 8-10 min mark.

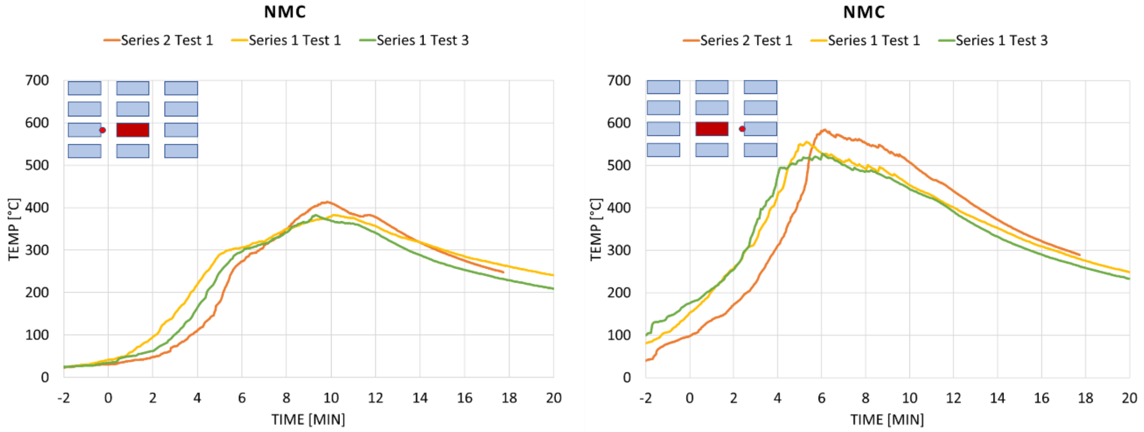


Figure 48 Surface temperatures from reference tests with NMC batteries. The measurement location, relative to the live module, is indicated by the red dot

Studying some measurement points at module 6 and 10, left and right of the live module for the LFP tests, respectively, shows however that the variation between indoor tests and outdoor tests compared to closed- and open-door test was of the same magnitude. This is shown in Figure 49. In general, variations for the measured temperatures were larger here than for the NMC batteries. From the first test series, it was observed that heating was similar on both sides of the live module. In the second series, more heat was released toward the right of the live module, which was also noted for the surfaces above the live module.

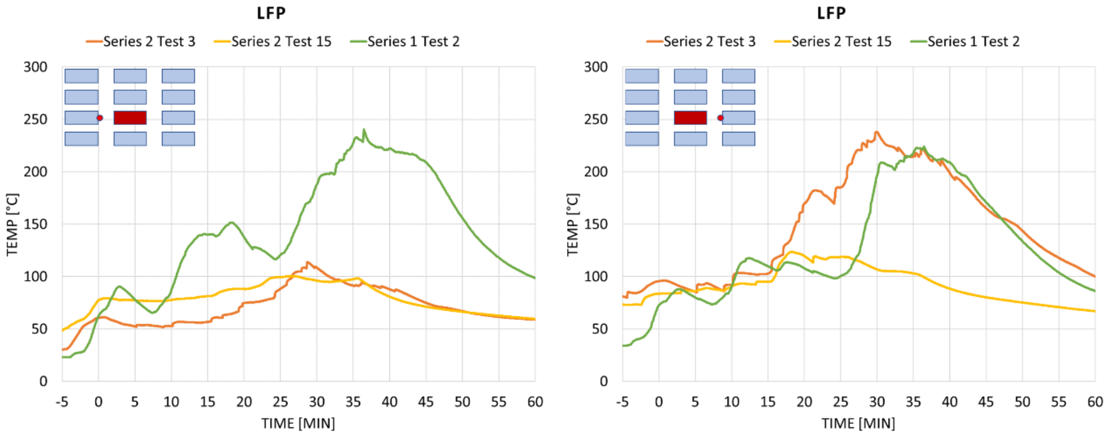


Figure 49 Surface temperatures from reference tests with LFP batteries. The measurement location, relative to the live module, is indicated by the red dot

Figure 50 presents the Plate Thermometer readings during the reference tests using NMC tests, as seen the results are similar for all three tests.

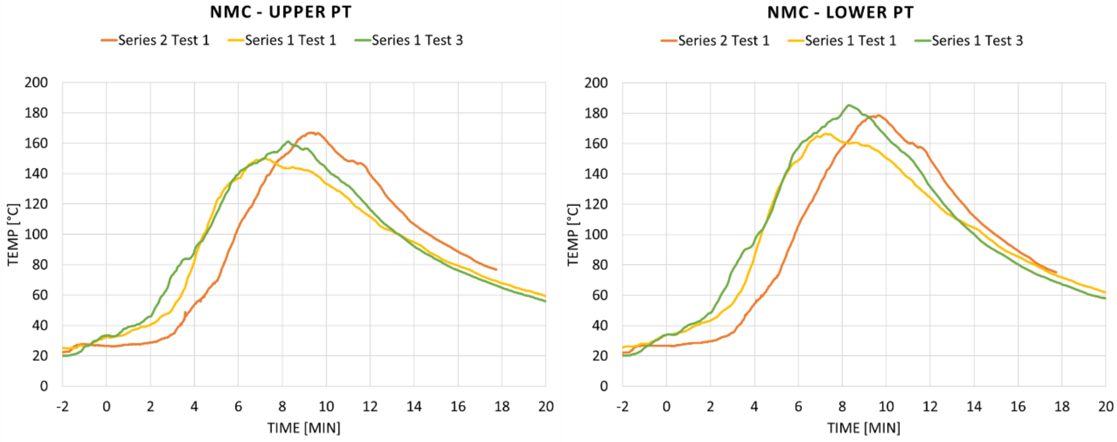


Figure 50. Plate thermometer reading for the reference tests using NMC modules

For the LFP tests there were a difference in Plate Thermometer readings between the test conducted indoors and the tests conducted outdoors as can be observed from Figure 51. The greatest difference was obtained for the closed container test, Test 15, where temperatures were significantly greater.

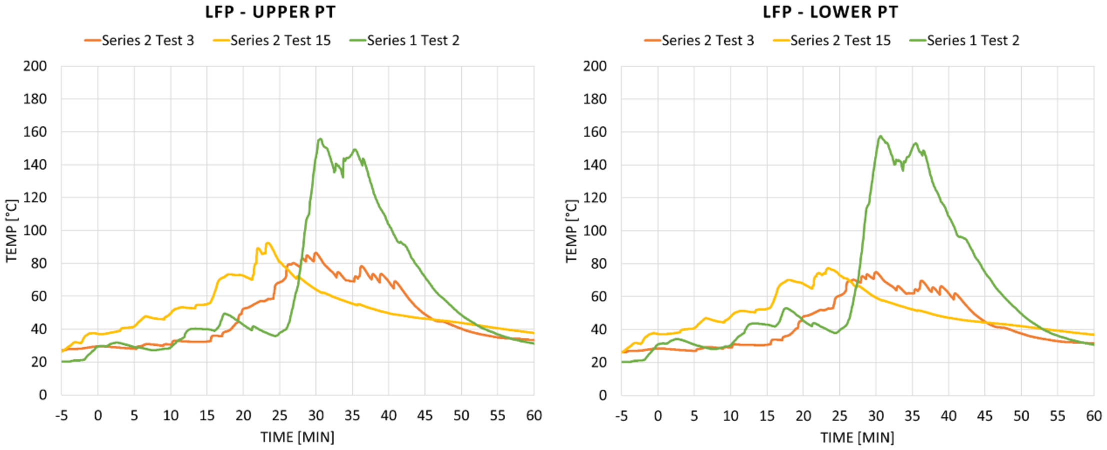


Figure 51 Plate thermometer reading for the reference tests using LFP modules

6.2.5 Results – Initiation and criterion

An overview of times at which the activation criterion was met for all the tests is given in Table 16. For the NMC modules, the trigger criteria were reached after similar amounts of time. Ignoring Test 1, the burner had to be active for 14 minutes in average with a standard deviation of 2 minutes. In this case, the external burner proved to be a reliable and consistent method for initiating thermal runaway.

It was more challenging when the LFP module was used, however. As mentioned, there were issues with the burner. To fix this, tests sometimes had to be paused and the burner restarted. This caused a greater variation as seen in Table 16. Compensating for the times where the burner was not working properly however, suggest that it is possible to obtain repeatable conditions also for LFP modules. The criteria were then reached after the burner was active for an average of 56 minutes with a standard deviation of 10 minutes.

Table 16 Summary of the times when trigger points were reached as well as when the fire suppression systems were engaged and disengaged.

Test	Battery	Suppression system	Total amount time where the burner was active [HH:MM:SS]	Trigger reached [HH:MM:SS]*	Activation [HH:MM:SS]	Fire Suppression system end [HH:MM:SS]
1	NMC	None	00:34:54	00:36:54**	-	-
2	LFP	None	02:17:55	02:19:55	-	-
3	LFP	None	01:05:26	01:07:26	-	-
4	NMC	Water mist	00:17:33	00:19:33	00:20:03	00:30:15
5	LFP	Water mist	00:44:47	00:46:47	00:47:17	00:57:16
6	NMC	Sprinkler	00:13:55	00:15:55	00:16:25	00:26:30
7	NMC	Water mist	00:15:11	00:17:11	00:17:41	00:27:40
8	NMC	Sprinkler	00:14:37	00:16:37	00:17:07	00:27:07
9	LFP	Water mist	00:45:45	00:47:45	00:48:15	00:58:29
10	NMC	Local application	00:12:50	00:14:50	00:15:20	00:18:18
11	NMC	Gaseous	00:10:55	00:12:55	00:13:25	00:15:25 ******
12***	LFP	Local application	03:56:00	-	-	-
13****	LFP	Gaseous	01:10:40	01:15:10	01:15:40	01:17:40
14	NMC	Local application	00:13:11	00:15:11	00:15:41	00:21:19
15*****	LFP	None	01:11:12	01:27:42	-	-

* The burner was normally activated 2 min after the measurement file started, i.e. at 00:02:00

**Note that the heat release rate for the burner was different here than in other tests. The subsequent tests considered a higher flow rate.

*** Test was aborted as thermal propagation was not achieved after 4 hours.

**** Problem with the burner. Started at 00:06:30. Total time of 4 .5 min where the burner was not "active".

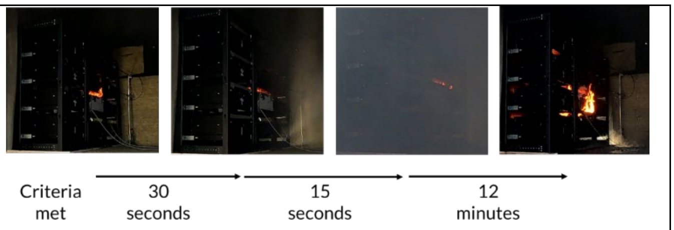
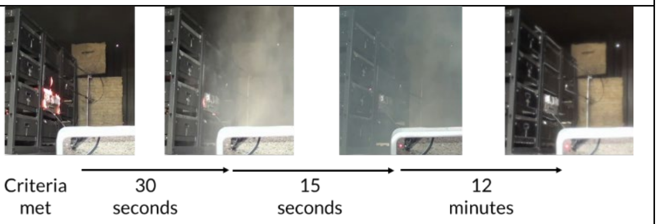
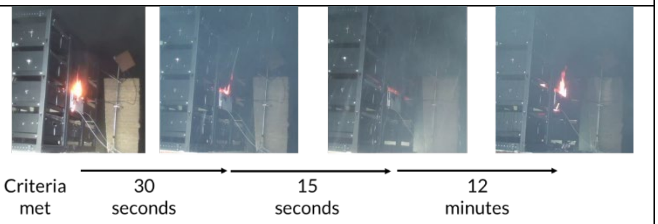
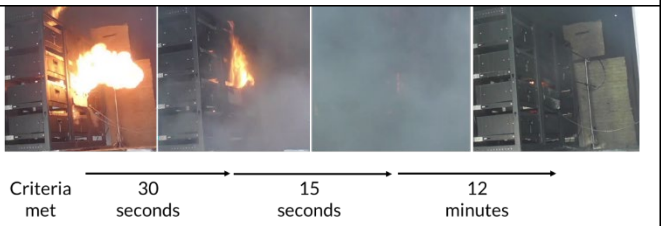
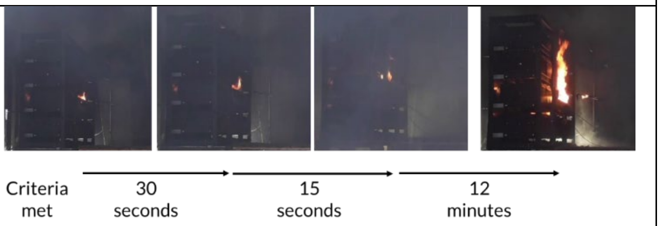
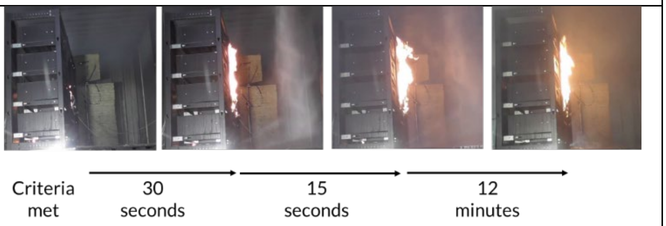
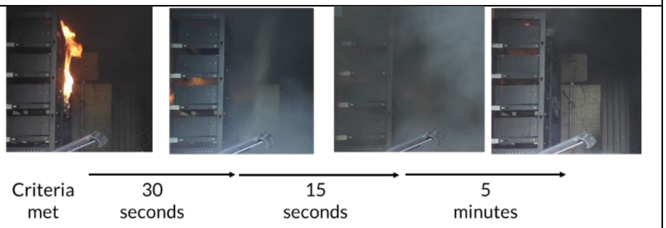
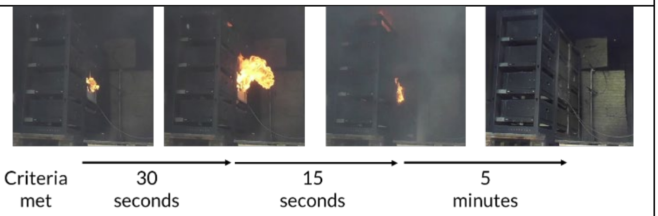
***** Problem with the burner. Restarted at 00:14:00. Second restart at 00:53:00. Total time of 16 .5 min where the burner was not "active".

****** The system was designed to release all gaseous agent in 1 minute yet during the test it appeared to take 2 minutes.

6.2.6 Results – Mitigating propagation

All temperature readings are available in Appendix A: Test data. A few examples are provided here to support the discussion. An overview of the fire development when the criteria were met and after activation of fire suppressions systems is given in Table 17. The fire development before the fire suppression systems were activated was like what was observed in the first test series. Once the criteria were met, there was a delay of 30 seconds before the fire suppression system was activated. When the system was activated, the severity of the fire was reduced, at least towards the front of the test setup. Throughout the time the fire suppression systems were kept active, thermal runaway continued to propagate throughout the initiating module, however. Note that this result was expected. The challenge for the tested systems here was to control temperatures and lower the risk for module-to-module and rack-to-rack propagation.

Table 17 Overview of fire development after the criteria was met in Test 4- Test 10 and Test 14.

Test 4	NMC Water mist	
Test 5	LFP Water mist	
Test 6	NMC Sprinkler	
Test 7	NMC Water mist	
Test 8	NMC Sprinkler	
Test 9	LFP Water mist	
Test 10	NMC Local Application	
Test 14	NMC local	

In Tests 10, Test 11 and 14 the fires in the initiating module were very severe when the fire suppression system was activated. This can be seen in Figure 52. The rack is shown from the side so that the rear of the live module may be seen. Most of the flames were observed here. As a result, the fire was 1) more hidden from the fire suppression system and 2) the fire size was significantly larger when the criteria were met compared to other tests.

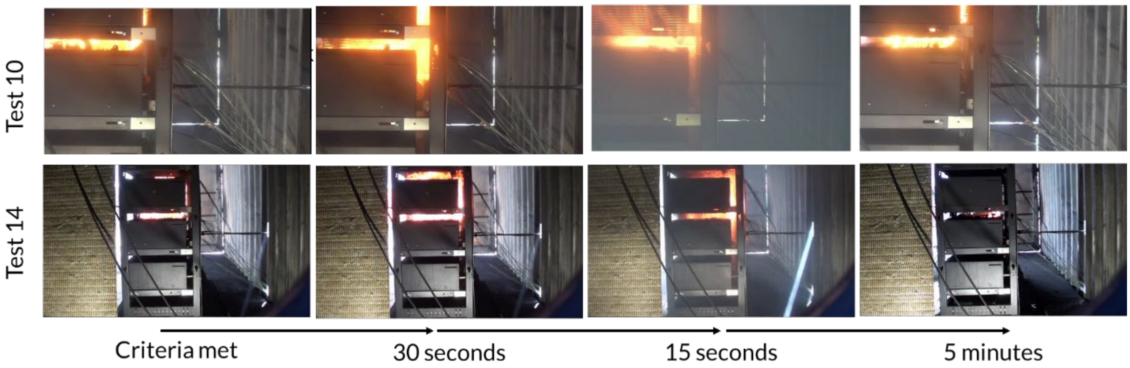


Figure 52 Fire development after the criteria was met in Test 10 and 14.

The modules used for Tests 10, Test 11 and Test 14 were slightly different than the modules used for all the other NMC tests. Specifically, there was a slightly different arrangement of the individual cells. In these modules there were more cells at the rear of the module, and they were placed closed towards the rear.

Upon inspection of the one of the modules used for these tests, it was found that the module had opened/ruptured during the test, see Figure 53. The connections holding the lid in place appeared to have failed during the test, creating a path through which flames could enter and exit. This may explain why the fire development was different in this specific test. It also shows the importance of having the same modules to objectively compare fire suppression system performance.

Figure 53 The NMC battery module after Test 10 (left) and Test 14 (right). Note that the module had opened up towards the rear, which is also where the fire was observed to be very intense.

Figure 54 shows the temperature readings on the module directly above the live module for the tests where only water was used compared with the reference test in test 1. As seen the temperature reading is significantly reduced in some cases i.e. on the front and below the module in the test using water mist and local application while the temperature was not that affected on the other locations of that module. The impact on the front is probably due to a direct hit from the water mist spray while the temperature reduction underneath is due to that water has been able to penetrate the dummy module and thus cool the module in the bottom from the inside. This is also seen from the temperature reading staying at 100 °C. Studying the temperatures at module 6 in Figure 55 one can also see a reduction in temperature readings from all the tests for the thermocouple on the side nearest the live module while it is not so apparent at the front of that module. This demonstrates the differences in results that may be encountered when studying positions that are affected by variations in flame direction.

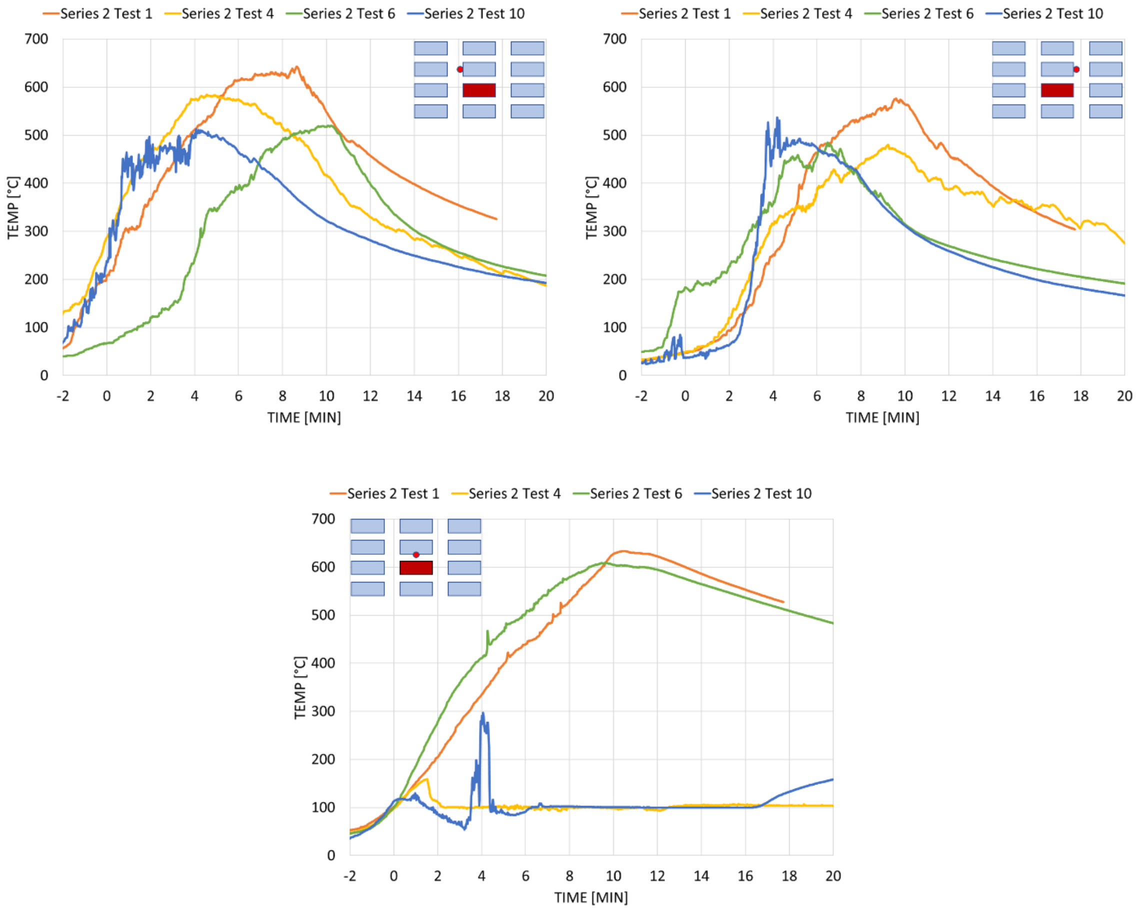


Figure 54. Temperature readings on the module directly above the live module for tests using water as extinguishing media against NMC module.

Studying the temperature reading on module 6 and 10 in Figure 55 for the tests where only water was applied a strange pattern is seen, i.e. the drastic increase of temperature above module 10 in the test with local application of water. Fire development was different in this test which probably delayed reaching the temperature criteria and then when the system was released the rather high momentum probably forced the flames towards module 10.

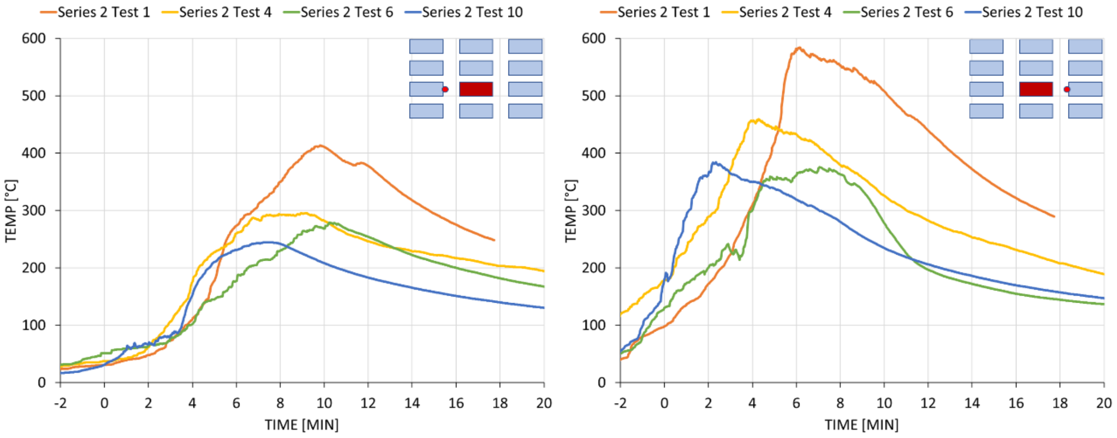


Figure 55 Temperature readings on module 6 and module 10 for reference test and tests using water as extinguishing media against NMC module.

The fire development after the criteria was met during the tests where the gaseous fire suppression system was used is shown in Table 18. In both cases the visible flames seen near the front of the module were extinguished shortly after the system was released. The fire continued to burn some time near the rear, but even this flame was extinguished by the 3 min mark. Note that although there were no visible flames, the live module continued to release flammable gas. In other words, cell-to-cell propagation continued.

Table 18 Overview of the fire development after the criteria was met in Test 11 and 13.

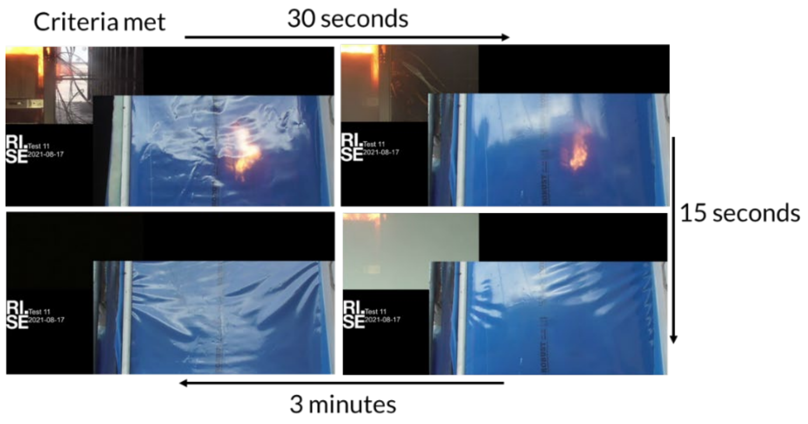
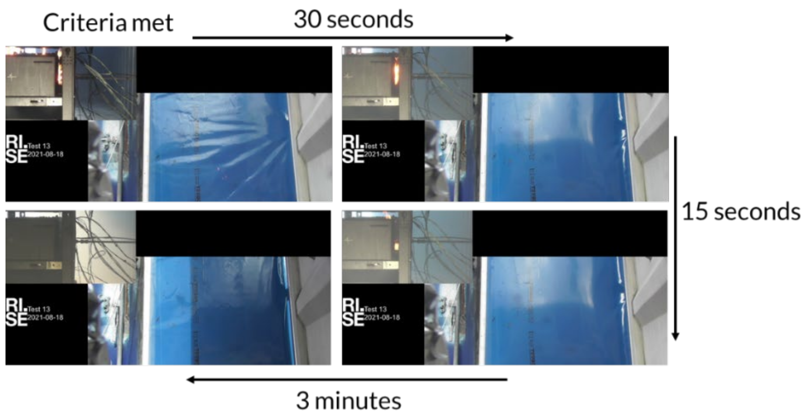
Test 11	NMC Gaseous	
Test 13	LFP Gaseous	

Figure 56 shows the results from the test using a gaseous agent system against a NMC module. Activation of the system resulted in a fast temperature decrease, likely due to the extinguishment of the flames. This shows that flame extinguishment is an effective short term cooling method. However, as temperatures are above critical limits (85 °C criteria of DNV GL), module-to-module propagation may still occur.

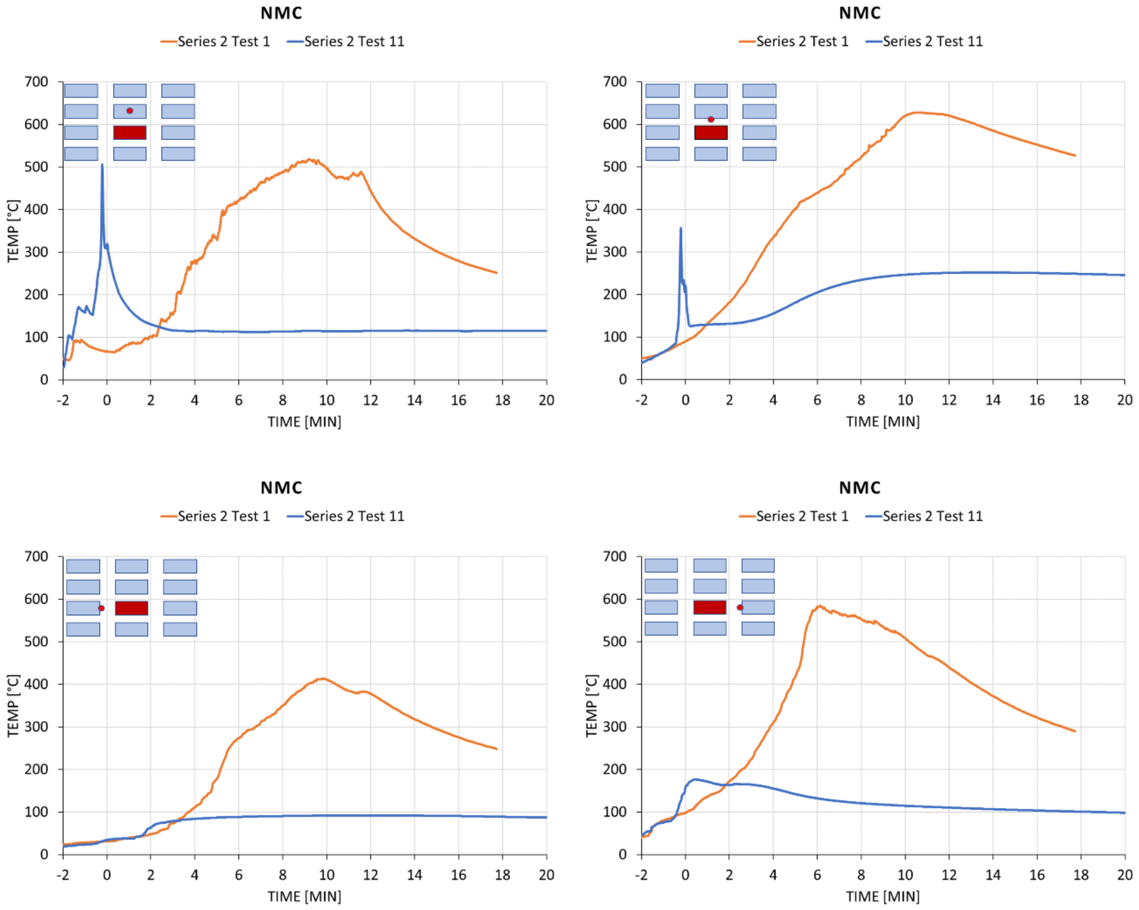


Figure 56. Result for the gas system against NMC module.

Looking at the results on the LFP tests, see Figure 57, the effectiveness of the system's ability to extinguish flames is even more pronounced. Here the temperatures are below 85 °C except for the temperatures at the module directly above the live module.

The readings from the tests where sprinklers were used against NMC module are shown in Figure 58. There is a positive impact from the sprinklers and a tendency to an increased impact when using an additive. The differences from the additive are however rather small in most cases and almost in the same order of magnitude as the differences between the reference tests.

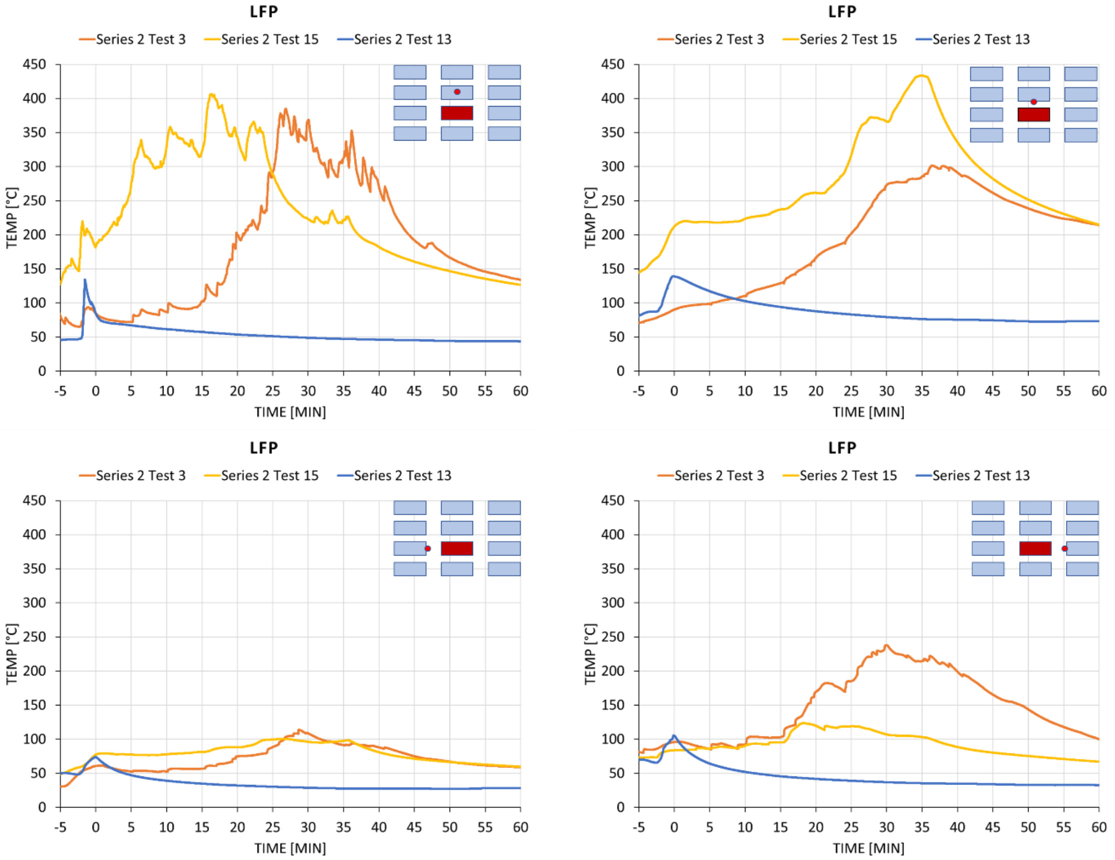


Figure 57. Test results reference test and gas system against LFP module

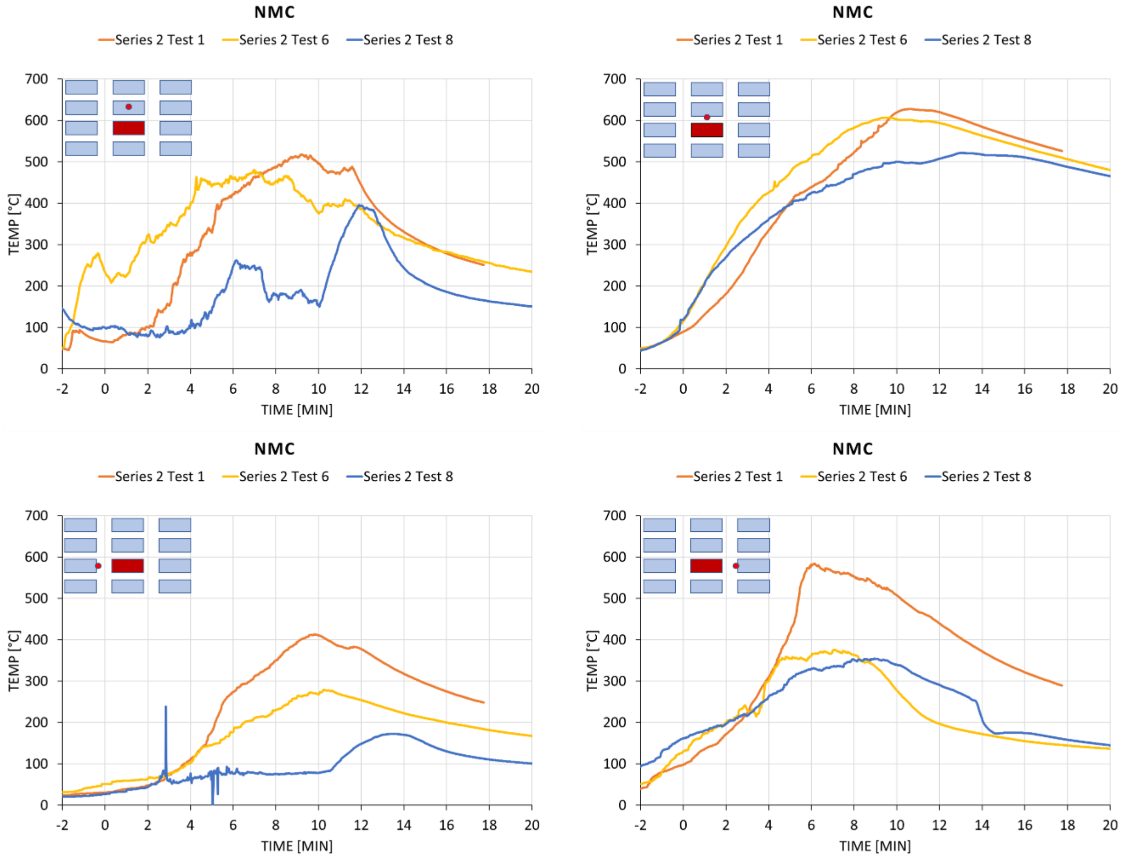


Figure 58. Temperature readings reference and sprinkler tests against NMC module.

Figure 59 and Figure 60 present the average temperatures inside module 3 after the fire suppression system activates. First an average was taken for thermcouples within module 3, then this result was averaged over a 5, 15, or 40 min interval. This gives and indication on the immediate, short term, and long term cooling effect the different systems have. Note that this assumes that the test conditions are similair to what was observed in the reference tests however.

For the NMC tests seen in Figure 59, the immediate result was that average temperatures remained below critical levels, even without fire suppression. Temperatures then become increasingly hazardous as time progresses. The progression inside M3 appears to be halted or slowed down however in Test 4, Test 10, and Test 11. Considering M6 and M10, most systems appeared to have delayed this progression. Based on these graphs, it may appear as if matters were made worse in Test 10 and Test 14. Temperatures here were highest immediately after the fire suppression system activated (except for in M3, Test 10) and then reduced. It cannot be concluded that this result is due to the fire suppression system, as a slightly different module was used in Test 10 and 14. This module appears to have had a different fire behavior, resulting in a more intense fire by the time the trigger criteria were met, and the fire suppression system released.

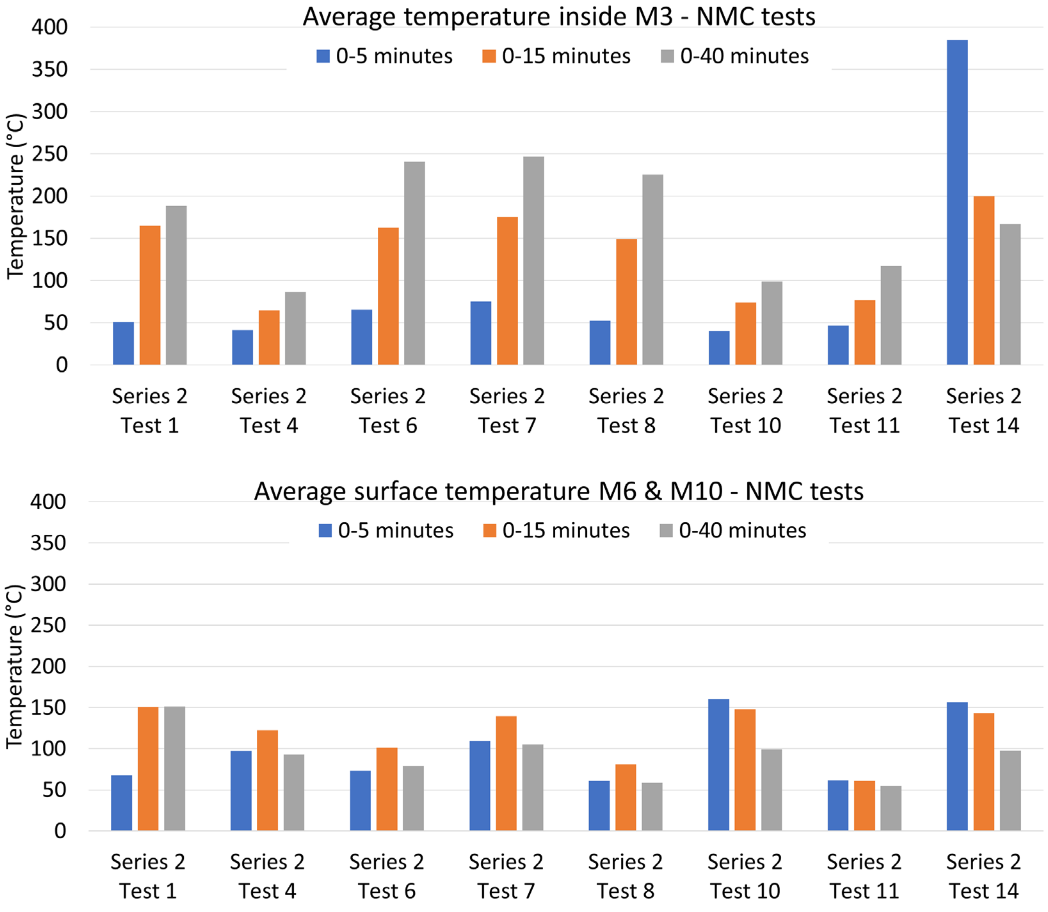


Figure 59 Average temperatures taken over different intervals for the NMC tests. The time starts when the fire suppression system activates (30 s after the criteria are met).

Average temperatures in M3 for the LFP tests are seen in Figure 60. The overall effect of the fire suppression systems does not appear to be significant. Test 5 and Test 13 appeared to be more successful in limiting temperatures at M6, M10 and inside M3.

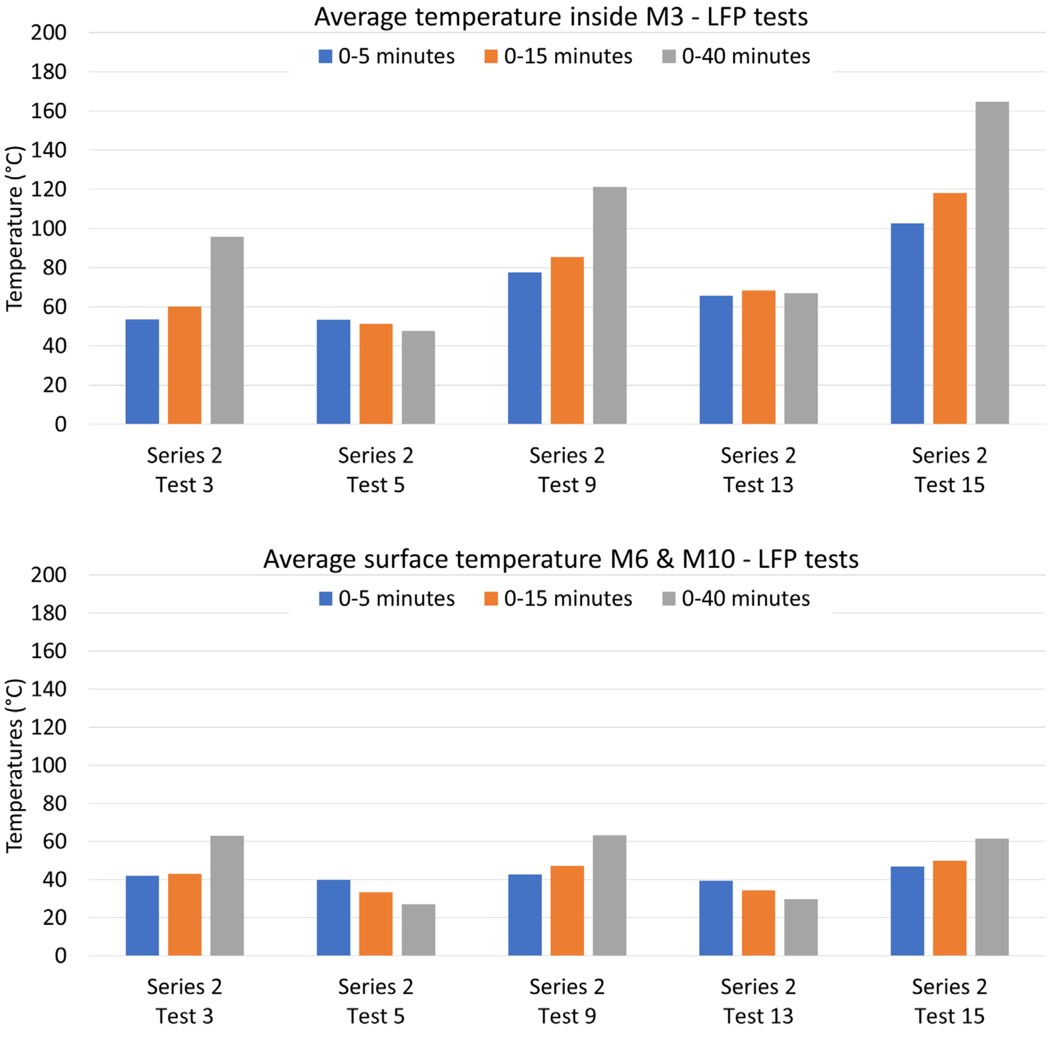


Figure 60 Average temperatures taken over different intervals for the LFP tests. The time starts when the fire suppression system activates (30 s after the criteria are met).

Once the trigger criteria were met, thermal runaway continued to propagate through the live module. The modules were opened after each test as shown in Figure 61. The NMC modules were all severely damaged after the test. As was seen in Figure 36, they fell apart as soon as they were removed from the rack. The LFP modules however remained intact. As such, it was possible to weigh them after testing.

Figure 61 State of the modules after testing, NMC module (left); LFP module (right) after having its lid removed.

An overview of the recorded weights is given in Table 19. The mass loss is comparable for all the tests. This result is reasonable since it was found that there were no active cells (i.e. cells carrying electrical charge) in any of the modules after the tests except in Test 12 which were terminated due to problem with initiating thermal runaway. It appeared that the cells were at 50 % SOC despite the module indicating 100 % SOC. This explains why thermal runaway propagation could not be achieved in this specific test despite significant heating.

Table 19 Battery weight after testing

Test	Battery	Suppression system (see Table 9)	Weight after testing (kg)	Mass loss (%)
2	LFP	None	37.9	15.6
3	LFP	None	37.3	17.2
5	LFP	Water mist	36.9	18.1
9	LFP	Water mist	35.4	21.2
13	LFP	Gaseous	36.8	18.2
15	LFP	None	36.7	18.4

7 Discussion

This work was conducted to provide input for potential future development of a test method for suppression systems towards Li-ion battery fires and to add on to the publicly available test data on different types of extinguishing systems and medias performance against Li-ion battery fires. Two test series was conducted where the first series had a focus on the experimental apparatus and test protocol while the second series also involved different extinguishing systems and media. The test series were limited but still provided useful experiences which are discussed further in this section.

7.1 Performance of the experimental method

The experimental set-up chosen was a 19” open rack system 4 modules high. In the bottom there was a dummy module and then one live module above that, and on top of those two dummy modules. A rack with 4 dummy modules was placed adjacent to the rack with the live modules. The racks were fixed together to match what was observed in commercial battery systems.

The experimental set-up using a 19” rack system turned out to be robust enough to run several tests on the same set-up. In some cases, water was able to penetrate in to the dummy modules. Some of these modules were deformed due to the repeated heat and therefore it was not possible to completely prevent water from entering even if the modules were sealed used tape in between tests. The measurements clearly show when water penetrated the dummy modules. In a sense, the fact that water did penetrate some of the modules showed that the system was able to reach a distance in between modules.

Thermocouples were welded on the exterior of the dummy modules and in some of the modules were thermocouples also placed inside the dummy module. The setting with thermocouples turned out to be robust enough to last the entire test series.

The thermal runaway initiation using a burner resulted in very repeatable thermal runaway propagation for the NMC modules. This proved more challenging for the LFP modules. The trigger point chosen was the same for the NMC and LFP modules. The point was based on the temperature’s underneath and on the sides of the module directly above the live module. It might be that the repeatability for the LFP modules could have been improved by choosing a somewhat later trigger point. If a trigger point was to be selected for the NMC module only, an earlier point could have been chosen.

Table 20 shows a comparison between the experimental set-up in this study towards previous studies. The test setups considered in the different studies are comparable but with slight differences in terms of size of rack and configuration, which adds to the publicly available data on fire suppression tests against li-ion batteries.

Table 20 Comparison between setup in this study and other studies

	This work	DNV-GL [3]	FM Global [27]	UL [28]
Number of modules (live modules)	12 (1)	18 (1)	16 (16)	45* (18)**
Type of rack / modules	Open	Open	Partially closed	Partially closed
Dimensions modules/rack (mm)	NMC: 440×352×173/ LFP: 440×420×173/	500×300×200 /	NMC-LMO: 650×320×240/ LFP: 700×270×180/	NMC: 508×406×171/
Horizontal spacing of modules (mm)	160	Unknown	Unknown	Unknown
Vertical spacing of modules (mm)	88.9	Unknown	Unknown	Unknown
Thermal runaway initiation	Gas burner (external)	Resistive heaters (internal)	Resistive heater (external)	Resistive heater (internal)
Activation of suppression (s)	30 s time delay after temperature criteria	30 s time delay	Sprinkler link actuation	30 s delay after sprinkler link actuation (sprinkler) Activation of smoke detector (gas)
* Assuming the dummy units contained dummy modules ** The target modules are counted as 0.5×live modules as half of them is filled with live cells				

Repeatability proved to be more promising for the NMC tests than for the LFP tests. There was a variation for some of the NMC tests where the flames were more on the rear of the modules. This was probably due to a slightly different placement of the individual cells in these modules. This shows the importance of having the same modules to be able to make a comparison between systems. Also, the activation criteria were affected in these cases.

7.2 Evaluating the test results

The goal with this test setup was to evaluate heat transfer from the initiating live battery module to surrounding dummy modules. In other words, to evaluate the risk for module-to-module propagation. Self-heating reactions inside li-ion battery cells may be triggered when their temperature exceeds about 80 °C [36]. To evaluate the risk of module-to-module propagation, the temperature of both the live and dummy modules had to be monitored. If a dummy modules external or internal temperature would surpass a certain threshold, one can assume that there is a significant risk that thermal runaway would be triggered if it had been a live battery module. According to DNV's rules for classification of ships [21], the passing criteria is that a temperature of 85 °C is not reached anywhere in the neighbouring modules, as detected at the least favourable locations.

Specific criteria and evaluation methods would be beneficial in order to interpret and evaluate test results. In these test series these were developed as testing progressed. Looking at the test results provided better insight into what happens, and which parameters/factors could indicate how a fire suppression system performed. Temperature measurements were the main interest as it would indicate the cooling effect of the systems, i.e. how well it can control temperatures and lower the risk for module-to-module propagation.

Evaluating the results with 60 data points as a function of time for each test was challenging. Especially as trends might vary in different positions between different tests. One system could be better in cooling at one position than another system, and the other way around in another position or at another time. Also, some systems can have an immediate effect while another system provided more long-term cooling. Long-term and short-term cooling effects were considered by looking at the average temperature inside the modules. The long-term cooling relates to the risk of reignition, i.e. how likely it is that the battery will catch fire again or Thermal runaway starting. To achieve this the cooling effect of a fire suppression agent needs to be lasting and keep temperatures under critical limits if possible. The short-term refers to the direct effect the system has on the fire as it activates. Some systems may perform better at reducing temperature quickly upon release as it not only cools but also extinguishes flames.

An overview of all the tests results and the effect each system had is given in Appendix A: Test data. Here all the temperature measurements are given over time for each test. In some cases, signals from the gas alarm, only present in the second container, are also given.

7.3 Adding to the knowledge base

One of the goals for this work was to complement the publicly available test data, aimed at extinguishing and controlling li-ion battery fires. A comparison on cells used and extinguishing systems used between this test series and previous studies is provided in Table 21.

Table 21 Comparison between tests conducted in this study and previous studies

	This work	DNV [3]	FM Global [27]	UL [28]
Cells (SOC)	NMC 18650 (100%) LFP prismatic (100 %)	NMC pouch (100%) LFP cylindrical (100%)	LFP prismatic (95%) NMC/LMO prismatic (95%)	NCA 18650 (100%)
Energy capacity (kWh)	4.8	1.3	LFP 5.2 NMC 7.8	28.9
Extinguishing systems	Sprinkler Low pressure water mist Local external application Gaseous (Inergen)	Sprinkler High pressure water mist Gaseous (Novec 1230) Internal application	Sprinkler (12 mm/min)	Sprinkler (20 mm/min - 0.5 gpm/ft^2) Gaseous (Novec 1230)
Additives	F500, AVD	CAFS, Novec 1230	None	Novec 1230

7.4 Mitigating thermal runaway propagation

The systems used in this study were not optimised for this application with fire in a Li-ion battery rack due to thermal runaway. One of the tested systems was specifically intended for Li-ion but not optimised for this configuration. The systems were in most cases designed according to the normal design procedures for any type of fire, except for the gaseous system. It was over-dimensioned compared to what is normally used for volumes of the same size as what was considered in the tests.

As the floor area was limited (about 2.4 m× 6 m) all the water-based systems chose to use only one nozzle. In all tests the door was open, a fact that might have influenced the total flooding water mist system as the water mist concentration in the air was not maintained as water was disappearing out through the open door and fresh air entering the container.

None of the systems were able to mitigate the spread of the thermal runaway propagation within the live module. This was not anticipated either. When the extinguishing systems were activated, one could see a decrease in flames at least at the front of the rack. Lowered temperatures could also be observed at some locations. The gaseous system was efficient in extinguishing the flames. But when the seal of the container was opened, burning started again. The differences between results with and without additives showed some positive effect of the additives at some locations but the differences were small, and it is not possible to rule out that differences observed are due to other factors. When studying the results, it is important to keep in mind that the systems used were not specifically designed for this extinguishing situation and the results might be different if properly designed.

As seen from Appendix A the systems had a positive impact on the risk for module-to-module propagation at some locations, but peak temperatures were still above critical levels. It should be kept in mind though that these temperatures are on the external surface, the temperatures will be somewhat lower inside the modules.

In some cases, water was able to penetrate the modules, which had a positive impact on the temperature development. The water reaching the different surfaces is important and penetrating the module would be an efficient way to provide cooling. Potential negative effects of penetrating the modules were not assessed in these tests.

8 Conclusions

This work provided input towards the development of a method for fire extinguishing tests on battery systems. Specifically, extinguishing systems whose aim it to prevent module-to-module, and beyond, propagation. In addition, the tests performed added to the publicly available full-scale tests results, information that is limited yet essential to design safe battery systems.

Study visits were performed to ships operating in Sweden and having li-ion battery systems on-board. Unfortunately, the ongoing global Corona pandemic meant that not all visits could be carried out as planned. Instead, information and documentation of the different installations, granted to the project, were reviewed. This background information was the foundation upon which the experimental setup was built. It also showed the different safety solutions that are considered today, apart from fire suppression, that enable safe operation.

Guidelines and requirements from ship classification societies for battery systems were investigated together with national regulations and standards. This information, combined with knowledge gained from previous studies and the literature, and the study visits, resulted in a mock-up for evaluating fire suppression systems. Specifically, an open 19” rack where a live module is surrounded by dummy modules. The dummy modules were filled with sand to reach a similar thermal mass as the live module.

Temperature sensors placed on external surfaces as well as inside one of the modules were used to evaluate the risk for module-to-module and rack-to-rack propagation. In addition, Plate Thermometers were used to assess risk for propagation to a potential opposite row of racks. Different thermal runaway initiation methods were investigated, and it was decided to utilise a localised burner.

Two test series were conducted. The first series focused on verifying the mock-up and chosen experimental parameters. The thermal runaway initiation method was investigated as well as suitable criteria for fire suppression system activation. These tests were conducted without any extinguishing systems, i.e. free burning reference tests. Tests were conducted using two different module types, one with NMC cylindrical 185650 cells and one with prismatic LFP cells.

The NMC tests showed great repeatability and allowed for the onset of thermal runaway propagation to be easily identified. This proved more challenging for the LFP test. A criterion was developed based on surface temperatures of the dummy module directly above the live module. Specifically, the surface temperature underneath and on either side of this dummy module. These surfaces were required to measure above 70°C for 10 seconds and, at least for one of the sides, above 100 °C for 10 seconds, respectively.

The second series involved fire extinguishing systems. These tests were conducted at an outdoor facility, while the developed test setup was installed in standard 20-ft. shipping containers. The extinguishing systems were selected to represent both those systems already used today in e.g. machinery spaces on-board and systems that are under development. This included water-based systems test, which were evaluated with only water and water plus an additive. The same principle, i.e. pure water and water plus additive, was followed for a local application system. Finally, a gaseous based system, utilising higher than normal design concentration, was used.

A total of fifteen tests were performed during the second test series. The developed rack was robust enough to manage this large number of tests without failing. The importance of using the same live battery modules became very clear from these tests. Especially if they are to be used as a reference to later compare other tests with. In two of the tests the modules were slightly different which affected the fire development and resulted in the activation criterion no longer being valid. In all other cases however, this criterion was effective in both the LFP and NMC tests. To improve the developed methodology however, the criterion should be developed for the specific live module that fire suppression systems are to be tested on. The test series also showed that multiple tests are likely needed due to the natural variation in fire tests. With the possibility to use dummy modules this would still be viable s the use of dummy modules would lower cost for testing.

A tremendous amount of data was gathered from these tests, in particular temperature measurements on the dummy modules. It was challenging to carefully evaluate such a volume of data. Temperatures varied with the locations that were studied. This was found to relate to differences in the trajectory of flames. Although most of the sensors were located external to the dummy modules, the internal sensors provided useful when interpreting results. A greater number of internal temperature sensors would be recommended in future tests.

All fire extinguishing systems achieved a positive impact on the temperature development at some point. For the local application system, it was difficult to assess performance due to the different module that was used. In some cases, the additives had a positive impact on module-to-module propagation risks. These differences were however rather small in most cases and almost the same order of magnitude as the variation observed from reference tests. In general, the systems were not optimized for handling a li-ion battery fire. There are no test methods that allow the suppliers to do so. Rather, conventional systems and water densities were used, except for the gaseous system. To arrive at such solutions, objective testing under repeatable conditions is a must, so that manufacturers may arrive at the effective solutions.

The gaseous system had the greatest impact. Its activation significantly lowered the immediate risk for module-to-module propagation. This specific system was not representative of a conventional system, however. It was over-dimensioned compared to what is normally used for volumes of the same size as what was considered in the tests. Regardless, this result is very interesting as its shows that gaseous system can be an effective approach. Arguably even more so when followed-up by other means of cooling.

Even if extinguishment or mitigation of a battery fire is key for the safety, it is still only one piece of the solution for a safe introduction of battery propulsion. Li-ion batteries present a special source of fire, and it is not always the best solution is to extinguish the fire, as it can pose an explosion risk when flammable gases are accumulated, this is something that is not covered directly in this work.

9 Future work

The work done in this project was a step towards a test method that may be used to evaluate fire suppression systems for battery systems. To finally arrive at an appropriate test method however, there is still work that needs to be done. Some suggestions for future work include:

- Investigate the impact of different parameters such as gaps between racks and within racks as well as alternative placement of the initiating module
- Investigate the impact of using different battery cells and module, as well as whether these should be standardised.
- Refine the activation criterion and possibly adjust this for specific chemistries and packaging of cells and configuration of modules
- Investigate the placement of thermocouples especially which ones should play a role in evaluating test results.
- Investigate run off from different systems to evaluate their potential environmental impact
- Building on the knowledge base with tests conducted on systems designed for dealing with fires in li-ion battery systems.

In addition, work to further develop solutions for mitigating module-to-module propagation could be done with the test setup used here. This includes investigating combination of different means like insulation and spacing between modules, combining different types of suppression systems, etc.

Also, potential impact of different types of mitigation methods on the toxic fumes emitted during a fire, as well as their environmental impact, can be an area for further research. This was not studied in this report.

References

1 Andersson, P., Wikman, J., Arvidson, M., Larsson, F., Willstrand, O., “Safe introduction of battery propulsion at sea”, SP Rapport 2017:34, SP Borås 2017

2 Andersson, P., Arvidson, M., Evegren, F., Jandali, M., Larsson, F., Rosengren, M., “Lion Fire: Extinguishment and mitigation of fires in Li-ion batteries at sea,” RISE Report 2018:77, RISE Borås 2018

3 “Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression,” DNV GL 2019-1025

[4] Guarnieri, M., “Looking back to electric cars,” Third IEEE HISTory of ELectro-technology CONference (HISTELCON), pp. 1-6, doi: 10.1109/HISTELCON.2012.6487583, 2012

[5] Nissan Motor Corporation, “A decade of innovation – the Leaf’s incredible journey.” Retrieved from https://global.nissanstories.com/en/releases/nissan-leaf-10years, accessed 2 December 2021

[6] Herold, M. et al, “Principles for risk-based fire protection strategies for li-ion battery cell production,” Siemens & TÜV SÜD, 2021

[7] European Environment Agency, “EU (Convention) – Share of transport greenhouse gas emissions.” Retrieved from https://www.eea.europa.eu/data-and-maps/daviz/share-of-transport-ghg-emissions-2#tab-googlechartid_chart_13, accessed 22 November 2021

[8] DNV GL, “Alternative Fuels Insight Platform,” Retrieved from https://afi.dnvgl.com/, accessed 5 December 2021

[9] RISE Research Institutes of Sweden and Chalmers University of Technology, “Electric light – Lätta elfartyg: Lightweight and electrically propelled Ro-Pax ship,” 2021

[10] Bisschop, R., Willstrand, O., Amon, F., & Rosenggren, M., “Fire Safety of Li-ion Batteries in Road Vehicles.” Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-38873, 2019

[11] Transportstyrelsen, “About us.” Retrieved from https://www.transportstyrelsen.se/en/About-us/, accessed 5 December 2021

[12] Wikipedia, “MF Tycho Brahe.” Retrieved from https://en.wikipedia.org/wiki/MF_Tycho_Brahe, accessed 5 December 2021

[13] Danish Maritime Authority, “OVIC2- Tycho Brahe.” Retrieved from https://shipregister.dma.dk/ship/df5c7976-052d-ec11-8128-0050569a1acd, accessed 5 December 2021

[14] Wikipedia, ”Göta älv,” accessed 5 December 2021

[15] Bång, K., ”Elvy vid Stenpiren,” Göteborg 2020-01-30, accessed 23 November 2021, retrieved from https://www.skargardsbatar.se/elvy_2019/

[16] Hörlin, D. and Jonsson, E., “Operational advantages and limitations of battery hybrid operations,” Chalmers University of Technology, 2020

[17] Vågen, A., - Own work, CC BY-SA 3.0, accessed 22 November 2021, https://commons.wikimedia.org/w/index.php?curid=28689052

[18] Halme, S., Own work, CC BY-SA 4.0, accessed 23 November 2021, retrieved from https://commons.wikimedia.org/w/index.php?curid=110413716

[19] Lloyds Register, “Rules and regulations for the classification of Ships,” July 2021

[20] Lloyd’s Register, “Type Approval System Test Specification Number 5 – Type testing for lithum battery systems,” Lloyds register, March 2019

[21] DNV GL, “Rules for classification – Ships – Part 6 Additional class notations – Chapter 2 Propulsion, power generation and auxiliary systems,” DNV GL July 2020

[22] DNV GL, “Class Programme – Type Approval, DNVGL-CP-0418, Li-ion batteries,” September 2018

[23] “Rules for the classification of Steel Ships – PART C- Machinery, Electricity, Automation and Fire Protection,” Bureau Veritas, July 2021

[24] Rules for the classification of Steel Ships – PART F- Other Additional Class Notations Sec 21 Battery System” Bureau Veritas, July 2021

[25] Baird A. R., Archibald E. J., Marr K. C., Ezekoye O. A., “Explosion hazards from li-ion battery vent gas,” J. Power Sources, (2020) 446, 227257

[26] Willstrand, O., Bisschop, R., Blomqvist, P., Temple, A., & Anderson, J. “Toxic Gases from Fire in Electric Vehicles.” Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:ri:diva-52000, 2020

[27] Ditch B. and Zeng D., “Development of Sprinkler Protection Guidance for Lithium Ion Based Energy Storage Systems,” Technical report FM Global 2019, RW000029

[28] UL “UL 9540A installation level tests with outdoor lithium-ion energy storage system mockups”, 2021

[29] UL, “UL9540A Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems,” Edition 4, 2019

[30] Golubkov A. W., Scheikl S., Planteu R., Voitic G., Wiltsche H., Stangl C., Fauler G., Thaler A., Hacker V., “Thermal runaway of commercial 18650 Li-ion batteries with LFP and NCA cathodes – impact of state of charge and overcharge,” RSC Adv., (2015) 5, 57171

[31] Hazard Control Technologies, “F-500 Encapsulator Agent (EA).” Retrieved from https://hct-world.com/products/chemical-agents/f-500-encapsulator-agent/, accessed on 5 December 2021

[32] AVD Fire, “What is Aqueous Vermiculite Dispersion?,” Retrieved from https://www.avdfire.com/what-is-aqueous-vermiculite-dispersion/, accessed 5 December 2021

[33] Q-fog, “Products,” Retrieved from http://qfog.se/wp/en/products/, accessed 5 December 2021.

[34] Ansul, “Inergen systems – 300-bar Iflow technology.” Retrieved from https://www.ansul.com/en/us/pages/ProductDetail.aspx?productdetail=INERGEN+Systems+%E2%80%93+300-Bar+iFLOW+Technology, accessed 6 December 2021.

[35] Bisschop, R., Willstrand, O. & Rosengren, M. Handling Li-ion Batteries in Electric Vehicles: Preventing and Recovering from Hazardous Events. Fire Technol 56, 2671–2694 (2020). https://doi.org/10.1007/s10694-020-01038-1

[36] Mao, B., Huang, P., Chen, H., Wang, Q., Sun, J., “Self-heating reaction and thermal runaway criticality of the lithium ion battery,” International Journal of Heat and Mass Transfer, Volume 149, 2020, 119178, ISSN 0017-9310, https://doi.org/10.1016/j.ijheatmasstransfer.2019.119178.

Appendix A: Test data

Test data from all tests that were performed including some discussions are included here.

First test series

Results from the first test series are presented in full here. A discussion of the results was presented in the report.

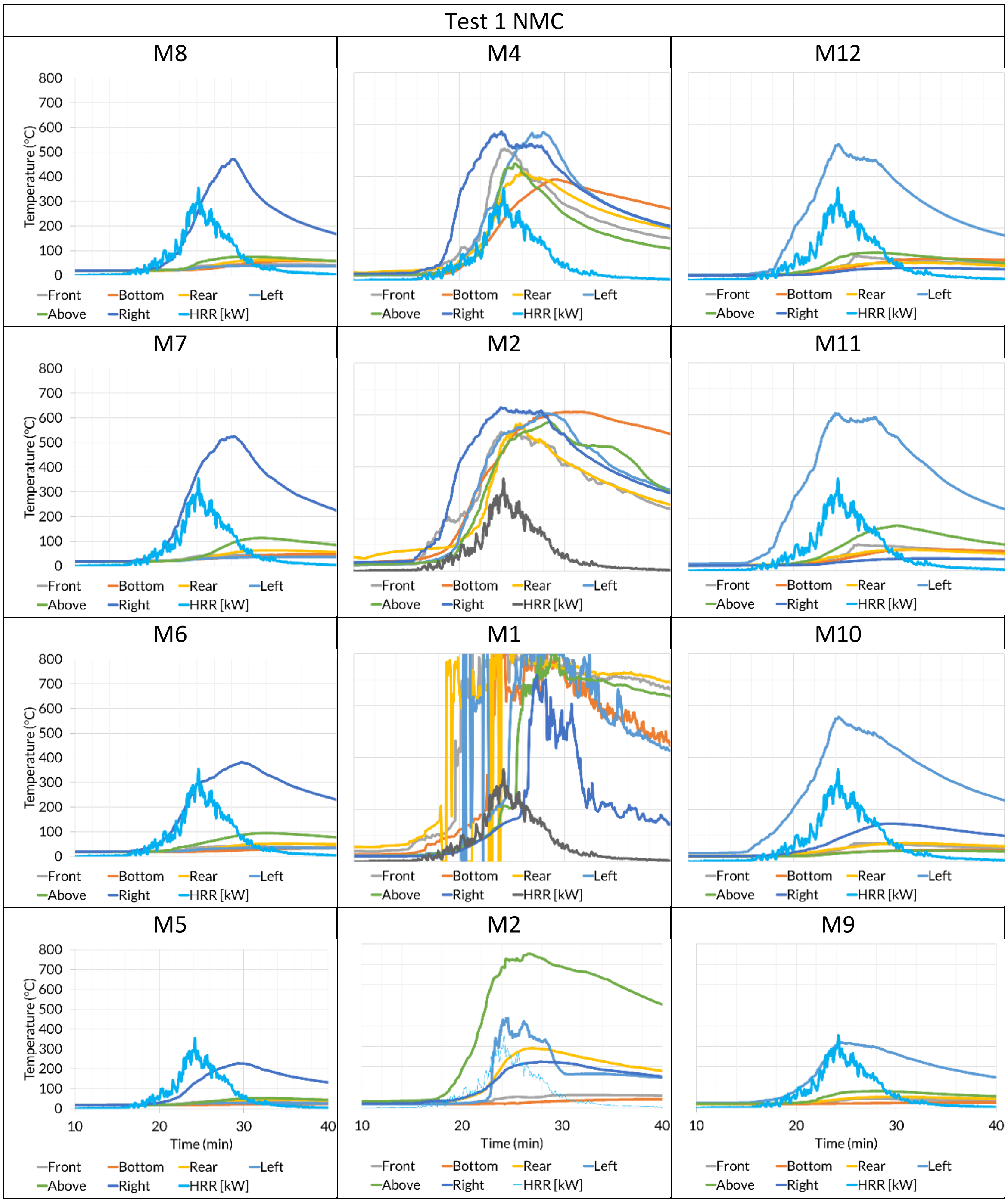


Figure 62 Test series 1: Test 1 – NMC

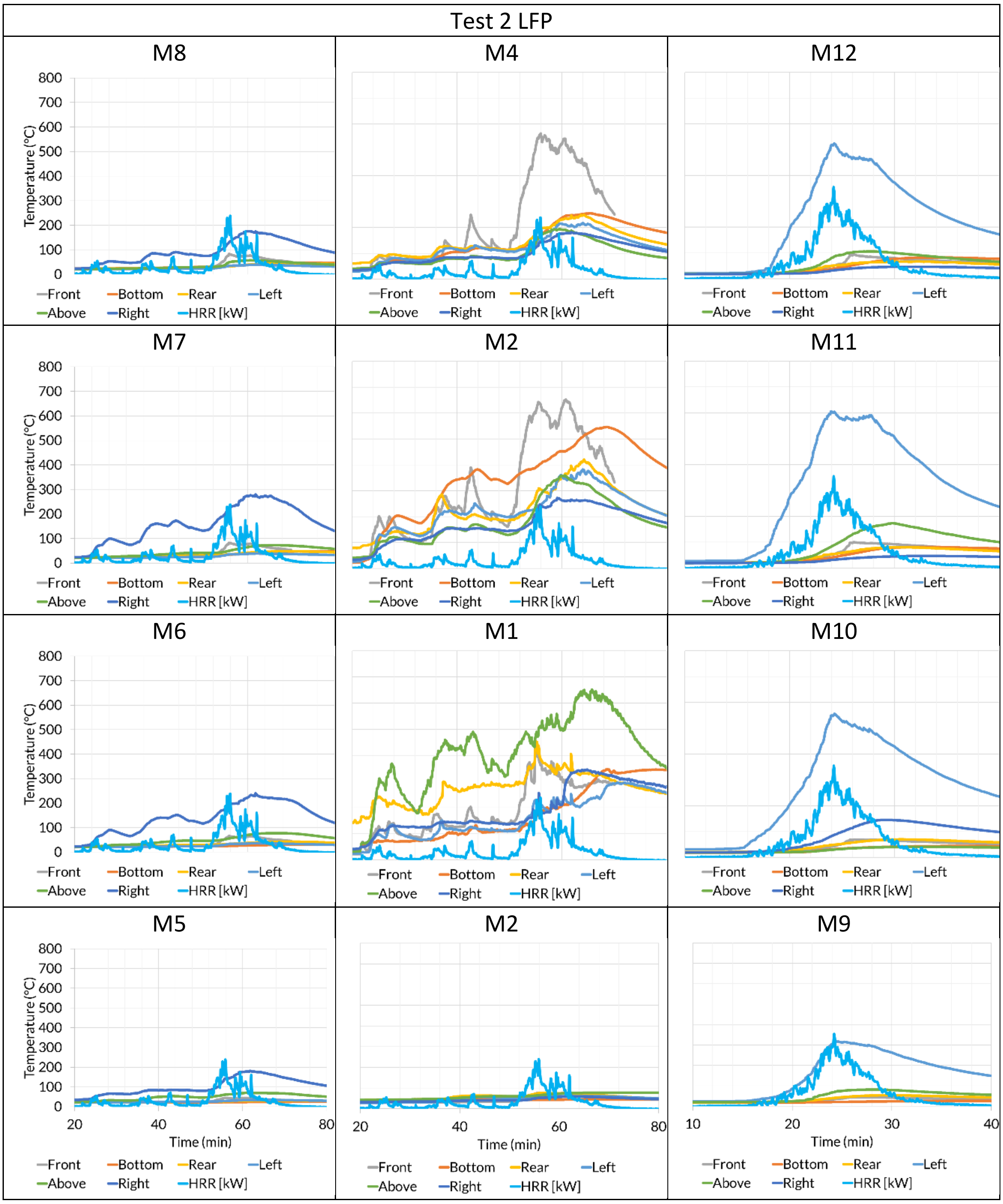


Figure 63 Test series 1: Test 2 – LFP

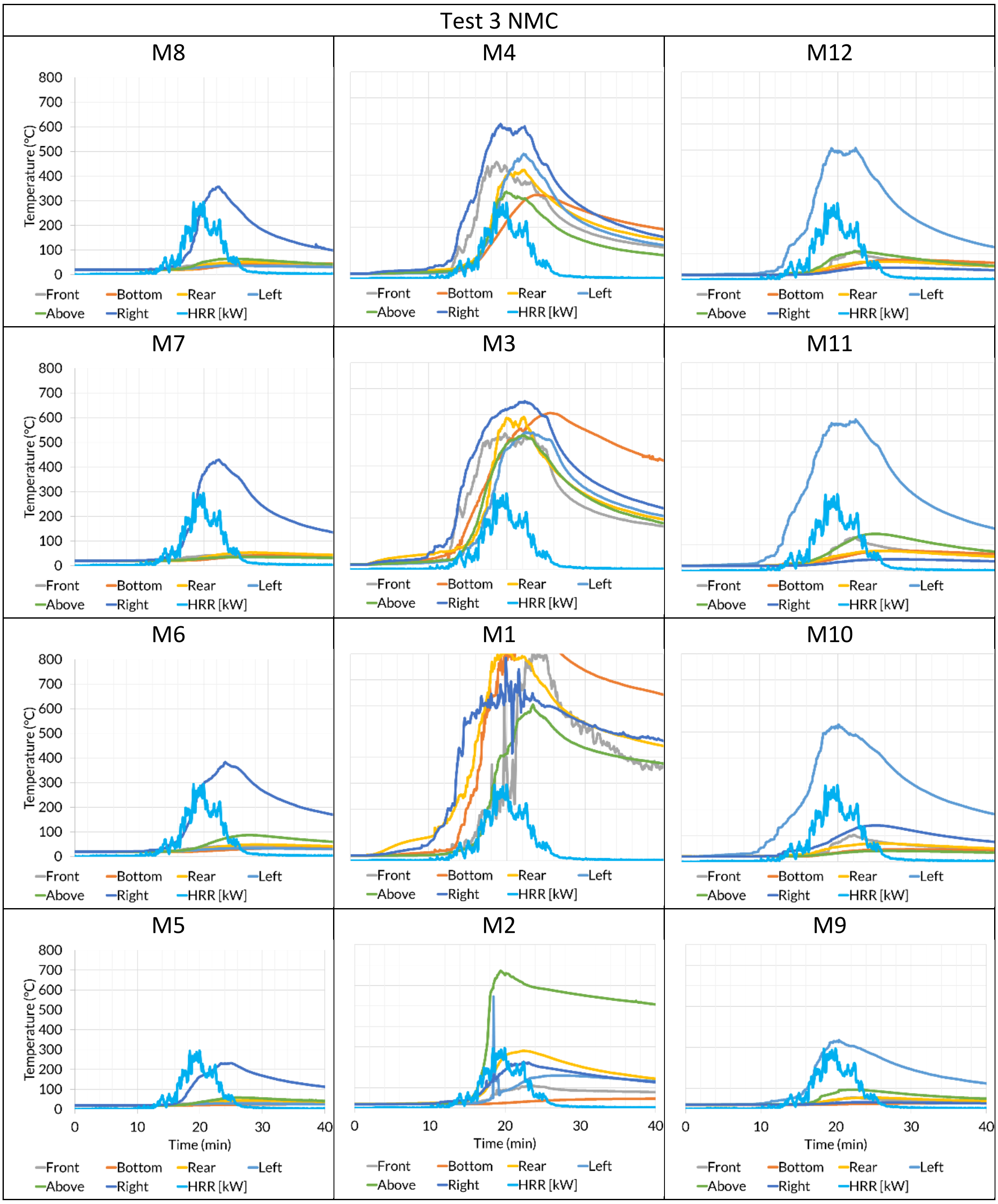


Figure 64 Test series 1: Test 3 - NMC

Second test series – NMC tests

Results from the second test series with NMC modules are shown and discussed in this section. The focus is on discussing the effect of the fire suppression system rather than the test setup.

Test 1 Reference test NMC

External surface temperatures during the reference test with an NMC module are shown in Figure 65. Here, heat mostly spreads upwards and towards the right (also the same side where the fire was initiated) in the rack. Looking at the modules that are at the same height or above M1, temperatures reached to about 400-600 °C. In case of M6-M12, this was recorded on the surface closest to the initiating module. For M3, temperatures are initially most significant on the left. This temperature then started to decrease while the temperature underneath increases. Modules at a lower height then M1 (M5, M2 and M9) show lower temperatures except for above M2, where almost 800 °C is measured. These results show, that from a single module failure, the entire row of racks may be lost if no mitigation measures are taken.

Temperatures inside M1 and M3 are seen in Figure 66. In case of M1, the time needed to trigger thermal runaway can be seen as well as how this propagates to different areas of the module. First, thermal runaway takes place at the initiating area. It then eats its way through the module from the initiating corner to the opposite corner where Internal 4 is located (close to the BMS and electronics). Inside M3, temperatures are higher next to the steel cover, reaching to about 350-450 °C. Further into the module, 1.5 cm to be precise, temperatures are lower at 200-300 °C, yet these are remained hazardous. If this were another live module, there would be a severe risk for module-module propagation.

Temperatures on the opposite row of racks, recorded by plate-thermometers, are about 170 °C -175 °C. This means that in this scenario there is even a risk for propagation to the opposite rack in case a single module fails.

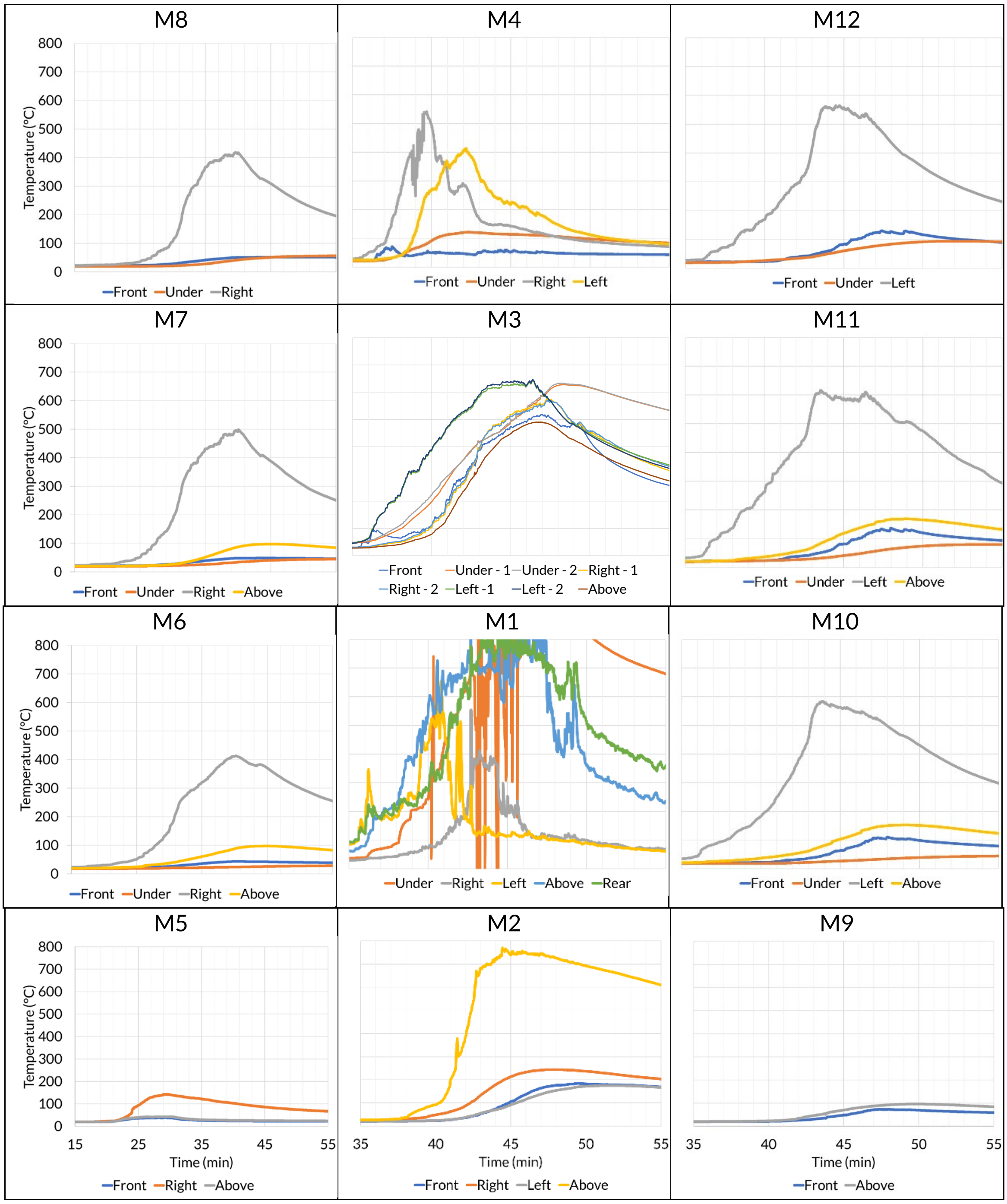


Figure 65 External surface temperatures: Test 1 – NMC. All scales are the same in the figure

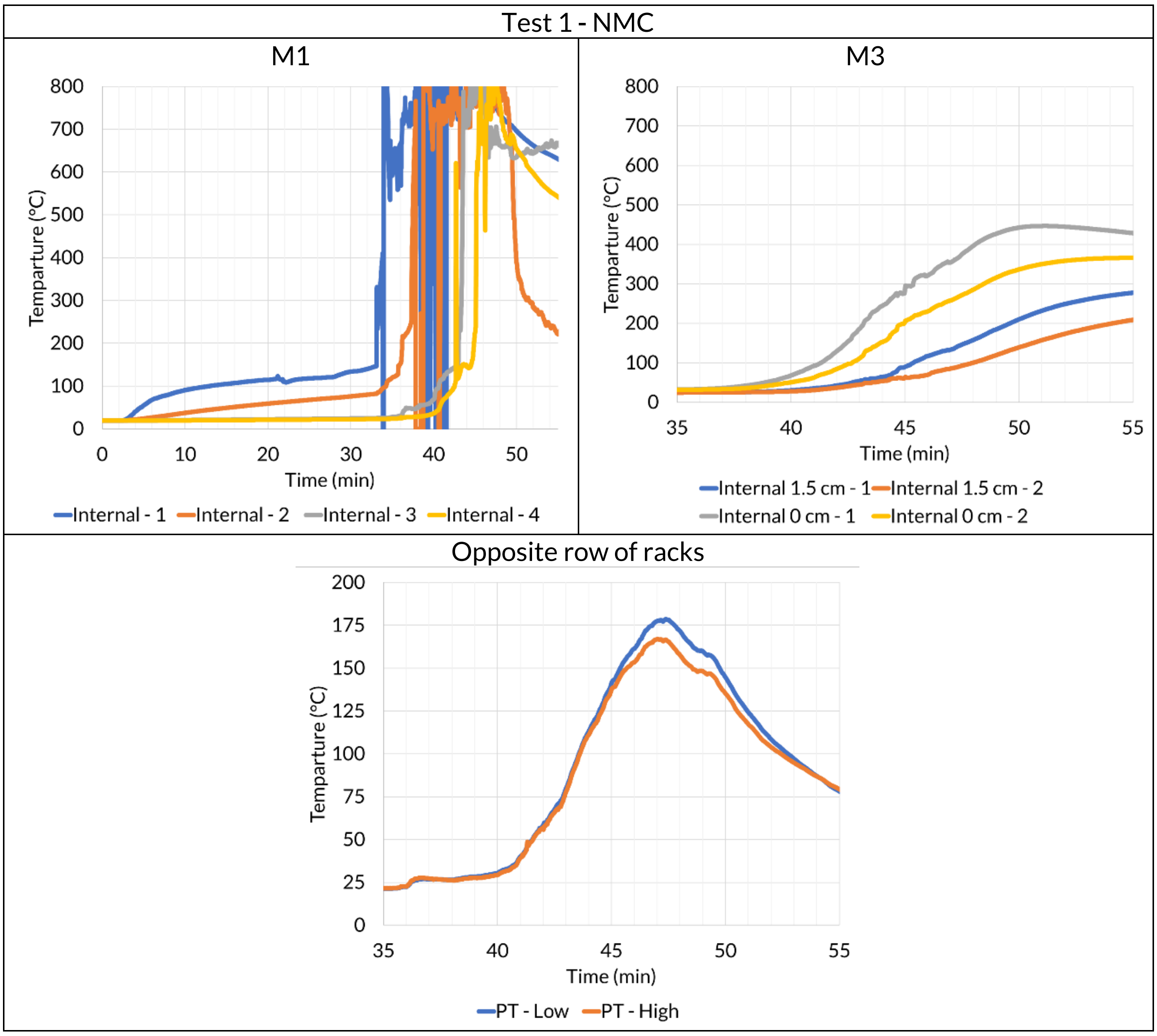


Figure 66 Internal temperatures and plate-thermometers: Test 1 – NMC

Test 4 NMC – Water mist system

Figure 67 gives results from Test 4. Here a mist system was used with water as the suppression agent. The system was activated at time 20 minutes and 3 seconds. Peak temperatures measure between 300 °C and 600 °C on modules at the same level or above the initiating module. Although these temperatures are far beyond critical levels, they do show that the suppression system lowered the risk for module-to-module propagation. Compared to the reference test, peak temperatures were reduced by about 100 °C at M2, M6, M7, M10 and M11. At the remaining modules, similar or slightly lower temperatures were observed. The temperatures between reference tests varies however also and this variation is in some cases in the same order of magnitude.

The system did not have much effect on the modules directly above the initiating module, M3 and M4. The agent may have struggled to reach this part of the rack which may be a consequence of the test conditions as the door to the container was open during the test. This affected the conditions within the container significantly for the mist system and hindered total flooding conditions to be reached due to the air draft.

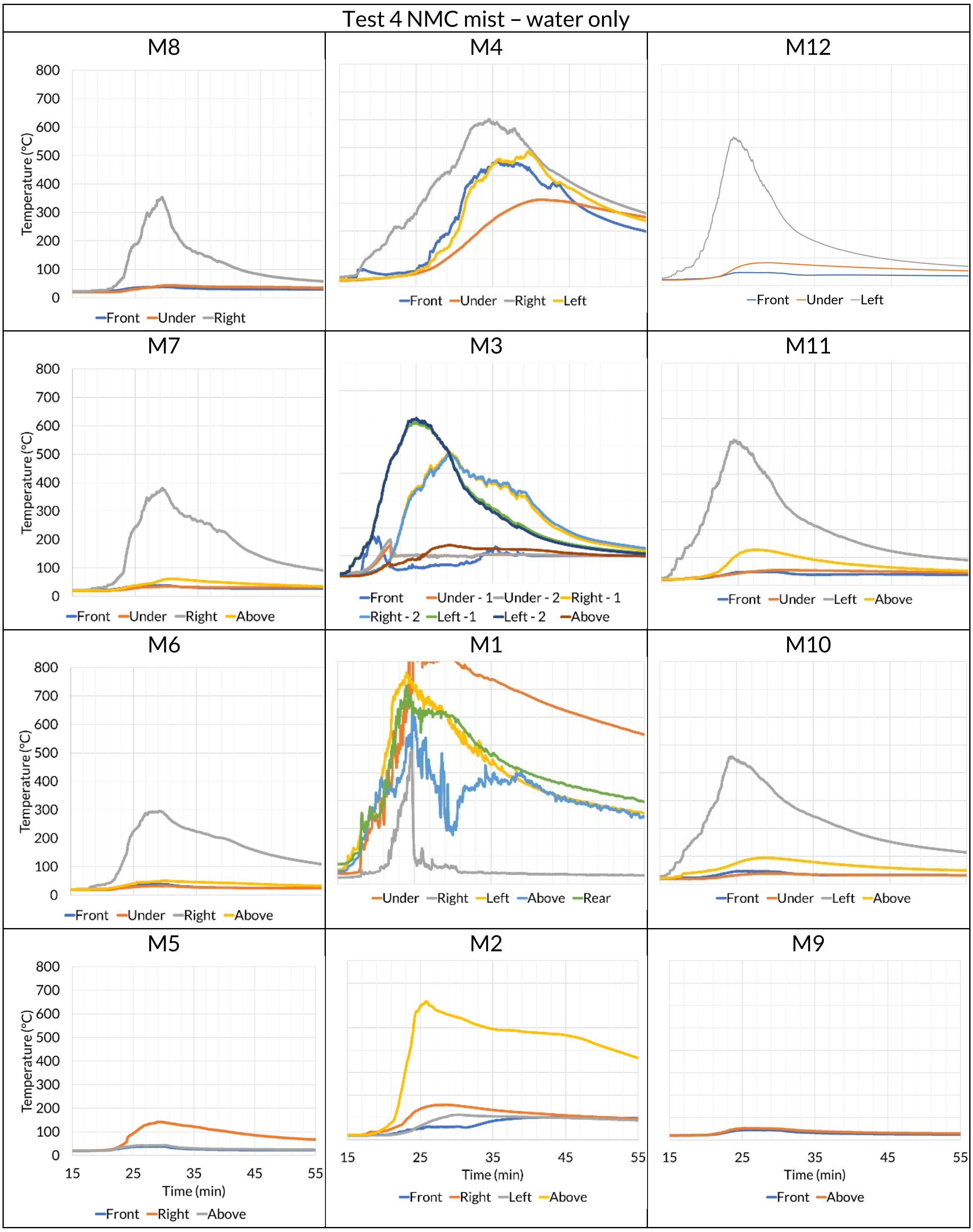


Figure 67 External surface temperatures: Test 4 – NMC – Mist - Water

The internal temperatures and plate-thermometer measurements for Test 4 are shown in Figure 68. The thermal runaway initiation and propagation in M1 was very similar to what was observed in the reference test. Temperatures in the module above, however, were not. The temperatures increased slowly to about 100 °C and are then constant. This shows that water from the suppression system penetrated M3. As such, temperatures remained at 100 °C. It is worth noting however that this test did not evaluate potential issues due to water reaching into a module as one might experience with live modules. Water within the dummy modules may however increase the uncertainty of the tests. That is, water may remain within the module after a test and thus affect temperatures during a later test. It is therefore important to make sure that each test is started with dry sand and that the conditions are similar for the systems to be tested, this can be e.g. to exchange dummy modules if it they become bent so that water can enter the module.

The effect of the mist system is most significant when it comes to lowering the risk for propagation to the opposite row of racks. As seen in Figure 4, peak temperatures are about 50 °C, which is much lower than the 170°C - 175°C observed in the reference tests. This is probably mainly due to cooling the Plate-Thermometers rather than lowering the fire in the initiating module.

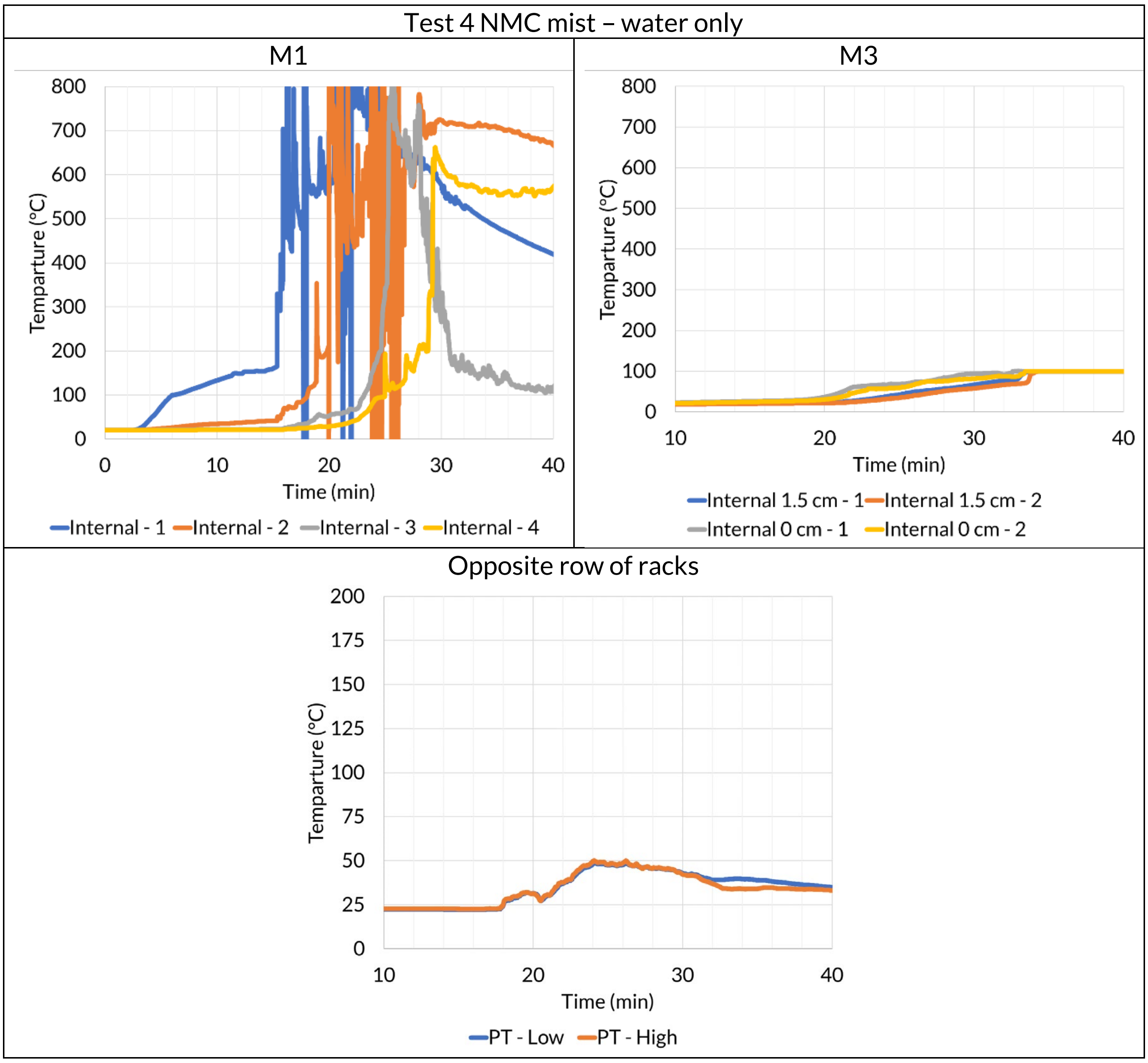


Figure 68 Internal temperatures and plate-thermometers: Test 4 – NMC – Mist - Water

Test 6 NMC – sprinkler with water

The surface temperatures in the test setup during Test 6 can be seen in Figure 69. This is a test using a standard sprinkler system with water as agent. The system was activated at time 16 minutes and 25 seconds. Peak temperatures in the test setup at modules on the same level and above M1 were around 100 °C – 600 °C. The overall performance of the sprinkler system was thus very positive, reducing temperatures significantly at most modules. The most significant effect of the sprinkler system is seen on the uppermost modules. At M8 and M12, temperatures are kept below 100 °C. This is a significant improvement compared to the 400-600 °C observed in the reference tests. The cooling effect was also noticeable on M11. Temperatures that were as high as 600 °C in the reference test, were now limited to 250 °C.

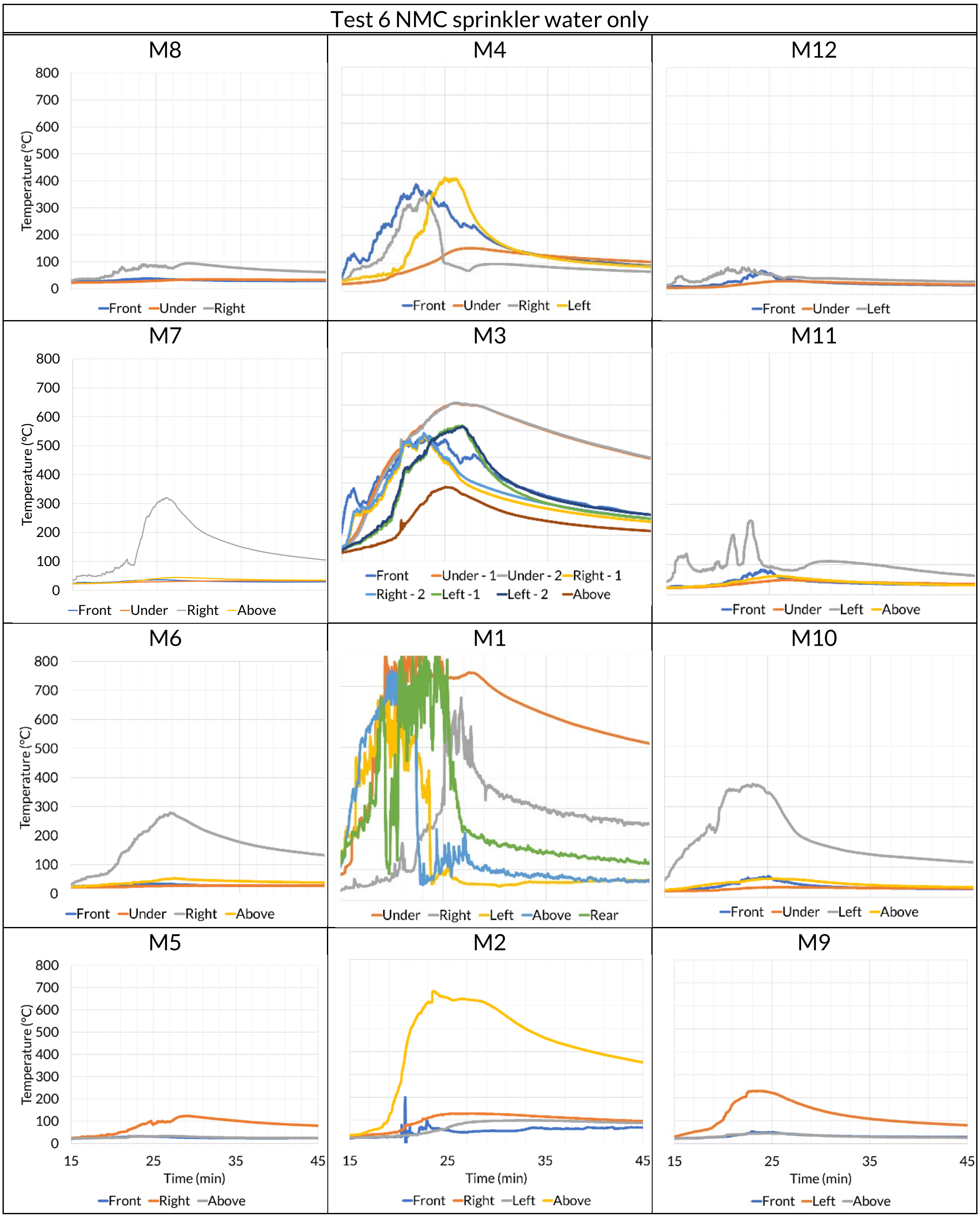


Figure 69 External surface temperatures: Test 6 – NMC -Sprinkler - Water

Figure 70 shows internal temperatures, signals from the gas alarm, and the temperatures recorded by plate-thermometers. Thermal runaway started earlier in this module, but it appears to take more time for it to propagate to the other areas in M1 compared to the reference test. Once it reached “Internal – 2” however, the temperature development becomes similar. Inside M3, temperatures reduced slightly.

The CO gas alarm was the first one to activate, see Figure 6. Its activation corresponds to the time when thermal runaway has propagated near to “Internal – 2”. The alarm stops briefly, then remains active if the live module burns. Alarms for flammable gas concentrations were triggered slightly before and after the 20 min mark when temperatures at “Internal -3” grow quickly.

The sprinkler system was also successful in lowering the risk for propagation to the opposite row of racks. Like the mist system, temperatures are kept to about 50 °C here.

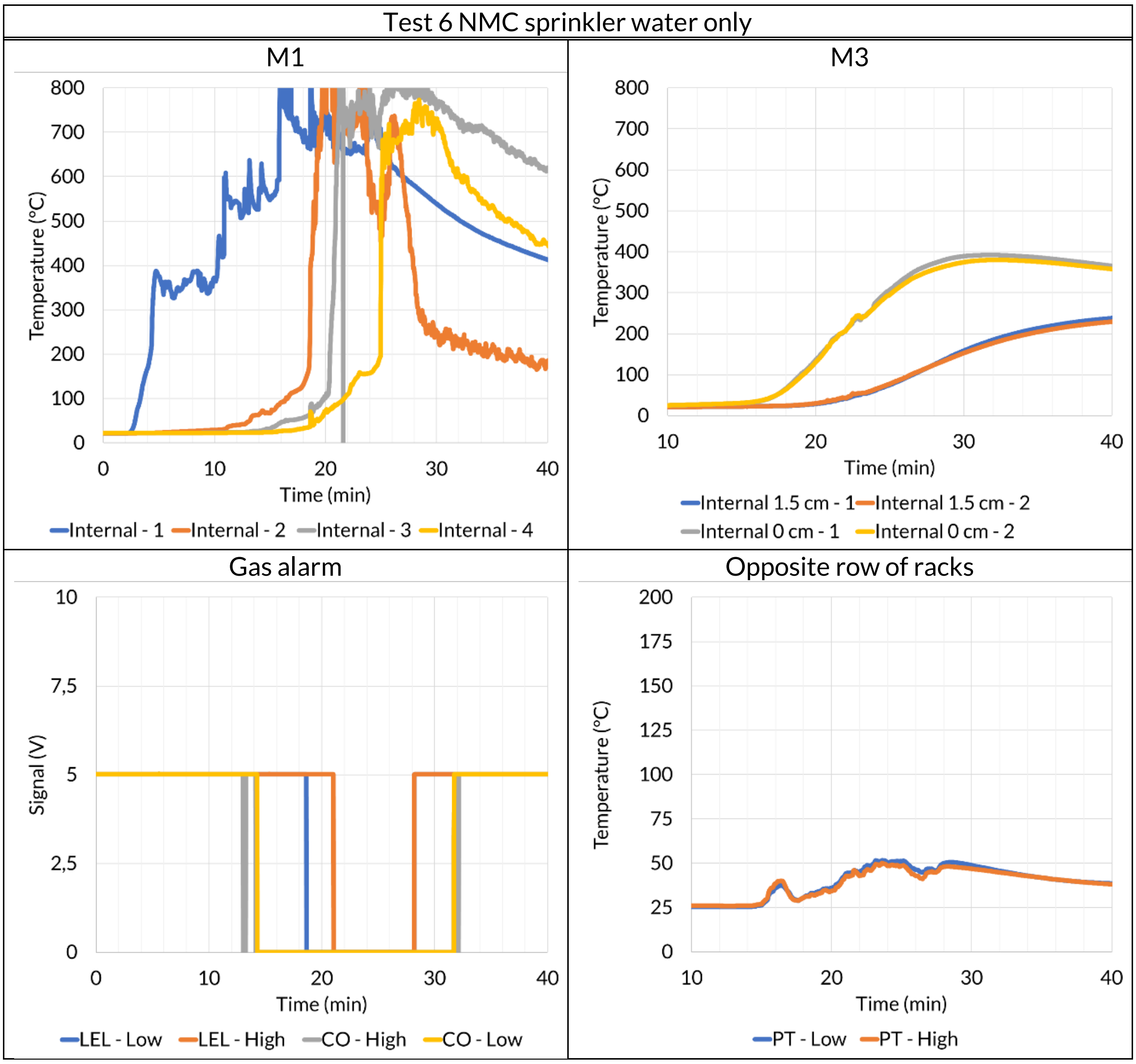


Figure 70 Internal temperatures and plate-thermometers: Test 6 – NMC -Sprinkler - Water

Test 7 – NMC – water mist with additive

External surface temperatures in the battery racks during Test 7 where water mist with 3% F500 added was used, are given in Figure 71. The system was activated at time 17 minutes and 41 seconds. Peak temperatures are in the range of 200 °C – 600 °C. Comparing this test with Test 4 where water only was used in the mist system one can see a difference when looking at M2 and M8. At M2, the peak temperature here is limited to about 400 °C as compared to 600 °C for Test 4. For M8, temperatures were

200 °C compared to 350 °C in Test 4. For all other modules the temperatures are about the same. It can however not be ruled out that any differences seen are due to differences in flame direction or differences in mist spray pattern due to other air draft conditions.

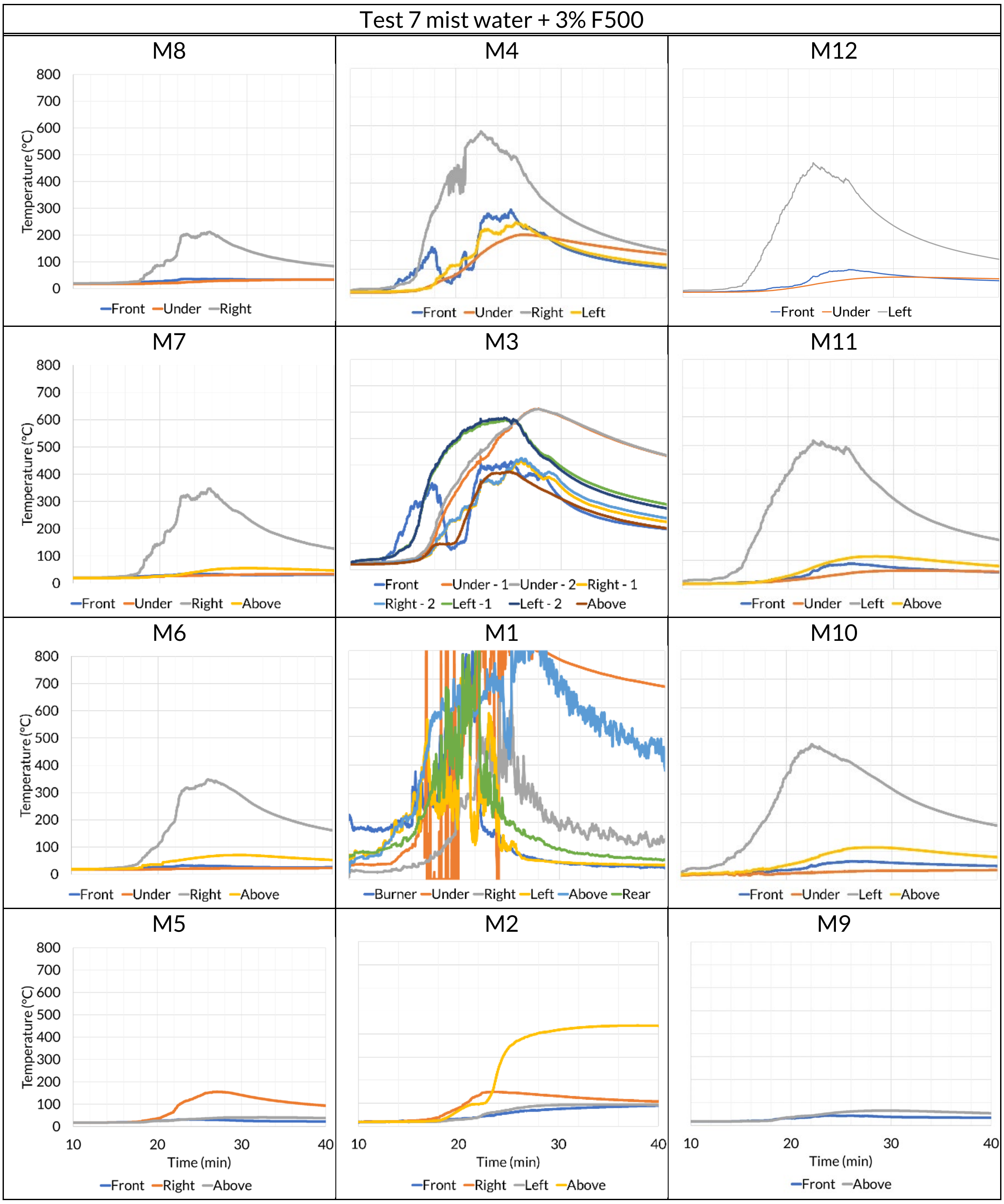
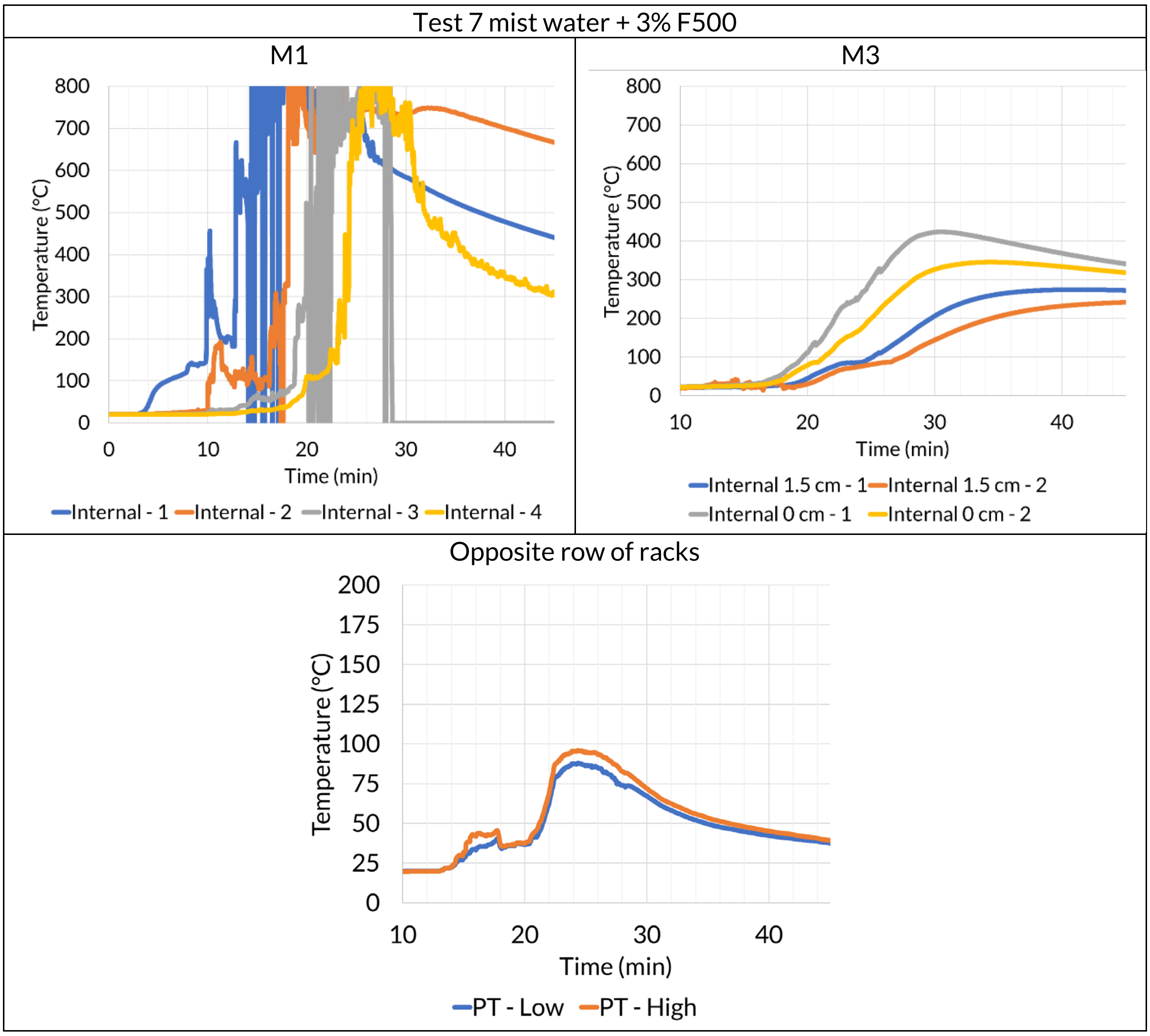


Figure 71 External surface temperatures: Test 7 – Mist – Water + 3 % F500

The remaining temperatures from Test 7 are shown in Figure 72. It took slightly less time for thermal runaway to start in this case. The subsequent propagation appears however like what was observed before.

Temperatures inside M3 were similar to what was observed before in the sprinkler tests. These results may appear much worse when compared to Test 4 as water seems not to have been able to enter inside the module. It cannot be determined if this is a result of the additive preventing the water to creep into the module or if the tape sealing of the module lasted better in this test.

On the opposite row of racks, see Figure 8, temperatures were slightly higher when the additive was used. In this case, about 80-90 °C was observed compared to 50 °C without the additive. The difference is small however, and it cannot be said whether this is a direct result of the additive or of other factors.


Test 7 mist water + 3% F500

M1

M3

Opposite row of racks

Figure 72 Internal temperatures and plate-thermometers: Test 7 – Mist – Water + 3 % F500

Test 8 NMC – Sprinkler with additive

Results showing external surface temperatures in Test 8 where a sprinkler with 3% F500 added was used, are shown in Figure 73. The system was activated at time 17 minutes and 7 seconds. Peak temperatures of 100 °C – 500 °C were observed. Compared to Test 6, where only water was used, the results are quite similar. The most significant difference is found on M2, where temperatures are kept to 500 °C rather than 100 °C.

Some temperature peaks appear to last shorter time in this case. This can be the result of water inside modules. At several locations, temperatures are kept to about 100 °C for at least some time. Specifically, at M4, M6, M7, M7, M11 and M12. This suggests that water entered these modules. In some cases, temperatures increase again after hovering at 100 °C. This might correspond to the water having evaporated.

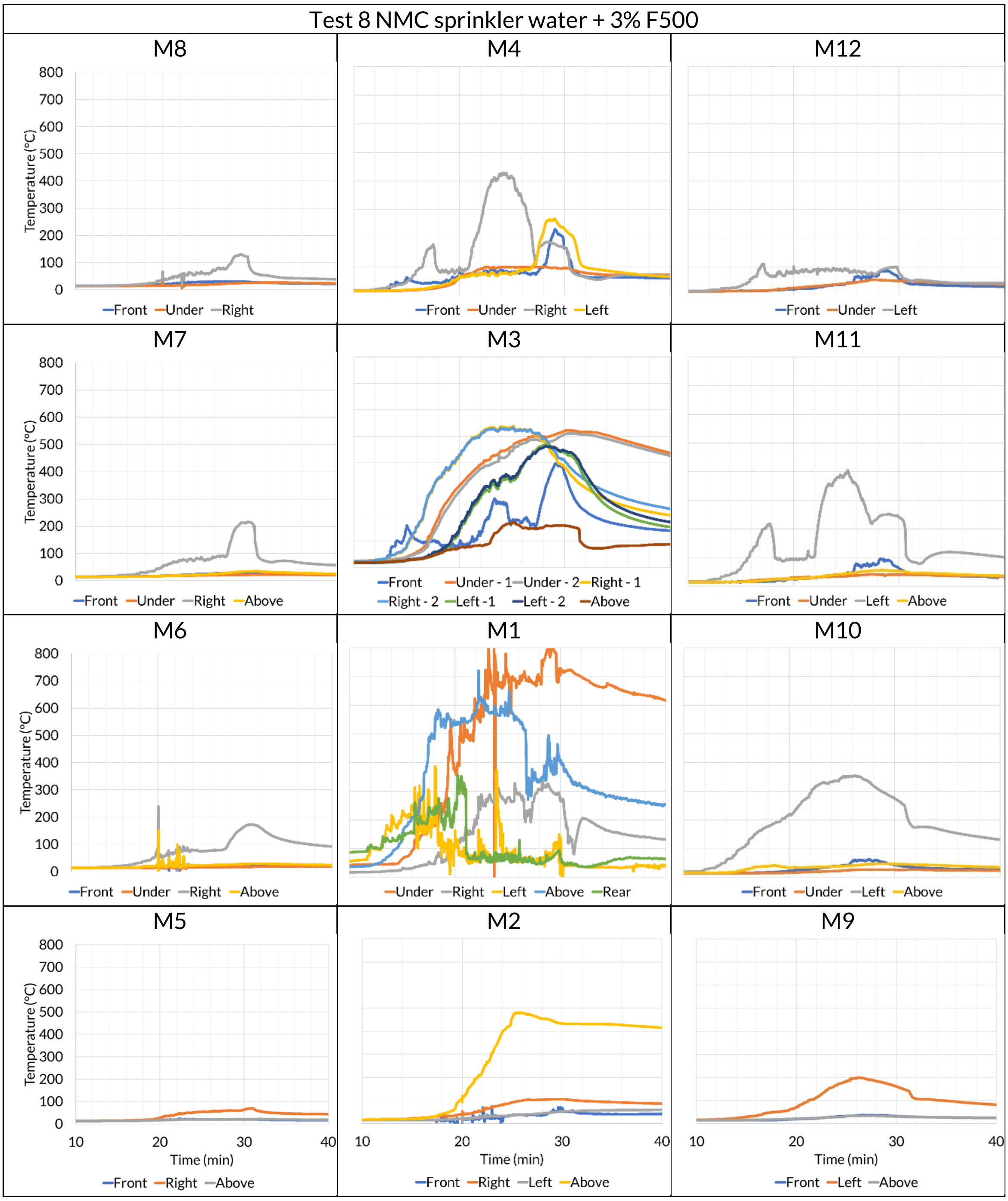


Figure 73 External surface temperatures: Test 8 – NMC – Sprinkler – Water + 3 % F500

Figure 74 shows the other temperatures as well as signals from the gas alarms. It took slightly longer time for the thermal runaway to start. The propagation behavior looks however comparable to Test 6.

Temperatures inside M3 were very similar to the test with water only (Test 6). It can be seen in Figure 10 that some water was able to enter M3. This likely evaporated eventually since temperatures continue to increase beyond 100 °C.

The CO gas alarms were triggered around the time when temperatures started growing at “Internal -2”. This was also observed in Test 6. Once temperatures at “Internal 4” increase as well, the CO alarm is triggered again and remained active until there was no more activity in M1. The flammable gas alarm was not triggered in this test.

Temperatures measured by the plate-thermometers at the opposite row of racks were slightly higher in Test 8 than in Test 6. They were about 65 °C in this case. Interestingly, this was also observed when comparing the water mist tests. When the additive was used, temperatures were higher at the opposite row of racks.

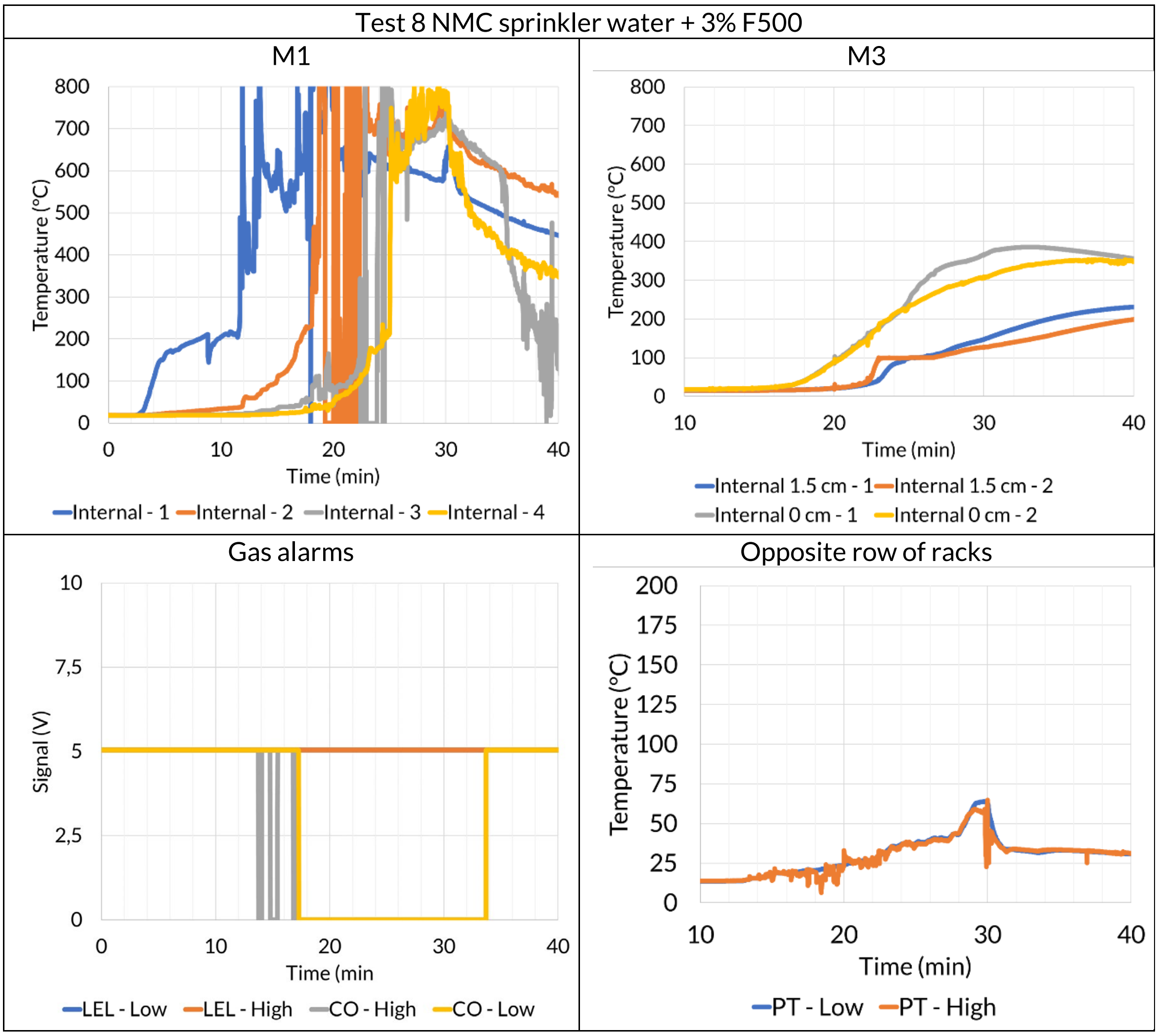


Figure 74 Internal temperatures and plate-thermometers: Test 8 – NMC – Sprinkler – Water + 3 % F500

Test 10 NMC - local application water

Results from the local application system with water only are given in Figure 75. The system was activated at time 15 minutes and 20 seconds. Peak temperatures in the range of 200 – 600 °C were observed on modules at the same level and above M1.

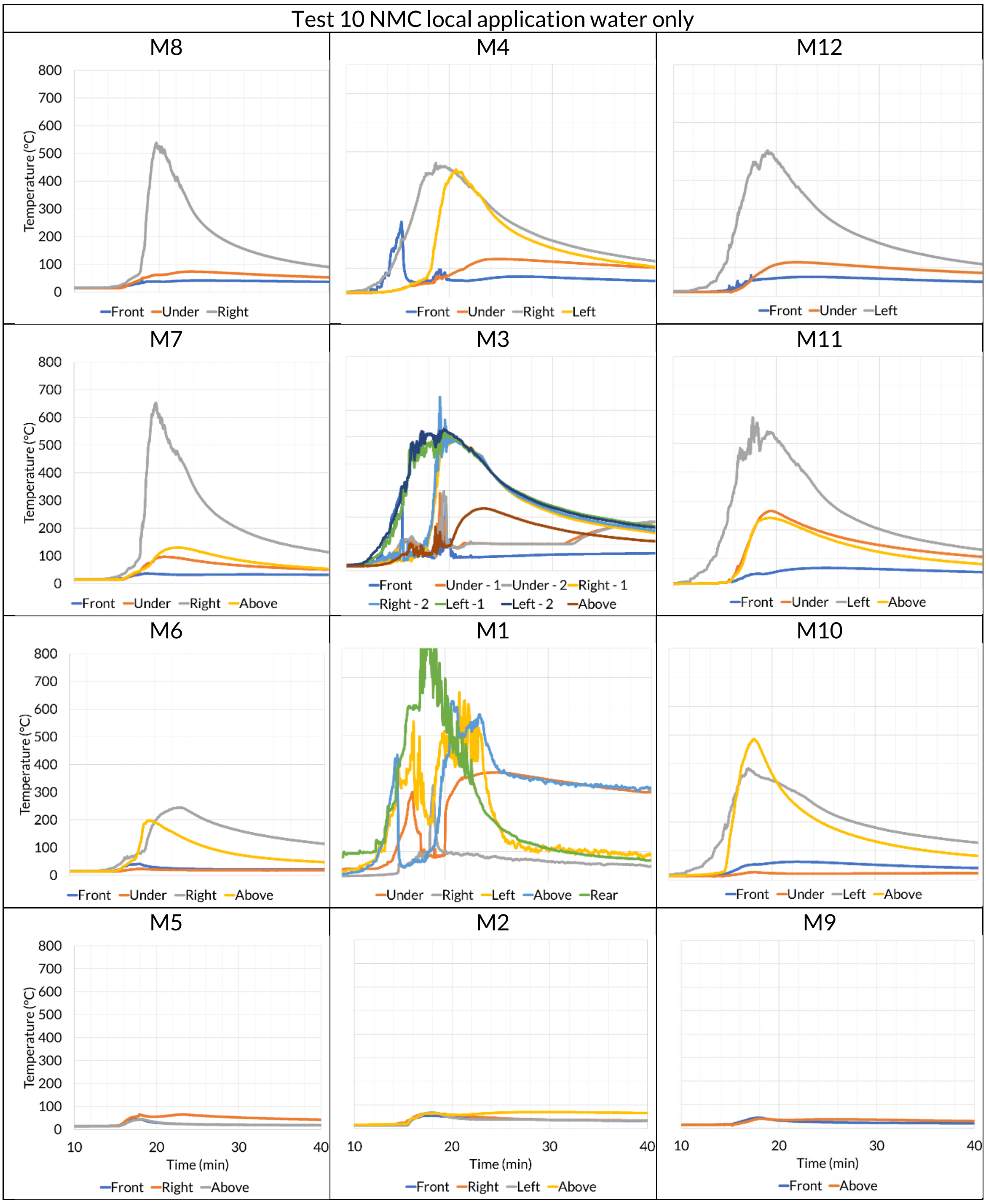


Figure 75 External surface temperatures: Test 10 – NMC – Local - Water

The effect of this system is most significant at M1, M2, and M3. At M1 temperatures were kept to 100 °C – 500 °C compared to 400 °C-800 °C in the reference test. Temperatures were not affected at the rear of M1 however as might be expected as this location is hidden from the suppression system. Also, it was observed already before the activation of the fire suppression system that flames were reaching more towards the rear of the modules. The temperature on M2 was held to less than 100 °C, a significant improvement over the 700 °C observed in the reference.

The temperatures underneath and on the front of M3 are much lower due to the fire suppression system. Specifically, they were limited to about 100 °C – 200 °C compared to 600 °C in the reference test. At the remaining locations, the local system was not effective. The impact on the lower parts of the racks is due to the localized spray directed towards M3 that resulted in water also running down to the modules underneath.

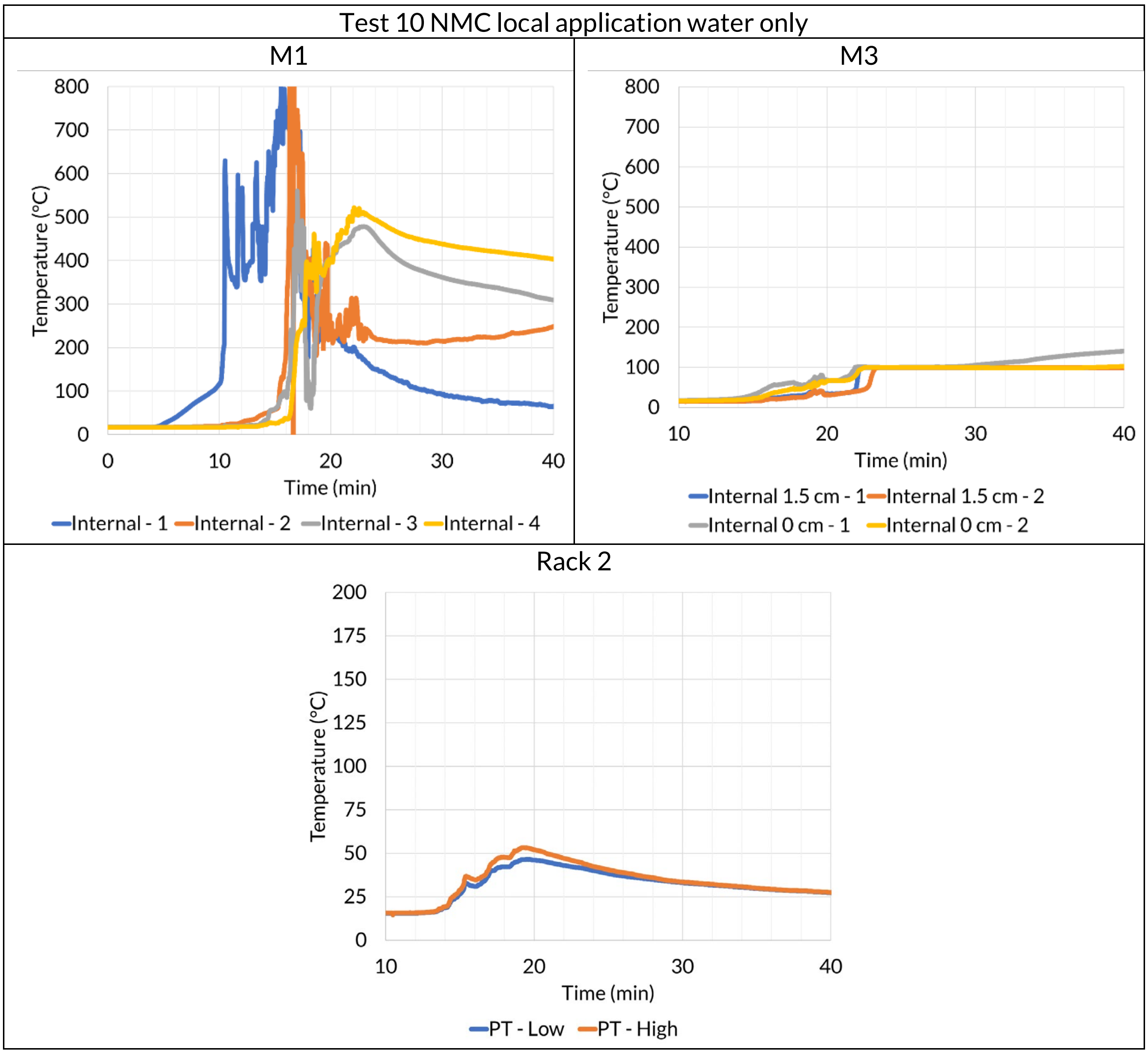


Figure 76 Internal temperatures and plate-thermometers: Test 10 – NMC –Local – Water

The remaining temperature measurements can be seen in Figure 76. The time to thermal runaway starts and subsequent propagation to “Internal 2” was similar to what was observed in the reference test. In this case however, once thermal runaway propagated to “Internal 2” it appeared to simultaneously involve the cells at “Internal 3” and “Internal 4”. As a result, the fire in M1 was more intense under a shorter period than what was observed in the other tests. This is likely related to the M1 used here had a different design than the M1 in the reference test.

Temperatures inside M3 were kept to about 100 °C. As seen before, this most likely meant that water penetrated the module casing. Finally, the system was effective at lowering the risk propagation to the opposite row of racks. The temperatures at the opposite rack position were limited to 50 °C which is a significant improvement over the 175 °C observed in the reference test.

Test 14 NMC – Local application AVD

External surface temperatures from Test 14 with the local application with additive, are presented in Figure 77. The system was activated at time 15 minutes and 41 seconds.

Here it is seen that there were significant temperatures near the front and right of M3 for a while before temperatures underneath increased. This was a different behavior from other tests which resulted in a delayed activation of the system as it took longer time for the activation criteria to be reached. Once the temperature underneath went up, temperatures grew very quickly. As such, the challenge faced by the suppression system in this test was different from what was observed in the other tests

The temperatures in this test are higher on modules at the same level or above M3. It cannot be determined if this is an effect of the different fire development in this case or if it is an effect of the media insulating the modules keeping the heat within the module. Temperatures at M2 are significantly lower here, however. They yield a maximum of 200 °C, an improvement compared to the 700 °C seen in the reference test.

Internal temperatures and the temperature recorded by plate-thermometers are seen in Figure 78. The initial thermal runaway stage was like that seen in other tests. It then appeared to have involved other areas of the module simultaneously, based on the rapid temperature increase that occurs around the same time at the other internal measurement points in M1.

The effect of the intense fire results in temperatures of 600 °C- 800 °C in M3. These were significantly higher than what was observed in the reference test. Temperatures at the opposite row of racks were kept below 75 °C.

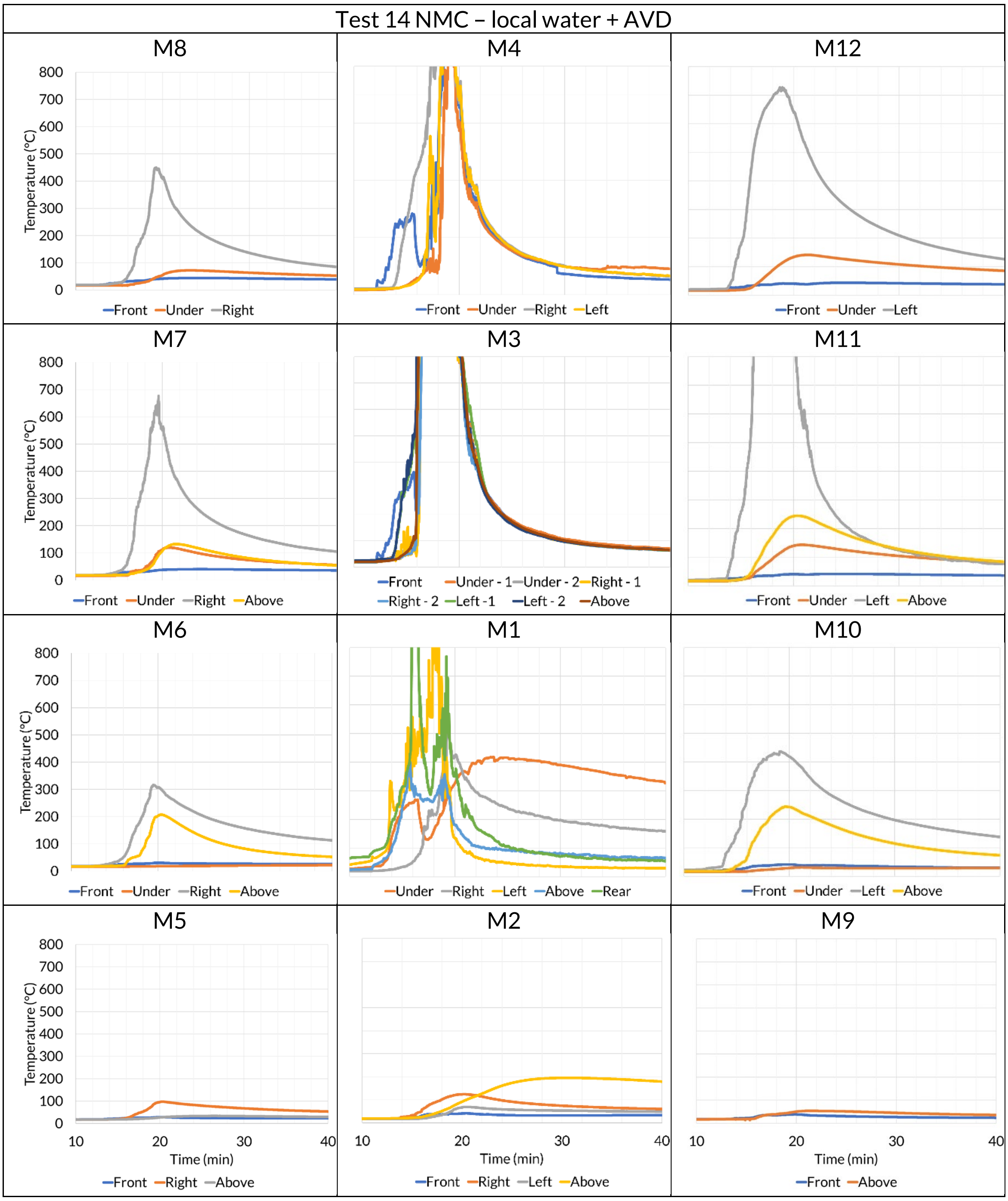


Figure 77External surface temperatures: Test 14 – NMC – Local - Water + AVD

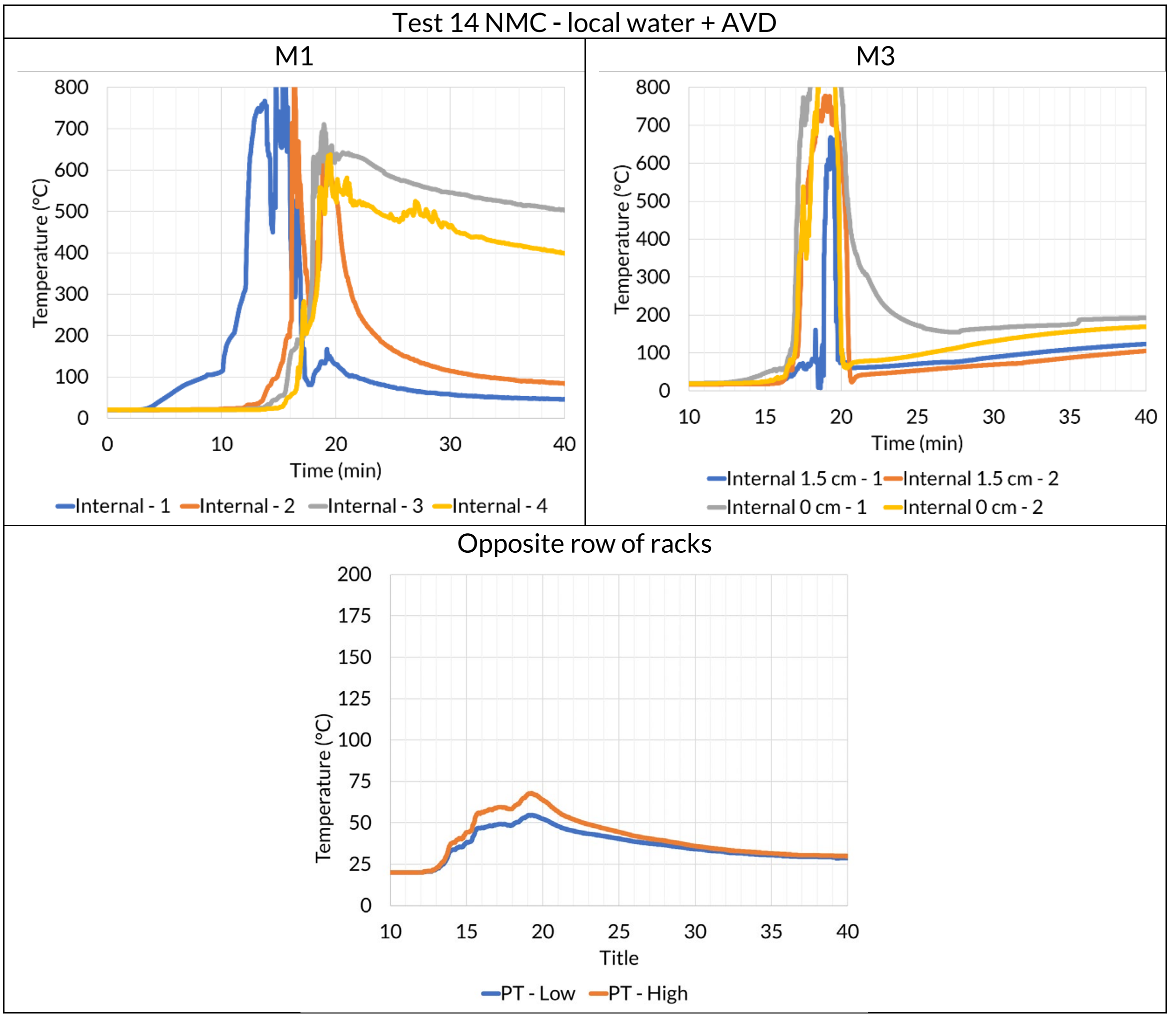


Figure 78 Internal temperatures and plate-thermometers: Test 14 – NMC – Local - Water + AVD

Test 11 – NMC gaseous

External surface temperatures from Test 11 with the gaseous system are seen in Figure 79. The system was activated at time 13 minutes and 25 seconds. Peak temperatures were limited to 100 °C – 300 °C compared to 400 °C - 600 °C in the reference test. The positive effect of this system is observed on all dummy modules in the test setup. The system also appeared to limit temperatures on the surface of the live module. These were kept to 300-600 °C compared to 600 °C -800 °C in the reference test.

Internal temperatures, gas alarms and plate-thermometer measurements are shown in Figure 80. Within M1, thermal runaway is initiated relatively early. There was not much of a delay between when temperatures grew quickly at “Internal 3” and “Internal 4”.

The gaseous system was very effective at quickly regaining control over temperatures inside M3. They were limited to about 100 °C-200 °C whereas in most other tests they would reach about 200 °C-400 °C.

The gas alarms all activated shortly after the gaseous system was released. Temperatures at the opposite row of racks were kept below 50 °C.

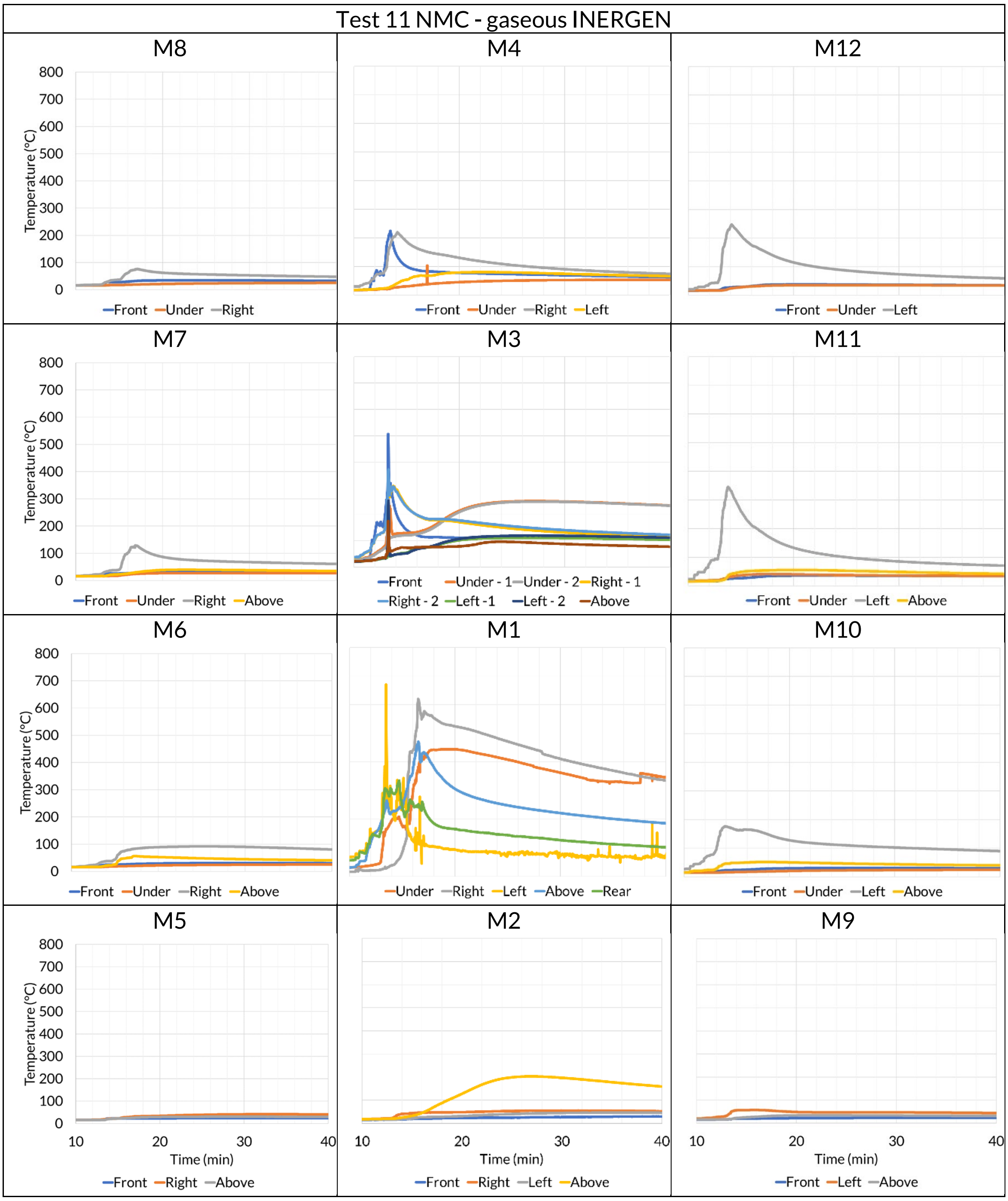


Figure 79 External surface temperatures: Test 11 – NMC – Gaseous - INERGEN

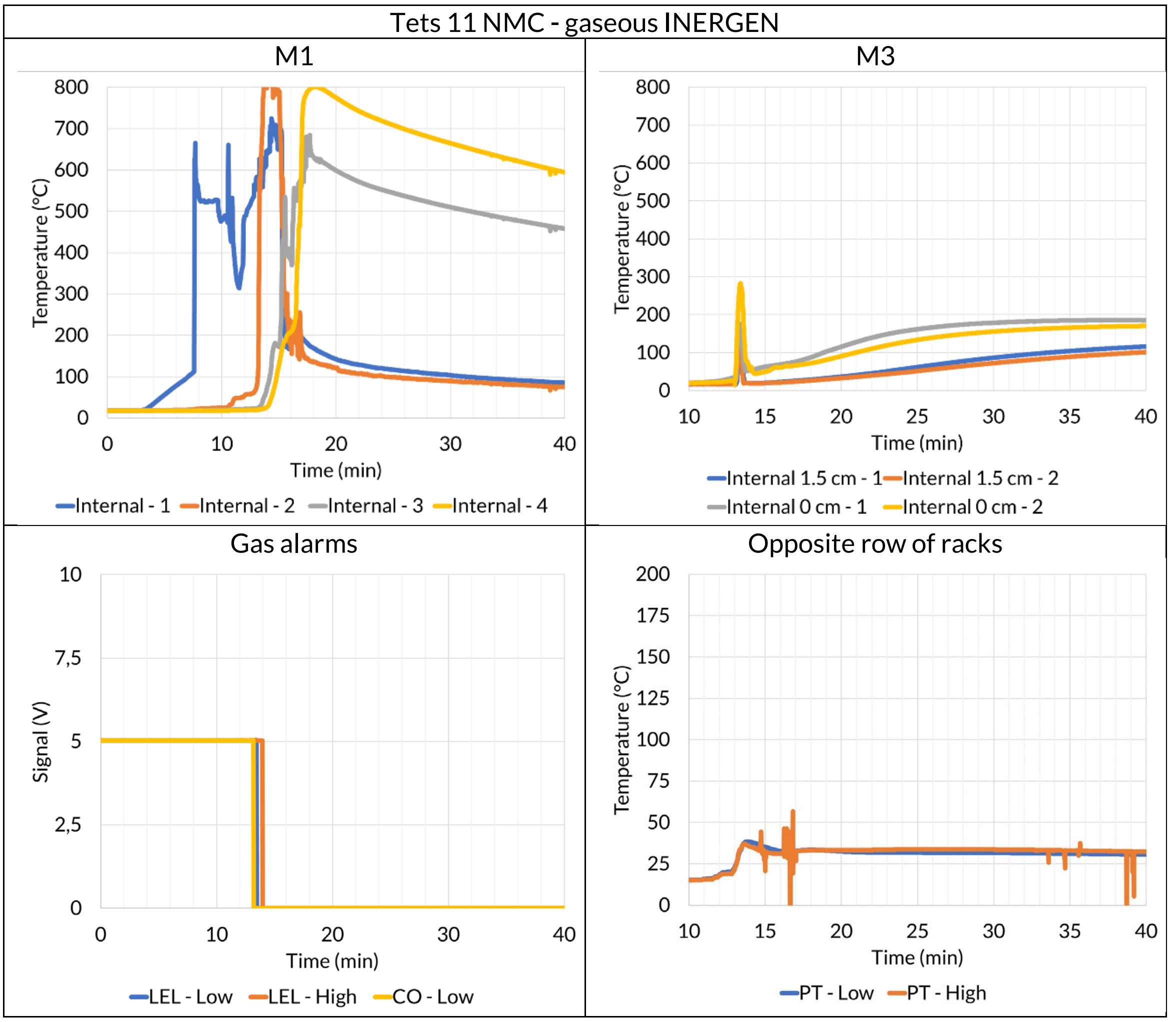


Figure 80 Internal temperatures and plate-thermometers: Test 11 – NMC – Gaseous - INERGEN

Second test series – LFP tests

Results from tests performed on LFP modules during the second test series are presented and discussed here. The focus is on discussing the effect of the fire suppression system rather than the test setup.

Test 3 LFP reference test open container

External surface temperatures during the reference test with a LFP module are shown in Figure 81. The trigger criteria were reached at time 67 minutes and 26 seconds. As very little happens before this point, the scale starts from 60 minutes.

The temperature distribution is similar to what was seen for the NMC modules tests where most of the heat spread upwards and to the right. In general, the temperatures are lower, reaching 100 °C – 500 °C at modules on the same level or above the live module M1. For M3, temperatures are most significant at the front and right of the module, i.e. the side where the initiating burner was placed. The scenario here is less severe than what was observed in the NMC tests. Modules to the left and below M1 are unlikely to suffer thermal runaway when only one module fails.

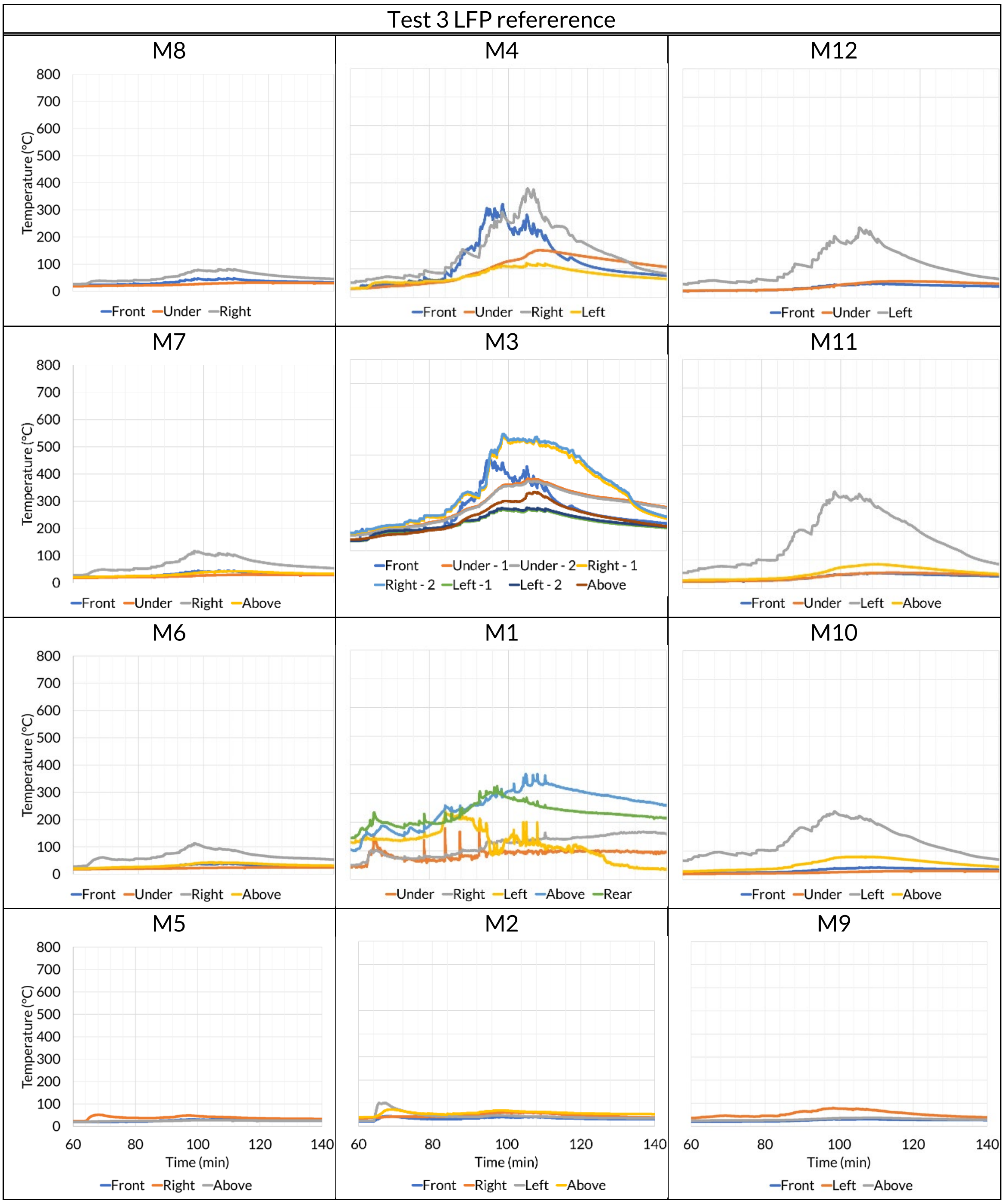


Figure 81 External surface temperatures: Test 3 – LFP

The temperature reading from the inside of M1 in Figure 82 shows that propagation took longer time to start than for the NMC tests. Thermal runaway starts around 40 minutes but then does not propagate to other areas until around time 70 minutes. Please note that the temperature scale starts at time 0 for the internal temperature for M1. The temperatures inside M3 are also lower than for the NMC tests. The temperatures at the opposite row of racks peak at less than 100 °C, meaning that it is unlikely that thermal runaway will be initiated at this location when only one module goes into thermal runaway.

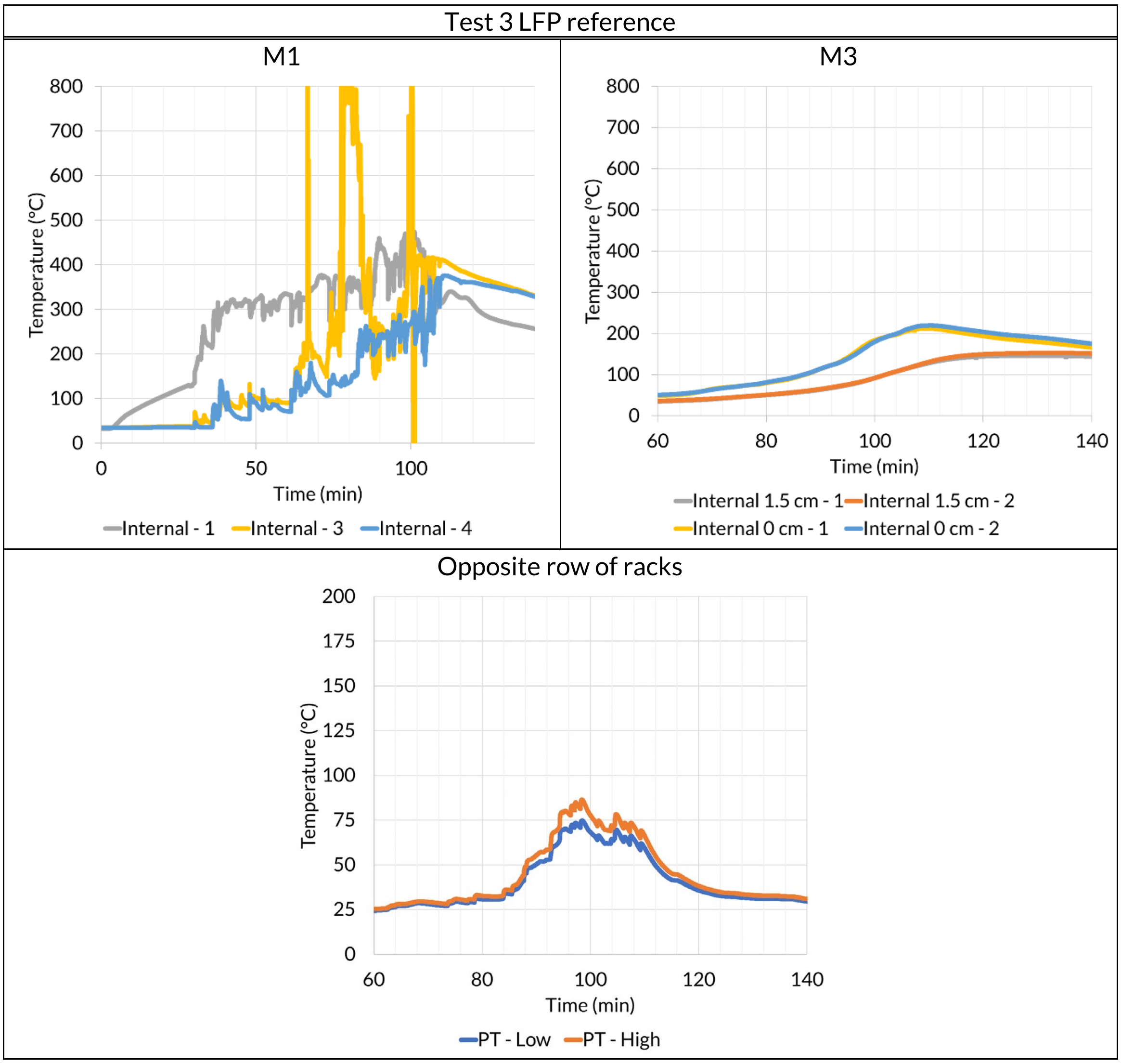


Figure 82 Internal temperatures and plate-thermometers: Test 3 LFP reference

Test 5 LFP water mist with additive

The temperature readings on the external surfaces for test 5 with water mist and additive are shown in Figure 83. As seen temperatures are in general low. A sudden peak is seen on the modules to the right of the live module when the fire suppression system is activated at time 47 minutes and 17 seconds. The system is on for 10 minutes in this case. The activity is lowered during this period but about 50 minutes after the system has been deactivated activity starts again. From the internal temperatures in Figure 84 it is seen that this activity in fact starts to increase already about 15 minutes after deactivation, but it is no seen very much on the external temperatures until later.

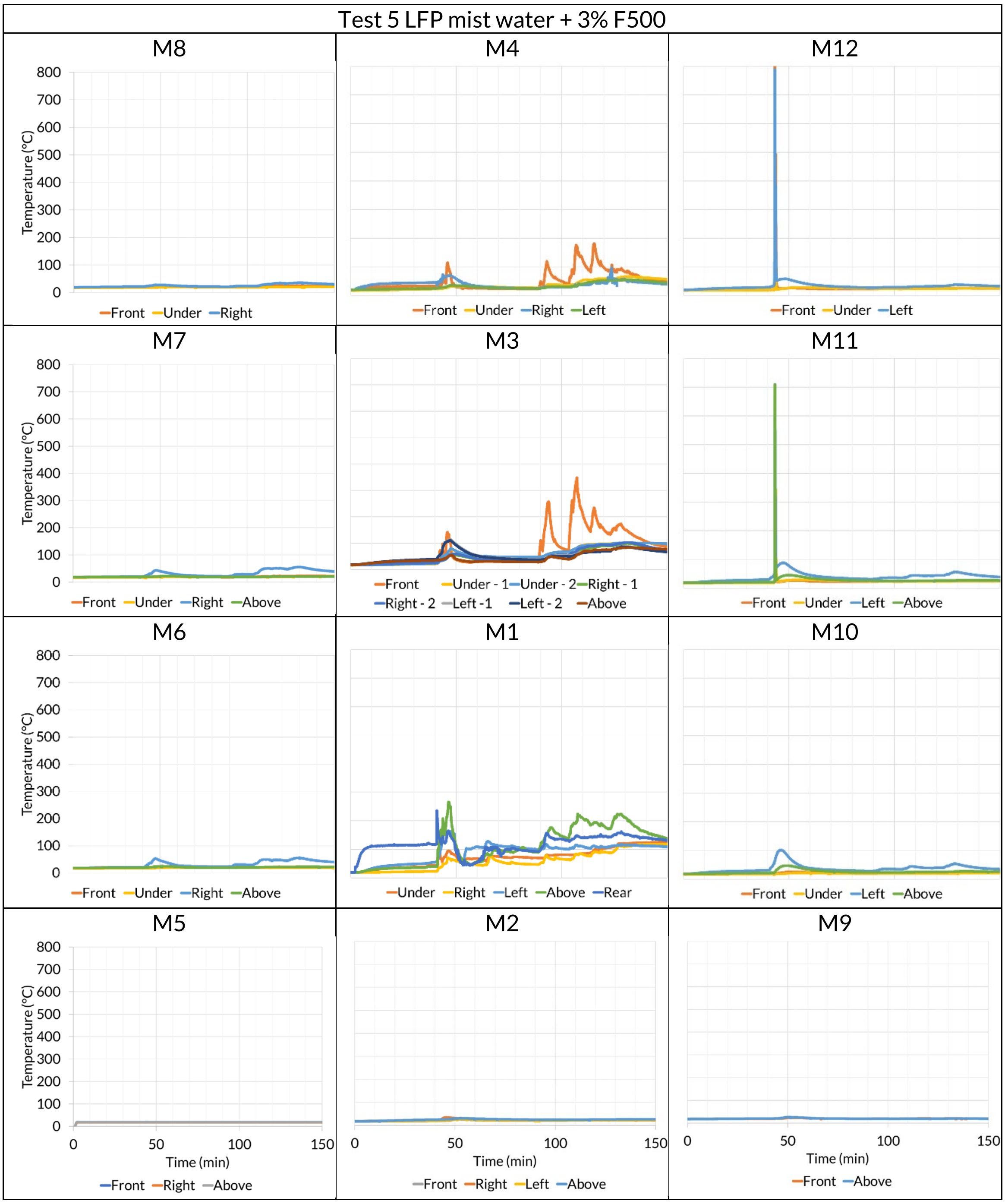


Figure 83 External surface temperatures Test 5 - LFP – Mist – Water + 3 % F500

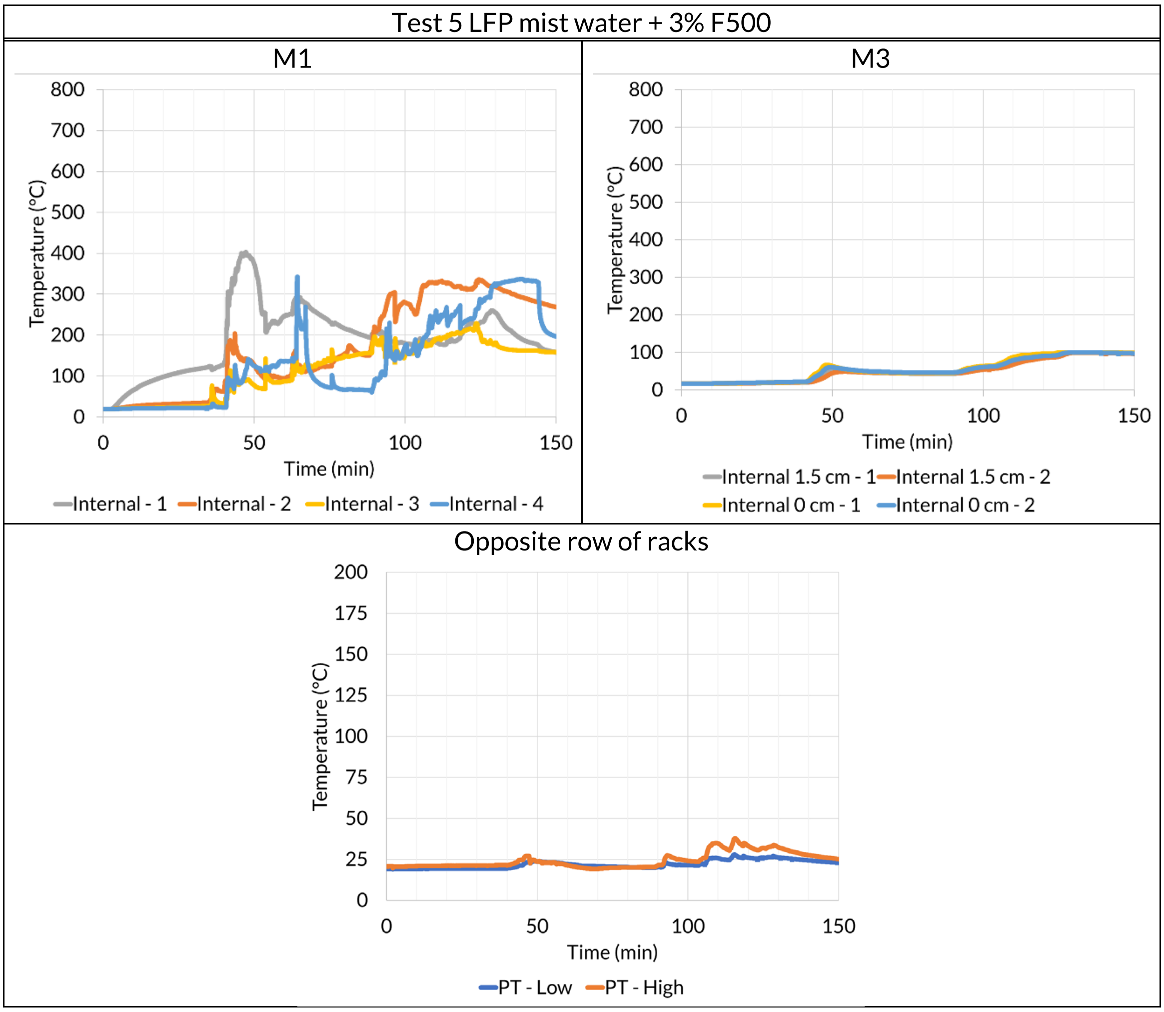


Figure 84 Internal temperatures and plate-thermometers: Test 5 – LFP – Mist – Water + 3% F500

Test 9 LFP - mist with additive

Figure 85 shows the external temperatures on the modules in Test 9 where a mist system was used with water as the extinguishing agent. The system was activated at time 48 minutes and 15 seconds. It was then active for 10 minutes. In this test, the door was a more closed compared to the other tests to mimic a total flooding concept. As seen in both Figure 85 and Figure 86, temperatures are higher than in the reference test on the front of the modules and at the opposite row of racks. It cannot be determined if this is due to a different propagation pattern from the beginning (the temperatures in M1 are higher as seen in Figure 86) or due to other reasons. For example, it is possible that the air draft was different, and thus affected the flames. In addition, activation of the mist system could also induce a draft and affect the flames. The flames were seen to increase around the same time the system activated.

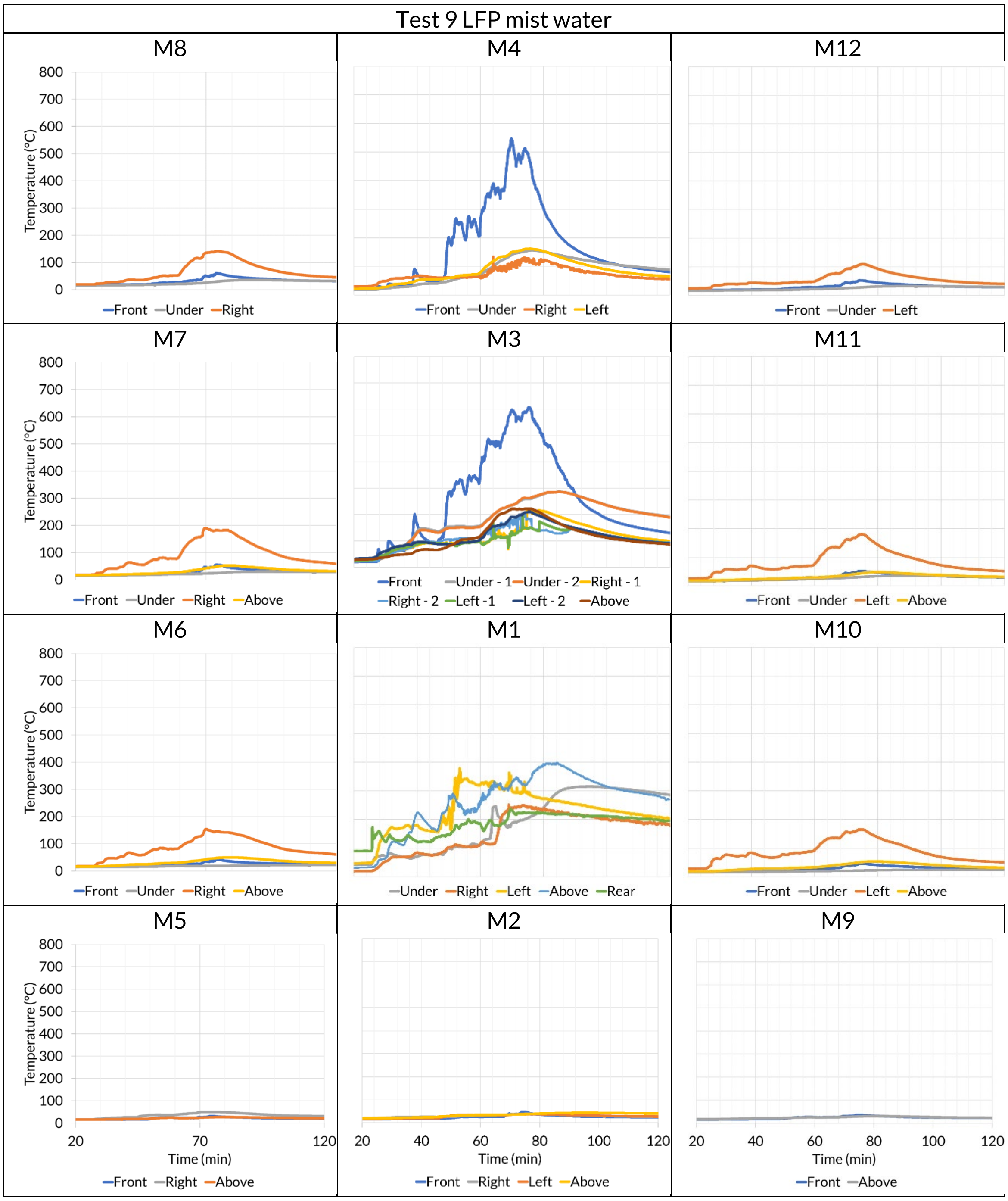


Figure 85 External surface temperatures: Test 9 – LFP – Mist – Water

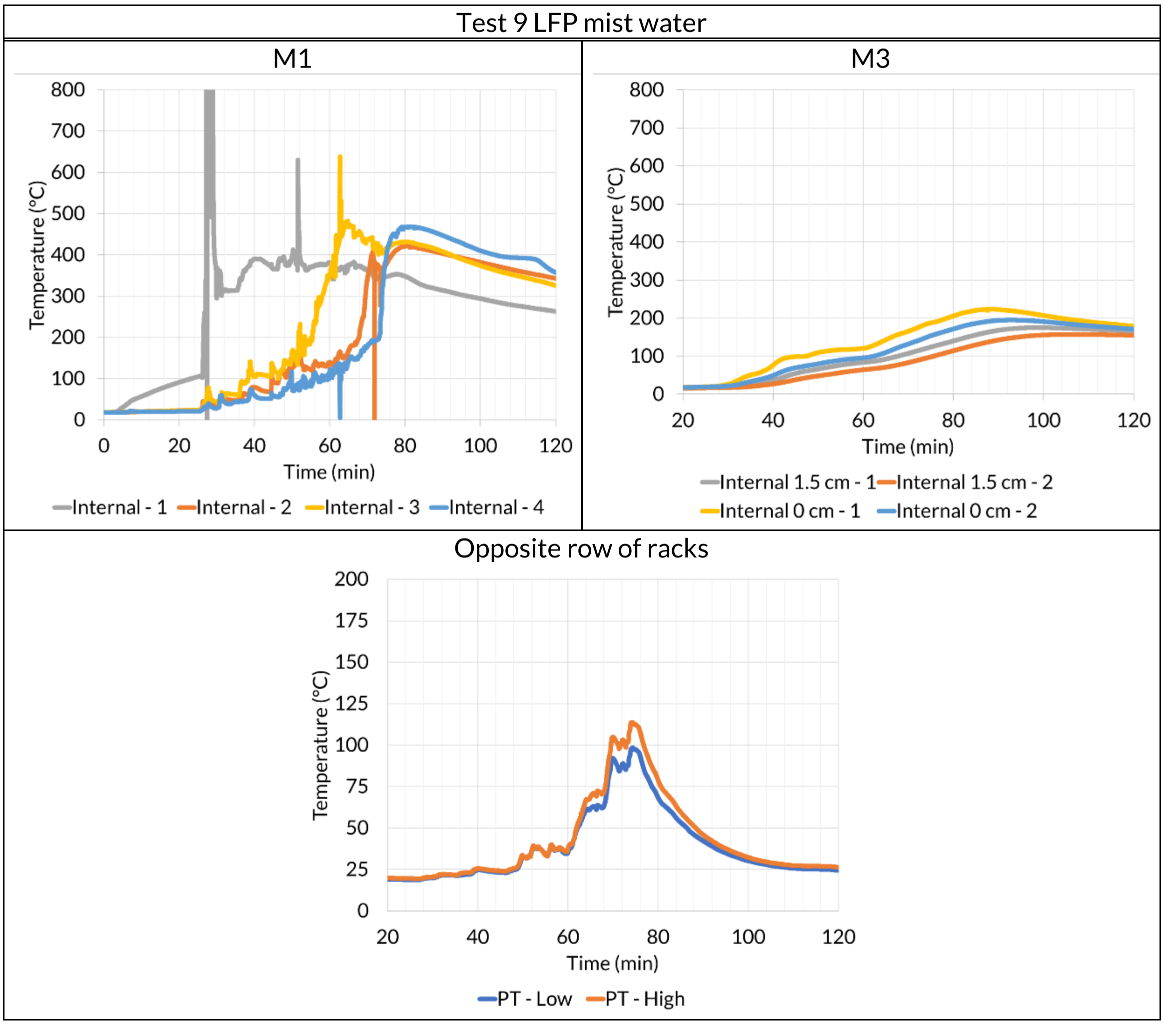


Figure 86 Internal temperatures and plate-thermometers: Test 9 – LFP -Mist – Water

Test 13 LFP gaseous system

The external temperatures on the modules in Test 13 with the gaseous suppression system are shown in Figure 87. The internal temperatures and temperatures on the opposite row of racks position together with gas alarms are shown in Figure 88. The system activates at time 75 minutes and 40 seconds. The time shown in the figures start from 20 minutes except for M1 internal in Figure 88 where the time starts at 0 minutes. All external temperatures are much lower, probably a result of extinguishing the flames. Temperatures at M3 are still high enough however for thermal propagation to be possible. This is unlikely for the remaining modules, as well as the opposite row of racks.

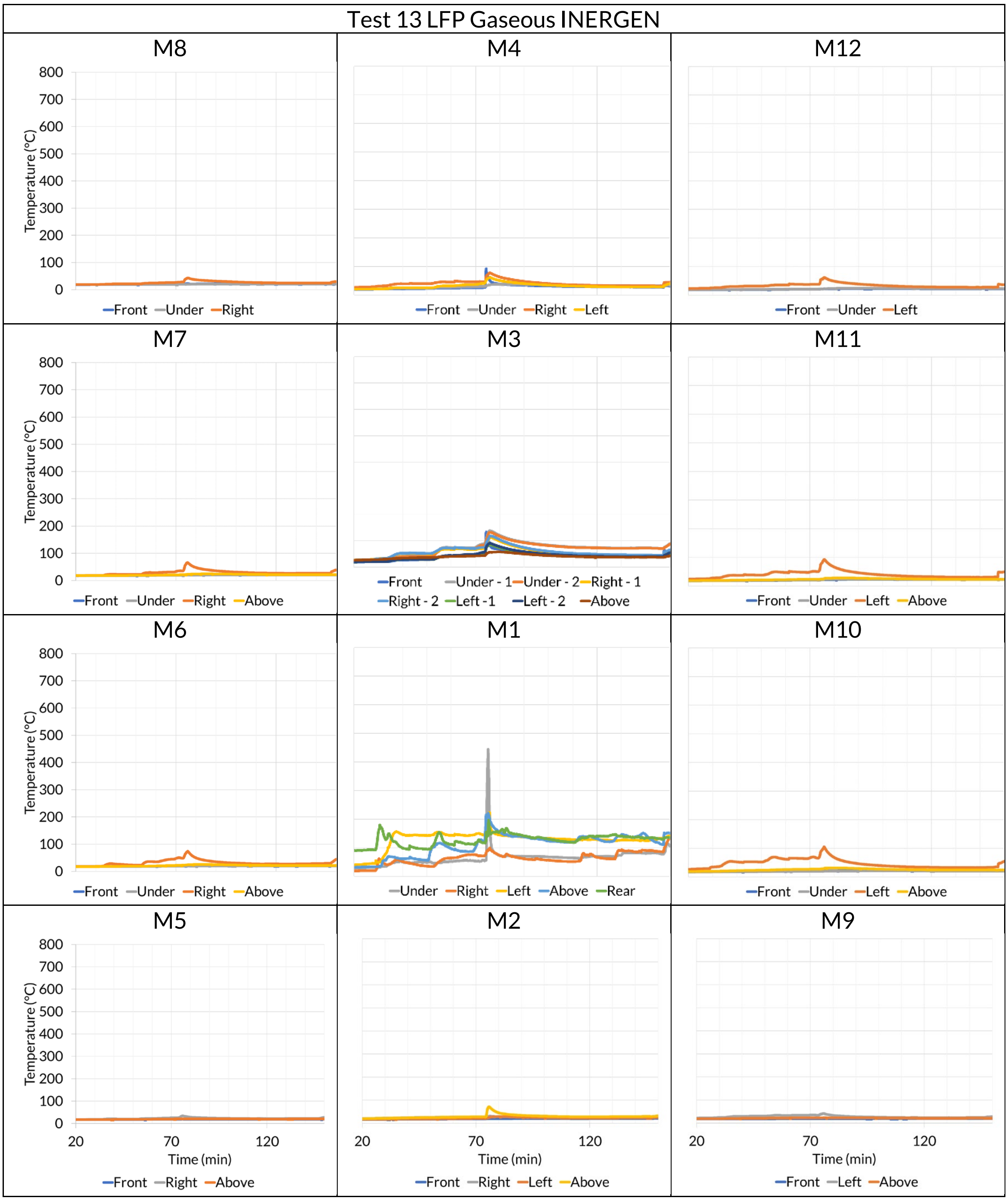


Figure 87 External surface temperatures: Test 13 - LFP -Gaseous INERGEN

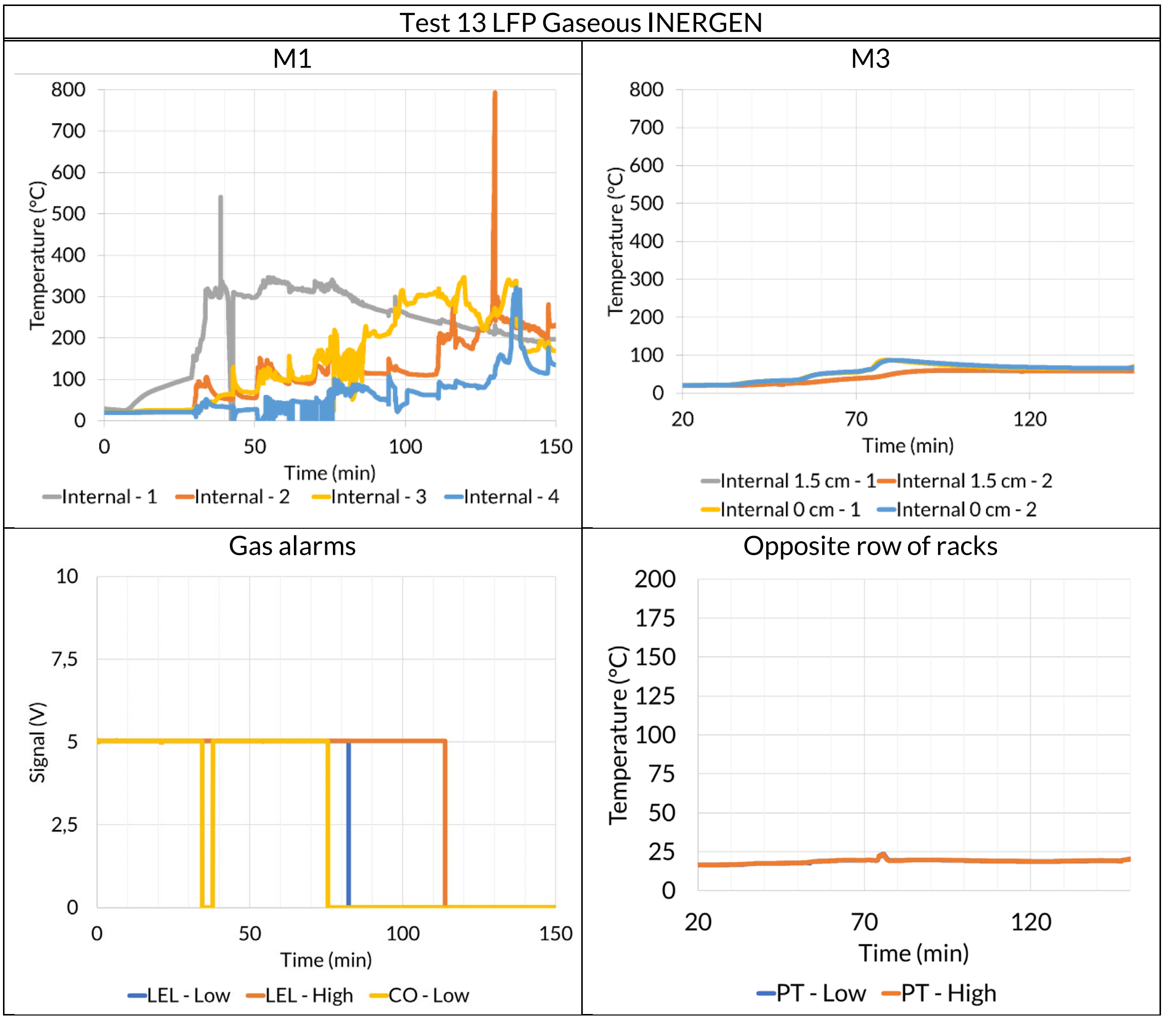


Figure 88 Internal temperatures and plate-thermometers: Test 13 – LFP – Gaseous INERGEN

Test 15 LFP reference test closed container

Test 13 with the gaseous system should be compared with results from a reference test using a closed and sealed container as conducted in Test 15. External temperatures of the modules from Test 15 are shown in Figure 89. Internal and opposite rack temperature together with gas alarms are found in Figure 90. In Test 15, the activation criteria were reached at time 87 minutes and 42 seconds. The time seen in the figures are from 50 minutes except for internal temperatures of M1 which start at 0 minutes. The temperatures here are lower than in Test 3 where the door was open. The closed container likely resulted in less oxygen being available and thus less efficient burning conditions. The temperatures were still significantly higher however when compared to Test 13 where a gaseous suppression system was used.

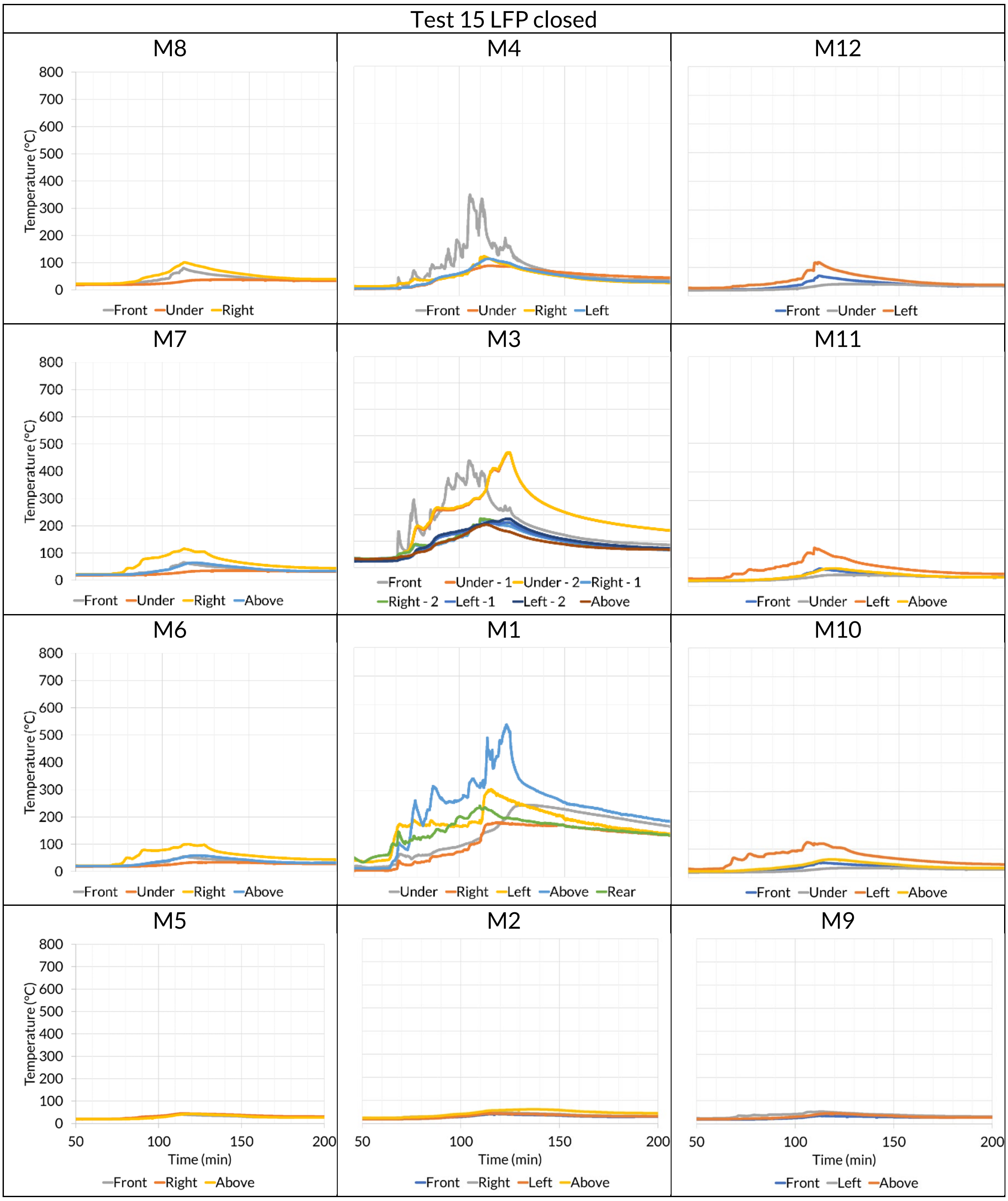


Figure 89 External surface temperatures: Test 15 - LFP – Closed

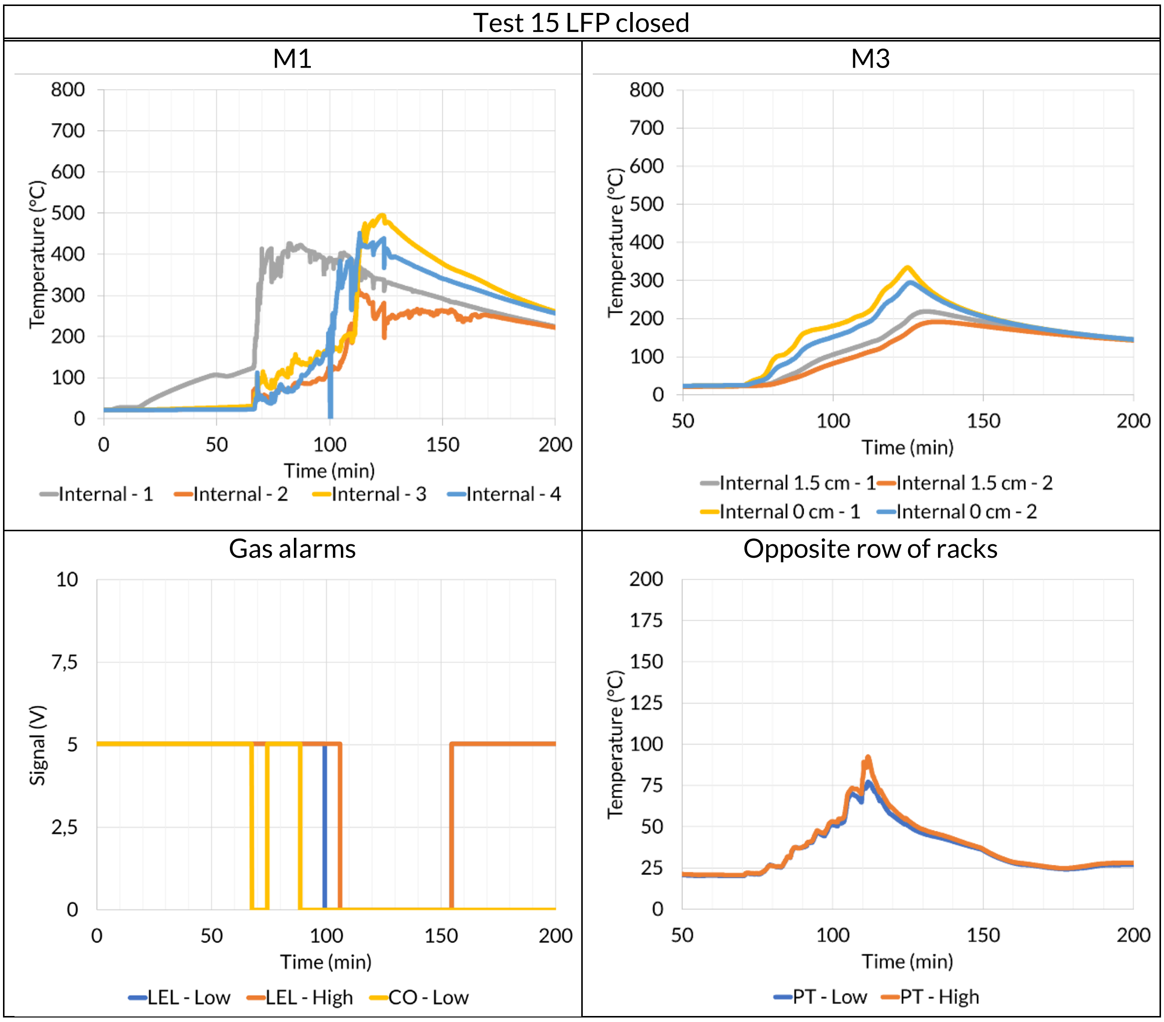


Figure 90 Internal temperatures and plate-thermometers: Test 15 – LFP - Closed

Through our international collaboration programmes with academia, industry, and the public sector, we ensure the competitiveness of the Swedish business community on an international level and contribute to a sustainable society. Our 2,800 employees support and promote all manner of innovative processes, and our roughly 100 testbeds and demonstration facilities are instrumental in developing the future-proofing of products, technologies, and services. RISE Research Institutes of Sweden is fully owned by the Swedish state.

I internationell samverkan med akademi, näringsliv och offentlig sektor bidrar vi till ett konkurrenskraftigt näringsliv och ett hållbart samhälle. RISE 2 800 medarbetare driver och stöder alla typer av innovationsprocesser. Vi erbjuder ett 100-tal test- och demonstrationsmiljöer för framtidssäkra produkter, tekniker och tjänster. RISE Research Institutes of Sweden ägs av svenska staten.

RISE Research Institutes of Sweden AB Box 857, 501 15 BORÅS, SWEDEN Telephone: +46 10-516 50 00 E-mail: info@ri.se, Internet: www.ri.se	Fire Safe Transport RISE Report 2021:111 ISBN: